Performance Analysis of a DS/SSMA Unslotted ALOHA System With Two User Classes

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***Abstract*—In this paper, we propose a direct-sequence spread spectrum multiple access (DS/SSMA) unslotted ALOHA system with two user classes and analyze the throughput of the proposed system. Mobile stations (MSs) are divided into two classes according to its priority or traffic characteristics such as delay-intolerant and delay-tolerant. Different permission probabilities are assigned to each class so that the appropriate quality of service can be provided. We assume that the generation of class 1 and 2 messages are Poisson distributed and the message is divided into several packets before transmission. The system is modeled as a two-dimensional Markov chain under the assumption that the number of packets transmitted immediately by both user classes is geometrically distributed and the packet length is constant. We calculate the packet success probability and the throughput as a function of the signal-to-noise ratio (SNR) during packet transmission, considering the number of overlapped class 1 and 2 messages and the amount of their time overlap. Moreover, we show that the proposed system differentiates user messages according to class and maintains a high throughput even under heavy traffic conditions using access control based on the channel load.**

***Index Terms*—Access control, service class, throughput, unslotted ALOHA.**

I. INTRODUCTION

RECENTLY, the code division multiple access (CDMA) method has attracted a great deal of attention among many multiple access techniques since its capacity is greater than other access techniques in cellular systems [1]. Present CDMA-based cellular systems have primarily been optimized for voice transmission. Wireless systems, however, must support multimedia services with a variety of quality-of-service requirements since the needs of data services, such as Internet web services, have experienced an exponential rate of increase in wireless mobile communication systems.

Many researches have been directed at accommodating voice and data users in DS/SSMA ALOHA based systems [2]–[6]. However, most studies have been restricted to slotted systems. In a DS/SSMA slotted ALOHA system, packet transmission is initiated only at the beginning of a slot and the success of packet transmission depends on the amount of user interference within a slot. However, a packet in a DS/SSMA unslotted ALOHA system can be transmitted at any time. Hence, in the unslotted system, the level of user interference fluctuates during packet transmission. Because of this fluctuation, analysis of unslotted systems is more difficult compared with slotted systems.

In a DS/SSMA unslotted ALOHA system, packet collisions occur when at least two packets are using the same spreading sequence and are starting at the same chip time. Although all users share the same spreading sequence, if there are sufficient time offsets among packets received at the hub station, the hub station can successfully distinguish packets [7]. This is possible because time-shifted signals using the same spreading code appear as components of a multipath channel output at the hub station [8], [9]. An example of receiver structures of an unslotted system is presented in [8] (see Fig. 1). The spread-spectrum receiver operates with a code-matched filter, a chip-rate sampler, and a following processor for envelope header detection as well as differential data demodulation. The processor includes a correlator that acts as a digital filter matched to a common header sequence with good correlation properties. The transmitted packet consists of a common header and information field, which contains addresses (source and destination address) and real data.

Both unslotted and slotted systems can use a common spreading code or different codes. In a slotted system with common code, only one user can successfully transmit a packet during a slot duration while in a slotted system with multiple codes, one more users can successfully transmit packets during a slot duration—up to the number of code channels. However, in an unslotted system, the erroneous reception is caused by the autocorrelation properties of the code. DS/SSMA unslotted ALOHA systems may sometimes be preferable to slotted systems from three viewpoints, as follows:

1) The throughput difference between two systems is so small that it may be neglected under the assumption that packet collisions only occur due to multiple access interference and channel noise (additive white Gaussian noise) (AWGN) [10], [11]. This assumption includes that the hub station in the slotted system assigns a different spreading sequence for each user. Generally, there is a $2:1$ capacity difference (i.e., 0.368 versus 0.184) between slotted and unslotted narrowband ALOHA systems. However, in the DS/SSMA slotted ALOHA system, the throughput performance is not improved compared with the unslotted system since the probability of successful transmission of packets in a DS/SSMA ALOHA system depends only on the number of interfering packets.
2) For packet generation, an MS in a slotted system always waits until the beginning of the next slot. However, an

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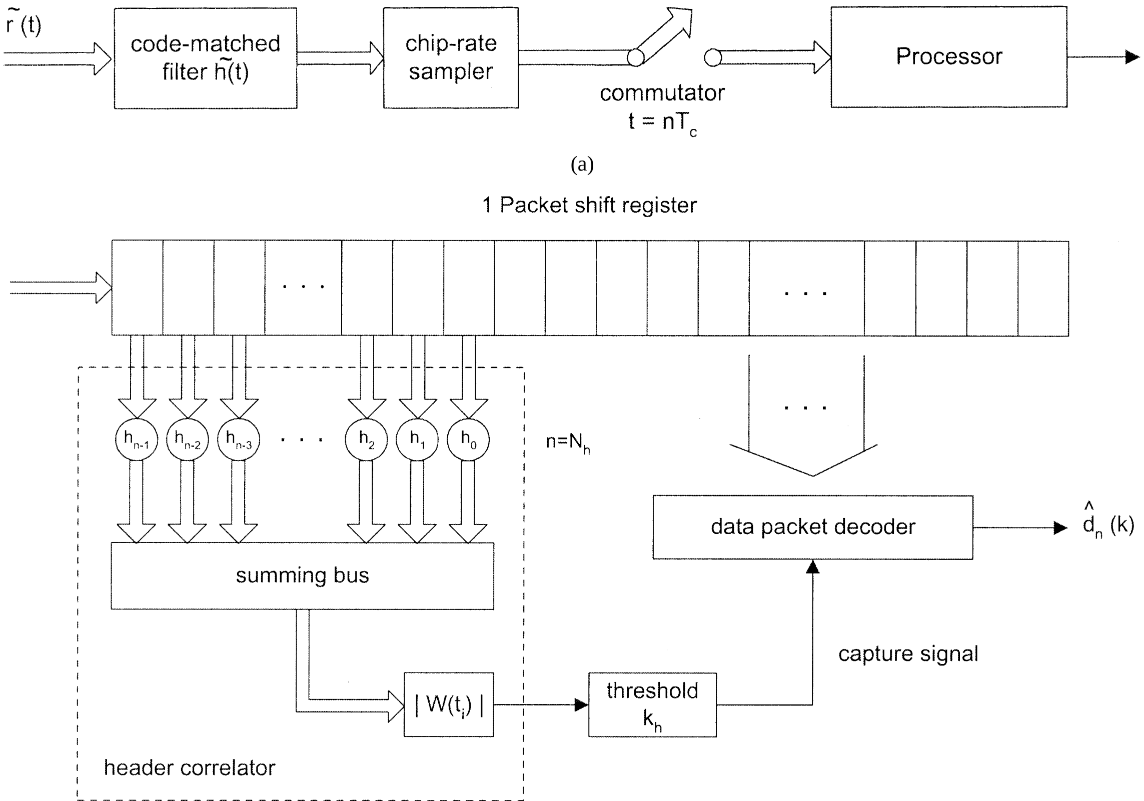

(b)

Fig. 1. Receiver block diagram. (a) Central receiver block diagram. (b) Realization of the processor.

MS in the unslotted system does not wait but transmits a packet at any time.

3) The unslotted ALOHA system may be preferable to the slotted ALOHA system because of the pure ALOHA-like implementation complexity and robustness advantages associated with completely uncoordinated channel access [12].

There are two reasons for errors in a received packet at a hub station in a DS/SSMA ALOHA system under the assumption of perfect power control [13]. First, a primary collision occurs when two or more users simultaneously transmit packets using the same spreading sequence. The packets involved in this primary collision will be lost and must be retransmitted. Note that, in the unslotted system, the probability that two or more users transmit packets at the same time (chip time) is very low and, therefore, the autocorrelation properties of the code determine whether a collision does or does not lead to erroneous reception. However, in the slotted system, the collision probability depends on the number of available codes and the offered load. A slotted system with multiple codes permits more successful transmission per slot–up to the number of codes. Also, in the slotted system, the collision probability increases as the offered load increases since packet transmission is initiated only at the beginning of a slot. The second reason for errors in received packets is interference from other users transmitting packets. The transmitted packet experiences multiple access interference and can suffer packet errors as a result.

A comparison of the slotted and unslotted schemes in a DS/SSMA ALOHA system considering primary collisions is presented in [14]. They investigated the performance of the slotte/unslotted system for a network consisting of a single base station and K mobile terminals sharing K_s spreading sequences, where users randomly choose a spreading code among K_s spreading sequences for transmission. In [14], packet bit errors was caused only by primary collisions and the effect of multiple interference was not taken into account. Since in a spread spectrum unslotted ALOHA system, the probability of multiple users transmitting packets at the same time is small, research results show that the unslotted system provides better delay and throughput performance than a slotted system. In [10], a comparison of two schemes is presented considering the effect of multiple access interference. They showed that the throughput are almost the same between DS/SSMA unslotted ALOHA systems and DS/SSMA slotted ALOHA systems.

In this paper, we propose a DS/SSMA unslotted ALOHA system with two user classes and analyze the throughput of the proposed system. We introduce an access control scheme based on channel load (the number of simultaneous transmissions). The hub station observes the channel load continuously for a certain period of time and estimates the average offered load. The hub station controls MSs access based on the estimated offered load and, therefore, the system offered load is always less than the allowable maximum offered load. Hence, the proposed system can maintain a high throughput even at high loading condition. In order to clarify the effect of access control, we analyze the throughput and evaluate the performance of a DS/SSMA unslotted ALOHA system with access control. This paper is organized as follows. In Section II, a system model is presented. The permission probability of each class is derived in Section III. In Section IV, a system analysis in view of the packet success probability and the throughput is described. In Section V, numerical results are provided, and concluding remarks are presented in Section VI.

II. System Description

To evaluate the throughput performance of a DS/SSMA unslotted ALOHA system with two user classes, we consider a single-hop spread spectrum packet radio network with the following assumptions.

1) The packet radio network consists of an infinite number of independent MSs and a hub station. A system to support two user classes is considered to have the following properties.
   - *Class 1:* The users of this class request priority service and they are delay intolerant. An example data message of this class would be a packet voice or an emergency data message.
   - *Class 2:* The users of this class are satisfied with best effort service. They are delay tolerant. Data messages of this class would be generated by electronic mail or a file transfer service.

   Class 1 and 2 messages are generated by a Poisson distribution with arrival rates of Λ_1 [messages/sec] and Λ_2 [messages/s], respectively. Generated messages are divided into packets. The number of packets in a message of each class is geometrically distributed with a mean of $\overline{B_1}$ for class 1 and $\overline{B_2}$ for class 2. The packet length is fixed to be L bits.
2) All MSs share the same spreading code and each MS transmits a message at any bit. Although the same spreading code is shared, the hub station can receive the message by properly resolving signals overlapped with random arrival times if there are sufficient time offsets among the received messages. Therefore, this assumption is equivalent to the case that each MS communicates with the hub station with a uniquely assigned spreading code if the probability that two or more users simultaneously transmit messages is almost zero, the hub station can distinguish the received messages, and the interference due to the correlation property of the spreading code is neglected.
3) Every transmitted message is received with equal power.
4) Bit errors in a packet are caused by the effect of multiple access interference and AWGN. In this paper, we consider an interference limited system and, therefore, the effect of AWGN is neglected. The bit error probability of chip synchronized DS/SSMA systems sharing the same spreading code is expressed as

$$P_b(k) = Q\left(\sqrt{\frac{2N}{k}}\right) \tag{1}$$

where N is the number of chips per bit, k is the number of interfering messages, and $Q(x)$ is given by

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

The derivation of (1) is given in the Appendix .

III. Access Control Algorithm

A. Derivation of Permission Probability

The hub station observes the offered loads of class 1 and 2 users for a certain period. The hub station calculates the permission probability $P_{tr,i}$ of class i users based on the observed offered load of class i users, then broadcasts the permission probability to MSs. An MS transmits a message with probability $P_{tr,1}$ or $P_{tr,2}$ or stops message transmission with probability $1-P_{tr,1}$ or $1-P_{tr,2}$ according to the class. The offered load G usually varies slowly and therefore the offered load can be regarded as constant during the time period for the access procedure [11]. Taking account of this fact, we can estimate the offered load G_i of class i users based on the channel load of each class measured during the observation time period T_s. Using the estimated offered load g_i, we calculate the permission probability $P_{tr,i}$ of class i users. To achieve maximum system throughput, the total offered load must always be less than $G_{\max}$, which is the total offered load giving the maximum system throughput in a DS/SSMA unslotted ALOHA system. Hence, the permission probabilities are derived as follows:

$$P_{tr,1} = \begin{cases} 1, & \text{if } g_1+g_2 \le G_{\max} \\ \frac{(G_{\max}-P_{tr,2}\cdot g_2)}{g_1}, & \text{if } g_1+g_2 > G_{\max} \end{cases} \tag{3}$$

$$P_{tr,2} = \begin{cases} 1, & \text{if } g_1+g_2 \le G_{\max} \\ \frac{(G_{\max}-P_{tr,1}\cdot g_1)}{g_2}, & \text{if } g_1+g_2 > G_{\max} \end{cases} \tag{4}$$

where g_i is the estimated offered load of class i users. These equations indicate that if the estimated total offered load $g = g_1+g_2$ exceeds $G_{\max}$, then an MS will transmit a message with the permission probability $P_{tr,1}$ or $P_{tr,2}$ according to its class. Otherwise, the message will be immediately transmitted upon request.

To give priority to class 1 users, as the estimated total offered load g increases to a value greater than $G_{\max}$, the hub station immediately controls the transmission of class 2 users and gradually controls the transmission of class 1 users. Hence, the (4) deriving permission probabilities is modified as follows:

$$P_{tr,1} = \begin{cases} 1, & \text{if } g_1 \le G_{\max} \\ \frac{G_{\max}}{g_1}, & \text{if } g_1 > G_{\max} \end{cases} \tag{5}$$

$$P_{tr,2} = \begin{cases} 1, & \text{if } g_1+g_2 \le G_{\max} \text{ and } g_1 \le G_{\max} \\ \frac{(G_{\max}-g_1)}{g_2}, & \text{if } g_1+g_2 > G_{\max} \text{ and } g_1 \le G_{\max} \\ 0, & \text{if } g_1+g_2 > G_{\max} \text{ and } g_1 > G_{\max}\,. \end{cases} \tag{6}$$

In practice, we must deal with the problem of how to estimate the offered load of each class. To solve this problem, each message has an information bit for its class. The hub station observes the offered load of each class using this information bit. If the hub station observes the offered load of each user class for a long period of time, the estimated offered load g_i of class i

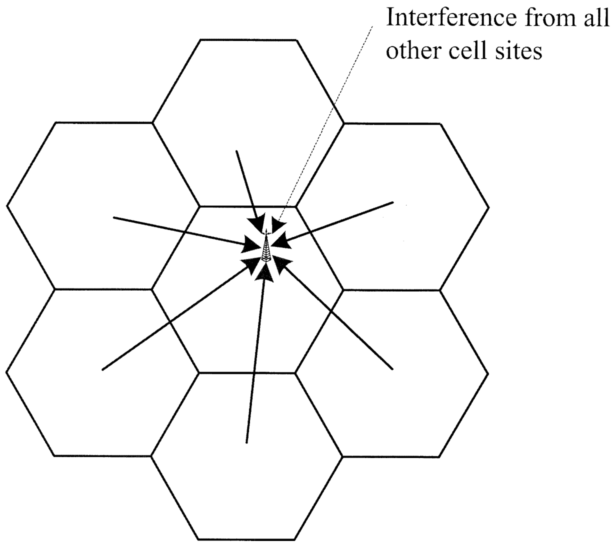

Fig. 2. Multicell geometry.

users is approximated to the real offered load G_i of class i users; that is, $g_i \approx G_i$ since G_i usually varies slowly [11].

The total offered load G, defined as the average number of generated packets within a packet duration, can be expressed as the sum of the offered loads of class 1 and 2 users

$$G = P_{tr,1} \cdot G_1 + P_{tr,2} \cdot G_2 \tag{7}$$

where $P_{tr,i}$ is the permission probability of class i users and the offered load G_i of class i users is calculated as follows:

$$G_i = \Lambda_i \cdot T_p \cdot \overline{B_i} \tag{8}$$

where T_p is a packet duration (i.e., $T_p = L/R$), L [bits] is the length of a packet, and R [bits/s] is the data rate. The value $\overline{B_i}$ is the average number of several continuous packets transmitted immediately by a class i user. Since we assume that B_i, the number of continuous packets transmitted immediately by a class i user, is geometrically distributed with a mean of $\overline{B_i}$, the probability that B_i is x is given by

$$P_x(B_i = x) = p_i \cdot (1 - p_i)^{x-1}, \quad p_i = \frac{1}{\overline{B_i}}. \tag{9}$$

We assume that the number of several continuous packets transmitted immediately by a class i user is less than or equal to $B_{MAX,i}$.

B. $G_{\max}$ in Multicell System

In the single-cell system, only single-cell interference (same-cell interference) is considered for the calculation of $G_{\max}$. However, in a multicell system, both the same cell and other-cell interference are considered for calculation of $G_{\max}$, as shown in Fig. 2.

In [1], other-cell interference in the multicell system was calculated under the following assumptions:

- each user in the cell communicates with the hub station with different codes;
- mobile unit is perfectly power controlled by the nearest hub station;
- path loss between the MS and the hub station is only described as a function of distance; therefore, the path loss is proportional to $10^{(\xi/10)}d^{-4}$, where d is the distance from the MS to the cell site and ξ is a Gaussian random variable with a standard deviation of $\sigma_\xi = 8$ and a zero mean;
- distribution of users across the cell is uniform; also, there are N_c users per cell who are equal to $3N_s$ where N_s is the number of users per sector, considering a system with three sectors.

Under above assumptions, when only voice traffic is considered and the activity factor of users is 3/8, the average of the total other-cell user interference-to-signal ratio is [1]

$$E\left(\frac{I}{S}\right) \le 0.247 N_s \tag{10}$$

where N_s is the number of users per sector.

In the unslotted system with two user classes, let the signal power of two message classes be equal. Then, under the assumption that users within the target cell use the same code and all the users in the adjacent cell use different codes, the maximum offered load $G_{\max,m}$ in the multicell system is recalculated from (10) as follows:

$$\begin{aligned} G_{\max,m} &= G_{\max,s} - 0.247 \cdot \frac{1}{3} \cdot \frac{8}{3} \cdot G_{\text{cell}} \\ &= G_{\max,s} - 0.220 \cdot G_{\text{cell}} \end{aligned} \tag{11}$$

where G_{cell} is the total offered load per cell and $G_{\max,s}$ is the maximum offered load in the target single-cell system. Although a single-cell system is considered in this paper, this analysis can be applied to a multicell system using $G_{\max,m}$ instead of the $G_{\max}$ value of a single-cell system, where $G_{\max,m}$ is calculated by (11).

If all the users in the adjacent cells as well as in the target cell use the same spreading code, the other-cell interference should be recalculated since the interferences from users in adjacent cells may become highly correlated. Generally, the use of a common channel in a cell instead of the use of packet channels with different codes results in a simplicity of the hub station but in view of throughput, improvements may be expected with multiple packet channels with different codes since two packets employing different codes are less likely to result in a collision requiring retransmission. However, in this paper, we consider only the effect of multi-user interference. That is, we assume that there is no primary collision which occurs when two or more users simultaneously start packet transmission. That is, only interference from other users (multiple access interference) causes the errors in the received packets. This assumption is equivalent to the case that each MS communicates with the hub station by using a different code and therefore we may use the (11) for a multicell system.

IV. Throughput Analysis

A. Transition of the Number of Interfering Messages

We analyze the throughput of a DS/SSMA unslotted ALOHA system under a single-cell system where the interference level varies during message transmission because MSs attempt to transmit messages at any bit. To evaluate the packet success

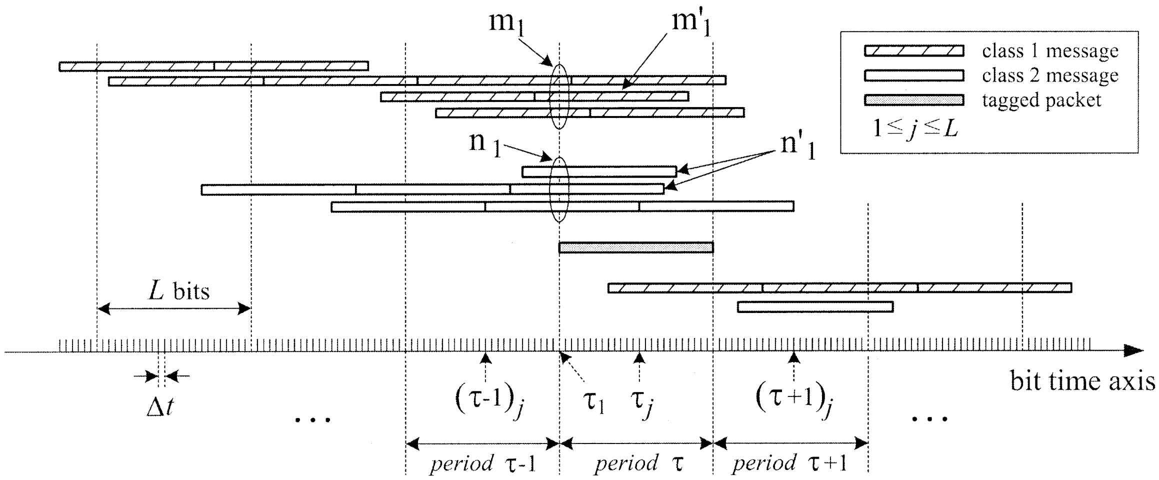

Fig. 3. Fluctuation of interference levels during tagged packet transmission.

probability such that there are no bit errors in the packet received at the hub station, we suppose a "tagged" packet, as shown in Fig. 3 and, for simplicity, arrange other messages in order. This figure shows that the number of class 1 and 2 interfering messages varies during transmission of the tagged packet. Because generation of class i messages is assumed to be Poisson distributed with an arrival rate of Λ_i, the probability $P_{0,i}(k)$ that k messages are transmitted during the packet duration T_p by class i users is given by

$$\begin{aligned} P_{0,i}(k) \equiv &\Pr(k \text{ messages are transmitted during } T_p \\ &\text{by class } i \text{ users}) \\ =&\frac{(\Lambda_i T_p)^k}{k!} e^{-\Lambda_i T_p}. \end{aligned} \tag{12}$$

Let the number of class 1 and 2 interfering messages be m_1 and n_1, respectively, at the beginning of transmission of the tagged packet. Now, we evaluate the probability $\Pr(\ (m_1, n_1) \text{ messages } \mid \text{ at time } \tau_1)$ that m_1 class 1 and n_1 class 2 messages are observed at time τ_1, as shown in Fig. 3. First, we calculate the probability $\Pr_i(k_1 \text{ messages} \mid \text{at time } \tau_1)$ that k_1 class i messages are observed at time τ_1. Here, we define index sets as follows.

- Let index set $T = \{\ldots, (\tau-1)_j, \tau_j, (\tau+1)_j, \ldots \mid j = 1, 2, \ldots, L\}$ denote the bit time axis where the interval between τ_j and $(\tau+1)_j$ is the packet duration T_p, which is equivalent to L bits. Also, let the interval $[\tau_1, (\tau+1)_1)$ be "period τ."
- Consider an index set $\mathcal{A}_i = \{a_1, a_2, \ldots, a_y, \ldots\}$. When observed at time τ_1, the y labeled arrival a_y is the number of class i messages that enter the hub station in the period $(\tau - y)$ and departs after time τ_1. The symbol y denotes the length of message; that is, the number of packets in a message.

Then

$$\begin{aligned} &\Pr_i(a_y \mid \text{at time } \tau_1) \\ &\quad \equiv \Pr(\text{At time } \tau_1, \text{ the number of class } i \text{ messages} \\ &\qquad \text{which enter into period } (\tau-y) \text{ and} \\ &\qquad \text{depart after time } \tau_1, = a_y) \\ &\quad = \sum_{k=a_y}^{\infty} \Pr((a_y \mid \text{at time } \tau_1), k \text{ class } i \text{ messages} \\ &\qquad \text{arrive during period } (\tau - y)) \\ &\qquad \cdot \Pr(k \text{ class } i \text{ messages arrive during period } (\tau-y)) \\ &\quad = \sum_{k=a_y}^{\infty} \binom{k}{a_y} \cdot P_x(B_i \geq y)^{a_y} \\ &\qquad \cdot (1 - P_x(B_i \geq y))^{k-a_y} \cdot P_{0,i}(k) \end{aligned} \tag{13}$$

where $P_x(B_i \geq y)$, which is the probability that the number of continuous packets transmitted immediately by a class i user is more than equal to y, is calculated as follows:

$$\begin{aligned} P_x(B_i \geq y) &= \sum_{x=y}^{\infty} p_i \cdot (1-p_i)^{x-1} \\ &= (1-p_i)^{y-1}, \text{ for } y \geq 1. \end{aligned} \tag{14}$$

For (13), the following items can be applied:

1) for class i, the k messages arrive during the period $(\tau - y)$ and depart after the beginning of period τ (after time τ_1);
2) only a_y messages among k messages are observed at time τ_1.

We define a probability $\Pr(\mathcal{A}_i \mid \text{at time } \tau_1)$ as the probability that the number of class i messages that enter into $\{\text{period } \tau-1, \text{ period } \tau-2, \ldots, \text{ period } \tau-y, \ldots\}$ and depart from the channel after time τ_1 is equal to $\{a_1, a_2, \ldots, a_y, \ldots\}$. As message arrivals are independently generated, the probability $\Pr(\mathcal{A}_i \mid \text{at time } \tau_1)$ is obtained by multiplication of each $\Pr_i(a_y \mid \text{at time } \tau_1)$ as follows:

$$\begin{aligned} \Pr_i(\mathcal{A}_i \mid \text{at time } \tau_1) &= \Pr_i(a_1, a_2, \ldots, a_y, \ldots \mid \text{at time } \tau_1) \\ &= \prod_{y=1}^{B_{MAX,i}} \Pr_i(a_y \mid \text{at time } \tau_1). \end{aligned} \tag{15}$$

Accordingly, the probability $\Pr_i(k_1 \text{ messages} \mid \text{at time } \tau_1)$ that k_1 class i messages are observed at time τ_1 is given by

$$\begin{aligned} &\Pr_i(k_1 \text{ messages} \mid \text{at time } \tau_1) \\ &\quad \equiv \Pr(\text{At time } \tau_1, \text{ the number of class } i \text{ messages} = k_1) \end{aligned}$$

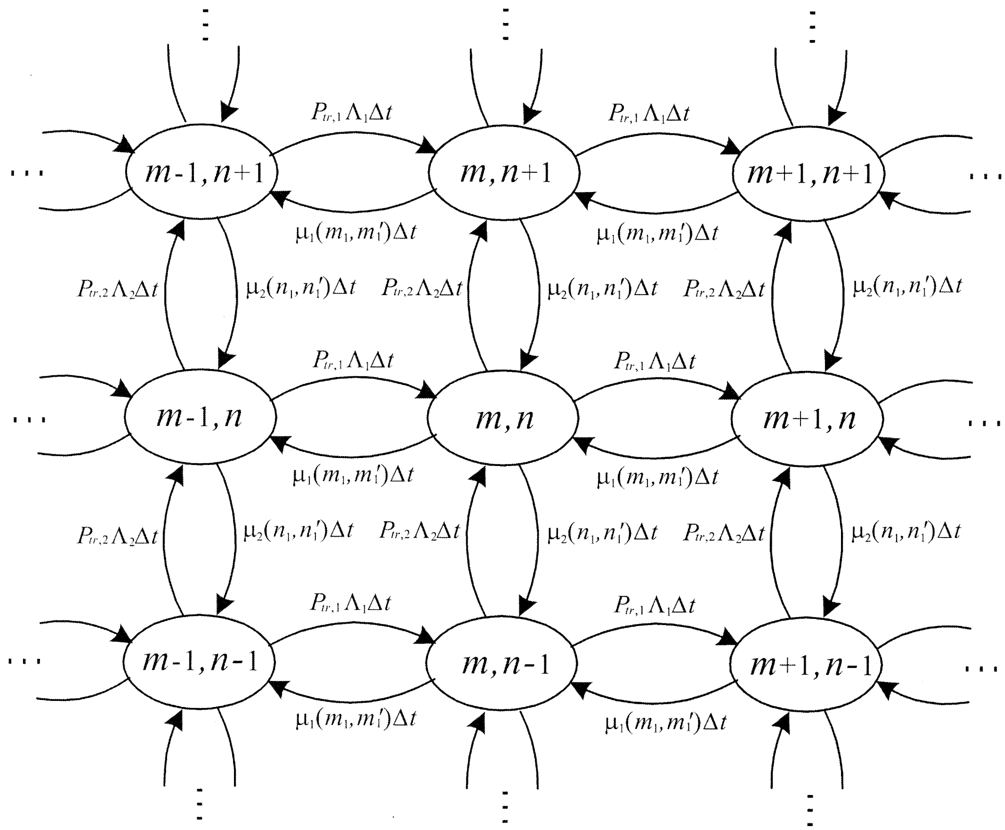

Fig. 4. State transition of the number of interfering messages.

$$
\begin{aligned}
&= \sum_{\mathcal{U}_i} \Pr(\mathcal{A}_i \mid \text{at time } \tau_1) \\
&\equiv P_{T,i}(k_1)
\end{aligned} \tag{16}
$$

where $\mathcal{U}_i$ is the set $\{\forall a_y \in \mathcal{A}_i \mid \sum_{y=1}^{B_{MAX,i}} a_y = k_1,\ a_y \geq 0\}$.

As class 1 and 2 messages are independently generated, the joint probability $\Pr(\ (m_1, n_1) \text{ messages} \mid \text{at time } \tau_1)$ that m_1 class 1 and n_1 class 2 messages are observed at time τ_1 is obtained by multiplication of $\Pr_1(m_1 \text{ messages} \mid \text{at time } \tau_1)$ and $\Pr_2(n_1 \text{ messages} \mid \text{at time } \tau_1)$.

$$
\begin{aligned}
\Pr(&(m_1, n_1) \text{ messages} \mid \text{at time } \tau_1) \\
&= P_{T,1}(m_1) \cdot P_{T,2}(n_1) \\
&\equiv P_T(m_1, n_1).
\end{aligned} \tag{17}
$$

When the system state is defined as the number of interfering messages of each class, we consider the state transition during the transmission of the tagged packet. Let the number of interfering messages at the jth bit of the tagged packet be (m_j, n_j), where m_j and n_j are the number of class 1 and 2 messages at the jth bit, respectively. Then, under the assumption that the bit duration is small, the number of interfering messages, 1) increases to $(m_j + 1, n_j)$ or $(m_j, n_j + 1)$, 2) decreases to $(m_j - 1, n_j)$ or $(m_j, n_j - 1)$, 3) remains the same during bit timing since the interference level varies bit by bit during tagged packet transmission. If the bit duration Δt is small, then the system can be modeled as a two-dimensional Markov chain, as shown in Fig. 4.

Let (m_1, n_1) be the number of messages at the first bit of the tagged packet. If (m_1', n_1') messages among (m_1, n_1) depart during the packet duration T_p, as shown in Fig. 3, the average service times of m_1' and n_1' messages are T_p/m_1' and T_p/n_1', respectively. Therefore, the death rates of class 1 and 2 messages are derived as [15]

$$
\mu_1(m_1, m_1') = \frac{m_1'}{T_p} \text{ and } \mu_2(n_1, n_1') = \frac{n_1'}{T_p}. \tag{18}
$$

Also, the birth rate Λ_i of class i messages is obtained by (8) as follows:

$$
\Lambda_i = \frac{G_i}{T_p \cdot \overline{B_i}} \approx \frac{g_i}{T_p \cdot \overline{B_i}} \tag{19}
$$

where G_i is the real offered load of class i users and g_i is the estimated offered load of class i users. The hub station continuously observes the offered load as well as the message length of class i users and estimates G_i and B_i. Then, the hub station calculates the the birth rate Λ_i from observed parameters g_i and B_i.

Accordingly, the conditional state transition probability from $(j-1)$th bits to jth bits is given by (20), shown at the bottom of the next page.

B. Derivation of Packet Success Probability

To calculate the packet success probability, we define a function $f_j(m_j, n_j, m_1, n_1, m_1', n_1')$ as follows [15], [16]:

1) the function $f_j(m_j, n_j, m_1, n_1, m_1', n_1')$ is the probability that the tagged packet is successfully transmitted from the first bit to the $(j-1)$ th bit, where m_j and n_j are the number of interfering class 1 and 2 messages at the jth bit, respectively.

2) The values m_1' and n_1' are the number of messages that depart during the packet duration T_p among m_1 and n_1 messages, respectively, when the level of interference at the first bit is (m_1, n_1).

We evaluate the function $f_j(m_j, n_j, m_1, n_1, m_1', n_1')$ recursively based on the Markovian property of m_j and n_j. For $j = 1$, $f_j(m_j, n_j, m_1, n_1, m_1', n_1')$ is equal to $\Pr(m_1, n_1, m_1', n_1')$, which is the probability that m_1' messages depart during the packet duration T_p among m_1 messages and n_1' messages depart in the same duration among n_1 messages when the level of interference at the first bit is (m_1, n_1). Hence, we have

$$\begin{aligned} f_j(m_j,&n_j, m_1, n_1, m_1', n_1') \\ &= \Pr(m_1, n_1, m_1', n_1') \\ &= \Pr(m_1, m_1') \cdot \Pr(n_1, n_1') \\ &= P_{T,1}(m_1) P(m_1'|m_1) \cdot P_{T,2}(n_1) P(n_1'|n_1) \\ &= P_{T,1}(m_1) \binom{m_1}{m_1'} \left(\frac{P(B_1 = y)}{P(B_1 \geq y)}\right)^{m_1'} \\ &\quad \cdot \left(1 - \frac{P(B_1 = y)}{P(B_1 \geq y)}\right)^{m_1 - m_1'} \cdot P_{T,2}(n_1) \binom{n_1}{n_1'} \\ &\quad \cdot \left(\frac{P(B_2 = y)}{P(B_2 \geq y)}\right)^{n_1'} \left(1 - \frac{P(B_2 = y)}{P(B_2 \geq y)}\right)^{n_1 - n_1'} \\ &= P_T(m_1, n_1) \binom{m_1}{m_1'} \binom{n_1}{n_1'} p_1^{m_1'} (1 - p_1)^{m_1 - m_1'} \\ &\quad \cdot p_2^{n_1'} (1 - p_2)^{n_1 - n_1'}, \text{ for } j = 1 \end{aligned} \tag{21}$$

where $P_T(m_1, n_1)$ is obtained by (17).

When j is not the first bit of tagged packet, $f_j(m_j, n_j, m_1, n_1, m_1', n_1')$, the probability that a packet is successfully transmitted from the first bit to the $(j-1)$th bit, becomes the probability that there is no error at the $(j-1)$th bit in a packet successfully transmitted to the $(j-2)$th bit. Hence, $f_j(m_j, n_j, m_1, n_1, m_1', n_1')$ is calculated recursively as (22), shown the bottom of the page.

Using $f_j(m_j, n_j, m_1, n_1, m_1', n_1')$, we calculate the packet success probability Q_s, recursively. Since the packet length L is constant, the packet success probability is calculated by setting $j = L$ as (23), shown at the bottom of the next page.

On the other hand, the system throughput is defined as the average number of successful transmissions during packet duration T_p. Hence, the system throughput S and the throughput S_i of class i users are obtained by

$$\begin{aligned} S &= G \cdot Q_s \\ S_i &= P_{tr,i} \cdot G_i \cdot Q_s. \end{aligned} \tag{24}$$

C. Throughput Analysis of DS/SSMA Slotted ALOHA System

Using the process for deriving the system throughput of a DS/SSMA unslotted ALOHA system, we can also analyze the throughput of a DS/SSMA slotted ALOHA system under the assumptions described in Section II. In addition, we assume that all users transmit messages with a uniquely assigned spreading sequence and, therefore, primary collisions do not occur. Thus, unsuccessful transmissions are caused entirely by multiple access interference. Since the interference level of a slotted system is constant during packet duration, the packet success probability Q_s^s is given by (25), shown at the bottom of the next page, where the probability $Pr^s((m, n)$ messages $|$ at time $\tau_1)$ that there are m class 1 and n class 2 messages at time τ_1 is the same as (17).

$$q(m_j, n_j \mid m_{j-1}, n_{j-1}) = \begin{cases} 1 - P_{tr,1}\Lambda_1 \Delta t - \mu_1(m_1, m_1')\Delta t - P_{tr,2}\Lambda_2 \Delta t - \mu_2(n_1, n_1')\Delta t, & \text{if } m_j = m_{j-1}, n_j = n_{j-1} \\ \mu_1(m_1, m_1')\Delta t, & \text{if } m_j = m_{j-1} - 1, n_j = n_{j-1} \\ P_{tr,1}\Lambda_1 \Delta t, & \text{if } m_j = m_{j-1} + 1, n_j = n_{j-1} \\ \mu_2(n_1, n_1')\Delta t, & \text{if } m_j = m_{j-1}, n_j = n_{j-1} - 1 \\ P_{tr,2}\Lambda_2 \Delta t, & \text{if } m_j = m_{j-1}, n_j = n_{j-1} + 1 \\ 0, & \text{otherwise.} \end{cases} \tag{20}$$

$$\begin{aligned} f_j(m_j, n_j, &m_1, n_1, m_1', n_1') \\ &= \sum_{m_{j-1} = m_j - 1}^{m_j + 1} \sum_{n_{j-1} = n_j - 1}^{n_j + 1} \Big[f_{j-1}(m_{j-1}, n_{j-1}, m_1, n_1, m_1', n_1') \cdot q(m_j, n_j \mid m_{j-1}, n_{j-1}) \cdot \{1 - P_b(m_{j-1} + n_{j-1})\} \Big] \\ &\text{for } j > 1. \end{aligned} \tag{22}$$

$$Q_s = \sum_{m_L=0}^{\infty} \sum_{n_L=0}^{\infty} \sum_{m_1=0}^{\infty} \sum_{n_1=0}^{\infty} \sum_{m_1'=0}^{m_1} \sum_{n_1'=0}^{n_1} \Big[f_L(m_L, n_L, m_1, n_1, m_1', n_1') \cdot \{1 - P_b(m_L + n_L)\} \Big]. \tag{23}$$

TABLE I
SIMULATION PARAMETERS

Item	Symbol	Value
Data rate (kbps)	R	9.6
Spreading factor	N	30
Average number of packets transmitted immediately by a class 1 user	$\overline{B_1}$	7
Average number of packets transmitted immediately by a class 2 user	$\overline{B_2}$	5
Packet length (bits)	L	512

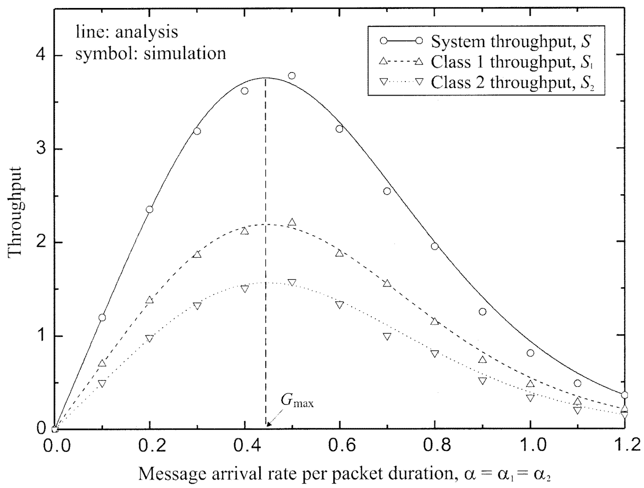

Fig. 5. Throughput versus message arrival rate per packet duration T_p when $\alpha_1 = \alpha_2$.

Under the assumption that the considered slotted system is chip synchronized system, the bit-error probability $P_b^s(\cdot)$ is equal to $P_b(\cdot)$. Therefore, in the slotted system, the system throughput and the throughput of class i users are obtained using Q_s^s instead of Q_s in (24).

V. Numerical and Simulation Results

We compare numerical results with simulation results for an unslotted system with two user classes. Because the number of messages transmitted at the same time may be neglected, we assume that packet bit errors are caused only by multi-user interference. Also, for simplicity, the effect of additive white Gaussian noise is not considered. In this simulation, the data rate is assumed to be 9.6 kbps [17] and the data traffic model of class 1 users is assumed to be a packet voice model with an average message length of 448 bytes [18]. The data traffic model of class 2 users is assumed to have variable length with an average message length of 320 bytes, based on web traffic [19]. The simulation parameters are summarized in Table I.

Figs. 5 and 6 show the system throughput (S) versus the message arrival rate per packet duration ($\alpha = \alpha_1 = \alpha_2$). Here,

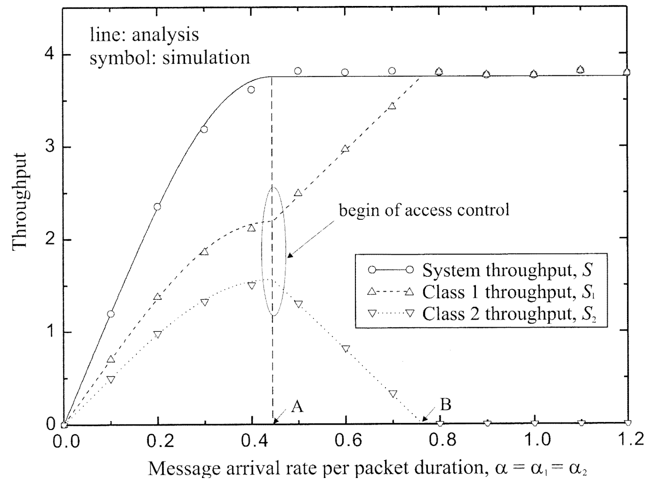

Fig. 6. Throughput versus message arrival rate per packet duration T_p when $\alpha_1 = \alpha_2$ in DS/SSMA unslotted ALOHA system with access control.

the symbol α_i indicates the arrival rate of class i messages per packet duration T_p ($\alpha_i = \Lambda_i \cdot T_p$). When the hub station does not control MSs access, S increases with α, but eventually decreases as α becomes larger. Thus, the system throughput decreases as the total offered load G becomes larger than the maximum allowable offered load $G_{\max}$. The throughput of class 1 users (S_1) is higher than that of class 2 users since the average length of class 1 messages ($\overline{B_1} = 7$) is longer than the average length of class 2 messages ($\overline{B_2} = 5$). When the hub station controls MSs access, the throughput values of class 1 and 2 users are shown in Fig. 6. Since the hub station begins to control MSs transmission at the point *A* where the total offered load becomes $G_{\max}$, the curve is kinked at the point *A*. As the total offered load becomes larger, the hub station suppresses the transmissions of class 2 users so that the total offered load does not become greater than $G_{\max}$. When the offered load of class 1 users becomes $G_{\max}$ (i.e., reaches the point *B*), the hub station controls the transmission of class 1 users and rejects the transmission of class 2 users. The total offered load, therefore, is always less than $G_{\max}$ and the maximum system throughput is maintained even under heavy traffic conditions.

When the arrival rate of class 2 messages is constant ($\alpha_2 = 0.3$), the throughput of class 1 users (S_1) versus the arrival rate of class 1 messages (α_1) is shown in Figs. 7 and 8. As mentioned before, the throughput values of class 1 and 2 users increase with α_1, but eventually decrease as α_1 becomes larger, as shown in Fig. 7. When the hub station controls the offered load, the throughput of class 1 users remains high under heavy traffic conditions, as shown in Fig. 8. As the total offered load becomes larger, the hub station suppresses the transmission of class 2 users at the point *A* where the total offered load becomes $G_{\max}$. The hub station then controls the transmissions of class 2 and

$$Q_s^s = \sum_{m=0}^{\infty}\sum_{n=0}^{\infty}\left[Pr^s((m,n)\text{ messages} \mid \text{at time } \tau_1)\cdot\{1-P_b^s(m+n)\}^L\right] \quad (25)$$

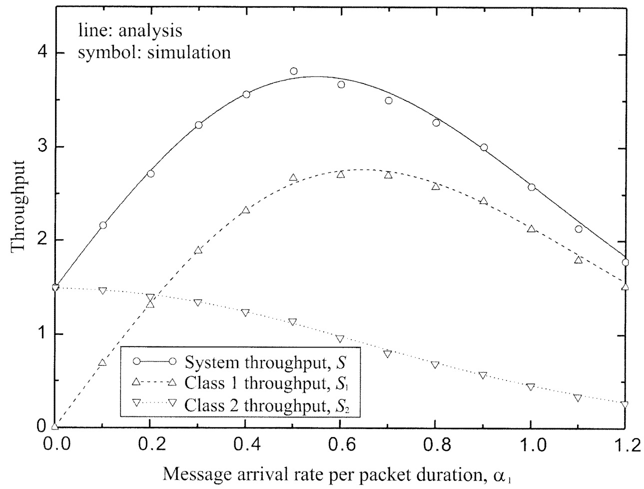

Fig. 7. Throughput versus class 1 message arrival rate per packet duration T_p when $\alpha_2 = 0.3$.

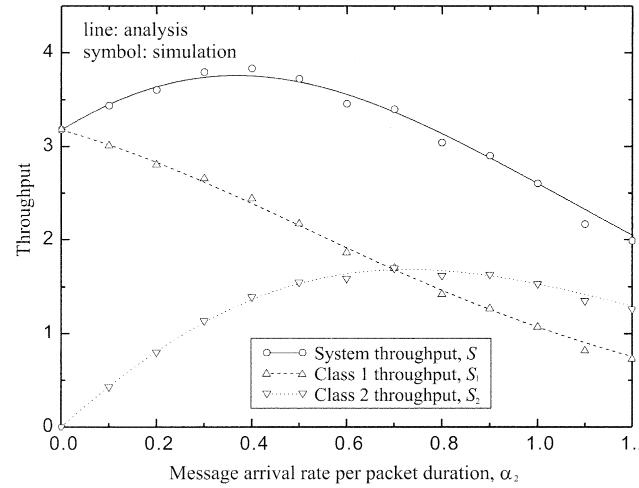

Fig. 9. Throughput versus class 2 message arrival rate per packet duration T_p when $\alpha_1 = 0.5$.

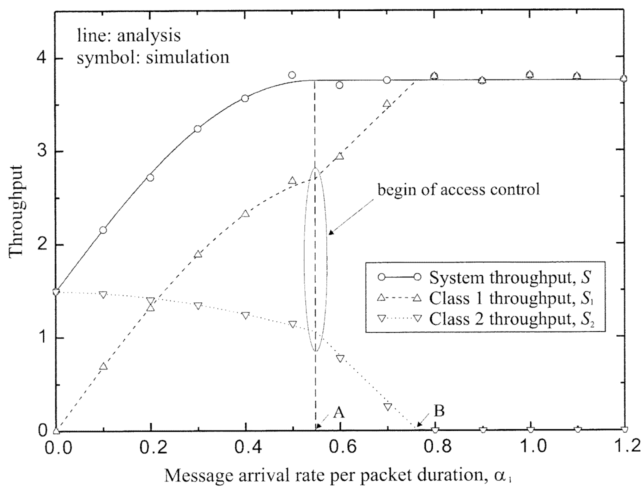

Fig. 8. Throughput versus class 1 message arrival rate per packet duration T_p when $\alpha_2 = 0.3$ in DS/SSMA unslotted ALOHA system with access control.

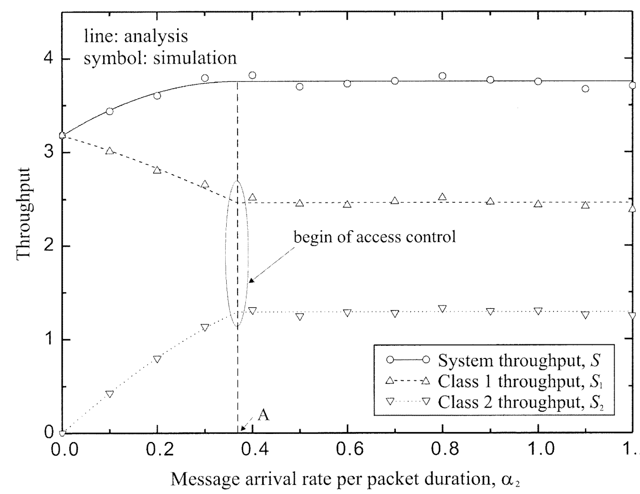

Fig. 10. Throughput versus class 2 message arrival rate per packet duration T_p when $\alpha_1 = 0.5$ in DS/SSMA unslotted ALOHA system with access control.

1 users at the point *B* where the offered load of class 1 users becomes $G_{\max}$.

When the arrival rate of class 1 messages is constant ($\alpha_1 = 0.5$), the throughput of class 2 users (S_2) versus the arrival rate of class 2 messages (α_2) is shown in Figs. 9 and 10. The behavior of throughput values with respect to α_2 is similar to the relationships shown in Figs. 7 and 8. Under heavy traffic conditions, the total throughput decreases as the total offered load becomes greater than $G_{\max}$ when the hub station does not control MSs transmission, as shown in Fig. 9. The throughput of each class, however, remains constant under heavy traffic conditions when the hub station broadcasts the permission probability of each class, as shown in Fig. 10.

We have omitted the analytical results for a DS/SSMA slotted ALOHA system since both numerical and simulation results are similar to the results for a DS/SSMA unslotted ALOHA system [10], [11]. Unsuccessful transmissions in a DS/SSMA slotted ALOHA system are assumed to be caused by multiple access interference. Therefore, system performance depends not on access timing but on the number of interfering messages. Therefore, there is almost no difference between DS/SSMA slotted and unslotted ALOHA systems in view of system performance.

VI. Conclusion

In the near future, many mobile users will require services with different qualities-of-service and the number of them will also dramatically increase. We have proposed a DS/SSMA unslotted ALOHA system with two user classes and analyzed the throughput of the proposed system. An access control scheme based on the channel load of each class is used. As the transmission of each user packet is controlled by the permission probability from the hub station, the proposed system maintains a high throughput even under heavy traffic conditions and differentiates user packets according to class. This system analysis, while limited to two classes herein, can be applied without modification to DS/SSMA unslotted ALOHA systems with multiple classes.

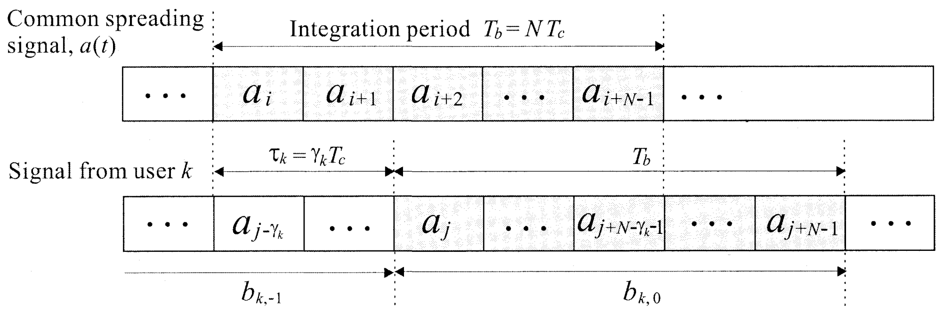

Fig. 11. Timing of the common spreading signal $a(t)$ and the received signal from user k, $s_k(t-\tau_k)$.

APPENDIX
BIT ERROR PROBABILITY IN A SYSTEM SHARING THE SAME SPREADING CODE

We denote multiple access interference (MAI) in the system using the same spreading code and MAI in the system using random code by $U_{ma,s}$ and $U_{ma,r}$, respectively.

In [20], $U_{ma,r}$ was derived. For random codes in the same packet channel, when bit errors are caused by multiple access interference, the bit error probability is expressed as $P_{b,r} = Q(\sqrt{3N/k})$, where N is the number of chips per bit and k is the number of interfering messages. However, $U_{ma,s}$ is more complicated than $U_{ma,r}$ because it is dependent on the adjacent bits, as well as on the assigned signature code and its partial autocorrelation properties. The variance of $U_{ma,r}$ does not depend on the spreading waveform (or spreading sequence) [20], [21]. The variance of $U_{ma,s}$, however, is clearly dependent on the spreading sequence [22]. This dependence on spreading sequence implies that, in order to find the average BER, the conditional BER must be averaged over all possible sequences, which is computationally not feasible.

In a spread-spectrum CDMA using binary signaling and common spreading signal $a(t)$, the received signal at a hub station from the kth MS (assuming no fading or multipath) is given by

$$s_k(t-\tau_k) = \sqrt{2P}\, a(t-\tau_k) b_k(t-\tau_k)\cos(\omega_c t + \phi_k) \quad (26)$$

where $b_k(t)$ is the data signals for user k, τ_k is the delay of user k relative to some reference user 0, P is the received signal power, ω_c is the carrier frequency, and ϕ_k is the phase shifts relative to reference user 0.

There are N chips per data pulse. M is the number of chips sent before the cyclical pseudonoise (PN) sequence repeats itself and MT_c is the repetition period of the PN sequence where T_c is the chip period. The pulse and chip amplitudes are all independent, identically distributed random variables of ± 1 with probability of 1/2. At the receiver, the signal available at the input to the correlator is given by

$$r(t) = \sum_{k=0}^{K-1} s_k(t-\tau_k) + n(t). \quad (27)$$

The decision statistic for user 0 is given by

$$U = \int_0^{T_b} r(t) a(t) \cos(\omega_c t + \phi_k) dt \quad (28)$$

$$= U_s + U_{ma,s} + U_N \quad (29)$$

where T_b is bit period, U_s is the desired contribution to the decision statistic from the desired user ($k = 0$), $U_s \approx \sqrt{P/2}\, b_{k,0} T_b$[23], and U_N is the thermal nose contribution.

$U_{ma,s}$ is the summation of $K-1$ terms, $U_{ma,s} = \sum_{k=1}^{K-1} U_{ma,s}^{(k)}$, where $U_{ma,s}^{(k)}$ is given by

$$U_{ma,s}^{(k)} = \int_0^{T_b} \sqrt{2P}\, b_k(t-\tau_k) a(t-\tau_k) \cdot a(t) \cos(\omega_c t + \phi_k) \cos(\omega_c t) dt. \quad (30)$$

In the chip synchronized system, the relationship among $b_k(t-\tau)$, $a(t-\tau_k)$, and $a(t)$ is illustrated in Fig. 11. The integration of (30) may be rewritten as

$$U_{ma,s}^{(k)} = T_c \sqrt{\frac{P}{2}} \cos\varphi_k \times \left\{ \sum_{l=0}^{\gamma_k - 1} b_{k,-1} a_{l+j-\gamma_k} a_{l+i} + \sum_{l=\gamma_k}^{N-1} b_{k,0} a_{l+j-\gamma_k} a_{l+i} \right\}. \quad (31)$$

Here, we can see that $U_{ma,s}^{(k)}$ is dependent on the adjacent bits, as well as on the assigned signature code and its partial autocorrelation properties.

The autocorrelation properties of maximal-length sequences are defined over a complete cycle of the sequence. That is, the two-valued autocorrelation can be guaranteed only when the integration is done over a full period of the sequence $a(t)$. Since the partial autocorrelation is associated with an integration over a fraction of the code period, the partial autocorrelation function is dependent on the size of this fraction and the starting time of the integration. The discrete partial autocorrelation function of a sequence $a(t)$ is defined by [24]

$$\theta_a(k, k', W) = \frac{1}{W} \sum_{m=k'}^{k'+W-1} a_m a_{m+k} \quad (32)$$

where k is the time difference between two partial codes, k' is the starting time of the correlation, and W is the duration of the correlation.

When $a(t)$ is generated by the primitive polynomial $x^{18} + x^7 + 1$, which is correspondent to circuit implementation with only two feedback connections, the partial autocorrelation during the bit period $T_b = 30$ is shown in Fig. 12. We assume

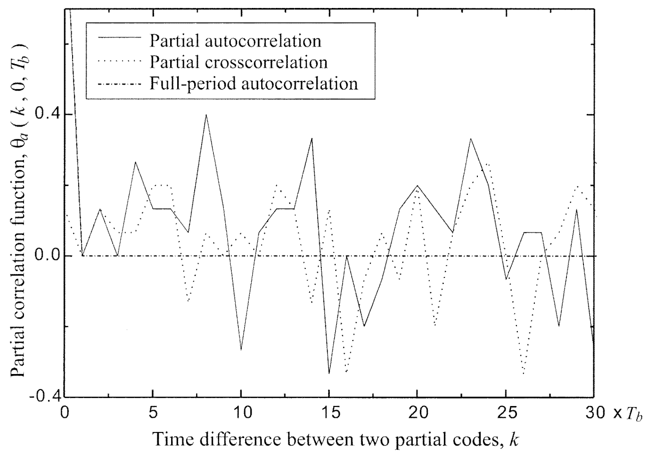

Fig. 12. Partial autocorrelation and partial crosscorrelation.

that $k' = 0$ and another spreading sequence is given by the primitive polynomial $x^{18} + x^7 + x^5 + x^2 + x + 1$.

Observe that the partial autocorrelation function is not well behaved compared with the full-period autocorrelation function. The partial-period autocorrelation shows the randomness and its variation is given by a function of window size and window placement. In Fig. 12, we do not consider the effect of the adjacent bits, b_{-1} and b_0. However, since the adjacent bits are identically distributed random variables, we expect that MAI due to user k has the randomness. This leads to Gaussian approximation of $U_{ma,s}$. In practice, IS-95 systems use one PN sequence with the period of $2^{42} - 1$ chips.

The remainder of the derivation of $U_{ma,s}$ is the same as [20]. Under chip synchronized systems, a factor of 3/2 is introduced in the variance of $U_{ma,r}$ [22], [25]. Therefore, in the interference limited CDMA systems sharing the same code, the bit error probability is given by

$$P_b(k) = Q\left(\sqrt{\frac{2N}{k}}\right) \quad (33)$$

where k is the number of interfering users.

Consequently, Gaussian approximation is employed based on the following reasons.

Case 1) The MAI is dependent on the adjacent bits whose values are independent, identically distributed random variables of ± 1 with probability of 1/2.

Case 2) The MAI is dependent on the partial autocorrelation properties. The partial autocorrelation appears as the crosscorrelation because mutual independence is shown in two code blocks which are randomly and partially selected within one code period.

Case 3) The MAI is dependent on the assigned signature code. Therefore, in order to find the average BER, the MAI must be be averaged over all possible sequences.

Therefore, the usage of the same spreading code for the different message arrivals of each user is equivalent to that of the same packet channel for random code of each user.

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