

## PAPER

# Application of Successive Interference Cancellation to a Packet-Recognition/Code-Acquisition Scheme in CDMA Unslotted ALOHA Systems

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**SUMMARY** Packet-recognition/code-acquisition (PR/CA) is one of the most important issues in packet communication systems. In a CDMA Unslotted ALOHA system, Multiple Access Interference (MAI) may bring about errors in PR/CA. The MAI mainly stems from already recognized packets and newly arriving packets under the execution of PR/CA. This characteristic of asynchronous transmission in CDMA U-ALOHA systems implies that only one or a few packets arrive at the receiver within a short interval of a execution. Furthermore, newly arriving packets are recognized and code-acquired by using a short preamble part. Consequently, the MAI from the packets under the execution of the PR/CA will be small. Focusing on that point, this paper proposes applying the IC scheme in order to suppress the MAI from the already recognized and code-acquired packets. A performance evaluation demonstrates that such an application is valid due to the small amount of MAI from the packets under the execution of PR/CA. In addition, we demonstrate that the scheme reduces false recognition rather than mis-recognition. Such a scheme improves the performance of not only PR/CA, but also the throughput.

**key words:** CDMA Unslotted ALOHA, successive interference cancellation, throughput, packet recognition, code acquisition

## 1. Introduction

CDMA ALOHA systems are attracting much attention due to their potential to realize efficient wireless packet communication[1]–[4]. In particular, the CDMA Unslotted ALOHA (CDMA U-ALOHA) system allows asynchronous and random transmission of packets; this system requires no synchronization of packet transmission among user stations. In addition, such a random access inherence enables a simple structure at a user station. Because of these advantages, many studies have been undertaken on CDMA U-ALOHA systems[5]–[9]. In a system using a CDMA technique like CDMA U-ALOHA, multiple access interference (MAI) arises and limits performance. To reduce it, interference cancellation (IC) schemes are applied to CDMA ALOHA systems[3], [4], [8].

In random-access systems such as CDMA U-ALOHA, the receiver always monitors the received signal to recog-

nize the existence of newly arriving packets (packet recognition: PR). In the event that packet existence is recognized, code-acquisition (CA) of the packet is carried out[11], [12]. However, errors in PR make it impossible to perform demodulation and IC, and in addition, correct demodulation and effective IC cannot be performed due to CA error. These result in significant performance degradation; as a result it is imperative to reduce the errors. The main cause of the errors is MAI from both the already recognized packets and the newly arrived packets under the execution of PR/CA. The former can be suppressed by using the IC schemes[9]. However, the latter cannot be reduced by using IC schemes since IC cannot be performed until PR/CA is finished, which is why the application of IC schemes has not been studied for the purpose of reducing the PR/CA error.

In CDMA U-ALOHA systems, packet arrivals at the receiver are scattered due to asynchronous transmission. Then, both the already recognized packets and the newly arrived packets exist simultaneously. In contrast with synchronous systems such as slotted ALOHA, this characteristic of CDMA U-ALOHA makes it possible to apply the IC scheme for the already recognized and code-acquired packets. The reduction of PR/CA error could, therefore, be realized by the suppression of MAI from them. Furthermore, newly arriving packets are recognized and code-acquired by using the short preamble part. The MAI from the packets under the execution of PR/CA will be small since only one or a few packets arrive at the receiver during the short interval of execution.

This paper proposes applying the IC scheme to PR/CA scheme in order to suppress MAI from the already recognized and code-acquired packets. If subtraction-type IC schemes such as successive interference cancellation (SIC) are considered, the residual received signal after the IC might contain only the packets' signal, which should be recognized and code-acquired[8], [10]. This may mean a performance improvement in PR/CA due to the application of the SIC scheme. However, such an improvement may be degraded when the wrong SIC operation is performed. SIC operations are executed based on information obtained in a past PR/CA. Thus, if the PR/CA had failed, an incorrect SIC operation would be executed[9]. To clarify the influence of such a situation, this paper evaluates the performances in terms of both error probability of PR/CA and throughput.

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## 2. System Model

In this paper, we deal with the reverse link of the CDMA U-ALOHA system, in which there are  $K_t$  user stations (US) and one base station (BS). The time interval between consecutive packet transmissions at a US is assumed to follow the exponential distribution with the mean  $1/\lambda$ . This assumption indicates that US transmits its packet randomly and asynchronously. The offered load  $G$ , which is the average number of transmitted packets per time duration of a packet  $T_p$ , can be expressed as  $G = \lambda T_p K_t$ . Note that we call the US transmitting its packet an active user station (AUS). Clearly, the number of AUSes  $K_a(t)$  varies at any time. The US can transmit only one packet simultaneously, which implies  $K_a(t) \leq K_t$ .

Each AUS transmits a fixed-length packet to the BS in one hop. The packet consists of a preamble part and a data part, where the length of the preamble part is  $L_p$  [bits] and that of the data part is  $L_d$  [bits]. The preamble part is used for PR/CA.

At an AUS, a packet's signal is modulated and spread before the transmission. Binary Phase Shift Keying (BPSK) is used as the modulation scheme. The spreading sequence is the random sequence, which is uniquely assigned to each US. For simplicity, we assume that all packets are received with equal power, thus the received signal at the BS can be expressed as

$$r(t) = \sum_{k=1}^{K_a(t)} \sqrt{2P} a_k(t - \tau_k) b_k(t - \tau_k) \cos(2\pi f_c t + \phi_k) + n(t), \quad (1)$$

where  $a_k(t)$  is the spreading signal,  $b_k(t)$  denotes the data signal,  $\tau_k$  represents the time-delay, and  $\phi_k$  is the carrier phase of the signal transmitted by the  $k$ th AUS. In addition,  $f_c$  is the carrier frequency,  $P = E_b/T_b$  means the power,  $E_b$  denotes signal energy in a bit,  $T_b$  is the bit duration, and  $n(t)$  represents the AWGN with a two-sided power spectrum density  $\frac{N_0}{2}$ . It is assumed that  $\phi_k$  and  $\tau_k$  are i.i.d uniform random variables in  $[0, 2\pi)$  and  $[0, T_b)$ , respectively.

## 3. Receiver Structure

### 3.1 Principle

Figure 1 shows an example of packet arrivals at the BS. At  $t = t_1$ ,  $K_a(t)$  packets are transmitted by the AUSes. Since packets are asynchronously and randomly transmitted, only a few  $K_p(t)$  new packets simultaneously arrive at the BS and are recognized and code-acquired. The other packets are classified into four groups[11], [12]. The first one is for  $K_c(t)$  correctly recognized and code-acquired packets, while the second is for falsely recognized packets, which is the case that a non-transmitted packet is recognized and code-acquired. The quantity of them is  $K_F(t)$ . The third group includes transmitted packets that are recognized but

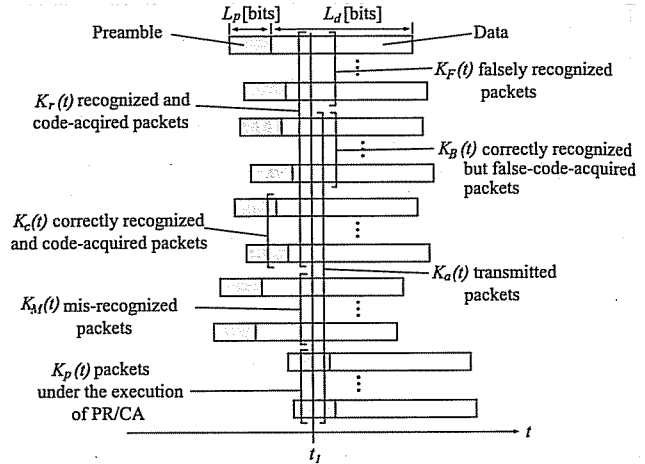


Fig. 1 Example of packet arrivals.

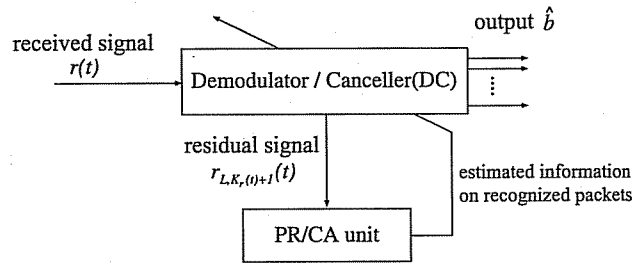


Fig. 2 Receiver structure.

not correctly code-acquired. The number of them is  $K_B(t)$ , and the fourth is a mis-recognized packet that is neither recognized nor code-acquired. The number of those is  $K_M(t)$ . The  $K_r(t)$  recognized and code-acquired packets include the  $K_F(t)$  falsely recognized packets,  $K_B(t)$  correctly recognized but false-code-acquired packets, and  $K_c(t)$  correctly recognized and code-acquired packets.

Let us describe the PR/CA scheme shown in Fig. 2. In this scheme, the receiver consists of a Demodulator/Canceller (DC) and a PR/CA unit. SIC is used as the subtraction-type IC scheme in the DC. The signals of the  $K_r(t)$  recognized and code-acquired packets are successively subtracted from the received signal in the DC, and PR/CA is carried out by using the residual signals. Estimated information on the recognized packets is then fed back to the DC.

### 3.2 Demodulator / Canceller

For the demodulation and the IC scheme, we employ the SIC scheme proposed in [8], [10]. The structure of the DC is depicted in Fig. 3. The DC consists of a low-pass filter (LPF) and  $K_r(t)$  DC blocks assigned to the signal of the already recognized and code-acquired packets, which include the  $K_F(t)$  falsely recognized packets. We define the first recognized and code-acquired US as the US which has the packet arriving first at the BS of all the  $K_r(t)$  recognized and code-acquired packets.

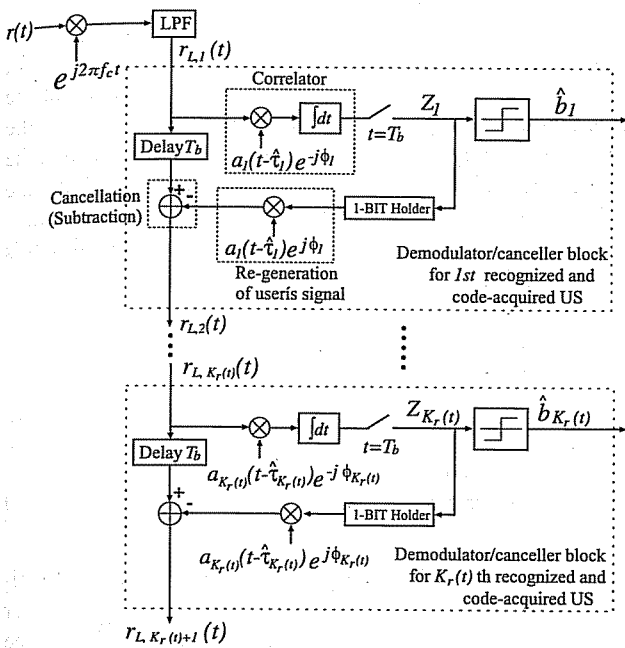


Fig. 3 Demodulator / Canceller(DC).

The received signal  $r(t)$  is first multiplied by the carrier  $e^{-j2\pi f_c t}$  and then passed through a LPF. In this process, the following complex baseband signal  $\mathbf{r}_L(t)$  is obtained as [8]:

$$\begin{aligned} \mathbf{r}_L(t) &= \text{LPF}[r(t)e^{-j2\pi f_c t}] \\ &= \frac{1}{2} \sum_{l=1}^{K_a(t)} \sqrt{2P} a_l(t - \tau_l) b_l(t - \tau_l) e^{j\phi_l} + \frac{1}{2} \mathbf{n}_L(t) \end{aligned} \quad (2)$$

where  $\mathbf{n}_L(t)$  denotes the noise component.

The following is an outline of the operation of the demodulation and the IC in the DC block for the  $k$ th recognized and code-acquired US. The input baseband signal  $\mathbf{r}_{L,k}(t)$  is correlated with spreading signal  $a_k(t - \hat{\tau}_k) e^{-j\phi_k}$ , where  $\hat{\tau}_k$  is the estimated time-delay of the spreading signal. The correlator output  $Z_k$  is compared with the decision threshold, and the demodulated data  $\hat{b}_k$  is derived. In addition, the correlation  $Z_k$  is respread so that the packet's signal could be regenerated. Since it takes one bit interval  $T_b$  to calculate the correlator output, the regenerated signal is subtracted from the complex received baseband signal delayed by  $T_b$ . Because the interfering signal estimated based on the correlator output, the subtraction can be expressed as

$$\mathbf{r}_{L,k+1}(t) = \mathbf{r}_{L,k}(t) - Z_k a_k(t - \hat{\tau}_k) e^{j\phi_k}. \quad (3)$$

The residual signal  $\mathbf{r}_{L,k+1}(t)$  passes to the next DC block. Note that since this paper focuses on PR/CA, the phase  $\phi_k$  of the signal of the transmitted packets is assumed to be known.

The IC is performed for  $K_r(t)$  recognized and code-acquired packets, which include  $K_c(t)$  correctly recognized and code-acquired packets,  $K_F(t)$  falsely recognized packets, and  $K_B(t)$  false-code-acquired packets, but does not include  $K_M(t)$  mis-recognized packets, or  $K_p(t)$  packets under the execution of PR/CA. Then, the unnecessary subtraction

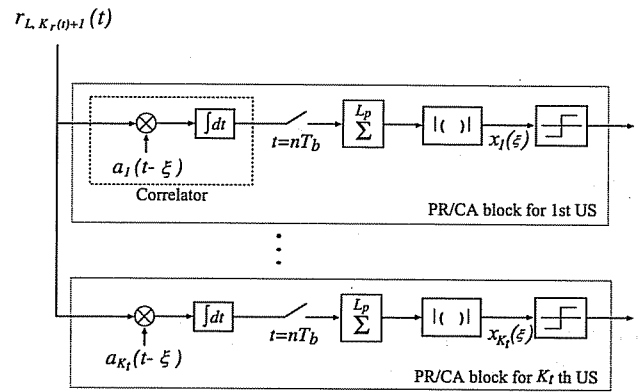


Fig. 4 PR/CA unit.

for the signals of  $K_F(t)$  falsely recognized packets and  $K_B(t)$  false-code-acquired packets are performed. However, the signals of  $K_M(t)$  mis-recognized packets and  $K_p(t)$  packets are not subtracted from those of  $K_a(t)$  transmitted packets, and still remain.

After the ICs in all the  $K_r(t)$  DC blocks, the residual baseband signal  $\mathbf{r}_{L, K_r(t)+1}(t)$  is

$$\begin{aligned} \mathbf{r}_{L, K_r(t)+1}(t) &= \frac{1}{2} \mathbf{n}_L(t) - \frac{1}{2} \sum_{i=1}^{K_r(t)} C_i a_i(t - \hat{\tau}_i) e^{j\phi_i} \\ &+ \frac{1}{2} \sum_{i=K_r(t)+1}^{K_r(t)+K_M(t)+K_p(t)} \sqrt{2P} a_i(t - \tau_i) b_i(t - \tau_i) e^{j\phi_i}, \end{aligned} \quad (4)$$

where  $C_i$  is the noise and the interference component for the  $i$ th recognized and code-acquired US[8], [10]. The first term in Eq. (4) means the noise on the channel, and the second term is the cumulative noise due to the imperfect cancellation for  $K_r(t)$  recognized packets[8], [10]. The third term represents the signals of both  $K_M(t)$  mis-recognized packets and  $K_p(t)$  packets under the execution of PR/CA. Note that imperfect cancellation indicates that the packet signal is partly left in the received signal after the subtraction. The residual baseband signal includes the signal of the packets under the execution of PR/CA, in addition to the cumulative noise, the signal of mis-recognized packets, and channel noise.

### 3.3 Packet-Recognition/Code-Acquisition Unit

In this work, we use the conventional serial-parallel search scheme as the PR/CA scheme[11]. Figure 4 shows the PR/CA unit, where the unit has  $K_r$  PR/CA blocks assigned to each US. These blocks run parallel with each other.

The operation at each PR/CA block is as follows. At first, the residual signal  $\mathbf{r}_{L, K_r(t)+1}(t)$  is correlated with the spreading signal assigned to the PR/CA block. The correlation is summed up for  $L_p$  bits, after which the absolute value is calculated. The PR/CA decision is made by a comparison of the normalized absolute value (decision variable) and the threshold  $\alpha$ . The decision variable  $x_k(\xi)$  normalized by the preamble length can be written as

$$x_k(\xi) = \left| \frac{1}{L_p T_b} \sum_{n=1}^{L_p} \int_{(n-1)T_b}^{nT_b} \mathbf{r}_{L, K_r(t)+1}(t) a_k(t - \xi) dt \right|$$

$$= \left| \mathcal{R}_k(\mathbf{r}_{L, K_r(t)+1}(t), \xi) \right|, \quad (5)$$

where

$$\mathcal{R}_k(f(t), \xi) = \frac{1}{L_p T_b} \sum_{n=1}^{L_p} \int_{(n-1)T_b}^{nT_b} f(t) \cdot a_k(t - \xi) dt. \quad (6)$$

Both packet-recognition and code-acquisition are declared under the following condition :

$$x_k(\xi) > \alpha. \quad (7)$$

Time-delay is estimated as  $\hat{\tau}_k = \xi$ . Provided that a packet is not recognized,  $T_r$  is added to  $\xi$ , after which such an operation restarts, where  $T_r$  is the time interval of the PR/CA.

Substituting Eq. (4) into Eq. (5), the decision variable can be expressed as

$$x_k(\xi) = \left| \mathcal{R}_k \left( \frac{1}{2} \sqrt{2P} a_k(t - \tau_k) b_k(t - \tau_k) e^{j\phi_k}, \xi \right) \right.$$

$$+ \mathcal{R}_k \left( \frac{1}{2} \sum_{\substack{i=K_r(t)+K_M(t)+1 \\ i \neq k}}^{K_r(t)+K_M(t)} \sqrt{2P} a_i(t - \tau_i) b_i(t - \tau_i) e^{j\phi_i}, \xi \right)$$

$$+ \mathcal{R}_k \left( \frac{1}{2} \sum_{i=K_r(t)+1}^{K_r(t)+K_M(t)} \sqrt{2P} a_i(t - \tau_i) b_i(t - \tau_i) e^{j\phi_i}, \xi \right)$$

$$- \mathcal{R}_k \left( \frac{1}{2} \sum_{i=1}^{K_r(t)} C_i a_i(t - \tau_i) e^{j\phi_i}, \xi \right) + \mathcal{R}_k \left( \frac{1}{2} n_L(t), \xi \right) \left. \right|$$

$$= \left| S^{k,\xi} + I_p^{k,\xi} + I_M^{k,\xi} + N_{IC}^{k,\xi} + N_n^{k,\xi} \right|, \quad (8)$$

where  $S^{k,\xi}$  is the component of the signal,  $I_p^{k,\xi}$  denotes the MAI from  $K_p(t)$  packets under the execution of PR/CA,  $I_M^{k,\xi}$  represents the MAI from  $K_M(t)$  mis-recognized packets,  $N_{IC}^{k,\xi}$  means the cumulative noise due to the IC for  $K_r(t)$  recognized packets, and  $N_n^{k,\xi}$  is the noise on the channel. In the case that the packet is transmitted from the  $k$ th US and PR/CA is performed at  $\xi = \tau_k$ ,  $S^{k,\xi}$  equals  $\sqrt{2P}/2$ .

Since no packet transmission from the  $k$ th US means  $S^{k,\xi} = 0$  for all  $\xi$ , the packet from the  $k$ th US is falsely recognized at a delay  $\xi$  under the condition:

$$\mathcal{H}_F^{k,\xi} : \left\{ \{x_k(\xi) > \alpha\} \right.$$

$$\left. \text{no packet transmission from the } k\text{th US} \right\}$$

$$\cup \left\{ \{x_k(\xi) > \alpha \mid \xi \neq \tau_k\} \right.$$

$$\left. \text{packet transmission from the } k\text{th US} \right\}$$

$$= \left\{ \left| I_p^{k,\xi} + I_M^{k,\xi} + N_{IC}^{k,\xi} + N_n^{k,\xi} \right| > \alpha \right\}$$

$$\cup \left\{ \left| S^{k,\xi} + I_p^{k,\xi} + I_M^{k,\xi} + N_{IC}^{k,\xi} + N_n^{k,\xi} \right| > \alpha \right\}, \quad (9)$$

where  $\xi$  equals  $\xi$  except  $\xi = \tau_k$ . The first inequality shows that PR/CA is declared at  $\xi = \tau_k$ , though the packet is not actually transmitted. The second one is brought up in the case that the wrong PR/CA is declared at  $\xi \neq \tau_k$ , even if the packet is actually transmitted. This equation implies that the packets could be easily falsely recognized provided that the noise or the MAI is large enough to exceed the threshold.

For the mis-recognition, the packet from the  $k$ th US is mis-recognized at a delay  $\xi$  under the condition:

$$\mathcal{H}_M^{k,\xi} : \left\{ \{x_k(\xi) < \alpha \mid \xi = \tau_k\} \right.$$

$$\left. \text{packet transmission from the } k\text{th US} \right\}$$

$$= \left\{ \left| \frac{\sqrt{2P}}{2} + I_p^{k,\tau_k} + I_M^{k,\tau_k} + N_{IC}^{k,\tau_k} + N_n^{k,\tau_k} \right| < \alpha \right\}; \quad (10)$$

that is, PR/CA is performed at  $\xi = \tau_k$  but the decision variable does not exceed the threshold. This case might occur due to the decrease in the signal component  $\sqrt{2P}/2$  by the noise and the MAI.

From Eqs. (9) and (10), whether packets are falsely, mis-, or correctly recognized depends on the three terms  $I_p^{k,\xi}$ ,  $I_M^{k,\xi}$ , and  $N_{IC}^{k,\xi}$ , in addition to the noise term  $N_n^{k,\xi}$ . Note that there is no relation between the MAI  $I_p^{k,\xi}$  and the threshold  $\alpha$  because the MAI  $I_p^{k,\xi}$  depends only on both the number of packets under the execution of the PR/CA and the characteristic of the cross-correlation of the spreading signal. In contrast, since the threshold  $\alpha$  determines whether the packets are falsely, mis-, or correctly recognized, both  $K_r(t)$  and  $K_M(t)$  depend on  $\alpha$ . Generally, as the threshold  $\alpha$  increases,  $K_r(t)$  decreases but  $K_M(t)$  increases[12]. Both terms, the cumulative noise  $N_{IC}^{k,\xi}$  and the MAI from the mis-recognized packets  $I_M^{k,\xi}$ , vary according to the threshold. Note that because of the small number of packets under the execution of PR/CA, the MAI  $I_p^{k,\xi}$  might be negligible; the cumulative noise  $N_{IC}^{k,\xi}$  and the MAI  $I_M^{k,\xi}$  would swell in the case of a large number of falsely or mis-recognized packets.

#### 4. Performance Evaluation

In this section, we evaluate the treated scheme's performance. In packet communication systems, it is of course important whether the packets are successfully transmitted or not. This implies an evaluation in terms of throughput, which is defined as the number of successfully transmitted packets in the time duration of a packet. Successful packet transmission means that all data in packets are correctly demodulated. Note that from the definition of throughput, degradation from the overhead of preamble is considered. In addition, since the correct PR/CA is a necessary condition for the success of packet transmission, we consider the probability of falsely recognition  $P_F$  and the probability of mis-recognition  $P_M$ , which are defined as

Table 1 Simulation parameters.

Parameter	Value
$L_p$	100 [bits]
$L_d$	500 [bits]
$K_t$	180
$T_r$	$\frac{1}{2}T_c$
$E_b/N_0$	30 [dB]
$N$	31

$$P_F = E_{k,\xi} \left[ \Pr \{ \mathcal{H}_F^{k,\xi} \} \right] \quad (11)$$

$$P_M = E_{k,\xi} \left[ \Pr \{ \mathcal{H}_M^{k,\xi} \} \right] \quad (12)$$

where  $E_{k,\xi}[\cdot]$  takes the expectation with respect to US  $k$  and delay  $\xi$ . For convenience, the terms in Eqs. (9) and (10) are normalized by  $\sqrt{2P}/2$  so that the signal component for desired packet  $S^{k,\xi}$  becomes 1. We define the normalized threshold  $\bar{\alpha}$  as  $2\alpha/\sqrt{2P}$ , and calculate the performance by running a computer simulation whose parameters are as shown in Table 1. Chip duration is defined as  $T_c = T_b/N$ , where  $N$  is the processing gain. Since we consider mobile communication systems like 3G systems as an application of the scheme,  $L_d$ ,  $N$  and  $L_p$  are set as in Table 1.

To enhance the influence of MAI, we consider the situation of low noise, such as  $E_b/N_0=30$  [dB]. In a system using the DS/SS technique, code acquisition must be performed below a chip rate such as  $T_r = T_c/2$ . Since the time interval between consecutive packet transmissions at a US is assumed to follow the exponential distribution, the number of user stations must be large enough.

For comparison, we introduce a system without SIC, in which packets are recognized by using the received signal  $r(t)$  itself. In the system without SIC, since no interference cancellation scheme is considered, MAI from the recognized packets cannot be reduced. Thus, using the MAI from the recognized packets  $I_D^{k,\xi}$  instead of the cumulative noise  $N_{IC}^{k,\xi}$ , the decision variable can be expressed as

$$\tilde{x}_k(\xi) = \left| S^{k,\xi} + I_p^{k,\xi} + I_M^{k,\xi} + I_D^{k,\xi} + N_n^{k,\xi} \right|, \quad (13)$$

where

$$I_D^{k,\xi} = \mathcal{R}_k \left( \frac{1}{2} \sum_{i=1}^{K_r(t)} \sqrt{2P} a_i(t - \tau_i) b_i(t - \tau_i) e^{j\phi_i}, \xi \right) \quad (14)$$

represents the MAI from  $K_r(t)$  recognized packets.

Throughput depends on the number of falsely and mis-recognized packets[9], and also depends on the threshold and the sum of  $N_{IC}^{k,\xi} + I_M^{k,\xi} + I_p^{k,\xi}$  as to whether the packets are falsely or mis-recognized. In the case that a packet is not transmitted, the packet is falsely recognized provided that the sum  $N_{IC}^{k,\xi} + I_M^{k,\xi} + I_p^{k,\xi}$  exceeds the threshold. Similarly, in the case that a packet is transmitted, the decision variable might be decreased by the sum  $N_{IC}^{k,\xi} + I_M^{k,\xi} + I_p^{k,\xi}$  so that the decision variable often falls below the threshold; the packet is then miss-recognized, implying that mis- or false recognition is easily declared if the magnitude (variance) of the

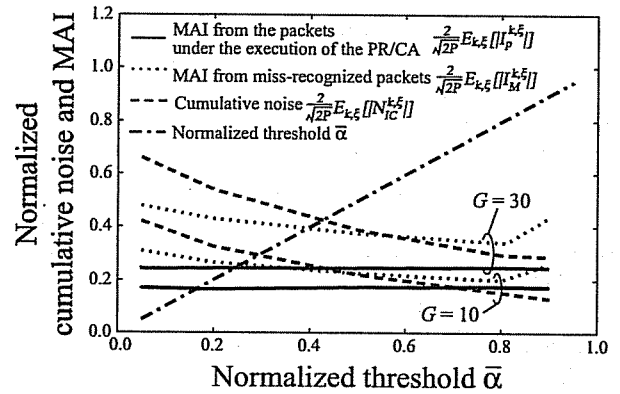


Fig. 5 Normalized cumulative noise and MAI on the decision variable for various thresholds.

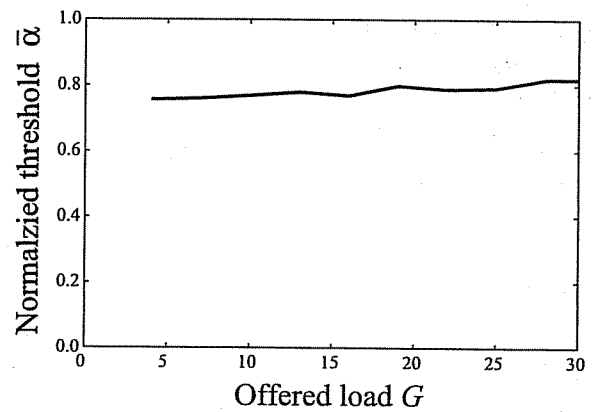


Fig. 6 The optimum threshold.

sum  $N_{IC}^{k,\xi} + I_M^{k,\xi} + I_p^{k,\xi}$  approaches the threshold. Such variance can be evaluated by using the magnitude of the three components  $N_{IC}^{k,\xi}$ ,  $I_M^{k,\xi}$ , and  $I_p^{k,\xi}$ , since the three terms are independent of each other. Therefore, in order to discuss the optimum threshold that maximizes the throughput, we pick up the magnitude of cumulative noise  $N_{IC}^{k,\xi}$  and MAI from mis-recognized packet  $I_M^{k,\xi}$  and the packet under the execution of the PR/CA  $I_p^{k,\xi}$ .

Figure 5 shows the the expected magnitude of cumulative noise and MAI from mis-recognized packets and packets under the execution of the PR/CA, that is,  $E_{k,\xi}[N_{IC}^{k,\xi}]$ ,  $E_{k,\xi}[I_M^{k,\xi}]$ , and  $E_{k,\xi}[I_p^{k,\xi}]$ . Given a threshold and an offered load, these are obtained by simulation. The straight line in Fig. 5 shows the threshold, and PR/CA is declared if the decision variable crosses this line. Based on the relation between the magnitudes and the threshold in Fig. 5, we can explain the threshold optimized in terms of throughput at every offered load, which is shown in Fig. 6.

From Fig. 5, the threshold is lower than the cumulative noise and MAI from mis-recognized packets and packets under the execution of the PR/CA in the case of a low threshold. This shows that the variance of the sum  $I_p^{k,\xi} + I_M^{k,\xi} + N_{IC}^{k,\xi}$  is so large that the decision variable often exceeds the threshold, resulting in a large number of falsely recognized pack-

ets. Since the IC is performed not only for the correctly recognized packets but also the many falsely recognized ones, a large amount of the cumulative noise arises. Such cumulative noise causes demodulation error, which brings about degradation of the throughput. Note that the MAI from the mis-recognized packet  $I_M^{k,\xi}$ , that is, the number of mis-recognized packets, is also found to be large in this case. From Eq. (8), the variance of the decision variable could be reduced by the large MAI from the mis-recognized packets, which implies that the decision variable often falls below the threshold.

In contrast, in the case of a high threshold, the sum of the cumulative noise, MAI from mis-recognized packets, and the packets under the execution of the PR/CA hardly exceed the threshold. Thus, because of the small number of the falsely recognized packets, the cumulative noise  $N_{IC}^{k,\xi}$  may decrease. However, the MAI from the mis-recognized packets might increase because the threshold is so high and the variance of the decision variable is decreased enough that the decision variable could often fall below the threshold. The MAI from such mis-recognized packets cannot be reduced by using the SIC, which implies that the throughput is also degraded. Therefore, the maximum throughput is obtained at the optimized threshold at which both the mis-recognized and the falsely recognized packets could be reduced.

From Fig. 5, the MAI  $I_P^{k,\xi}$  from the packets under the execution of PR/CA may be nearly constant even if the threshold varies. The error of PR/CA could occur provided that the MAI  $I_P^{k,\xi}$  is greater than the threshold, which implies that the MAI might be critical. However, the MAI  $I_P^{k,\xi}$  is smaller than the threshold where the throughput is maximized. Consequently, the reduction of PR/CA errors can be realized due to the small effect of the MAI  $I_P^{k,\xi}$ .

Figure 5 also shows that the cumulative noise is reduced as the threshold increases, implying that the number of recognized packets  $K_r(t)$  decreases as the threshold increases. The MAI from mis-recognized packets is gradually suppressed until the optimum threshold, though the threshold exceeds the optimum one, it increases. Then, the number of mis-recognized packets  $K_M(t)$  decreases until the optimum threshold; if the threshold exceeds the optimum one, it increases.

Figure 6 shows that the threshold for maximizing the throughput is about  $\alpha = 0.8$ , and as the offered load increases, the threshold slightly increases. Furthermore, as the offered load increases, the cumulative noise, the MAI from mis-recognized packets, and the MAI from the packets under the execution of the PR/CA also increase, as shown in Fig. 5. This implies an increase of the variance of the decision variable. Then, the decision variable for an actually transmitted packet can easily fall below the threshold, suggesting that many packets are mis-recognized. Similarly, many packets might be falsely recognized in this situation. Since the MAI from mis-recognized packets is larger than the cumulative noise from falsely recognized packets[9], the

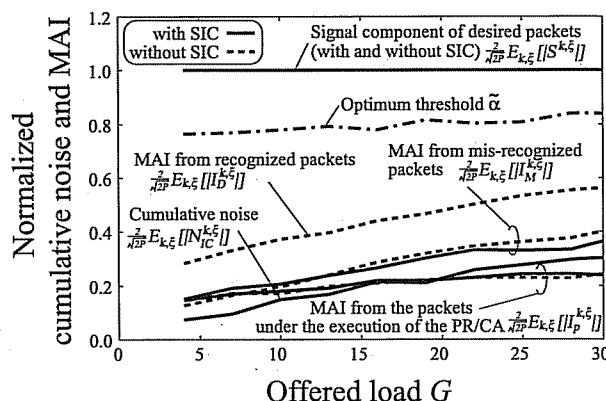


Fig. 7 Normalized cumulative noise and MAI on the decision variable for offered load.

optimum threshold increases as the offered load increases.

Because the probabilities of  $P_F$  and  $P_M$  depend on the cumulative noise and the MAI from mis-recognized packets and the packets under the execution of the PR/CA,  $E_{k,\xi}[I_P^{k,\xi}]$ ,  $E_{k,\xi}[I_M^{k,\xi}]$ ,  $E_{k,\xi}[N_{IC}^{k,\xi}]$ , and  $E_{k,\xi}[I_D^{k,\xi}]$  are plotted in Fig. 7. This figure can be obtained by simulation when the threshold is set according to the result in Fig. 6.

As the offered load increases, many packets arrive at base station, and when this occurs, the number of packets under the execution of the PR/CA and recognized packets also increases. This indicates that the cumulative noise  $|N_{IC}^{k,\xi}|$  and the MAI from packets under the execution of the PR/CA  $|I_P^{k,\xi}|$  swell. From Eq. (10), such noise and MAI increase the variance of the decision variable in the case that a packet is transmitted, which causes the mis-recognition. Note that such an increase of mis-recognition can be found from the increase of the MAI from mis-recognized packets  $I_M^{k,\xi}$ .

Here, the cumulative noise and the MAI in both cases of using SIC and not using SIC are compared. The MAI from the recognized packets is very large when SIC is not used, whereas when SIC is used, the large MAI is reduced into the cumulative noise. This reduction may be brought about by the suppression of the MAI from the correctly recognized packets. The MAI from mis-recognized packets cannot be reduced, even in the case of using SIC, because of the high threshold.

The error probabilities of PR/CA are plotted in Fig. 8. Such probabilities can be obtained by counting the events of mis- and false recognition in the simulation. The probability of false recognition  $P_F$  for the system with SIC becomes much better than that for the system without SIC, since the cumulative noise can be reduced by using SIC. From Eqs. (9) and (11), the reduction introduces improvement to the false-recognition probability, whereby the probabilities of mis-recognition  $P_M$  may be approximately the same.

Figure 9 shows the throughput for the system both with and without SIC. To clarify the effect of using SIC for PR/CA, the throughput when SIC is used for demodulation and not used for PR/CA is also depicted. The simulation pa-

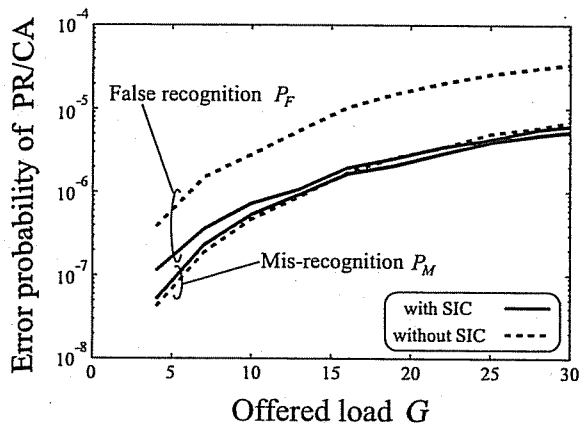


Fig. 8 Error probabilities of mis-recognition and false recognition.

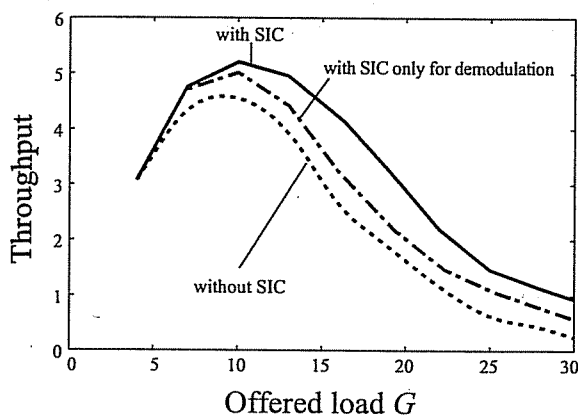


Fig. 9 Throughput performance versus offered load.

rameters are the same in all cases. This figure illustrates that the throughput for the system with SIC is better than those for the other systems. These throughput may be degraded by PR/CA error and the overhead of preamble. Although applying SIC only to the demodulation could improve the throughput compared with the system without SIC, the large number of falsely recognized packets limits throughput improvement because of the cumulative noise. The treated system decreases the number of falsely recognized packets, and then improves the throughput; therefore, applying SIC to PR/CA is also effective from the point of view of throughput improvement.

## 5. Conclusion

The PR/CA error may arise because of MAI from already recognized packets and newly arriving packets under the execution of the PR/CA. In CDMA U-ALOHA systems, the characteristic of asynchronous transmission and the short preamble part, the MAI from the packets under the execution of the PR/CA will be small. Using such a characteristic, this paper proposed applying the IC scheme to PR/CA to suppress the MAI from the already recognized and code-acquired packets. We used the SIC scheme since it provides a residual signal in which the MAI from the al-

ready recognized and code-acquired packets is suppressed. PR/CA was performed by a simple scheme of serial-search using the residual signal. A performance evaluation revealed that the MAI from the packets under the execution of the PR/CA can be negligible. Consequently, the suppression of only the MAI from the already recognized and code-acquired packets can realize improvement to PR/CA. In particular, the suppression reduces false recognition, while mis-recognition is hardly reduced. In addition, the treated scheme improves the performance of not only the error probabilities of PR/CA, but also the throughput.

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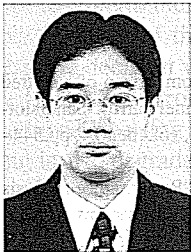
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