A Novel Spread Slotted Aloha System with Channel Load Sensing Protocol

Kiyoshi Toshimitsu, Takaya Yamazato, Masaaki Katayama, and Akira Ogawa

Abstract—**This paper presents a noval spread slotted Aloha system with channel load sensing protocol (CLSP). CLSP is an effective scheme to improve the throughput performance in spread unslotted Aloha systems. In spread slotted Aloha systems, however, it does not make sense to utilize CLSP because the slot size is usually the same as the packet size. The slot size of the proposed system is set less than the packet size, thereby enabling us to apply CLSP and improving the throughput performance. Another feature of the proposed system is that the system is not likely affected by the time difference between channel load sensing and timing of packet access, which we call the access timing delay. Throughput performance of the proposed system is evaluated in the presence of the access timing delay and a significant increase of the throughput is shown compared with that of spread unslotted Aloha with CLSP.**

I. INTRODUCTION

RECENTLY, Spread Aloha systems have drawn much attention for satellite-based mobile and personal communications because of the capability of simultaneous access and low peak power in the transmitter. Many investigations have been performed so far in order to improve the system performance [1]–[5]. One of the techniques for improving the throughput performance is the packet access control based on Channel Load Sensing Protocol (CLSP) [3]–[5].

In CLSP, a hub station senses the channel load, which is the number of ongoing transmissions. If the channel load is less than a certain threshold, then packet accesses are allowed. Otherwise, packet accesses are rejected until the ongoing transmissions fall below the threshold. Without the access timing delay, which means the time difference between channel load sensing and timing of packet access, the throughput of a spread unslotted Aloha system with CLSP is satisfactory. When the access timing delay is no longer negligible, a wrong channel load information may be given as the channel load changes moment by moment. The packet access control based on this wrong information results in degradation of the system performance. Therefore, a spread unslotted Aloha system with CLSP is not practical with the access timing delay. There has been no mention of the effect of the access timing delay in any of the papers.

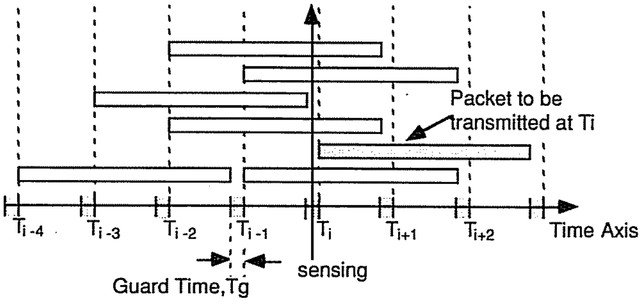

Fig. 1. Behavior of the proposed system at the hub station.

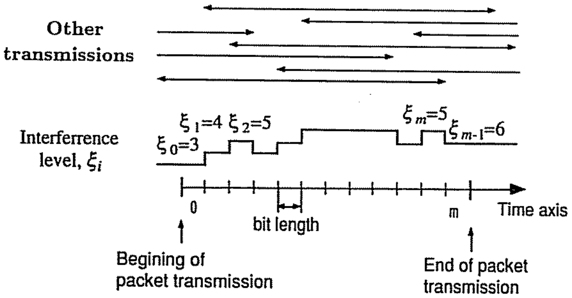

Fig. 2. Example of interference level seen at a receiver.

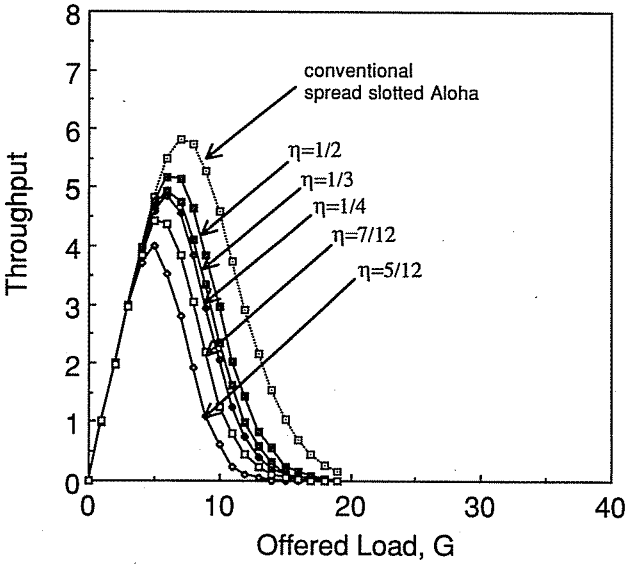

Fig. 3. Throughput of the proposed system without CLSP for slot size $\eta = 1/4, 1/3, 5/12, 1/2, 7/12$, and $\beta = 10$ along with the conventional spread slotted Aloha.

The object of this paper is to propose a novel spread slotted Aloha system with CLSP and show a significant improvement of the throughput performance even in the presence of access timing delay. The slot size of the proposed system is less than a packet size. Therefore, the packets overlap partially like spread unslotted Aloha system. This overlapping of the packets enable us to use CLSP. As the channel load of the proposed system is uniform during a slot, the proposed system can be designed

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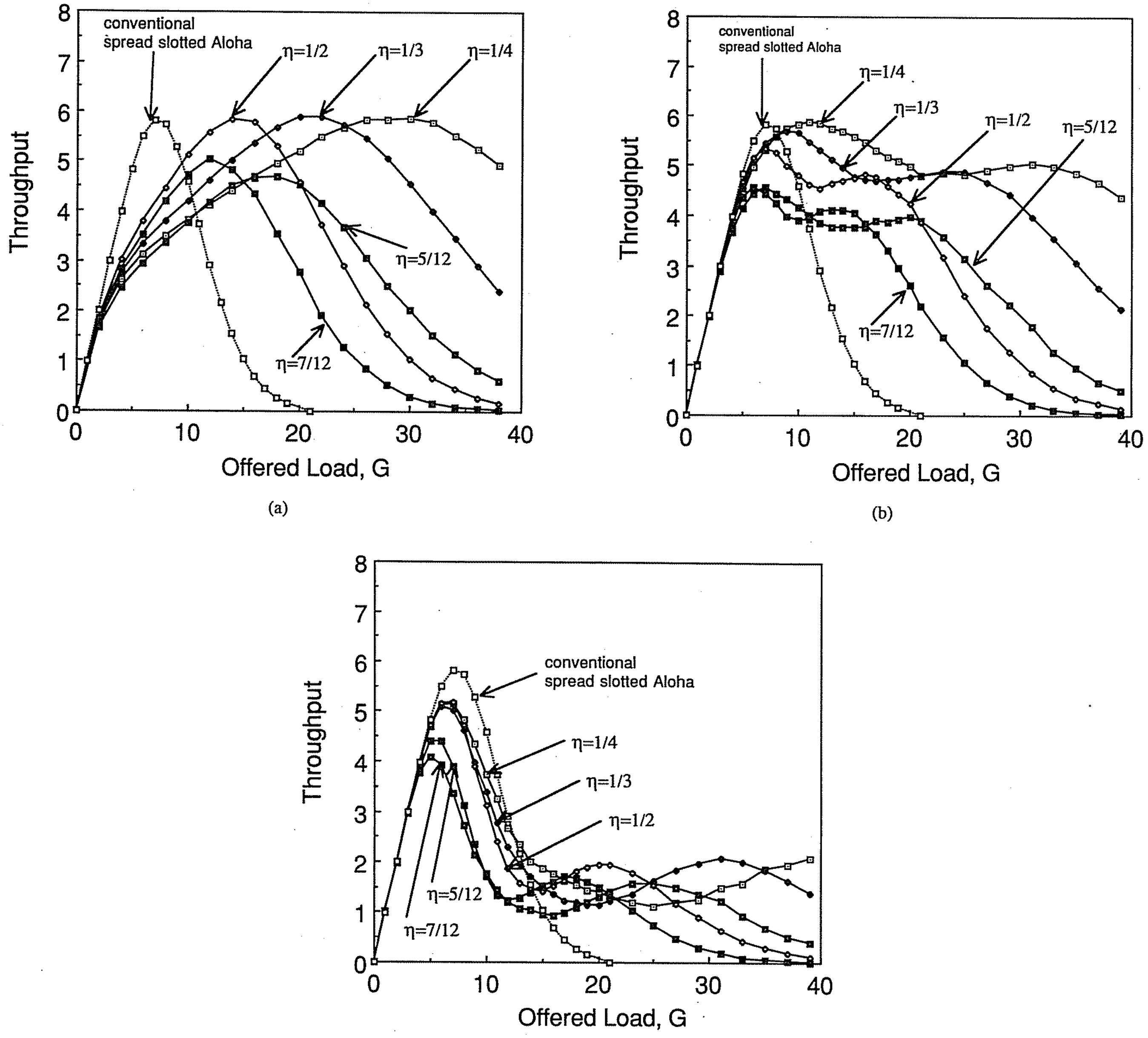


(a)

(b)

(c)

Fig. 4. Throughput of the proposed system with CLSP for slot size $\eta = 1/4, 1/3, 5/12, 1/2, 7/12$, and $\beta = 10$ along with the conventional spread slotted ALOHA for (a) ($\alpha = 3$), (b) ($\alpha = 6$), and (c) ($\alpha = 9$)

robust for the access timing delay due to the flexibility of the channel-sense timing.

The remainder of this paper is structured as follows: In Section II, the system model of the proposed system is presented. In Section III, the throughput performance of the proposed system is evaluated as the parameter of the slot size and the access timing delay. In Section IV, the throughput performance of the proposed system which can allow the maximum access timing delay is analyzed taking the effect of the CLSP threshold into account. Concluding remarks are presented in Section V.

II. SYSTEM MODEL

Assume that a communication network which has an infinite number of mobile stations and a hub station. In this paper, we consider a reverse link (mobile stations to the hub station). Each mobile station has its own pseudonoise (PN) code, and data is transmitted as a packet which is spreaded by the PN code. In order to apply CLSP to the spread slotted Aloha system, there should be an overlap of packets; thus, we propose to employ the slot size less than the packet size. Let a slot size be T_S (seconds) and η be a slot size normalized by T_P as:

$$\eta = \frac{T_S}{T_P}, \qquad 0 < \eta < 1 \tag{1}$$

where T_P (seconds) is a packet size. In CLSP, a hub station senses the channel load and controls the packet access. If the channel load, which is the number of ongoing transmissions, is less than a certain threshold, then packet accesses are allowed. Otherwise, packet accesses are denied until the ongoing transmissions fall below the threshold. Fig. 1 shows the behavior of the proposed system at the hub station. In order to make the traffic control on the ith slot, the hub station senses the number of packets, X_i, which give interference in the ith slot. These interfering packets are transmitted at $T_{i-1}, T_{i-2}, \cdots, T_{i-m}$, where m is the maximum integer which satisfies:

$$m \cdot \eta < 1. \tag{2}$$

For the sensing of X_i (as shown in Fig. 1), the system utilizes a guard time between the slots to accommodate transmission timing error of packets, denoted as T_g, and the hub station senses X_i just before T_i. By using X_i, the hub station can control the packet access with CLSP.

III. THROUGHPUT PERFORMANCE

Due to the partial overlapping of the packets, the throughput of the proposed system depends on the slot size. In this section, for the purpose of clarifying the effect of the slot size, we analyze the throughput of the proposed system for various slot sizes. We compare the proposed system with the conventional spread slotted Aloha system, in which slot size equals a packet size, and spread unslotted Aloha system with CLSP. Throughput degradation, due to access timing delay, is also considered here.

Throughput is defined as the average number of successfully transmitted packets per packet size. We assume that all unsuccessful transmissions are caused by multiple-access interferences. All packets are received at the hub station with equal power, and the packet length is sufficiently long. We deal with a packet error probability, P_{e_p}, assumed to be as follows:

$$P_{e_p} = \begin{cases} 1; & K > \beta \\ 0; & \text{otherwise} \end{cases} \tag{3}$$

where K is the level of multiple-access interference and β is the threshold. The validity of this assumption is shown in the Appendix. In the proposed system, the level of multiple-access interference fluctuates during the packet transmission because the slot size is less than the packet size. Let $\xi_i (i = 0, 1, 2, \cdots, m)$ be the multiple-access interference on each slot during a packet transmission, where m is given from (2). The packet is successfully transmitted only if all ξ_i is below a threshold. This implies that the packet error probability is bounded by the maximum level of ξ_i. Therefore, K of (3) is given as:

$$K = \max\{\xi_0, \xi_1, \cdots, \xi_m\}. \tag{4}$$

Fig. 2 shows the example of interference level seen at a receiver.

We assume that the access timing error at the hub station is less than T_g, and that the effect of T_g on the throughput is negligible. It is also assumed that a packet occurrence of new transmission and retransmission is Poisson process with rate λ (packets/second).

A. Effect of the Slot Size

Figs. 3 and 4 show the throughput of the proposed system obtained by computer simulation. The offered load G per packet size is:

$$G = \lambda \times T_P. \tag{5}$$

In Fig. 3, for the case of no CLSP, the conventional spread slotted Aloha system gives the best throughput. On the contrary, when CLSP is employed, the proposed system gives better throughput than the conventional system in the high offered load as shown in Fig. 4(a)–(c). According to Figs. 3 and 4, the throughput tends to be better when $\eta = 1/n$ (n: integers); that is, $(m+1)\eta = 1$. We may explain the reason for this by observing the cases where $\eta \neq 1/n$. As is shown in Fig. 5, where $\eta \neq 1/n$, the total duration of the slots interfered by one packet, $(m+1)/T_S$, is longer than the packet duration T_P, and there exists the useless interval at the end of the packets in the last slot. This useless interval causes a waste of time and degradation of the throughput. Fig. 4, however, shows that the throughput for the case $\eta = 5/12$ is superior to $\eta = 1/2$ in the high offered load range. This is an effect of CLSP. In fact, Fig. 3 shows that the throughput for the case $\eta = 5/12$ is inferior to $\eta = 1/2$ without employing CLSP.

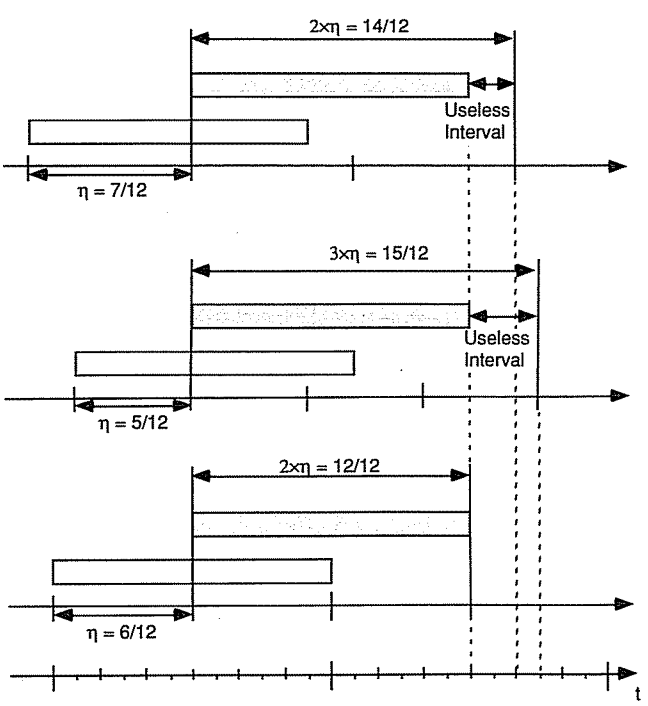
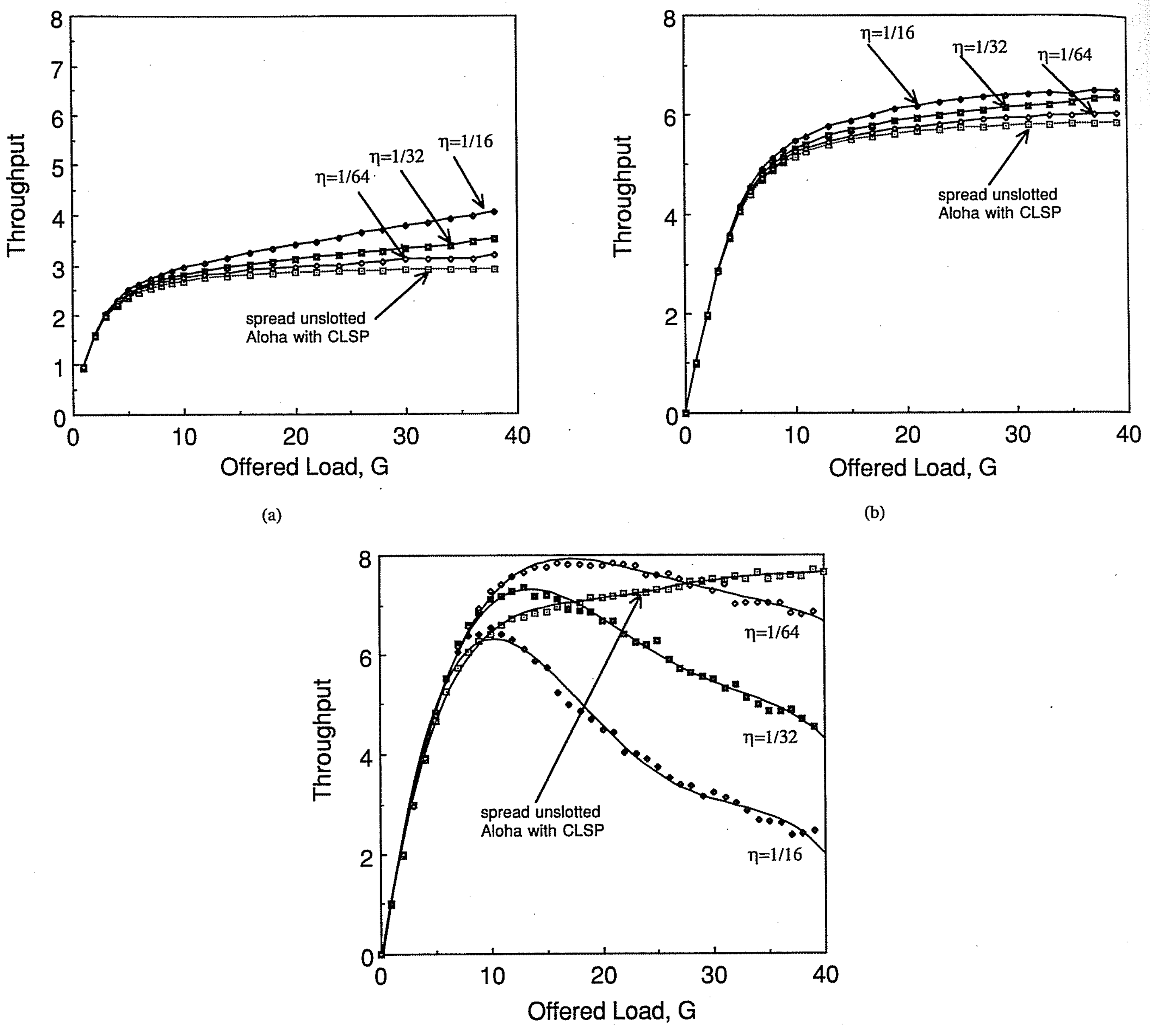


Fig. 5. Total duration of the slots interfered by one packet.

It is found that η had better be one fraction of an integer. Fig. 6 shows the throughput of the proposed system in the case $\eta = 1/n$. The throughput is improved due to the effect of CLSP as n becomes bigger; that is, the slot size becomes shorter. When the slot size is longer, a packet error is likely to occur by the burst packet access even if packet access is permitted. On the other hand, when a slot size is shorter, fewer packets per slot are transmitted and a packet error has not even occurred. Also, the increase of n means that the throughput of the proposed system tends to be close to that of the spread unslotted Aloha system with CLSP. On the optimal condition, the best throughput is obtained when $n \rightarrow \infty$ and $\alpha \rightarrow$ channel capacity. This is the case of a spread unslotted Aloha system with CLSP when $\alpha \rightarrow$ channel capacity [3].



(a)

(b)

(c)

Fig. 6. Throughput of the proposed system for slot size $\eta = 1/8, 1/16, 1/32, 1/64$, and $\beta = 10$ along with spread unslotted ALOHA with CLSP for (a) ($\alpha = 3$), (b) ($\alpha = 6$) , and (c) ($\alpha = 9$) .

B. Throughput Degradation Due to the Access Timing Delay

In the previous section, it is shown that the best throughput is obtained by a spread unslotted Aloha system with CLSP ($\alpha \rightarrow$ channel capacity) without consideration of the access timing delay. In this section, degradation of the throughput due to the access timing delay is discussed. Fig. 7 shows throughput degradation due to the access timing delay for the case of a spread unslotted Aloha system with CLSP ($\alpha = 9$) as a parameter of the access timing delay, τ, normalized by T_P. As τ increases, the throughput of spread unslotted Aloha systems with CLSP degrades. In the presence of the access timing delay, the hub station may not control the packet access by the appropriate channel load, as it changes moment by moment. Therefore, CLSP does not work well.

In the previous section, the sensing of the channel load was done on the preceding guard time. Considering the access timing delay, this channel sensing method is not effective. In order to avoid the effect of the access timing delay, we propose a multiple sensing method as shown in Fig. 8. When the packet access request occurs at T_i, the hub station senses the channel load of the ith slot, X_i, which will partially overlap with packets to be transmitted at T_i. The hub station senses each number of newly transmitted packets at $T_{i-1}, T_{i-2}, \cdots, T_{i-m}$. Let the number of newly transmitted packets at T_{i-j} be $Y_{i-j}(1 \leq j \leq m)$. The hub station get X_i from the sum of $Y_{i-1}, Y_{i-2}, \cdots, Y_{i-m}$, which is expressed as:

$$X_i = \sum_{j=1}^{m} Y_{i-j}. \tag{6}$$

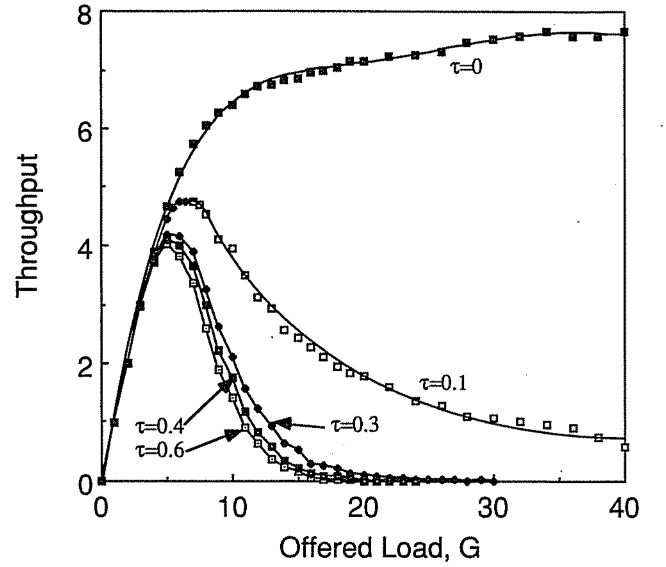


Fig. 7. Throughput degradation of spread unslotted Aloha due to the access timing delay $\tau = 0, 0.1, 0.3, 0.4, 0.6, \alpha = 9$, and $\beta = 10$.

The hub station senses the channel load twice at T_{i-j} and $T_{i-j} + T_g$, in order to sense Y_{i-j}. The first sensing at T_{i-j} gives the hub station X_{i-j}. The second sensing at $T_{i-j} + T_g$ gives the hub station the sum of X_{i-j} and Y_{i-j}. The difference gives the hub station Y_{i-j}. This sensing method can allow the access timing delay less than a slot size.

Fig. 9 shows the throughput of the proposed system as a parameter of the access timing delay, τ, with CLSP ($\alpha = 3, 6, 9$). When the access timing delay is less than a slot size ($\tau < \eta$), the throughput of the proposed system is excellent. In other words, we can neglect the effect of the access timing delay if it is less than the slot size, while it is no longer negligible for $\tau \geq \eta$. In the previous section, it was found that a slot size should be $1/n$ of the packet size. Therefore, we can obtain the best throughput performance by minimizing η while satisfying $\eta > \tau$. The system which can allow maximum access timing delay is the one with $\eta = 1/2$. Thus, the system with $\eta = 1/2$ may be the best from a practical viewpoint.

IV. SPREAD 1/2-SLOTTED ALOHA SYSTEM

It was found that the proposed system with $\eta = 1/2$ is practical in the presence of access timing delay. In this section, we focus on the system with $\eta = 1/2$ and discuss the effect of the threshold of CLSP on the throughput [6]. We assume $\tau < \eta$ in this analysis; therefore, there is no performance degradation due to the access timing delay.

The throughput of the conventional spread slotted Aloha is expressed by [1], [7]:

$$S = \sum_{i=0}^{\beta} i \cdot P(i, T = T_p) = \sum_{i=1}^{\beta} \frac{G^i}{(i-1)!} \cdot \exp(-G) \quad (7)$$

where $P(k, t)$ is a Poisson process given by:

$$P(k, t) = \frac{(\lambda \cdot t)^k}{k!} \times \exp(-\lambda \cdot t). \quad (8)$$

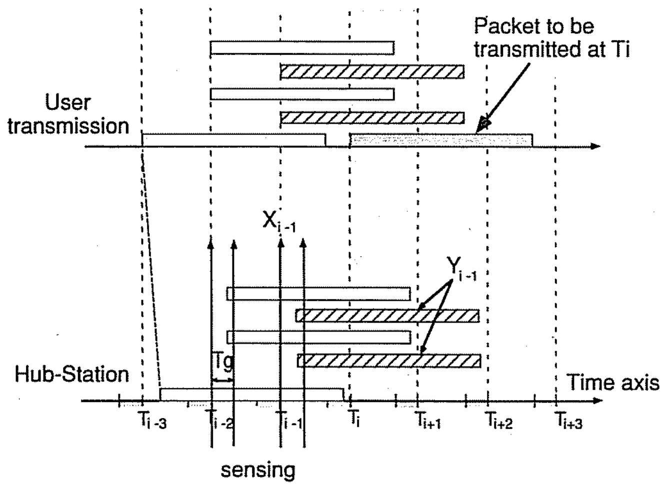


Fig. 8. The multiple sensing method.

In the proposed system, the packet access is rejected when the number of interfering packets in the preceding slot is more than threshold α. A packet to be transmitted at T_i is controlled by CLSP based on X_i. Three individual cases are considered according to X_i.

(Case 1) $X_i = 0$ Two cases are considered:

a) The packet access is allowed, but there is no request for access.

b) The packet access is rejected.

Therefore, the probability P_0 that the number of access packets at T_{i-1} is zero is given by:

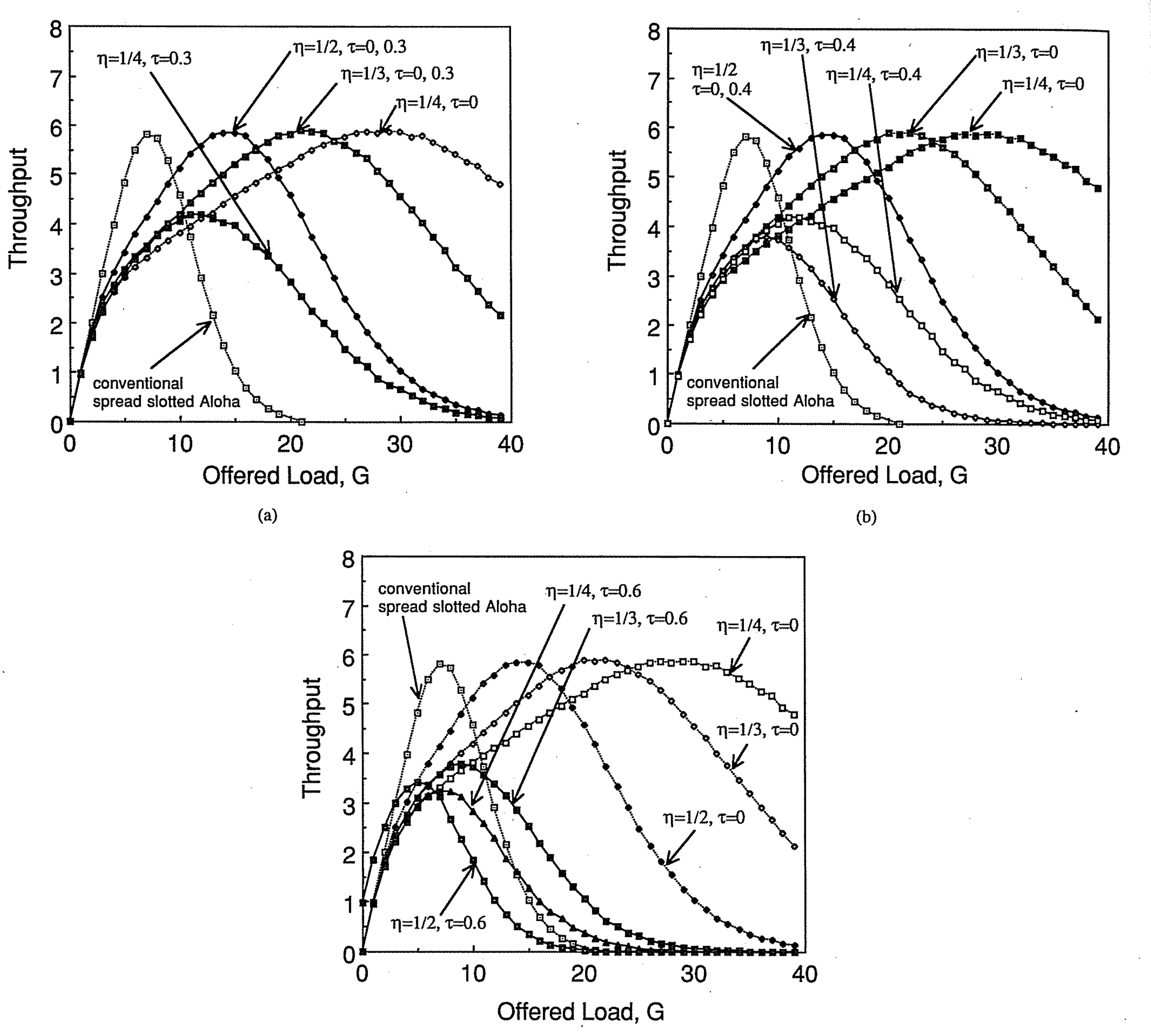
$$\begin{aligned} P_0 &= P(0, T = T_p/2) + \frac{1}{2} \cdot \left\{ 1 - \sum_{h=0}^{\alpha-1} P(h, T_p/2) \right\} \\ &= \exp(-G/2) + \frac{1}{2} \cdot \left\{ 1 - \sum_{h=0}^{\alpha-1} \frac{(G/2)^h}{h!} \cdot \exp(-G/2) \right\}. \end{aligned} \quad (9)$$

Throughput S_1, for *case 1*, is given by:

$$\begin{aligned} S_1 &= 2 \cdot \left\{ \sum_{j=0}^{\alpha-1} \sum_{k=0}^{\beta-j} j \cdot P_0 \cdot P(j, T_p/2)\, P(k, T_p/2) \right. \\ &\quad \left. + \sum_{j=\alpha}^{\beta} j \cdot P_0 \cdot P(j, T_p/2) \right\} \\ &= 2 \cdot \left\{ \sum_{j=1}^{\alpha-1} \sum_{k=0}^{\beta-j} P_0 \cdot \frac{(G/2)^{j+k}}{(j-1)!k!} \cdot \exp(-G) \right. \\ &\quad \left. + \sum_{j=\alpha}^{\beta} P_0 \cdot \frac{(G/2)^j}{(j-1)!} \cdot \exp(-G/2) \right\}. \end{aligned} \quad (10)$$

(Case 2) $1 \leq X_i < \alpha$: The packet transmitted at T_i is successfully transmitted if the following two conditions are satisfied:

a) The sum of the number of packets, which are transmitted at T_{i-1}, T_i is less than β.



(a) (b)

(c)

Fig. 9. Throughput degradation of the proposed system due to the access timing delay for slot size $\eta = 1/2, 1/3, 1/4, \alpha = 9$, and $\beta = 10$ along with the conventional spread slotted Aloha for (a) $\tau = 0$, (b) $\tau = 0, 0.4$, and (c) $\tau = 0, 0.6$.

b) The sum of the number of packets, which are transmitted at T_i, T_{i+1} is less than β.

Therefore, the throughput S_2 for *case 2* is given by:

$$\begin{aligned}S_2 =& 2 \cdot \sum_{i=1}^{\alpha-1} \left\{ \sum_{j=0}^{\alpha-1-i} \sum_{k=0}^{\beta-j} j \cdot P(i, T_p/2) P(j, T_p/2) P(k, T_p/2) \right. \\ &\left. + \sum_{j=\alpha-i}^{\beta-1-i} j \cdot P(i, T_p/2) P(j, T_p/2) \right\} \\ =& 2 \cdot \sum_{i=1}^{\alpha-1} \left\{ \sum_{j=1}^{\alpha-1-i} \sum_{k=0}^{\beta-j} \frac{(G/2)^{i+j+k}}{i!(j-1)!k!} \cdot \exp\left(-3G/2\right) \right. \\ &\left. + \sum_{j=\alpha-i}^{\beta-1-i} \frac{(G/2)^{i+j}}{i!(j-1)!} \cdot \exp\left(-G\right) \right\} \qquad (11)\end{aligned}$$

(Case 3) $\alpha \le X_i$*:* The packet access at T_i is rejected. Therefore, throughput S_3 for *case 3* is:

$$S_3 = 0 \qquad (12)$$

Consequently, the throughput of the proposed system is:

$$S = S_1 + S_2 + S_3. \qquad (13)$$

In Fig. 10, the throughput of the spread 1/2-slotted Aloha system is shown and compared with that of the conventional spread slotted Aloha system. Both simulation and numerical results are depicted in the figure. When the offered load is high, the proposed system is superior in throughput to the conventional spread slotted Aloha system. When a threshold α is set at low value, the effect of CLSP is remarkable, and the satisfactory throughput is obtained in the high offered load range. In the low offered load range, however, the throughput

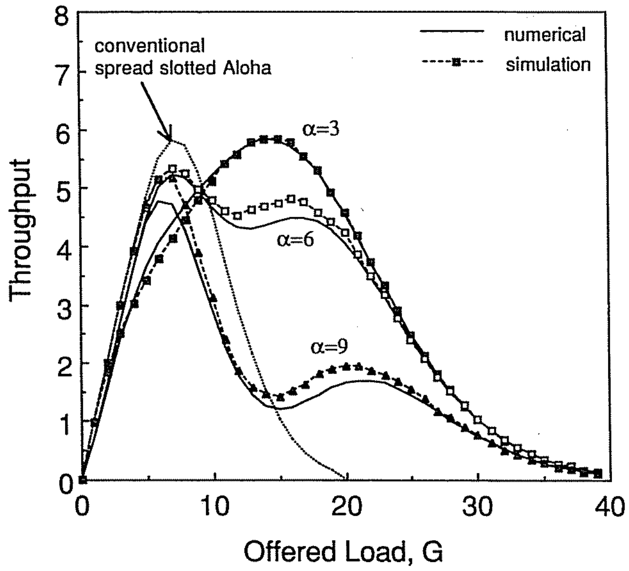


Fig. 10. Throughput of spread 1/2-slotted Aloha for threshold $\alpha = 3, 6, 9$, and $\beta = 10$, along with the conventional spread slotted Aloha.

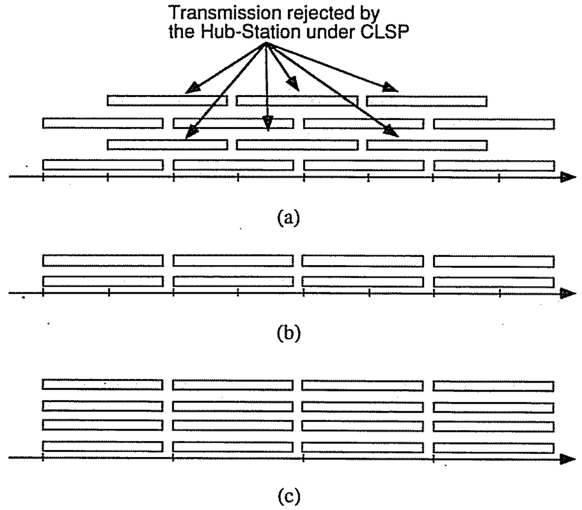


Fig. 11. State of the channel at high offered load of the spread 1/2-slotted Aloha along with the conventional spread slotted Aloha. (a) Transmission request, (b) Permitted by the hub station under CLSP, and (c) State of the channel of the conventional spread slotted Aloha.

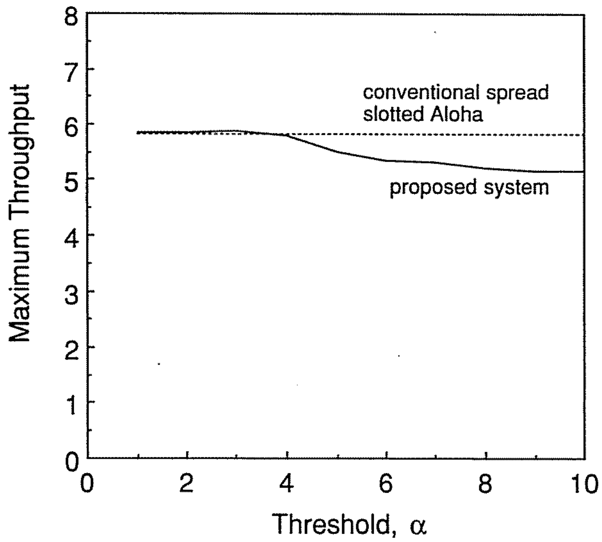


Fig. 12. Maximum throughput of the proposed system along with that of the conventional spread slotted Aloha ($\beta = 10$).

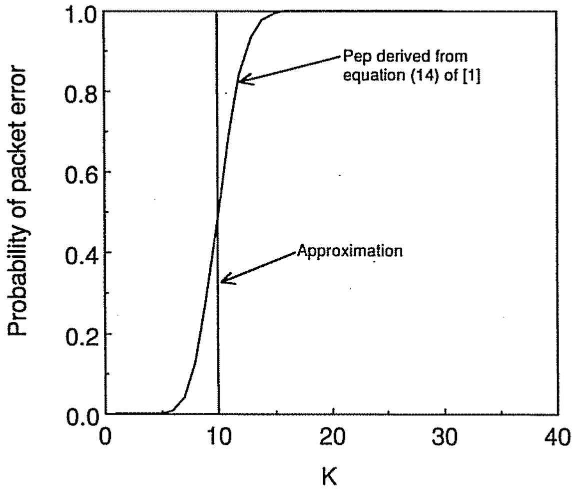


Fig. 13. Probability of packet error for packet length $L = 1000$[bit].

is somewhat poor. On the other hand, if the threshold α is set at high value, no degradation of the throughput in the low offered load range is found, but the improvement of throughput is not as high as the case of low threshold value in the high offered load range.

In the spread 1/2-slotted Aloha system, the average number of the packets to be transmitted in one slot is a half of G. As G increases, the number of packets actually transmitted equals a half of the number of packets to be transmitted if α is small, as shown in Fig. 11 (a) and (b). Comparing this with the conventional spread slotted Aloha where offered load per shot is $G/2$ shown in Fig. 11(c), it is supposed the maximum throughput of the proposed system does not exceed that of the conventional spread slotted Aloha system. This supposition is confirmed to be true by the results of the computer simulation given in Fig. 12.

V. CONCLUSIONS

A novel spread slotted Aloha system with CLSP has been proposed. Significant throughput improvement has been achieved especially in the high offered load, as a result of applying CLSP. We have shown that the throughput of the proposed system tends to be close to that of spread unslotted Aloha system with CLSP as the slot size approaches to zero ($\eta \rightarrow 0$). However, in the presence of the access timing delay, the throughput of spread unslotted Aloha system with CLSP degrades. It has been shown that the proposed system can allow the access timing delay up to the slot size and the throughput does not degrade. Throughput analysis of the system in which slot size equals 1/2-packet size has been made. This is the case of the maximum access timing delay that the proposed system can allow.

APPENDIX
VALIDITY OF (3)

Consider the bit error probability, P_{e_b}, assumed as:

$$P^1_{e_b} = \begin{cases} 1; & K > \beta \\ 0; & \text{otherwise.} \end{cases} \tag{A1}$$

K: the level of multiple-access interference

β: the threshold

and the bit error probability (14) of [1], given as:

$$P^2_{e_b} = Q\left(\sqrt{\frac{3N}{K-1}}\right). \tag{A2}$$

N: the number of chip per bit.

Equation (A-1) is used for the analysis of the spread unslotted Aloha system [3]. Equation (A-2) is the case of random signature sequences [1]. Although the throughput analyses based on these different bit error probabilities (A-1) and (A-2) have been done, both packet error probabilities can be approximated as (3) when the packet length is sufficiently long. The pocket error probability, P_{e_p}, is given as:

$$P_{e_p} = 1 - (1 - P_{e_b})^L \tag{A3}$$

where L(bit) is the packet length. It is evident that P_{e_p} is exact of (3) when (A-1) is given as P_{e_b}. P_{e_p} can also be approximated by (3) when (A-2) is given as P_{e_b}. Fig. 13 shows P_{e_p} derived from (A-2) and P_{e_p} of (3). As shown in the figure, we can confirm that the difference of two curves is little. Therefore, (3) can be used as an approximation of packet error probability.

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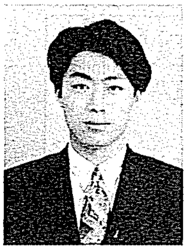

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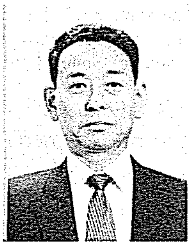

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