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CDMA Multiuser Delay-Tracking and Detection

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Abstract— **We propose a low complexity CDMA multiuser delay tracking receiver as an alternative to the more complex extended Kalman filter (EKF) based CDMA multiuser delay trackers. It integrates delay-tracking into CDMA multiuser detection by the delay-robust successive interference cancellation (SIC) technique, which was initially proposed for robust CDMA multiuser detection when there exists time delay estimation errors. When the delay error is small, the true user signature vector can be approximately expanded around the estimated time delay as a linear combination of an estimated signature vector and an error vector. This error vector is equivalent to a single-branch realization of the delay-late delay locked loop in a conventional single user CDMA receiver. The error signal is recursively estimated and cancelled in the multistage SIC iterations by using the tentative feedback decisions. Since the relative amplitude of the error signal provides information about the delay error, we propose the application of error signal feedback to improve the delay estimation. In a sliding window implementation, the delay-robust SIC is used to track multiple time varying user delays. For constant or slowly varying channels, a soft-decision function can be used to improve the delay-robust SIC. For fast fading channels, a linear decision function is used. Delay tracking results for both rectangular chip pulse and band-limited chip pulses are shown.**

I. Introduction

CDMA multiuser detection is an effective method to suppress multiple access interference (MAI) from other users in the same cell and increase cell capacity [1]. Low complexity multiuser detectors, including the decorrelating detector [2], MMSE detector, successive interference cancellation (SIC) receiver [3] and parallel interference cancellation (PIC) receiver.

These multiuser detectors all need accurate time delay information from all users. Their performances will degrade dramatically when there exists even small time delay errors [5]. So it is very important to obtain accurate time delay estimates and track multiuser time delay variations.

The synchronization procedure can be divided into two phases: initial delay estimation (acquisition) and delay tracking. There is a rich literature on initial delay estimation (acquisition) of either a single user or of all users for a multiuser CDMA system [4]. However, compared to acquisition, less research has been done on tracking the multiuser delays after the initial acquisition.

Known multiuser delay tracking receivers can be categorized into two types: those based on the extended Kalman filter (EKF) [6] [7] [8] and those based on multistage interference cancellation combined with delay-locked loops (DLL) [9] [10]. Both kinds of delay trackers require the initial conditions (time delay, amplitude) to be close to their true values or they will not converge.

The extended Kalman filter (EKF) based delay tracking receiver [6] [7] has received most of the attention. However, its complexity is high since it needs to compute a matrix inverse for the innovation matrix over every symbol for all users.

An existing delay tracking receiver based on parallel interference cancellation (PIC) combined with delay-locked loops (DLL) has lower computational complexity [9] [10]. This approach uses the two-branch early-late delay locked loop, where the delay error signal is detected but not cancelled, and is able to track user delays under ideal power control conditions, i.e, a near-far ratio of 0 dB. However, when the near-far ratio increases to 10 dB, the scheme in [9] [10] breaks down since the residual interference due to delay errors from the strong users causes the weak users to make incorrect symbol decisions.

The objective in this paper is to improve tracking performance for the weak users. To successfully track the delays of the weak users, the interference due to delay error from strong users has to be estimated and cancelled. This can be achieved by using a delay-robust SIC for delay tracking. The delay-robust SIC is based on a Taylor expansion of the true user signature vector into the sum of an estimated signature vector and an error vector. The early-late delay locked loop is widely used in single-user receivers for tracking time delay variations [12]. Since the error vector used in the delay-robust SIC is equivalent to a single-branch implementation of the early-late delay locked loop, the delay-robust SIC implicitly combines a DLL into the SIC. Due to its robustness to delay errors even under severe near-far conditions, the tracking ability of the weak users can be greatly improved.

We use SIC instead of PIC since SIC has better convergence properties. The SIC regenerates and cancels the interference from other users before data detection of the desired user. The delay-robust SIC adds a delay error signal estimation and cancellation procedure onto the standard multistage SIC algorithm, by using tentative decision-feedback. Since the amplitude of the delay error signal is proportional to the time delay error, the time delay error estimate is implicitly obtained by the delay-robust SIC and can be used to refine the delay estimate. To track the users' time delays, the delay-robust SIC is implemented as a sliding window. The delay error estimate of the current window is used to update the time delay information used

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in the next window. We consider delay tracking for both slowly fading and fast fading channels.

Section II describes the system model. Section III introduces the delay-robust SIC and applies it to multiuser delay tracking for multipath fading CDMA channels. Section IV provides simulation results for both constant channels and fast fading channels.

II. System Model

We consider the base station receiver for the asynchronous uplink multipath fading CDMA channel with binary phase shift keying (BPSK) modulation.

The equivalent baseband received signal at the basestation is

$$r(t) = \sum_{i=-\infty}^{\infty} \sum_{k=1}^{K} \sum_{l=1}^{L} c_{k,l}(i) b_k(i) \tilde{s}_k(t - iT - \tau_{k,l}) + n(t) \quad (1)$$

where $b_k(i) \in \{+1, -1\}$ is the kth user's data symbol for the ith time interval, $\tilde{s}_k(t)$ is the kth user's normalized signature waveform, and $n(t)$ is the white Gaussian noise. $\tau_{k,l} \in [0, T)$ is the kth user's propagation delay for the lth path, T is the symbol duration and K is the total number of users. The amplitude is absorbed into the complex channel gain for the lth path of the kth user, $c_{k,l}(i)$. The channel is assumed to remain constant for the duration of a symbol interval, and varies from symbol to symbol. For simplicity, the number of multipaths are assumed to be the same for all users, L.

In (1), the normalized signature waveform of user k, $\tilde{s}_k(t)$, is

$$\tilde{s}_k(t) = \sum_{j=0}^{N-1} c_k(j) h(t - jT_c) \quad (2)$$

where $N = T/T_c$ is the spreading factor, $\{c_k(j)\}_{j=0}^{N-1}$ is the spreading code, T_c is the chip duration and $h(t)$ is the chip pulse. The spreading codes of all users are assumed to be known at the receiver.

We use an observation window of length $(M+1)T$ to detect the M transmitted data symbols from each user, $b_k(i)$, $i = 1, \ldots, M$ and $k = 1, \ldots, K$. After chip-matched filtering and chip-rate sampling, the received signal is discretized and the $(M+1)T$ observations can be organized into the vector

$$\mathbf{r} = \sum_{i=1}^{M} \sum_{k=1}^{K} \sum_{l=1}^{L} c_{k,l}(i) b_k(i) \mathbf{d}_{k,l}(i) + \mathbf{n} \quad (3)$$

where $\mathbf{d}_{k,l}(i)$ is the discretized signature waveform of user k for the ith symbol and lth path, and $\mathbf{n}$ is the noise vector. The received vector $\mathbf{r}$ is the concatenation of $M+1$ vectors each of length N, i.e.,

$$\mathbf{r} = [\mathbf{r}^T(1)\ \mathbf{r}^T(2)\ \ldots\ \mathbf{r}^T(M+1)]^T \in \mathcal{C}^{(M+1)N} \quad (4)$$

where the element vector $\mathbf{r}(m)$ in (4) corresponds to the mth observation interval $[(m-1)T, mT)$

$$\mathbf{r}(m) = [r(mN+1)\ \ldots\ r(mN+N)]^T \in \mathcal{C}^N \quad (5)$$

Similarly we may organize the zero-mean white Gaussian noise vector $\mathbf{n}$.

The time delay of lth path of the kth user is composed of an integer, $p_{k,l}$, and a fractional part, $\delta_{k,l}$, where $\tau_{k,l} = (p_{k,l} + \delta_{k,l})T_c$, $p_{k,l} \in \{0, 1, \ldots, N-1\}$ and $\delta_{k,l} \in [0, 1)$.

We denote $\mathbf{c}_k(p_{k,l}, i)$ as $\mathbf{c}_k$ right-shifted by $(i-1)N + p_{k,l}$ chips, where $\mathbf{c}_k \in \mathcal{R}^{(M+1)N}$ is the kth user's spreading code vector for the $(M+1)T$ length interval defined as

$$\mathbf{c}_k = [c_k(0)\ c_k(1)\ \ldots\ c_k(N-1)\ \underbrace{0\ 0\ \ldots\ 0}_{MN}]^T \quad (6)$$

The received discretized signature waveform of the ith symbol of the lth path of the kth user, $\mathbf{d}_{k,l}(i)$, is the convolution of the user spreading codes with the chip-matched filter response at the sampling points, i.e.,

$$\mathbf{d}_{k,l}(i) = \mathbf{c}_k(p_{k,l}, i) * \mathbf{g}_{k,l} \quad (7)$$

where vector $\mathbf{g}_{k,l}$ is the lth path of the kth user's chip-matched filter response at the chip-rate sampling points. If the chip-matched filter response is truncated to length PT_c, then the vector $\mathbf{g}_{k,l}$ will be of length P, and the signature waveform $\mathbf{d}_{k,l}(i)$ will have $N + P - 1$ non-zero elements. The mth element of $\mathbf{g}_{k,l}$ is given by

$$\begin{aligned} g_{k,l}(m) &= \int_{-\infty}^{\infty} h(\tau - \delta_{k,l}T_c) h^*(mT_c - \tau) d\tau, \\ \text{m} &\in \{1, 2, \ldots, P\} \end{aligned} \quad (8)$$

For the special case of rectangular chip pulse $h(t)$ with duration $[0, T_c)$, $P = 2$ and $\mathbf{g}_{k,l} = [(1 - \delta_{k,l})\ \delta_{k,l}]$. Substituting into (7), the discretized signature waveform is

$$\mathbf{d}_{k,l}(i) = (1 - \delta_{k,l}) \mathbf{c}_k(p_{k,l}, i) + \delta_{k,l} \mathbf{c}_k(p_{k,l} + 1, i) \quad (9)$$

The received signal vectors $\mathbf{r}(i)$ over the $(M+1)T$ observation intervals, $i = 1, \ldots, M+1$, provide sufficient statistics for detecting the transmitted data symbols from the K users.

III. Delay-Robust SIC with Multiuser Delay Tracking

In practical systems, the time delay is not known and must be estimated at the receiver. Denote the estimated time delay of the lth path of the kth user as $\hat{\tau}_{k,l} = (\hat{p}_{k,l} + \hat{\delta}_{k,l})T_c$. Since most current time delay estimation methods have a delay estimation error standard deviation within $0.1T_c$ [4], we assume that the delay error $\Delta\tau_{k,l} = \tau_{k,l} - \hat{\tau}_{k,l}$ is small compared to T_c.

We adopt a delay-robust multiuser receiver based on successive interference cancellation (SIC) implementation, which is denoted as delay-robust SIC [14]. At each SIC iteration, the timing delay error introduced interference is estimated and cancelled.

When the delay error is small, the kth user's signature waveform for the ith interval and the lth path, $\mathbf{d}_{k,l}(i)$, is first-order Taylor expanded as

$$\mathbf{d}_{k,l}(i) \approx \hat{\mathbf{d}}_{k,l}(i) + (\delta_{k,l} - \hat{\delta}_{k,l}) \Delta\mathbf{d}_{k,l}(i) \quad (10)$$

where $\hat{\mathbf{d}}_{k,l}(i)$ is similar to $\mathbf{d}_{k,l}(i)$ with $\hat{p}_{k,l}$ replacing $p_{k,l}$ and $\hat{\delta}_{k,l}$ replacing $\delta_{k,l}$.

The error vector $\Delta\mathbf{d}_{k,l}(i)$ is the convolution of the user spreading codes with the first derivative vector $\mathbf{f}_{k,l}$ of the lth path of the kth user's chip-matched filter response at the sampling points, i.e.,

$$\Delta\mathbf{d}_{k,l}(i) = \mathbf{c}_k(p_{k,l}, i) * \mathbf{f}_{k,l} \tag{11}$$

with elements

$$\begin{aligned} f_{k,l}(m) &= \frac{\partial}{\partial t}\int_{-\infty}^{\infty} h(\tau - \delta_{k,l}T_c)h^*(t-\tau)d\tau \mid_{t=mT_c}, \\ &\quad \text{m } \in \{1, 2, \ldots, P\} \end{aligned} \tag{12}$$

In the special case of a rectangular chip pulse, $P = 2$ and $\mathbf{f}_{k,l} = [-1\ 1]$. The error vector

$$\Delta\mathbf{d}_{k,l}(i) = -\mathbf{c}_k(\hat{p}_{k,l}, i) + \mathbf{c}_k(\hat{p}_{k,l}+1, i) \tag{13}$$

The performance degradation of the CDMA multiuser detectors is caused by the delay error signal which is a multiple of the error vector $\Delta\mathbf{d}_{k,l}(i)$. Since the error vector $\Delta\mathbf{d}_{k,l}(i)$ is known, we may estimate the amplitude of error signal by using the tentative decision-feedback in the iterations of the SIC and cancel this interference.

To improve the estimation accuracy of the error signal, at each iteration, the M error vectors of each user are combined into a long error vector, $\mathbf{e}_{k,l}$, based on the tentative data symbol decisions, $\hat{b}_k(i)$. If the complex fading gains $c_{k,l}(i)$ are known, then

$$\mathbf{e}_{k,l} = \frac{1}{M}\sum_{i=1}^{M}\Delta\mathbf{d}_{k,l}(i)\hat{b}_k(i)c_{k,l}(i) \tag{14}$$

We note that this is actually averaging the estimate over a window of M symbols.

To simplify the algorithm description, we let the number of paths be $L = 1$ and drop the subscript l for the paths. The delay-robust SIC algorithm is as follows [15]:

Initialization:

Calculate all $\Delta\mathbf{d}_k(i)$ and $\Delta\mathbf{d}_k(i)$, and set all initial values to zeros.

Iteration:

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For $j = 1, 2, \ldots, J$ do:
    For $k = 1, 2, \ldots, K$ do:
        Steps (1) through (4):
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(1) Estimate user k's received signal for the $(j+1)$st iteration by subtracting other users' reconstructed signals and error signals from the received signal:

$$\begin{aligned} \mathbf{r}_k^{j+1} &= \mathbf{r} - \sum_{l=1}^{k-1}(\hat{\mathbf{r}}_l^{j+1} + \widehat{\Delta a}_l^{j+1}\mathbf{e}_l^{j+1}) \\ &\quad - \sum_{l=k+1}^{K}(\hat{\mathbf{r}}_l^{j} + \widehat{\Delta a}_l^{j}\mathbf{e}_l^{j}) - \widehat{\Delta a}_k^{j}\mathbf{e}_k^{j} \end{aligned} \tag{15}$$

where $\mathbf{e}_l^j = \sum_{i=1}^{M}\Delta\mathbf{d}_l(i)\hat{b}_l^j(i)c_l(i)$ and $\hat{\mathbf{r}}_l^j = \sum_{i=1}^{M}\hat{b}_l^j(i)c_l(i)\hat{\mathbf{d}}_l(i)$.

(2) For each symbol in the block, $i = 1, \ldots, M$, obtain the normalized soft data symbol estimate and make a data symbol decision. For the ith symbol, the soft data symbol estimate is normalized with respect to $c_l(i)$:

$$\tilde{b}_k^{j+1}(i) = Re\left(\frac{(\hat{\mathbf{d}}_k(i))^T\,\hat{\mathbf{r}}_k^{j+1}(i)}{c_l(i)}\right)$$

where $Re(\cdot)$ takes the real value. The data symbol decision is then made by the decision function $f_{dec}(\cdot)$:

$$\hat{b}_k^{j+1}(i) = f_{dec}(\tilde{b}_k^{j+1}(i))$$

(3) Estimate the error signal of the kth user due to time delay error as:

$$\Delta\mathbf{r}_k^{j+1} = \mathbf{r}_k^{j+1} - \hat{\mathbf{r}}_k^{j+1} + \widehat{\Delta a}_k^{j}\mathbf{e}_k^{j} \tag{16}$$

(4) Update the normalized amplitude of the error signal:

$$\widehat{\Delta a}_k^{j+1} = (\mathbf{e}_k^{j+1})^H(\Delta\mathbf{r}_k^{j+1}) \tag{17}$$

We note that since $\widehat{\Delta a}_k = (\delta_k - \hat{\delta}_k)$ from (10), the estimate of the normalized error signal amplitude $\widehat{\Delta a}_k$ at $(j+1)$st iteration in (17) can be used to improve the delay estimate.

We propose using a sliding window version of the delay-robust SIC as a multiuser delay tracking receiver. It is required that all users are initially under acquisition, i.e., within $\pm 0.5T_c$ of the true delay. This initial acquisition can be obtained by using other delay estimation algorithms [4].

The delay is updated in small steps, i.e., $0.05T_c$. When the delay error estimate is larger than $\pm 0.05T_c$, the user time delay is updated by $\pm 0.05T_c$ and then used in the next window where the same procedure is repeated.

It was shown in [11] that when the observation window length M is larger than 8 symbols, edge effects can be neglected. It is also shown in [14] that the delay-robust receiver has a capacity of $\frac{M}{M+1}$ of the standard SIC. As a compromise, and we choose $M = 9$ in our simulations.

When the complex fading channel gains $c_{k,l}(i)$ are known, which is the case of slow fading or additive white Gaussian noise (AWGN) channels, where the channel gains and amplitudes can be easily estimated, we may use a soft decision function in the SIC to improve BER performance [15].

However, channel estimation for a fast fading multiuser CDMA channel is a difficult problem, since the effect of MAI must be suppressed or eliminated first to obtain an accurate channel estimate for the desired user. One suboptimum solution is the multipath decorrelating detector [16] [17]. The multipath decorrlating detector can be used first to decorrelate each path of each user before channel estimation. The channel estimator works on these MAI-free decorrelator outputs [16]. The price paid for this MAI-free decorrelation is the noise enhancement and reduced system capacity, since each user is detected as L users.

As shown in [13], the linear SIC (multistage SIC with linear decision function) is an iterative implementation of the decorrelator. The linear decision function is $f_{dec}(x) = x$, which is equivalent to estimate the data symbol $b_k(i)$ and complex channel gain $c_{k,l}(i)$ as a composite signal $o_{k,l}(i)$ at stage $(j+1)$:

$$\hat{o}_{k,l}^{j+1}(i) = (\mathbf{d}_{k,l}(i))^T \ \tilde{\mathbf{r}}_{k,l}^{j+1} \tag{18}$$

and $\mathbf{e}_{k,l}$ at stage $(j+1)$ is:

$$\mathbf{e}_{k,l}^{j+1} = \sum_{i=1}^{M} \Delta\mathbf{d}_{k,l}(i)\hat{o}_{k,l}(i) \tag{19}$$

With this new $\mathbf{e}_{k,l}^{j+1}$, we replace $\hat{b}_k^j(i)c_k(i)$ by $\hat{o}_k^j(i)$ in Step (1) and we replace the entire Step (2) by (18). The resulting delay-robust SIC with a linear decision function can be used to track the time delays of all users for fast fading channels,

IV. NUMERICAL AND SIMULATION RESULTS

Throughout the simulations, Gold code sequences of length $N = 31$ are used. The number of users is fixed at $K = 20$ to account for a highly-loaded system. The signal-to-noise ratio (SNR) is defined with respect to the user of interest, user 1. The near-far ratio is defined as the power ratio between the strongest user and user 1, which is fixed at 10 dB. All other users have an amplitude uniformly distributed between those of the strongest user and the weakest user. We let the sliding window length be $M = 9$ symbols. Rectangular chip pulses are used.

First, we consider the channel coefficients are known case, where an additive white Gaussian noise (AWGN) channel is assumed. Here, we can take advantage of the constant amplitude property by using a soft decision function. The tracking for fast Rayleigh fading channels using a linear decision function is simulated in IV-C.

A. *Tracking for rectangular chip pulses*

We tracked a total of $K = 20$ users' delays. The SNR of the weakest user is 14 dB. The initial acquisition has a delay error standard deviation of $0.5T_c$. The weakest user's and the strongest user's delay tracking curves are shown in Fig. 1, where the solid line and the dashed line represent the actual and estimated delay trajectories, respectively. The update step of the delay tracker is $0.05T_c$. As we can see, the delay-robust SIC based delay tracker can track the time delays for both the strongest user and the weakest user.

The delay variation with time is modeled as a first-order Gauss-Markov process as in [6]:

$$\tau(m+1) = \tau(m) + w(m) + u(m) \tag{20}$$

where $w(m)$ is a zero-mean noise process with variance σ_w^2, and $u(m)$ is a deterministic scalar that models global drift. We use $\sigma_w^2 = 0.01\sigma^2$. The global time variation $u(m)$ is selected to change at a rate of $0.005T_c$ per symbol. Assuming a propagation speed of 3.0×10^8 m/s, this is equivalent to $\frac{0.005}{31} \times 3.0 \times 10^8 \approx 5 \times 10^4$ m/s, or 1.8×10^5 km/h [7].

B. *BER performance*

In Fig. 2, the BER of the delay-robust SIC using dynamic tracking is compared to the BER of the delay-robust SIC in the static model. The initial acquisition has a delay error standard deviation of $0.1T_c$. The time delay variation in the tracking model adds only a small amount of noise, and the BER error floor is not obvious. As a comparison, the BER curve of the single user case is shown as a lower bound which can only be achieved by the ideal multiuser detector with true time delay and amplitude information.

C. *Tracking for time varying fading channels*

The delay-robust SIC with a linear decision function is used to track the delay variations. Since the data symbol $b_k(i)$ and complex channel gain $c_{k,l}(i)$ are estimated as a composite signal $\hat{o}_{k,l}(i)$, data detection is not possible before knowing $c_{k,l}(i)$. The tracking results are shown in Fig. 3 for the weakest and strongest users. The near-far ratio is reduced to 5 dB. Time-correlated Rayleigh fading channel gains are generated with a normalized Doppler fading rate of $f_D T = 0.01$. Because of the noisy estimate $\hat{o}_{k,l}(i)$, the tracking performance of the weakest user is reduced. Note that this simulation is approximately equivalent to a $K = 10$ user system with $L = 2$ paths for each user.

By assuming the exact knowledge of the transmitted data symbol $b_k(i)$, the complex channel gain is tracked in Fig. 4 for user 1. The delay-robust SIC decorrelates the fading signal for different users, so it can be used to track both delay and channel variations.

V. CONCLUSION

We have proposed to use a delay-robust SIC detector for multiuser time delay tracking. The time delay error vector in the robust SIC can be used to estimate the time delay changes of all users. The delay-robust SIC implicitly combined the delay tracking into the multiuser detection. For a static delay channel, the delay-robust SIC has a BER close to single user bound. For dynamic delay tracking, the BER of the multiuser delay tracking receiver based on the sliding window implementation of delay-robust SIC is slightly higher than that of the static channel. Accurate tracking results are obtained for both for both constant channels and fast fading channels.

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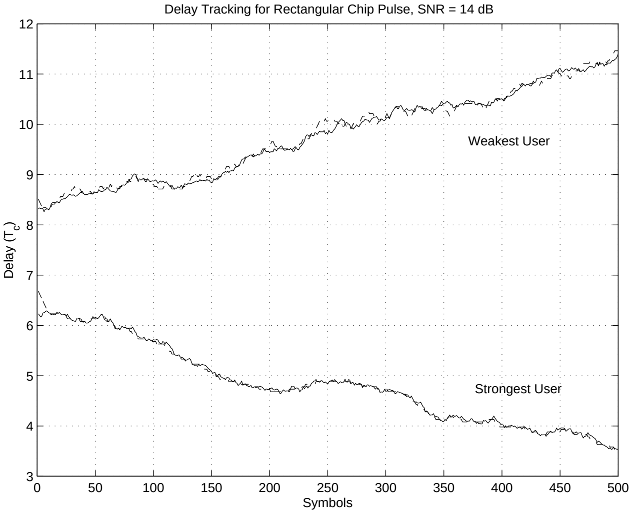

Fig. 1. Delay tracking curves of delay-robust SIC. $K = 20$ users. Near-far ratio = 10 dB. The weakest user has $SNR = 14$ dB. Soft decision function is used. The solid line is the true delay and the dashed line is the tracking results.

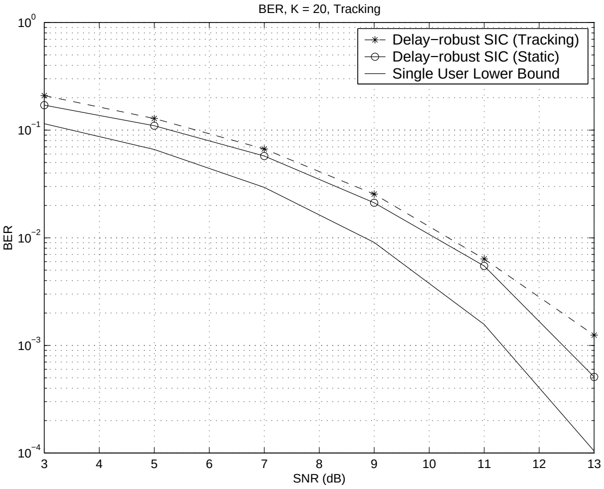

Fig. 2. Bit error rate (BER) of weakest user (user 1) for delay-robust SIC detector in tracking time delays. $K = 20$ users. Near-far ratio = 10 dB. Soft decision function is used.

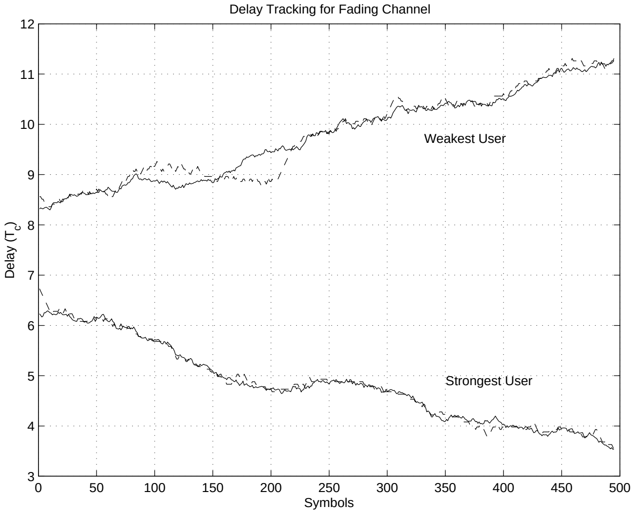

Fig. 3. Delay tracking curves of delay-robust SIC for Rayleigh fading channels. Normalized Doppler fading rate is $f_D T = 0.01$. $K = 20$ users. Near-far ratio = 5 dB. The weakest user has $SNR = 14$ dB. Linear decision function is used. The solid line is the true delay and the dashed line is the tracking results.

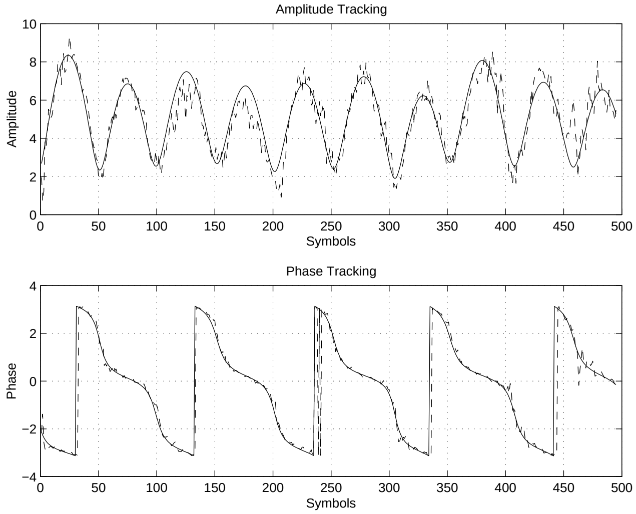

Fig. 4. Channel amplitude and phase tracking curves of delay-robust SIC for Rayleigh fading channels for the weakest user. Normalized Doppler fading rate is $f_D T = 0.01$. $K = 20$ users. Near-far ratio = 5 dB. The weakest user has $SNR = 14$ dB. Linear decision function is used. The solid line is the true delay and the dashed line is the tracking results.

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