PAPER

Throughput Performance of CDMA Slotted ALOHA Systems Based on Average Packet Success Probability Considering Bit-to-Bit Dependence

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SUMMARY We propose the analytical calculation method of average packet success probability of CDMA Slotted ALOHA systems, which derives accurate probability, and that is applicable to the system with any spreading codes and any amplitude distributions. In the method, we consider the bit-to-bit dependence of amplitude of signals, used spreading sequences, relative timing delays, and relative carrier phases. This bit-to-bit dependence is the case that the parameters above mentioned are constant for a slot time. By using the method to obtain the average packet success probability, we derive useful throughput performance of CDMA Slotted ALOHA systems on fading channel, and show that the normalized throughput becomes worse in the case of larger spreading factor.

key words: CDMA Slotted ALOHA, packet success probability, bit-to-bit dependence, throughput

1. Introduction

CDMA packet radio system has been considered to provide promising high efficient and multimedia communication system [1]. In such CDMA packet communication systems, CDMA Slotted ALOHA system may be strong candidate for high speed wireless data transmission protocol, because it allows high throughput performance and the structure of the receiver will not be so complex as the receiver for unslotted system. So, many works about CDMA Slotted ALOHA system have been published related to performance analysis or improvement of the system [2]–[8].

To investigate the performance of CDMA packet communication systems, it is very important to obtain an accurate average packet success probability, which is the average probability of successfully received packets per one packet transmission [2],[9]. In many previous works, the probability has been calculated based on an average bit error probability. That is to say, every data bit is considered to occur error with the same probability which is the average bit error probability, because it is assumed to use random sequences and to be independent of bit-to-bit relations. The packet success probability given by this calculation has been reported that it is pessimistic compared with accurate value and it shows somewhat lower bound related to bit-to-bit dependence [3]. Because, if some good bit error probabilities and some bad ones are summed and averaged, then, the resulted average probability tends to be near bad error probabilities. Moreover, in the case of fading channel, the performance is extremely pessimistic, therefore, it is almost meaningless to evaluate some kinds of performance based on the results obtained from that calculation. Morrow analyzed the average packet success probability considering bit-to-bit dependence by using the theory of moment spaces [3]. However, that work is not enough for covering the cases of fading environment and the use of any spreading codes.

In the packet communication systems in which one packet duration is shorter than a changing rate of amplitude of signals, relative timing delays, and relative carrier phases, the partial cross correlation values between any two signals are kept in constant values for one packet time. This is valid for slowly fading channel and for pedestrian users.

In this paper, we show the analytical calculation method of average packet success probability of CDMA Slotted ALOHA systems. The average packet success probability is derived by averaging the packet success probabilities for the cases of various values of parameters. We consider the bit-to-bit dependence of amplitude of signals, used spreading sequences, relative timing delays, and relative carrier phases, that is, these parameters keep constant for a slot time. Therefore, the partial cross correlations also keep constant, and it enables us to be free from calculating the cross correlations bit by bit.

In the method, firstly, it is calculated the packet success probabilities for given values of parameters by analytical equations of the probability, then, the average value of those values is calculated, and the result is the average packet success probability. By these docile calculations, accurate average packet success probability can be obtained.

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Moreover, the method does not need any limitation to spreading code and the distribution of signal amplitude. This applicability is quite unlike to conventional methods of calculating the average packet success probability.

2. System Model

A single hop CDMA packet radio network system is considered. The system model is shown in Fig. 1. K_{max} user stations and a base station exist in this system. In this paper, we consider only up-link (link from user stations to the base station).

Each user station transmits a packet signal $s(t)$, which includes L data bits and whose time duration is T_p. The packet signal of the k-th user's l-th bit in a slot is represented as

$$s_{k,l}(t) = \sqrt{2P}a_k(t)\,d_{k,l}(t)\cos(\omega_c t + \theta_{k,l}) \qquad (1)$$

where P is the signal power of the bit signal, $a_k(t)$ is spreading code signal of the k-th user, $d_{k,l}(t)$ is data bit signal of the l-th bit, ω_c is carrier angular frequency and $\theta_{k,l}$ is the initial phase of the l-th bit. The data bit signal and spreading code signal are assumed to be the sequences of unit amplitude $\{-1,+1\}$ rectangular pulses. Spreading code sequence is uniquely assigned to each user station in advance, and consists of N chips per bit. Data bit signal interval is T_b, and it follows that $T_p = LT_b$.

Transmitted packet signals pass through a channel, where noise signal $n(t)$ with twosided spectral density $N_0/2$ is added. And the signals are attenuated with a rate α_k for the signal of k-th user. We consider the channel as a slowly fading channel whose coherence time is larger than one slot time. Therefore, the attenuation factor is assumed to be constant for a slot time. We consider the users are pedestrians.

Based on above assumptions about fading and the speed of users, we assume that amplitude of signals, relative timing delays, and relative carrier phases are constant for a slot time. We assume perfect power control for AWGN channel, and no power control for fading channel. The path model is assumed to be the single path model. Then the base station receives those signals.

As an access protocol, CDMA Slotted ALOHA protocol is considered. Figure 2 shows packet flow diagram at the base station under the protocol.

In CDMA Slotted ALOHA, user stations transmit their packets to synchronize with each time slot, whose length is T_{slot}. Packets generate with rate λ per one slot time for one user station.

When K users transmit packets in a slot, the received signal is shown as

$$r(t) = \sum_{k=1}^{K} \alpha_k s(t-\tau_k) + n(t) \qquad (2)$$

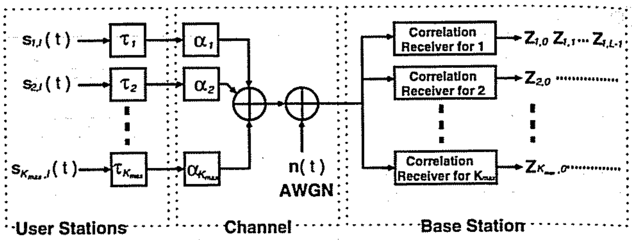

Fig. 1 System model.

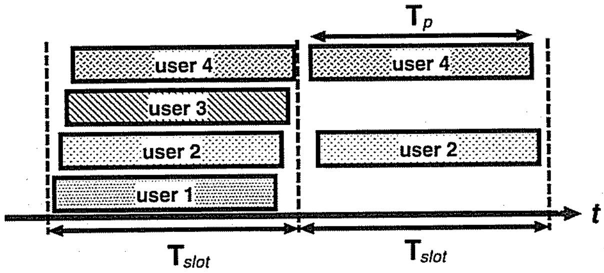

Fig. 2 Packet flow diagram at the base station in CDMA Slotted ALOHA system.

This signal is fed into the correlator of each user. The correlators output decision variables for data detection in each of the bit signal intervals. The correlator output for the i-th (desired) user's packet signal is shown as

$$\boldsymbol{Z}_i = (Z_{i,0}, \cdots, Z_{i,l}, \cdots, Z_{i,L-1}) \qquad (3)$$

and its l-th component is given by

$$Z_{i,l} = \sqrt{\frac{P}{2}}T_b \left[\alpha_i d_{i,l} + \sum_{\substack{k=1\\k\neq i}}^{K} I_{i,k,l}(\alpha_k, d_{k,l-1}, d_{k,l}, \boldsymbol{a}_k, \tau_k, \phi_k)\right] + Z_{noise} \qquad (4)$$

where α_k denotes the attenuation factor of k-th user's packet signal, $d_{k,l}$ the l-th data bit sequence for the k-th user, $\boldsymbol{a}_k = (a_{k,0}, a_{k,1}, \cdots, a_{k,N-1})$ the spreading code sequence for the k-th user, τ_k and ϕ_k relative timing delay and carrier phase between the k-th user signal and the i-th one, and Z_{noise} the noise component. With generality, it is assumed that $\phi_i = 0$ and $\tau_i = 0$. We consider bit level synchronization, therefore, the relative timing delays τ_k can be assumed to be uniformly distributed between $[\tau_i - T_b/2, \tau_i + T_b/2]$. And the relative carrier phases are assumed to be uniformly distributed between $[-\pi/2, \pi/2]$.

The multiple access interference component $I_{i,k,l}$ is given by [10]

$$\begin{aligned} I_{i,k,l}&(\alpha_k, d_{k,l-1}, d_{k,l}, \boldsymbol{a}_k, \tau_k, \phi_k) \\ &= \alpha_k \left\{ d_{k,l-1}R_{k,i}(\tau_k) + d_{k,l}\hat{R}_{k,i}(\tau_k) \right\} \cos\phi_k \end{aligned} \qquad (5)$$

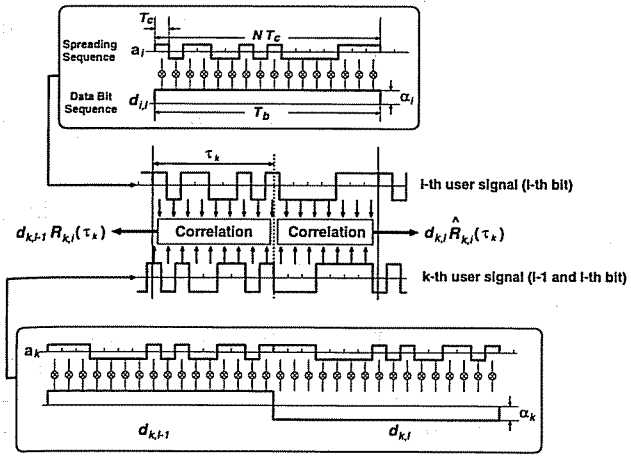

Fig. 3 Timing relation between desired signal and interference signal.

And the continuous-time partial cross correlation functions $R_{k,i}$ and $\hat{R}_{k,i}$ are given in terms of the discrete aperiodic cross correlation $C_{k,i}$ between the k-th and the i-th spreading sequences $\boldsymbol{a}_k$, $\boldsymbol{a}_i$.

$$R_{k,i}(\tau) = C_{k,i}(m-N)T_c + \{C_{k,i}(m-N+1) - C_{k,i}(m-N)\}(\tau - mT_c) \quad (6)$$

$$\hat{R}_{k,i}(\tau) = C_{k,i}(m)T_c + \{C_{k,i}(m+1) - C_{k,i}(m)\}(\tau - mT_c) \quad (7)$$

where T_c is a period of a spreading sequence chip and $m = \lfloor \tau/T_c \rfloor$ (the integer part of τ/T_c). The discrete aperiodic cross correlation $C_{k,i}$ is defined as

$$C_{k,i}(l) = \begin{cases} \sum_{j=0}^{N-1-l} a_{k,j}a_{i,j+l} & 0 \le l \le N-1 \\ \sum_{j=0}^{N-1+l} a_{k,j-l}a_{i,j} & 1-N \le l < 0 \\ 0 & |l| \ge N \end{cases} \quad (8)$$

Figure 3 shows the timing relation between desired signal and interference signal and the calculation process of (5), by using Eqs. (6) and (7). The operation "Correlation" denote the calculation of the product of partial cross correlation function and data for a given relative timing delay.

When K packets are received in a slot, the bit error probability for the desired user's l-th bit $p_{e_i}^{(l)}$ is given by

$$p_{e_i}^{(l)}(K, \boldsymbol{\alpha}, \boldsymbol{d}_{l-1}, \boldsymbol{d}_l, \boldsymbol{a}, \boldsymbol{\tau}, \boldsymbol{\Phi}) = \mathrm{Q}\left(\sqrt{\frac{2E_b}{N_0}}\left(\alpha_i d_{i,l} + \boldsymbol{I}_{i,l}(K, \boldsymbol{\alpha}, \boldsymbol{d}_{l-1}, \boldsymbol{d}_l, \boldsymbol{a}, \boldsymbol{\tau}, \boldsymbol{\Phi})\right)\right) \quad (9)$$

where Q() is Q function which is defined as

$$\mathrm{Q}(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-t^2/2}dt \quad (10)$$

and $\boldsymbol{\alpha}$ is the set of the attenuation factors for K users, $\boldsymbol{a} = (\boldsymbol{a}_0, \cdots, \boldsymbol{a}_{K-1})$ is the set of spreading sequences used in the slot, $\boldsymbol{d}_l = (d_{1,l}, \cdots, d_{K,l})$, $\boldsymbol{\tau} = (\tau_1, \cdots, \tau_K)$, $\boldsymbol{\Phi} = (\phi_1, \cdots, \phi_K)$ respectively show data bit sequences, relative timing delays and relative carrier phases to the i-th user and

$$\boldsymbol{I}_{i,l}(K, \boldsymbol{\alpha}, \boldsymbol{d}_{l-1}, \boldsymbol{d}_l, \boldsymbol{a}, \boldsymbol{\tau}, \boldsymbol{\Phi}) = \sum_{\substack{k=1 \\ k \ne i}}^{K} I_{i,k,l}(\alpha_k, d_{k,l}, \boldsymbol{a}_k, \tau_k, \phi_k). \quad (11)$$

3. Average Packet Success Probability

In this section, we derive an average packet success probability of CDMA Slotted ALOHA. In this paper, the meaning of "packet success" is defined that all of data bits are received without errors.

3.1 Average Packet Success Probability for General Cases

On CDMA Slotted ALOHA system, it can be considered that amplitude of packet signals, being used spreading sequences, relative timing delays, and relative carrier phases are invariant in a slot time. In this system, users employ uniquely assigned spreading sequences, so, the set of being used sequences and the number of simultaneous transmissions also dose not change in a slot time interval. This characteristic leads us to the result which partial cross correlation values between any two packet signals is constant in a packet time.

When K packets are transmitted on conditions of $\boldsymbol{\alpha}$, $\boldsymbol{d}$, $\boldsymbol{\tau}$, and $\boldsymbol{\Phi}$, the packet success probability of the i-th user is shown as following equation.

$$P_{s_i}(K, \boldsymbol{\alpha}, \boldsymbol{d}, \boldsymbol{a}, \boldsymbol{\tau}, \boldsymbol{\Phi}) = \prod_{l=0}^{L-1}\left(1 - p_{e_i}^{(l)}(K, \boldsymbol{\alpha}, \boldsymbol{d}_{l-1}, \boldsymbol{d}_l, \boldsymbol{a}, \boldsymbol{\tau}, \boldsymbol{\Phi})\right) \quad (12)$$

The average packet success probability $E(P_s(K))$ can be derived by averaging (12) on the parameters conditions.

$$E(P_s(K)) = \sum_{i \in \{1,\cdots,K_{sys}\}} \int_{\boldsymbol{\alpha}} \sum_{\boldsymbol{d}} \int_{\boldsymbol{\tau}} \int_{\boldsymbol{\Phi}} P_{s_i}(K, \boldsymbol{\alpha}, \boldsymbol{d}, \boldsymbol{a}, \boldsymbol{\tau}, \boldsymbol{\Phi}) f_{\boldsymbol{\alpha}}(\boldsymbol{\alpha}) f_{\boldsymbol{\tau}}(\boldsymbol{\tau}) f_{\boldsymbol{\Phi}}(\boldsymbol{\Phi}) d\boldsymbol{\alpha} d\boldsymbol{\tau} d\boldsymbol{\Phi} \quad (13)$$

Where $f_{\boldsymbol{X}}(\boldsymbol{X})$ shows the K fold probability density function of the random variables $\boldsymbol{X}$.

We call this average packet success probability (13), the average packet success probability by PSP method, because this is derived by averaging packet success probability.

3.2 Average Packet Success Probability for Random Sequences Case

In this section, we derive average packet success probability for a special case of using random sequences as spreading sequences. When random sequences are used, used spreading sequences of each slot vary. Therefore, cross correlation properties of each pair of spreading sequences have ergodicity, and it can be considered that correlator output of each bit is independent random variable.

Because of this ergodic cross correlation property, it can be regarded that error of each bit occurs with an average bit error probability. When K packets are transmitted, this probability is shown as follows.

$$E(p_e(K)) = \sum_{i\in\{1,\cdots,K_{sys}\}} \int_{\boldsymbol{\alpha}} \sum_{\boldsymbol{d}} \int_{\boldsymbol{\tau}} \int_{\boldsymbol{\Phi}} p_{e_i}^{(l)}(K, \boldsymbol{\alpha}, \boldsymbol{d}_{l-1}, \boldsymbol{d}_l, \boldsymbol{a}, \boldsymbol{\tau}, \boldsymbol{\Phi}) f_{\boldsymbol{\alpha}}(\boldsymbol{\alpha}) f_{\boldsymbol{\tau}}(\boldsymbol{\tau}) f_{\boldsymbol{\Phi}}(\boldsymbol{\Phi})\, d\boldsymbol{\alpha} d\boldsymbol{\tau} d\boldsymbol{\Phi} \quad (14)$$

By using (14), packet success probability in this case is written as follows.

$$P_s(K) = \{1 - E(p_e(K))\}^L \quad (15)$$

We call this average packet success probability (15) the average packet success probability by BEP method, because packet success probability obtained from average bit error probability is used.

Conventional works of calculating the average packet success probability, BEP method has been well used, in spite of treating each bit as independent. Because many approximation methods of the probability enable us to obtain well approximate average bit error probability without complex calculations.

In the following section, we will compare the average packet success probabilities by PSP and BEP as the comparison between proposed method and conventional method.

4. Numerical Examples

In this section, we introduce the throughput performance of CDMA Slotted ALOHA systems.

The throughput S is defined as the average number of packets that are received without data bit errors per one slot time, and is given by (10) of [9] as follows,

$$S(G) = \sum_{k=1}^{K_{max}} k \binom{K_{max}}{k} \lambda^k (1-\lambda)^{K_{max}-k} P_s(k) \quad (16)$$

where G is the offered load which is defined as the average number of packet generations per one slot time, and is shown as $G = \lambda \cdot K_{max}$.

In the following, we show the throughput and the offered load normalized by the spreading factor N. This normalization is aimed at comparing the throughput performance of CDMA ALOHA among different spreading factors and pure ALOHA and Slotted ALOHA systems.

To obtain the average packet success probability, we use two methods which were derived in Sect. 3.

It is too complex to obtain the exact average packet success probability shown as (13) and (15), therefore, we utilized Monte Carlo simulation for giving each parameter value. In this paper, we assume that the amplitude, a spreading sequence, a relative delay, and a relative carrier phase are constant for a slot time. Therefore, we give those parameter values obtained from random number generator slot by slot. On the other hand, each data bit is given bit by bit. For AWGN channel, the attenuation factor α_k is unit. And for Rayleigh fading channel, two independent gaussian random variables are generated, and the square root of the sum of those values squared is set as α_k. The gaussian random variables are beforehand normalized that $\overline{\alpha_k^2} = 1$. The relative delay and the relative carrier phase are given by the uniformly distributed random variables of the each range. Spreading sequences for given number of users are randomly selected from the whole sequences, in order not to be assigned one sequence to multiple users.

Figure 4 shows the average packet success probabilities against the number of packets in a slot. Orthogonal Gold sequences of $N = 32$ are used as spreading sequences, and we assume $E_b/N_0 = 20$ [dB] and packet length $L = 500$ [bits], in the simulation. For a given number of packets, the sequences used for each simulation trial are randomly selected from all the sequences in a code. For AWGN channel, the average packet success probabilities obtained from PSP and BEP base methods are almost similar in the region of small number of packets. By the PSP base method, higher packet

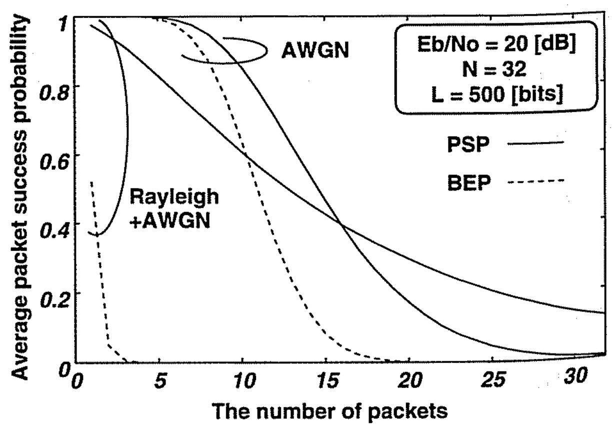

Fig. 4 Average packet success probability of CDMA Slotted ALOHA system with orthogonal Gold sequences.

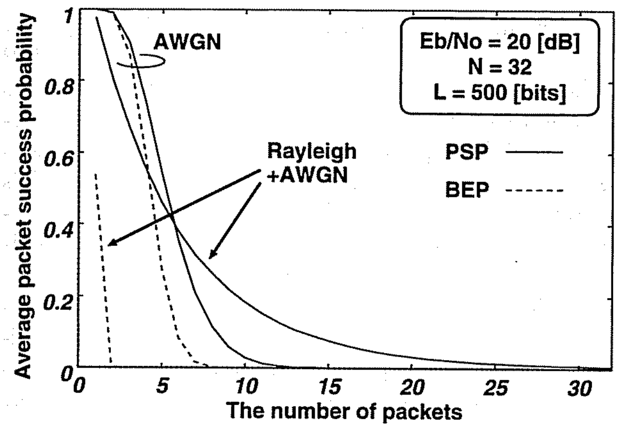

Fig. 5 Average packet success probability of CDMA Slotted ALOHA system with random sequences.

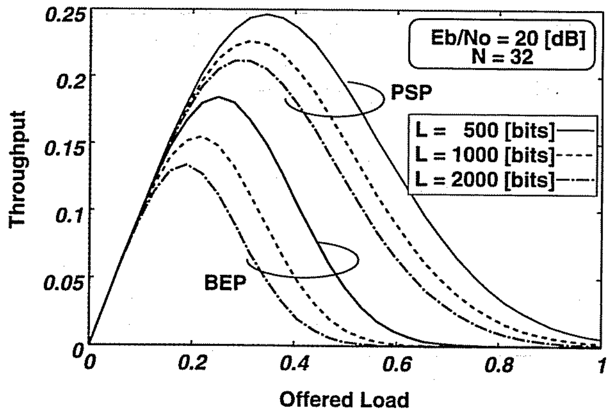

Fig. 6 Throughput performance of CDMA Slotted ALOHA system with orthogonal Gold sequences for various packet sizes in AWGN channel.

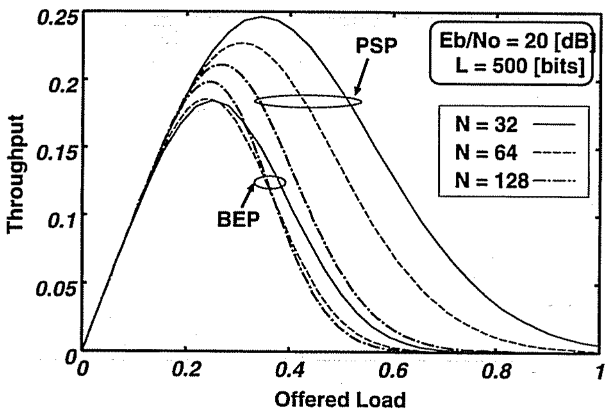

Fig. 7 Throughput performance of CDMA Slotted ALOHA system with orthogonal Gold sequences for various spreading factors in AWGN channel.

success probability can be obtained in the case of large number of packets. Because orthogonal Gold sequences are not random sequences, the cross correlation property of each pairs of the sequences may not be ergodic. And the average packet success probability by BEP base method tends to be pessimistic compared with the probability by PSP. From those reasons, the average packet success probability by the PSP base method shows higher performance. For Rayleigh fading and AWGN channel, the average packet success probability by BEP base method is extremely low for almost all the number of packets. This is because some samples of extremely high bit error probability by the bad conditions of parameters makes whole average packet success probability very low. On the other hand, the probability by PSP method gently degrades according to increase of number of packets, and the value does not so worse than the case of BEP base method. From the results of BEP base method in this figure, we can see that ignoring bit-to-bit dependence underestimates the performance. In particular, the result of BEP base method shows very low in Rayleigh fading environment. Moreover, in the case of large number of packets, the average packet success probability for fading environment is better than that for AWGN channel, because some large power packets survive even in the existence of large number of interference packets.

Figure 5 shows the average packet success probabilities by random sequences as against the number of packets in a slot. The sequences length $N = 32$, $E_b/N_0 = 20$ [dB] and packet length $L = 500$ [bits], in this simulation. For all conditions, the average packet success probabilities are less than those by orthogonal Gold sequences, but the tendency of curves is nearly the same. For AWGN channel, the average packet success probabilities obtained from PSP and BEP base methods are almost similar in whole region compared with results of Fig. 4.

Figure 6 shows the throughput performance of CDMA Slotted ALOHA system with $N = 32$ orthogonal Gold sequences for variant packet bit lengths. Packet length is set at $L = 500, 1000, 2000$ [bits]. Increased packet length L results in lower packet success probability according to multiplications of bit success probability, giving lower throughput in both methods.

Figure 7 shows the throughput performance with orthogonal Gold sequences for variant spreading factors $N = 32, 64$ and 128. E_b/N_0 is set at 20 [dB] and packet length L is set at 500 [bits]. When the PSP method is used, increasing spreading factor gives lower throughput performance. The packet success probability depends on whether the bit error probability is small over the whole bits in a packet. In the case of large spreading factor, the number of accommodated users becomes large, and the number of combinations of cross correlation values increase. Total amount of the interference from undesired packet signals may be regarded as the sum of such cross correlation values multiplied by random data bits. The increase of the number of packets also increases the probability that large interference occurs for a packet. On the other hand, when

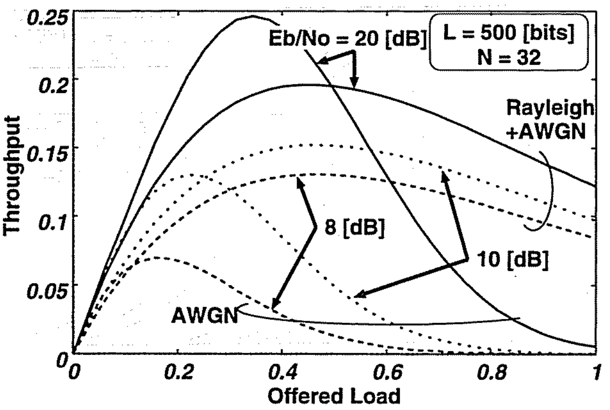

Fig. 8 Throughput performance of CDMA Slotted ALOHA system with orthogonal Gold sequences by PSP method for various SNRs.

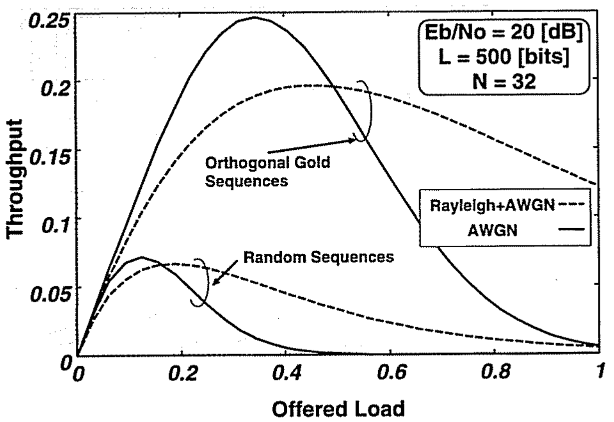

Fig. 9 Throughput comparisons between the system with orthogonal Gold sequences and random sequences.

the BEP method is used, increasing spreading factor makes throughput higher because of large mass effect. Moreover, it can be seen that throughput performance by both methods may converge in the case of longer spreading sequences.

Figure 8 shows the throughput performance with orthogonal Gold sequences by PSP method for various E_b/N_0. Spreading factor is $N = 32$ and packet length is $L = 500$ [bits]. For high SNR $E_b/N_0 = 20$ [dB], maximum throughput at AWGN channel is higher than one at fading channel in low offered load, and then, throughput at fading channel overcomes in high offered load. For low SNR $E_b/N_0 = 8, 10$ [dB], maximum throughput and almost whole throughput at fading channel are superior to those at AWGN channel, because the packet success probability of each packet is degraded same extent by same signal powers in AWGN channel, and some larger power signals at fading channel survive even in noisy channel.

Figure 9 shows throughput comparisons between the system with orthogonal Gold sequences and random sequences on AWGN and AWGN with Rayleigh fading channels. Spreading factor is $N = 32$ and packet length is $L = 500$ [bits] and E_b/N_0 is set at 20 [dB]. PSP method is used for obtaining average packet success probabilities. For both channels, the system with orthogonal Gold sequences indicates about three times as high maximum throughput as random sequences. This difference is caused from the difference of cross correlation property between both spreading sequences. This result suggests that the sequence set having good cross correlation property would have better suitability as a spreading sequence set of CDMA packet communication systems than pseudo-random sequences, for example, concatenated sequences of long code and short code.

5. Conclusions

In this paper, two calculation methods of the average packet success probability in CDMA Slotted ALOHA systems have been shown, that is, packet success probability (PSP) based method and bit error probability (BEP) based method.

PSP method derives more accurate average packet success probability than that by BEP method, because of docile calculations of the average packet success probability and considering bit-to-bit dependence of the parameters which are amplitude, spreading sequences, relative delay, and relative carrier phase. Especially, in the case of a fading channel, the average packet success probability from BEP method is almost meaningless, but the performance is clarified by PSP method.

PSP is applicable to any channel model or system model, and is specially suitable for the case of slowly fading channel and pedestrian users, however, it is not suitable for the system that the parameters above mentioned varies very fast, because of the necessity of huge amount of calculations.

The BEP method is applicable to the system model that equal amplitude signals and random sequences are assumed or large spreading factors, and the model that the parameters change very fast. And BEP method can be utilized the approximations of the average bit error probability, in this case, the amount of calculation dramatically decreases.

Acknowledgments

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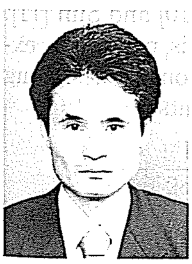

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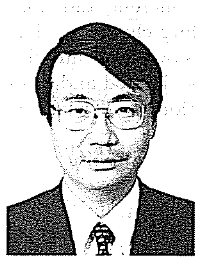

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