Adaptive Multistage Parallel Interference Cancellation for CDMA

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Abstract— **An *adaptive* multistage parallel interference cancellation technique based on a partial interference cancellation (IC) approach [1] was proposed in [2] for multipath fading channels. In this paper, the proposed technique is applied to develop a receiver structure in an AWGN environment. Unlike the scheme in [1], the weighting factors in this proposed scheme are derived by minimizing the mean-square error between the received signal and its estimate through an LMS algorithm. Neither training sequence nor pilot signal is needed. The complexity of the proposed *adaptive* multistage PIC structure is much lower than that of linear multiuser detectors. Simulation results show superior performance of the proposed receiver structure over an AWGN channel and in various conditions.**

I. INTRODUCTION

There has been a great interest in finding suboptimum detectors with acceptable complexity and low performance degradation. Parallel interference cancellation (PIC) is attractive for its simplicity. However its performance is inferior to linear multiuser detectors. As shown in [1], if data from all interfering users are known *a priori*, the optimum decision for the desired user in the maximum-likelihood (ML) sense should be based on the received signal with all interference canceled. Multistage is introduced in [3] to enhance the performance of PIC. For multistage interference cancellation, the exact knowledge of the interfering bits is unknown, their estimates are used instead. As the estimates from the previous stages improve, the performance of the multistage PIC can also be improved.

Multistage PIC cannot always guarantee a performance improvement with additional stages. This is because when the bit error rate (BER) is high enough, a wrong bit decision used in cancellation will cause more degradation than benefit. In view of this disadvantage, Divsalar *et al.* [1] suggested a partial cancellation of MAI, the amount of IC is decided by a weighting factor at each stage for all users. When the weight is properly chosen at each stage, this method can ensure a better performance after the partial interference cancellation.

Clearly, the poorer performance of the multistage PIC is caused by the lack of an exact knowledge of the interfering users. This is also applicable to the partial cancellation scheme, where a compromise is made between canceling MAI and reducing the cost caused by a wrong estimation. Obviously, if a certain knowledge about MAI is available, the performance of IC will be further enhanced.

In this paper, we consider the partial IC problem from another perspective. In the first place, we propose a cost function which takes the weighting factors into account. Our objective is to minimize the squared Euclidean distance between the received signal and the weighted sum of the estimate of each user's signal during a bit interval with respect to the weights. We will demonstrate that the optimum solution to the proposed cost function is equivalent to a maximum likelihood sequence estimation with a complexity exponentially proportional to the number of active users. For a suboptimal solution, the IC problem with weighting can be solved by means of least square (LS) or mean-square error (MSE). Specifically, we can keep the MAI estimates unchanged but update the weighting factors through an adaptive algorithm for each user during each bit. When the LS criteria is used, the solution to the suboptimum cost function can be obtained through an RLS algorithm [4]. As shown in [4], at convergence this method is equivalent to a decorrelating detector. However, the computational complexity of this method is $O(NK^2)$ per bit, where N is the processing gain and K is the number of active users. This complexity is similar to that of a matrix-inverse-based decorrelating detector.

In view of the excessive complexity of the RLS algorithm and the fact that the convergence rate of the RLS algorithm decreases at low SNR [5], a low-complexity normalized LMS algorithm is proposed in searching for the optimum weights. In contrast to [4], the final bit estimation is based on the MAI canceled signal instead of the weights obtained from the adaptive algorithm. The IC can be performed in a multistage manner with a complexity of only $O(NK)$ for each stage.

The rest of the paper is organized as follows. The system model is described in Section 2. Section 3 presents the introduced perspective for IC after a very brief overview of previous PIC methods. The LMS multistage PIC approach in an AWGN channel is introduced in Section 4. In Section 5, performance of various interference cancellation schemes are compared by means of simulation. Section 6 concludes the paper.

II. SYSTEM MODEL

We consider a synchronous DS-CDMA system with QPSK modulation in an AWGN channel. The block di-

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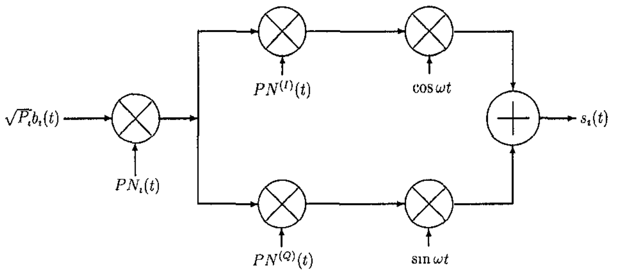

Fig. 1. Transmitter model for the QPSK CDMA system

agram of the transmitter model is shown in Figure 1. The equivalent complex baseband representation of the received signal at the base station can be expressed as:

$$r(t) = \sum_{i=1}^{K} s_i(t) + z(t) = \sum_{i=1}^{K} \sqrt{P_i} b_i(t) c_i(t) + z(t) \quad (1)$$

where subscript i denotes the ith user,

- P_i is the signal power.
- $b_i(t) = \sum_{m=-\infty}^{\infty} a_i^{(m)} p(t - mT_b)$ is the data signal, $a_i^{(m)}$ represents the binary sequence taking values ± 1 with equal probability, T_b represents bit duration and $p(t)$ is the rectangular chip waveform.
- $c_i(t)$ is the complex valued PN waveform defined as $c_i(t) = PN_i(t)[PN^{(I)}(t) + jPN^{(Q)}(t)]$, where $PN^{(I)}(t)$, $PN^{(Q)}(t)$ are the PN waveforms of branch I and Q of QPSK modulation. $PN_i(t)$ is the signature waveform.
- $z(t)$ is the additive Gaussian noise with double-sided density $N_0/2$.
- K is number of active users.

We assume that the users have the purely random PN codes. For despreading, the output from the matched filter of the ith user is given by

$$\begin{aligned} y_i^{(m)} &= \frac{1}{\sqrt{T_b}} \int_{(m-1)T_b}^{mT_b} r(t) c_i^*(t) dt \\ &= \sqrt{E_{bi}} a_i^{(m)} + \sum_{\substack{j=1 \\ j \neq i}}^{K} \sqrt{E_{bj}} a_j^{(m)} \rho_{ji} + z_i \end{aligned} \quad (2)$$

where "*" represents complex conjugate, $E_{bi} = P_i T_b$ is the bit energy of the ith user, and

$$\rho_{ij} = \frac{1}{T_b} \int_0^{T_b} c_i(t) c_j^*(t) dt, \qquad i, j = 1, 2, \cdots, K \quad (3)$$

denoting the cross-correlation coefficient between c_i and c_j. z_i is the Gaussian noise component after despreading, which is expressed as

$$z_i = \frac{1}{\sqrt{T_b}} \int_{(m-1)T_b}^{mT_b} z(t) c_i^*(t) dt \quad (4)$$

For convenience, we will drop the index m in the following discussing. Let us define

$$Y_i = \mathrm{Re}\{y_i\} \quad (5)$$

The conventional single-user receiver estimates data a_i as

$$\hat{a}_i = sgn\{Y_i\} \quad (6)$$

where sgn{} is the sign function.

III. Parallel Interference Cancellation

Without loss of generality, we focus on the first user. For a conventional multistage PIC [6], the MAI is estimated at the kth stage as

$$\hat{I}_1(k) = \mathrm{Re}\{\sum_{i=2}^{K} \sqrt{E_{bi}} \hat{a}_i(k-1) \rho_{i1}\} \quad (7)$$

The receiver then makes a decision based on the following rule

$$\hat{a}_1(k) = sgn\{Y_1 - \hat{I}_1(k)\} \quad (8)$$

Since the estimation of MAI may not always be correct, Divsalar *et al.* [1] suggested in their partial PIC approach to remove only part of it at a time. In addition, the amount of cancellation increases for each successive stage in their method. The procedures for an iterative interference cancellation is as follows [1, 7]

$$\begin{aligned} \tilde{a}_1(k) &= p_k[Y_1 - \hat{I}_1(k)] + (1 - p_k)\tilde{a}_1(k-1) \\ \hat{a}_1(k) &= sgn\{\tilde{a}_1(k)\} \end{aligned} \quad (9)$$

where p_k is the weighting factor for interference cancellation at the kth stage.

Divsalar *et al.*'s work motivated us to find the optimum weights for MAI cancellation. Suppose that the power levels of all users are known to the receiver at the base-station, we define an optimum cost function in terms of squared Euclidean distance between the received signal $r(t)$ and the weighted sum of the estimates of all users' signals

$$\epsilon = \int_0^{T_b} \left| r(t) - \sum_{i=1}^{K} \lambda_i \sqrt{P_i} \hat{a}_i c_i(t) \right|^2 dt \quad (10)$$

where λ_i is the weighting factor for the ith user, $\hat{a}_i$ denotes the estimate of a_i. Our objective is to find the optimum weights λ_i such that ϵ is minimized. From (10), we observe the following:

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1. Without Gaussian noise, the optimum weight should be $\lambda_i^o = \frac{a_i}{\hat{a}_i}$ and equals to 1 or -1 depending on whether the estimate $\hat{a}_i$ is correct or not.
2. Instead of searching for the optimum weight λ_i, we can fix $\lambda_i = 1$ and search the optimum sequence $(\hat{a}_1, \cdots, \hat{a}_K)$ to minimize ϵ. This results in a maximum likelihood sequence detector.
3. For a suboptimal solution of weights λ_i, a modified cost function can be formed in the sense of LS or MSE. We will show that the corresponding problem can be solved in an iterative manner by means of an RLS or LMS algorithm.

Chen and Roy proposed an adaptive multiuser structure [4], where they try to estimate the received data during each symbol by RLS algorithm through the PN codes known to the receiver. As shown in [4], at convergence this method is equivalent to the decorrelating detector.

IV. ADAPTIVE MULTISTAGE PIC

The main drawback of Chen and Roy's RLS-based decorrelating method [4] is its complexity. Although the RLS algorithm has a complexity of $O(K^2)$, in their method it is performed on a chip basis, hence the complexity per bit is $O(NK^2)$. Since normally $N > K$ for a practical DS-CDMA system, the complexity of the RLS based decorrelating detector is actually $O(K^3)$, similar to that of the matrix inverse decorrelating detector.

To reduce the complexity, we suggest an LMS algorithm in the proposed adaptive multistage PIC approach. To illustrate our method, we need to sample the continuous received signal at the chip rate after the chip matched filter. This is sufficient for a synchronous system. The N samples of the received signal within a bit can be written as

$$r(m) = \sum_{i=1}^{K} \sqrt{P_i} a_i c_i(m) + z(m) \tag{11}$$

Since LMS is based on MSE criteria, the cost function given in (10) should be modified as follows

$$\min_{\boldsymbol{\lambda}^{(k)}} \; E\left[\left| r(m) - \hat{r}^{(k)}(m) \right|^2 \right] \quad 0 \le m \le N-1 \tag{12}$$

where $\boldsymbol{\lambda}^{(k)}$ is the weighting vector at the kth stage. $\hat{r}^{(k)}(m)$ represents the estimate of the received signal at the kth stage which is defined as

$$\hat{r}^{(k)}(m) = \sum_{i=1}^{K} c_i(m) \hat{a}_i^{(k-1)} \lambda_i^{(k)}(m) \tag{13}$$

$\hat{a}_i^{(k-1)}$ is the estimate of a_i at the $(k-1)$th stage.

Since the LMS algorithm has a slower convergence rate and is more sensitive to its initial state as compared to the RLS, the conventional single user correlators are employed. The outputs from these correlators are served as the inputs of the first stage of LMS PIC, i.e.,

$$\hat{a}_i^{(0)} = sgn(Y_i) \tag{14}$$

where Y_i is defined in (5). The optimum weights are derived via a normalized LMS algorithm which operates in a bit interval and a chip basis as follows

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

where μ is a step size. $\hat{\mathbf{s}}^{(k)}$ denotes the input vector of the LMS filter at the kth stage, its ith element represents the estimate of the ith user's transmitted signal defined as

$$\hat{s}_i^{(k)}(m) = c_i(m) \hat{a}_i^{(k-1)} \tag{16}$$

$e^{(k)}(m)$ is the error between the desired response and the output of the LMS filter of the kth stage, i.e.,

$$e^{(k)}(m) = r(m) - \hat{r}^{(k)}(m) \tag{17}$$

The block diagram of the weight estimation using an LMS algorithm is illustrated in Figure 2.

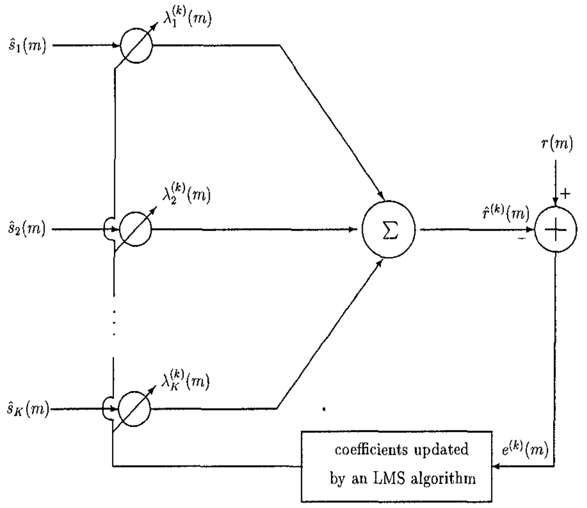

Fig. 2. Weight estimation via an LMS algorithm for adaptive IC

At each bit, $\boldsymbol{\lambda}^{(k)}(N-1)$ is used as the weight in the IC. Consider the ith user, the IC is performed as

$$y_{ci}^{(k)}(m) = r(m) - \sum_{\substack{j=1 \\ j \ne i}}^{K} \lambda_j^{(k)}(N-1) \hat{s}_j^{(k)}(m) \tag{18}$$

A more reliable decision is based on the less interfered signal $y_{ci}^{(k)}(m)$, namely

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

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where

$$Y_i^{(k)} = \mathrm{Re}\left\{\frac{1}{N}\sum_{m=0}^{N-1} y_{ci}^{(k)}(m)c_i^*(m)\right\} \tag{20}$$

The step size μ plays an important role in LMS algorithm. For a normalized LMS algorithm deployed in our approach, μ must satisfy $0 < \mu < 2$ in order to ensure convergence [5]. Another important factor that affects the convergence rate of LMS algorithm is its initial state. When a perfect knowledge of all users' power is available, the initial value of the weighting factor for each user can be set to its corresponding amplitude. Ideally, with this setting, if the bit estimation from previous stage is perfect, the LMS filter will not update its coefficients due to a zero error signal. In a non-ideal situation, more accurate bit estimates lead to a faster convergence of the weighting factors to their optimum values.

V. SIMULATION RESULTS

Simulations have been carried out to evaluate the performance of various IC schemes discussed in this paper. The system model described in Section 2 is used in our simulation. The processing gain is set to 64. Generating functions for random PN sequences employed in our simulations are identical to those specified in IS-95 for its reverse link.

For a system with perfect power control, E_b/N_0=7dB is assumed for all users in all simulations, where $E_b = P_i T_b$. For a power-unbalanced system, the power level is assumed to be uniformly distributed over the range from 0 to 15dB. Only the performance of the weakest user is plotted where E_b/N_0=7dB.

Figures 3(a) and 3(b) show the performance of various multiuser detection schemes in a CDMA system with perfect power control. The *partial PIC* used in these plots refers to Divsalar *et al.*'s partial PIC approach [1,7]. As shown in Figure 3(a), all methods provide a better performance than the conventional single-user detector. Among the single-stage schemes, the *LMS PIC* and the *RLS decorrelating* methods have the best performance. By increasing the number of stages to 2, the performance of the *LMS PIC* technique is further improved. For example, to maintain a BER of 0.01, the conventional single-user detector can support 7 users. The *single-stage partial PIC* improves the capacity to 21 users while the *single-stage LMS PIC* and *RLS decorrelating* have a comparable performance and can accommodate 27 active users (Figure 3(a)). With an additional stage, the *2-stage partial PIC* offers a capacity of 30 users and the *2-stage LMS PIC* can support 35 users (Figure 3(b)). The introduced adaptive PIC scheme provides a significant performance improvement with a complexity much less than the *RLS decorrelating* method.

Figures 3(c) and 3(d) show the performance of these multiuser detection schemes in a power-unbalanced system. The introduced *single-stage LMS PIC* outperforms both the *single-stage conventional* and the *partial PIC*, but has a worse performance than the *RLS decorrelating* due to a comparatively slower convergence rate than the RLS algorithm. For a BER of 0.01, the *single-stage conventional* and *single-stage partial PIC* can support 8 and 7 users, respectively. The weighting in the *partial PIC* scheme does not have much advantage in this case. The introduced *single-stage LMS PIC* can accommodate 18 users and the *RLS decorrelating* has a capacity of 27 users. With an additional stage, the number of active users can be supported by the *2-stage conventional*, *2-stage partial PIC*, and *2-stage LMS PIC* are 18, 22, and 34, respectively. Comparing results in Figures 3(b) and 3(d), the unbalance in power almost has no impact on the performance of the introduced adaptive PIC and the RLS decorrelating schemes, while it introduces a drop in capacity of the *2-stage partial PIC* from 30 to 22.

VI. CONCLUSIONS

In this paper, we propose a new adaptive multistage PIC scheme. Unlike the previous partial PIC [1,7], a set of weights are obtained from an LMS algorithm. When the LMS algorithm converges to its optimum solution, it can provide an MMSE estimation to all MAI. Due to the relatively slow convergent rate and the impact of gradient noise, the LMS algorithm may not converge to its optimum solution within one bit interval. The introduction of multiple stages overcomes this problem and greatly improves the performance. Weights obtained in the proposed method contain additional knowledge on the accuracy of each estimated interference which is indispensable to enhance the performance. Simulation results show a significant performance improvement over the conventional multistage detector and partial PIC detector [1].

REFERENCES

[1] D. Divsalar and M. K. Simon, "Improved CDMA performance using parallel interference cancellation," Tech. Rep. 95-21, JPL Publication, Oct. 1995.

[2] G. Q. Xue, J. F. Weng, T. Le-Ngoc, and S. Tahar, "Adaptive multistage parallel interference cancellation for CDMA over multipath fading channels," in *Proc. of VTC'99*, (Vancouver, Canada), June 1999.

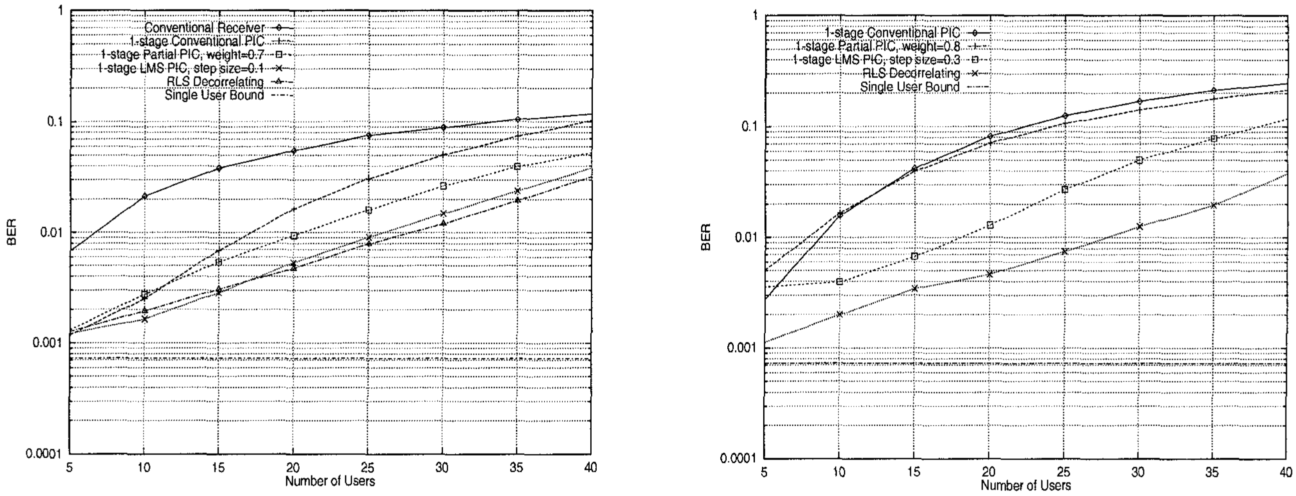
[3] M. K. Varanasi and B. Aazhang, "Near-optimum detection in synchronous code-division multiple-access systems," *IEEE Trans. Commun.*, vol. 39, pp. 725–736, May 1991.

[4] D. S. Chen and S. Roy, "An adaptive multi-user receiver for CDMA systems," *IEEE J. Select. Areas Commun.*, vol. 12, pp. 808–816, June 1994.

[5] S. Haykin, *Adaptive Filter Theory*. Prentice Hall, 3rd ed., 1996.

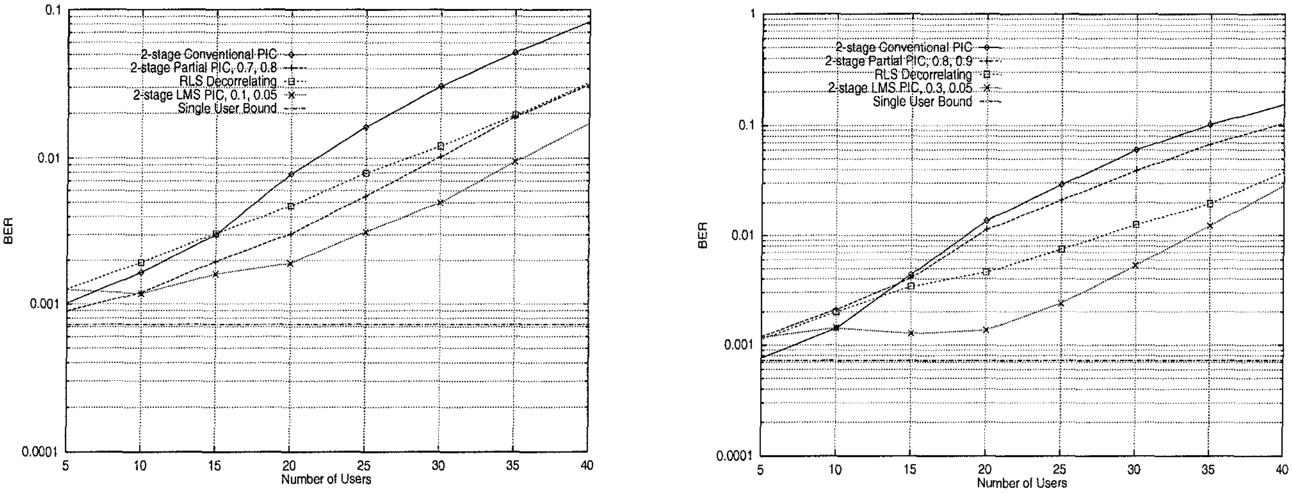
[6] M. K. Varanasi and B. Aazhang, "Multistage detection in asynchronous code-division multiple-access communications," *IEEE Trans. Commun.*, vol. 38, pp. 509–519, April 1990.

[7] D. Divsalar, M. K. Simon, and D. Raphaeli, "Improved parallel interference cancellation for CDMA," *IEEE Trans. Commun.*, vol. 46, pp. 258–268, Feb. 1998.



(a) single stage, perfect power control

(c) single-stage, power unbalanced



(b) 2-stage, perfect power control

(d) 2-stage, power unbalanced

Fig. 3. Performance of various multiuser detection (E_b/N_o =7dB)

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