Performance Evaluation of CDMA ALOHA Systems with Modified Channel Load Sensing Protocol

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Abstract— **The one of the problems that arise in the satellite packet communication system is the existence of a long access timing delay. In this paper, we clarify the effect of this access timing delay on the performance of CDMA ALOHA systems and then propose a new access control protocol, called Modified Channel Load Sensing Protocol (MCLSP), for the CDMA ALOHA systems. As a result, we found that by employing MCLSP, a significant improvement in the throughput performance was obtained even in the presence of a long access timing delay.**

I. Introduction

Because of the features such as the random access capability, the potentiality for the high throughput performance and the low peak power transmission, the packet CDMA systems draw much attention for satellite-based mobile and personal communications. Many works have been made so far aiming at improving the throughput performance [1]–[9]. One of the techniques for improving the throughput performance is the packet access control based on the Channel Load Sensing Protocol (CLSP) [4]–[9].

In the CLSP, a hub station senses the channel load status, which is the number of ongoing packets transmitted from user stations. If the channel load is less than a certain threshold, then the packet access is allowed. Otherwise, the packet access is rejected until the channel load falls below the threshold.

Without the access timing delay, which is a time difference between channel load sensing and associated packet access timing, the throughput performance of the system would be satisfactory. If the access timing delay is no longer negligible, however, wrong information on the channel load may be given, since the channel load may change moment by moment. The packet access control based on the incorrect channel load information will result in a degradation of the throughput performance.

In the satellite packet communication systems, the access timing delay is remarkable. For example, in the low earth orbital satellite (LEO) system, the access timing delay is about 0.02 [sec] and, in the geostationary satellite (GEO) system, it reaches as much as 0.5 [sec], where data rate is 9.6 [kbps]. It is reported that throughput performance of CDMA ALOHA system with CLSP would degrade even for the case of LEO system (0.02 [sec]). For the case of GEO, the throughput becomes worse than the system without CLSP [8], [9]. CDMA ALOHA system with CLSP would become impractical in the presence of the long access timing delay.

In this paper, we propose a new access protocol called the Modified Channel Load Sensing Protocol (MCLSP). In the MCLSP, the hub station observes the channel load continuously for a certain period of time and estimates the average offered load. Since the average offered load can be regarded as the constant during the period of the access procedure, the access control protocol based on this estimated offered load is expected to be robust against the long access time delay. In order to clarify the advantages of MCLSP, we analyze the throughput and evaluate the performance of CDMA ALOHA with MCLSP. In this paper, we consider unslotted system as well as slotted system.

II. System Model

To evaluate the throughput performance of the CDMA ALOHA system, the following system model is assumed.

(1) The system consists of infinite number of user stations and a single hub station. Each user station transmits the packet to the hub station by satellite.
(2) Each packet is a fixed length of L [bits] and spectrum-spread with a uniquely assigned random signature sequence.
(3) The process of packet transmission demand is Poisson with an average offered load G, which is defined as the average number of packet transmission demands existing within one packet time duration T_p. The average offered

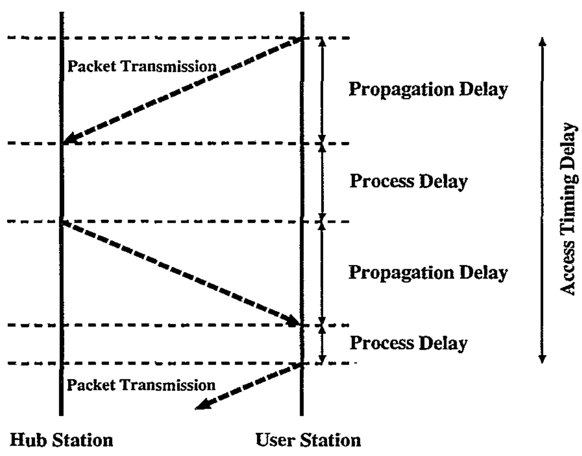

Fig. 1. Access timing delay.

load G is equal to λT_p, where λ is the birth rate of packet transmission demand.

(4) We assume that the access timing delay, which is a time difference between channel load sensing and associated packet access timing shown in Fig.1, can not be ignored. Let T_D be the access timing delay, and τ_D be normalized access timing delay obtained as T_D/T_p.

(5) All packets are received at the hub station with an equal power.

(6) Unsuccessful transmissions are due to interferences from other packets and additive white Gaussian noise. The bit error probability $P_b(k)$ is expressed as [10],

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

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 packets, E_b is the bit energy of the signal, N_0 is two-sided spectral density of Gaussian noise and,

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

(7) We assume that error correcting codes are not used, that is, packet transmission succeeds only if all bits in a packet are transmitted successfully.

(8) We assume that the preamble of every packet is transmitted successfully. Therefore, the hub station can sense the channel load almost perfectly.

III. Modified Channel Load Sensing Protocol

A. Principle of MCLSP

The packet access control based on the Channel Load Sensing Protocol (CLSP) is attractive as it can improve the throughput of CDMA ALOHA systems [4]-[8]. The hub station, first, senses the channel load status that is the number of ongoing packets. If the channel load is less than a certain threshold, then the information of the packet access is broadcasted to all the users. Otherwise, the information of the rejection is broadcasted until the number of ongoing packets falls below the threshold. In CLSP, the control of the packet access is done by the instantaneous information of the channel load.

Figure 2 shows the throughput performance of CDMA ALOHA system with CLSP, where we set the threshold

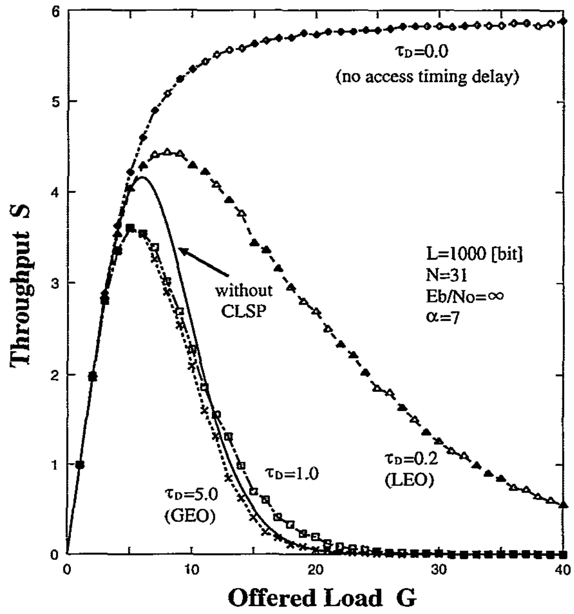

Fig. 2. Throughput performance of CDMA Unslotted ALOHA with conventional CLSP.

$\alpha = 7$. As shown in the figure, the maximum throughput of CDMA ALOHA system with CLSP can reach almost 1.5 times of maximum throughput of conventional CDMA ALOHA system, if there is no access timing delay. However, when the access timing delay is no longer negligible, the performance degrades. As we can recognize from the figure, even with the case of small access timing delay, say $\tau_D = 0.2$, the performance degrades especially in the large offered load. This is the case of LEO system. For the case of $\tau_D = 5.0$, which is the case of GEO system, we see that the performance is worse than the CDMA ALOHA without employing CLSP. We observe that in the presence of the access timing delay, since the packet access control is done by the past information, the performance would degrade.

In order to avoid this effect, we propose the protocol that controls the packet access based on the estimated average offered load. We call it Modified CLSP (MCLSP) and it can mitigate the effect of the access timing delay.

In the MCLSP, the hub station observes the channel load continuously for a certain period of time T_s, and calculates probability P_{tr} with which each user station transmits a packet, then broadcasts this probability to user stations. When packet transmission demand is generated at user station, user station transmits its packet with probability P_{tr} or stops transmitting its packet with probability $1 - P_{tr}$ according to the notice from the hub station.

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

B. Algorithm for Deriving the Probability P_{tr}

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

Assume that a user station starts transmitting a packet at time $t = t_{ps}$. Let $X_A(t_{ps} - T_D, T_s)$ be the number of packets received in the hub station during the time period from $(t_{ps} - T_D - T_s)$ to $(t_{ps} - T_D)$. The hub station senses the channel load, and obtains $X_A(t_{ps} - T_D, T_s)$. Let $\overline{P_{tr}(t_{ps} - T_D, T_s)}$ be the average packet transmission probability during the same time period. The hub station memorizes packet transmission probability each a certain time duration, which is enough to estimate the offered load, and calculates $\overline{P_{tr}(t_{ps} - T_D, T_s)}$ by averaging memorized packet transmission probability. The offered number of packets $X_O(t_{ps} - T_D, T_s)$ is expressed as

$$X_O(t_{ps} - T_D, T_s) = \frac{X_A(t_{ps} - T_D, T_s)}{\overline{P_{tr}(t_{ps} - T_D, T_s)}}. \quad (4)$$

Based on $X_O(t_{ps} - T_D, T_s)$, the estimated offered load g, which is the estimated number of packet transmission demands existing within one packet duration, is derived as follows:

$$\begin{aligned} g(t_{ps} - T_D, T_s) &= \frac{X_O(t_{ps} - T_D, T_s)}{\tau_s} \\ &= \frac{X_A(t_{ps} - T_D, T_s)}{\overline{P_{tr}(t_{ps} - T_D, T_s)} \cdot \tau_s}, \end{aligned} \quad (5)$$

where τ_s is normalized observation time period derived as T_s/T_p. Based on this estimated offered load $g(t_{ps} - T_D, T_s)$, the packet transmission probability at $t = t_{ps}$ is derived by the following equation aiming at ensuring to achieve the maximum value of the throughput that is to be obtained for the CDMA ALOHA without CLSP, even in the presence of a long access time delay.

The packet transmission probability $P_{tr}(t)$ at $t = t_{ps}$ is derived as

$$P_{tr}(t_{ps}) = \min\left\{ \frac{G_{max}}{g(t_{ps} - T_D, T_s)}, 1.0 \right\}, \quad (6)$$

where G_{max} is the average offered load giving the maximum throughput in the CDMA ALOHA without CLSP, and g is the estimated offered load. This equation means that if g exceeds G_{max}, then the user will transmit the packet with the probability of G_{max}/g. Otherwise the packet will be transmitted immediately upon request.

IV. Throughput Analysis

In ALOHA system (without employing CDMA), if two or more users transmit in a time interval such that the hub station receives more than one packet simultaneously, the hub station can not receive their packets. On the other hand, in CDMA ALOHA system, if two or more users transmit simultaneously, the probability of unsuccessful packet transmission will only become higher with increase in the number of simultaneous transmitted packets because of interferences from other packets. Therefore, CDMA ALOHA system can take better throughput performance [3].

In this section, we analyze the throughput performance of CDMA ALOHA with MCLSP. We consider the unslotted system of CDMA Unslotted ALOHA (CDMA U-ALOHA) and slotted system of CDMA Slotted ALOHA (CDMA S-ALOHA).

A. CDMA U-ALOHA with MCLSP

In CDMA U-ALOHA system, each user transmits a packet asynchronously, and channel load fluctuates frequently. The observation by the hub station is modeled as shown in Fig.3. The observation time period T_s is divided into small pieces of time Δt which is small enough to enable us to assume that the channel load changes by ± 1 channel at most between adjacent Δt's.

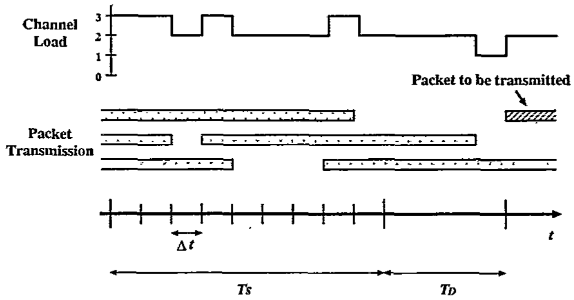

Fig. 3. Model of CDMA Unslotted ALOHA with MCLSP.

Let us assume that an estimation error of average offered load will hardly happen when the observation time period T_s is taken sufficiently long. In this case, we can consider that the estimated offered load g is equal to actual offered load G. Since we can regard the offered load as constant during the time period for the access procedure, we can derive the birth rate of packet transmission demand as λ and packet transmission probability as $P_{tr} = \min\{G_{max}/G, 1.0\}$, regardless of time t.

As the packet generation is Poisson and the packet length is constant, CDMA U-ALOHA system can be considered as $M/D/\infty$ queue, and we can obtain the throughput by using the state transition equation of $M/D/\infty$ queue. Let us define $P_S(k, i, k_1)$ as the probability that the packet is transmitted successfully from the first bit to the $i-1$-th bit, and the number of interfering packets is k on the i-th bit, and the number of interfering packets on the first bit is k_1.

Case $i = 1$;

Using the steady state probability of $M/D/\infty$ queue, we obtain as the following [11].

$$\begin{aligned} P_S(k = k_1, i, k_1) &= \frac{(P_{tr}\lambda T_p)^{k_1}}{k_1!} \exp(-P_{tr}\lambda T_p) \\ &= \frac{(P_{tr}G)^{k_1}}{k_1!} \exp(-P_{tr}G) \end{aligned} \quad (7)$$

Case $i > 1$;

We approximate that interference level is constant over a bit period, and Δt is equal to a bit interval. Because of this assumption and Poisson packet generation, after Δt seconds, at $i+1$-th bit ,the number of interfering packets will increase 1 to be $k+1$, or decrease 1 to be $k-1$, or remain to k. So we obtain $P_S(k,i,k_1)$ as the following.

$$\begin{aligned} P_S(k,i,k_1) = P_S(k,i-1,k_1)\cdot\{1-\mu(k_1)\Delta t - P_{tr}\lambda\Delta t\} \\ \cdot\{1-P_b(k)\} \\ +P_S(k+1,i-1,k_1)\cdot\mu(k_1)\Delta t \\ \cdot\{1-P_b(k+1)\} \\ +P_S(k-1,i-1,k_1)\cdot P_{tr}\lambda\Delta t \\ \cdot\{1-P_b(k-1)\}, \end{aligned} \quad (8)$$

where $\mu(k_1)$ is the death rate obtained as k_1/T_p [7].

Using $P_S(k,i,k_1)$, the packet success probability $Q_S(G)$ of the CDMA U-ALOHA system with MCLSP is derived as,

$$Q_S(G) = \sum_{k=0}^{\infty}\sum_{k_1=0}^{\infty} P_S(k,L,k_1)\cdot(1-P_b(k)). \quad (9)$$

Accordingly, the throughput performance is the following.

$$S = P_{tr}G\cdot Q_S(G) \quad (10)$$

B. CDMA S-ALOHA with MCLSP

In CDMA S-ALOHA, the time axis is divided into a slot. All of users must synchronize their transmission so that they initiate at the beginning of a slot. Therefore, the channel load within the slot is kept constant and we can derive better throughput performance. The observation by the hub station is modeled as shown in Fig.4. Time is divided into slots of unit length T_p, where time is normalized so that one packet can be transmitted in one slot. Let us denote the time interval $(t, t+T_p)$ as slot j, then the packet transmission probability P_{tr} is derived at each slot j.

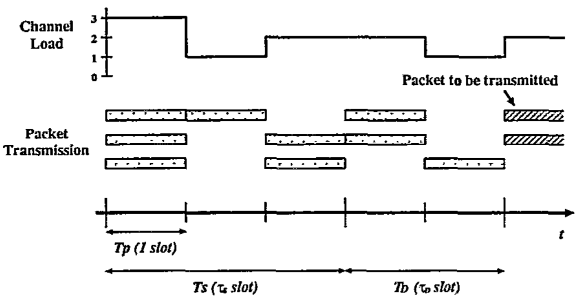

Fig. 4. Model of CDMA Slotted ALOHA with MCLSP.

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

$$\begin{aligned} P_o(m) &= \frac{(P_{tr}\lambda T_p)^m}{m!}\exp(-P_{tr}\lambda T_p) \\ &= \frac{(P_{tr}G)^m}{m!}\exp(-P_{tr}G) \end{aligned} \quad (11)$$

Since the number of ongoing packets is constant within the slot time duration in CDMA S-ALOHA system, packet success probability is derived as follows:

$$Q_S(G) = \sum_{m=0}^{\infty} P_o(m)\{1-P_b(m-1)\}^L. \quad (12)$$

Therefore, the throughput performance of the CDMA S-ALOHA system with MCLSP is derived as

$$S = P_{tr}G\cdot Q_S(G). \quad (13)$$

V. Numerical Examples

Figure 5 shows the throughput performance of the CDMA U-ALOHA with MCLSP under the situation that the access timing delay is identical among user stations and the average offered load G is constant during the access process. The analytical and simulated results of the throughput are shown with the parameter of normalized observation time period τ_s and of the access timing delay τ_D, where we set $N = 31$, $L = 1000$ [bit], and $E_b/N_0 = \infty$. In the simulations, the hub station estimates the offered load by counting the number of packets received at the hub station. Therefore, there may be an estimation error of the offered load. When the observation time period is taken sufficiently long ($\tau_s = 10$, for example),

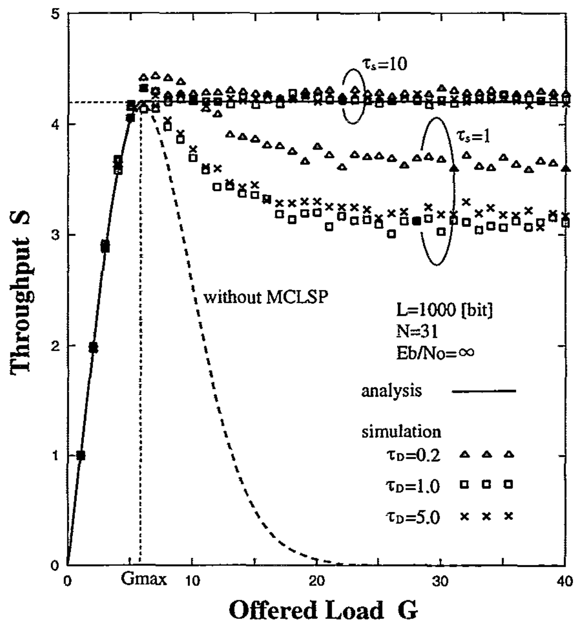

Fig. 5. Throughput performance of CDMA Unslotted ALOHA with MCLSP.

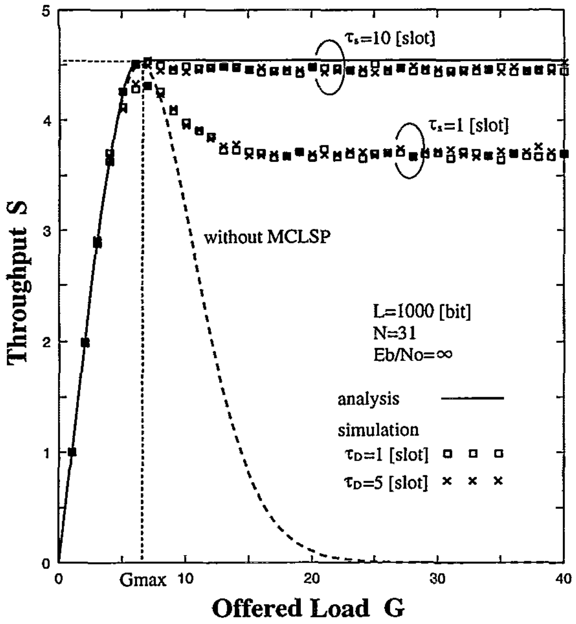

Fig. 6. Throughput performance of CDMA Slotted ALOHA with MCLSP.

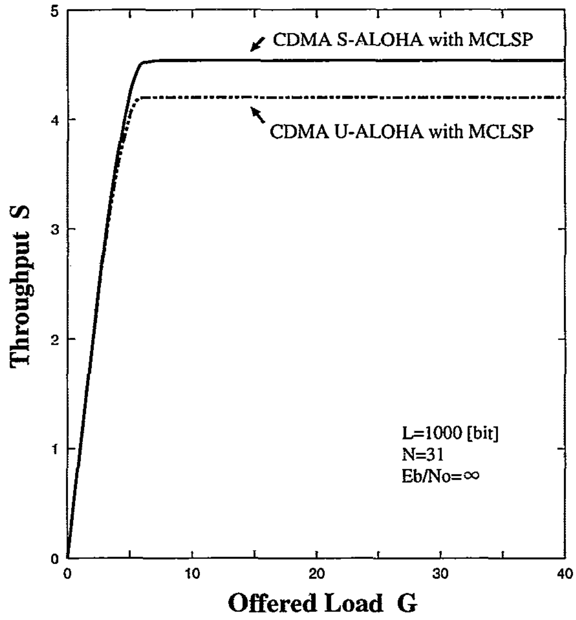

Fig. 7. Comparison between CDMA Unslotted ALOHA and CDMA Slotted ALOHA with MCLSP.

we can observe that estimation error of offered load hardly happens. Therefore, it can be seen from this figure that the throughput with the MCLSP can be kept as high as the maximum value of the CDMA U-ALOHA without the MCLSP even in a long access timing delay and large offered load. We also observe from the figure that the analytical results come close to the simulated results.

Figure 6 shows the throughput performance of the CDMA S-ALOHA with MCLSP under the same situation. The analytical and simulated results of the throughput are shown in this figure. Similarly in the case of CDMA U-ALOHA system, if the observation time period is taken sufficiently long, the throughput with the MCLSP can be kept as high as the maximum value of the CDMA S-ALOHA without the MCLSP even in a long access timing delay and large offered load. We also observe from the figure that the analytical results come close to the simulated results.

Figure 7 shows the throughput performances of both CDMA U-ALOHA and CDMA S-ALOHA with the MCLSP. In this figure, we see that the throughput of the CDMA S-ALOHA with MCLSP is higher than that of the CDMA U-ALOHA with MCLSP by about 0.4. However, the difference is small.

VI. Conclusions

The throughput performance of CDMA ALOHA with MCLSP has been discussed. As the control of the packet access is based on the estimation of the average offered load, the significant improvement in the throughput performance was obtained by CDMA ALOHA with MCLSP even in the presence of a long access timing delay. Since it is robust against even with the case of GEO system, we conclude that CDMA ALOHA with MCLSP is better suited for the satellite packet communication system.

Acknowledgment

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