CDMA Packet Recognition and Signal Acquisition using LMS-based Adaptive Receiver

T. Kume, T. Yamazato, K. Ban, H. Okada and M. Katayama
Dept. of Information Electronics, Graduate School of Eng., Nagoya University.
Furocho Chikusa-ku Nagoya, 464-8603, Japan.

Abstract— **In this paper, we propose a new packet recognition and signal acquisition scheme with an adaptive linear filter based on an Least Mean Square (LMS) algorithm for code-division multiple access (CDMA) packet systems. In CDMA systems, conventional receivers with matched filtering suffer from the near-far problem due to multiple access interference (MAI). In general, closed-loop power control is used in order to reduce the influence of the near-far problem. However, closed-loop power control is unsuitable for packet systems. Hence, in order to eliminate the influences of the near-far problem, we focus on an adaptive receiver based on an LMS algorithm for a packet recognition and signal acquisition in CDMA packet systems.**

I. INTRODUCTION

With the introduction of the third generation (3G) systems starting in 2001, a vast growth of data traffic is expected. A tendency of such growth can be observed by the fact that mobile Internet access services, such as i-mode, EZweb and J-sky in Japan, had approximately 47 million subscribers in November 2001, with an increase of about 250,000 subscribers per a week[1]. As a perspective, the mobile radio systems should support such services. Major requirement for fourth generation (4G) wireless systems is, therefore, to support IP-traffic which may be delivered using efficient *CDMA packet systems*.

Fast and reliable recognition and acquisition of packets are of great significance in CDMA packet systems. Matched filtering is a commonly used method for signal recognition and acquisition[2]. However, since matched filtering is vulnerable to the near-far problem due to multiple access interference (MAI) inherent in a CDMA environment, the system capacity is limited by MAI.

Many interference suppression schemes, which can reduce the near-far problem by exploiting the structure of MAI, are previously proposed[3][4][5]. These schemes are more complex than the scheme with matched filters and require explicit knowledge or estimates of interference parameters such as the spreading sequences, amplitudes, and timing offsets. As a result, the receivers with matched filters supported by closed-loop power control are often used.

Although closed-loop power control, which requires feedback from the receiver to the transmitter, may reduce the influence of MAI, the requirement of frequent feedback is unsuitable for highly efficient CDMA packet systems. Therefore, we focus on an adaptive receiver with a linear filter based on a basic Least Mean Square (LMS) algorithm. That adaptive receiver is based on the minimum mean square error (MMSE) criterion and can reduce the influence of MAI without explicit knowledge of interference parameters since filter parameters can be adapted to achieve the Wiener-Hopf solution[6].

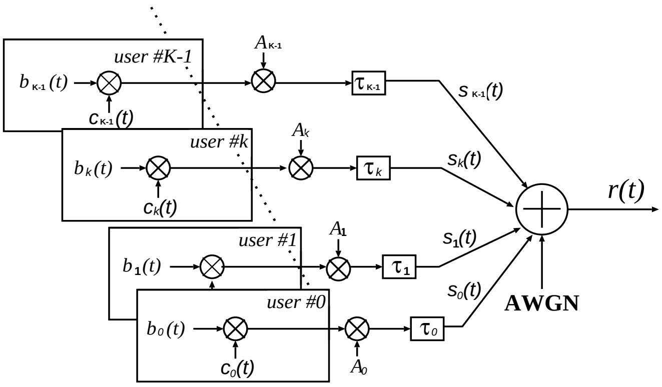

Fig. 1. CDMA packet system.

In this paper, we propose a new packet recognition and signal acquisition scheme with an LMS-based adaptive linear filter for CDMA packet systems in order to mitigate the near-far problem.

II. SYSTEM MODEL

We consider the uplink of CDMA packet mobile radio systems. Figure 1 shows the model of a CDMA packet system. In a CDMA environment with K active users' packets, the received signal $r(t)$ can be expressed as

$$r(t) \quad = \quad \sum_{k=0}^{K-1} A_k s_k(t-\tau_k) + n(t) \qquad (1)$$

where A_k is the kth user's amplitude, $s_k(t)$ is the kth user's transmitted signal, $n(t)$ is the additive white Gaussian noise (AWGN) with two-sided power spectral density of $N_0/2$, and τ_k is the kth user's timing offset from a timing reference. For a notational convenience, we consider the baseband model.

The kth user's transmitted signal $s_k(t)$ is expressed as

$$s_k(t) \quad = \quad \sum_{i=-\infty}^{\infty} b_k(i) c_k(t-iT) \qquad (2)$$

where $b_k(i)$, ($\{\in 0, \pm 1\}, -\infty < i < \infty$), is the ith symbol of the kth user's packet, T is the symbol duration and $c_k(t)$ is the kth user's spreading signal waveform expressed as

$$c_k(t) \quad = \quad \sum_{j=0}^{L_c-1} c_k^{(j)} p_c(t-jT_c) \qquad (3)$$

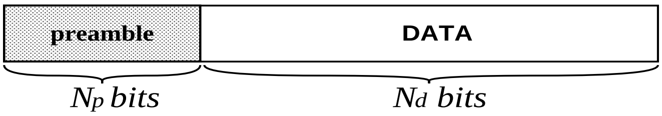

Fig. 2. Structure of a packet.

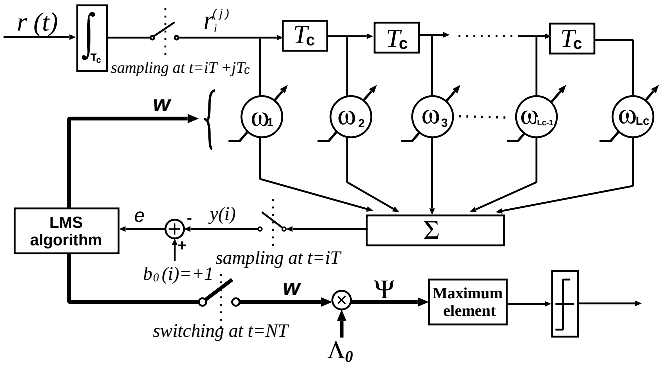

Fig. 3. Structure of an adaptive receiver.

where T_c is the chip duration, $L_c(= T/T_c)$ is the processing gain, $c_k^{(j)}$, $(\{\in \pm 1\}, 0 \leq j \leq L_c - 1)$, is the jth chip component of the kth user's spreading sequence, and $p_c(t)(= \ 1\ (0 \leq t \leq T_c - 1), \ \ 0$ (otherwise)) is the chip pulse waveform. As shown in Fig.2, the transmitted packet consists of a preamble part and a data part. It is assumed that all of the symbols of a preamble take $+1$ and the symbols of a data take ± 1 at random.

At the receiver, described in Fig.3, the received signal $r(t)$ enters the chip-matched filter followed by a chip rate sampler. The jth chip-matched filter output $r_i^{(j)}$, $(j = 0, 1, \cdots, L_c - 1)$, of the ith received symbol is

$$r_i^{(j)} \;=\; \frac{1}{T_c} \int_{iT+jT_c}^{iT+(j+1)T_c} r(t)dt. \tag{4}$$

The ith chip-matched filter output vector within the symbol interval T is expressed as

$$\mathbf{r}_i = [r_i^{(0)}, \cdots, r_i^{(L_c-1)}]^T \tag{5}$$

where $[\cdot]^T$ denotes the transposition. For simplicity, we assume the case of chip-synchronous transmission.

If the number of active users K is constant in an observation period, a CDMA packet system can be considered as an asynchronous CDMA system. It is well known that an asynchronous CDMA system of K users can be equivalently recognized as a synchronous CDMA system with $2K-1$ users [6][9]. Therefore, as shown in Fig.4, $K-1$ interfering packets which are asynchronous to the 0th user's packet are divided into $2K-2$ interfering packets which are synchronous to the 0th packet. Hence the ith chip-matched filter output vector is

$$\mathbf{r}_i \;=\; [r_i^{(0)}, \cdots, r_i^{(L_c-1)}]^T \tag{6}$$

$$= \mathbf{A}_0\mathbf{b}_0\mathbf{c}_0 + \sum_{k=1}^{2(K-1)} \mathbf{A}_k\mathbf{b}_k\hat{\mathbf{c}}_k + \mathbf{n}_i \tag{7}$$

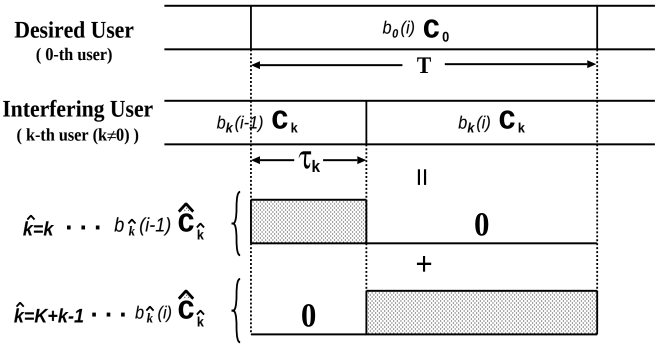

Fig. 4. Example of MAI.

where $\mathbf{A}_k$ and $\mathbf{b}_k$ are a L_c-by-L_c matrix whose diagonal are respectively $A_k \quad (0 \leq k < K)$ or $A_{k-(K-1)} \quad (K \leq k \leq 2(K-1))$ and $b_k(i) \quad (0 \leq k < K)$ or $b_{k-(K-1)}(i) \quad (K \leq k \leq 2(K-1))$. $\mathbf{c}_0$ is the 0th user's spreading sequence vector whose jth row is $c_0^{(j)}$ and $\hat{\mathbf{c}}_k$ is the kth user's spreading sequence vector whose jth row is expressed when $0 < k < K$ as

$$\hat{c}_k^{(j)} = \begin{cases} c_k^{(j)} & (0 \leq j \leq \tau_k/T_c - 1) \\ 0 & (\tau_k/T_c - 1 < j \leq T/T_c - 1) \end{cases} \tag{8}$$

and when $K \leq k \leq 2(K-1)$ as

$$\hat{c}_k^{(j)} = \begin{cases} 0 & (0 \leq j \leq \tau_k/T_c - 1) \\ c_{k-(K-1)}^{(j)} & (\tau_k/T_c - 1 < j \leq T/T_c - 1) \end{cases} . \tag{9}$$

The arrangement of (7) yields

$$\mathbf{r}_i = \mathbf{C}\mathbf{A}\mathbf{b} + \mathbf{n}_i \tag{10}$$

where

$$\mathbf{C} \;=\; \begin{bmatrix} c_0^{(0)} & \hat{c}_1^{(0)} & \cdots & \hat{c}_{2(K-1)}^{(0)} \\ \vdots & \vdots & & \vdots \\ c_0^{(L_c-1)} & \hat{c}_1^{(L_c-1)} & \cdots & \hat{c}_{2(K-1)}^{(L_c-1)} \end{bmatrix}, \tag{11}$$

$$\mathbf{A} \;=\; diag[A_0, A_1, \cdots, A_{2(K-1)}], \tag{12}$$

$$\mathbf{b} \;=\; [b_0(i), b_1(i) \cdots, b_{2(K-1)}(i)]^T, \tag{13}$$

, and $\mathbf{n}_i$ is the L_c-by-1 vector of independent Gaussian random variables.

III. LMS-BASED ADAPTIVE RECEIVER

We consider an adaptive receiver with a linear filter based on a basic LMS algorithm as a single user receiver. Figure 3 shows the structure of the adaptive receiver that we consider in this paper. We apply an LMS algorithm which is simple and well known as an adaptive algorithm to adjust MMSE criterion. The receiver is implemented as a tapped-delay line. When chip-synchronous is assumed, such a receiver is equivalent to the MMSE linear receiver[6].

Now let us consider a packet recognition. We have two cases; A) the desired packet is present in the observation period, B) the desired packet is absent in the observation period.

A. *The desired packet is present in the observation period*

Suppose that the desired (0th) user's packet arrives at the receiver in the presence of $K-1$ interfering users' packets. The normalized tap weight vector $\mathbf{w}_0$ of the MMSE receiver are adjusted to minimize the mean square value of the error

$$J(\mathbf{w}_0) = \frac{1}{2}E[(b_0(i) - y(i))^2] \tag{14}$$

where $b_0(i)$ is the information symbol transmitted in the ith signaling interval and $y(i)$ is the estimate of that symbol at the output of the receiver [8]. The normalized tap weight vector minimizing (14) is known as the normalized Wiener-Hopf solution and expressed as

$$\mathbf{w}_0 = \frac{\mathbf{R}^{-1}\mathbf{P}}{||\mathbf{R}^{-1}\mathbf{P}||} \tag{15}$$

where $||\cdot||$ denotes the Euclidean norm, $\mathbf{P}$ is $E[b_0(i)\mathbf{r}_i]$, and $\mathbf{R}$ is the correlation matrix of the received signal, given by

$$\begin{aligned} \mathbf{R} &= E[\mathbf{r}_i\mathbf{r}_i^H] \\ &= \mathbf{C}\mathbf{A}\mathbf{A}^H\mathbf{C}^H + \sigma_n^2\mathbf{I}_{L_c} \end{aligned} \tag{16}$$

where H denotes the Hermitian transpose, σ_n^2 is the variance of AWGN and $\mathbf{I}_{L_c}$ is an L_c-by-L_c identity matrix. The receiver has to accomplish the packet recognition and signal acquisition of a desired packet within a preamble of the packet. The transmitted information symbols of a preamble are known at the receiver.

Since all of the transmitted information symbols of a preamble take $+1$, we obtain

$$\begin{aligned} \mathbf{P} &= E[b_0(i)\mathbf{r}_i] \\ &= E[\mathbf{A}_0\mathbf{b}_0\mathbf{c}_0] \\ &= A_0\mathbf{c}_0. \end{aligned} \tag{17}$$

Substitution of (16) and (17) into (15) yields the desired user's normalized Wiener-Hopf solution

$$\mathbf{w}_0 = \frac{(\mathbf{C}\mathbf{A}^2\mathbf{C}^H + \sigma_n^2\mathbf{I}_{L_c})^{-1}\mathbf{c}_0}{||(\mathbf{C}\mathbf{A}^2\mathbf{C}^H + \sigma_n^2\mathbf{I}_{L_c})^{-1}\mathbf{c}_0||}.$$

It is well known that the tap weight vector of an adaptive filter based on an LMS algorithm converges to the Wiener-Hopf solution [8]. Therefore, it is assumed that the tap weight vector obtained by the adaptive receiver is equivalent to the Wiener-Hopf solution.

We next consider the correlation between the spreading sequence and the normalized Wiener-Hopf solution. The correlation between the spreading sequence $\mathbf{c}_k$ and the normalized Wiener-Hopf solution $\mathbf{w}_0$ is

$$\begin{aligned} \rho_k &= \mathbf{c}_k^H\mathbf{w}_0 \\ &= \frac{\mathbf{c}_k^H(\mathbf{C}\mathbf{A}^2\mathbf{C}^H + \sigma^2\mathbf{I})^{-H}\mathbf{c}_0}{\sqrt{\mathbf{c}_0^H(\mathbf{C}\mathbf{A}^2\mathbf{C}^H + \sigma^2\mathbf{I})^{-H}(\mathbf{C}\mathbf{A}^2\mathbf{C}^H + \sigma^2\mathbf{I})^{-1}\mathbf{c}_0}}. \end{aligned} \tag{18}$$

It is obvious in (18) that the correlation of $k=0$ is larger than the correlation of $k \neq 0$. That is because, in the case that the desired user's packet is present, the MMSE receiver forms the tap weights that can eliminate MAI while securing the desired signal. By using the correlation, the receiver can recognize the desired packet, distinguished from the other interfering users.

B. *The desired packet is absent in the observation period*

When the desired packet is absent in the observation period, the received signal $\mathbf{r}_i$ and the desired response $b_0(i)$ are uncorrelated and then the expectation of the tap weights of the adaptive receiver becomes $\mathbf{0}$. Since $\mathbf{P} = \mathbf{0}$, the correlation between the spreading sequence of the desired user and the normalized tap weight vector is a zero-mean random variable. Therefore, by using the correlation, the receiver can recognize that a desired packet is not present in the observation period.

In the next section, we provide the packet recognition and signal acquisition scheme using this correlation.

IV. SCHEME FOR PACKET RECOGNITION & SIGNAL ACQUISITION

Figure 5 shows the flow chart of the proposed packet recognition and signal acquisition scheme. In this scheme, the receiver judges whether a desired packet is present or not every N symbols of the observation period, which we call a *window*. If a desired packet is not detected in a window, the receiver searches the next window for the desired packet.

The tap weights of the adaptive filter, whose initial are fixed to be all 0, are updated by an LMS algorithm every symbol duration T. After the tap weights are updated N times, the receiver calculates the inner product between the L_c-by-L_c matrix Λ_0 and the normalized tap weight vector $\mathbf{w}$

$$\Psi = \Lambda_0\mathbf{w} \tag{19}$$

where Λ_0 is the matrix whose row is the cyclic shifted version of the desired user's spreading sequence vector $\mathbf{c}_0$ and expressed as

$$\Lambda_0 = \begin{bmatrix} c_0^{(0)} & c_0^{(1)} & \cdots & c_0^{(L_c-1)} \\ c_0^{(L_c-1)} & c_0^{(0)} & \cdots & c_0^{(L_c-2)} \\ \vdots & & \ddots & \vdots \\ c_0^{(1)} & c_0^{(2)} & \cdots & c_0^{(0)} \end{bmatrix}. \tag{20}$$

Λ_0 is used in order to acquire the desired user's PN code timing. And then the receiver selects the maximum element

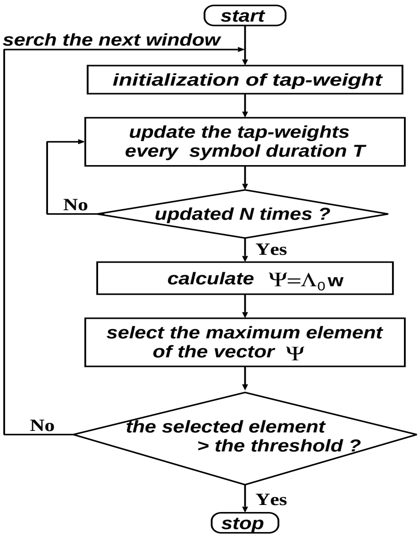

Fig. 5. The proposed packet recognition and signal acquisition scheme.

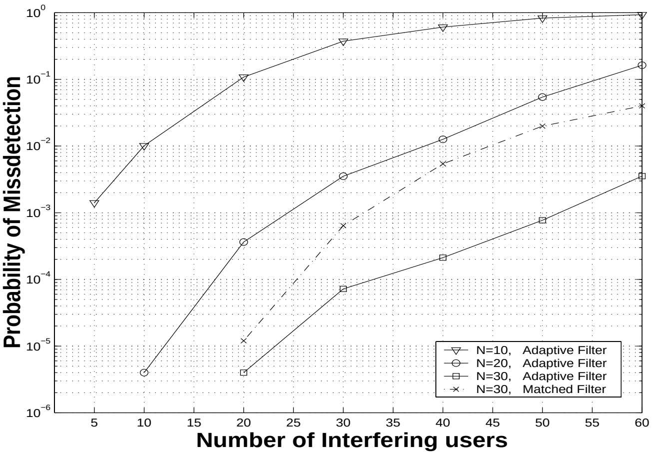

Fig. 6. Probability of miss-detection vs the number of interfering users.

of the vector Ψ and the selected value enters into the threshold detector. At the threshold detector, if the selected value is larger than the given threshold, the receiver judges that the desired packet is present. On the other hand, if the selected value is less than the threshold, the receiver judges that the desired packet is absent and then searches the next window in the same way.

If a larger size of the window to search is assigned, the receiver can recognize a desired packet more accurately but the longer preamble is necessary and the efficiency of the system becomes lower.

V. PERFORMANCE ANALYSIS

In this section, we provide some numerical examples to demonstrate the performance of the scheme we proposed in the previous section.

A. *Performance Measurement*

In CDMA systems, mean acquisition time, which is the expectation of the time needed to acquire the timing of PN code, has been most widely used as the measurement of performance of acquisition schemes. However, in CDMA packet systems, mean acquisition time is not an appropriate measurement of the performance because the receiver has to accomplish the packet recognition and signal acquisition within the preamble of a desired packet and it is more important than mean acquisition time whether the receiver succeeds or fails in the recognition and acquisition of the desired packet. Therefore we use the miss-detection probability and the false-detection probability as the measurement of the performance of the proposed scheme. The miss-detection probability is defined as the probability that the receiver fails to recognize a desired packet in spite of the presence of the desired packet. On the other hand, the false-detection probability is defined as the probability that the receiver recognizes a desired packet by mistake despise the desired packet is absent. There is a tradeoff between the miss-detection probability and the false-detection probability. Hence we evaluate the miss-detection probability when the false-detection probability is set to a given value.

B. *Simulation Conditions*

We numerically compare the performance of the proposed packet recognition and signal acquisition scheme with the adaptive filter (AF) with the one of the scheme with a matched filter (MF) for a specific example. Computational simulations are carried out on the condition that the desired packet appears while interfering users' packets, all of which are assumed to be a data part of the packet, are present in the observation period. It is assumed in all of the following results that all packets is transmitted by BPSK modulation, the spreading sequences are Gold sequences whose code length L_c is $2^6 - 1$, and each user is assigned a different spreading sequence. E_b/N_0 is 10 [dB], where E_b is the bit energy, and step size λ, which is a coefficient of an LMS algorithm, is 0.0001. We evaluate the miss-detection probability when the false-detection probability is 0.01.

The packet recognition and signal acquisition scheme with MF, which the proposed scheme with AF is compared with, is assumed to cumulate the output of the filter matched to a desired user during N symbols and then make the decision of packet recognition by the threshold detector[2].

C. *Numerical Results*

Figure 6 illustrates the miss-detection probability versus the number of interfering users for the proposed scheme with AF and the scheme with MF. We assume that the signal power of all packets is equal. We can find that the performance of the proposed scheme with AF becomes better as window size N is larger. That is because it takes about 30 symbols or so for the tap weights of the receiver using an LMS algorithm to converge. Compared with the scheme with MF when $N = 30$, the proposed scheme with AF has better performance as the

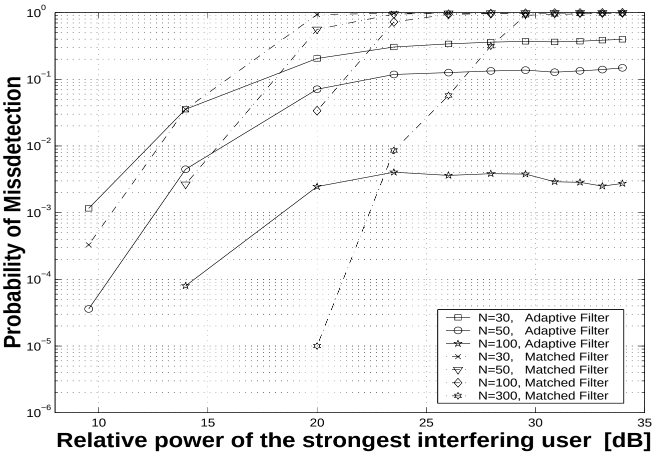

Fig. 7. Probability of miss-detection vs relative power of the largest interfering user.

number of interfering users increases. Therefore this result shows that the proposed scheme with AF reduces the influence of MAI.

Figure 7 shows the miss-detection probability versus the relative power of the largest interfering user. It is assumed that the number of interfering users is 10, where only one of those users has larger power than the desired packet and the other interfering users have the power equal to the desired packet. We can find that when the relative power is small, the performance of the scheme with MF is a little better than that of the proposed scheme with AF. However, as the relative power is larger, the performance of the scheme with MF becomes worse while the proposed scheme with AF converges to a certain performance. Compared at $N = 100$, the proposed scheme with AF maintains the good performance while the scheme with MF does not work at all when the relative power is over 25 [dB]. Consequently, this result shows that the proposed scheme is near-far resistant.

VI. CONCLUSIONS

In this paper, we have proposed a packet recognition and signal acquisition scheme with an LMS-based adaptive linear filter for CDMA packet radio systems. We have provided some numerical examples to demonstrate the performance of the proposed scheme with the adaptive filter. Simulation results have shown that the proposed scheme mitigates the influence of MAI and also is robust against strong interferences. Such a near-far resistant scheme as we have proposed is suitable especially for packet systems, in which closed-loop power control technique is unsuitable. In addition, the proposed scheme realizes rapid recognition and acquisition of desired packets because the proposed scheme requires less symbols of the window to achieve a given performance than the scheme with a matched filter.

ACKNOWLEDGEMENTS

This work is supported in part by Telecommunications Advancement Organization of Japan, The Hori Information Science Promotion Foundation and Fujitsu Laboratories.

REFERENCES

[1] http://www.tca.or.jp/index-e.html
[2] A.Polydoros and C.Weber, “A Unified Approach to Serial Search Spread-Spectrum Code Acquisition-Part II:A Matched-Filter Receiver,” IEEE Trans. Commun., vol.32, no.5, pp.550-560. May 1984.
[3] A.Duel-Hallen, “Decorrelating decision-feedback multiuser detector for synchronous code-division multiple-access channel,” IEEE Trans. Commun., vol.41, pp.285-290,Feb. 1993.
[4] R.Lupas and S. Verdu, “Near-far resistance of multi-user detctors in asynchronous channels,” IEEE Trans. Commun., vol.38, pp. 496-508, Apr. 1990.
[5] Sergio Verdu, Multiuser Detection, Cambridge University Press, Cambridge, 1998.
[6] U.Madhow and M. Honig, “MMSE interference suppression for direct-sequence spread-spectrum CDMA,”IEEE Trans. Commun., vol.42, pp.3178-3188, December 1994.
[7] Michael Honig, “Adaptive linear interference suppression for packet DS-CDMA,” European Transactions on Telecommunications, vol.9, no.2, pp.173-181, March-April 1998.
[8] Simon Haykin, Adaptive Filter Theory, 3rd ed.,Prentice-Hall Inc.,New Jersey,1996.
[9] J.Murata and S.Tachikawa, “A proposal of novel synchronous acquisition method with an adaptive filter in asynchronous DS/CDMA,” IEICE Trans. fundamentals, vol.80, no.12, pp.2382-2388, December, 1997