Reverse Link Bit Error Rate for Cellular CDMA with Antenna Arrays, Rayleigh Fading, and Power Control Error

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Abstract —

The performance of code-division multiple-access (CDMA) systems is affected by multiple factors such as large-scale fading, small-scale fading, and cochannel interference (CCI). Most of the published research on the performance analysis of CDMA systems usually accounts for subsets of these factors. In this work we provide an analysis that combines several of the most important factors affecting the performance of CDMA systems. In particular, new analytical expressions are developed for reverse link bit error probability (BEP) of CDMA systems. These expressions account for adverse effects such as path loss, large-scale fading (shadowing), small-scale fading (Rayleigh fading), and CCI, as well as for correcting mechanisms such as power control (compensates for path loss and shadowing), spatial diversity (mitigates against Rayleigh fading), and voice activity gating (reduces CCI). The new expressions may be used as convenient analysis tools that complement computer simulations.

I. Introduction

Code-division multiple-access (CDMA) systems are currently being deployed around the country and around the world in response to the ever increasing demand for cellular/personal communications services. Extensive research has been published on the performance analysis of CDMA systems. Fading is among the major factors affecting the performance of such systems. Large-scale fading consists of path loss and shadowing, the latter term referring to fluctuations in the received signal mean power. In this work, the combined effect of large and small-scale fading is considered. Small-scale fading is assumed to be governed by the Rayleigh distribution (Rayleigh fading).

In addition to fading, CDMA systems are susceptible to the *near-far* problem. It is well known that owing to the near-far problem, power control is an important system requirement in the design of CDMA. Power control circuits, however, have finite accuracy, which implies that CDMA systems are still faced with residual shadowing effects. The signal received at the base station from a power-controlled user can be modeled as governed by the log-normal distribution [1]. The standard deviation of the received signal power is defined as the *power control error* (PCE) and is typically of the order of 1.5 to 2.5 dB. The same fading that affects the desired user's signal also affects signals from other users which serve as cochannel interference (CCI) to the desired user. Thus the resultant CCI power can be modeled as the power sum of multiple log-normal contributions. This observation serves as the starting point for the performance analysis of CDMA systems in fading channels. The computation of the distribution of a sum of log-normal variates has been examined in [2, 3]. A closed-form solution for the distribution is not known; alternatively, the sum of log-normal variates is approximated as another log-normal variate. This approach is justified by a theorem proved by Marlow that states that under very general conditions, the power sum of independent variates is asymptotically normally distributed [4]. Although, when the number of variates is finite, the power sum of these variates does not strictly follow normal distribution, the approximation to normal is often used, and its validity was evaluated in [2, 5].

While large-scale fading effects are compensated by power control, small-scale fading can be mitigated by space-time diversity provided by an adaptive antenna array along with a Rake receiver. In addition to fading, CDMA systems are adversely affected by CCI. The effect of CCI needs to be taken into account in any performance analysis of CDMA systems. On two-way telephone connections, measurements have established that a typical voice signal is active less than 50 percent of the time. Interference in CDMA systems is reduced by providing voice activity gating. This technique involves the monitoring of voice activity such that each transmitter is switched off during periods of no voice activity, thus reducing CCI. A performance analysis needs to take voice gating into account.

Due to the complexity of the mobile communications scenario, most published results account for only some of the adverse effects mentioned above. For accurate predictions of CDMA systems performance, it is of great interest to be able to develop closed-form expressions that simultaneously incorporate the effects of shadowing, power control error, Rayleigh fading, voice activity and space-time processing.

The paper is organized as follows: the system model is given in Section 2; Section 3 contains the main theoretical results including probability of bit error and some extensions for more general cases; numerical results are presented in Section 4, and our conclusions are summarized in Section 5.

II. System Model

The system model represents the reverse link of a single cell CDMA system which serves K_u users, and uses a base station with an M-element antenna array. The received signals are assumed to undergo independent, flat Rayleigh fading. It is

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further assumed that the fading is slowly varying such that the lowpass equivalent channel seen by each antenna can be characterized by a complex-valued scalar. The system is assumed interference limited with negligible thermal noise. The complex envelope of the signal received at the base station is then expressed by the M-dimensional vector:

$$\begin{aligned}\mathbf{x}(t) &= \sqrt{\lambda_1}\, m_1(t-\tau_1)u_1(t-\tau_1)\mathbf{c}_1 \\ &+ \sum_{k=2}^{K_u} \epsilon_k \sqrt{\lambda_k}\, m_k(t-\tau_k)u_k(t-\tau_k)\mathbf{c}_k, \qquad (1)\end{aligned}$$

where the first and second terms respectively, represent the desired signal and the CCI, λ_k $(k = 1, \cdots, K_u)$ are the powers of the received signals, $\mathbf{c}_k$ are normalized complex Gaussian channel vectors with $E\left[\mathbf{c}_k\mathbf{c}_k^H\right] = \mathbf{I}$, $\mathbf{I}$ is the $M \times M$ identity matrix, the superscript denotes transpose and complex conjugate, $m_k(t)$ are NRZ waveforms of the users' data, $u_k(t)$ are the spreading sequences, ϵ_k are binary random variables indicating the users' voice activity, τ_k are the users' delays. Let $m_k(t) = \sum_i s_k(i)\, h(t - iT_s)$, where $h(t)$ is the basic pulse shape, T_s is the symbol interval, i is the symbol interval index, and $s_k(i) \in \{-1, 1\}$ are the users' binary data. It is assumed that $E[s_k(i)] = 0$, and $E[s_k(i)\, s_l(j)] = \delta_{kl}\delta_{ij}$, where $\delta_{ij} = 1$ for $i = j$, and $\delta_{ij} = 0$ otherwise. The signature waveforms are normalized to unit energy over the symbol interval. For convenience, $\tau_1 = 0$. In a system that provides a single service (such as voice) with the same bit error rate and with perfect power control, all λ_k's are equal. The received powers λ_k, $k = 1, \ldots, K_u$, are the result of path loss, shadowing and imperfect power control, and are modeled as independent, identically distributed (i.i.d.) random variables with log-normal distribution. If λ_k has a log-normal distribution, then the received power expressed in dB, $\alpha_k = 10\log_{10}\lambda_k$ has a normal distribution with mean m_α and variance σ_α^2. The standard deviation of α_k is the PCE measured in dB. Since $\alpha_k < m_\alpha$ with probability $\frac{1}{2}$, $10^{m_\alpha/10}$ is the median value of λ_k. The voice activity ϵ_k is modeled as a Bernoulli (p) random variable with $\Pr(\epsilon_k = 1) = p$, where p is the *voice activity factor*.

Following spread spectrum demodulation and sampling at the symbol interval, the received signal can be written:

$$\begin{aligned}\mathbf{y}(i) &= \int_{iT_s}^{(i+1)T_s} \mathbf{x}(t)u_1(t)dt \\ &= \sqrt{\lambda_1}s_1(i)\mathbf{c}_1 + \sum_{k=2}^{K_u} \epsilon_k\sqrt{\lambda_k}\,\cdot \\ &\quad \left(s_k(i-1)\,\rho_k^- + s_k(i)\,\rho_k^+\right)\mathbf{c}_k, \qquad (2)\end{aligned}$$

where $\rho_k^- = \int_{iT_s}^{iT_s+\tau_k} u_k(t-\tau_k)u_1(t)dt$, $\rho_k^+ = \int_{iT_s+\tau_k}^{(i+1)T_s} u_k(t-\tau_k)u_1(t)dt$ are the correlations between user signatures. It is assumed that the correlations above are independent of the symbol interval index i. If the CCI is spatially white, the optimum output SIR is provided by maximal ratio combining (MRC). The array weight vector $\mathbf{w}$ then acts as a channel matched filter, $\mathbf{w} = \mathbf{c}_1$. The array output is expressed:

$$\begin{aligned}z(i) &= \mathbf{w}^H\mathbf{y}(i) = \mathbf{c}_1^H\mathbf{y}(i) \\ &= \phi_s(i) + \phi_j(i), \qquad (3)\end{aligned}$$

where

$$\phi_s(i) = \sqrt{\lambda_1}s_1(i)\mathbf{c}_1^H\mathbf{c}_1 \qquad (4)$$

and

$$\phi_j(i) = \mathbf{c}_1^H \sum_{k=2}^{K_u} \epsilon_k\sqrt{\lambda_k}\left(s_k(i-1)\,\rho_k^- + s_k(i)\,\rho_k^+\right)\mathbf{c}_k \qquad (5)$$

are the desired signal and CCI respectively, at the array output. Over the duration of a bit, it is assumed that the interference can be approximated by an equivalent source using the following expression:

$$\phi_j(i) = s(i)\mathbf{c}_1^H \sum_{k=2}^{K_u} \epsilon_k\sqrt{\eta_k\lambda_k}\mathbf{c}_k, \qquad (6)$$

where $s(i)$ combines the total interference bit effects during the bit duration and η_k is a gain factor incorporating the effect of cross-correlation with the desired user's signal. This model is a worst case of sorts, in which interference sources are not independent, however, it has the advantage of being analytically tractable (see also [6]). The instantaneous output SIR is then written:

$$\gamma = \frac{|\phi_s(i)|^2}{|\phi_j(i)|^2}. \qquad (7)$$

III. Computation of the Error Probability

Computation of the bit error requires knowledge of the distribution of the interference at the array output. Due to dissimilar shadowing and fading affecting the various users, interferers are not identically distributed, hence the central limit theorem cannot be strictly invoked to claim the Gaussian property. Nevertheless, the Gaussian property is often assumed in such analyses [7, 8]. In this paper, the Gaussian assumption is validated by a chi-square test presented in the next section.

For BPSK and Gaussian interference, the conditional bit error probability (BEP) is given by

$$b = P(e \mid \gamma) = Q\left(\sqrt{2\gamma}\right), \qquad (8)$$

where γ is the *instantaneous* SIR and is given by (7). The variate γ is a function of Rayleigh fading, shadowing (PCE), and voice activity. The distribution of γ is required to determine the average probability of bit error. The density of γ conditional shadowing and voice activity was found in [9]

$$f_\gamma(\gamma \mid \mu) = \frac{M(\gamma/\mu)^{M-1}}{\mu(1+\gamma/\mu)^{M+1}}. \qquad (9)$$

where μ is defined by:

$$\mu = \frac{\lambda}{\mathcal{J}} = \frac{\lambda}{\sum_{k=2}^{K_u}\epsilon_k\eta_k\lambda_k}. \qquad (10)$$

The BEP b is a function of the instantaneous SIR γ, hence a random variable. The density of b can be found from [10, p.125]:

$$f_b(b \mid \mu) = \left.\frac{f_\gamma(\gamma \mid \mu)}{|db/d\gamma|}\right|_{\gamma=\frac{1}{2}[Q^{-1}(b)]^2}, \qquad (11)$$

where Q^{-1} is the inverse function of Q. After a few manipulations it can be shown that,

$$\frac{db}{d\gamma} = -\frac{1}{2\sqrt{\gamma\pi}}\, e^{-\gamma}. \qquad (12)$$

Substituting (12) into (11), one has the conditional density of b,

$$f_b(b \mid \mu) = \frac{M\,(\gamma/\mu)^{M-1}}{\mu\,(1+\gamma/\mu)^{M+1}}\; 2\sqrt{\gamma\pi}\; e^{\gamma}\Bigg|_{\gamma=\frac{1}{2}[Q^{-1}(b)]^2}. \qquad (13)$$

The function Q^{-1} can be evaluated by numerical integration. The unconditional density of b can be obtained by averaging over the distribution of μ

$$f_b\,(b) = \int_0^{\infty} f_b\,(b \mid \mu)\;\; f_\mu\,(\mu)\, d\mu. \qquad (14)$$

Following the argument [11], μ has a log-normal distribution. Replacing μ by $\mu = e^g$, one gets

$$\begin{aligned} f_b\,(b) &= \int_0^{\infty} f_b\,(b \mid e^g)\;\; f_g\,(g)\;\; e^g\;\, dg \\ &= E_g\,[G\,(b,g)]\,, \end{aligned} \qquad (15)$$

where $f_g\,(g) = f_\mu\,(g)\,/\,|dg/d\mu|_{\mu=e^g}$ and $G(b,g) = f_b\,(b \mid e^g)\; e^g$. Since μ has a log-normal distribution, $g = \ln\mu$ is normally distributed. An exact closed-form result for the integral in (15) is not available, however an approximation exists for $E_g\,[G(b,g)]$ when g has a normal distribution. The approximation is valid for an arbitrary probability function $G(b,g)$ and is expressed in terms of the mean m_g and the standard deviation σ_g [12]:

$$f_b\,(b) \cong \frac{2}{3}G(b,\, m_g) + \frac{1}{6}G(b,\, m_g + \sqrt{3}\,\sigma_g) + \frac{1}{6}G(b,\, m_g - \sqrt{3}\,\sigma_g). \qquad (16)$$

The computation of the mean and variance of g, m_g and σ_g, respectively, is discussed in [13], thus the previous relation expresses $f_b\,(b)$ in terms of known quantities. Notice that $f_b\,(b)$ accounts for the effects of Rayleigh fading, shadowing (PCE), and voice activity. The BEP density function in (16) is a more complete characterization of system performance than the more common average BEP. The latter, can be obtained by using the density of b, or from the following argument. The conditional BEP can be expressed as:

$$\begin{aligned} P(e \mid \mu) &= \int_0^{\infty} P(e \mid \gamma)\;\; f_\gamma(\gamma \mid \mu)\, d\gamma \\ &= M\mu \int_0^{\infty} Q\left(\sqrt{2\gamma}\right)\; \frac{\gamma^{M-1}}{(\mu+\gamma)^{M+1}} d\gamma. \end{aligned} \qquad (17)$$

Following [14], (17) can be expressed utilizing hypergeometric functions:

$$\begin{aligned} P(e \mid \mu) &= \frac{M}{2\Gamma(M+1)}[\,2\mu\,\Gamma(M+1)\,{}_2F_2(M+1,1;3/2,2;\mu) \\ &\quad -2\sqrt{\mu}\,\Gamma(M+1/2)\,{}_2F_2(M+1/2,1/2;1/2,3/2;\,\mu) \\ &\quad +\Gamma(M)\,], \end{aligned} \qquad (18)$$

where ${}_2F_2(\cdot)$ is the standard generalized hypergeometric function [15]. Expression (18) can be evaluated numerically by using software packages such as Maple, Mathematica, etc. Alternatively, (17) can be evaluated numerically. The unconditional BEP is found by averaging $P(e \mid \mu)$ over the distribution of μ:

$$P_e = \int_0^{\infty} P(e \mid \mu)\;\; f_\mu(\mu)\;\, d\mu \qquad (19)$$

In terms of the normal random variable g, $g = \ln\mu$, one gets

$$P_e = \int_{-\infty}^{\infty} P(e \mid g)\;\; f_g(g)\;\, dg = E_g\,[P(e \mid g)]\,. \qquad (20)$$

Finally, using the same approach as in (16), one can obtain the average probability of bit error:

$$\begin{aligned} P_e &= E_g\,[P(e \mid g)] = E_g\,[H(g)] \\ &\cong \frac{2}{3}H(e^{m_g}) + \frac{1}{6}H\left(e^{m_g+\sqrt{3}\,\sigma_g}\right) + \frac{1}{6}H\left(e^{m_g-\sqrt{3}\,\sigma_g}\right), \end{aligned} \qquad (21)$$

where we introduced $H(g) = P(e \mid g)$ as a notational convenience.

Frequency-Selective Channel

Here we generalize the previous results to the case of a frequency-selective channel. The reverse link channel is assumed frequency-selective with L resolvable paths. A Rake receiver is used to track and combine the paths. Following spread spectrum demodulation, the signal received at the antenna array from the lth path can be written as an M-dimensional vector:

$$\begin{aligned} \mathbf{y}_l(i) &= \sqrt{\lambda_{1l}}\, s_1(i)\mathbf{c}_{1l} + \sum_{\substack{n=1\\ n\neq l}}^{L} \sqrt{\lambda_{1n}}\left(s_1(i-1)\rho_{1ln}^{-} + s_1(i)\rho_{1ln}^{+}\right)\mathbf{c}_{1n} \\ &+ \sum_{k=2}^{K_u}\sum_{n=1}^{L} \epsilon_k \sqrt{\lambda_{kn}}(s_k(i-1)\rho_{kln}^{-} + s_k(i)\rho_{kln}^{+})\mathbf{c}_{kn}, \\ &\qquad l = 1,\cdots,L, \end{aligned} \qquad (22)$$

where $k = 1,\ldots,K_u$ is the user index, $n = 1,\ldots,L$ is the path index, λ_{kn} are the received signal powers, $\mathbf{c}_{kn}$ are the channel vectors, $\rho_{kln}^{-} = \int_{iT_s}^{iT_s+\tau_{kn}} u_k(t-\tau_{kn})u_1(t-\tau_{1l})dt$, $\rho_{kln}^{+} = \int_{iT_s+\tau_{kn}}^{(i+1)T_s} u_k(t-\tau_{kn})u_1(t-\tau_{1l})dt$, τ_{kl} and τ_{kn} are the delays Assume that the cross-correlations are independent of the path l, i.e., $\rho_{kln}^{-/+} = \rho_{kn}^{-/+}$. The terms in (22) represent the desired signal, self-interference, and CCI, respectively. In the following, it is assumed that the self-interference contribution is negligible in comparison with the CCI. Signal vectors associated with the different paths, $\mathbf{y}_l(i)$ $(l = 1,\cdots,L)$, are stacked to form an ML-dimensional vector, $\mathbf{y}(i)$, and grouped according to components related to the desired signal and CCI, yielding the expression (see [16] for details):

$$\mathbf{y}(i) = \sqrt{\lambda_1}s_1(i)\,\mathbf{c}_1 + \mathbf{j}(i), \qquad (23)$$

where $\mathbf{y}(i) = \left[\mathbf{y}_1^T(i),\cdots,\mathbf{y}_L^T(i)\right]^T$, $\mathbf{c}_1 = \left[\mathbf{c}_{11}^T,\cdots,\mathbf{c}_{1L}^T\right]^T$. The first term in the relation above represents the desired signal, $\mathbf{j}(i)$ is the interference, the superscript "T" denotes transpose. With MRC in both space (antenna array) and time (Rake) domains, the output is equivalent to applying MRC to the stacked vector in (23). The MRC weight vector is then given by $\mathbf{w} = \mathbf{c}_1$. Similar to the approach taken earlier, it is assumed that the interference can be expressed as an equivalent source:

$$\mathbf{j}(i) = s(i) \sum_{k=2}^{K_u} \sum_{n=1}^{L} \epsilon_k \sqrt{\eta_{kn} \lambda_{kn}}\, \mathbf{c}_{kn}, \tag{24}$$

where $s(i)$ is the CCI source bit, η_{kn} is a gain factor representing the cross-correlation between codes. The double sum over the scaled ML-dimensional Gaussian distributed vectors $\mathbf{c}_{kn}$ is equivalent to another Gaussian vector,

$$\sum_{k=2}^{K_u} \sum_{n=1}^{L} \epsilon_k \sqrt{\eta_{kn} \lambda_{kn}}\, \mathbf{c}_{kn} = \sqrt{\mathcal{J}}\, \mathbf{c}_p, \tag{25}$$

where

$$\begin{aligned} \mathcal{J} &= \sum_{k=2}^{K_u} \sum_{n=1}^{L} \epsilon_k \eta_{kn} \lambda_{kn} \\ &= \sum_{k=2}^{K_u} \epsilon_k \nu_k \lambda_k, \end{aligned} \tag{26}$$

and $\nu_k = \sum_{n=1}^{L} \eta_{kn}$. The distribution of the output SIR is obtained from (9), by substituting M with ML, to account for the additional diversity paths provided by the frequency-selective channel:

$$f_\gamma(\gamma \mid \mu) = \frac{ML(\gamma/\mu)^{ML-1}}{\mu(1+\gamma/\mu)^{ML+1}}. \tag{27}$$

All other results in the section hold by substituting M with ML.

IV. Numerical Results

Results in this section are derived from computer simulations of a CDMA system employing BPSK modulation and BPSK spreading, with a voice activity factor of $p = 3/8$ and a spreading ratio of 85. The spreading ratio corresponds to an information data rate of 14.4 kb/s and a signal bandwidth of 1.23 MHz. Unless specified otherwise, the number of antenna elements assumed in the simulations was $M = 4$. The channel was assumed flat and subject to Rayleigh fading and shadowing.

First, the validity of the Gaussian approximation for the CCI was evaluated for $K_u = 30$ users, and PCE = 1.5 dB. To that end, the histogram of the interference level was generated and compared to the theoretical Gaussian curve. This is shown in Figure 1. Additionally, a chi-square test following the method presented in [10] was applied to evaluate the goodness of the fit. The sample space was partitioned into 21 disjoint intervals corresponding to a test with 20 degrees of freedom. Standard chi-square test tables show that for 20 degrees of freedom, the threshold for a 1% significance level is 37.57. Calculated from the simulation and averaged over 200 Monte Carlo runs, the chi-square statistic D^2 was 22.14, which does not exceed the threshold. It is concluded that the Gaussian approximation is valid for the interference.

Figures 2 and 3 depict the distribution of the probability of bit error (b) with various values of PCE and number of antennas. These PDF curves shift toward to lower value of b as PCE decreases and the number of antennas increases. Figure 4 displays the analytical results for the average probability of bit error as a function of the number of users per cell. If the desired performance is $P_e = 10^{-3}$, capacity is respectively 55, 45 and 32 users/cell for PCE = 0, 1.5, and 2.5 dB. In a CDMA system with a PCE from 1.5 to 2.5 dB, the system capacity degrades from 18% to 42% compared to the case of perfect power control.

V. Conclusions

In this paper, we studied the reverse link performance of cellular CDMA systems, with space-time processing, Rayleigh fading, shadowing, power control error and voice activity gating. The performance was analyzed in terms of average probability of bit error. Analytical results were obtained that that can be used to evaluate system performance. All parameters needed for the computations can be obtained from measured data. The analysis shows that space-time processing provided by cell site antenna arrays along with a Rake receiver, compensates for performance degradations due to PCE in cellular CDMA systems.

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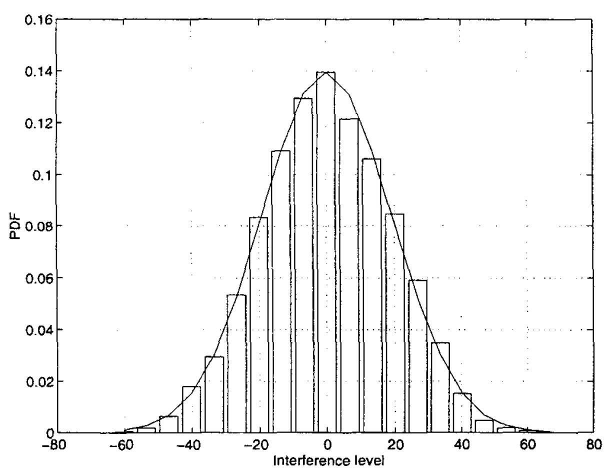

Figure 1: Gaussian fit to the interference histogram.

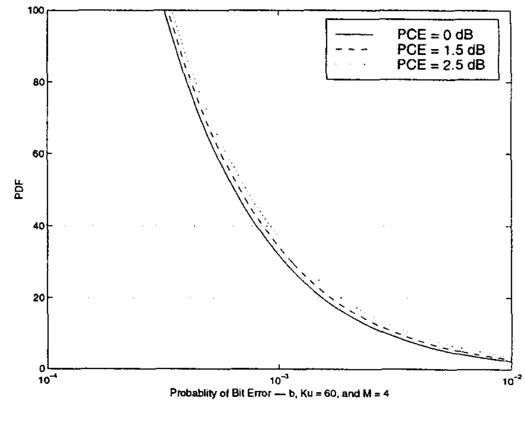

Figure 2: PDF of probability of bit error with $K_u = 100$ and $M = 4$.

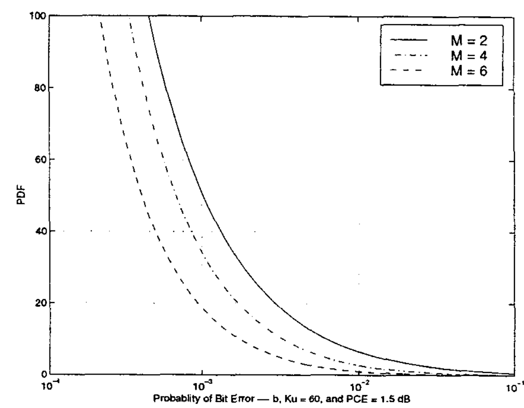

Figure 3: PDF of probability of bit error with $K_u = 100$ and PCE = 1.5 dB.

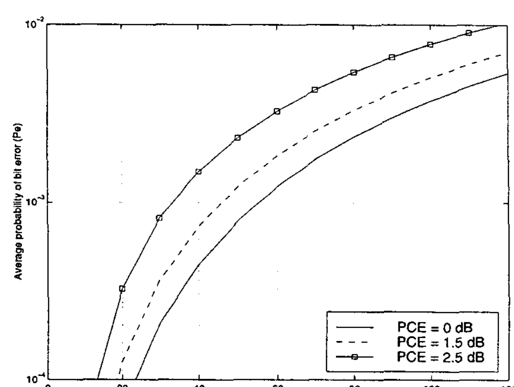

Figure 4: Average probability of bit error versus capacity. Four antenna elements, $M = 4$, various PCE's, and $p = 3/8$.