EFFECT OF INTERLEAVING AND FEC ON THE THROUGHPUT OF CDMA UNSLOTTED ALOHA SYSTEM WITH ADAPTIVE MULTIUSER RECEIVER

Hiraku Okada, Takaya Yamazato, and Masaaki Katayama

Center for Information Media Studies, Nagoya University,
Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan.
{okada, yamazato, katayama}@nuee.nagoya-u.ac.jp

Abstract – A CDMA unslotted ALOHA system is a connectionless-type of CDMA packet communication system. In this system, a user station can transmit a packet asynchronously and randomly, and so the packet birth/death event is one of the most important problems for multiuser detection. We have proposed the CDMA unslotted ALOHA system using an adaptive filter receiver based on minimum mean square error criterion in [8], and shown the improvement in the throughput performance even considering the effect of birth/death event. The ensemble-averaged squared error, however, increases at the point of packet birth. In this paper, we employ interleaving and forward error correction (FEC) coding techniques to mitigate the momentary increase in ensemble-averaged squared error. The use of FEC, however, causes the increase in MAI due to redundancy bits of FEC. Moreover, signal power is reduced under the condition that the energy of an information bit is the same. In such cases, whether an adaptive filter can operate effectively or not interests us. We evaluate the system performance and show that the improvement in throughput is achieved with interleaving and FEC techniques.

Keywords –CDMA, ALOHA, adaptive multiuser receiver, FEC, interleave.

I. Introduction

Wireless packet communication systems are becoming widely used with the rapid growth of wireless communication. A Code-Division Multiple-Access (CDMA) ALOHA, which is a connectionless-type of CDMA packet communication system, has drawn much attention for wireless data communications because of features such as random access capability, the potential for high throughput performance and low peak power transmission [1], [2]. Moreover, since initialisation occurs at the beginning of a slot in slotted systems, CDMA unslotted ALOHA (CDMA U-ALOHA) systems have the advantage of not requiring synchronisation of the packet transmissions. Many works have investigated improving the system performance beyond that of the conventional receiver [3]–[5].

In a CDMA system, multiple access interference (MAI) is an important obstacle to overcome. In order to reduce the effect of MAI, several multi-user detection techniques have been investigated [6], [7]. Most of these, however, focus on non-packet data, and multi-user detection techniques are seldom applied to CDMA U-ALOHA because other problems arise. One of the most important problems is the birth/death scenario because packets are transmitted randomly and intermittently.

We have proposed to apply the adaptive multiuser receiver based on minimum mean square error (MMSE) criterion to CDMA U-ALOHA to compensate for the birth/death of a packet [8]. In the reference [8], we have shown that significant improvements in throughput have been achieved with the proposed system under the perfect information assumption, which means that all information required for the MMSE multiuser detector is known even if a packet birth/death occurs. Even employing an adaptive filter and considering the effect of birth/death events, the throughput performance is improved although not to the level of that for perfect information. The ensemble-averaged squared error, however, increases at the point of packet birth. This phenomenon would degrade the system performance. Therefore, the use of interleaving and forward error correction coding techniques may prove beneficial, since such techniques may be expected to mitigate the momentary increase in ensemble-averaged squared error.

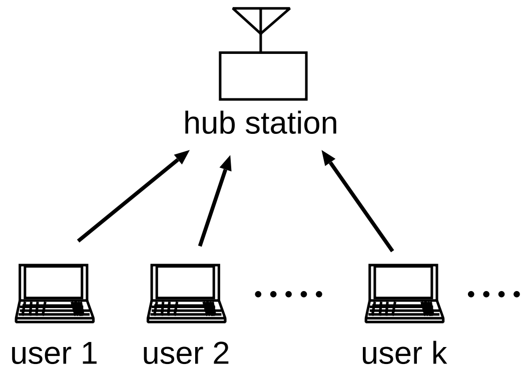

Fig. 1. System model of a CDMA unslotted ALOHA system.

In this paper, we employ interleaving and forward error correction (FEC) coding techniques to mitigate the momentary increase in ensemble-averaged squared error. The use of FEC, however, causes the increase in MAI due to redundancy bits of FEC. Moreover, signal power is reduced under the condition that the energy of an information bit is the same. In such cases, whether an adaptive filter can operate effectively or not interests us. We evaluate the system performance and clarified the effect of interleaving and FEC techniques.

In Section II, we describe the system model. In Section III, we evaluate the throughput performance and discuss the results. Finally some conclusions are presented in Section IV.

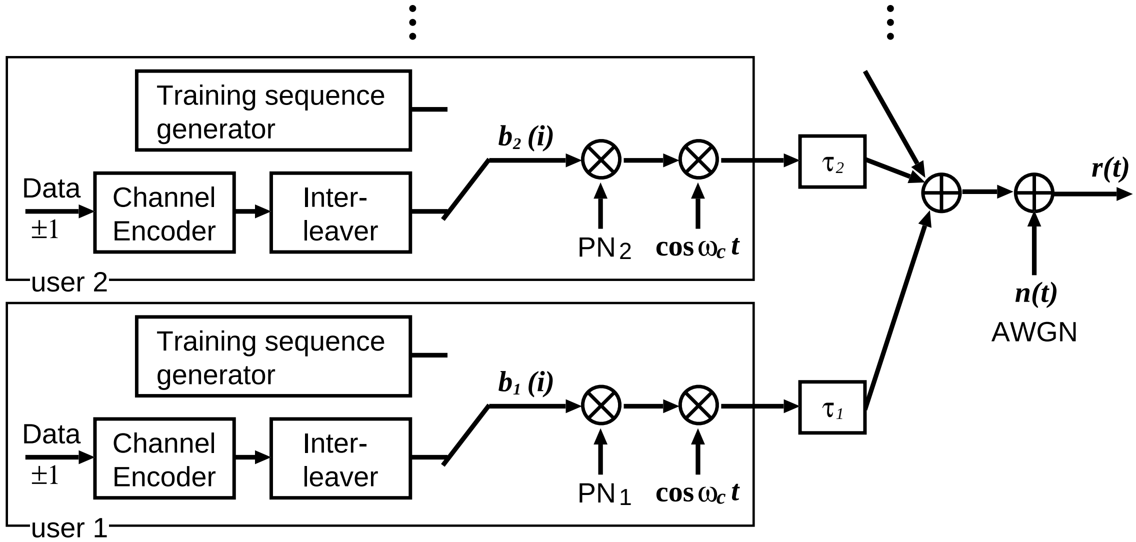

Fig. 2. Transmitter structure and channel model.

II. The System Model

A. Traffic Model

Figure 1 shows the system model of the CDMA U-ALOHA system. This consists of a single hub station and an unspecified number of user stations. Each user station transmits a packet to the hub station by one hop, and we only consider up-link packet access. Packets are generated at a rate which follows a Poisson process with a birth rate λ. The length of each packet is fixed. Each packet contains a data block sequence of L_d bits. The offered load G is defined as the average number of packet generated during one data duration $T_d = L_d/R_d$, where R_d is the data rate, and may be expressed as $G = \lambda \cdot T_d$. The offered load corresponds to the traffic intensity of generated data. The throughput S is also defined as the average number of successful packets during one data duration, and is our main performance measure.

B. Transmitter Structure

Transmitter structure and channel model are shown in Figure 2. Binary phase shift keying (BPSK) is assumed as the modulation scheme. A data block sequence is channel-encoded and interleaved. A convolutional code with termination bits to the initial state is employed as a channel coding, and a block interleaver is employed as an interleaver. A preamble sequence of L_t bits is added to this coded and interleaved data sequence, so the whole packet length is $L = L_t + (L_d + L_z)/R_c$ bits, where R_c is the code rate and L_z is the number of termination bits. Since the interleaver can work effectively, the size of interleaver is set at the same size as coded data sequence, that is, $(L_d + L_z)/R_c$ bits. Each packet's sequence is then spread with a uniquely assigned random signature sequence of length N chips. We assume that all packets are received with equal power and all data bit errors are caused by the effect of MAI and additive white Gaussian noise (AWGN). The received waveform of the kth user may be expressed as

$$r_k(t) = \sqrt{2P} \sum_{i=-\infty}^{\infty} b_k(i) a_k(t - iT - \tau_k) \cos(\omega_c t + \theta_k), \quad (1)$$

where P is the received power of each user's signal ($P = R_c E_b/T$, where E_b is the bit energy and T is the bit interval), $b_k(i) \in \{+1, -1\}$ is the ith bit of the kth user, $a_k(t)$ is a binary spreading waveform, ω_c is the carrier frequency, τ_k is the transmission delay, and θ_k is the carrier phase. The transmission delay τ_k and the carrier phase θ_k are taken to be independent and uniformly distributed over $0 \le \tau_k < T$ and $0 \le \theta_k < 2\pi$, respectively. These values can be assumed to be constant during reception of the packet because packet length is generally very short. Without loss of generality, we can assume $\tau_1 = 0$ and $\theta_1 = 0$. The spreading waveform may be expressed as

$$a_k(t) = \sum_{j=0}^{N-1} a_{k,j} p_{T_c}(t - jT_c), \quad (2)$$

where $a_{k,j} \in \{+1, -1\}$ is the jth element of the spreading sequence for the kth user, T_c is the chip interval, and $p_{T_c}(t)$ is the rectangular chip waveform expressed as

$$p_{T_c}(t) = \begin{cases} 1 & (0 \le t < T_c) \\ 0 & \text{otherwise} \end{cases}. \quad (3)$$

Then the received signal at the hub station may be expressed as

$$r(t) = \sum_{k=1}^{K} r_k(t) + n(t), \quad (4)$$

where K is the number of simultaneously transmitted signals, $n(t)$ is the AWGN signal with power spectral density $N_0/2$.

C. Receiver Structure

We use an adaptive finite impulse response (FIR) filter receiver to compensate for the birth/death of a packet. The use of adaptive algorithms is not only motivated by the time-varying channel but also by the dynamic user profile [9].

An adaptive FIR filter receiver structure is shown in Figure 3. We focus on the 1st user. After down-converting the received signal to baseband, it is passed through a chip matched filter and sampled at the end of every chip interval T_c. The lth normalized

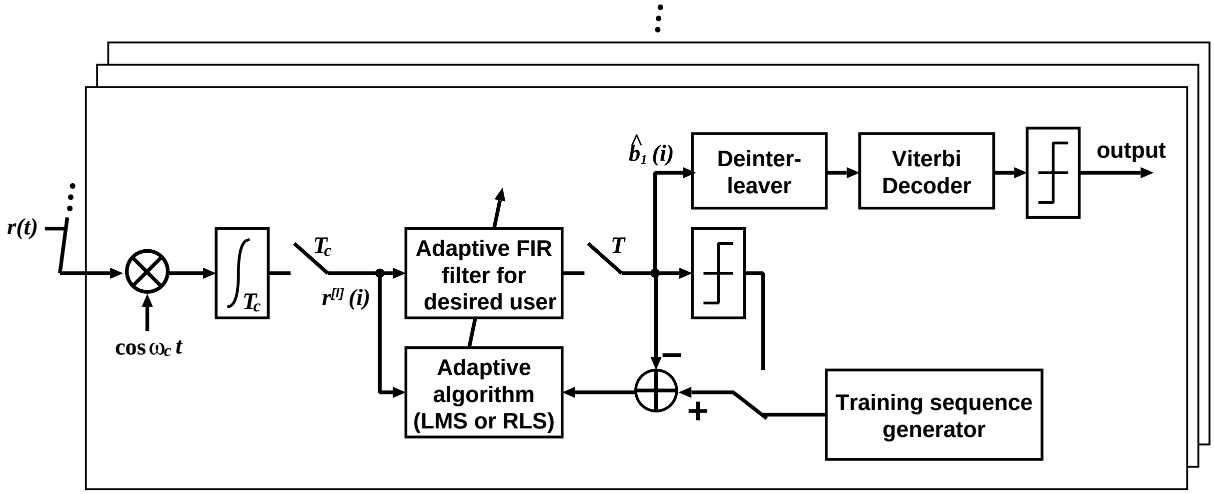

Fig. 3. Adaptive FIR filter receiver structure at the hub station.

sample of the ith bit at the output of the chip matched filter of the 1st user may be expressed as

$$r^{[l]}(i) = \sqrt{\frac{2}{P}}\frac{1}{T_c}\int_{lT_c+iT}^{(l+1)T_c+iT} r(t)p_{T_c}(t)\cos(\omega_c t)dt. \qquad (5)$$

Let $\boldsymbol{r}(i) = (r^{[0]}(i), \cdots, r^{[N-1]}(i))^T$ be the vector of received samples of the ith bit, and $\boldsymbol{a}_k = (a_{k,0}, \cdots, a_{k,N-1})^T$ be the vector of spreading sequence of the kth user. The vector of the received samples may be expressed as [10]

$$\boldsymbol{r}(i) = b_1(i)\boldsymbol{a}_1 + \sum_{k=2}^{K} b_k(i)\cos\theta_k \boldsymbol{I}_k(i) + \boldsymbol{n}(i), \qquad (6)$$

where

$$\boldsymbol{I}_k(i) = \begin{cases} \frac{\delta_k}{T_c}\boldsymbol{a}_k^{(p_k+1)} + (1-\frac{\delta_k}{T_c})\boldsymbol{a}_k^{(p_k)} \\ \qquad \text{if } b_k(i-1) = b_k(i) \\ \frac{\delta_k}{T_c}\hat{\boldsymbol{a}}_k^{(p_k+1)} + (1-\frac{\delta_k}{T_c})\hat{\boldsymbol{a}}_k^{(p_k)} \\ \qquad \text{if } b_k(i-1) = -b_k(i) \end{cases}, \qquad (7)$$

$$\boldsymbol{a}_k^{(m)} = (a_{k,N-m}, a_{k,N-m+1}, \cdots, \cdots, a_{k,N-1}, a_{k,0}, a_{k,1}, \cdots, a_{k,N-m-1}), \qquad \text{(8-a)}$$

$$\hat{\boldsymbol{a}}_k^{(m)} = (-a_{k,N-m}, -a_{k,N-m+1}, \cdots, \cdots, -a_{k,N-1}, a_{k,0}, a_{k,1}, \cdots, a_{k,N-m-1}). \qquad \text{(8-b)}$$

and $\boldsymbol{n}(i)$ is the AWGN vector, whose element is independent Gaussian random variables with zero mean and variance of $\sigma^2 = (2E_b/N_0N)^{-1}$. Also the delay τ_k is written as $\tau_k = p_kT_c + \delta_k$, where p_k is an integer and $0 \le \delta_k < T_c$.

The received samples are fed into the chip-level adaptive FIR filter, which has N taps. The tap weight vector $\boldsymbol{w}(i)$ is adjusted according to an adaptive algorithm. We use the two most popular adaptive algorithms, least mean squares (LMS) and recursive least squares (RLS) [11]. We choose an initial value for the tap-weight vector as

$$\boldsymbol{w}(0) = \boldsymbol{a}_1 \qquad (9)$$

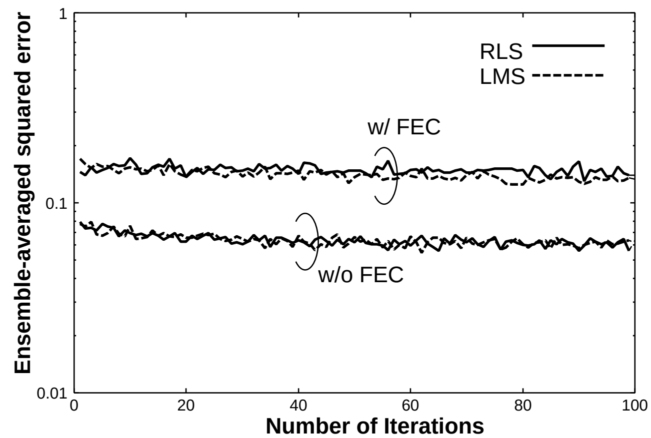

Fig. 4. Convergence properties of squared error ($E_b/N_0 = 10$ dB, $R_c = 1/2$).

so that the ensemble-averaged squared error converges fast. During reception of the preamble (training sequence), the outputs of the training sequence generator are used as reference signals. After this training period, the outputs of the threshold device are used to adjust the tap weights (decision direction).

The outputs of the FIR adaptive filter are sampled at the end of each bit interval T. These samples may be expressed as

$$\hat{b_1}(i) = \boldsymbol{w}(i-1)^T\boldsymbol{r}(i). \qquad (10)$$

These samples are deinterleaved, decoded by the soft decision Viterbi decoder, and demodulated by the threshold device.

We assume that only the information required for the adaptive algorithm such as the timing of the desired packet and the training sequence is known. The birth/death of interfering packets is therefore unknown. Even so, the adaptive filter has a possibility to compensate for the birth/death of a packet.

III. Results

In this section, the system performance is evaluated by Monte Carlo simulation. The operating parameters are shown in Table I. We use convolutional code with two cases of code rate. The step size for LMS is chosen as the throughput becomes high. The

TABLE I

OPERATING PARAMETERS.

modulation scheme	BPSK		
E_b/N_0	10 dB	7 dB	
process gain N	60		
spreading sequence	random signature		
channel code	convolutional code		
code rate R_c	1/2		2/3
constraint length	7		4
interleaving	block interleaving		
packet generation	Poisson process		
preamble length L_t	50 bits		
data length L_d	500 bits		
packet length L (w/ FEC)	1062 bits		809 bits
(w/o FEC)	550 bits		
step size for LMS (w/ FEC)	0.00001	0.00001	0.00001
(w/o FEC)	0.0005	0.00005	0.00005
forgetting factor for RLS	1.0		

step size of a system with FEC is different with that of a system without FEC because signal power is different, so we use the different step size in each case.

Figure 4 shows the squared error (ensemble-averaged over 1,000 trials) of RLS and LMS algorithm with and without FEC. In this figure, the number of simultaneously transmitted packets is equal to 5 in the case without FEC. When the FEC is employed, the packet length with FEC becomes about twice as long as that without FEC. So, considering the increase in MAI due to redundancy bits, we set the number of simultaneously transmitted packets equal to 10 in the case with FEC. Furthermore, signal power is reduced under the condition that the energy of an information bit is the same. Because we choose an initial value for the tap-weight vector, convergence of squared error is very fast. Note that the degradation of squared error performance due to the increase in MAI and the reduction of signal power is very large. In this case, the squared error in the case with FEC is about 0.13, and that in the case without FEC is about 0.06.

Figures 5 and 6 show the throughput performance of CDMA unslotted ALOHA with adaptive FIR filter receiver, interleaving and FEC. For comparison, the throughput curves of the system in which a matched filter (MF) is used to despread the received signal are also shown. From these figures, it can be seen that the throughput of a system with FEC is higher than that of a system without FEC although the use of FEC causes an increase in MAI and a reduction in signal power. Moreover, the throughput of adaptive filter with FEC is better than that of MF with FEC. These things indicate that an adaptive filter with FEC can operate effectively and prove beneficial even if MAI increases and signal power is reduced.

Next, we focus on the effect of interleaving. As can be seen, the throughput of the system with interleaving is better than that of the system without interleaving whenever FEC is employed. Note that we does not assume fading channel but AWGN stationary channel. The reason for improvement with interleaving is that a frequent occurrence of packet birth/death events causes momentary increase in ensemble-averaged squared error

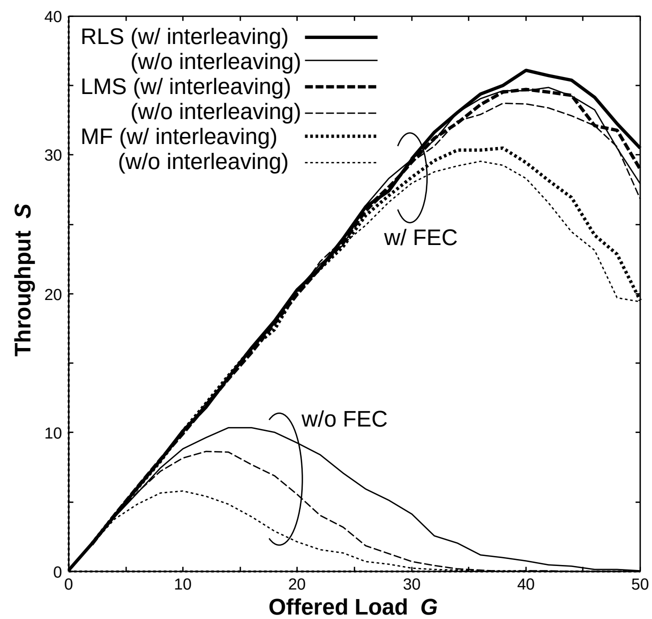

Fig. 5. Throughput performance of CDMA unslotted ALOHA with adaptive filter receiver, interleaving and FEC ($E_b/N_0 = 10$ dB, $R_c = 1/2$).

and nonuniform distribution of MAI for the duration of reception of noticed packet. So interleaving technique is effective in such cases.

Compare with the case of $E_b/N_0 = 10$ dB in Figure 5 and the case of $E_b/N_0 = 7$ dB in Figure 6. In the case of $E_b/N_0 = 10$ dB, the throughput of RLS without FEC is better than that of LMS without FEC, and the throughput of RLS with FEC is only slightly better than that of LMS with FEC. On the other hand, in the case of $E_b/N_0 = 7$ dB, the throughput of RLS with/without FEC is almost the same as that of LMS with/without FEC, respectively. Because of a very noisy environment, it may make little difference between RLS and LMS. Considering the complexity of each adaptive algorithm, it is expected that the LMS

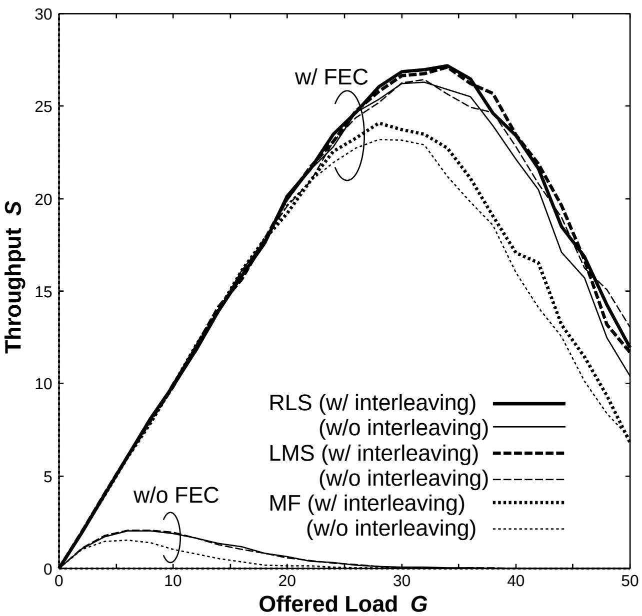

Fig. 6. Throughput performance of CDMA unslotted ALOHA with adaptive filter receiver, interleaving and FEC ($E_b/N_0 = 7$ dB, $R_c = 1/2$).

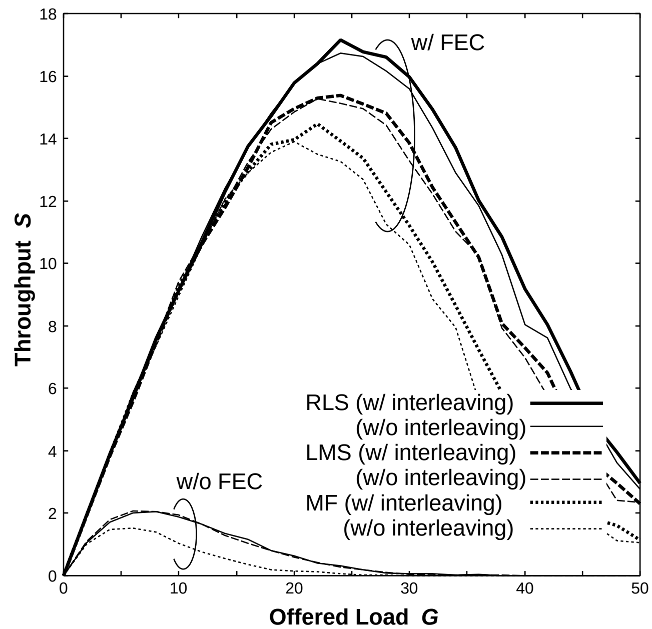

Fig. 7. Throughput performance of CDMA unslotted ALOHA with adaptive filter receiver, interleaving and FEC ($E_b/N_0 = 7$ dB, $R_c = 2/3$).

algorithm is more beneficial than the RLS algorithm in a noisy environment.

Because of high code rate, it is no supprise that the throughput in the case of $R_c = 2/3$ in Figure 7 is worse than that in the case of $R_c = 1/2$ in Figure 6. But, higher code rate brings a little reduction in signal power, so the difference between RLS and LMS in the case of $R_c = 2/3$ is bigger than that in the case of $R_c = 1/2$.

IV. Conclusions

We have applied interleaving and FEC techniques to the CDMA U-ALOHA with an adaptive filter receiver, and evaluated the system performance in consideration of the increase in MAI and reduction of signal power due to redundancy bits of FEC. As a result, improvements in the throughput of CDMA U-ALOHA with an adaptive filter receiver have been achieved with interleaving and FEC techniques although MAI increases and signal power is reduced. We have also shown that interleaving technique is effective in CDMA U-ALOHA with an adaptive filter receiver even a stationary channel environment. Considering the complexity of each adaptive algorithm, the LMS algorithm may be more beneficial than the RLS algorithm in a very noisy environment.

Acknowledgment

This work was supported in part by Japan Society for the Promotion of Science under Grant-in-Aid for Encouragement of Young Scientists, the Hori Information Science Promotion Foundation, and Telecommunications Advancement Organization of Japan.

References

[1] R. K. Morrow, Jr. and J. S. Lehnert, "Packet throughput in slotted ALOHA DS/SSMA radio systems with random signature sequences, " IEEE Trans. Commun., vol.40, no.7, pp.1223-30, July 1992.

[2] H. Okada, M. Saito, T. Sato, T. Yamazato, M. Katayama, A. Ogawa, "CDMA ALOHA systems with modified channel load sensing protocol for satellite communications," IEICE Trans., E79-A, No.12, pp.2035-2042, Dec. 1996.

[3] M. Yin and V. O. K. Li, "Unslotted CDMA with fixed packet lengths," IEEE J. Selected Areas Commun., vol.8, No.4, pp.529-541, May 1990.

[4] A. H. Abdelmonem and T. N. Saadawi, "Performance analysis of spread spectrum packet radio network with channel load sensing," IEEE J. Selected Areas Commun., vol.7, No.1, pp.161-166, Jan. 1989.

[5] T. Yamazato, A. Ogawa, M. Katayama, and A. Jamalipour, "Introduction to CDMA ALOHA," IEEE Global Telecommunications Conference, Tutorial Note, TI-13, Nov., 1998.

[6] A. Duel-Hallen, J. M. Holtzman, and Z. Zvonar, "Multi-user detection for CDMA systems," IEEE Personal Commun. Magazine, vol.2, no.2, pp.46-58, Apr. 1995.

[7] S. Moshavi, "Multi-user detection for DS-CDMA communications," IEEE Commun. Magazine, pp.124-136, Oct. 1996.

[8] H. Okada, P. M. Grant, I. W. Band, and A. Ogawa, "Application of MMSE multi-user detection to CDMA unslotted ALOHA system," IEEE International Symposium on Personal, Indoor and Mobile Radio Communication (PIMRC), Sep. 2000.

[9] P. M. Grant, S. M. Spangenberg, D. G. M. Cruickshank, S. McLaughlin and B. Mulgrew, "New adaptive multiuser detection technique for CDMA mobile receivers," IEEE International Symposium on Personal, Indoor and Mobile Radio Communication (PIMRC), vol.1, pp.52-55, Osaka, Japan, Sep. 1999.

[10] S. L. Miller, "An adaptive direct-sequence code-division multiple-access receiver for multiuser interference rejection," IEEE Trans. Commun., vol.43, no.2/3/4, pp.1746-1755, Feb./Mar./Apr., 1995.

[11] S. Haykin, *Adaptive Filter Theory*, Prentice-Hall, 1996.