Effect of the Interference Canceler on the Nonorthogonal CSK/CDMA ALOHA

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Abstract: Nonorthogonal Code Shift Keying Code Division Multiple Access (CSK/CDMA) ALOHA is expected to improve the throughput in advanced wireless network, such as sensor networks and ad-hoc networks. The throughput of the nonorthogonal CSK/CDMA ALOHA is expected to get better by introducing interference cancellation technique. It is not clear how much the throughput improved by introducing interference canceler. This paper presents the throughput performance of the nonorthogonal CSK/CDMA ALOHA with interference canceler by theoretical analysis. Consequently, it is found that the throughput performance of our system is over 1.0. It is also found that the throughput performance shows more than 295 % increase by using the interference canceler when E_b/N_0 is high.

1. Introduction

The CDMA ALOHA systems are widely used in wireless communication networks because of its advantages; simple transmission procedure and multiple access [1][2]. However, the throughput is not so high. To improve the throughput performance of the DS/CDMA ALOHA system, we have proposed and investigated the nonorthogonal Code Shift Keying Code Devision Multiple Access (CSK/CDMA) ALOHA system [4]. In our system, the sequences which are used for CSK are constructed by concatenating M_{con} primitive orthogonal sequences. We have shown that the throughput performance of our system is 2.0 times or more higher than that of the conventional CDMA ALOHA system [4]. However, the throughput performance deteriorates significantly when the number of ongoing users exceeds the network capacity. To overcome this problem, we introduce the interference cancellation technique into the nonorthogonal CSK/CDMA ALOHA system [3]. Using the interference canceler into the nonorthogonal CSK/CDMA ALOHA system is expected to improve the throughput, but its effect is unclear.

This paper presents the effect of interference cancellation technique on the nonorthogonal CSK/CDMA ALOHA system. We derive the throughput of the nonorthogonal CSK/CDMA ALOHA system theoretically, And then we evaluate its throughput. We investigate the improvement factor of the throughput by using interference canceler. And we compare our system with the conventional CDMA ALOHA systems; the DS/CDMA ALOHA system and the orthogonal CSK/CDMA ALOHA system. The notation on the following discussion is shown in Table 1.

Table 1. Notations

L_{p-info}	Number of bits of the packet [bit]
L_p	Packet length [sequences]
L_{frame}	Frame length [chips]
M_{os}	Number of orthogonal sequences
M_{con}	Number of concatenations
M_{non}	Number of nonorthogonal sequences
N_{bit}	Number of bits per sequence ($= \log_2 M_{os} + M_{con}$)
K	Number of users
k	Number of interfering packets
G	Average number of generated packets in a packet duration (Offered load)
E_b/N_0	Ratio of transmitted signal energy per bit to noise power spectral density

2. System Model

To distinguish users, each user has the assigned particular Pseudo-Noise (PN) sequence. All users have the same M_{non} nonorthogonal sequences which are used for CSK.

2.1 Transmitter

Figure 1 shows the transmitter of our system. And In the transmitter, (1) the amount of information of the packet, L_{p-info}, is divided into $\frac{L_{p-info}}{N_{bit}} (= L_p)$. (2) One of M_{non} nonorthogonal sequences is selected. (3) The selected nonorthogonal sequence is multiplied by the assigned PN sequence. (4) One packet which consists of L_p frames is multiplied by the carrier, and it is transmitted. In our system, a nonorthogonal sequence is constructed by concatenating M_{con} primitive orthogonal sequences. A frame is constructed by concatenating M_{con} primitive orthogonal sequences. The number of bits per frame is $N_{bit} = \log_2(2^{M_{con}} M_{os})$[bit], and the frame length is $L_{frame} = M_{os}M_{con}$.

2.2 Canceler

Figure 2 shows the canceler of our system. Timing of each transmission is assumed to be synchronized completely. And each adjustment of time delay is obtained perfectly. Firstly, the received signal is multiplied by each PN sequence. Next, the sequence is correlated with CSK sequences and then remodulated with the same sequence. Next, the demodulated signal is re-spread by the same PN sequence again. Then the

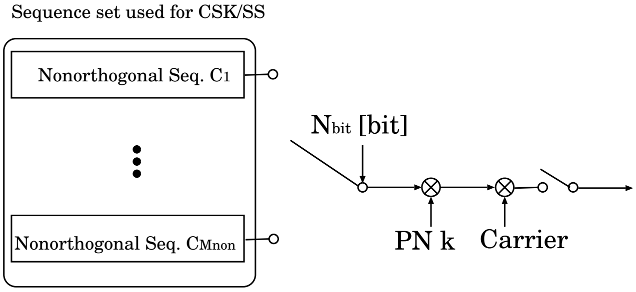

Figure 1. Transmitter

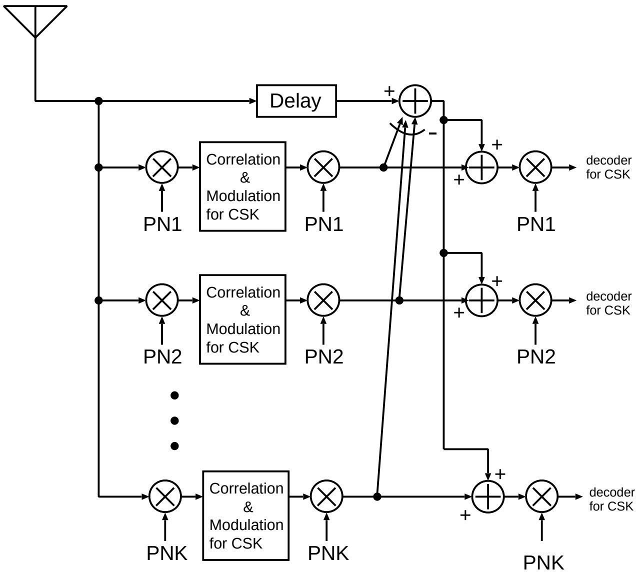

Figure 2. Receiver

re-spread signal is subtracted from the original received signal. Subtraction is done for each PN sequence. Finally, the subtracted signal is demodulated for each PN sequence.

3. Theoretical analysis

3.1 Assumptions

We assume the following when analyzing the throughput performance.

- Every transmitted signal is received by equal power in the central station: i.e. the power is controlled by the central station.
- The number of bits per packet is fixed to be L_{p-info} bits. When the duration of an orthogonal sequence is Δt, a packet duration, T_p, is

$$\begin{aligned} T_p &= \frac{L_{p-info}}{N_{bit}} M_{con} \Delta t \\ &= L_p M_{con} \Delta t. \end{aligned}$$

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

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

We assume that the length of a frame is the same as that of a PN sequence.

- Packets are generated according to binomial distribution.

3.2 success rate of one frame

If a sequence error occur, an incorrect sequence is subtracted from the desired signal. In our system, each sequence is constructed by concatenating primitive orthogonal sequences. There are some patterns of cancellation error:

- Primitive orthogonal sequence is estimated incorrectly. Then the cancellation signal includes twice in power. That is the power of interfering signal is twice. (Error pattern 1)
- Primitive orthogonal sequence is estimated correctly but its polar characters are estimated incorrectly. Then the power of interfering signal is fourfold. (Error pattern 2)

Error rate of one sequence for error pattern 1, $Pe_1(k)$, is given by

$$Pe_1(k) = 1 - \left\{ 1 - \frac{1}{2} erfc \left(\sqrt{\frac{SNR(Ka)}{M_{con}}} \right) \right\}^{M_{con}} \times \left\{ \int_{-\infty}^{\infty} f(x_1) \left\{ \int_{-\infty}^{x_1} f(x_{\underset{j \neq 1}{j}}) dx_j \right\}^{M_{os}-1} dx_1 \right\}. \quad (1)$$

where Ka is the number of interfering packets after remodulation,

$$Ka = 2k(1 - P_{ocs}(k)). \quad (2)$$

$SNR(Ka)$ indicates the ratio of the transmitted signal to the noise power spectral density.

$$SNR(Ka) = \frac{1}{2} \left\{ \frac{Ka}{3L_{frame}} + \frac{1}{2} \left(\frac{N_0}{N_{bit} E_b} \right) \right\}^{-1}. \quad (3)$$

$P_{ocs}(k)$ is the success rate of sequence when the number of simultaneous transmitted packet is k, and it is given by [4]

$$P_{ocs}(k) = \int_{-\infty}^{\infty} f(x_1) \left\{ \int_{-\infty}^{x_1} f(x_{\underset{j \neq 1}{j}}) dx_j \right\}^{M_{os}-1} dx_1, \quad (4)$$

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

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

q_j is the output of the jth correlator, u_j is the mean of random variable q_j, $\sigma_j = \frac{N_{bit}/M_{con}}{2SNR(Ka)}$, and '$\otimes$' expresses the convolution integral.

Error rate of one sequence for error pattern 2 $Pe_2(k)$ is given by

$$Pe_2(k) = 1 - P_{ocs}(k_j) \times \prod_{j=1}^{M_{con}} \left\{ 1 - erfc \left(\sqrt{\frac{SNR(k_j)}{M_{con}}} \right) P_{ocs}(k) \right\}, \quad (7)$$

where k_j is the number of interfering packet for jth primitive orthogonal sequence, and it is given by

$$k_j = 4kPe_{1j}(k)P_{ocs}(k), \quad (8)$$

$$Pe_{1j}(k) = \frac{1}{2}erfc\left(\sqrt{\frac{SNR(k)}{M_{con}}}\right). \quad (9)$$

From above, we can obtain the success rate for one frame, $Pc(k)$,

$$Pc(k) = \left\{1 - Pe_1(k) - Pe_2(k)\right\}. \quad (10)$$

3.3 Throughput

We assume that the number of interfering packets changes at one packet interval (i.e. we assume perfect capture). Then the success rate of one packet, $Ps(k)$ is expressed as

$$Ps(k) = \left\{Pc(k)\right\}^{L_p}, \quad (11)$$

where L_p is the packet length.

The probability of generating k packets in a packet duration is

$$B\left(k, \frac{G}{K}\right) = {}_K C_k \left(\frac{G}{K}\right)^k \left(1 - \frac{G}{K}\right)^{K-k}, \quad (12)$$

where K is the number of users. The throughput S, which is defined as the number of success bits per chip, is given by

$$S = \frac{\log_2 M_{os} + M_{con}}{L_{frame}} \sum_{k=0}^{K} \left(\frac{G}{K}\right)^k \left(1 - \frac{G}{K}\right)^{K-k} Ps(k). \quad (13)$$

The probability of packet success, $Ps(k, i, k_1)$, can be obtained as,

$$\begin{aligned} Ps(k, i, k_1) = & Ps(k, i-1, k_1)(1 - \mu(k_1) - \lambda)Pc(k) \\ & + Ps(k-1, i-1, k_1)\lambda Pc(k-1) \\ & + Ps(k+1, i-1, k_1)\mu(k_1)Pc(k+1), \quad (14) \end{aligned}$$

We can obtain the success rate of one packet, $\overline{Q}$,

$$\overline{Q} = \sum_{k=0}^{K} \sum_{k_1=0}^{K} Ps(k, L_p, k_1)Pc(k).$$

The throughput, S, is

$$S = \frac{\log_2 M_{os} + M_{con}}{L_{frame}} \frac{\sum_{j=0}^{K} j \cdot G^j/j!}{\sum_{j=0}^{K} G^j/j!} \overline{Q}. \quad (15)$$

4. Numerical Results

4.1 Normalized throughput

Figure 3 shows the normalized throughput when the number of users, $K = 100$, the number of bits per packet,

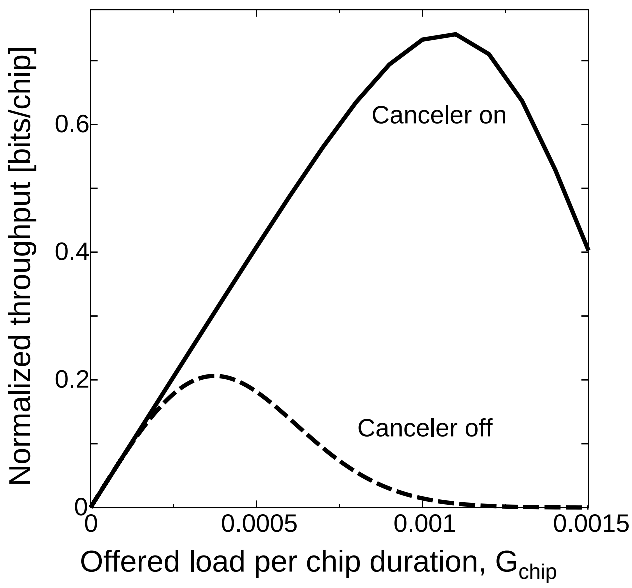

Figure 3. Normalized throughput versus Offered load when $K = 100$, $L_{p-info} = 840$, $E_b/N_0 = 5$[dB], $M_{os} = 64$, and $M_{con} = 4$.

$L_{p-info} = 840$[bit], the number of primitive orthogonal sequences, $E_b/N_0 = 5$[dB], $M_{os} = 64$, and the number of concatenations, $M_{con} = 4$. The vertical axis represents the normalized throughput [bits/chip], and the horizontal axis represents the offered load in a chip duration, G_{chip}. The solid line is the throughput of our system with the interference canceler, and the dashed line is that without the interference canceler. The maximum throughput of our system with interference canceler is about 0.74, while that with interference canceler is about 0.20. The throughput performance with the interference canceler is 3.6 times greater than that without the interference canceler.

4.2 Comparison of normalized throughput

Figure 4 shows the normalized throughput versus the offered load per chip duration when $K = 100$, $L_{p-info} = 840$[bit], $L_{frame} = 256$. In the nonorthogonal CSK/CDMA ALOHA system, $L_{frame} = 256$, $M_{os} = 64$ and $M_{con} = 4$. In the orthogonal CSK/CDMA ALOHA system, $L_{frame} = M_{os} = 256$. And in the DS/CDMA ALOHA system, $L_{frame} = 256$. The solid line is the throughput of our system, the dotted line is that of the DS/CDMA ALOHA with the interference canceler, and the dot-dashed line is that of the orthogonal CSK/CDMA ALOHA with the interference canceler. The maximum throughput of the nonorthogonal CSK/CDMA ALOHA is 1.05 times better than that of the orthogonal CSK/CDMA ALOHA system, and 2.04 times better that of the DS/CDMA ALOHA system. From Fig. 4, the maximum throughput of our system exceeds 1.0. It is due to the advantage of multilevel modulation system.

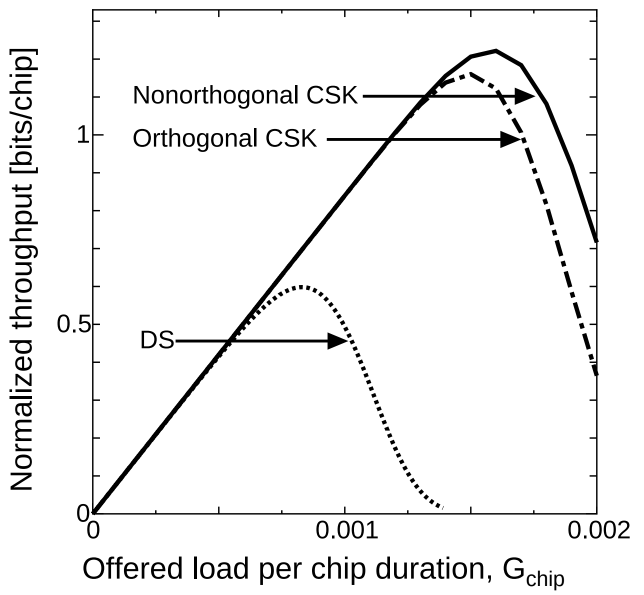

Figure 4. Normalized throughput versus Offered load when $K = 100$, $L_{p-info} = 840$, $E_b/N_0 = 10$[dB], $L_{frame} = 256$.

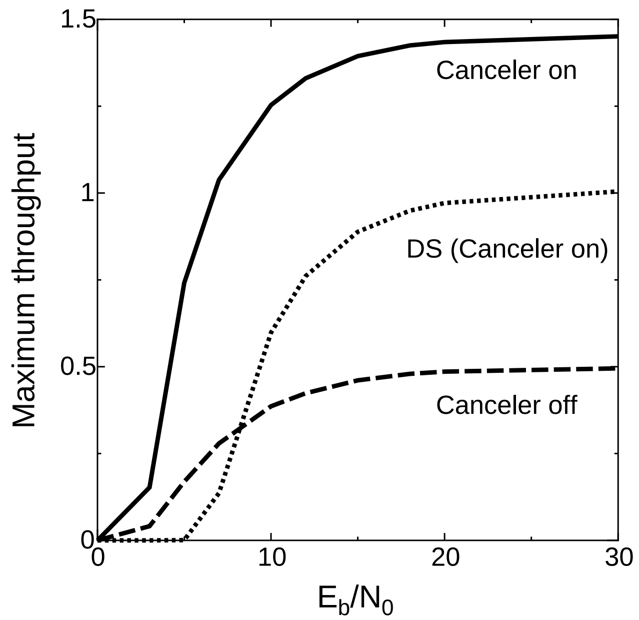

Figure 5. Maximum throughput versus E_b/N_0 when $K = 100$, $L_{p-info} = 840$, $M_{os} = 64$, and $M_{con} = 4$.

4.3 Comparison of maximum throughput

Figure 5 shows the maximum throughput versus E_b/N_0. In Fig. 5, $K = 100$, $L_{p-info} = 840$[bit], $M_{os} = 64$, and $M_{con} = 4$. The solid line is the throughput of our system with the interference canceler, and the dashed line is that without the interference canceler. The dotted line is the throughput performance of the DS/CDMA ALOHA with the interference canceler. When E_b/N_0 is low, the throughput performance of our system does not improve so much. It is because some incorrect sequences may be subtracted from the received signal under noisy channel. On the other hand, the throughput performance shows more than 295 % increase by using the interference canceler when E_b/N_0 is high. Moreover, the throughput of our system is over 1.0 while that of the DS/CDMA is equal or less than 1.0. The throughput is expected to improve by using multi-stage interference canceler when E_b/N_0 is law.

5. Discussion and Conclusion

This paper presents the throughput performance of the nonorthogonal CSK/CDMA ALOHA with an interference cancellation technique. In the nonorthogonal CSK/CDMA ALOHA system, the nonorthogonal sequences are constructed by concatenating M_{con} primitive orthogonal sequences. Our study indicated that using an interference cancellation technique into the nonorthogonal CSK/CDMA ALOHA system is very effective. The nonorthogonal CSK/CDMA system is one of the multilevel modulation systems, and it has the usual effect of the orthogonal CSK/CDMA (M-ary/CDMA) system. And the spectral efficiency of our system can exceed 1.0 as well as that of the M-ary/CDMA system[3]. Thus the throughput of our system can exceed 1.0. Our study revealed that the throughput of the nonorthogonal CSK/CDMA ALOHA system is better than those of the conventional CDMA ALOHA systems. Future works include the investigation of the interference cancellation technique on the nonorthogonal CSK/CDMA ALOHA system under fading channel, the way to reduce the sequence error, and the investigation of the nonorthogonal CSK/CDMA system with an access control scheme and the interference cancellation technique.

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