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Description	



# Joint Decorrelating Multiuser Detection and Channel Estimation in Asynchronous CDMA Mobile Communications Channels

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**Abstract**—The asymptotic efficiencies of two decorrelators, path-by-path and channel-matched decorrelators, are analyzed in fading multipath propagation environments, and based upon the analytical results, a new joint multiuser detection and channel estimation scheme is proposed for asynchronous code division multiple access (CDMA) mobile communications channels. In the path-by-path decorrelator, each of the received signals corresponding to one of the multiple propagation paths is regarded as an independent interference source. On the contrary, in the channel-matched decorrelator, each composite signal transmitted from an identical user is regarded as a response of the multipath channel to the corresponding user's spreading sequence. The asymptotic efficiency of the path-by-path decorrelator is shown to drop rapidly as the number of simultaneous users increases. It is shown that the asymptotic efficiency can be made independent of the number of the propagation paths by the channel-matched decorrelator at the expense of requiring knowledge about the fading complex envelopes of all the propagation paths.

The proposed joint multiuser detection and channel estimation scheme uses both path-by-path and channel-matched decorrelators. The path-by-path decorrelator is used for providing the channel estimator with the (noisy) channel information path-by-path, and decisions are made on the output of the channel-matched decorrelator. The decision results are fed back to the channel estimator, and used as the reference signals. The received complex envelope of each of the propagation paths is estimated in the channel estimator. Results of a series of exhaustive computer simulations are presented in order to demonstrate the overall performance of the proposed scheme, both in non-fading and fading multipath propagation environments.

## I. INTRODUCTION

AS SUGGESTED by previous papers [1]–[3], the near-far problem is the principal obstacle to be overcome for mobile/personal communications systems using direct sequence code division multiple access (DS/CDMA) signaling schemes, in which, so far, interference signals transmitted from other users are regarded as equivalent to noise. Multiuser detection techniques have been considered as a breakthrough for this problem, and recently several algorithms have been proposed for multiuser detection [4]–[6]. The use of knowledge about the crosscorrelations between the simultaneous users for whom

symbol synchronism is not necessarily assumed, in the multiuser detection process, makes it possible to eliminate the near-far problem. The improvement in detected data quality, as well as the increase in the system user capacity over conventional CDMA mobile communications systems, is the major outcome wrought by multiuser detection at the expense of increased receiver complexity.

The optimum multiuser detector calculates the Euclidean distances between the received matched filter output vector and each of the candidate vectors constructed, assuming that all possible patterns of user information have been transmitted. The calculated distances are then compared, and the vector considered most likely to have been transmitted is output. This process can efficiently be performed using the Viterbi algorithm, whose complexity exponentially increases, unfortunately, with the number of the users. Hence, the recent research target has been multiuser detection using suboptimum algorithms of practical complexity [7]–[10], [12].

The decorrelator proposed by Lupas and Verdu [7], [8] is a suboptimum multiuser detector, and its complexity increases only in proportion to the number of the users. The bit error rate (BER) performance of the decorrelator is independent of the interferer's received energies, and hence is near-far resistant. It has been proven by Varanasi [9] that such near-far resistance can be inherited by a multiuser detection system in which the decorrelator is followed by a differential detector, aiming that decorrelators can even be used in the situations where the received signal phase varies, as in mobile communications.

One major drawback of the decorrelator is that it enhances the noise present in the received signals. The measure which well reflects the effect of the noise enhancement on the signal transmission performance is the asymptotic efficiency. The asymptotic efficiencies of the optimum and various suboptimum multiuser detection schemes were analyzed in [11].

In mobile communications environments, because there are many propagation paths with different delays between the transmitter and receiver, the transmitted signal components corresponding to these multiple propagation paths arrive at different times. If the chip duration  $T_c$  is smaller than all of the differences in propagation delay time, each signal component can be resolved in the despreading process. Recently, [16] derived the optimum multiuser detection scheme in Rician fading environments, and analyzed the effects of the multipaths on the asymptotic efficiencies of multiuser detection

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schemes, assuming *memoryless* fading for each user. This assumption makes the mathematical analysis simple. However, it characterizes the fading variation as *unestimatable*.

The first half of this paper also analyzes the asymptotic efficiency of the decorrelator under the multipath propagation environment. It is shown that, if each received signal corresponding to one of the multiple propagation paths is regarded as an independent interference source in the decorrelator (this type decorrelator is referred to as “path-by-path decorrelator,” for convenience) even though it bears the identical information transmitted from the same user, the asymptotic efficiency drops rapidly as the number of the users increases. If there are  $L$  propagation paths for each of the simultaneous users, for example, the asymptotic efficiency is almost equivalent to that in the situation in which there is only one propagation path and there are  $L$  times the number of users.

This decrease in the asymptotic efficiency due to the multipaths can be recovered by decorrelating the composite of those waveforms that are matched to the convolutions of the corresponding user’s spreading sequences and channel impulse responses (referred to as “channel-matched” decorrelator), as proposed in [10]. However, the channel-matched decorrelator requires knowledge about the fading complex envelopes of all propagation paths.

Based upon the above analysis of the asymptotic efficiency, this paper proposes a new joint multiuser detection and channel estimation scheme for asynchronous CDMA mobile communications channels. Both the path-by-path and channel-matched decorrelators are used. The path-by-path decorrelator is *not used* for making decisions on the simultaneous users, but *is used* for providing the channel estimator with the (noisy) channel information path-by-path. Decisions are made on the output of the channel-matched decorrelator to obtain estimates of each user’s transmitted information. The estimates are fed back to the channel estimator, and used as the reference signals. The received complex envelope of each propagation path is estimated by the channel estimator, and then input to the channel-matched decorrelator.

This paper is organized as follows: Section II presents the system model used in this paper. The asynchronous CDMA communication channel suffering from multipath propagation is first described, and the matrix transfer functions of the path-by-path and channel-matched decorrelators are then presented. It is shown that these decorrelators can be implemented in the form of a vector digital filter whose implementation does not require the inverse of the matrix rational transfer function; instead, it only requires the inverse of the partial correlation matrices. This configuration corresponds to an infinite series expansion of the matrix transfer function. Section III presents a simple expression of the asymptotic efficiencies of the decorrelators, using the series expansion of the matrix transfer function. Section III then examines the effect of the multipath on the asymptotic efficiency. Section IV describes the proposed joint multiuser detection and channel estimation scheme, where the standard recursive least square (RLS) algorithm is used for channel estimation. Section V shows the results of computer simulations conducted for the performance evaluations of the proposed scheme.

## II. SYSTEM MODEL

### A. Multipath Channel Model

There are  $K$  simultaneous users in the system being considered. Each of the simultaneous users transmits its information symbol using the DS/CDMA signalling scheme. The complex received signal can be expressed as

$$z(t) = S(t, \mathbf{b}) + n(t) \quad (1)$$

where  $n(t)$  is additive white Gaussian noise (AWGN) with power spectral density  $\sigma^2$ , and

$$S(t, \mathbf{b}) = \sum_{i=-\infty}^{\infty} \sum_{k=1}^K \sum_{l=1}^{L_k} b_k(i) \sqrt{w_k(i)} z_{k,l}(i) \cdot s_k(t - iT - \tau_{k,l}). \quad (2)$$

$s_k(t)$  is the normalized spreading sequence, and is zero outside the interval  $[0, T]$  with  $T$  being the information symbol duration.  $\mathbf{b}(i) = [b_1(i), b_2(i), \dots, b_K(i)]^t$  is the information symbol vector and  $i \in \{-\infty, \infty\}$ .  $L_k$  is the number of the propagation paths encountered by the  $k$ th user.  $z_{k,l}(i)$  is the normalized fading complex envelope with the  $l$ th path of the  $k$ th user, and  $w_k(i)$  is the  $k$ th user’s received energy, both of which are in the  $i$ th time slot.  $w_k(i)$  reflects the normalization on  $z_{k,l}(i)$ ’s such that

$$\sum_{l=1}^{L_k} Z_{k,l}(i) z_{k,l}^*(i) = 1, \quad \text{for } 1 \leq k \leq K \quad (3)$$

where  $*$  denotes the complex conjugate.  $\tau_{k,l}$  is the delay on  $z_{k,l}(i)$ . It is assumed that  $\tau_{11} = 0$ , without loss of generality, and others lie within the range of  $[0, T]$ ,<sup>1</sup> and that the chip duration  $T_c$  is smaller than all of the differences in propagation delay time.

### B. Decorrelators

The received signal components corresponding to the multipaths are despread path-by-path. The  $z$ -transform  $\mathbf{Y}(z)$  of output vector  $\mathbf{y}(i) = [y_{1,1}(i), \dots, y_{1,L_1}(i), y_{2,1}(i), \dots, y_{K,L_K}(i)]^t$  of the matched filters, each of which is matched to its corresponding spreading sequence, can be expressed as

$$\mathbf{Y}(z) = [\mathbf{R}^H(1)z + \mathbf{R}(0) + \mathbf{R}(1)z^{-1}][\mathbf{PWB}](z) + \mathbf{N}(z) \quad (4)$$

where  $\mathbf{R}(0)$  and  $\mathbf{R}(1)$  are the partial correlation matrices, and  $\mathbf{R}^H(m)$  with  $m = 0, 1$  denotes the transposed complex conjugate of  $\mathbf{R}(m)$ . The  $(p, q)$  element of  $\mathbf{R}(m)$  is given by [8]

$$R_{pq}(m) = \int_{-\infty}^{\infty} s_k(t - \tau_{k,j}) s_{k'}(t + mT - \tau_{k',j'}) dt \quad (5)$$

with

$$p = \sum_{m=1}^{k-1} L_m + j$$

<sup>1</sup>For delays lying out of the range of  $[0, T]$ , a similar theory may be derived by denoting the channel gain matrix  $\mathbf{P}$ , given by (6), a function of  $z$ . This is out of the scope of this paper.

and

$$q = \sum_{m=1}^{k'-1} L_m + j'.$$

$p$  corresponds to the  $k$ th user's  $l$ th path,  $q$  corresponds to  $k'$ th user's  $l'$ th path with  $1 \leq j \leq L_k$ ,  $1 \leq j' \leq L_{k'}$ ,  $1 \leq k \leq K$  and  $1 \leq k' \leq K$ .  $[PWB](z)$  and  $N(z)$  are the  $z$ -transforms of the vector sequence  $P(i)W(i)b(i)$  with  $W(i) = \text{Diag}[\sqrt{w_1(i)}, \sqrt{w_2(i)}, \dots, \sqrt{w_K(i)}]$  and the noise sequence  $\mathbf{n}(i) = [n_{1,1}(i), \dots, n_{1,L_1}(i), n_{2,1}(i), \dots, n_{K,L_K}(i)]^t$  at the matched filter output, respectively.  $P$  is the channel gain matrix given by

$$P = \begin{bmatrix} z_{1,1} \cdots z_{1,L_1} & & & & \\ & z_{1,1} \cdots z_{2,L_2} & \cdots & & \\ & 0 & & & \\ & & & & 0 \\ & & & z_{K,1} \cdots z_{K,L_K} & \end{bmatrix}^t \quad (6)$$

1) *Path-by-Path Decorrelator*: The path-by-path decorrelator assumes that each of the received signals corresponding to the propagation paths is an independent interference [13], [17], [18]. Hence, signal processing of the path-by-path decorrelator is equivalent to the inverse filter of  $[R^H(1)z + R(0) + R(1)z^{-1}]$ . The  $z$ -transform  $Z_p(z)$  of its output vector  $z_p(i) = [z_{p1,1}(i), \dots, z_{p1,L_1}(i), z_{p2,1}(i), \dots, z_{pK,L_K}(i)]^t$  becomes

$$Z_p(z) = [PWB](z) + G_p(z)N(z) \quad (7)$$

where

$$G_p(z) = [R^H(1)z + R(0) + R(1)z^{-1}]^{-1} \quad (8)$$

is the matrix transfer function of the path-by-path decorrelator.

The combiner combines all the decorrelated signal components transmitted from the identical users. Assuming that the complex envelopes  $z_{k,l}(i)$ 's are known to the receiver, maximum ratio combining (MRC) can be used. The output vector  $z'_p(i) = [z'_{p1}(i), z'_{p2}(i), \dots, z'_{pK}(i)]^t$  of the MRC combiner can be expressed as

$$z'_p(i) = P^H z_p(i). \quad (9)$$

2) *Channel-Matched Decorrelator*: The other type of decorrelator combines all the received signal components transmitted from the identical users prior to decorrelation. The  $z$ -transform  $Y'(z)$  of the combiner output  $y'(i) = [y'_1(i), y'_2(i), \dots, y'_K(i)]^t$  can therefore be expressed as

$$\begin{aligned} Y'(z) &= CY(z) \\ &= C[R^H(1)z + R(0) + R(1)z^{-1}] \\ &\quad \cdot [PWB](z) + CN(z) \end{aligned} \quad (10)$$

where matrix  $C$  corresponds to combining. If the channel gains  $z_{k,l}(i)$ 's are constant in time, the matrix  $P$  in (10) can be taken out of  $[PWB](z)$ ; the result is that the  $z$ -

transform  $Z_c(z)$  of the decorrelator output vector  $z_c(i) = [z_{c1}(i), z_{c2}(i), \dots, z_{cK}(i)]^t$  becomes

$$Z_c(z) = [WB](z) + G_c(z)CN(z) \quad (11)$$

where

$$G_c(z) = \{C[R^H(1)z + R(0) + R(1)z^{-1}]P\}^{-1} \quad (12)$$

is the matrix transfer function. Furthermore, if  $C = P^H$ , (12) is equivalent to decorrelating the composite of those waveforms that are matched to the convolutions of the corresponding users' spreading sequences and channel impulse responses (or equivalently, matched to the channel responses to the users' spreading sequences) [10]. Hence, this decorrelator is referred to as a "channel-matched" decorrelator.<sup>2</sup> The assumption that the channel gains  $z_{k,l}(i)$ 's are constant is reasonable if the memory length (= length of the impulse response) of the decorrelator is sufficiently small compared to the speed of the channel variation. If so, matrix  $P$  can be updated every time the new estimates of  $z_{k,l}(i)$ 's are obtained. This effect will be investigated in Section V.

### C. Series Expansion of Matrix Transfer Function

Both matrix transfer functions,  $G_p(z)$  and  $G_c(z)$ , respectively, of the path-by-path and channel-matched decorrelators, have the same form of

$$G_p(z) \quad \text{or} \quad G_c(z) = [A_1 z + A_0 + A_{-1} z^{-1}]^{-1} \quad (13)$$

where, for the path-by-path decorrelator,  $A_1 = R^H(1)$ ,  $A_0 = R(0)$ , and  $A_{-1} = R(1)$ , and for the channel-matched decorrelator,  $A_1 = P^H R^H(1)P$ ,  $A_0 = P^H R(0)P$ , and  $A_{-1} = P^H R(1)P$ . It is likely that  $P$  is column full rank since  $P$ 's elements are the samples of independent complex fading envelopes. Assume that  $R(0)$  is nonsingular.  $P^H R(0)P$  then becomes nonsingular. Because of the nonsingularity of matrix  $A_0$  for both decorrelators, (13) can be expanded into an infinite series as

$$G_p(z) \quad \text{or} \quad G_c(z) = \left[ \sum_{m=0}^{\infty} (-1)^m z^m \{A_0^{-1}(A_1 + A_{-1}z^{-2})\}^m \right] A_0^{-1}. \quad (14)$$

Equation (14) has terms of  $z^m$  with  $m > 0$  which correspond to noncausal components in the decorrelator's impulse response. In practice, at the cost of appreciable performance degradation, these noncausal components can be truncated after an appropriate delay. Let  $k_T$  denote the delay for the truncation. Equation (14) can then be approximated by the

<sup>2</sup>[19] has used this "channel matched" concept for the multiuser maximum likelihood sequence detection scheme in multipath Rayleigh fading channels, assuming the perfect knowledge of  $z_{k,l}(i)$ .

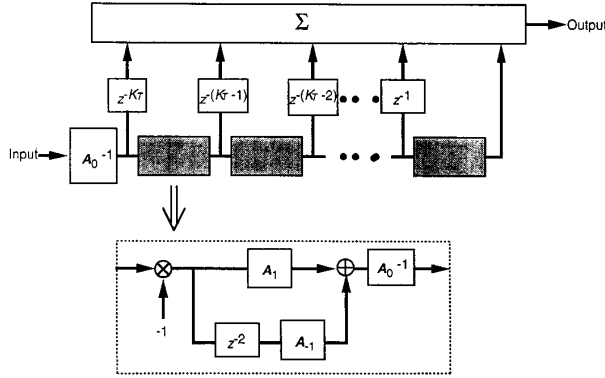
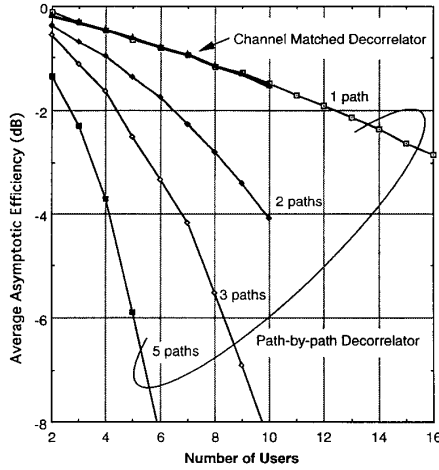

 Fig. 1. Block diagram of decorrelator with truncation length  $k_T$ .


Fig. 2. Asymptotic efficiency versus number of users.

causal filter

$$z^{-k_T} \mathbf{G}_p(z) \quad \text{or} \quad z^{-k_T} \mathbf{G}_c(z) \approx \left[ \sum_{m=0}^{k_T} (-1)^m z^{-(k_T-m)} \{ \mathbf{A}_0^{-1} (\mathbf{A}_1 + \mathbf{A}_0 z^{-2}) \}^m \right] \mathbf{A}_0^{-1} \quad (15)$$

which indicates that the impulse response of the approximated decorrelator has a length of  $2k_T + 1$ .

A block diagram of the signal processing required to implement the approximated decorrelators given by (15) is shown in Fig. 1. Obviously, the inverse matrix of the rational transfer function is not needed; only matrix inversion for  $\mathbf{A}_0^{-1}$  is needed. This is promising for the practical implementation of the decorrelators.

### III. ASYMPTOTIC EFFICIENCY

Asymptotic efficiency is known to well express the near-far resistance of multiuser detectors. Several suboptimum multiuser detectors' near-far resistance have been analyzed in [11] from the asymptotic efficiency viewpoint. This section

evaluates the asymptotic efficiencies of the path-by-path and channel-matched decorrelators.

The  $k$ th user's asymptotic efficiencies  $\eta_k^p$  and  $\eta_k^c$ , of the path-by-path and channel-matched decorrelators, respectively, are related to the vector impulse response of the *noncausal* linear filter  $[\mathbf{A}_1 z + \mathbf{A}_0 + \mathbf{A}_{-1} z^{-1}]$  at timing 0. Let  $\mathbf{d}_{pk,l}(0)$  denote the response of  $\mathbf{G}_p(z)$  at time 0 to the input vector

$$\mathbf{i}_p(i) = [0 \cdots 0 \quad 1 \quad 0 \cdots 0]^t, \quad i = 0$$

$$\left( \sum_{m=1}^{k-1} L_m + l \right) \text{th element} \quad (16)$$

and let  $\mathbf{d}_{ck}(0)$  denote the impulse response of  $\mathbf{G}_c(z)$  at time 0 to the input vector

$$\mathbf{i}_c(i) = [0 \cdots 0 \quad 1 \quad 0 \cdots 0]^t, \quad i = 0$$

$$k \text{th element} \quad (17)$$

for which  $\mathbf{i}_p(i) = \mathbf{0}$  and  $\mathbf{i}_c(i) = \mathbf{0}$  for  $i \neq 0$ .  $\mathbf{d}_{pk,l}(0)$  and  $\mathbf{d}_{ck}(0)$  can be approximately calculated as the responses of the *causal* linear filter of (15) to the input vectors of  $\mathbf{i}_p(i)$  and  $\mathbf{i}_c(i)$ , respectively, at time  $k_T$ .  $\eta_k^p$  and  $\eta_k^c$  are calculated below.

#### A. Path-by-Path Decorrelator

Let  $\mathbf{N}_p(z)$  denote the  $z$ -transform of the vector noise sequence  $\mathbf{n}_p(i) = [n_{p1}(i), n_{p2}(i), \dots, n_{pK}(i)]^t$  at the MRC combiner output. Obviously,  $\mathbf{N}_p(z) = \mathbf{P}^H \mathbf{G}_p^H(z) \mathbf{N}(z)$ , and thus the  $z$ -transform of the covariance matrix sequence  $\langle \mathbf{n}_p(\bullet) \mathbf{n}_p^H(\bullet + i) \rangle$  is equal to  $\sigma^2 \mathbf{P}^H \mathbf{G}_p(z) \mathbf{P}$ , since the  $z$ -transform of the covariance matrix sequence  $\langle \mathbf{n}(\bullet) \mathbf{n}^H(\bullet + i) \rangle$  of the noise sequence at the matched filter output is equal to  $\sigma^2 \mathbf{G}_p^{-1}(z)$ . Hence,  $n_{pk}(i)$  is a zero mean Gaussian random variable with variance  $\sigma^2 [\mathbf{P}^H \mathbf{D}_p(0) \mathbf{P}]_{k,k}$ , where

$$\mathbf{D}_p(0) = [\mathbf{d}_{p1,1} \cdots, \mathbf{d}_{p1,L_1}, \mathbf{d}_{p2,1} \cdots, \mathbf{d}_{pK,L_K}] \quad (18)$$

and the  $k$ th user's asymptotic efficiency  $\eta_k^p$  of the path-by-path decorrelator turns out to be

$$\eta_k^p = 1 / [\mathbf{P}^H \mathbf{D}_p(0) \mathbf{P}]_{k,k}. \quad (19)$$

#### B. Channel-Matched Decorrelator

The  $z$ -transform  $\mathbf{N}_c(z)$  of the vector noise sequence  $\mathbf{n}_c(i) = [n_{c1}, n_{c2}(i), \dots, n_{cK}(i)]^t$  at the channel-matched decorrelator output can be expressed as  $\mathbf{N}_c(z) = \mathbf{G}_c(z) \mathbf{P}^H \mathbf{N}(z)$ . Thus, the  $z$ -transform of the covariance matrix sequence  $\langle \mathbf{n}_c(\bullet) \mathbf{n}_c^H(\bullet + i) \rangle$  is equal to  $\sigma^2 \mathbf{G}_c(z)$  since, with the  $z$ -transform of  $\langle \mathbf{n}(\bullet) \mathbf{n}^H(\bullet + i) \rangle$  being  $\sigma^2 \mathbf{G}_p^{-1}(z)$ ,  $\mathbf{G}_c(z) = [\mathbf{P}^H \mathbf{G}_p^{-1}(z) \mathbf{P}]^{-1}$ . Hence,  $n_{ck}(i)$  is a zero mean Gaussian random variable with variance  $\sigma^2 [\mathbf{D}_c(0)]_{k,k}$ , where

$$\mathbf{D}_c(0) = [\mathbf{d}_{c1}, \mathbf{d}_{c2}, \dots, \mathbf{d}_{cK}] \quad (20)$$

and the  $k$ th user's asymptotic efficiency  $\eta_k^c$  of the channel-matched decorrelator becomes

$$\eta_k^c = 1/[D_c(0)]_{k,k}. \quad (21)$$

### C. Numerical Calculations

Under fading, the received normalized fading complex envelope  $z_{k,l}(i)$  with the  $l$ th path of the  $k$ th user is an independent complex random Gaussian variable. Also, in practical asynchronous CDMA mobile communications environments, delays  $\tau_{k,l}$ 's are random variables. Hence, the  $k$ th user's asymptotic efficiencies  $\eta_k^p$  and  $\eta_k^c$ , respectively, of the path-by-path and of the channel-matched decorrelators, become random variables.

For numerical calculations, the  $\eta_k^p$  and  $\eta_k^c$  values were evaluated for fixed values of  $z_{k,l}(i)$ 's and  $\tau_{k,l}$ 's. The spreading sequences for each user were randomly picked from among the length 31 Gold sequences. The calculated  $\eta_k^p$ 's and  $\eta_k^c$ 's were then averaged over a large number of sets of the values of  $z_{k,l}(i)$ 's and  $\tau_{k,l}$ 's, and among the users.  $\tau_{k,l}$ 's took values of  $nT_c$ , where  $n$  is an integer uniformly distributed over the range of [0, 30]. Fig. 2 shows the calculated average asymptotic efficiencies  $\langle \eta^p \rangle$  and  $\langle \eta^c \rangle$  versus the number  $K$  of the simultaneous users with the number of the propagation paths as a parameter. It is found from this figure that, in the multipaths, the average asymptotic efficiency of the path-by-path decorrelator decreases rapidly as  $K$  increases. If there are  $L$  propagation paths for each simultaneous user, for example,  $\langle \eta^p \rangle$  is almost equivalent to that in the situation in which there is only one propagation path and there are  $L$  times as many as users. On the other hand,  $\langle \eta^c \rangle$  does not rapidly decrease as  $K$  increases, and is equivalent to the path-by-path decorrelator's asymptotic efficiency with one propagation path.

## IV. JOINT DECORRELATING MULTUSER DETECTION AND CHANNEL ESTIMATION

An important outcome of the numerical calculations in Section III is the fact that the average asymptotic efficiency of the channel-matched decorrelator does not degrade in the presence of multipaths at the expense of a complexity increase for channel estimation. However, the information about each of the multipath channels is lost at the output of the channel-matched decorrelator. On the contrary, path-by-path channel estimation is possible at the path-by-path decorrelator output which, unfortunately, suffers from increased noise enhancement due to the presence of multipaths.

One reasonable solution to the problem of joint multiuser detection and channel estimation using decorrelators is to use the path-by-path decorrelator to provide the channel estimator with the (noisy) channel information path-by-path, and to use the channel-matched decorrelator for making the decisions that yield estimates of each user's transmitted information symbol. A block diagram of the proposed joint multiuser detection and channel estimation system is shown in Fig. 3(a). The input to the system is the sum of the signals transmitted from  $K$  users.  $k$ th user is suffering from the multipaths comprised of  $L_k$

propagation paths. The outputs of the matched filters, which are matched to each user's spreading sequence, have signal components corresponding to the propagation paths;  $k$ th user's matched filter output has  $L_k$  signal components in one symbol duration  $T$ . Assuming that the delays on each propagation paths are known, these signal components are sampled, and input to both the path-by-path and channel-matched decorrelators. In the channel-matched decorrelator, combining takes place *prior to* decorrelation, where an estimate of the channel gains matrix  $P$  output from the channel estimator is used. The  $P$ 's estimate is also used in the channel-matched decorrelator to calculate the matrices of  $A_1 = P^H R^H(1)P$ ,  $A_0 = P^H R(0)P$  and  $A_{-1} = P^H R(1)P$ .

As shown in Fig. 3(b), training sequences are embedded in each user's information symbol stream to be transmitted in order to enhance the convergence of the algorithm used for channel estimation. Fig. 3(c) shows a block diagram of the channel estimator for the  $k$ th user's  $l$ th path. Assuming that the timing, at which the training sequences are transmitted from each user, is known to the receiver, each user's training pattern can be used in the channel estimator as the reference signal during the training period (Selectors in Fig. 3(a) and (c) are switched to "Training.") Decisions are made on the output of the channel-matched decorrelator output to obtain the estimates of the transmitted information. These estimates are not only the system output, but they are also used as the reference signals outside the training period.

The received complex envelope  $z_{k,l}$  of the  $k$ th user's  $l$ th propagation path is estimated by the channel estimator using the path-by-path decorrelator outputs and the reference signals. The estimation process for the  $k$ th user is done independently of other users. The estimated values of  $z_{k,l}$ 's are then used to construct the channel gain matrix  $P$ . The approximated decorrelators with the truncation length of  $2k_T + 1$  are used for both the path-by-path and channel-matched decorrelators. Therefore, the influence of one sample vector of the matched filter outputs lasts for  $(2k_T + 1)T$  after the sampling takes place.

The standard RLS algorithm [14] was used to estimate the fading complex envelopes  $z_{k,l}$ 's. The estimate of the channel gain matrix  $P$  can be updated every time the path-by-path decorrelator output  $z_p(i)$  and the reference signal vector are obtained. However, the approximated decorrelator's matrix transfer function of (15), whose block diagram was depicted in Fig. 1, suggests that the values of  $z_{k,l}$ 's in the matrix  $P$  should be kept constant during the period of  $2k_T + 1$ . Nevertheless, updating the  $P$ 's estimate in the approximated decorrelator at every symbol timing may not affect the overall performance of the proposed system, if the required truncation length  $k_T$  for an acceptable approximation is sufficiently small compared to the channel variation. This effect was examined through computer simulations, and the results are presented in Section V.

## V. SIMULATION RESULTS

An exhaustive series of computer simulations was conducted in order to examine what factor of the proposed system dominates the overall performance. Results of the simulations are described below.

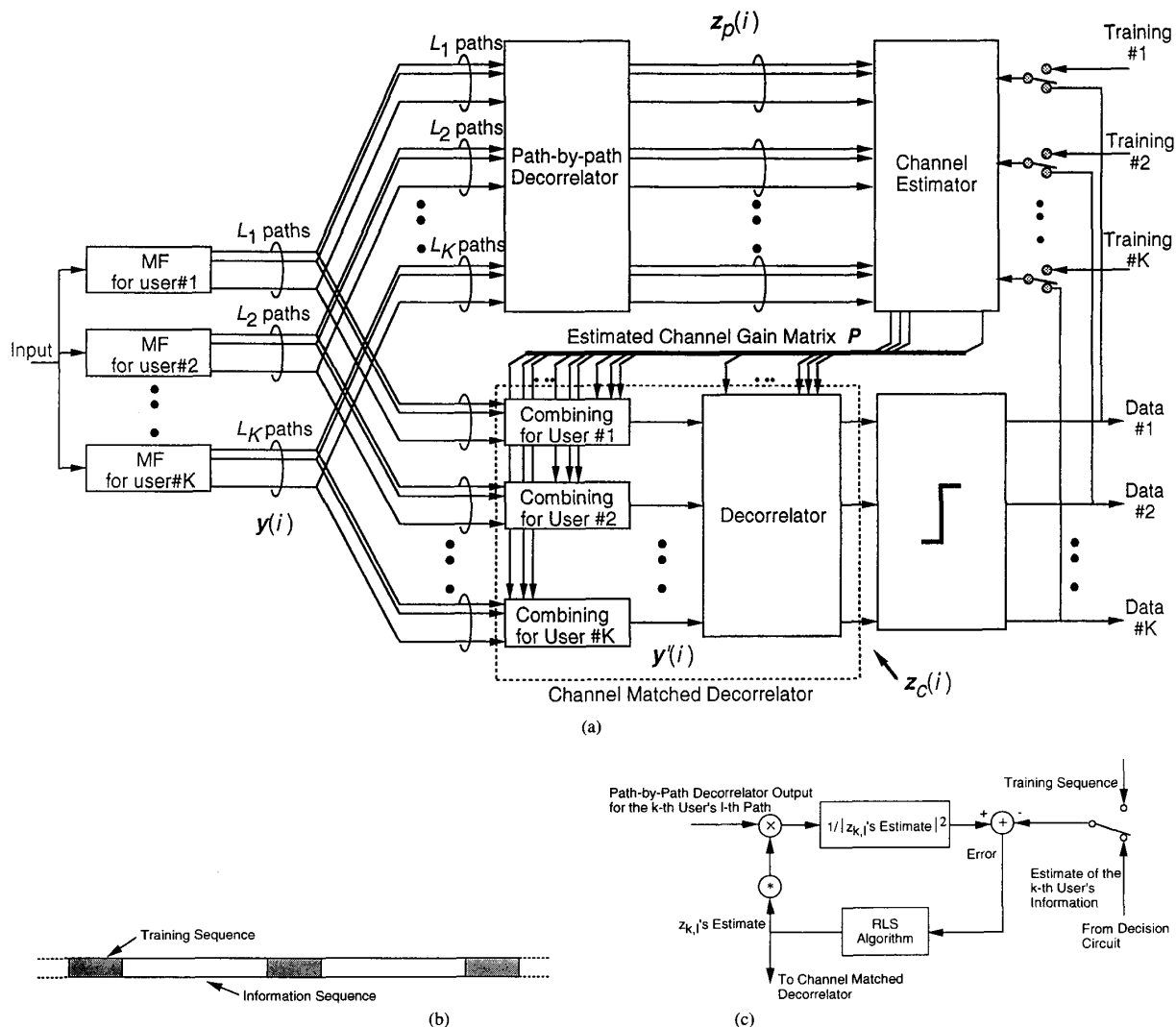


Fig. 3. (a) Block diagram of proposed joint multiuser detection and channel estimation system. (b) Frame format. (c) Block diagram of channel estimator for the  $k$ th user's  $l$ th path.

1) *Without Fading*: First, it was determined how large the truncation length  $k_T$  must be for (15) to accurately approximate decorrelation. To do so, in the initial stage of the simulations, neither multipath nor fading was assumed. Even in this simple situation, each user's BER performance is affected by the relative delays. Hence, in the simulations, each user's BER was evaluated for fixed values of the relative delays; this process was repeated many times for different values of the relative delays. The spreading sequences were randomly picked up from among the length 31 Gold sequences. The obtained BER's were then averaged over the relative delays and among the users. Binary phase shift keying (BPSK) was assumed. Fig. 4 shows the average BER performance versus the truncation length  $k_T$  (length of the impulse response is  $2k_T + 1$ ) for the signal-to-noise (SNR) power ratio after despreading of 7 dB with the number of users as a parameter. In this case, each user's received signal is assumed to have

identical energy. It is found that if  $k_T \geq 2$ , the BER reduction plateaus. Hence, in this case,  $k_T = 2$  is sufficient.

The approximated decorrelators may lose the near-far resistance originally offered by the decorrelator. In order to examine the effect of truncation on the near-far resistance, BER's were evaluated assuming that the received signal energies of interferers are larger than that of the one reference user. Fig. 5 shows the reference user's BER averaged over the relative delays versus the received signal energy ratio of  $w_1/w_k$  with  $2 \leq k \leq K$ ; it was assumed that each interferer has identical received signal energy. Parameters are the number of users  $K$  and truncation length  $k_T$ . It is found that  $k_T = 2$  truncation length obviously degrades the near-far resistance. If  $k_T = 4$  and  $K = 5$ , the approximated decorrelator is still near-far resistant up to  $w_1/w_k = -10.0$  dB. If  $k_T = 4$  and  $K = 10$ , power control with the aim of achieving  $w_1/w_k \geq -10$  dB is required.

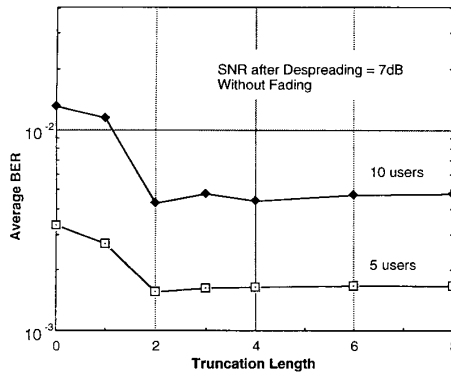


Fig. 4. Average BER versus truncation length.

Fig. 6 shows the BER's of the path-by-path and channel-matched decorrelators, averaged over various values of the channel gains  $z_{k,l}$ 's satisfying (3) and among users, versus SNR after despreading in one-path and equal energy two-path propagation environments for  $K = 5$  and  $K = 10$  ("L-path propagation" indicates that there are  $L$  propagation paths for each user, for convenience).  $k_T = 4$  was used for the approximation. Perfect knowledge about the channel gains was assumed. It is found that for the path-by-path decorrelator, the average BER performance for the five-user two-path propagation environment is almost equivalent to that for the ten-user one-path propagation environment. As observed in this figure, the channel-matched decorrelator's average BER performance is independent of the multipaths: the BER's for  $K = 5$  and 10 in two-path propagation environment are equivalent, respectively, to that for  $K = 5$  and to that for  $K = 10$  in one-path propagation environment. These results support the analysis of the asymptotic efficiency made in Section III.

In the proposed scheme, the channel-matched decorrelator uses estimates of channel gains  $z_{k,l}$ 's. Hence, the overall performance depends largely on the accuracy of the channel estimation using the path-by-path decorrelator output and the results of the data decision made at the output of the channel-matched decorrelator. The behavior of the estimated channel gains,  $z_{11}, z_{12}$ , is demonstrated in Fig. 7 for the three-user two-path propagation environment with the SNR after despreading of 15 dB. The length 8 training symbols were embedded among the information data streams to be transmitted, which are asynchronous among the users, but whose timings are assumed to be known to the receiver. The channel gain matrix  $P$  in this case was (see bottom of this page). It is found that these values converge after 20 input symbols, including training.

2) *With Fading*: Under fading, the channel gains  $z_{k,l}$ 's (or equivalently fading complex envelopes), vary as the users move. Hence, mismatch between the channel-matched decorrelator and the actual channel gains  $z_{k,l}$ 's may result in

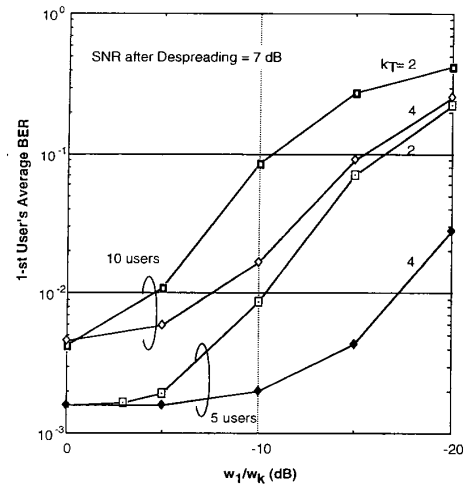
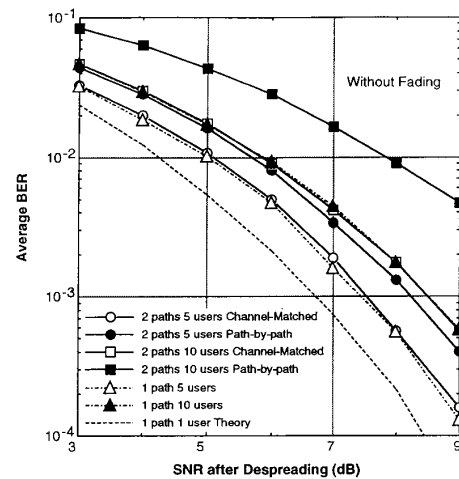
Fig. 5. First user's average BER versus received signal energy ratio  $w_1/w_k$ .

Fig. 6. BER versus SNR after despreading (without fading).

an overall performance degradation of the proposed system. This mismatch is caused by two factors: 1) too large a required truncation length  $k_T$  compared to the speed of the channel variation, and 2) insufficient tracking performance of the RLS algorithm used for channel estimation. Fortunately, however, Fig. 5 indicated that  $k_T = 4$  truncation length, which corresponds to the impulse response length of 9, can prevent the near-far resistance from being degraded, if  $K = 5$ . Therefore, even under fading, if channels can be regarded as remaining unchanged during 9 time slots of information symbols, the effect of the update of the matrix  $P$ 's estimate at every symbol timing is of no significance.

$$P = \begin{bmatrix} -0.80 + j0.76 & -0.87 - j0.29 & 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.35 + j0.81 & 0.90 - j0.61 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & -0.51 - j0.10 & 0.69 + j0.44 \end{bmatrix}^t$$



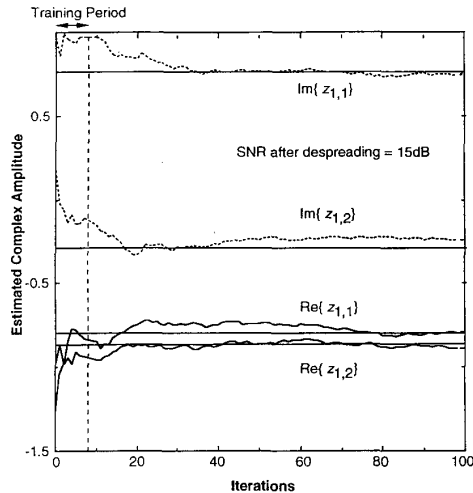


Fig. 7. Behavior of estimated channel gains.

Fig. 8 compares, for  $k_T = 4$ , the average BER performance of the proposed system to those with three other (unrealistic) systems using *actual* values of the channel gains: a) the decisions are made using channel-matched decorrelator output; b) the path-by-path decorrelator outputs are combined by the MRC combiner, and the decisions are made using its output; and c) the matched filter outputs are combined by the MRC combiner, and the decisions are made using its output, in which a 3-path propagation environment is assumed and the matrix  $P$ 's estimate is updated at every symbol timing (these three systems are referred to as system (a), (b), and (c), respectively, for convenience). Assuming that every user moves with the same speed, the normalized maximum Doppler frequency  $f_D T$  given by *speed of users' move*  $\times$  *symbol duration/carrier wave length* was set at 0.002. The frame length was 64 symbols, which includes an 8-symbol raining sequence. Binary 8-symbol random sequences were picked up and used as training sequences for the users, and the results were averaged over the users.

In the fading  $L$ -path propagation environment, the theoretical average BER  $P_b$  for the BPSK coherent detection can be calculated from [15]

$$P_b = \frac{1}{2(\Gamma/L)} \int_0^\infty \text{erfc}\sqrt{\gamma} \frac{1}{(L-1)!} \left(\frac{L\gamma}{\Gamma}\right)^{L-1} d\gamma \quad (22)$$

where  $\Gamma$  is the average SNR. The theoretical average BER is also plotted in Fig. 8. Obviously, the best performance is achieved by system (a). The simulation results indicate that, because of the noise enhancement, the system (a)'s BER performance is slightly worse than the theoretical curve (the average asymptotic efficiency is 0.6 dB in this case; however, because of data dispersion, this 0.6 dB noise enhancement cannot be clearly observed). This indicates that, for  $f_D T = 0.002$ , the effect of the update of the matrix  $P$ 's estimate at every symbol timing is not significant.

Because of the increased noise enhancement in the multipath propagation environment, the BER of system (b) is 2 dB worse than that of system (a) at  $\text{BER} \approx 10^{-3}$ . The BER of system

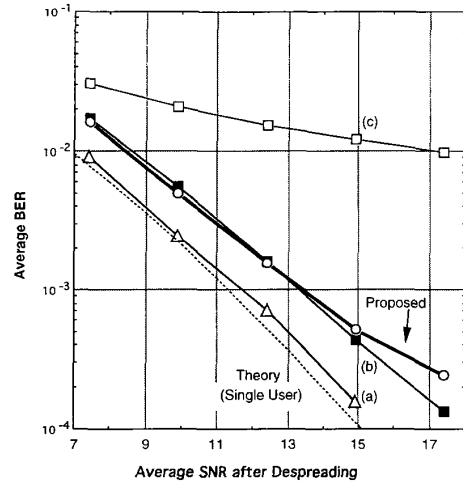


Fig. 8. Average BER versus average SNR after despreading (in fading).

(c) is far worse than the systems with decorrelators. For the proposed system, the BER is worse than that of system (a), and is almost equivalent to that of system (b) for small values of average SNR after despreading. The BER curve deviates from that of system (b) as the average SNR becomes larger. These BER degradations are due to insufficient tracking performance of the channel estimator.

Fig. 9 shows, for frame lengths of 32, 64, and 128, the average BER's of the proposed system and system (a) versus the normalized maximum Doppler frequency  $f_D T$ . The average BER of the proposed system increases as  $f_D T$  becomes larger, and the BER degradation is more significant for a larger frame length than a smaller one. This can easily be understood because it is likely to happen that, for a longer frame length, the channel estimation error becomes larger at the tail of the frame than at other parts of the frame. The average BER of system (a) stays the same even when  $f_D T$  increases. Hence, the major cause of bit error in the proposed scheme is the channel estimation error. The effects of the truncation in the approximated decorrelator and the update of the matrix  $P$ 's estimate at every symbol timing are of no significance.

## VI. CONCLUSION

In this paper, we have analyzed the asymptotic efficiencies of the path-by-path and channel-matched decorrelators in the multipath propagation environment, and proposed a new joint multiuser detection and channel estimation scheme for asynchronous CDMA mobile communications channels. It has been shown that in the multipath propagation environment, the asymptotic efficiency of the path-by-path decorrelator drops rapidly as the number of the simultaneous users increases. If there are  $L$  propagation paths for each simultaneous user, for example, the asymptotic efficiency is almost equivalent to that in the situation in which there is only one propagation path and  $L$  times as many users.

It was shown that this decrease in the asymptotic efficiency due to the multipaths can be recovered by the channel-matched decorrelator for those waveforms that are matched

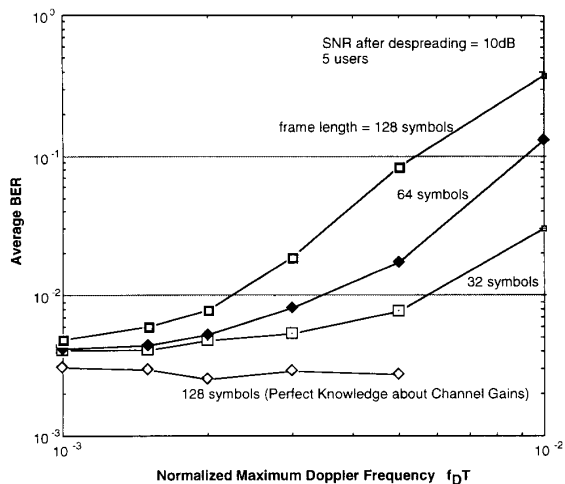


Fig. 9. Average BER versus normalized maximum Doppler frequency  $f_D T$ .

to the multipath channel responses to the users' spreading sequences. The channel-matched decorrelator does, however, require knowledge about the fading complex envelopes of all propagation paths.

In the proposed joint multiuser detection and channel estimation scheme, both path-by-path and channel-matched decorrelators are used. The path-by-path decorrelator is *not used* for making decisions on the simultaneous users, but is *used* for providing the channel estimator with the channel information path-by-path. Decisions are made on the output of the channel-matched decorrelator to obtain estimates of each users' transmitted information. The estimates are fed back to the channel estimator, and used as the reference signals. The received complex envelope of each propagation path is estimated in the channel estimator using the RLS algorithm, and then input to the channel-matched decorrelator. Assuming that the truncation length required to achieve an acceptable approximation is sufficiently small compared to the channel variation, the channel gain matrix is updated every time the path-by-path decorrelator output and the reference vector are obtained.

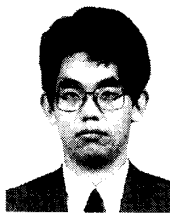
An exhaustive series of computer simulations was conducted in order to evaluate the overall performance of the proposed scheme, and examine what factor of the proposed system dominates performance. Reasonable results were obtained in the non-fading and fading environments. It was shown that the truncation length assumption is not a major cause of overall performance degradation. The simulation results showed that a major cause of bit error in the proposed scheme is channel estimation error. Hence, it should be emphasized that improving the tracking performance of the channel estimator improves the overall performance of the proposed joint decorrelating multiuser detection and channel estimation scheme.

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