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Throughput Improvement of CDMA Slotted ALOHA Systems

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SUMMARY In this paper, we evaluate the throughput performance of CDMA Slotted ALOHA systems. To improve the throughput performance, we employ the Quasi-synchronous sequences and the Modified Channel Load Sensing Protocol as an access control procedure. As a result, we found a good throughput by the QS-sequences. By employing MCLSP, we can keep the maximum throughput even in high offered load and in the presence of a long access timing delay, which is one of the issue in satellite packet communication systems.

key words: *CDMA slotted ALOHA systems, QS-sequences, access timing error, modified channel load sensing protocol, access timing delay*

1. Introduction

Recently, Code Division Multiple Access (CDMA) ALOHA systems draw much attention for advanced satellite-based mobile and personal communications. So many works have been made so far aiming at improving the system performance of CDMA ALOHA systems [1]–[11]. In this paper, we focus on the CDMA Slotted ALOHA system.

In CDMA Slotted ALOHA systems, each user transmits his packet so that it starts at the beginning of an interval, called slot. If perfect synchronization is fulfilled, we can employ the orthogonal code and CDMA Slotted ALOHA system shows an ideal throughput performance. This perfect synchronization, however, is very difficult to implement. The performance will degrade in the presence of *access timing error*, which may likely be occurred in the link from user terminals to a base station. For this reason, the asynchronous sequences are often employed. Unfortunately, the improvement of the throughput performance is not as much as we gain for narrow band ALOHA systems, and the throughput are almost same between CDMA Unslotted ALOHA system and CDMA Slotted ALOHA system [6].

Another important issue on CDMA Slotted ALOHA system is a degradation of the throughput performance in large offered load. For CDMA Unslotted system, Channel Load Sensing Protocol (CLSP) has been proposed. In the CLSP, a hub station senses the instantaneous channel load status, which is the number of ongoing packets. The protocol controls the number of simultaneous transmitting packets to be less than a certain threshold. The maximum throughput reaches almost 1.5 times as large as that of CDMA Unslotted ALOHA system without CLSP and the throughput is kept even in the high offered load [8], [9]. Unfortunately we can not apply it to CDMA Slotted ALOHA system, since the channel load is constant within a slot and it takes independent value in different slots.

In this paper, we present the performance improvement of CDMA Slotted ALOHA system. In order to improve the performance, we first consider employing the Quasi-synchronous (QS)-sequences [12]. QS-sequences allows a certain amount of *access timing error*, and shows better cross-correlation than that of the asynchronous sequences. Therefore, it is considered as suitable PN sequences for CDMA Slotted ALOHA systems. For an access control method, we employ the Modified Channel Load Sensing Protocol (MCLSP) [10]–[11]. In the MCLSP, the hub station observes the channel load continuously for a certain number of slots and estimates the average offered load. Then the hub station computes the probability with which each user station is to transmit its packet and broadcasts the computed values. Since MCLSP is based not on the instantaneous channel load but on the estimated offered load, we can apply it to CDMA Slotted ALOHA system.

The remainder of this paper is structured as follows: In Sect. 2, the system model is presented and in Sect. 3, Quasi-synchronous sequences are briefly described. In Sect. 4, Modified Channel Load Sensing Protocol is described and in Sect. 5, throughput analysis of CDMA Slotted ALOHA systems with MCLSP is evaluated. In Sect. 6, numerical results are shown and concluding remarks are presented in Sect. 7.

2. System Model

We consider a single-hop CDMA packet radio network with an infinite number of user stations and a hub station.

Figure 1 shows channel state of CDMA Slotted ALOHA system that can be seen at the hub station. Time axis is divided into slots (where slot time is T_{slot}),

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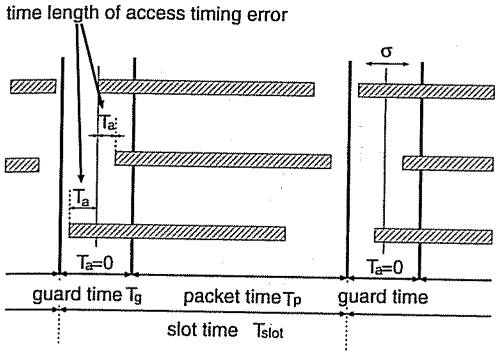

Fig. 1 Model of channel status of CDMA slotted ALOHA system.

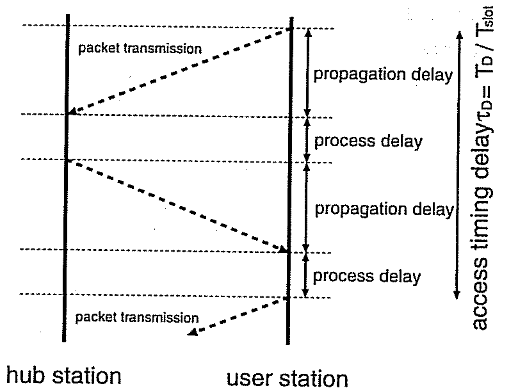

Fig. 2 Access timing delay.

which consist of guard time T_g and packet time T_p. We assume that there exists an *access timing error* T_a.

Packet generation, including both transmission and re-transmission, is assumed to be Poisson with rate λ, and all transmissions are received with equal powers.

We define the offered load G as the average number of generating packets in a packet duration and $G = \lambda T_P$.

The number of signature sequences is limited. We assume that each user selects one of the sequences and no packet is simultaneously transmitted using the same sequences.

We define the *access timing delay* as a time difference between channel load sensing and associated packet access timing, as shown in Fig. 2. Let T_D be the *access timing delay* and τ_D be the access timing delay normalized by slot length T_{slot}.

2.1 Transmitter and Receiver Model Using QS-Sequences

Figure 3 shows the model of transmitter and receiver channels. The packet is modulated by direct-sequence spread spectrum (DS/SS).

The k-th user's transmitted signal $s_k(t)$ has the form

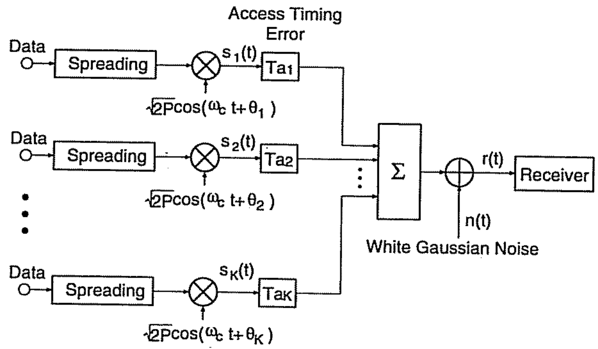

Fig. 3 Model of transmitter and receiver.

of

$$s_k(t) = \sqrt{2P} \sum_{i=-\infty}^{\infty} \{b_{k,i'} a_{k,i} \cos(\omega_c t + \theta_k)\} \qquad (1)$$

$$i' = \left[\frac{i}{N}\right]$$

where P is the signal power, ω_c is the carrier frequency, and θ_k is an initial phase. We denote $b_{k,i'}$ as i'-th data bit signal and $a_{k,i}$ as i-th signature sequence, i.e. $+1$ or -1. We employ QS-sequences as the signature sequences in order to allow a certain amount of *access timing error* $T_{a,k}$ [12]. We assume that the *access timing error* $T_{a,k}$ is Gaussian distribution and σ is a standard deviation of *access timing error*, as shown in Fig. 1.

At the channel, the interference signals from the other users is added together with the channel noise. Received signal $r(t)$ at the hub station is expressed as

$$\begin{aligned} r(t) &= \sqrt{2P} \sum_{k=1}^{K} \sum_{i=-\infty}^{\infty} \{b_{k,i'} a_{k,i} \cos(\omega_c t + \theta_k \\ &\quad - \omega_c T_{a,k})\} + n(t) \\ &= \sqrt{2P} \sum_{k=1}^{K} \sum_{i=-\infty}^{\infty} \{b_{k,i'} a_{k,i} \cos(\omega_c t + \phi_k)\} \\ &\quad + n(t) \end{aligned} \qquad (2)$$

where $\phi_k = \theta_k - \omega_c T_{a,k}$ and $n(t)$ is the channel noise process which we assume to be white and Gaussian process with two-sided spectral density $N_0/2$. We denote K as the number of simultaneous packets in a slot.

The received signal $r(t)$ is sampled and then fed into the correlator. The output from the correlator is of the following form

$$Z = \sqrt{\frac{P}{2}} \left(Z_d + \sum_{\substack{k=1 \\ (k \neq d)}}^{K} Z_k \right) + Z_{noise} \qquad (3)$$

$$Z_d = b_{d,0}$$

$$Z_k = \frac{1}{N} \sum_{i=-\infty}^{\infty} \sum_{n=0}^{N-1} \{a_{k,i} b_{k,i'} a_{d,n} \cos(\phi_k)\}$$

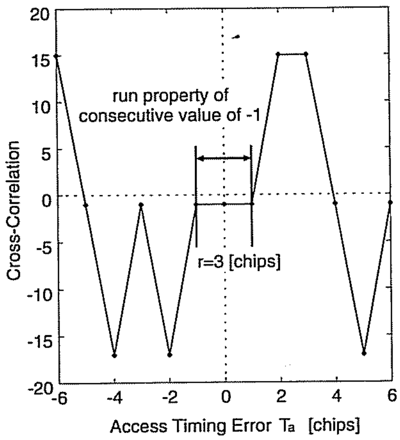

Fig. 4 An example of cross-correlation of QS-sequences.

where N is the number of chips per bit. We denote Z_d as the desired signal component, Z_k as the interference component against desired signal, and Z_{noise} as the noise component.

Finally, bit error rate (BER (K)) of desired packet is expressed as [12]:

$$\mathrm{BER}\,(K) = \frac{1}{2}\mathrm{erfc}\left\{\sqrt{\frac{E_b}{N_0}}\left(Z_d + \sum_{\substack{k=1 \\ (k \neq d)}}^{K} Z_k\right)\right\} \quad (4)$$

where E_b is the bit energy.

3. QS-Sequences

3.1 Characteristics

QS-sequences have been proposed to allow a certain amount of *access timing error*, while achieving a good error performance [12]. In this paper we employ the QS-sequences(G-r) having an allowance of *access timing error* up to the range of r. We can generate it from Gold sequences [12]. Figure 4 shows an example of cross correlation property of QS-sequences(G-3). As we can recognize from the figure, QS-sequences have run property of consecutive value of -1 nearby $T_a = 0$. Because of this property we can expect good throughput performance even in the presence of *access timing error*. In Table 1, we show the maximum number (M_N) of QS-sequences (G-r). If we increase the allowance of *access timing error*, which equivalently increases r, the number of sequences decreases.

3.2 Sequence Allocation to Each User

If we have a large number of signature sequences, it is possible to allocate each sequence to all the user. Unfortunately, the maximum number of QS-sequence is limited as mentioned in the previous subsection. We, therefore, consider the following method to allocate the sequence to each user.

Table 1 The maximum number of sequences (M_N), for QS-sequences (G-r).

$N\backslash r$	1	3	5	7
63	64	16	8	4
127	128	32	8	4
511	511	128	32	8
1024	1024	256	64	16

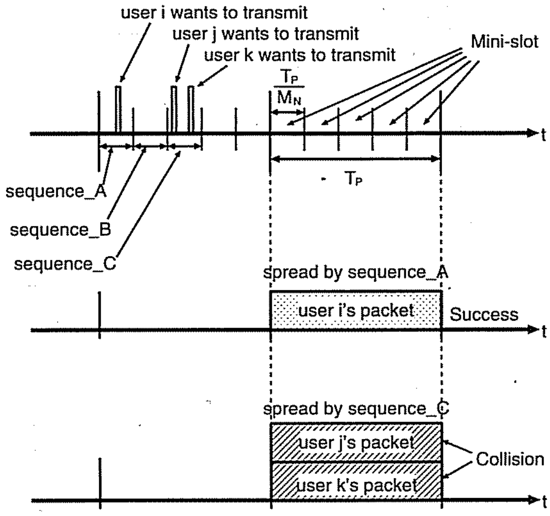

Fig. 5 Sequence allocation and collision of sequence (guard time is omitted).

We consider the mini-slot, as shown in Fig. 5, where we obtain the time interval of mini-slot by T_{slot}/M_N. So there are M_N mini-slots in a slot. Let us consider the case that user i wants to transmit. If such offer occurs in the first mini-slot duration, then he transmits with the sequence allocated to that mini-slot. If another user, say j, wants to transmit and such offer occurs in another mini-slot, then he transmits with sequence **C**, as shown in the figure. If two or more offers occur in the same mini-slot, the collision occurs and the transmission would fail. However, by increasing M_N, we can decrease the possibility of the collision.

4. Modified Channel Load Sensing Protocol (MCLSP)

4.1 Principle of MCLSP

In CDMA Slotted ALOHA systems, although the channel load status is constant within a slot, it takes independent value in different slots. However, for given offered load G, we can expect the same value of G even in different slots as G is the average number of generating packets. If we can estimate the offered load G, it is possible to control the number of ongoing packets of CDMA Slotted ALOHA systems. The Modified Channel Load Sensing Protocol (MCLSP) controls the packet access by the estimation of the offered load [10].

In MCLSP, the hub station observes the channel load continuously for a certain period of time T_s, and calculates packet transmission probability P_{tr}, then broadcasts this probability to user stations. Each user transmits his packet according to this probability P_{tr} and holds back the transmission with probability $1 - P_{tr}$.

To carry out this protocol effectively, it is important to develop a proper algorithm for deriving the packet transmission probability P_{tr}. The algorithm is described in the following.

4.2 Algorithm for Deriving the Probability P_{tr}

The average offered load G usually varies slowly and can be regarded as being constant during the time period for the access procedure. Taking this fact into account of this fact, we can estimate G basing on the channel load measured during T_s. By using the estimated G, it can be expected to reduce the degradation of the throughput due to the long *access timing delay*.

Assume that a user station starts transmitting a packet at time $t = t_{ps}$. Let $X_A(t_{ps} - T_D, T_s)$ be the number of packets received in the hub station during the time period from $(t_{ps} - T_D - T_s)$ to $(t_{ps} - T_D)$. Let $\overline{P_{tr}(t_{ps} - T_D, T_s)}$ be the average packet transmission probability during the time period. Let $X_O(t_{ps} - T_D, T_s)$ be the number of packets that user wishes to transmit. We express it as

$$X_O(t_{ps} - T_D, T_s) = \frac{X_A(t_{ps} - T_D, T_s)}{\overline{P_{tr}(t_{ps} - T_D, T_s)}}. \tag{5}$$

The estimated value of G at $t = t_{ps} - T_D$ is expressed as

$$\begin{aligned} g(t_{ps} - T_D, T_s) &= \frac{X_O(t_{ps} - T_D, T_s)}{\tau_s} \\ &= \frac{X_A(t_{ps} - T_D, T_s)}{\overline{P_{tr}(t_{ps} - T_D, T_s)} \cdot \tau_s}. \end{aligned} \tag{6}$$

where $\tau_s = T_s / T_{slot}$.

Based on this estimated offered load $g(t_{ps} - T_D, T_s)$, the packet transmission probability at $t = t_{ps}$ is derived by the following equation. We derive the probability to achieve the maximum value of the throughput even in the presence of a long *access timing delay*. The packet transmission probability $P_{tr}(t)$ at $t = t_{ps}$ is derived as

$$P_{tr}(t_{ps}) = \min\left\{\frac{G_{\max}}{g(t_{ps} - T_D, T_s)}, 1.0\right\}, \tag{7}$$

where $G_{\max}$ is the average offered load when achieving the maximum throughput. We denote g as the estimated offered load. This equation means that if g exceeds $G_{\max}$, then the user will transmit the packet with the probability of $G_{\max}/g$, otherwise the packet will be transmitted immediately upon request.

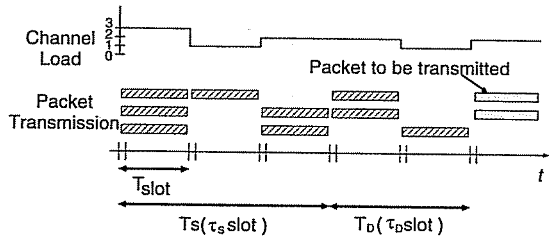

Fig. 6 Model of CDMA slotted ALOHA systems with MCLSP.

5. Throughput Analysis

The channel load observed by the hub station is shown in Fig. 6.

Let us assume that an estimation error of average offered load will hardly happen when the observation time period T_s is taken sufficiently long. In this case, we can consider that the estimated offered load g in (6) is equal to the actual offered load G. Let $P_o(m)$ be the probability that m packets received on the hub station within one slot time duration T_{slot}. Because we can regard the offered load as constant during the time period for the access procedure, we can write (7) as $P_{tr} = \min\{G_{\max}/G, 1.0\}$. Accordingly, the number of packets received on the hub station within one slot time duration is Poisson process with the birth rate $P_{tr}\lambda$, and the following equation is derived.

$$\begin{aligned} P_o(m) &= \frac{(P_{tr}\lambda T_P)^m}{m!} \exp(-P_{tr}\lambda T_P) \\ &= \frac{(P_{tr}G)^m}{m!} \exp(-P_{tr}G) \end{aligned} \tag{8}$$

Using the above equation and bit error probability of (4), we obtain the packet success probability as follows:

$$Q_S(G) = \sum_{m=0}^{M_N} P_o(m)\{1 - \mathrm{BER}(m)\}^L. \tag{9}$$

Where L denotes the number of bit length per one packet.

We define the throughput S as the average number of received packets successfully in one packet time duration. With the consideration of the effect of the guard time length, the throughput of the CDMA Slotted ALOHA systems with MCLSP is derived as

$$S = \frac{T_P}{T_{slot}} P_{tr} G \cdot Q_S(G). \tag{10}$$

As mentioned in 3.2, if two or more users select same sequence, the collision occurs and the performance would be degraded. Such degradation is not considered in (10), therefore, the throughput we derived shows an upper-bound performance rather than the actual throughput.

6. Numerical Examples

Figure 7 shows the throughput performance of CDMA

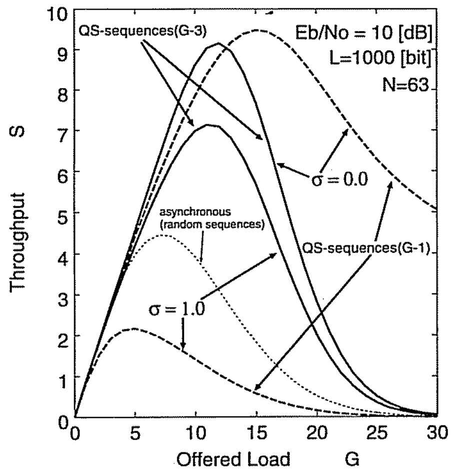

Fig. 7 Throughput performance of CDMA slotted ALOHA systems.

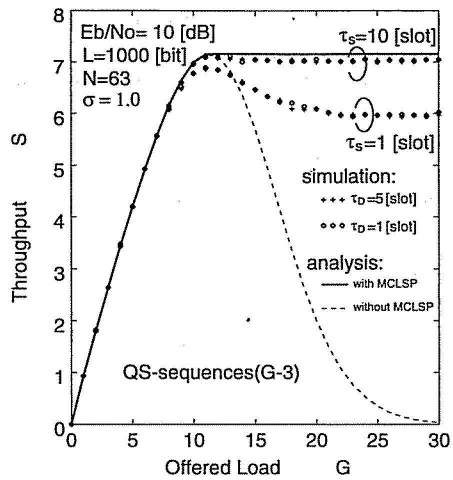

Fig. 8 Throughput performance of CDMA slotted ALOHA systems with MCLSP.

Slotted ALOHA systems employing QS-sequences (G-3) and QS-sequences (G-1) under the situations that $\sigma = 0.0$ (perfect synchronization is fulfilled) and 1.0. The case of asynchronous sequences (random sequences) is also plotted in the figure. We set $N = 63$, $L = 1000$ [bit], and $E_b/N_0 = 10$ [dB]. We assume that the guard time is much small in comparison with the slot time, we neglect the effect of the guard time on the throughput performance. If there is no *access timing error*, i.e., perfect synchronization is fulfilled, we can achieve more than 2 times higher throughput by the QS-sequences than that of asynchronous sequences. Between QS-sequences, QS-sequences (G-1) shows a little better performance than that of QS-sequences (G-3). In the presence of *access timing error* ($\sigma = 1.0$), the performance degradation is found for QS-sequences (G-1), while we find the slight degradation for QS-sequences (G-3). Although there is no performance degradation on the system employing asynchronous sequences, QS-sequences (G-3) shows the best throughput performance.

In Fig. 8, we obtain the throughput performance of CDMA Slotted ALOHA systems with MCLSP. Analytical and simulated results for observation time slot $\tau_s = 1, 10$ and *access timing delay* $\tau_D = 1, 5$ are plotted in the figure. *Access timing delay* $\tau_D = 1$ corresponds to the case of LEO systems and $\tau_D = 5$ corresponds to the GEO systems, when baud rate is 9600 [bps]. The other parameters are the same as those of Fig. 7. We observe from the figure that the analytical results come close to the simulated results. If the observation time slot is taken sufficiently long ($\tau_s = 10$, for example), estimation error of offered load will hardly happen. Therefore, it can be seen from this figure that the throughput with the MCLSP can be kept as high as the maximum value of the CDMA Slotted ALOHA systems without MCLSP even in a long *access timing delay* and large offered load.

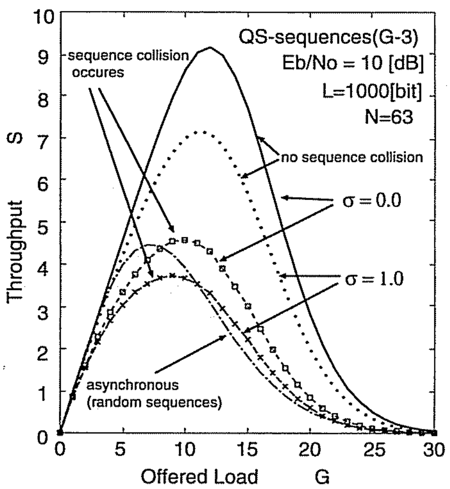

Fig. 9 Performance degradation due to the collision of the sequences.

In Sect. 2, we assume that no packet is simultaneously transmitted using the same sequence. Such assumption is valid when the maximum number of the sequences is large. For the case of QS-sequences (G-3) depicted in Fig. 7 and Fig. 8, since the maximum number of the sequence is 16, it is likely to occur that two or more users select the same sequence. Therefore, actual performance will be degraded. The simulation results of such degradation are plotted in Fig. 9 where we used the method described in 4.2 to assign the sequence. We consider the case of Fig. 7 and Fig. 8 as the upper-bound.

7. Conclusions

In this paper, we have evaluated throughput performance of CDMA Slotted ALOHA systems with MCLSP. We have employed the QS-sequences as signature sequences to improve the throughput performance. As a result, we have found that the throughput is more than two times higher than the system employing asynchronous signature sequences and found a slight degradation on the throughput in the presence of *access timing delay*.

To achieve further improvement of the performance we have employed MCLSP. We have found that by employing MCLSP the effect of a long *access timing delay* is avoidable, which is one of the issues in satellite packet communication systems. Moreover, we can keep as high as maximum throughput value even in the large offered load.

However, since the maximum number of the QS-sequences we employed is rather small, we found the degradation in the actual situation. It is necessary to study the QS-sequence that has a large number of sequence while having a large allowance of *access timing error*.

Acknowledgment

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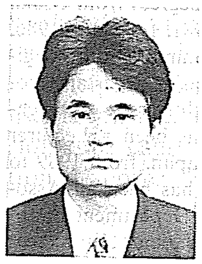

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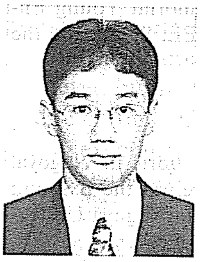

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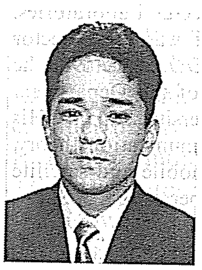

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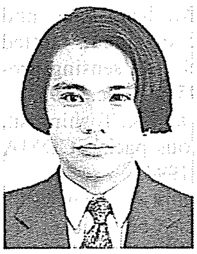

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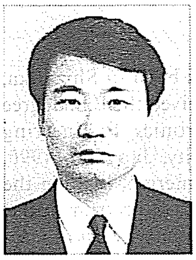

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