SUBOPTIMUM MULTIUSER DETECTION OF THE QS-CDMA SYSTEMS USING ANTENNA ARRAY

Kwang Soon Kim[1], Sun Yong Kim[2], Jooshik Lee[1], Iickho Song[1], Seong Ro Lee[1], and Jinsoo Bae[1]

[1]Department of Electrical Engineering
Korea Advanced Institute of Science and Technology (KAIST)
373-1 Guseong Dong, Yuseong Gu
Daejeon 305-701, Korea
Tel : +82-42-869-3445
Fax : +82-42-869-3410
e-mail : isong@sejong.kaist.ac.kr

[2] Department of Electronics Engineering
Hallym University, 1 OkChon Dong, Chunchon
Kangwon Do 200-702, Korea

ABSTRACT

Recently, multiuser detection has been an interesting topic because of its capability of eliminating multiuser interference and resistance to the near-far problem. The decorrelator approach has been investigated as a suboptimum multiuser detector for low complexity in receiver at the expense of the enhancement and correlation of noise. In this paper, we consider a quasi maximum likelihood (quasi-ML) detector in the reverse link system which uses antenna arrays in quasi-synchronous channels. It is shown that the performance of the system is better than that of the conventional decorrelator and that the performance gain over the conventional decorrelator system increases as the number of active users and number of antenna arrays increase.

INTRODUCTION

Although the CDMA technology offers higher spectral efficiency than the others [1], its capacity would not satisfy the explosive demands for mobile communication in near future. Thus, some additional methods to increase the spectral efficiency should be considered. It has been shown that the capacity of the system can be increased [2][3] with antenna arrays.

As a technique to eliminate interuser interference and to resist the near-far problem, multiuser detection has been considered recently [4][5][6]. While the performance of an optimum multiuser detector gives the lower bound of error probability, the complexity of the decision algorithm increases exponentially with the number of users. Because of the complexity of an optimum multiuser detector, a decorrelating approach is considered as a suboptimum multiuser detector in [6], and a system that uses decorrelator and antenna array is introduced in [7]. The performance of these systems is better than that of conventional systems because the multiuser interference can be eliminated at the expense of noise correlation and enhancement, when the cross correlation matrix of signature waveforms is perfectly known. These systems, however, have a drawback that decorrelating enhances and correlates the noise, and the enhancement and correlation of noise gets larger as the cross correlation gets larger or the number of user gets larger.

In considering multiuser detection for mobile communication systems, the channel should be considered to be asynchronous because of the difference among the distances from the mobile stations to the base station and because of multipath fading. However, we can treat it as a quasi-synchronous channel if the difference of time delays is small. Currently, DS/CDMA systems in quasi-synchronous channels in which all users try to transmit synchronously and use global positioning system (GPS)-derived clock become an interesting research area because of recent development in GPS receiver. In such a system, we can reduce the delay uncertainty into a few chip durations [8][9].

In this paper, we will propose a quasi maximum like-

0-7803-4249-6/97/$10.00 © 1997 IEEE

lihood (quasi-ML) detector in the reverse link from the mobile to the base station which uses antenna arrays in quasi-synchronous channels. We will consider the case with Rake multipath diversity, and the performance of the proposed system will be investigated.

SYSTEM MODEL

We consider the reverse link from a mobile station to a base station with antenna arrays in quasi-synchronous channel. In this channel model, the delay uncertainty is much smaller than the symbol duration. Thus, the interference from previous user symbols in the received signal which is unavoidable in asynchronous systems can be ignored. In the mobile station, the information bits are multiplied by a spreading sequence. After multiplied by carrier, the signal is assumed to be transmitted with binary phase shift keying (BPSK). Then, the transmitter signal modulated by a carrier frequency f_c is

$$u_k(t) = \sqrt{P_k} Re\{x_k(t)c_k(t)\exp[j(\omega_c t + \psi_k)]\}, \quad (1)$$

where $x_k(t)$ is the kth user's baseband information symbol, $c_k(t)$ is the signature waveform of the kth user, ψ_k is the random phase of the kth carrier, and P_k is the kth user's transmitted power.

Then the equivalent complex baseband received signal vector at the receiver of the base station with antenna arrays can be written as

$$r(t) = \sum_{k=1}^{K}\sum_{l=1}^{L} s_{k,l}(t-\tau_{k,l})c_k(t-\tau_{k,l})a_{k,l} + n(t), \quad (2)$$

where

$$s(t) = \sqrt{P_k}\alpha_{k,l}x_k(t)e^{j\phi_{k,l}}, \quad (3)$$

K is the number of users, $\alpha_{k,l}$ is the attenuation factor of the kth user in the lth multipath component, $\phi_{k,l} = \psi - \omega_c \tau_{k,l}$, in which we can assume that $\psi_k = 0$ without loss of generality, L is the number of resolvable multipath components, $a_{k,l}$ is the $M \times 1$ channel vector of the kth user in the lth multipath component, and $n(t)$ is the $M \times 1$ additive temporally and spatially white complex Gaussian noise vector with covariance matrix ${\sigma_n}^2 I$.

The receiver schemes considered in this paper is shown in Fig. 1. We use a uniform linear array which has M element. Let $Y(n)$ be the $M \times KL$ output matrix from the Rake receiver, then we can write $Y(n)$ as

$$Y(n) = [y_{1,1}(n)\cdots y_{1,L}(n)\cdots y_{K,1}\cdots y_{K,L}(n)], \quad (4)$$

where

$$y_{p,q}(n) = \sum_{k=1}^{K}\sum_{l=1}^{L} s_{k,l}(n)\gamma_{p,q,k,l}a_{k,l} + n_{p,q}(n), \quad (5)$$

$$\gamma_{p,q,k,l} = \frac{1}{T_s}\int_{\tau_{p,q}}^{\tau_{p,q}+T_s} c_k(t-\tau_{k,l})c_p(t-\tau_{p,q})dt, \quad (6)$$

and

$$n_{p,q}(n) = \frac{1}{T_s}\int_{\tau_{p,q}+(n-1)T_s}^{\tau_{p,q}+nT_s} n(t)c_p(t-\tau_{p,q})dt. \quad (7)$$

If we assume an ideal low pass filter with bandwidth $B = \frac{1}{T_c}$ and the same amount of energy regardless of the chip waveform, the cross covariance matrix between $n_{p,q}(n)$ and $n_{k,l}(n)$ is

$$E\{n_{p,q}(n)n_{k,l}^H(n)\} = \gamma_{p,q,k,l}{\sigma'_n}^2 I, \quad (8)$$

where ${\sigma'_n}^2 = \frac{{\sigma_n}^2}{T_s}$.

QUASI-ML DETECTION

In this section, we will investigate the quasi-ML detection of user signals. The sampled code filtered output of the qth path of the pth user is

$$y_{p,q}(n) = \sum_{k=1}^{K}\sum_{l=1}^{L} s_{k,l}(n)\gamma_{p,q,k,l}a_{k,l} + n_{p,q}(n). \quad (9)$$

Since $n_{p,q}(n)$ is temporally and spatially white, the log-likelihood function $L_{p,q}(n)$ of $y_{p,q}(n)$ can be written as

$$L_{p,q}(n) = -\left(y_{p,q}(n) - \sum_{k=1}^{K}\sum_{l=1}^{L} s_{k,l}(n)\gamma_{p,q,k,l}a_{k,l}\right)^H \cdot \left(y_{p,q}(n) - \sum_{k=1}^{K}\sum_{l=1}^{L} s_{k,l}(n)\gamma_{p,q,k,l}a_{k,l}\right), \quad (10)$$

Taking the derivative of (10) and setting the result to zero yields

$$\hat{s}_{p,q}(n) = \left(a_{p,q}^H a_{p,q}\gamma_{p,q,p,q}\right)^{-1} \cdot \left[a_{p,q}^H y_{p,q}(n) - \sum_{k=1}^{K}\sum_{\substack{l=1 \\ (k,l)\neq(p,q)}}^{L} s_{k,l}(n)\gamma_{p,q,k,l}a_{p,q}^H a_{k,l}\right]. \quad (11)$$

If we replace the lth estimates $\hat{s}_{k,l}(n)$ for $s_{k,l}(n)$ in the above equation and consider all the likelihood functions for each path of each user, we can obtain

$$\hat{X}(n) = Q^{-1}Y_a(n), \quad (12)$$

where Q is the $KL \times KL$ matrix whose $p \circ q, k \circ l$th element is $\sqrt{P_k}\alpha_{k,l}e^{j\phi_{k,l}}\ \gamma_{p,q,k,l}a_{p,q}^H a_{k,l}$, $p \circ q = (p-1)L + q$, $\hat{X}(n) = [\hat{x}_{1,1}(n) \cdots \hat{x}_{1,L}(n) \cdots \hat{x}_{K,1}(n) \cdots \hat{x}_{K,L}(n)]^T$ is an estimate of $X(n)$, and $Y_a(n) = [a_{1,1}^H y_{1,1}(n) \cdots a_{1,L}^H y_{1,L}(n) \cdots a_{K,1}^H y_{K,1}(n) \cdots a_{K,L}^H y_{K,L}(n)]^T$.

If we know $a_{k,l}$, $\phi_{k,l}$, and $\sqrt{P_k}\alpha_{k,l}$ for $k = 1, 2, \cdots, K$ and $l = 1, 2, \cdots, L$, we can obtain the quasi-ML estimates of each user signal. The estimation method of $a_{k,l}$, $\phi_{k,l}$, and $\sqrt{P_k}\alpha_{k,l}$ of the kth user signal is investigated in [3]. Using the covariance matrix of the kth code correlated output $y_k(n)$, $a_{k,l}$, $\phi_{k,l}$, and $\sqrt{P_k}\alpha_{k,l}$ can be estimated by solving a generalized eigenvalue problem. Here, we use a similar but better method for the estimation. We can rewrite (4) as

$$Y(n) = D(n)\Gamma + N(n), \tag{13}$$

where

$$D(n) = [d_{1,1}(n) \cdots d_{1,L}(n) \cdots d_{K,1}(n) \cdots d_{K,L}(n)], \tag{14}$$

$$d_{k,l}(n) = s_{k,l}(n)a_{k,l}, \tag{15}$$

$$N(n) = [n_{1,1}(n) \cdots n_{1,L}(n) \cdots n_{K,1}(n) \cdots n_{K,L}(n)], \tag{16}$$

and Γ is a $KL \times KL$ matrix whose $p \circ q, k \circ l$th element is $\gamma_{p,q,k,l}$. If we post-multiply $Y(n)$ by Γ^{-1}, we obtain

$$\begin{aligned} \hat{D}(n) &= Y(n)\Gamma^{-1} \\ &= D(n) + N(n)\Gamma^{-1}. \end{aligned} \tag{17}$$

In order to estimate $a_{k,l}$, we choose the $k \circ l$th column $\hat{d}_{k,l}(n)$ of $\hat{D}(n)$, and evaluate the covariance matrix of $\hat{d}_{k,l}(n)$ as

$$\begin{aligned} R_{\hat{d}\hat{d},k,l} &= E\{\hat{d}_{k,l}(n)\hat{d}_{k,l}^H(n)\} \\ &= P_k E\{\alpha_{k,l}^2\}a_{k,l}a_{k,l}^H + \sigma_n'^2[\Gamma^{-1}]_{kol,kol}I, \end{aligned} \tag{18}$$

where $[R]_{i,j}$ is the ijth element of R. Thus, we can obtain $a_{k,l}$ as the eigenvector corresponding to the largest eigenvalue. If we set the covariance matrix $R_{\hat{d}\hat{d},k,l}$ as a function of $\tau_{k,l}$, we can estimate $\tau_{k,l}$ and P_k by computing the maximum largest eigenvalue of $R_{\hat{d}\hat{d},k,l}(\tau)$ as τ changes over the range of possible time delays. The value of τ that corresponds to the maximum point of the largest eigenvalue is a good estimate of $\tau_{k,l}$ and the maximum largest eigenvalue is a good estimate of $P_k\alpha_{k,l}^2$. Since $\phi_{k,l} = -\omega_c\tau_{k,l}$, the estimate of $\phi_{k,l}$ can be obtained, too. Thus, we can compute Q, Y_a, and the quasi-ML estimates of user signals. In addition, let W be the diagonal matrix whose $k \circ l$th diagonal element is $\sqrt{P_k a_{k,l}^H a_{k,l}}\alpha_{k,l}e^{j\phi_{k,l}}$, and Λ be the $KL \times KL$ matrix whose $p \circ q, k \circ l$th element is $\gamma_{p,q,k,l}a_{p,q}^H a_{k,l}/\|a_{p,q}\|\|a_{k,l}\|$. Then, we can write the beamformed signal $Y_a(n)$ as

$$Y_a(n) = \Lambda W X(n) + N(n), \tag{19}$$

where $N(n)$ is a $KL \times 1$ column vector whose $k \circ l$th element is $a_{k,l}^H n_{k,l}(n)/\|a_{k,l}\|$, $R_{nn} = \sigma_n'^2\Lambda$. Then, we can also see that the proposed system is a decorrelator with decorrelating matrix Λ^{-1}.

In [7], a system which uses antenna arrays, a Rake receiver, and a decorrelator is investigated. This system performs decorrelating first and then beamforming later. The system proposed in this paper, on the other hand, can be considered as a system which performs beamforming first and decorrelating later. Let $V(n)$ be the output of the decorrelator shown in the previous section, then

$$\begin{aligned} V(n) &= \Lambda^{-1}Y_a(n) \\ &= WX(n) + N'(n), \end{aligned} \tag{20}$$

where $N'(n) = [n'_{1,1}(n) \cdots n'_{1,L}(n) \cdots n'_{K,1}(n) \cdots n'_{K,L}(n)]^T = \Lambda^{-1}N(n)$. Thus, we can get $Y_a(n)$ by beamforming from $Y(n)$, and $V(n)$ by decorrelating from $Y_a(n)$.

Then the off-diagonal term of the decorrelating matrix Λ is smaller than those of the conventional decorrelating matrix because $\|a_{p,q}^H a_{k,l}\|/(a_{k,l}^H a_{k,l})$, $(k,l) \neq (p,q)$, is less than 1 provided that $a_{p,q}$ is not a constant multiple of $a_{k,l}$. This implies enhancement and correlation of noise can be reduced.

PERFORMANCE ANALYSIS

The $L \times 1$ decorrelator output vector of the first user is

$$v_1(n) = W_1 x_1(n) + n'_1(n), \tag{21}$$

where W_1 is an $L \times 1$ column vector whose lth element is $\sqrt{P_1 a_{1,l}^H a_{1,l}}\alpha_{1,l}e^{j\phi_{1,l}}$.

Since the noise vector $n'_1(n)$ is correlated, a whitening technique can be applied. The correlation matrix of $n'_1(n)$ is ${\sigma'_n}^2[(\Lambda^{-1})^H]_L$, where $[R]_L$ is the $L \times L$ submatrix of R whose ijth element is the ijth element of R. We can get an $L \times L$ whitening matrix T such that $(T^{-1})(T^{-1})^H = [(\Lambda^{-1})^H]_L$ by Cholesky decomposition. Then, we get the output of the whitening filter as

$$v_{1,w}(n) = TW_1 x_1(n) + n_{1,w}(n), \tag{22}$$

where $E\{n_{1,w}(n)n_{1,w}^H(n)\} = {\sigma'_n}^2 I$. If we assume coherent reception with maximum ratio combining (MRC), we can get the decision variable $\rho_1(n)$ as

$$\begin{aligned}\rho_1(n) &= W_1^H T^H v_{1,w}(n) \\ &= W_1^H T^H T W_1 x_1(n) + W_1^H T^H n_{1,w}(n), \quad (23)\end{aligned}$$

and the instantaneous SNR ν_1 of $\rho_1(n)$ as

$$\begin{aligned}\nu_1 &= \frac{(W_1^H T^H T W_1)^2}{\sigma_n'^2 W_1^H T^H T W_1} \\ &= \frac{W_1^H T^H T W_1}{\sigma_n'^2} \\ &= \frac{E_1 W_1'^H T^H T W_1'}{\sigma_n^2}, \quad (24)\end{aligned}$$

where W_1' is an $L \times 1$ column vector whose lth element is $\alpha_{1,l} e^{j\phi_{1,l}} \|a_{1,l}\|$ and $E_1 = P_1 T_s$ is the transmitted symbol energy of the first user. Then the conditional bit error probability $P_{b,1}(\nu_1)$ is

$$P_{b,1}(\nu_1) = \frac{1}{2} erfc(\sqrt{\nu_1}). \quad (25)$$

Now, the vector W_1' is a complex Gaussian vector with mean zero and covariance matrix

$$R_{W_1' W_1'} = diag(\mu_1, \mu_2, \cdots, \mu_L), \quad (26)$$

where $\mu_i = a_{1,i}^H a_{1,i} E\{\alpha_{1,i}^2\}$. Since $R_{W_1' W_1'} T^H T$ is symmetric, the characteristic function of $\rho_1(n)$ can be obtained as

$$\Phi_{\rho_1}(\omega) = \frac{1}{\prod_{j=1}^{L}(1 + 2j\omega\xi_{1,j})}, \quad (27)$$

where $\xi_{1,j}$ are the eigenvalues of $R_{W_1' W_1'} T^H T$. Then, the bit error probability can be obtained as

$$\begin{aligned}P_{b,1} &= \int_0^\infty P_{b,1}(x) f_{\nu_1}(x) dx \\ &= \sum_{l=1}^{L} \frac{\pi_{1,l}}{2} \left[1 - \sqrt{\frac{\kappa_{1,l}}{1+\kappa_{1,l}}}\right], \quad (28)\end{aligned}$$

where $\pi_{1,l} = \prod_{\substack{j=1 \\ j \neq l}}^{L} \frac{\xi_{1,l}}{\xi_{1,l} - \xi_{1,j}}$ and $\kappa_{1,l} = \frac{E_1 \xi_{1,l}}{\sigma_n^2}$.

SIMULATION RESULTS

In this section, we use randomly generated channel vectors. For each resolvable path, we set the channel response vector as the linear combination of 10 array response vectors whose angles are uniformly generated in $[0, 2\pi]$ and whose coefficients are randomly generated with a complex Gaussian pdf and normalized, i.e. the sum of the square of the absolute value of the coefficients is equal to 1. The time delay of each resolvable path is also uniformly generated. In the following result, we set the number of resolvable paths $L = 3$, for $k = 1, 2, \cdots, K$ and the Rayleigh distribution parameter $\alpha_{k,l}$, $k = 1, 2, \cdots, K$, $l = 1, 2, \cdots, L$ are 0.2, and use Gold sequence of period 63. The following results are comparisons of two systems: one is the conventional decorrelator system that uses antenna arrays and we will call it System A. The other is the proposed system and we will call it System B.

In Figs. 2 and 3, the bit error probabilities of the two systems are plotted when the number of active users is 10 and 20, respectively. In each figure, we have three solid lines and three dotted lines. The solid lines are the bit error probability curves when the number M of antenna arrays is 2, 3, and 4 for System B and the dotted lines are the bit error probability curves for System A. We can see that we can get more gain over the conventional system as the number of antenna arrays gets larger and as the number of active users increases.

In Fig. 4, the bit error probabilities of the two systems are plotted versus the number of active users when the number of antenna arrays is 2, 3, and 4, and $\frac{E_1}{\sigma_n^2}$ is $10dB$. Again we can clearly see that the performance gain of the proposed system over the conventional decorrelator system increases as the number of active users increases.

CONCLUDING REMARKS

In this paper, we proposed a quasi-ML detector employing antenna arrays in quasi-synchronous channels. We analyzed the performance of the proposed system and showed that the enhancement and correlation of noise, which is the major drawback of the conventional decorrelator system, could be reduced. The proposed quasi-ML detector can be considered as a system which performs beamforming first and decorrelating later. It was shown that we could get some gain over the conventional decorrelator system and the gain got larger as the number of active users increased and the number of antenna arrays increased: with the proposed system, we can get a capacity considerably higher than that with the conventional decorrelator system.

ACKNOWLEDGEMENT

This research was supported by Korea Science and Engineering Foundation (KOSEF) under Grant 971-0916-097-2, for which the authors would like to express their thanks.

REFERENCES

[1] K.S. Gilhousen, I.M. Jacobs, R. Padovani, A.J. Viterbi, L.A. Weaver, and C. Wheatly, "On the capacity of a cellular CDMA system," *IEEE Tr. Veh. Tech.*, Vol. VT-40, pp. 303-312, May 1991.

[2] B. Suard, A.F. Naguib, G. Xu, and A. Paulaj, "Performance analysis of CDMA mobile communication system using antenna arrays," *Proc. ICASSP*, Minneapolis, MN, pp. 153-156, April 1993.

[3] A.F. Naguib, A. Paulaj, and T. Kailath, "Capacity improvement with base station antenna array in cellular CDMA," *IEEE Tr. Veh. Tech.*, Vol. VT-43, pp. 691-689, August 1994.

[4] S. Verdu, "Minimum probability of error for asynchronous Gaussian multiple-access channels," *IEEE Trans. Inform. Theory*, Vol. IT-32, pp. 85-96, January 1986.

[5] S. Verdu, "Optimum multiuser asymptotic efficiency," *IEEE Trans. Commun.*, Vol. COM-34, pp. 890-897, September 1986.

[6] S. Verdu, "Multiuser Detection," in *Advances in Signal Processing* (H.V. Poor and J.B. Thomas, eds.), vol. 2: Signal Detection, pp. 369-409, CT: JAI Press, 1992

[7] Z. Zvonar, "Combined multiuser detection and diversity reception for wireless CDMA systems," *IEEE Trans. Veh. Tech.*, Vol. VT-45, pp. 205-211, February 1996.

[8] R.A. Iltis, "Demodulation and code acquisition using decorrelator detectors for QS-CDMA," *IEEE Trans. Comm.*, Vol. COM-44, pp. 1553-1560, November 1996.

[9] R.A. Iltis and L. Mailaender, "Multiuser detection of Quasisynchronous CDMA signals using linear decorrelators," *IEEE Trans. Comm.*, Vol. COM-44, pp. 1561-1571, November 1996.

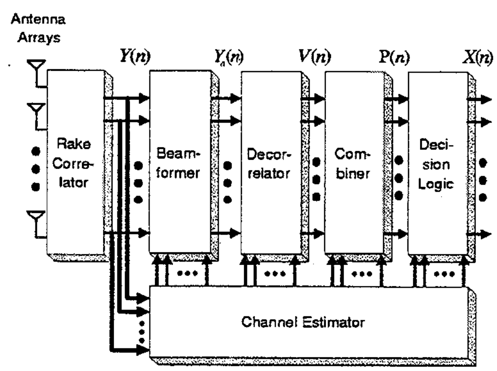

Figure 1: The receiver system architecture.

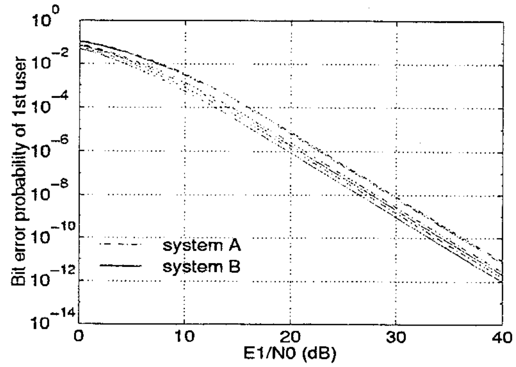

Figure 2: The bit error probabilities of the two systems when the number of active users $K = 10$, the number of antenna arrays M is 2, 3, and 4.

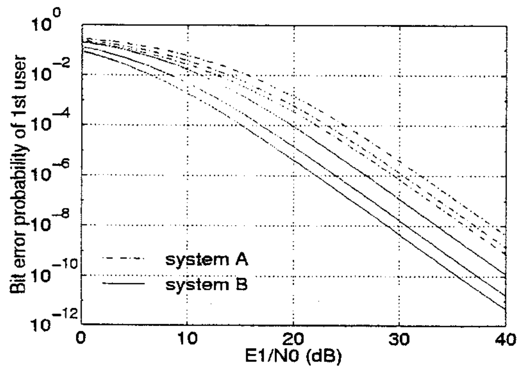

Figure 3: The bit error probabilities of the two systems when the number of active users $K = 20$, the number of antenna arrays M is 2, 3, and 4.

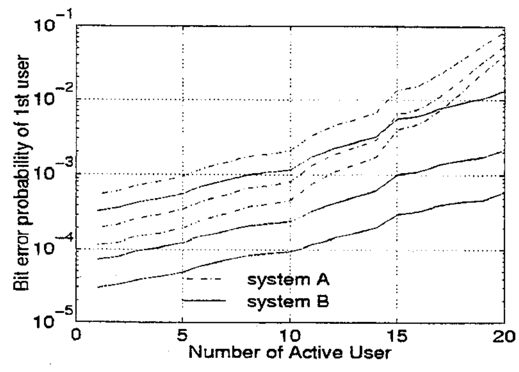

Figure 4: The bit error probabilities of the two systems versus the number of active users K when $\frac{E_1}{\sigma_n^2}$ is $10dB$, the number of antenna arrays M is 2, 3, and 4.