Impact of Interference Cancellation Technique on Throughput of Nonorthogonal CSK/SSMA ALOHA System

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***Abstract*— The nonorthogonal Code Shift Keying (CSK)/SSMA ALOHA system was proposed in order to improve DS/SSMA ALOHA system performance. Its throughput improves with the length of the nonorthogonal signals. However, it is not efficient for each user to have exceedingly-long signals in a wireless network with finite population. Introducing interference cancellation into our system is expected to raise system performance without increasing signal length. This paper presents a theoretical analysis of the throughput performance of nonorthogonal CSK/SSMA ALOHA system with an interference canceler. The results show that the throughput performance of the nonorthogonal CSK/SSMA ALOHA can exceed 1.0 with the interference canceler. It is also found that the throughput of this system exceeds that of DS/SSMA ALOHA system.**

***Index Terms*— ode Shift Keying (CSK), Nonorthogonal signal, ALOHA, Interference Canceler, maximum throughput**

I. INTRODUCTION

THE advanced wireless networks, such as Wireless Personal Area Networks (WPANs) are attracting more interest [1]-[4] The Direct Sequence Spread Spectrum Multiple Access (DS/SSMA) ALOHA system is widely used in such wireless networks because of its two key advantages; simple transmission procedure and multiple access [5] and [6].

In [7]-[12], multiple-access-interference cancellation techniques are studied for achieving high throughput. The nonorthogonal Code Shift Keying/Spread Spectrum Multiple Access (CSK/SSMA) ALOHA system, which is one of the code-multilevel modulations, is proposed for improving the throughput performance of the DS/SSMA ALOHA system [13] and [14].

In [13] and [14], it is showed that the throughput performance of the nonorthogonal CSK/SSMA ALOHA system is better than that of the conventional DS/SSMA ALOHA system. It is also showed that the throughput of the system in [13] and [14] improves as nonorthogonal signal length is increased. Unfortunately, achieving high throughput needs exceedingly long signals. Such signals are not efficient in small-sized wireless networks. It is expected that the introduction of interference cancellation in order to overcome this issue [7].

Introducing an interference canceler into the nonorthogonal CSK/SSMA ALOHA system is expected to improve the spectral efficiency and the throughput. The effect of interference cancellation on DS/SSMA ALOHA system has been investigated [8] and [9]. Some papers [11] and [12] study the cancellation algorithm for enhancing the interference cancellation capabilities. Combination of the cancellation technique and the other technique for achieving high throughput is not really studied. The effect of the interference cancellation on the nonorthogonal CSK/SSMA ALOHA system is unclear. Its effect is expected to be great because the code-multilevel modulations and the interference canceler go well together.

In this paper, the authors derive the throughput of the nonorthogonal CSK/SSMA ALOHA system theoretically, and then evaluate its throughput. The authors investigate the improvement in throughput made possible by adding interference cancellation. The authors compare it to two conventional SSMA ALOHA systems: the DS/SSMA ALOHA system and the orthogonal CSK/SSMA ALOHA system. The outline of this paper is as follows. Section 2 details the model of our system. Section 3 analyzes its throughput performance. Section 4 describes its measured throughput performance. Section 5 summarizes the main results.

II. SYSTEM MODEL

A. Network model

Figure 1 shows the model of our system. In order to distinguish users, each user has a unique Pseudo-Noise (PN) code. All users have the same M_{non} nonorthogonal signals, $(C_1, C_2, \ldots, C_{Mnon})$, which are used for CSK.

The notation used in the following discussion is shown in Table 1.

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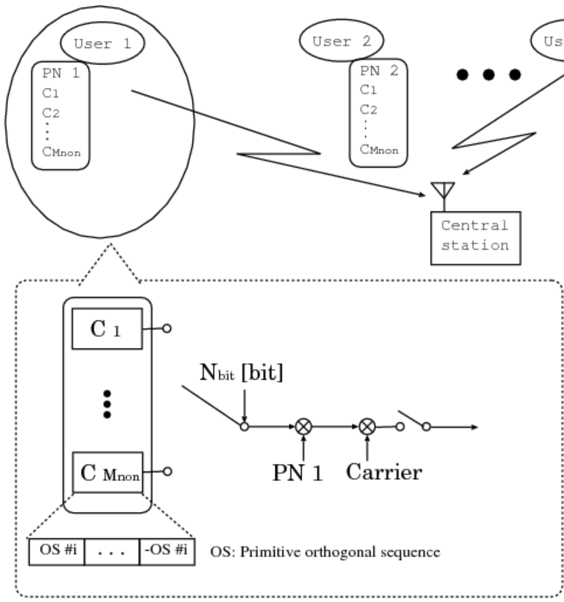

Fig. 1. System model

TABLE I
NOTATIONS

Parameter	Definition
$L_{p\text{-}info}$	Number of bits of a packet [bit]
L_p	Packet length [signals]
L_{signal}	Signal length
M_{os}	Number of orthogonal codes
M_{con}	Number of concatenations
M_{non}	Number of nonorthogonal signals
N_{bit}	Number of bits per nonorthogonal signal (=$\log_2 M_{os}+M_{con}$)
K	Number of users
k	Number of interfering packets
G	Average number of generated packets in a packet duration (Offered Load)

B. *Transmitter*

When transmitting, the transmitter carries out the following procedures:

1. The information carried by the packet, $L_{p\text{-}info}$, is divided into $\frac{L_{p-\inf o}}{N_{bit}}(=L_p)$.
2. One of M_{non} nonorthogonal signals is selected.
3. The selected nonorthogonal signal is multiplied by the assigned PN code. Each nonorthogonal signal has the same length and the same chip interval as the PN code.
4. One packet, which consists of L_p signals, is multiplied by the carrier, and the result is transmitted.

C. *Nonorthogonal signals*

Figure 2 shows an example of nonorthogonal signals. In our system, nonorthogonal signals are constructed systematically. One nonorthogonal signal is constructed by concatenating 3 orthogonal codes, which we call primitive orthogonal codes. The nonorthogonal signals are constructed by concatenating with following patterns: (0,0,0), (0,0,1), (0,1,0), (0,1,1), (1,0,0), (1,0,1), (1,1,0), and (1,1,1). One primitive orthogonal codes constructs $8\ (=2^3)$ nonorthogonal signals. The group of nonorthogonal signals constructed from orthogonal code *#i* is called group *#i*. The signals are orthogonal among the groups, but nonorthogonal in the same group.

D. *Cross correlation value*

Table II shows the cross-correlation values of the nonorthogonal CSK/SSMA system when $M_{os}=64$, $M_{con}=3$.

The correlation values, which are normalized to the number of CSK signals, are {1, $1/3$, 0, $-1/3$, -1}, and the number of signals, whose correlation values are 0, is $8M_{os}$-1. The correlation values of the orthogonal CSK/SSMA ALOHA system are $\{1,0\}$, and the number of signals, whose correlation values are 0, is M_{os}-1.

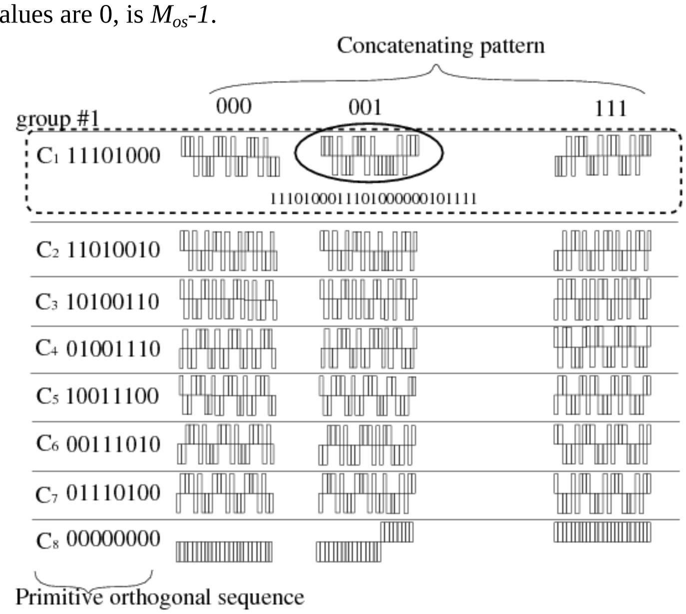

Fig. 2. Structure of nonorthogonal signal

TABLE II
CORRELATION VALUES

System	Correlation value	Num. of seq.
Nonorthogonal CSK/SSMA ($M_{con}=3$)	1	1
	$1/3$	3
	0	$8(M_{os}-1)$
	$-1/3$	3
	-1	1
Orthogonal CSK/SSMA	1	1
	0	M_{os}-1

E. Receiver with interference canceler

Figure 3 shows the canceler of our system. All transmissions are assumed to be synchronized completely, and each time delay adjustment is perfect. The receiver carries out the following procedures:

1. The received signal is multiplied by each PN code.
2. The signal is correlated with CSK signals and then re-modulated with the same signal.
3. The re-modulated signal is re-spread by the same PN code again in order to re-construct the interfering packets.
4. The re-spread signal is subtracted from the original received signal. Subtraction is done for each signal.
5. The subtraction result is demodulated for each signal.
6. N_{bit} [bit] data is demodulated by estimating the transmitted primitive orthogonal sequence and the concatenating pattern.

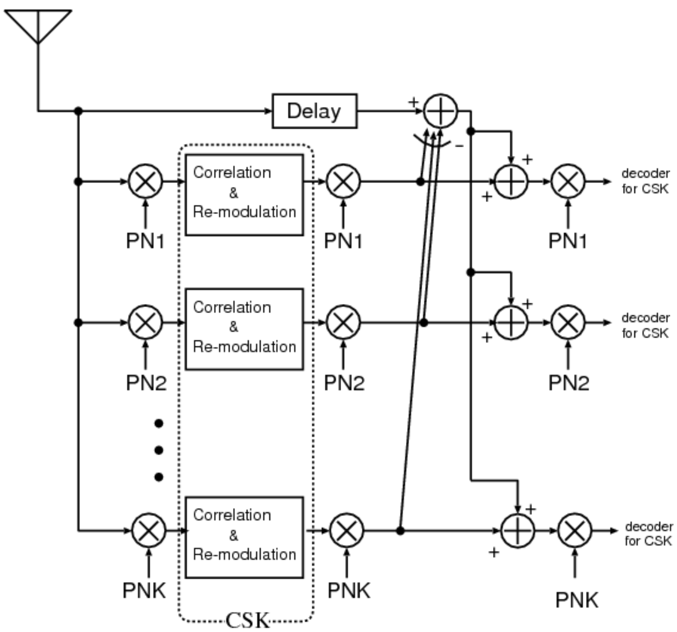

Fig. 3. Model of canceler

III. THEORETICAL ANALYSIS

A. Assumptions

The authors assume the following when analyzing the throughput performance. Notations used in the analysis are written in Table III.

- Every transmitted signal is received by the central station with equal power: i.e. transmitted signal power is controlled by the central station.
- The number of bits per packet is fixed at $L_{p\text{-}info}$ bits. When the duration of a nonorthogonal signal is Δt, packet duration, T_p, is

$$T_p = \frac{L_{p-\inf o}}{N_{bit}} \Delta t = L_p \Delta t.$$

- The offered load, G, is defined as the average number of generated packets in T_p. G_{chip} is defined as the offered load in the chip interval:

$$G_{chip} = \frac{G}{L_p M_{con} M_{os}} = \frac{G}{L_p L_{signal}}.$$

The authors assume that each signal has the same length as its PN code.

- The number of users is finite. Packet generation follows a binomial distribution.

TABLE III
NOTATIONS 2

Parameter	Definition
Pe(k)	Error rate of a nonorthogonal signal when the number of interfering packets is *k*
SNR(z)	Signal to noise ratio when the interfering energy is *z*
$P_{ocs}(z)$	Probability that a primitive orthogonal code is estimated successfully when the number of interfering packets is *k*
ke_1	Number of interfering packets after re-modulation
ke_2	Number of interfering packets for the primitive orthogonal code
Pc(k)	Probability that a nonorthogonal signal is received successfully when the number of interfering packets is *k*
Ps(k)	Probability that one packet is received successfully when the number of interfering packets is *k*

B. Frame success rate

If a signal error occurs, the incorrect signal is subtracted from the desired signal. In our system, each signal is constructed by concatenating primitive orthogonal codes. Cancellation error occurs in two ways:

- Primitive orthogonal code is estimated incorrectly. Then, the power of the interfering signal is doubled. (Error pattern 1)
- Primitive orthogonal code is estimated correctly but its polar characteristics are estimated incorrectly. That is, the power of the interfering signal is quadrupled. (Error pattern 2)

We assume that signal to noise ratio (SNR) at the receiver fluctuates according to Gaussian distribution. When the number of interfering packets is k, error rate of one signal for error pattern 1, $Pe(ke_1)$, is given by

$$Pe(ke_1)=\int_{ke_1-2\sigma_I^2}^{ke_1+2\sigma_I^2}\frac{1}{\sqrt{2\pi\sigma_I^2}}\exp\left(-\frac{(z-ke_1)^2}{2\sigma_I^{\ 2}}\right)$$
$$\times\left\{1-\left[1-\frac{1}{2}erfc\left(\sqrt{\frac{SNR(z)}{M_{con}}}\right)\right]^{M_{con}}P_{ocs(z)}\right\}dz, \tag{1}$$

where ke_1 is the number of interfering packets after re-modulation,

$$ke_1=2k(1-P_{ocs}(k)). \tag{2}$$

SNR(z) indicates the ratio of the transmitted signal to the noise power spectral density [13].

$$SNR(z)=\frac{1}{2}\left[\frac{|z|}{3L_{signal}}+\frac{1}{2}\left(\frac{N_0}{N_{bit}E_b}\right)\right]^{-1}. \tag{3}$$

$P_{ocs}(z)$ is the success rate for a primitive orthogonal code when the amount of interference is k; it is given by [13]

$$P_{ocs}(z)=\int_{-\infty}^{\infty}f(x_1)\left[\int_{-\infty}^{x_1}\underset{j\neq 1}{f(X_j)}dx_j\right]^{M_{os}-1}dx_{1,} \tag{4}$$

$$f(x_j)=\underbrace{g(|q_j|)\otimes\cdots\otimes g(|q_j|)}_{M_{con}\ times}, \tag{5}$$

$$g(q_j)=\frac{1}{\sqrt{2\pi\sigma_j^{\ 2}}}\exp\left[-\frac{1}{2}\left(\frac{q_j-\mu_j}{\sigma_j}\right)^2\right]. \tag{6}$$

q_j is the output of the j-th correlator, μ_j is the mean of random variable q_j, $\sigma_j=\frac{N_{bit}M_{con}}{2SNR(z)}$, and '$\otimes$' expresses the convolution integral. Similar to Eq. (1) the error rate of one signal for error pattern 2, $Pe(ke_2)$ is given by

$$Pe_2(k)=Pe_1(ke_2), \tag{7}$$

where ke_2 is the number of interfering packets for the primitive orthogonal code; it is given by

$$ke_2=4k\left[\frac{1}{2}erfc\left(\sqrt{\frac{SNR(z)}{M_{con}}}\right)P_{ocs}(z)\right], \tag{8}$$

From the above, the authors can obtain the success rate for one signal, *Pc(k)*,

$$Pc(k)=\left[1-Pe(ke_1)-Pe(ke_2)\right]. \tag{9}$$

C. *Throughput*

The authors assume that the interfering packets are canceled every one packet. In this case the success rate of one packet, *Ps(k)* is expressed as

$$Ps(k)=\left[Pc(k)\right]^{L_p}, \tag{10}$$

where L_p is packet length [signals]. The throughput *S*, which is defined as the number of success bits per chip, is given by

$$S=\frac{\log_2 M_{os}+M_{con}}{L_{signal}}$$
$$\times\sum_{k=0}^{K}\left(\frac{G}{K}\right)^{k+1}\left(1-\frac{G}{K}\right)^{K-k-1}Ps(k). \tag{11}$$

IV. Numerical Results

In this section, the authors show the throughput performance and the maximum throughput of our system. From [14], the authors found that the optimum number of concatenations is 4 in our system with access control. Thus, the authors set the number of concatenations M_{con} to 4. The authors compare our system with the conventional systems. In the comparison, the number of bits per packet is fixed, thus the packet length differs by systems; our system, the orthogonal CSK/SSMA ALOHA system and the DS/SSMA ALOHA system.

A. *Throughput of our system*

Figure 4 shows the throughput of our system for the number of bits per packet, $L_{p\text{-}info}=2520$ [bit], the number of users, $K=200$, the number of primitive orthogonal codes, M_{os}=32, the number of concatenations, M_{con}=4, the signal length, $L_{signal}=128$, the packet length, $L_p=280$ [signals], and $E_b/N_0=\infty$ [dB]. The vertical axis represents the normalized throughput [bits/chip], and the horizontal axis represents the offered load in a chip duration, G_{chip}. The throughput improves by introducing the interference cancellation technique. The maximum throughput of nonorthogonal CSK/SSMA ALOHA with the interference canceler is 3.5 times better than that without the interference canceler.

Figure 5 shows the maximum throughput of our system versus the number of concatenations, M_{con}. The vertical axis represents the maximum throughput, and the horizontal axis represents M_{con}. In this figure, (M_{os}, M_{con}) = (128,1), (64,2), (32,4), (16,1). There is an optimum number of concatenations, M_{con}. The reason why the optimum number exists is the trade-off between the effect of inter-symbol-interference and the increase of data-transmission rate per symbol. The throughput for $M_{con}=4$ is the highest in the nonorthogonal CSK/SSMA ALOHA system. The following throughput evaluations consider $M_{con}=4$.

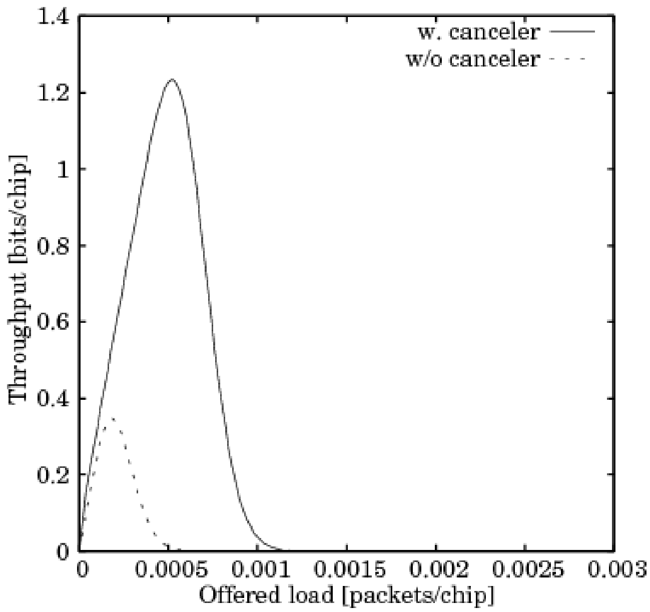

Fig. 4. Normalized throughput of our system versus offered load ($L_{p\text{-}info}=2520$, $M_{os}=32$, $M_{con}=4$, $E_b/N_0=\infty$ [dB], $K=200$, $L_{signal}=128$)

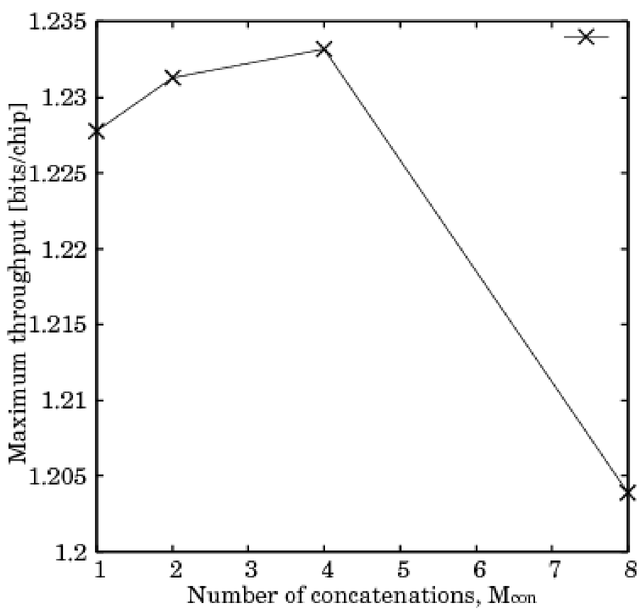

Fig. 5. Maximum throughput of our system versus number of concatenations ($L_{p\text{-}info}=2520$, $M_{os}=32$, $E_b/N_0=\infty$ [dB], $K=200$)

B. Throughput comparison

Figure 6 shows the normalized throughput versus G_{chip} when $K=200$, $L_{p\text{-}info}=2520$ [bit], and $E_b/N_0=\infty$ [dB]. In the nonorthogonal CSK/SSMA ALOHA system, $M_{os}=32$, $M_{con}=4$, $L_{signal}=128$, and $L_p=280$. In the orthogonal CSK/SSMA ALOHA system, $L_{signal}=M_{os}=128$ and $L_p=360$. In the DS/SSMA ALOHA system, $L_{signal}=128$ and $L_p=2520$. Nonorthogonal CSK/SSMA ALOHA has 1.02 times higher maximum throughput than orthogonal CSK/SSMA ALOHA, and 1.29 times higher maximum throughput than DS/SSMA ALOHA. From Fig. 6, the maximum throughputs of the nonorthogonal CSK/SSMA ALOHA system exceed 1.0 due to the advantage of multilevel modulation.

Figure 7 shows the maximum throughput versus E_b/N_0 for $K=200$, $L_{p\text{-}info}=2520$ [bit], $L_{signal}=128$. In the nonorthogonal CSK/SSMA ALOHA system, $M_{os}=32$, $M_{con}=4$, and $L_p=280$. $M_{os}=128$ and $L_p=360$ in the orthogonal CSK/SSMA ALOHA system. $L_p=2520$ in the DS/SSMA ALOHA system. Figure 8 shows that the throughput performance of our system does not improve so much in noisy channels (E_b/N_0 is low). This is because some incorrect signals may be subtracted from the signal received over noisy channels. The authors also found that the nonorthogonal CSK/SSMA ALOHA with the interference canceler offers the highest maximum throughput. Moreover, the CSK/SSMA ALOHA systems have throughputs of over 1.0 while DS/SSMA does not exceed 1.0.

Figure 8 shows the throughput versus the offered load for $\sigma_I^2=0.25$, 1.0, and 4.0 when $K=200$, $L_{p\text{-}info}=2520$ [bit], $L_{signal}=128$, $M_{os}=32$, and $M_{con}=4$. Figure 9 shows the maximum throughputs of the nonorthogonal CSK/SSMA ALOHA system, the orthogonal CSK/SSMA ALOHA system and the DS/SSMA ALOHA system versus σ_I^2. The throughput performance degrades when the influence of cancellation-error increases. Especially, the CSK/SSMA ALOHA systems affects the influence of cancellation-error compared with the DS/SSMA ALOHA system. The throughput of the CSK/SSMA ALOHA system, however, is better than that of the DS/SSMA ALOHA system.

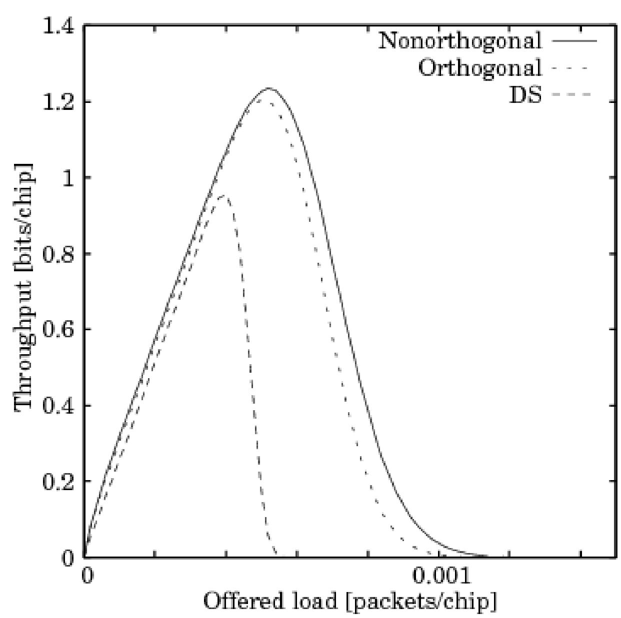

Fig. 6. Normalized throughput versus offered load ($L_{p\text{-}info}=2520$, $E_b/N_0=\infty$ [dB], $K=200$, $L_{signal}=128$)

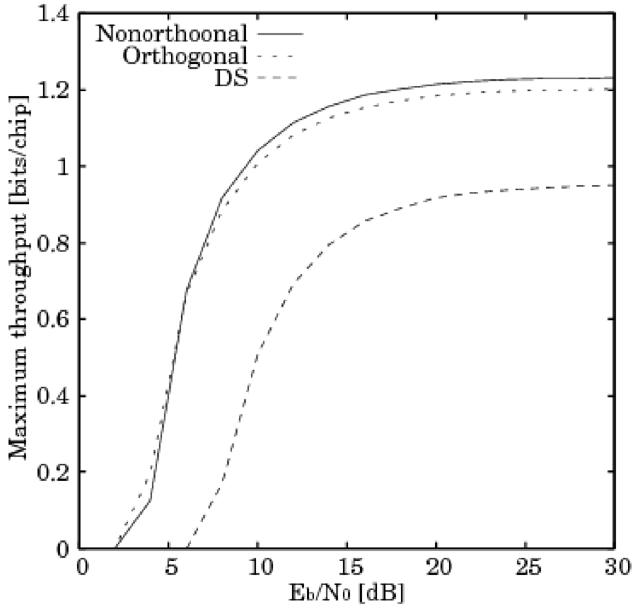

Fig. 7. Maximum throughput versus E_b/N_0 ($L_{p\text{-}info}=2520$, $K=200$, $L_{signal}=128$)

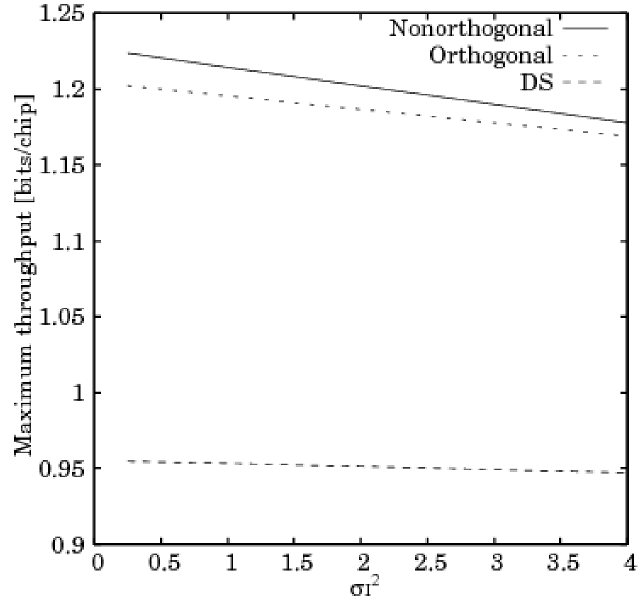

Fig. 9. Maximum throughput of our system versus σ_I^2 ($L_{p\text{-}info}=2520$, $E_b/N_0=\infty$ [dB], $K=200$, $L_{signal}=128$)

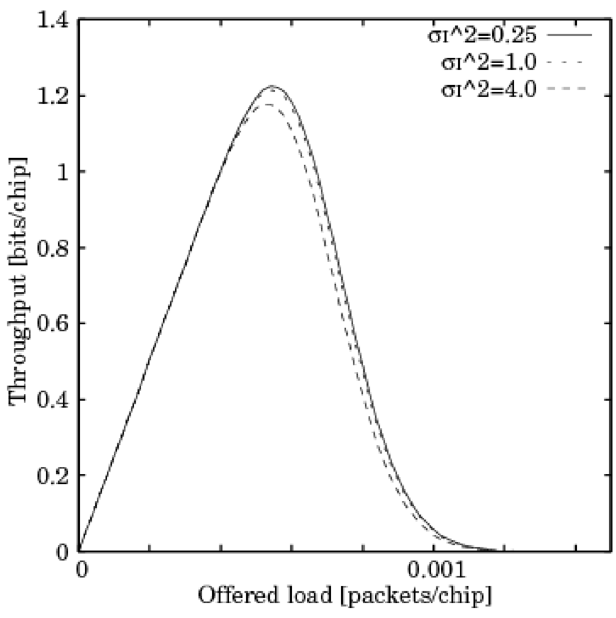

Fig. 8. Normalized throughput of our system versus offered load ($L_{p\text{-}info}=2520$, $M_{os}=32$, $M_{con}=4$, $E_b/N_0=\infty$ [dB], $K=200$, $L_{signal}=128$)

V. CONCLUSION

This paper presents the evaluation of throughput performance of the nonorthogonal CSK/SSMA ALOHA with an interference cancellation technique. In the nonorthogonal CSK/SSMA ALOHA, the nonorthogonal sequences which are used for CSK are constructed by concatenating M_{con} primitive orthogonal sequences. Our study indicated that introducing an interference cancellation technique into the nonorthogonal CSK/SSMA ALOHA is very effective. From the numerical results, we obtained the following points;

- The normalized throughput (maximum throughput) can exceed 1.0. The nonorthogonal CSK is one of the multilevel modulation systems, and it has the usual effect of M-ary/SSMA. So, some bits can be demodulated successfully at the same time. Moreover, the spectral efficiency of our system can exceed 1.0 as well as that of M-ary/SSMA [7].
- The throughput performance of our system shows about 3.5 times increase by using the interference cancellation technique.
- When comparing the nonorthogonal CSK/SSMA ALOHA system with the conventional SSMA ALOHA systems, the maximum throughput of nonorthogonal CSK/SSMA ALOHA system with the interference canceler is the highest.

From above, we can conclude that the nonorthogonal CSK/SSMA ALOHA with the interference canceler is effective.

Future works include investigating the impact of the interference cancellation technique on nonorthogonal CSK/SSMA ALOHA under fading channels, finding a way to reduce the signal error, evaluating the proposed system by simulation, the implementation of successive interference canceler, and investigating the nonorthogonal CSK/SSMA system that uses access control together with the interference cancellation.

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