Throughput Improvement of a Dual-Class Multi-Code CDMA ALOHA System with Modified Channel Load Sensing Protocol

A. Sandouk†, H. Okada †, T. Yamazato††, M. Katayama†, and A. Ogawa†

† Ogawa Lab., Dept. of Info. Elec., Graduate School of Eng., Nagoya University.
†† Center for Information Media Studies., Nagoya University.
Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan.
Tel: +81-52-789-2743 Fax: +81-52-789-3173
E-mail: sandouk@ogawa.nuee.nagoya-u.ac.jp

Abstract— **In this paper, we propose a CDMA Slotted-ALOHA (CDMA S-ALOHA) system with low-bit-rate and high-bit-rate classes of data users applying multi-code CDMA (MC-CDMA) scheme. Performance evaluation is obtained in the respect of the throughput. Contrary to one might expect, we show that the throughput of the class with higher bit rate can be improved by the MC-CDMA scheme. Moreover, we show that applying the modified channel load sensing protocol (MCLSP) to the system gives further improvement in the throughput of the higher bit rate class, as well as to the total throughput of the channel.**

I. Introduction

Current cellular systems based on code division multiple access (CDMA) have primarily been optimized for voice transmission. In order to interface to the broadband networks of the future, wireless systems will be required to support sources with a variety of rates and quality-of-service (QoS) requirements [1].

Packet-switched network architecture based on CDMA, which is known as CDMA ALOHA, has recently attracted attention as the technology best suited for multimedia communications since it shows promise in being able to deal with multimedia traffic flexibly [2], [3], rather than the circuit-switched architecture employed for first and second generation.

In CDMA ALOHA systems, CDMA Slotted-ALOHA (CDMA S-ALOHA), which is a combination of CDMA and slotted-ALOHA that provides packet transmission at specific time instants, is a proper scheme to support a randomly and bursty-access users, it allows us to have further efficient systems [4].

In this work, we consider the problem of making present packet CDMA systems more efficient with respect to the throughputs they provide.

The CDMA ALOHA system under consideration uses a total spreading bandwidth of W [MHz] and is required to support two classes of data users. Class I requires transmission at a high bit-rate, while class II tolerates transmission at a low bit-rate.

To support multi-rate transmission with direct sequence CDMA (DS-CDMA) systems, many techniques have been proposed such as multi-modulation CDMA (MM-CDMA) [5], multi-processing gain CDMA (MPG-CDMA) [6], and multi-code CDMA (MC-CDMA) [7]. We adopt the multi-code CDMA method to transmit the packets from users of class I because it has some advantages over the other methods [7], [8].

The MC-CDMA has some interesting properties that the other techniques lack. For example, when it comes to integration of multi-class or multi-media traffic, traffic streams with significantly different transmission rates can be easily integrated into unified architecture, with all the transmissions over the radio channel occupying the same bandwidth and having the same processing gain. In addition, self-interference among the multiple codes in a same user's multi-rate transmission can be eliminated by a technique called sub-code concatenation [7].

We propose an MC-CDMA S-ALOHA system that supports the users from both classes and evaluate its performance in the respect of the throughput.

Multiple access interference (MAI) from both classes results in throughput degradation. Therefore, applying some kind of traffic control is necessary to improve the throughput. One of the effective techniques for improving the throughput performance is the packet access control based on the Modified Channel Load Sensing Protocol (MCLSP) [9].

In this paper, we apply the MCLSP technique to improve the throughput and to control the access *from class I* taking into account the offered load of the users from both classes.

II. System Model

We deal with a system of a single central CDMA packet radio network (base station) with a large number of independent data users from class I and class II sharing random signature, as shown in Fig. 1.

CDMA S-ALOHA transmission is used, i.e, time axis is divided into slots, each of duration of one packet, T_p[sec]. All users synchronize their transmission so that they initiate at the begining of a slot.

A. Assumptions for Class I

A Poisson process is used to model packet arrivals from class I with rate λ_1.

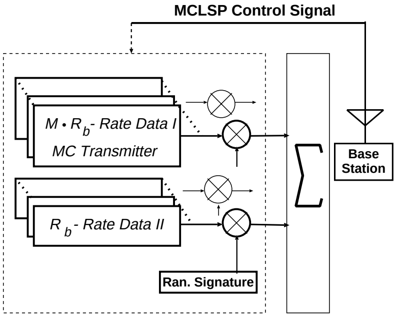

Fig. 1. System model

Each transmitter of this class is provided with an MC-CDMA transmitter with multi-code factor M. The original message stream of the user of this class is generated at a bit rate R_b[bits/sec], then it is split into M sub-streams before transmission , each of which has a length L_b[bits] and a duration equal to one slot duration. (*In this paper, R_b is called the basic bit rate, and one sub-stream is called sub-packet*). The user transmits M sub-packets at a time in one slot. Thus, the bit rate, packet length, and packet duration of class I, respectively, are $M \cdot R_b$[bits/sec], $M \cdot L_b$[bits], and T_p[sec].

B. Assumptions for Class II

A Poisson process is also used to model packet arrivals from class II with rate λ_2.

Since the users of this class do not mind transmission in a low bit rate, multi-code scheme is not applied for this class. A mobile client transmits one packet in one slot at the basic bit rate with packet length equal to one sub-packet of class I. Therefore, the bit rate, packet length and packet duration assigned to class II, respectively, are R_b[bits/sec], L_b[bits], and T_p[sec].

In Fig. 2 we have plotted an exapmle of simultaneous transmissions from the users of both classes.

Since the packet of both classes has a fixed length, with Poisson process, traffic from both classes can be corresponded with an $(M_1 + M_2)/D/\infty$ process, where M_1, M_2 are the exponential interarrival time distribution of the users of class I and II, respectively, D is the deterministic service time distribution for both classes at the base station, and the number of allowed simultaneous transmission is ∞, [10].

To fulfill the low bit error rates required by the users, it is assumed that each packet is transmitted successfully if, and only if, all its bits succeeded, and no error correcting code is applied.

Perfect power control is assumed ensuring that all sub-packets from class I and packets from class II are received with equal power at the base station. In other words, the packet from the user of class II is received with power P, while the packet from the user of class I is received with power MP.

BPSK modulation of the transmitted bit stream for users from both classes is assumed.

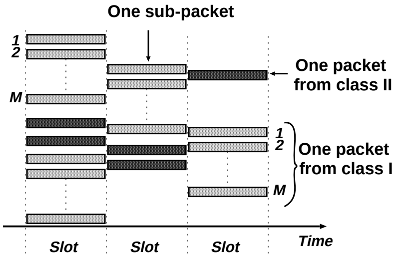

Fig. 2. An example of packet transmission from both classes

III. Performance Analysis of the System with MC-CDMA

We assume that bit errors (BER) in the transmission are caused by the additive white Gaussian noise (AWGN) and the MAI of transmission from both classes.

Our starting point is the equation of BER in DS/CDMA systems with Gaussian approximation [11]

$$BER(k) = Q[(\frac{k-1}{3N} + \frac{N_0}{2E_b})^{-0.5}], \qquad (1)$$

where k is the number of simultaneous transmissions, N is the processing gain (spectrum spreading factor) [chips/bit], N_0 is the spectral density of Gaussian noise, E_b is the energy per information bit in the received signal, and

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

A. Throughput of Class I:

With some modification to (1), the probability of bit errors of this class is [12]

$$BER_1(k_1, k_2) = Q[(\frac{M(k_1-1)+k_2}{3N} + \frac{N_0}{2E_b})^{-0.5}], \quad (3)$$

where k_1, k_2 are the simultaneous transmissions from data users of class I and class II, respectively.

In our system, each user of class I sends M sub-packets in parallel. Since we are applying MC-CDMA to class I, each one of these sub-packet is multiplied by an orthogonal code before transmission [7]. Therefore, transmission of one user of class I in this system can be corresponded with a simultaneous transmissions from M users in the conventional CDMA S-ALOHA. Which means that the number of simultaneous transmissions in our system is large enough so that eq. (1) of Gaussian approximation can be modified as shown in (3).

In eq. (3), we note that the number of interfering packets from class I, $k_1 - 1$, has been multiplied by M. The reason is that the user of class I sends a packet consists of M sub-packets at a time, while each user of class II sends only one packet which is equal in length and duration to one sub-packet of class I. Therefore, since in multi-code scheme the same processing gain is used for all users, the power density of the packet of class I is M times bigger than that of class II, so that, the effect of interference from the user of class I will be M times greater than that of class II.

We define the throughput of class I as the number of succeeded sub-packets from users of this class in one slot duration.

The number of simultaneous transmissions from class I in one slot duration is given by the steady-state probability of Poisson process as [10]

$$P_1(k_1, G_1) = \frac{(G_1/M)^{k_1}}{k_1!} exp(-G_1/M), \qquad (4)$$

which is the probability that k_1 users (Mk_1 sub-packets) exist in one slot duration, where G_1 is the offered load of class I defined as the average number of generated sub-packets from class I in one slot duration, T_p.

With the assumption of perfect capture, which means that the number of generated packets in one slot duration is fixed and is equal to the number of interfering packets at the begining of the slot, we can consider that the number of transmissions from class II, k_2, is constant in one slot duration, i.e., during the transmission of a packet from data class I user.

The number of transmissions from data class II, k_2, can be also obtained from the steady-state probability of Poisson process [10]

$$P_2(k_2, G_2) = \frac{{G_2}^{k_2}}{k_2!} exp(-G_2), \qquad (5)$$

where G_2 is the offered load of class II, which is the average number of generated packets (users) from class II in one slot duration.

Under this assumption, the throughput of class I is obtained following the same steps of [12] as

$$S_1(G_1, k_2) = \sum_{k_1=1}^{\infty} M \cdot k_1 \cdot P_1(k_1, G_1) \cdot P_{s_1}(k_1, k_2, L_b), \qquad (6)$$

where $P_{s_1}(k_1, k_2, L_b)$ is the sub-packet success probability in the transmission from class I. This probability is given by [13]

$$P_{s_1}(k_1, k_2, L_b) = (1 - BER_1(k_1, k_2))^{L_b}. \qquad (7)$$

Averaging over all the possible values of k_2 we obtain the throughput of class I as

$$S_I(G_1, G_2) = \sum_{k_2=0}^{\infty} \Big(\sum_{k_1=1}^{\infty} M \cdot k_1 \cdot P_1(k_1, G_1) \cdot P_{s_1}(k_1, k_2, L_b) \Big) P_2(k_2, G_2). \qquad (8)$$

B. Throughput of Class II:

The probability of bit error of this class, again with Gaussian approximation, is [11], [12]

$$BER_2(k_1, k_2) = Q[(\frac{Mk_1 + (k_2 - 1)}{3N} + \frac{N_0}{2E_b})^{-0.5}]. \qquad (9)$$

The throughput of class II, which is the number of succeeded packets from class II in one slot duration, can be obtained by the same method used for class I taking into account the interference from class I as

$$S_{II}(G_1, G_2) = \sum_{k_1=0}^{\infty} \Big(\sum_{k_2=1}^{\infty} k_2 \cdot P_2(k_2, G_2) \cdot P_{s_2}(k_1, k_2, L_b) \Big) P_1(k_1, G_1), \qquad (10)$$

where $P_{s_2}()$ is packet success probability of class II given as [13]

$$P_{s_2}(k_1, k_2, L_b) = (1 - BER_2(k_1, k_2))^{L_b}. \qquad (11)$$

Finally, the total throughput of the data medium becomes

$$S_{tot}(G_1, G_2) = S_I(G_1, G_2) + S_{II}(G_1, G_2). \qquad (12)$$

IV. Daul-class MC-CDMA ALOHA with MCLSP

In MCLSP, the base station observes the channel load continuously for a certain period of time, estimates the offered load and calculates packet transmission probability, P_{tr}, with which each user station transmits a packet, then broadcasts this probability to the user stations. When packet transmission demand is generated at user station, the user transmits its packet with probability P_{tr} or stops transmission with probability $1 - P_{tr}$ according to the notice from the base station [9].

Algorithm for deriving the probability P_{tr} in a single-class system has been presented in [9].

In our system, we apply the MCLSP to the class I only. But the number of simultaneous transmissions from class II should be considered in calculating the packet transmission probability.

The base station estimates the offered load of class I, g_{1es},and class II, g_{2es}. Assuming no estimation error in the average offered load, we can consider that the estimated offered load g_{1es} is equal to the actual offered load of class I, G_1, and the estimated offered load g_{2es} is equal to the actual offered load of class II, G_2.

Since our interest, for the time being, is to improve the throughput of class I, the base station calculates packet transmission probability for this class and broadcasts it to the terminals of class I. This probability is obtained as [12]

$$P_{tr} = \begin{cases} 1.0 & (G_{max} - G_2 \geq G_1) \\ \frac{G_{max} - G_2}{G_1} & (G_{max} - G_2 < G_1) \\ 0 & G_2 \geq G_{max} \end{cases} \qquad (13)$$

where G_{max} is the *total* offered load (from both classes) which gives the maximum total throughput without MCLSP.

Equation (13) means that if $(G_{max} - G_2)$, which is the available transmission for class I, is greater than the estimated offered load of class I, G_1, the packet from class I will be transmitted immediately. And if it is less than G_1, user of class I transmits with probability $(G_{max} - G_2)/G_1$. Otherwise, if

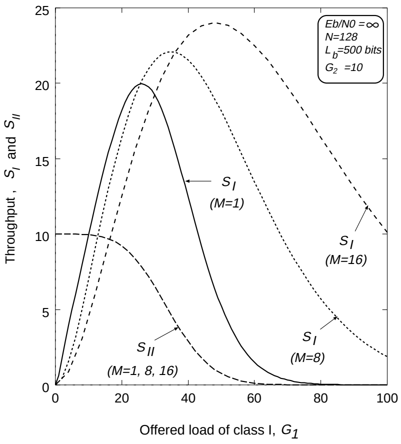

Fig. 3. Throughput improvement of class I by applying MC-CDMA for different values of mutli-code factor

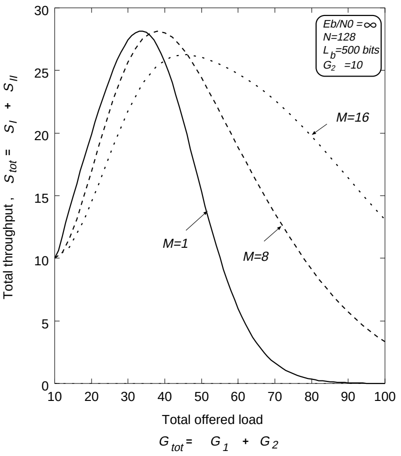

Fig. 4. Total throughput of the channel with MC-CDMA

the estimated offered load of class II, G_2, is greater than G_{max}, the user of class I cannot transmit.

In this case, the probability $P_1(k_1, G_1)$, which is defined in eq. (4) becomes

$$P_{1m}(k_1, G_1) = \frac{(P_{tr}G_1/M)^{k_1}}{k_1!} \exp(-P_{tr}G_1/M). \quad (14)$$

The throughput of class I with MCLSP taking into account the interference from class II becomes

$$S_I(G1, G_2) = \sum_{k_2=0}^{\infty} \Big(\sum_{k_1=1}^{\infty} M \cdot k_1 \cdot P_{1m}(k_1, G_1) \cdot P_{s_1}(k_1, k_2, L_b) \Big) P_2(k_2, G_2). \quad (15)$$

The throughput of class II is the same which is given in (10).

V. Numerical Example

In our numerical example, we work with a CDMA S-ALOHA system with spreading factor $N = 128$ [chip/bit]. The sub-packet length is given as $L_b = 500$ [bits].

For simplicity, we assume that the effect of AWGN is neglected; i.e., $E_b/N_0 = \infty$, and the errors are caused only by the MAI.

User of class I transmits packets by MC-CDMA technique with factor $M = 1, 8, 16$.

In Fig. 3, we have plotted the throughput versus the offered load of class I in the case of $M = 1$ (single bit rate), $M = 8$, and $M = 16$ at $G_2 = 10$. From this figure, we show that as the multi-code factor increases, as S_I increases, does not decrease as one may expect. This is, as we have mentioned, by the virtue of the capability of self-interference elimination of the MC-CDMA scheme.

The total throughput of the channel versus the total offered load (the offered loads from both classes) applying MC-CDMA is shown in Fig. 4. We note that when $M = 8$, the throughput has almost the same maximum point of that in the case of $M = 1$, but at a higher value of offered load. When $M = 16$, the peak point decreases, but the throughput is still better at high vlaues of offered load. The reason of the decrement in the peak point can be understood from Fig. 3. In this figure, we have plotted S_{II} versus G_1 at $G_2 = 10$. This throughput has the same curve when $M = 1, 8, 16$. From this figure, it is clear that as M increases, at the same values of G_1 and G_2, the gap between S_I ans S_{II} increases. In other words, S_{II} doesn't decrease when M increases, but the difference between S_I and S_{II} decreases rapidly, and we can see on Fig. 3 that the vertical distance between the peak points of S_I when M increases and the curve of S_{II} increases rapidly, so that the total throughput of the system will have some degradation when M becomes higher.

Figure 5 shows S_I with MCLSP versus G_1 for two values of G_2 at $M = 8$. From this figure, we note that the throughput can reach a constant value even at high values of the offered load.

In a single class MCLSP system, the throughput reaches a constant value at its peak point. But here, as we see in Fig. 5, the throughput of class I becomes constant at a point lower than the peak. The reason of this little-degradation is that selecting the value of G_{max} perfectly in the Algorithm of P_{tr} makes the Algorithm more complicated. Here we have used a simple Algorithm, so that selecting G_{max} was not optimum.

In Fig. 6, we show S_I versus G_1 at $G_2 = 10$ for different values of multi-code factor.

It is shown in this figure that further improvement in the throughput can be obtained by using higher multi-code factor.

Figure 7 shows the total throughput of the channel versus the total offered load in three cases, namely, at $M = 1$, $M = 8$ without MCLSP, and at $M = 8$ with MCLSP. It is clear from this figure that the throughput performance can be improved by applying the MC-CDMA technique. Furthermore, we can get additional improvement by applying the MCLSP to the

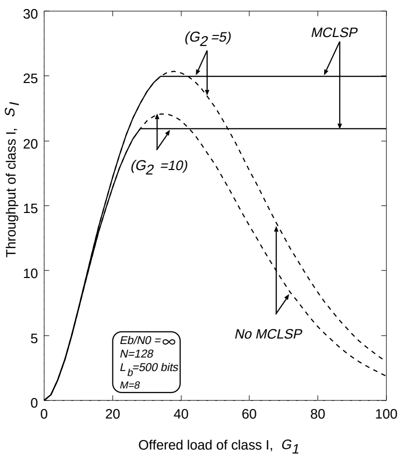

Fig. 5. Throughput improvement of class I with MCLSP, fixed multi-code factor and different offered load values of class II

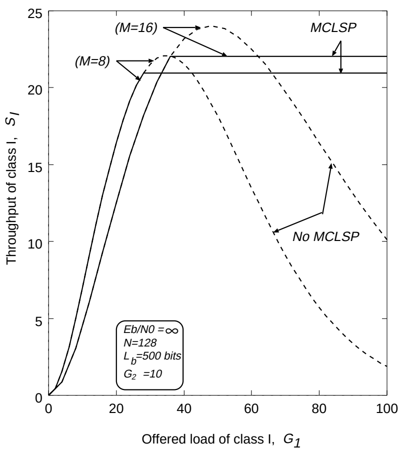

Fig. 6. Further improvement in the throughput of class I with MCLSP by increasing the multi-code factor

system.

VI. Conclusions

An MC-CDMA Slotted-ALOHA system supporting two classes of data users has been proposed.

Performance evaluation has been obtained in the respect of the throughput. We have shown that with an MC-CDMA technique, the throughput of the class required higher bit rate can be increased as the multi-code factor increases.

Moreover, to improve the throughput performance, we have applied the modified channel load sensing protocol to the system to control the access of the users from class I.

In our numerical example, we have shown that further improvement in the throughput can be obtained by applying the MCLSP. And the throughput of class I, as well as the total throughput, can reach a constant value even at high values of the offered load.

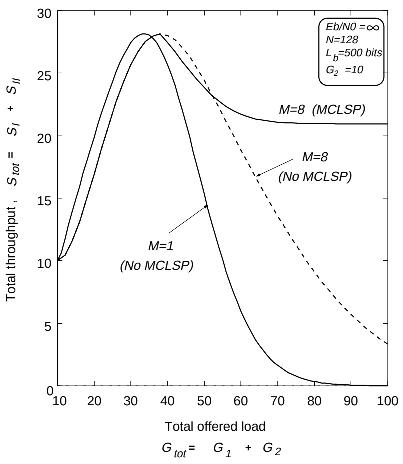

Fig. 7. Total throughput improvement by MC-CDMA and MCLSP

Acknowledgment

This work has been partly supported by the Ministry of Education, Science, Sports and Culture, Government of JAPAN, under Grant-in Aid for Scientific Research.

REFERENCES

[1] K. Pahlavan, A. H. Levesque “Wireless data communications,”*Proc. of The IEEE, Vol. 82, No. 9, Sep. 1994.*

[2] M. Soroushnejad and E. Geraniotis, “Multi-Access Strategies for an Integrated Voice/Data CDMA Packet Radio Network,”*IEEE, Trans. Commun., Vol. 43, No. 2/3/4, Feb./Mar./Apr. 1995.*

[3] K. Mori and K. Ogura, “An Adaptive Permission Probability Control Method for Integrated Voice/Data CDMA Packet Communications, ” *IEICE Trans. Fundamentals, Vol. E81-A, No. 7, Jul. 1998.*

[4] D. Makrakis, K. M. Sundaru Murthy, “Spread Slotted ALOHA Techniques for Mobile and Personal Satellite Communication Systems,” *IEEE JSAC., Vol. 10, No. 6, Aug. 1992.*

[5] T. Ottosson, A. Svensson, “Multi-rate Schemes in DS/CDMA Systems,” *IEEE VTC’95, Vol. 2 , 1995.*

[6] I. Chih-Lin, K. K. Sabnani, “Variable Spreading Gain CDMA with Adaptive Control for True Packet Switching Wireless Network,”*IEEE ICC’95, Vol. 2, 1995.*

[7] I. Chih-Lin, R. D. Gitlin, “Multi-code CDMA Wireless Personal Communications Networks,” *IEEE ICC’95, vol. 2, 1995.*

[8] T. Ottosson and A. Svensson, “On schemes for multirate support in DS-CDMA systems,” Wireless Personal Communications, Kluwer Academic Publishers, Vol. 6, No. 3, March 1998.

[9] H. Okada, M. Saito, T. Sato, T. Yamazato, M. Katayama, A. Ogawa “CDMA ALOHA Systems with Modified Channel Load Sensing Protocol for Satellite Communications,”*IEICE Trans. Fundamentals, Vol. E79-A, No.12, Dec. 1996.*

[10] L. Kleinrock, “Queueing Systems; volume. 1, Theory,” *New York : Wiley-Inter-Science, 1975.*

[11] M. B. Pursley, “Performance evaluation for phase-coded spread spectrum multiple-access communication-Part I: System analysis,”*IEEE Trans. Commun., Vol. COM-25, No.8, Aug. 1977.*

[12] A. Sandouk, T. Yamazato, M. Katayama, A. Ogawa, “A Study on the Throughput of Multi-Code CDMA ALOHA System with Modified Channel Load Sensing Protocol”*IEICE Technical Report, SST98-40, Oct. 1998.*

[13] M. Saito, H. Okada, T. Yamazato,, M. Katayama, A. Ogawa, “Throughput Performance of Spread Slotted ALOHA system with Modified Channel Load Sensing Protocol,”*IEICE Technical Report, SAT95-83, Dec. 1995.*