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CDMA ALOHA Systems with Modified Channel Load Sensing Protocol for Satellite Communications

Hiraku OKADA[†], **Masato SAITO**[†], **Takeshi SATO**[†], *Student Members*, **Takaya YAMAZATO**[†], **Masaaki KATAYAMA**[†], *and* **Akira OGAWA**[†], *Members*

SUMMARY The one of the problems in the satellite packet communication system is the existence of a long time delay, which may cause an improper packet access control resulting in a great deal of degradation of the system performance. In this paper, we clarify the effect of long time 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 show that a significant improvement in the throughput performance was obtained with MCLSP even in the presence of a long time delay.

key words: *CDMA ALOHA, throughput, access control, access timing delay*

1. Introduction

Recently, Code-Division Multiple-Access (CDMA) ALOHA systems draw much attention for satellite-based mobile and personal communications because of the features such as the random access capability, the potentiality for the high throughput performance and the low peak power transmission. Many works have been made so far aiming at improving the throughput performance [1]–[10]. One of the techniques for improving the throughput performance is a packet access control based on the Channel Load Sensing Protocol (CLSP) [5]–[10].

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 of the channel load may be provided, 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 remarkably long. 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]. 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 [9], [10]. CDMA ALOHA system with CLSP would become impractical in the presence of a 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 constant during the period of the access procedure, the access control protocol based on this estimated offered load is expected to be robust against a 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 apply the MCLSP to both unslotted and slotted systems, and show that the systems can keep high throughputs even in presence of the long access timing delay.

2. 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 way of a satellite.
(2) Each packet length, denoted as L [bits], is fixed, 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 $T_p(= L/R)$, where R is the data rate. The average offered load G is equal to λT_p, where λ is the birth rate of packet transmission demand.

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[†]The authors are with the School of Engineering, Nagoya University, Nagoya-shi, 464–01 Japan.

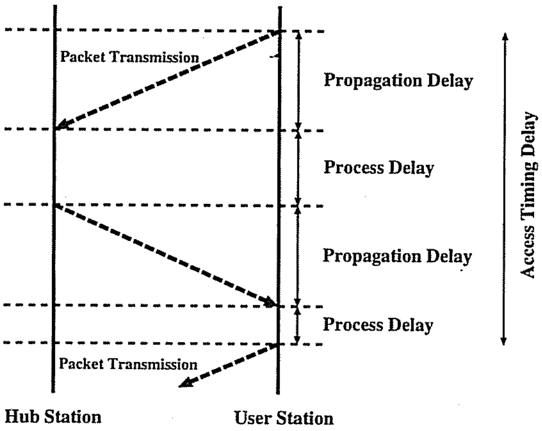

Fig. 1 Access timing delay.

(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, cannot be ignored. Let T_D be the access timing delay, and τ_D be access timing delay normalized by packet time duration T_p.

(5) All packets are received at the hub station with 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 [11],

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

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.

3. Modified Channel Load Sensing Protocol (MCLSP)

3.1 Principle of MCLSP

In conventional ALOHA system (without employing CDMA), if a hub station receives more than one packet simultaneously, the probability of successful transmission will become very small. On the other hand, in CDMA ALOHA system, even if the hub station receives more than one packet simultaneously, the probability of unsuccessful packet transmission will gradually increase with increase in the number of simultaneous transmitted packets because of interferences from other packets. Therefore, CDMA ALOHA system can be expected to be of better throughput performance [3], [4]. When the offered load is very large, however, many of transmitted packets may be incorrectly received and throughput performance may become unacceptable. The access control technique is, therefore, important for CDMA ALOHA system.

In the CDMA ALOHA system, because of capability of simultaneous transmission, the packet access control different from the case of conventional ALOHA system is required. The packet access control based on the Channel Load Sensing Protocol (CLSP) is attractive as it can improve the throughput of CDMA ALOHA system [5]–[9]. 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 hub station broadcasts permission of packet access to all users. Otherwise, prohibition of packet access is broadcasted until the number of ongoing packets falls below the threshold. In CLSP, the control of 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 $\alpha = 7$. 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, when we set $R = 9,600$ [bps] and $L = 1000$ [bits]. 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 access timing delay, since the packet access control is done by the past information, the performance would degrade [9]. Even

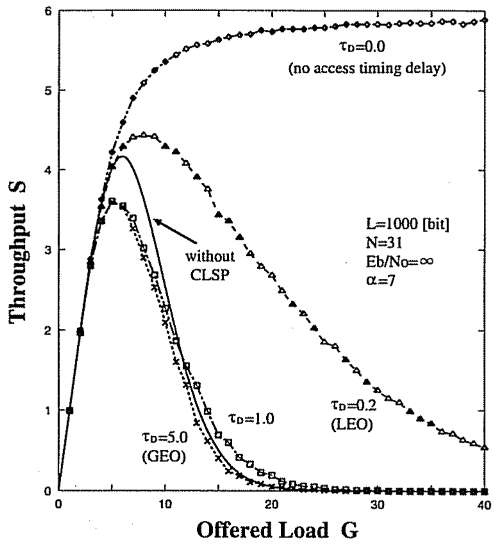

Fig. 2 Throughput performance of CDMA unslotted ALOHA with conventional CLSP.

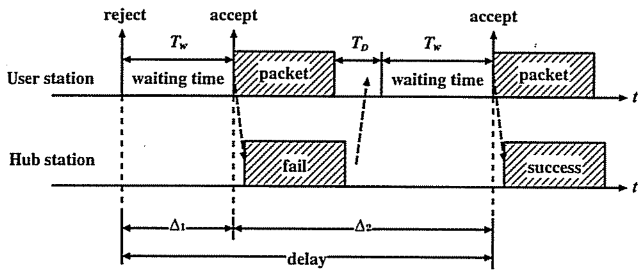

Fig. 3 Process of packet retransmission.

if the parameter of R and L is different, we will observe such degradation.

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.

Figure 3 shows the process of packet retransmission. If a user station stops transmitting his packet, he tries it again after waiting for exponentially distribution average time intervals T_w. Otherwise, user station transmits his packet. After examining the entire packet at the hub station, if an error is detected, a retransmission request message will return to each user. The user station retransmits its packet after waiting for exponentially distribution average time intervals T_w, so that, hopefully, the users who collided before will not do so again. This operation is repeated until packet is transmitted successfully.

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 [10].

3.2 Algorithm for Deriving the Probability P_{tr}

The average offered load G usually varies slowly and can be regarded as being constant during the time period for the access procedure. Taking 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

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

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:

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

where τ_s is observation time period normalized by packet time duration 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. This equation is derived 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 follows:

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

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.

4. Throughput Analysis

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

4.1 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. 4. 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.

When the observation time period is taken sufficiently long, estimation error of offered load will hardly happen. Let us assume no estimation error of average offered load. 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.

We assume that the system is in stationary state. As the packet generation is Poisson and the packet length is constant, CDMA U-ALOHA system can be considered as M/D/∞ queue, and we can obtain the throughput by using the state transition equation of M/D/∞ 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

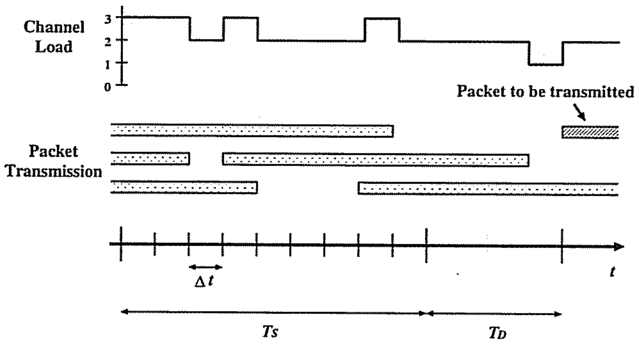

Fig. 4 Observation model of CDMA unslotted ALOHA with MCLSP.

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/∞ queue, we obtain as the following [12].

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

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.

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

where $\mu(k_1)$ is the death rate obtained as k_1/T_p [8].

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.

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

Next, we will calculate the delay performance of CDMA U-ALOHA system.

The elapsed time Δ_1 between the packets when packet access is rejected, and rejection probability of packet access $Q_R(G)$ are derived as,

$$\Delta_1 = T_w, \quad (11)$$
$$Q_R(G) = 1 - P_{tr}. \quad (12)$$

The elapsed time Δ_2 between the packets when packet transmission is unsuccessful, and packet unsuccessful probability Q_F are derived as,

$$\Delta_2 = T_w + T_D + T_p, \quad (13)$$
$$Q_F(G) = 1 - Q_S(G). \quad (14)$$

Then, the average delay time is derived as follows:

$$D = \frac{1}{T_p}\{\Delta_1 Q_R(G) + \Delta_2 P_{tr} Q_F(G) + 2\Delta_1 Q_R^2(G) + 2(\Delta_1+\Delta_2) Q_R(G)\, P_{tr} Q_F(G) + 2\Delta_2 (P_{tr} Q_F(G))^2 + \cdots\} P_{tr} Q_S(G)$$
$$= \frac{1}{T_p}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\binom{n}{m}\{m\Delta_1 + (n-m)\Delta_2\} \cdot Q_R^m(G)\,(P_{tr}Q_F(G))^{n-m}\, P_{tr} Q_S(G). \quad (15)$$

4.2 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. 5. 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.

Let us assume no estimation error of average offered load. 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.

$$P_o(m) = \frac{(P_{tr}\lambda T_p)^m}{m!}\exp(-P_{tr}\lambda T_p) = \frac{(P_{tr}G)^m}{m!}\exp(-P_{tr}G) \quad (16)$$

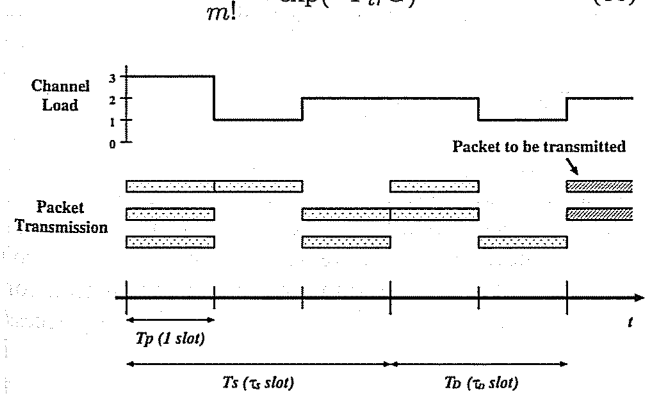

Fig. 5 Observation model of CDMA slotted ALOHA with MCLSP.

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:

$$Q_S(G) = \sum_{m=0}^{\infty} P_o(m)\{1 - P_b(m-1)\}^L. \quad (17)$$

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

$$S = P_{tr} G \cdot Q_S(G). \quad (18)$$

Similarly in the case of CDMA U-ALOHA system, the delay time of CDMA S-ALOHA system is derived by Eq. (15) as follows:

$$D = \frac{1}{T_p}\sum_{n=0}^{\infty}\sum_{m=0}^{n}\binom{n}{m}\{m\Delta_1 + (n-m)\Delta_2\} \cdot Q_R^m(G)\,(P_{tr}Q_F(G))^{n-m}\, P_{tr} Q_S(G). \quad (19)$$

5. Numerical Examples

Figure 6 shows the throughput performance of the CDMA U-ALOHA with MCLSP under the situation where 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 parameters of normalized observation time period τ_s and of normalized 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), we can observe that

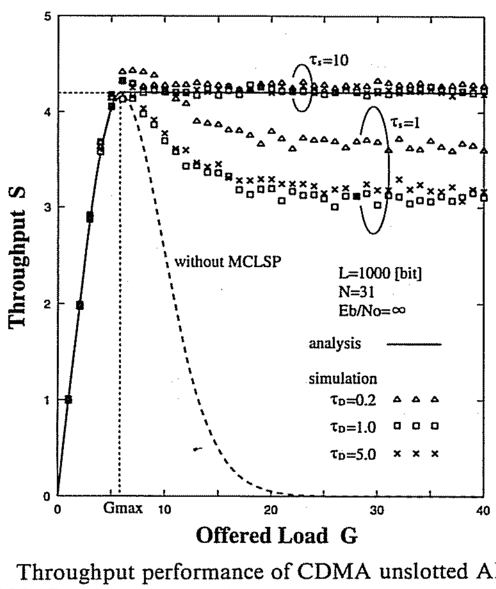

Fig. 6 Throughput performance of CDMA unslotted ALOHA with MCLSP.

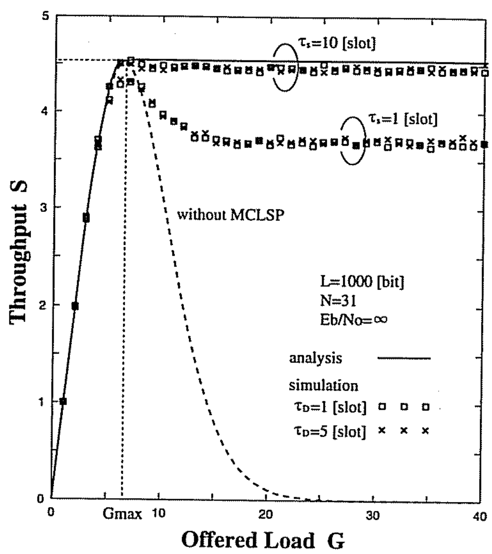

Fig. 7 Throughput performance of CDMA slotted ALOHA with MCLSP.

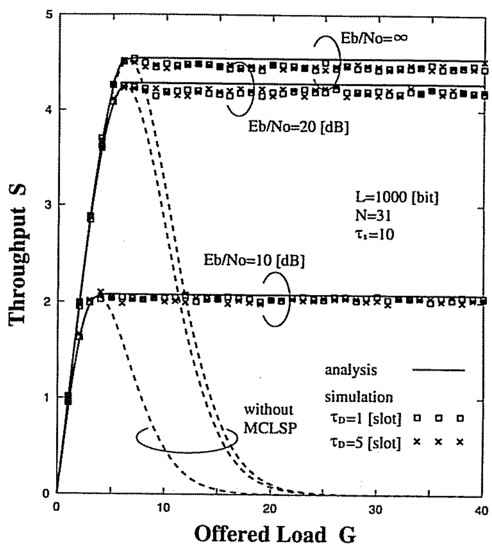

Fig. 9 Throughput performance of CDMA slotted ALOHA using MCLSP with the parameter of E_b/N_0.

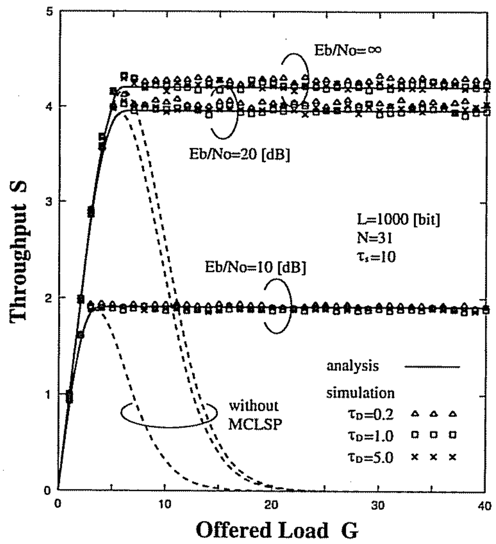

Fig. 8 Throughput performance of CDMA unslotted ALOHA using MCLSP with the parameter of E_b/N_0.

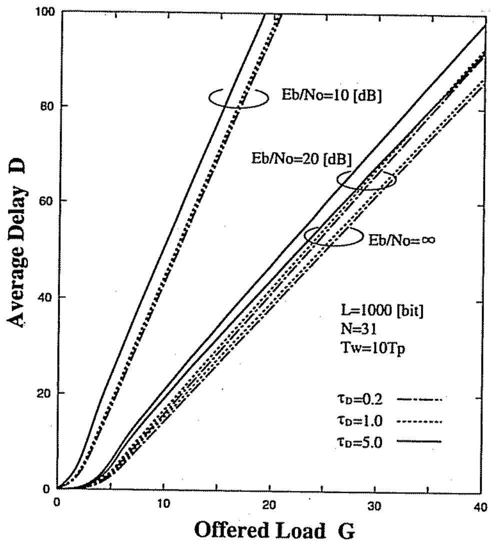

Fig. 10 Average delay performance of CDMA unslotted ALOHA with MCLSP.

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 7 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.

The throughput performances of CDMA U-ALOHA and S-ALOHA using MCLSP are shown in Fig. 8 and Fig. 9 with the parameter of E_b/N_0, for 10 [dB], 20 [dB] and infinity. In these figures, we observe that the effect of thermal noise degrades the throughput performance. However, we see that the access control by using MCLSP maintains maximum throughput for large offered load even in the presence of a long access timing delay.

The average delay performances of CDMA U-ALOHA and S-ALOHA are shown in Fig. 10 and Fig. 11, where we set the average waiting time T_w =

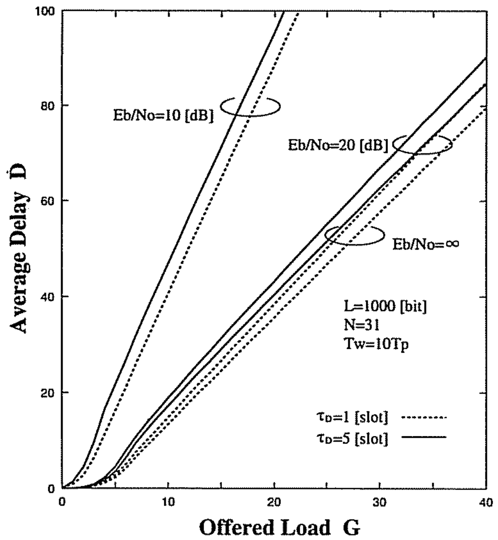

Fig. 11 Average delay performance of CDMA slotted ALOHA with MCLSP.

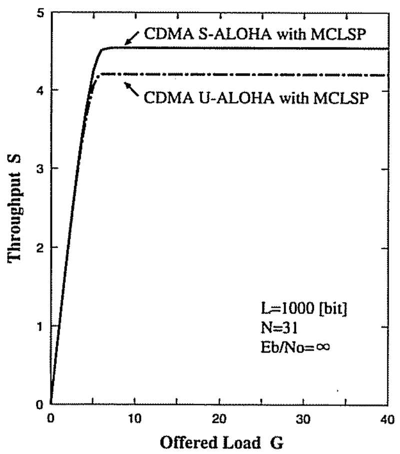

Fig. 12 Comparison between CDMA unslotted ALOHA and CDMA slotted ALOHA with MCLSP.

$10T_p$. We observe that average delay time is very small for $G < G_{\max}$, and linearly increases for $G > G_{\max}$. We also observe that the effect of thermal noise increases the average delay time.

Figure 12 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.

6. Conclusions

We have proposed CDMA ALOHA system with Modified Channel Load Sensing Protocol, and the throughput performance of this system 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.

In this paper, we assume that hub station can sense the channel load almost perfectly. However, we suspect that the MCLSP is not sensitive to sensing error of the channel load and estimation error of the offered load, because the gradient of the curve of the throughput without access control is almost zero at the maximum point and the throughput performance does not vary greatly at this point.

Acknowledgment

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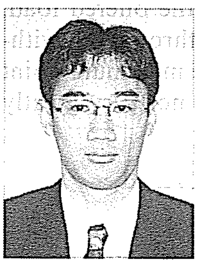
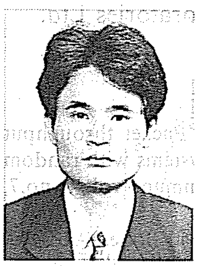
References

[1] R.K. Morrow, Jr. and J.S. Lehnert, "Packet throughput in slotted ALOHA DS/SSMA radio systems with random signature sequences," IEEE Trans. Commun., vol.40, no.7, pp.1223–30, July 1992.
[2] D. Makrakis and K.M.S. Murthy, "Spread slotted ALOHA techniques for mobile and personal satellite communication systems," IEEE J. Select. Areas Commun., vol.10, no.6, pp.985–1002, Aug. 1992.
[3] R.D.J. van Nee, R.N. van Wolfswinkel, and R. Prasad, "Slotted ALOHA and Code Division Multiple Access techniques for land-mobile satellite personal communications," IEEE J. Select. Areas Commun., vol.13, no.2, pp.382–388, Feb. 1995.
[4] T. Yamazato, T. Sato, H. Okada, K. Nishida, M. Katayama, and A. Ogawa, "Performance analysis of CDMA ALOHA," ISCOM'95, pp.434–441, Dec. 1995.
[5] M. Yin and V.O.K. Li, "Unslotted CDMA with fixed packet lengths," IEEE J. Select. Areas Commun., vol.8, no.4, pp.529–541, May 1990.
[6] A.H. Abdelmonem and T.N. Saadawi, "Performance analysis of spread spectrum packet radio network with channel load sensing," IEEE J. Select. Areas Commun., vol.7, no.1, pp.161–166, Jan. 1989.
[7] K. Toshimitsu, T. Yamazato, M. Katayama, and A. Ogawa, "A novel spread slotted Aloha system with channel load sensing protocol," IEEE J. Select. Areas Commun., vol.12, no.4, pp.665–672, Aug. 1994.
[8] T. Sato, H. Okada, T. Yamazato, M. Katayama, and A. Ogawa, "Throughput analysis of DS/SSMA unslotted Aloha with channel load sensing," GLOBECOM'95, vol.2, pp.1492–96, 1995.
[9] T. Sato, H. Okada, T. Yamazato, M. Katayama, and A. Ogawa, "Effects of the access timing delay on CDMA unslotted ALOHA with channel load sensing," IEICE Trans. Commun., vol.E-79B, no.9, pp.1339–1345, Sept. 1996.
[10] A. Ogawa, T. Yamazato, M. Katayama, and K. Toshimitsu, "A new access protocol for asynchronous packet CDMA systems," ISITA '94, pp.917–920, 1994.
[11] J.M. Holtzman, "A simple, accurate method to calcu-

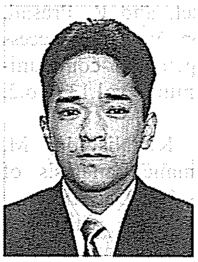
late Spread-Spectrum Multiple-Access error probabilities," IEEE Trans. Commun., vol.40, no.3, March 1992.
[12] L. Kleinrock, "Queueing Systems, vol.1," Wiley-Inter-Science, New York, 1975.



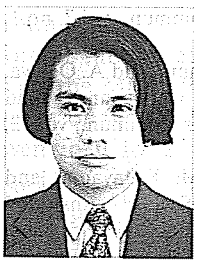
Hiraku Okada was born in Nagoya, Japan in 1972. He received the B.S. degree in Information Electronics Engineering from Nagoya University, Japan in 1995. His current research interests include the packet radio and spread-spectrum radio networks. He is currently working toward the M.S. degree at Nagoya University. Mr. Okada received the Inose Science Award in 1996. He is a student member of IEEE.



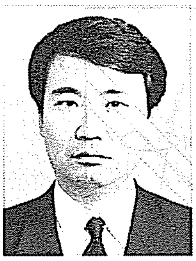
Masato Saito was born in Shizuoka, Japan in 1973. He received the B.S. degree in Information Electronics Engineering from Nagoya University, Japan in 1996. His current research interests include the packet radio and spread-spectrum radio networks. He is currently working toward the M.S. degree at Nagoya University. Mr. Saito is a student member of IEEE.



Takeshi Sato was born in Nagoya, Japan in 1969. He received the B.S. and M.S. degrees in Information Electronics Engineering from Nagoya University, Japan in 1994 and 1996, respectively. His current research interests include the packet radio and spread-spectrum radio networks. He is currently working toward the Ph.D. degree at Nagoya University. Mr. Sato is a student member of IEEE.



Takaya Yamazato was born in Okinawa, Japan in 1964. He received the B.S. and M.S. degrees from Shinshu University, Nagano, Japan, in 1988 and 1990, respectively, and received the Ph.D. degree from Keio University, Yokohama, Japan, in 1993, all in Electrical Engineering. He is now a Assistant Professor of the Department of Information Electronics at Nagoya University, Japan. His research interests include satellite and mobile communication systems, spread-spectrum modulation schemes, and coded modulations. Dr. Yamazato received the IEICE Young Engineer Award in 1995. He is a member of IEEE and SITA.



Masaaki Katayama was born in Kyoto, Japan in 1959. He received the B.S., M.S. and Ph.D. degrees from Osaka University, Japan in 1981, 1983, and 1986, respectively, all in Communication Engineering. In 1986, he was an Assistant Professor at Toyohashi University of Technology, Japan, and was been a Lecturer at Osaka University, Japan, from 1989 to 1992. Since 1992, he has been an Associate Professor of the Department of Information Electronics at Nagoya University, Japan. His current research interests include satellite and mobile communication systems, spread-spectrum modulation schemes, nonlinear digital modulations, coded modulations, and computer networks. Dr. Katayama received the IEICE Shinohara Memorial Young Engineer Award in 1986. He is a member of IEEE, SITA, and the Information Processing Society of Japan.

Akira Ogawa was born in Nagoya, Japan in 1937. He received the B.S. and Dr. of Eng. degrees from Nagoya University, Japan, in 1960 and 1984, respectively. In 1961, he joined the Research Laboratories of Kokusai Denshin Denwa (KDD) Co. Ltd. From 1981 to 1985, he was the Deputy Director of KDD Laboratories. From 1985 to 1988 he was the Director of Sydney Office of KDD. Since 1988, he has been a Professor of the Department of Information Electronics at Nagoya University, Japan. His current research interests include digital communication theory, spread-spectrum and CDMA schemes, and mobile and satellite communication systems. Dr. Ogawa is a member of IEEE, SITA, and IREE Australia.