다매체 직접수열 대역확산 다중접속 시스템의 성능분석

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Performance Evaluation of a Multi-Media DS/SSMA System

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Abstract

A multi-media binary DS/CDMA system with variable processing gain and coherent correlation receivers are considered under additive white Gaussian noise channels. Two types of information sources with different rates and transmitting powers are assumed to be transmitted simultaneously in the same channel. Average signal-to-noise ratios at the correlation receiver outputs for each type of information sources are analytically derived as functions of discrete partial cross-correlations between spreading code sequences. The analysis is expected to provide analytical tools for use in preliminary system design and spreading code selection.

1 Introduction

DS/CDMA systems with fixed chip rate and variable processing gain are recommended as an access method for multi-media wireless communication systems [1]. Fixing chip rate simplifies the receiver RF front end and code synchronization requirements. However, in this case, different bit rates are translated into different processing gains. Thus, different transmitting powers must be allocated for each type of information sources so that the quality requirements are satisfied. Many studies on the power control and capacity of such systems were reported [2]–[5]. Most of these studies are based on the approximation [6] of the signal-to-noise ratio (SNR) of the correlation receiver output. The approximation of SNR is obtained by regarding the spreading codes as random sequences. Since the user code sequences are not random but pseudo random, however, the approximation may result in some differences in system performance. In the case of asynchronous DS/CDMA systems which accommodate only one type of sources, the numerical formula of the average SNR was derived as a function of cross-correlations between user code sequences [6]–[8]. It seems that there does not exist a published work analyzing the performance of asynchronous DS/CDMA systems which accommodate more than two types of information sources.

In this paper, we thus formulate the average SNR of the asynchronous DS/CDMA system with variable processing gain as a function of cross-correlations between user spreading code sequences. We consider the DS/CDMA system which accommodates two (or more) types of information sources with different bit rates and quality requirements (consequently, the different transmitting powers).

Section 2 gives the asynchronous DS/CDMA system model, and Section 3 definitions of some partial cross-correlation functions. The average SNR's for two types of information sources are formulated in Section 4. Performance evaluation for specific code sequences is presented in Section 5.

2 Asynchronous DS/CDMA System Model

The DS/CDMA system model that we will consider in the paper is shown in Fig. 1. There are two types of information sources as shown in Fig. 2. The number of types 'A' and 'B' users are denoted by K and L, respectively. If $\{b_{i,\ell}\}$ is the information sequence of $\{+1,-1\}$ for the i-th user, then we can write the data signal $b_i(t)$ as

$$b_i(t) = \begin{cases} \sum_{\ell=-\infty}^{\infty} b_{i,\ell} P_{T_A}(t-\ell T_A) & \text{for } 1 \le i \le K, \\ \sum_{\ell=-\infty}^{\infty} b_{i,\ell} P_{T_B}(t-\ell T_B) & \text{for } K+1 \le i \le K+L, \end{cases} \tag{1}$$

where $P_T(t) = 1$ for $0 \le t \le T$ and $P_T(t) = 0$ otherwise. The bit duration T_A is assumed to be an integer multiple of T_B. Then $M = T_A/T_B$ bits of a type 'B' information source are transmitted during one bit duration of type 'A' sources.

The code waveform assigned to the i-th user can be

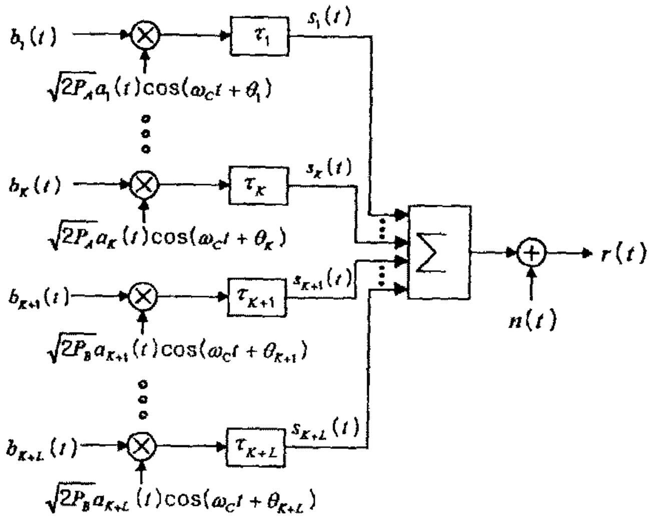

Fig. 1: Asynchronous DS/CDMA transmitter model

expressed as

$$a_i(t) = \sum_{j=-\infty}^{\infty} a_j^{(i)} P_{T_c}(t - jT_c) \ , \tag{2}$$

where $\{a_j^{(i)}\}$ is the corresponding code sequence of $\{+1, -1\}$ and T_c is the chip duration. We assume that all the code sequences have period $N = T_A/T_c = MT_B/T_c$ as shown in Fig. 2. Note that the processing gain of type $'A'$ source is N and that of type $'B'$ source is N/M.

The data signal $b_i(t)$ is spread and modulated by a phase coded carrier $c_i(t)$ given by

$$c_i(t) = \begin{cases} \sqrt{2P_A} a_i(t) \cos(\omega_c t + \theta_i) & \text{for } \ 1 \le i \le K \ , \\ \sqrt{2P_B} a_i(t) \cos(\omega_c t + \theta_i) & \text{for } \ K+1 \le i \le K+L \ , \end{cases} \tag{3}$$

where θ_i represents the phase of the i-th carrier, ω_c represents the common center frequency, and P_A and P_B represent the transmitting powers of each source type. Since the transmitters are not generally time-synchronized, the transmitters in this paper are assumed to be asynchronous. For the asynchronous systems the received signal $r(t)$ in Fig. 1 is given by

$$\begin{aligned} r(t) &= \sum_{i=1}^{K} \sqrt{2P_A} a_i(t - \tau_i) b_i(t - \tau_i) \cos(\omega_c t + \phi_i) \\ &\quad + \sum_{i=K+1}^{K+L} \sqrt{2P_B} a_i(t - \tau_i) b_i(t - \tau_i) \cos(\omega_c t + \phi_i) \\ &\quad + n(t) \ , \end{aligned} \tag{4}$$

where $\phi_i = \theta_i - \omega_c \tau_i$ and $n(t)$ is the white Gaussian channel noise with two-sided spectral density $N_0/2$.

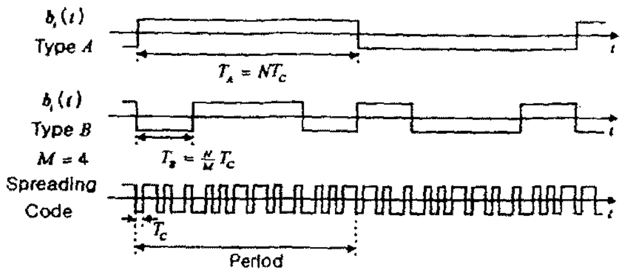

Fig. 2: Characteristics of two types of information sources and spreading code

3 Definition of Partial Cross-Correlation Functions

In order to formulate the signal-to-noise ratios of correlation receiver outputs, we must define two continuous-time partial cross-correlation functions and two discrete partial cross-correlation functions. We define the continuous-time partial cross-correlation functions between two user code waveforms $a_k(t)$ and $a_i(t)$. As shown in Fig. 3, one period NT_c of a user code waveform is divided into G parts. The number G is determined by the types of the k-th and i-th users. If both users are type $'A'$ users, then $G = 1$, and if at least one of the two users is a type $'B'$ user, then $G = M = T_A/T_B$. If the delay difference $\tau = |\tau_k - \tau_i|$ $(0 \le \tau < NT_c)$ between the k-th and i-th users is in the range of $(m-1)\frac{N}{G}T_c \le \tau < m\frac{N}{G}T_c$ (where $m \in \{1, 2, 3, \cdots, G\}$) as shown in Fig. 3, then continuous-time partial cross-correlation functions $R_{k,i}(\tau, n)$ and $\widehat{R}_{k,i}(\tau, n)$ are defined by

$$R_{k,i}(\tau, n) \ = \ \int_{(m+n)\frac{N}{G}T_c}^{\tau + (n+1)\frac{N}{G}T_c} a_k(t - \tau) a_i(t) d\tau \tag{5}$$

for $-m \le n \le G - m - 1$ and

$$\widehat{R}_{k,i}(\tau, n) \ = \ \int_{\tau + n\frac{N}{G}T_c}^{(m+n)\frac{N}{G}T_c} a_k(t - \tau) a_i(t) d\tau \tag{6}$$

for $-m + 1 \le n \le G - m$.

Next, we define the discrete partial cross-correlation functions between two user code sequences $\{a_j^{(k)}\}$ and $\{a_j^{(i)}\}$. As in the case of continuous-time partial cross-cross correlation functions, one period N of a user code sequence is divided into G parts. If we let $\tau = \ell T_c$ and ℓ is in the range of $(m-1)\frac{N}{G} \le \ell < m\frac{N}{G}$ (where $\ell \in \{0, 1, 2, 3, \cdots, N-1\}$ and $m \in \{1, 2, 3, \cdots, G\}$), then the discrete partial cross-correlation functions $C_{k,i}(\ell, \eta, n)$ and $\widehat{C}_{k,i}(\ell, \eta, n)$ (where $\eta \in \{0, 1\}$) are defined by

$$C_{k,i}(\ell, \eta, n) = \sum_{j=(m+n)\frac{N}{G}}^{\ell + \eta + (n+1)\frac{N}{G} - 1} a_{j-\ell-\eta}^{(k)} a_j^{(i)} \tag{7}$$

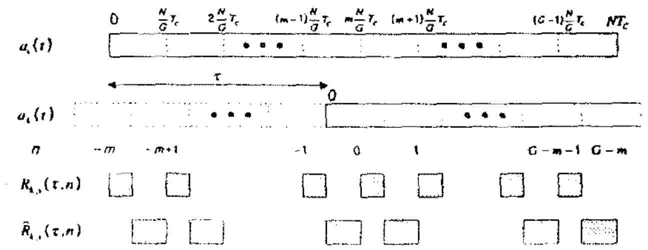

Fig. 3: Definition of continuous-time partial cross-correlation functions

for $-m \leq n \leq G-m-1$, and

$$\widehat{C}_{k,i}(\ell,\eta,n) = \sum_{j=\ell+\eta+n\frac{N}{G}}^{(m+n)\frac{N}{G}-1} a_{j-\ell-\eta}^{(k)} a_j^{(i)} \quad (8)$$

for $-m+1 \leq n \leq G-m$.

It is easy to see that for $\ell T_c \leq \tau < (\ell+1)T_c$, the continuous-time partial cross-correlation functions can be rewritten as functions of the discrete partial cross-correlation functions as

$$\begin{aligned} R_{k,i}(\tau,n) &= C_{k,i}(\ell,0,n)T_c \\ &\quad + \{C_{k,i}(\ell,1,n) - C_{k,i}(\ell,0,n)\}(\tau - \ell T_c) \quad (9) \end{aligned}$$

and

$$\begin{aligned} \widehat{R}_{k,i}(\tau,n) &= \widehat{C}_{k,i}(\ell,0,n)T_c \\ &\quad + \{\widehat{C}_{k,i}(\ell,1,n) - \widehat{C}_{k,i}(\ell,0,n)\}(\tau - \ell T_c). (10) \end{aligned}$$

Using (9) and (10), we can reduce enormously the amount of computation for the calculation of the continuous-time partial cross-correlation.

4 Average Signal-to-Noise Ratio

We formulate the average SNR's for the two types of information sources as functions of the discrete partial cross-correlation. In this approach, we treat the noise, phase shifts, time delays, and data symbols as mutually independent random variables. The signal-to-noise ratio is computed by means of probabilistic averages (expectations) with respect to these random variables. Since coherent correlation receivers are used and we are concerned with relative phase shifts modulo 2π and relative time delays modulo NT_c, there is no loss of generality in assuming $\theta_i = 0$, $\tau_i = 0$ and considering only $0 \leq \tau_k < NT_c$, $0 \leq \theta_k < 2\pi$ for $k \neq i$ for the i-th user. If the received signal $r(t)$ is the input to the correlation receiver matched to $a_i(t)\cos\omega_c t$, the output Z_i is

$$Z_i = \begin{cases} \int_0^{T_A} r(t)a_i(t)\cos\omega_c t \, dt & \text{for } \ 1 \leq i \leq K \, , \\ \int_0^{T_B} r(t)a_i(t)\cos\omega_c t \, dt & \text{for } \ K+1 \leq i \leq K+L \, . \end{cases} \quad (11)$$

In all that follows we assume $\omega_c \gg T_A^{-1}$ and $\omega_c \gg T_B^{-1}$ so that we can ignore the double frequency component of $r(t)\cos\omega_c t$. Also, because of the symmetry involved, we need to consider only $b_{i,0} = +1$.

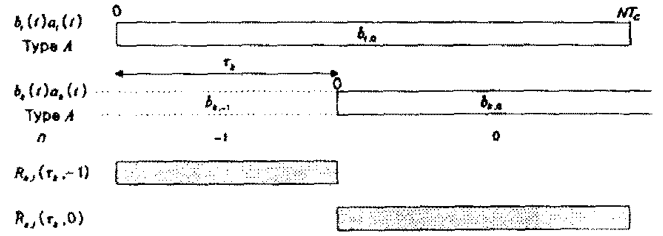

Fig. 4: $I_{AA}^{(i)}$: Multi-user interference from the other type $'A'$ users to the i-th user of type $'A'$

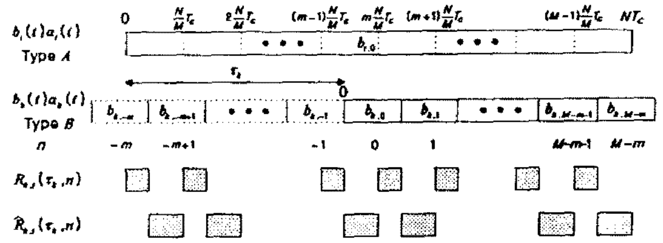

Fig. 5: $I_{BA}^{(i)}$: Multi-user interference from the type $'B'$ users to the i-th user of type $'A'$

The i-th correlation receiver output Z_i for $1 \leq i \leq K$ (type $'A'$) can then be expressed as

$$Z_i = \sqrt{\frac{P_A}{2}} T_A + I_{AA}^{(i)} + I_{BA}^{(i)} + \int_0^{T_A} n(t)a_i(t)\cos\omega_c t \, dt \, , \quad (12)$$

where $I_{AA}^{(i)}$ is the multi-user interference from the other type $'A'$ users to the i-th user and $I_{BA}^{(i)}$ is the multi-user interference from type $'B'$ users to the i-th user.

As shown in Fig. 4, the term $I_{AA}^{(i)}$ is given by

$$I_{AA}^{(i)} = \sqrt{\frac{P_A}{2}} \sum_{\substack{k=1 \\ k \neq i}}^{K} [b_{k,-1} R_{k,i}(\tau_k,-1) + b_{k,0} \widehat{R}_{k,i}(\tau_k,0)] \cos\phi_k \, , \quad (13)$$

where $\phi_k = \theta_k - \omega_c \tau_k$. In this case, since both the k-th and i-th users are all type $'A'$ users, $G = 1$. As shown in Fig. 5, the term $I_{BA}^{(i)}$ is given by

$$I_{BA}^{(i)} = \sqrt{\frac{P_B}{2}} \sum_{k=K+1}^{K+L} \sum_{n=-m}^{M-m} b_{k,n} \{R_{k,i}(\tau_k,n) + \widehat{R}_{k,i}(\tau_k,n)\} \cos\phi_k \quad (14)$$

where $G = M$ because interferers are type $'B'$ users.

We assume that phase shifts ϕ_k are distributed uniformly on the interval $[0,2\pi)$ and time delays τ_k are distributed uniformly on the interval $[0,NT_c)$ for $k \neq i$. Also, the data symbol $b_{k,\ell}$ is assumed to take values +1 or −1 with equal probability for $k \neq i$. Then, the desired signal component (mean) of Z_i is $\sqrt{P_A/2} \cdot T_A$, while the variance of Z_i is the sum of the variances of the noise and interference terms in (12). The variance of $I_{AA}^{(i)}$ is

$$
\begin{aligned}
Var\{I_{AA}^{(i)}\} &= \frac{P_A}{4NT_c}\sum_{\substack{k=1\\k\neq i}}^{K}\int_0^{NT_c}\left[R_{k,i}{}^2(\tau_k,-1)+\widehat{R}_{k,i}{}^2(\tau_k,0)\right]d\tau_k \\
&= \frac{P_A}{4NT_c}\sum_{\substack{k=1\\k\neq i}}^{K}\sum_{\ell=0}^{N-1}\int_{\ell T_c}^{(\ell+1)T_c}\left[R_{k,i}{}^2(\tau_k,-1)+\widehat{R}_{k,i}{}^2(\tau_k,0)\right]d\tau_k \\
&= \frac{P_A T_c^2}{12N}\sum_{\substack{k=1\\k\neq i}}^{K}\gamma_{AA}^{(k)(i)}, \qquad (15)
\end{aligned}
$$

where

$$
\begin{aligned}
\gamma_{AA}^{(k)(i)} = \sum_{\ell=0}^{N-1}\Big[&C_{k,i}{}^2(\ell,0,-1)+C_{k,1}{}^2(\ell,1,-1) \\
&+C_{k,i}(\ell,0,-1)\cdot C_{k,i}(\ell,1,-1) \\
&+\widehat{C}_{k,i}{}^2(\ell,0,0)+\widehat{C}_{k,i}{}^2(\ell,1,0) \\
&+\widehat{C}_{k,i}(\ell,0,0)\cdot\widehat{C}_{k,i}(\ell,1,0)\Big]. \qquad (16)
\end{aligned}
$$

Similarly, the variance of $I_{BA}^{(i)}$ is

$$
Var\{I_{BA}^{(i)}\} = \frac{P_B T_c^2}{12N}\sum_{k=K+1}^{K+L}\gamma_{BA}^{(k)(i)}, \qquad (17)
$$

where

$$
\begin{aligned}
\gamma_{BA}^{(k)(i)} = \sum_{\ell=0}^{N-1}\sum_{n=-m}^{M-m}\Big[&C_{k,i}{}^2(\ell,0,n)+C_{k,i}{}^2(\ell,1,n) \\
&+C_{k,i}(\ell,0,n)\cdot C_{k,i}(\ell,1,n) \\
&+\widehat{C}_{k,i}{}^2(\ell,0,n)+\widehat{C}_{k,i}{}^2(\ell,1,n) \\
&+\widehat{C}_{k,i}(\ell,0,n)\cdot\widehat{C}_{k,i}(\ell,1,n) \\
&+2C_{k,i}(\ell,0,n)\cdot\widehat{C}_{k,i}(\ell,0,n) \\
&+C_{k,i}(\ell,0,n)\cdot\widehat{C}_{k,i}(\ell,1,n) \\
&+C_{k,i}(\ell,1,n)\cdot\widehat{C}_{k,i}(\ell,0,n) \\
&+2C_{k,i}(\ell,1,n)\cdot\widehat{C}_{k,i}(\ell,1,n)\Big]. \qquad (18)
\end{aligned}
$$

Using (15) and (17), the average SNR for the i-th user, $1 \leq i \leq K$, is

$$
\begin{aligned}
SNR_i^{(A)} &= \frac{E\{Z_i\}}{\sqrt{Var\{Z_i\}}} \\
&= \left\{\frac{P_A}{6N^3P_A}\sum_{\substack{k=1\\k\neq i}}^{K}\gamma_{AA}^{(k)(i)}+\frac{P_B}{6N^3P_A}\sum_{k=K+1}^{K+L}\gamma_{BA}^{(k)(i)} + \frac{N_0}{2E_b^{(A)}}\right\}^{-1/2} \qquad (19)
\end{aligned}
$$

where $E_b^{(A)} = P_A T_A$.

Similarly, for type $'B'$ users, the average SNR is

$$
SNR_i^{(B)} = \left\{\frac{P_AM^2}{6N^3P_B}\sum_{k=1}^{K}\gamma_{AB}^{(k)(i)}+\frac{P_BM^2}{6N^3P_B}\sum_{\substack{k=K+1\\k\neq i}}^{K+L}\gamma_{BB}^{(k)(i)} + \frac{N_0}{2E_b^{(B)}}\right\}^{-1/2} \qquad (20)
$$

where $E_b^{(B)} = P_B T_B$, $K+1 \leq i \leq K+L$, and $\gamma_{AB}^{(k)(i)}$ and $\gamma_{BB}^{(k)(i)}$ are defined by

$$
\begin{aligned}
\gamma_{AB}^{(k)(i)} = \sum_{\ell=0}^{N-1}\Big[&C_{k,i}{}^2(\ell,0,-m)+C_{k,i}{}^2(\ell,1,-m) \\
&+C_{k,i}(\ell,0,-m)\cdot C_{k,i}(\ell,1,-m) \\
&+\widehat{C}_{k,i}{}^2(\ell,0,-m+1)+\widehat{C}_{k,i}{}^2(\ell,1,-m+1) \\
&+\widehat{C}_{k,i}(\ell,0,-m+1)\cdot\widehat{C}_{k,i}(\ell,1,-m+1)\Big] \\
+\sum_{\ell=N/M}^{N-1}\Big[&2C_{k,i}(\ell,0,-m)\cdot\widehat{C}_{k,i}(\ell,0,-m+1) \\
&+C_{k,i}(\ell,0,-m)\cdot\widehat{C}_{k,i}(\ell,1,-m+1) \\
&+C_{k,i}(\ell,1,-m)\cdot\widehat{C}_{k,i}(\ell,0,-m+1) \\
&+2C_{k,i}(\ell,1,-m)\cdot\widehat{C}_{k,i}(\ell,1,-m+1)\Big] \qquad (21)
\end{aligned}
$$

and

$$
\begin{aligned}
\gamma_{BB}^{(k)(i)} = \sum_{\ell=0}^{N-1}\Big[&C_{k,i}{}^2(\ell,0,-m)+C_{k,i}{}^2(\ell,1,-m) \\
&+C_{k,i}(\ell,0,-m)\cdot C_{k,i}(\ell,1,-m) \\
&+\widehat{C}_{k,i}{}^2(\ell,0,-m+1)+\widehat{C}_{k,i}{}^2(\ell,1,-m+1) \\
&+\widehat{C}_{k,i}(\ell,0,-m+1)\cdot\widehat{C}_{k,i}(\ell,1,-m+1)\Big]. \qquad (22)
\end{aligned}
$$

Equations (19) and (20) are the complete formulas of the average signal-to-noise ratios for the asynchronous DS/CDMA system which accommodates two types of information sources with different bit rates and transmitting powers. The results can be easily extended to systems which accommodate more than two types of information sources.

When code sequences are assumed to be random, approximations to the average SNR's are obtained: if random sequences are assumed, the SNR's (19) and (20) become

$$
SNR_i^{(A)} \approx \left\{\frac{1}{3NP_A}\{P_A\cdot(K-1)+P_B\cdot L\}+\frac{N_0}{2E_b^{(A)}}\right\}^{-1/2} \qquad (23)
$$

and

$$
SNR_i^{(B)} \approx \left\{\frac{M}{3NP_B}\{P_A\cdot K+P_B\cdot(L-1)\}+\frac{N_0}{2E_b^{(B)}}\right\}^{-1/2} \qquad (24)
$$

5 Performance Evaluation for Specific Code Sequences

In this section, we evaluate the accurate system performance (average SNR) using (19) and (20) when specific code sequences are employed as spreading codes. Here, the m-sequences and Gold codes are used as spreading sequences [9]. Both the m-sequence and Gold code used in the evaluation have period 511: we add $'-1'$ to the end of each code sequence so that $N = 512$ and N/M are integers for $M = 1, 2, 4, 8, 16$. As M increases, transmitting powers P_A and P_B are adjusted to maintain the approximations of SNR's at the given levels. If we denote the given levels of SNR's for type $'A'$ and $'B'$ sources by R_A and R_B, respectively, then, using approximations (25) and (26), we obtain the required chip energy-to-noise density ratios as

$$\frac{E_c^{(A)}}{N_0} = \frac{3/2}{C_A(1 - K/C_A - L/C_B)} \qquad (25)$$

and

$$\frac{E_c^{(B)}}{N_0} = \frac{3/2}{C_B(1 - K/C_A - L/C_B)}, \qquad (26)$$

where $E_c^{(A)} = P_A T_c$, $E_c^{(B)} = P_B T_c$, $C_A = 1 + 3N \cdot (R_A)^{-2}$, and $C_B = 1 + 3N/M \cdot (R_B)^{-2}$. In the above expressions, the following condition must be satisfied.

$$\frac{K}{C_A} + \frac{L}{C_B} \leq 1\,. \qquad (27)$$

If (27) is not satisfied, the number of users is beyond the system capacity.

We assume that $R_A = 4$ (dB) and $R_B = 6$ (dB). When there are only 13 type $'A'$ users (i.e., $K = 13$ and $L = 0$), the performance of a type $'A'$ user is shown in Fig. 6. We can see that the performance of both Gold code and m-sequence is almost the same as that of the random code. Fig. 7 shows the performance of a type $'B'$ user when there are only 13 type $'B'$ users (i.e., $K = 0$ and $L = 13$). Note that the performance of the m-sequence and Gold code differs from that of the random code for large M. Fig. 8 shows the case in which there are 13 type $'A'$ users and 13 type $'B'$ users (i.e., $K = 13$ and $L = 13$). In this case, the performance is almost the same as in Fig. 6 for a type $'A'$ user and as in Fig. 7 for a type $'B'$ user.

Consider another example in which the period of spreading code waveforms for type $'B'$ users is adjusted to be T_B for various M (i.e., the period of code sequence $= N/M$). For type $'A'$ users, codes with period 512 are used as in the previous example. Fig. 9 shows the performance when $K = 0$ and $L = 13$, and Fig. 10 shows the performance when $K = 13$ and $L = 13$. We can see that the performance of Gold code of period N/M is better than that of period N. Thus, when there are more than two types of sources, a more careful attention should be given in selecting the class of spreading codes and their periods.

6 Conclusion

In this paper, we have evaluated the performance of a multi-media DS/CDMA system which accommodates two types of information sources. The two types of sources are assumed to have different bit rates and transmitting powers. We have formulated accurate average signal-to-noise ratios for each type of sources as functions of the discrete partial cross-correlation between spreading code sequences. These formulas can be easily extended to systems which accommodate more than two types of information sources. We have also obtained approximations to the average signal-to-noise ratios in which random code sequences are assumed. These approximations can be used to determine roughly what spreading gains and transmitting powers are required to achieve given levels of signal-to-noise ratios. For specific code sequences, the accurate formula of average signal-to-noise ratios can be used in more detailed investigations.

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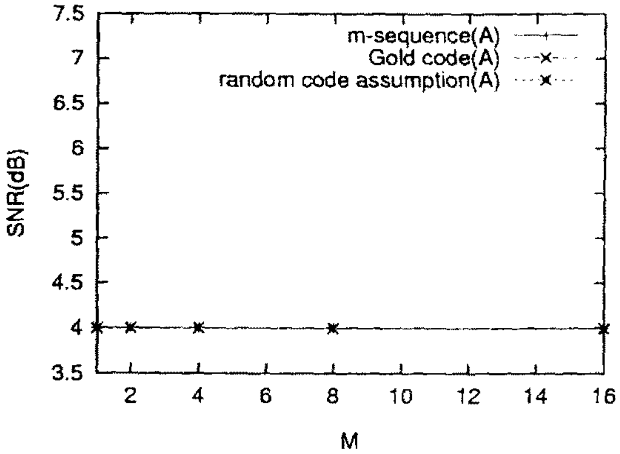

Fig. 6: Average signal-to-noise ratios for a type 'A' user for $M = 1, 2, 4, 8, 16$ when $K = 13$ and $L = 0$

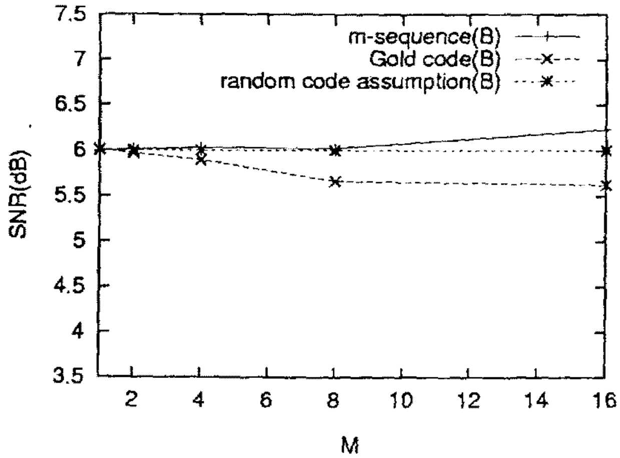

Fig. 7: Average signal-to-noise ratios for a type 'B' user for $M = 1, 2, 4, 8, 16$ when $K = 0$ and $L = 13$

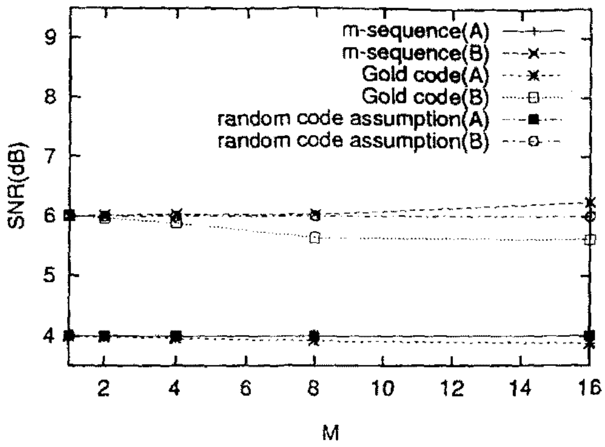

Fig. 8: Average signal-to-noise ratios for both type users for $M = 1, 2, 4, 8, 16$ when $K = 13$ and $L = 13$

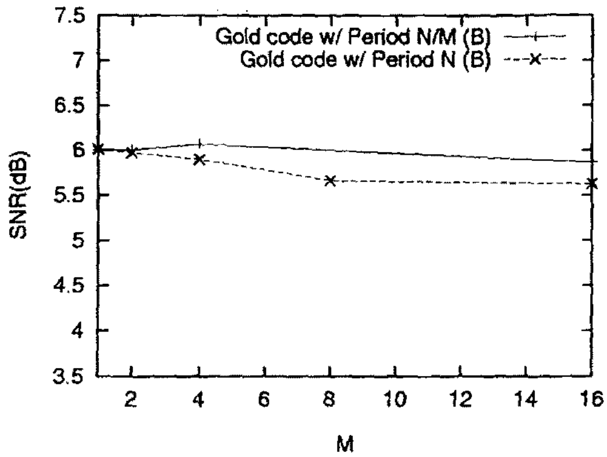

Fig. 9: Average signal-to-noise ratios for a type 'B' user for $M = 1, 2, 4, 16$ when $K = 0$ and $L = 13$

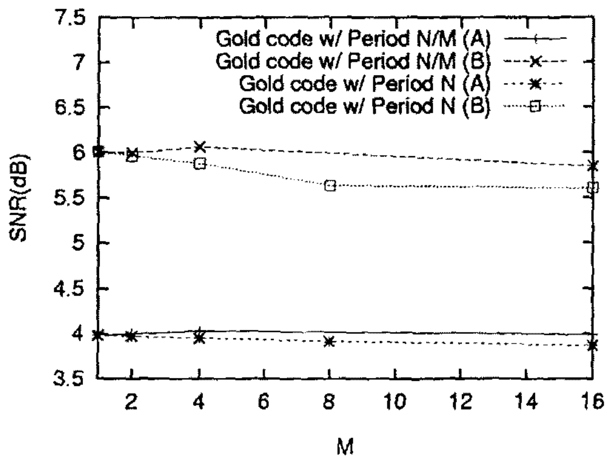

Fig. 10: Average signal-to-noise ratios for both type users for $M = 1, 2, 4, 16$ when $K = 13$ and $L = 13$