# Throughput Analysis of DS/SSMA Unslotted ALOHA System with Fixed Packet Length

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***Abstract*—Throughput analysis of direct-sequence spread spectrum multiple access (DS/SSMA) unslotted ALOHA with fixed packet length is presented. As the levels of multi-user interference fluctuate during the packet transmission, we calculate the packet error probability and the throughput by considering not only the number of overlapped packets but also the amount of time overlap. On the assumption that packet generation is Poisson, the system can be thought as the queueing system $M/D/\infty$. With Gaussian approximation of multi-user interference, we obtain the throughput as the function of the number of chips in a bit, the packet length, and the offered load of the system. We also analyze the channel load sensing protocol (CLSP), and obtain the optimum threshold of CLSP.**

## I. Introduction

RECENTLY, packet radio network systems based on code-division multiple-access (CDMA) have drawn much attention for use in mobile and personal communications because of their capability of random access, the potentiality for high throughput performance, and the low peak power in the transmitters. Thus, much literature has been devoted to improving system performance [1]–[9]. Most existing documentation on CDMA-packet systems, however, has been restricted to the slotted system, i.e., CDMA-slotted ALOHA [1]–[3]. In a CDMA-slotted ALOHA, the time axis is divided into a slot. Each slot is the sum of a packet interval and a guard time. All users must synchronize their transmissions so that they initiate at the beginning of a slot. Therefore, the success of the packet depends only on the number of interferences within the slot and performance analysis is rather easy.

CDMA-unslotted ALOHA is easier to implement, as it requires no synchronization. However, its analysis is very difficult, as the level of user interference that a given packet experiences fluctuates during the packet transmission period. Most of the literature devoted to CDMA-unslotted ALOHA assumes that the success of a packet solely depends on the capture of the preamble (perfect capture) [4], [9], and the number of interferences is assumed to be constant during packet transmission. Therefore, the success of the packet depends mostly on the power of the received signal and the multiple access interference at the beginning of the packet. Analysis of CDMA-unslotted ALOHA can be obtained by an extension of the analysis of CDMA-slotted ALOHA. In [2] and [8], although the analysis is based on nonperfect capture, the bit (or packet) error probability is based on a simplified model: that when the number of transmitted packets at any given instance is above a threshold, the probability of bit error is one, and is zero otherwise. Therefore, the advantage of spread spectrum signals, i.e., that the probability of bit (or packet) error tends to decrease gracefully as the number of transmitted packets increases, is not considered.

In this paper, we analyze the throughput performance of direct-sequence spread spectrum multiple access (DS/SSMA) unslotted ALOHA with a fixed-length packet by nonperfect capture. As the levels of multi-user interference fluctuate during the packet transmission, we calculate the packet error probability and the throughput by considering not only the number of overlapped packets but also the amount of time overlap. On the assumption that packet generation is Poisson, the system can be thought of as the queueing system $M/D/\infty$ [10]. The Gaussian approximation of multi-user interference plus noise is assumed in the calculation of the bit error probability. The effect of thermal noise, assumed to be Gaussian, is also considered, which is often ignored in the literature.

Moreover, we analyze the throughput performance of DS/SSMA-unslotted ALOHA with the channel load sensing protocol (CLSP) [2] [8], [9]. It is reported that the optimum throughput performance can be obtained with CLSP. In CLSP, a hub station senses the channel load, which is the number of on-going transmissions. If the channel load is below a certain threshold, then, the hub station broadcasts to all users information of the allowance of packet transmission. Otherwise, when the channel load is more than threshold, it broadcasts to users the information of the rejection of packet transmission.

The remainder of this paper is structured as follows: In Section II, the system model is presented. In Section III, throughput analyses of DS/SSMA-unslotted ALOHA is described. Section IV presents throughput analysis of DS/SSMA-unslotted ALOHA with CLSP. In Section V, throughput performances are evaluated and concluding remarks are presented in Section VI.

## II. System Model

We consider a single-hop spread spectrum packet radio network with an infinite number of independent users sharing random signature sequence. Packet generation is assumed to be Poisson with rate $\lambda$, and every transmission is received with

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equal power. Bit errors are caused by the effect of multiple access interference and additive white Gaussian noise (AWGN). The bit error probability of an asynchronous DS/SSMA system is expressed as [11]

$$P_b(k) = \frac{2}{3}Q\left[\left(\frac{k}{3N} + \frac{N_0}{2E_b}\right)^{-0.5}\right] + \frac{1}{6}Q\left[\left(\frac{k(N3)+\sqrt{3}\sigma}{N^2} + \frac{N_0}{2E_b}\right)^{-0.5}\right] + \frac{1}{6}Q\left[\left(\frac{k(N3)-\sqrt{3}\sigma}{N^2} + \frac{N_0}{2E_b}\right)^{-0.5}\right] \quad (1)$$

with

$$\sigma^2 = k\left[N^2\frac{23}{360} + N\left(\frac{1}{20} + \frac{k-1}{36}\right) - \frac{1}{20} - \frac{k-1}{36}\right] \quad (2)$$

where $N$ is the number of chip per bit, $k$ is the number of interfering packet, $N_0$ is the two-sided spectral density of Gaussian noise, and $Q(x)$ is given by

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp(-u^2/2)du. \quad (3)$$

We define the offered load $G$ as the average number of generating packets in a packet duration $T_p$, therefore

$$G = \lambda T_p \quad (4)$$

where $T_p$ is a packet duration, i.e., $T_p = L/R$ and $L$ [bits] is the length of a packet and $R$ [b/s] is the data rate. Furthermore, we define the normalized offered load as the following:

$$G_{\rm norm} = \frac{G}{N}\cdot\frac{L}{T_p} \quad [\text{b/Hz/s}]. \quad (5)$$

## III. Throughput Analysis of DS/SSMA-Unslotted Aloha

### A. Transition of the Number of Interfering Packets

Figure 1 shows an example of the fluctuation of the interference level during the packet transmission. As the packet generation is Poisson and the packet length is constant, the DS/SSMA-unslotted ALOHA network can be thought as the queueing system $M/D/\infty$ [10].

The probability that $k$ packets will enter the network in a time intervals $t$ is given by the Poisson distribution

$$P_0(k,t) = \frac{(\lambda t)^k}{k!}e^{-\lambda t}. \quad (6)$$

Let $P_0(k)$ be the steady-state probability, which is easily found by setting $t = T_p$ [10]

$$P_0(k) = P_0(k, t = T_p) = \frac{(\lambda T_p)^k}{k!}e^{-\lambda T_p} = \frac{G^k}{k!}e^{-G}. \quad (7)$$

Now, let us suppose that a "tagged" packet, shown in Fig. 1, newly generates. For simplicity, we arrange the packets in

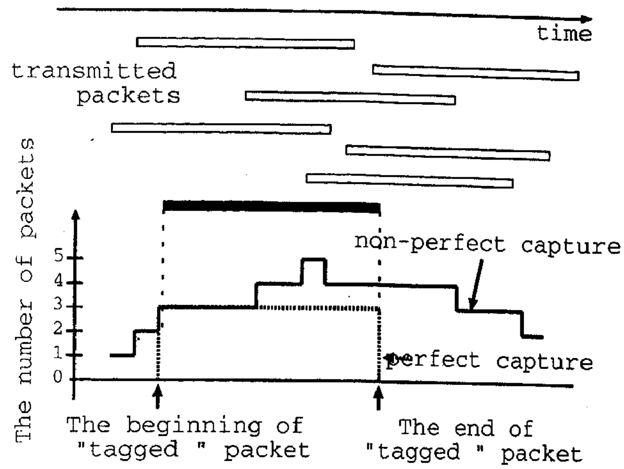


Fig. 1. An example of fluctuation of the interfering level during the packet transmission.

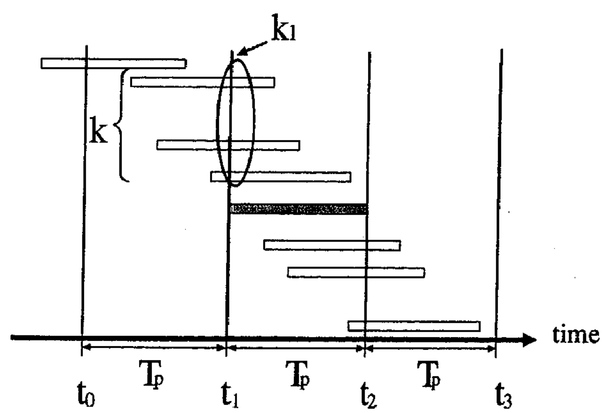


Fig. 2. The behavior of packet on the server.

Fig. 1 in order, as shown in Fig. 2. As we assume the Poisson packet generation, two or more packets can hardly generate simultaneously. The increase of the number of interfering packets is one in a short duration $\Delta t$, and since the packet length is constant, the decrease of the number of interfering packets is also one. The probability that both increase and decrease of packet occurs in $\Delta t$ is negligible. Therefore, after $\Delta t$ [s], the interference level $k$ of the $i$th bit of the packet will increases to $k+1$, decreases to $k-1$, or remains to $k$.

### B. Transition Rate

The state transition of the number of the interference level, shown in Fig. 3, is Markov chain model. Since the state transition is based on the packet generation and the termination of the packet service, we obtain the rate of packet generation, called the birth rate $\lambda$, and the rate of the termination of packet service, called the death rate $\mu$. In an analysis with exponential packet length, as the termination of the packet service is independent of the packet generation, we can obtain the death rate immediately [7]. This corresponds to the queueing system $M/M/\infty$ [10]. For the case of fixed packet length, however, it is difficult to deal in the death rate, because the termination of the packet service is dependent on the packet generation.

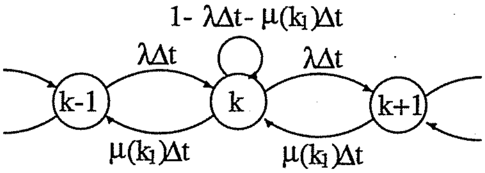


Fig. 3. State transition of the number of interfering packets.

Suppose that $k$ packets arrive in the intervals of $t_0 \leq t < t_1$, as shown in Fig. 2. Each packet is assumed to be independently and identically distributed. Since the packet length is constant, it is clear that $k$ packets will depart from the server in the intervals of $t_1 \leq t < t_2$. As we assume that the packet arrival process is Poisson and the arrival of a packet at certain time $t$ corresponds to a departure at time $t + T_p$, the packet departure process can also be assumed as Poisson. Thus, we obtain the death rate as follows:

$k$ packets depart in the time intervals $T_p$
↓
A packet departs in the average time intervals $T_p/k$.

Accordingly, the death rate is the following:

$$\mu(k) = \frac{k}{T_p}. \quad (8)$$

Because of the Poisson generation of the packet, we can obtain the birth rate of packet as the following:

$$\lambda = G/T_p. \quad (9)$$

### C. Throughput Analysis

Suppose that the "tagged" packet arrives at time $t_1$ and the packet service will terminate at $t_2$, as shown in Fig. 2. We can consider that the number of interfering packets on the first bit of the tagged packet equals the number of packets that have generated in the intervals of $t_0 \leq t < t_1$. Let the number of interfering packets on first bit be $k_1$. As $k_1$ corresponds to the number of generating packets in the time intervals $T_p$, $k_1$ is obtained by (7), the steady-state probability. Furthermore, since those interfering packets of $k_1$ will depart in the intervals of $t_1 \leq t < t_2$, the death rate is obtained by setting $k = k_1$ in (8), i.e., $\mu(k_1) = k_1/T_p$.

As we stated previously, the interference level may increase, decrease, or remain to the same level in $\Delta t$. Therefore, we can obtain the state equation of the number of interfering packets as

$$\begin{aligned} P_k(t + \Delta t) &= P_k(t) \cdot (1 - \mu(k_1)\Delta t - \lambda \Delta t) \\ &\quad + P_{k-1}(t) \cdot \lambda \Delta t + P_{k+1}(t) \cdot \mu(k_1)\Delta t. \end{aligned} \quad (10)$$

In the DS/SSMA-unslotted ALOHA protocol, a scheduled packet is transmitted immediately if the node is idle. Therefore, the level of interference that a given packet may experience may change even during a bit period. This makes the analysis complicated. To solve this problem, we approximate that interference level is constant over a bit period and $\Delta t$ equals a bit interval. This approximation is the same as the minislot approximation in [8].

In order to calculate the probability of packet success, we define the probability $P_S(k, i, k_1)$ as the following. The number of interference is $k_1$ on the first bit in a packet. The packet is transmitted successfully from first bit to the $i - 1$th bit, and the number of interfering packets becomes $k$ on the $i$th bit. $P_s(k, i, k_1)$ is obtained as follows.

*Case $i = 1$:* The number of interfering packets is $k_1$ on first bit.

As $k_1$ is obtained by the steady-state probability (6), we get

$$P_S(k = k_1, i = 1, k_1) = \frac{G^{k_1}}{k_1!} \cdot \exp(-G). \quad (11)$$

*Case $i > 1$:* The number of interfering packets is $k$ on $i$th bit.

As the transition of the number of interfering packets may occur every $\Delta t$ [s], and hence the $P_k(t)$ is conditioned on the bit error probability, we get

$$\begin{aligned} &P_S(k, i, k_1) \\ &\quad = P_S(k, i-1, k_1) \cdot (1 - \mu(k_1)\Delta t - \lambda \Delta t) \cdot (1 - P_b(k)) \\ &\quad\quad + P_S(k+1, i-1, k_1) \cdot \mu(k_1)\Delta t \cdot (1 - P_b(k+1)) \\ &\quad\quad + P_S(k-1, i-1, k_1) \cdot \lambda \Delta t \cdot (1 - P_b(k-1). \end{aligned} \quad (12)$$

Using $P_s(k, i, k_1)$ and the packet length $L$, the probability of packet success is calculated by setting $i = L$ and multiplication of the probability that the $L$th bit is successful. Averaging over all possible values of $k$ and $k_1$, we get the probability of packet success $Q_S$ as the following:

$$Q_S = \sum_{k=0}^{\infty} \sum_{k_1=0}^{\infty} P_S(k, L, k_1) \cdot (1 - P_b(k)). \quad (13)$$

The throughput of the system is defined as the average number of successful transmissions in a packet duration $T_p$. Thus, the throughput is

$$S = G \cdot Q_S. \quad (14)$$

## IV. DS/SSMA-Unslotted ALOHA with CLSP

### A. System Model

In this section, the throughput analysis of DS/SSMA-unslotted ALOHA with CLSP is presented. The analysis assumptions and conditions are the same as those of the previous analysis. In CLSP, when the channel load is more than a certain threshold $\alpha$, packet transmission is rejected by the hub station. Therefore, the number of ongoing packets on the server is always less than or equal to $\alpha$ and the generation rate of packet is zero. This can be considered as the queue system $M/D/\alpha/\alpha$.

We define $G_{\text{sys}}$, which is an average offered load on the server. $G_{\text{sys}}$ equals the rate at which packets are transmitted and is given by

$$G_{\text{sys}} = \frac{\sum_{j=0}^{\alpha} j \cdot G^j/j!}{\sum_{j=0}^{\alpha} G^j/j!} \quad (15)$$

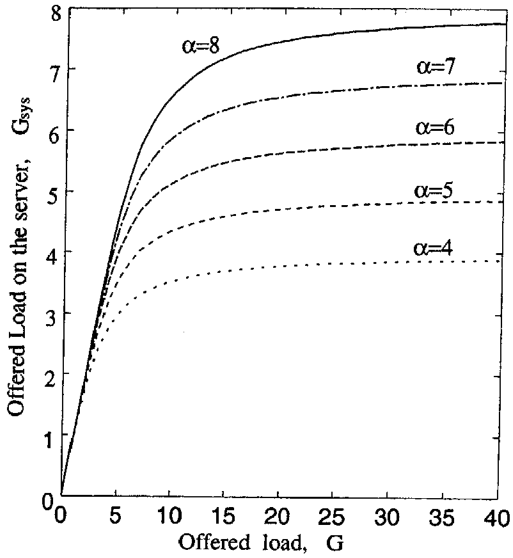


Fig. 4. Offered load in a system.

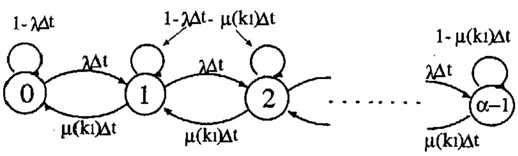


Fig. 5. State transition of the number of interfering packets for the case with CLSP.

where $j$ is the number of packets. Fig. 4 shows the performance of $G_{sys}$ versus $G$.

### B. Throughput Analysis

Fig. 5 shows the state transition of the number of interfering packets for the case of DS/SSMA-unslotted ALOHA with CLSP. This can be thought of as the queueing system $M/D/\alpha/\alpha$ [10]. The channel is $\alpha$-server station. All arriving packets that find all $\alpha$ servers of the channel busy will be rejected. The state transition is almost the same as the system without CLSP and the only difference is that there is no state transition beyond $\alpha - 1$. We define the probability $P_C(k, i, k_1)$ is defined as follows.

*Case* $i = 1$:

a) $k_1 \leq \alpha - 1$; the number of interfering packets is less than or equals $\alpha - 1$ on the first bit. Using the steady-state probability for the queue system $M/D/\alpha/\alpha$ , we obtain

$$P_C(k = k_1, i = 1, k_1 \leq \alpha - 1) = \frac{G^{k_1}/k_1!}{\sum_{k_1=0}^{\alpha} G^{k_1}/k_1!}. \quad (16)$$

b) $k_1 > \alpha - 1$; the number of interfering packets is more than $\alpha - 1$ on the first bit

$$P_C(k = \alpha - 1, i = 1, k_1 > \alpha - 1) = 0. \quad (17)$$

*Case* $i > 1$:

a) $k < \alpha - 1$; the number of interfering packets is below $\alpha - 1$. The state transition of the number of interfering packets is the same as that of the system without CLSP

$$\begin{aligned} P_C(k < \alpha - 1, i, k_1) &= P_C(k, i-1, k_1) \cdot (1 - \mu(k_1)\Delta t - \lambda\Delta t) \cdot (1 - P_b(k)) \\ &+ P_C(k+1, i-1, k_1) \cdot \mu(k_1)\Delta t \cdot (1 - P_b(k+1)) \\ &+ P_C(k-1, i-1, k_1) \cdot \lambda\Delta t \cdot (1 - P_b(k-1)). \quad (18) \end{aligned}$$

b) $k = \alpha - 1$; The number of all packets on the server equals to a threshold $\alpha$. In this case, we can also obtain from Fig. 5

$$\begin{aligned} P_C(k = \alpha - 1, i, k_1) &= P_C(k, i-1, k_1) \cdot (1 - \mu(k_1)\Delta t) \cdot (1 - P_b(k)) \\ &+ P_C(k-1, i-1, k_1) \cdot \lambda\Delta t \cdot (1 - P_b(k-1)). \quad (19) \end{aligned}$$

c) $k > \alpha - 1$; the number of all packets on the server is more than $\alpha - 1$

$$P_C(k > \alpha - 1, i, k_1) = 0. \quad (20)$$

The death rate and the birth rate are expressed as

$$\mu(k_1) = k_1/T_p, \qquad \lambda = G/T_p.$$

Finally, we get the probability of packet success $Q_C$ and throughput $S_C$ as follows:

$$Q_C = \sum_{k=0}^{\infty} \sum_{k_1=0}^{\infty} P_C(k, L, k_1) \cdot (1 - P_b(k)) \quad (21)$$

$$S_C = G_{sys} \cdot Q_C \quad (22)$$

where $G_{sys}$ is obtained by (15).

### C. Numerical Examples

We carry out the simulations to show the validity of our analysis. In the simulations, multiple arrivals and multiple departures are allowed even in a bit duration.

Normalized throughput is defined as the following, which is normalized to the bandwidth spreading factor $N$:

$$S_{norm} = \frac{S}{N} \cdot \frac{L}{T_p} \quad \text{[b/Hz/s]}. \quad (23)$$

We evaluate normalized throughput versus normalized offered load.

Figure 6 shows the throughput performance of DS/SSMA-unslotted ALOHA. For the case of $N = 30$, a data rate of 9.6 kbps, $E_b/N_0 = \infty$, packet length of $L = 1000$ b are examined along with simulated results. The throughput obtained by the perfect capture assumption is also depicted. We only consider multi-user interference. As it is clear from the figure, our analysis results are in agreement with the simulated results, but the perfect capture assumption overestimates the throughput.

In Fig. 7, we plot the throughput as a parameter of $E_b/N_0$. As expected, the throughput performance depends on $E_b/N_0$. If we could get $E_b/N_0 = 30$ dB, we would obtain the ideal throughput, which is the case without Gaussian noise.

Throughput performance of DS/SSMA-unslotted ALOHA with CLSP is plotted in Figs. 8 and 9 as a parameter of

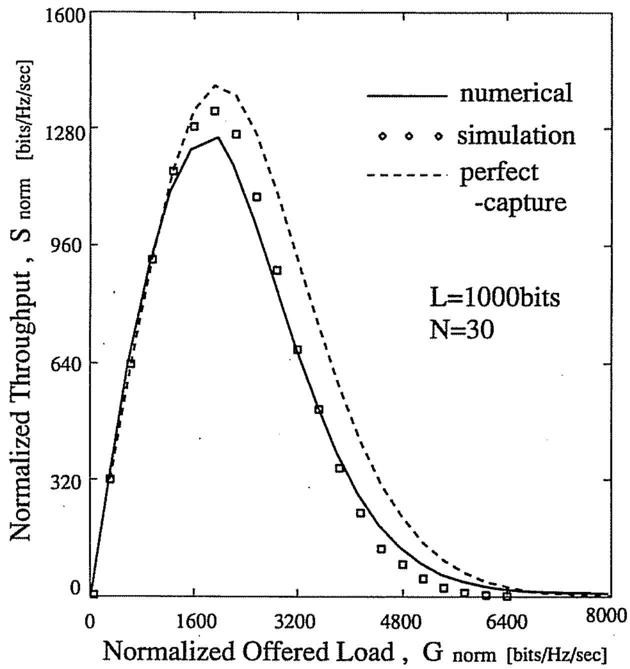


Fig. 6. The comparison with simulation and perfect capture.

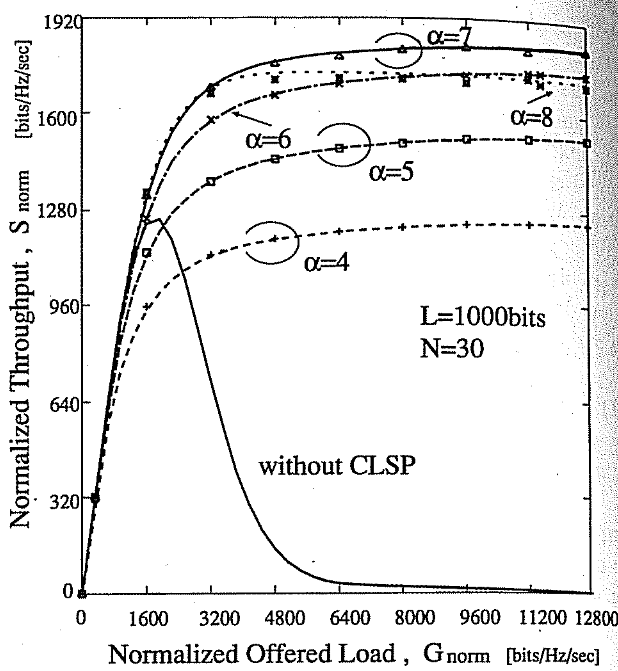


Fig. 8. Simulation and numerical results of CLSP ($\alpha \leq 8$).

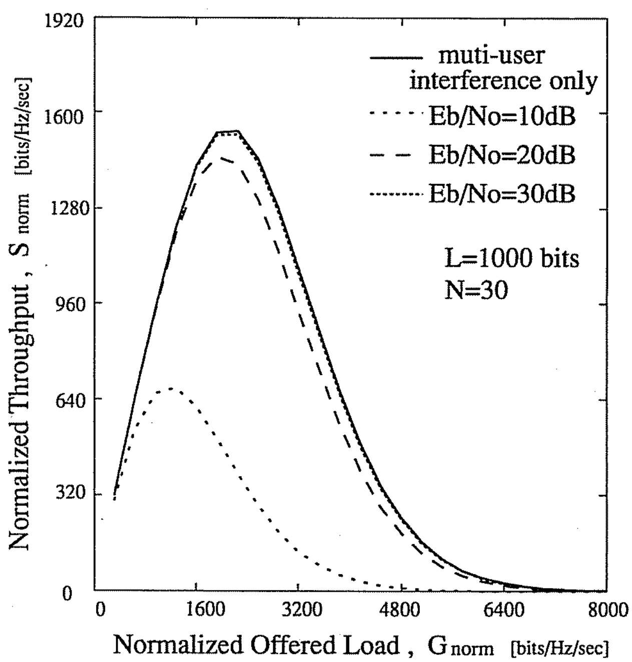


Fig. 7. Throughput performance as a parameter of $E_b/N_0$.

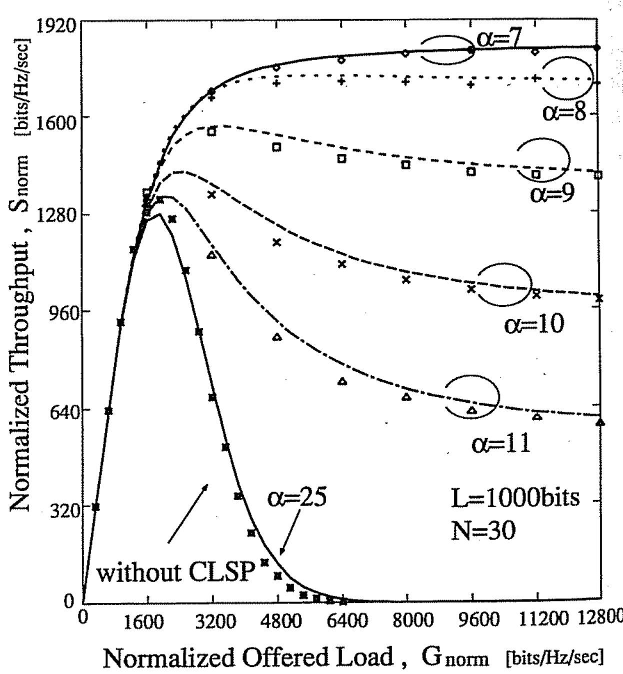


Fig. 9. Simulation and numerical results of CLSP ($\alpha \geq 7$).

threshold $\alpha$. The effect of Gaussian noise is neglected in the figures, $E_b/N_0 = \infty$. The comparison between simulation and theory proves the validity of our analysis.

Figure 8 depicts the simulation and numerical results of CLSP for the case of $\alpha \leq 8$. At the low offered load ($G_{\text{norm}} \leq 3$), as the number of packets on the server hardly reaches the threshold and the effect of CLSP is neglible, the throughput curves act like those of the system without CLSP. At the medium offered load ($3 \leq G_{\text{norm}} \leq 8$), some packets may be rejected due to CLSP even though the channel is able to support additional transmissions. This is the case of $\alpha \leq 5$; however, the throughput improvements can be found for $\alpha > 5$. This implies that there exists an optimum threshold value. At the high offered load ($G_{\text{norm}} > 8$), as CLSP may decrease the effect of multiple access interference, we can get better throughput than that of the system without CLSP. As $G_{\text{norm}}$ goes to $\infty$, a value of throughput reaches to an asymptotic limit.

Figure 9 shows the evaluations of the throughput at $\alpha \geq 7$. As $\alpha$ increases, additive transmissions are allowed and the

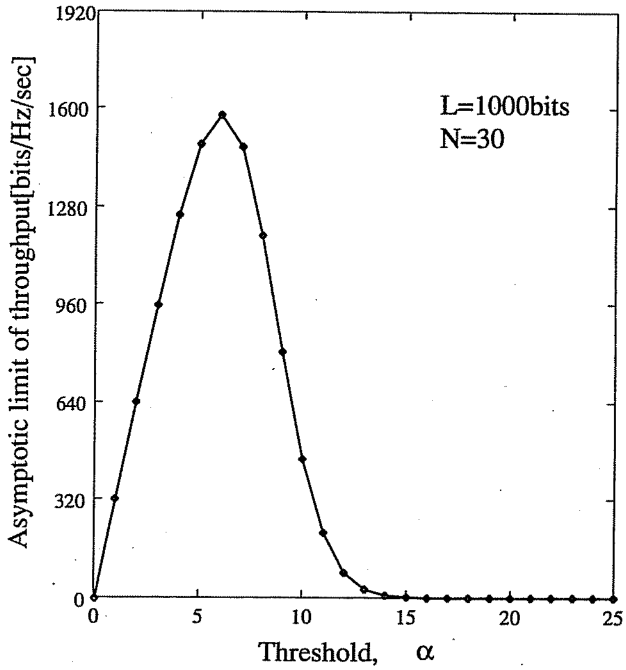


Fig. 10. The asymptotic limit versus threshold $\alpha$.

effect of interference becomes stronger. As a result, once the system reaches the maximum throughput, it decreases and then reaches to the asymptotic limit. Therefore, the asymptotic limit is smaller than its own maximum throughput. Moreover, for the case of $\alpha = 25$, the throughput performance is almost the same as that of the system without CLSP and we can hardly find the performance improvement by CLSP. From Figs. 8 and 9, the optimum throughput is performed with $\alpha = 7$. Now let us consider the asymptotic limit of the throughput. It is clear that as $G_{\text{norm}}$ goes to $\infty$, a value of throughput reaches to the asymptotic limit and the number of simultaneous transmissions is always threshold $\alpha$ under CLSP. Let $S_{G_{\text{norm}} \to \infty}$ be the asymptotic limit, which is expressed as

$$S_{G_{\text{norm}} \to \infty} = \alpha \cdot (1 - P_b(\alpha - 1))^L \tag{24}$$

where $P_b(*)$ is the bit error probability obtained by (1) and $L$ is the packet length.

Figure 10 shows the asymptotic limit versus the threshold $\alpha$. From the figure, we observe that the maximum throughput can be obtained by setting $\alpha = 7$ and it agrees with the results that are yielded by Figs. 8 and 9.

The performance of CLSP has already been analyzed by the $\beta$-channel model [2], [8], [9]. $\beta$ corresponds to the maximum number of the packets that can be transmitted simultaneously. It has been concluded that the maximum throughput performance is yielded by setting $\alpha = \beta$. Although the $\beta$-channel model is useful to evaluate the performance of the protocol such as CLSP, it is not clear that how to determine the value of $\beta$. As the relation of the maximum throughput performance and the threshold of CLSP is obtained by (24), our analysis bridges the gap between $\beta$-channel model and the more realistic model in evaluating the performance of DS/SSMA-unslotted ALOHA with CLSP.

## V. Conclusion

Throughput analysis of DS/SSMA-unslotted ALOHA with fixed packet length has been analyzed by nonperfect capture. On the assumption that packet generation is Poisson, the system can be thought as the queueing system$M/D/\infty$. And with Gaussian approximation of multi-user interference, we have obtained the throughput as the function of the number of chips in a bit, the packet length, and the offered load of the system. Furthermore, using the method of the analysis, we have analyzed the throughput performance of DS/SSMA-unslotted ALOHA with CLSP. We have obtained the asymptotic limit of the throughput and the optimum threshold of CLSP by (24). As the optimum threshold can be considered as the maximum number of simultaneous transmission of packets, we conclude that our analysis bridges the gap between the $\beta$-channel model and more realistic model in evaluating the performance of DS/SSMA-unslotted ALOHA with CLSP.

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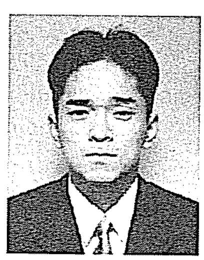

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His current research interests include the packet radio and spread-spectrum radio networks.

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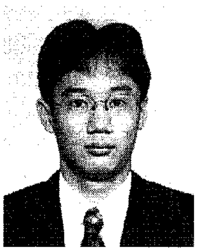

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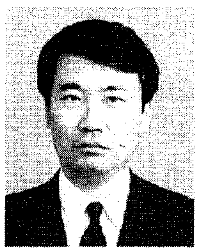

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