PERFORMANCE ANALYSIS OF CDMA-BASED WIRELESS COMMUNICATION SYSTEMS USING THE SIMPLIFIED IMPROVED GAUSSIAN APPROXIMATION METHOD.

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ABSTRACT
The limitations initially prevalent in CDMA-based systems have been gradually solved thereby making CDMA a very promising access mode for future communication systems. Following the move towards higher data transmission rates, however, a number of other problems have emerged that need to be tackled. As a result, current world-wide research on CDMA-based systems is geared towards high speed, highly mobile multimedia communication applications. In this paper, the performance of a multi-user DS-CDMA communication system operating in a Rayleigh fading environment is investigated. Performance expressions are derived and the variation of the performance with various system parameters is presented.

INTRODUCTION

The utilisation of communication channels by many users has been traditionally accomplished using Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) schemes, where users share the channel on a frequency or a time basis respectively. The adoption of the Code Division Multiple Access (CDMA) scheme, in which users share the channel utilising signalling characteristics or codes, has emerged as a prime contender for future multi-access communication networks.

Communication based on CDMA has a number of advantages over other access schemes (Opperman 2000). First, CDMA is wideband, highly tolerant to interference and jamming, and resistant to multipath interference. Secondly, it is attractive in cellular systems due to its low frequency reuse factor. Hence, there is no need to use multi-frequencies like in narrowband TDMA. Thirdly, CDMA has low spectral density and provides less interference to other systems, and is therefore used in areas where such other systems are used. These features promoted the use of CDMA in the military, where it was initially used, and the transmit power, bandwidth and total system efficiency were not the most important parameters, but rather, security, reliability, robustness and simplicity were. The limitations inherent in CDMA systems have been widely addressed to in the drive to utilise the technology. The limitations include multi-access interference (MAI), fading, inter-symbol interference (ISI) and the far-near problem,.

A review of MAI and its effects has been given by Proakis (1995), while the various interference cancellation techniques used to combat it can be found elsewhere (Buehrer and Woerner 1996, Rappaport 1996). Likewise, a treatment of Rayleigh, Rician and log-normal fading, including the various methods that have been devised to combat them have been given by various authors (Proakis 1995, Vandendorpe 1995, Dallas and Pavlidou 1996). A review of ISI, its effects and the methods used to counter it has been given by Proakis (1995) and Rappaport (1996), while that of the far-near problem has been given by Priscoli and Sestini (1996).

Most of the emphasis in future communication systems is in multimedia applications that require more bandwidth, fast transmission rates and higher reliability (Huber et al. 2000). The journey towards the realization of such systems has gone through first generation FDMA-based wireless analogue communication systems to second generation TDMA-based wireless digital communication systems termed Global System for Mobile Communications (GSM). It is now going through third generation systems and will lead to future fourth generation systems both of which employ the more advanced CDMA technology (Baier 1994, Chang and Lin 2000, Beredivin et al. 2002).

In this report, the error performance of a multi-user direct sequence CDMA (DS-CDMA) system operating in a Rayleigh fading channel is analyzed. Various researchers have utilised different methods to compute the error performance of such systems, focusing mainly on the contribution of MAI (Buehrer & Woerner 1996, Lataief 1997, Morrow 1998). The Standard Gaussian Approximation (SGA) method assumes that the MAI is Gaussian in nature. This method, however, becomes inaccurate at low bit-error-rate (BER) and when the number of users or interferers is small. The limitations of the SGA can be overcome by using the Improved Gaussian Approximation (IGA) method. This method is quite accurate, but quite computationally intensive, and a more attractive but still accurate version of it, the Simplified IGA (SIGA) method is used instead. In this report, the SIGA method is used for computing the error performance of a multi-user CDMA system in a Rayleigh fading environment. The performance expressions are derived, and numerical computations are carried out to illustrate the variation of the performance with number of users, number of multipaths, number of chips, transmitter power, and amount of fading.

SYSTEM MODEL AND ANALYSIS

In this scheme, there are K transmitters and one receiver. The receiver can be a base station and the transmitters can be mobile hand sets. Moreover, we assume that there are L possible paths from the transmitters to the receiver. For the kth transmitter, the bit sequence $b_k(t)$ to be transmitted is spread by the transmitter's code $a_k(t)$ and then modulated by the transmitter's carrier having amplitude A_k before being transmitted. Also, the bit duration is T and there are N = T/Tc chips per bit where Tc = chip duration. The transmitted signal from transmitter k is therefore given by

$$s_k(t) = A_k b_k(t) a_k(t) \cos(\omega_0 t + \theta_k) \tag{1}$$

where

$$b_k(t) = \sum_{n=-\infty}^{\infty} b_{k,n} P_T(t - \gamma_{Tk} - nT), \qquad b_{k,n} \in \{-1,1\} \tag{2}$$

$$a_k(t) = \sum_{m=-\infty}^{\infty} a_{k,m} P_{T_c}(t - \gamma_{Tk} - m T_c), \qquad a_{k,m} \in \{-1,1\} \tag{3}$$

$$P_u(t) = \begin{cases} 1, \; 0 \le t \le u \\ 0, \; otherwise \end{cases} \tag{4}$$

γ_{Tk} is the timing offset and θ_k is the phase offset of the transmitter. The composite signal at the receiver is therefore given by

$$r(t) = \sum_{k=1}^{K}\sum_{l=1}^{L} A_k \beta_{kl} b_k(t - \gamma_{Tk} - \gamma_{kl}) a_k(t - \gamma_{Tk} - \gamma_{kl}) \cos(\omega_0 t - \omega_0 \gamma_{kl} + \theta_k + \phi_{kl}) + n(t) \qquad \textbf{(5)}$$

where γ_{kl} is the timing offset and ϕ_{kl} is the phase offset due to the multipaths, and n(t) is the channel noise.
At the receiver, the demodulation and despreading are performed for transmitter of interest i to give

$$y_i(t) = r(t) a_i(t) \cos(\omega_0 t) \qquad \textbf{(6)}$$

which, after passing through the matched filter gives

$$\begin{aligned} y_i(t) \; = \; & \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{L} A_k \beta_{kl} b_k(t - \gamma_{Tk} - \gamma_{kl}) a_k(t - \gamma_{Tk} - \gamma_{kl}) a_i(t) \cos(\theta_k + \phi_{kl} - \omega_0 \gamma_{kl}) \\ & + \; n(t) a_i(t) \cos(\omega_0 t) \end{aligned} \qquad \textbf{(7)}$$

We now let $\gamma_{Tk} + \gamma_{kl} = \tau_{kl}$ and $\theta_k + \phi_{kl} - \omega_0 \tau_{kl} = \theta_{kl}$ to obtain

$$y_i(t) = \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{L} A_k \beta_{kl} b_k(t - \tau_{kl}) a_k(t - \tau_{kl}) a_i(t) \cos(\theta_{kl}) + n(t) a_i(t) \cos(\omega_0 t) \qquad \textbf{(8)}$$

The final output before the decision is then obtained as

$$\begin{aligned} Y_i(T) \; = \; & \frac{1}{2}\sum_{k=1}^{K}\sum_{l=1}^{L} A_k \beta_{kl} \cos(\theta_{kl}) \int_{(n-1)T}^{nT} b_k(t - \tau_{kl}) a_k(t - \tau_{kl}) a_i(t) dt \\ & + \int_{(n-1)T}^{nT} n(t) a_i(t) \cos(\omega_0 t) dt \end{aligned} \qquad \textbf{(9)}$$

which can be expressed in terms of interference terms I_{kl} as

$$Y_i(T) = \sum_{k=1}^{K}\sum_{l=1}^{L} \frac{1}{2} I_{kl} + \int_{(n-1)T}^{nT} n(t) a_i(t) \cos(\omega_0 t) dt \qquad \textbf{(10)}$$

with

$$I_{kl} \; = \; \frac{1}{2} A_k \beta_{kl} \cos(\theta_{kl}) \int_{(n-1)T}^{nT} b_k(t - \tau_{kl}) a_k(t - \tau_{kl}) a_i(t) dt. \qquad \textbf{(11)}$$

Various authors have developed more-or-less similar methods to represent the expression for the interference term when analyzing different CDMA systems (Wu and Tsaur 1994, Kwak and Kim 1995, Vandendorpe 1995, Dallas and Pavlidou 1996, Lataief 1997, Huang and Ng 1999). In this analysis, the despreading for the nth bit of the transmitter of interest is assumed to span bits n-1 and n of transmitter k, and the cross-correlation of the chip and bit sequences in the interference term can then be re-written as

$$\int_{(n-1)T}^{nT} b_k(t-\tau_{kl})\, a_k(t-\tau_{kl})\, a_i(t)dt = \\ b_{k,n-1}\int_0^{\tau_{kl}} a_k(t-\tau_{kl})a_i(t)dt + b_{k,n}\int_{\tau_{kl}}^{T} a_k(t-\tau_{kl})a_i(t)dt \tag{12}$$

where if the definitions

$$R_{ki}(\tau)=\int_0^{\tau} a_k(t-\tau)\, a_i(t)dt,\ \ \overline{R_{ki}}(\tau)=\int_{\tau}^{T} a_k(t-\tau)\, a_i(t)dt, \tag{13}$$

are used we obtain

$$I_{kl}=\frac{1}{2}A_k\,\beta_{kl}\cos(\theta_{kl})\left[b_{k,n-1}R_{ki}(\tau_{kl})+b_{k,n}\overline{R_{ki}}(\tau_{kl}).\right] \tag{14}$$

If we now let $\tau = sT_c+\Delta\tau$ where s = 0 .. N - 2, and $0\le\Delta\tau<T_c$, then

$$\begin{aligned} R_{ki}(\tau) &= \sum_{j=0}^{s} a_{k,N-s+j-1}a_{i,j}\Delta\tau + \sum_{j=0}^{s-1} a_{k,N-s+j}a_{i,j}(T_c-\Delta\tau) \\ \overline{R_{ki}}(\tau) &= \sum_{j=s+1}^{N-1} a_{k,j-s-1}a_{i,j}\Delta\tau + \sum_{j=s}^{N-1} a_{k,j-s}a_{i,j}(T_c-\Delta\tau) \end{aligned} \tag{15}$$

and we therefore obtain the result

$$\begin{aligned} b_{k,n-1}R_{ki}(\tau_{kl})+b_{k,n}\overline{R_{ki}}(\tau_{kl}) &= b_{k,n-1}\sum_{j=0}^{s} a_{k,N-s+j-1}a_{i,j}\Delta\tau_{kl} + b_{k,n-1}\sum_{j=0}^{s-1} a_{k,N-s+j}a_{i,j}(T_c-\Delta\tau_{kl}) \\ &+ b_{k,n}\sum_{j=s+1}^{N-1} a_{k,j-s-1}a_{i,j}\Delta\tau_{kl} + b_{k,n}\sum_{j=s}^{N-1} a_{k,j-s}a_{i,j}(T_c-\Delta\tau_{kl}). \end{aligned} \tag{16}$$

Further algebraic manipulation gives

$$b_{k,n-1}R_{ki}(\tau_{kl})+b_{k,n}\overline{R_{ki}}(\tau_{kl}) =$$

$$\left(b_{k,n-1}a_{k,N-s-1}a_{i,0} + b_{k,n-1}\sum_{j=0}^{s-1}a_{k,N-s+j}a_{i,j+1} + b_{k,n}\sum_{j=s}^{N-2}a_{k,j-s}a_{i,j+1}\right)\frac{\Delta\tau_{kl}}{T_c} \qquad \textbf{(17)}$$

$$+\left(b_{k,n-1}\sum_{j=0}^{s-1}a_{k,N-s+j}a_{i,j} + b_{k,n}\sum_{j=s}^{N-2}a_{k,j-s}a_{i,j}+b_{k,n}a_{k,j-N+1}a_{i,N-1}\right)\left(1-\frac{\Delta\tau_{kl}}{T_c}\right).$$

Since $a_{i,j}\, a_{i,j} = 1$, we can further obtain

$$b_{k,n-1}R_{ki}(\tau_{kl})+b_{k,n}\overline{R_{ki}}(\tau_{kl}) = \left(b_{k,n-1}a_{k,N-s-1}a_{i,0} + b_{k,n-1}\sum_{j=0}^{s-1}a_{k,N-s+j}a_{i,j}a_{i,j+1}a_{i,j}\right.$$

$$\left. + b_{k,n}\sum_{j=s}^{N-2}a_{k,j-s}a_{i,j}a_{i,j+1}a_{i,j}\right)\frac{\Delta\tau_{kl}}{T_c} \qquad \textbf{(18)}$$

$$+\left(b_{k,n-1}\sum_{j=0}^{s-1}a_{k,N-s+j}a_{i,j} + b_{k,n}\sum_{j=s}^{N-2}a_{k,j-s}a_{i,j}+b_{k,n}a_{k,N-s-1}a_{i,N-1}\right)\left(1-\frac{\Delta\tau_{kl}}{T_c}\right).$$

Various representations have also been adopted to represent the cross-correlations of the chip sequences (Wu and Tsaur 1994, Hong et al. 1996, Lataief 1997, Huang and Ng 1999). In this analysis, we define the random variables

$$Z_{kj} = \begin{cases} b_{k,n-1}a_{k,N-s+j}a_{i,j}, & j=0,s-1 \\ b_{k,n}a_{k,j-s}a_{i,j}, & j=s,N-2 \\ b_{k,n}a_{k,N-s-1}a_{i,N-1}, & j=N-1 \\ b_{k,n-1}a_{k,N-s-1}a_{i,0}, & j=N \end{cases} \qquad \textbf{(19)}$$

where each of the Z_{kj} are independent Bernoulli trials, equally distributed on {-1,1}
to obtain

$$b_{k,n-1}R_{ki}(\tau_{kl})+b_{k,n}\overline{R_{ki}}(\tau_{kl})=$$

$$\sum_{j=0}^{N-2}Z_{kj}\left(\left(1-\frac{\Delta\tau_{kl}}{T_c}\right)+a_{i,j+1}a_{i,j}\frac{\Delta\tau_{kl}}{T_c}\right)+Z_{kN-1}\left(1-\frac{\Delta\tau_{kl}}{T_c}\right)+Z_{kN}\frac{\Delta\tau_{kl}}{T_c}. \qquad \textbf{(20)}$$

If we now define F_k as the variable for the set of all integers in [0, N-2] for which $a_{i,j}\, a_{i,j+1} = 1$, G_k as the variable for the set of all integers in [0,N-2] for which $a_{i,j}\, a_{i,j+1} = -1$, $U_k = Z_{kN-1}$ and $V_k = Z_{kN}$ we can express the interference term as

$$I_{kl} = \frac{T_c}{2} A_k \beta_{kl} \cos(\theta_{kl}) \left[F_k + G_k \left(1 - \frac{2\Delta\tau_{kl}}{T_c} \right) + U_k \left(1 - \frac{\Delta\tau_{kl}}{T_c} \right) + V_k \frac{\Delta\tau_{kl}}{T_c} \right] \quad \textbf{(21)}$$

We therefore obtain the signal at the output of the receiver as

$Y_T = Y_i(T) = Y_s + Y_I + Y_n$ **(22)**where Y_s, Y_I and Y_n are the interference free, the interference and the channel noise terms

$$Y_s = \frac{T_c}{2} A_i \beta_{i1} \cos(\theta_{i1}) \left[F_i + G_i \left(1 - \frac{2\Delta\tau_{i1}}{T_c} \right) + U_i \left(1 - \frac{\Delta\tau_{i1}}{T_c} \right) + V_i \frac{\Delta\tau_{i1}}{T_c} \right] \quad \textbf{(23)}$$

respectively given by

$$\begin{aligned} Y_I = & \sum_{k=1,k\neq i}^{K} \sum_{l=1}^{L} \frac{T_c}{2} A_k \beta_{kl} \cos(\theta_{kl}) \left[F_k + G_k \left(1 - \frac{2\Delta\tau_{kl}}{T_c} \right) + U_k \left(1 - \frac{\Delta\tau_{kl}}{T_c} \right) + V_k \frac{\Delta\tau_{kl}}{T_c} \right] \\ & + \sum_{l=2}^{L} \frac{T_c}{2} A_i \beta_{il} \cos(\theta_{il}) \left[F_i + G_i \left(1 - \frac{2\Delta\tau_{il}}{T_c} \right) + U_i \left(1 - \frac{\Delta\tau_{il}}{T_c} \right) + V_i \frac{\Delta\tau_{il}}{T_c} \right] \end{aligned} \quad \textbf{(24)}$$

$$Y_n = N_i = \int_{(n-1)T}^{nT} n(t)\, a_i(t) \cos(\omega_0 t) dt = \int_0^T n(t)\, a_i(t) \cos(\omega_0 t) dt. \quad \textbf{(25)}$$

$$U_k, V_k \in \{1,-1\} \quad \textbf{(26)}$$

Now, since

$$E\{U_k^2\} = E\{V_k^2\} = 1. \quad \textbf{(27)}$$

then

$$E\{(F_k)^2 \mid B\} = A = N - 1 - B, \quad E\{(G_k)^2 \mid A\} = B, \quad A + B = N - 1. \quad \textbf{(28)}$$

Also, if A is the number of elements in F_k and B is the number of elements in G_k, then Therefore

$$Var\{I_{kl}\} = E\left\{ \left(\frac{T_c}{2} A_k \beta_{kl} \cos(\theta_{kl}) \left[F_k + G_k \left(1 - \frac{2\Delta\tau_{kl}}{T_c} \right) + U_k \left(1 - \frac{\Delta\tau_{kl}}{T_c} \right) + V_k \frac{\Delta\tau_{kl}}{T_c} \right] \right)^2 \right\} \quad \textbf{(29)}$$

which gives

$$Var\{I_{kl} \mid A_k, \beta_{kl}, \theta_{kl}, \Delta\tau_{kl}, B\} = \frac{T_c^2}{2} A_k^2 \beta_{kl}^2 \cos(\theta_{kl})^2 \left[\frac{N}{2} + (2B+1)\left(\left(\frac{\Delta\tau_{kl}}{T_c} \right)^2 - \frac{\Delta\tau_{kl}}{T_c} \right) \right]. \quad \textbf{(30)}$$

Hence, computing the probability of error using the SIGA method employs

$$\psi = Var\{(Y_T - Y_s - Y_n) \mid A_k, \beta_{kl}, \theta_{kl}, \Delta\tau_{kl}, B\}$$

$$\overline{Y_S}^2 = E\{Y_s\}^2, \; \sigma_n^2 = var\{Y_n\} \quad \textbf{(31)}$$

to give the probability of error as

$$P_E = E\left\{ Q\left(\sqrt{\frac{\overline{Y_s}^2}{\psi + \sigma_n^2}} \right) \right\} = \int_0^\infty Q\left(\sqrt{\frac{\overline{Y_s}^2}{\psi + \sigma_n^2}} \right) f_\psi(\psi)\, d\psi. \quad \textbf{(32)}$$

Using

$$\mu_\psi = E\{\psi\}, \; \sigma_\psi^2 = var\{\psi\} \quad \textbf{(33)}$$

and a Taylor series expansion (Buehrer and Woerner 1996, Morrow 1998), the probability of error can be expressed as

$$P_E = \frac{2}{3} a + \frac{1}{6} b + \frac{1}{6} c \quad \textbf{(34)}$$

where

$$a = Q\left(\sqrt{\frac{\overline{Y_s}^2}{\mu_\psi + \sigma_n^2}} \right), \; b = Q\left(\sqrt{\frac{\overline{Y_s}^2}{\mu_\psi + \sqrt{3}\,\sigma_\psi + \sigma_n^2}} \right), \; c = Q\left(\sqrt{\frac{\overline{Y_s}^2}{\mu_\psi - \sqrt{3}\,\sigma_\psi + \sigma_n^2}} \right). \quad \textbf{(35)}$$

The derivation of σ_n, μ_ψ and σ_ψ have been omitted for brevity, and interested readers who are interested in the details may contact the authors.

RESULTS AND DISCUSSION

The numerical results of the analysis are given in Figs. 1 to 6. In all of these results, unless indicated otherwise, the number of chips per bit, N, at 32, Eb/No at 8 dB, the signal power of all the transmitters the same, the Rayleigh fading factor the same for all the transmitters, the ratio of the transmitter power variance to the mean at -10 dB, and the ratio of the fading factor variance to the mean at -10 dB.

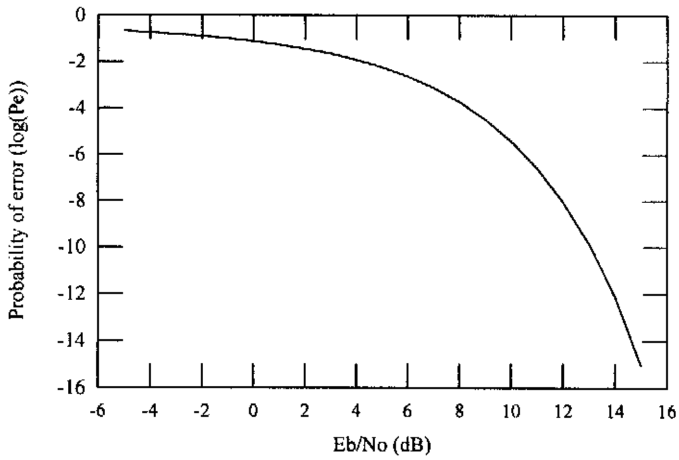

Figure 1: The variation of probability of error versus Eb/No with K = L = 1.

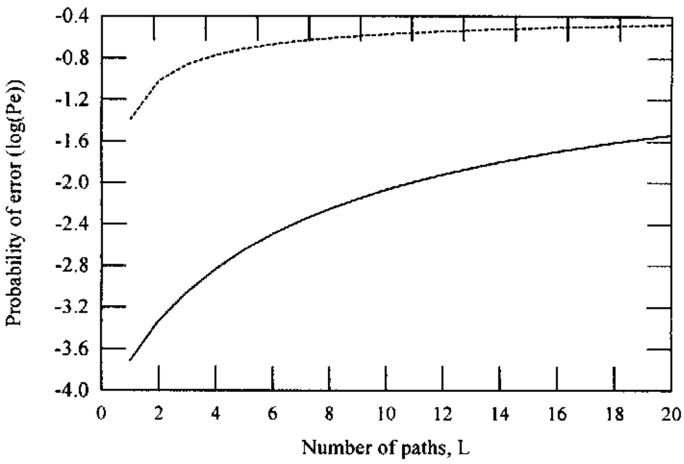

Figure 2: Variation of probability of error versus number of paths, L with K= 1 (——) and K = 25 (----------)

Fig. 1 shows how the BER varies with Eb/No with K = L = 1. These results were produced as a test of the accuracy of the method employed in computing the probability of error. The results agree with what is expected, namely that the channel noise degrades the performance of the system if it exceeds the signal power significantly. With K = L = 1, the results are comparable with those of BPSK systems, and are in agreement with those obtained by Letaief (1997). Fig. 2 shows how the BER varies with the number of paths for a single user and for 25 users. It is seen that the BER increases with the number of paths for both single and multiple users.

The results show that the interference from the multipaths is quite influential in lowering the system performance. Since multipath signals increase both ISI and adds to the total fading, the results indicate the combined effect of the two factors. Note that ISI becomes a major factor contributing to low system performance at high data transmission speeds. The effect of transmission rate, however, is not analyzed in this report.

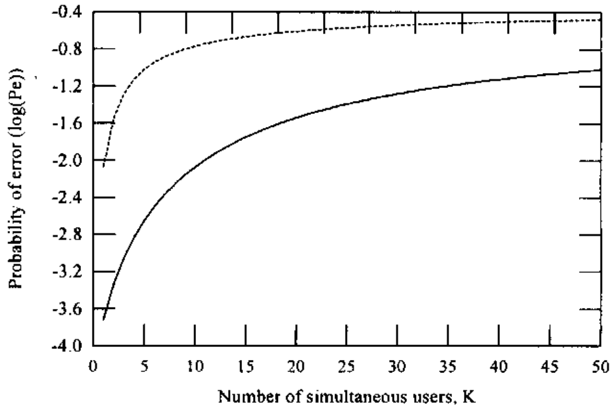

Figure 3: Variation of probability of error versus number of users, K with L = 1 (———)) and L = 10 (-----------).

Fig. 3 shows how the probability of error varies with the number of users for a single path and for 10 paths. It is seen that the BER increases with the number of users for both single and multiple paths. The interference from multiple users results into MAI. As expected, and since MAI is regarded as noise for the transmitter of interest, increase in MAI leads to increased degradation of the system performance. The results also indicate that when there is multipath interference, the performance of the system decreases even though the number of users remains the same. The obtained results also agree with those obtained by other researchers (Lataief 1996, Morrow 1998, Huang and Ng 1999). Therefore, the results of Fig. 3 illustrate why MAI has received considerable attention in multi-user CDMA systems.

Fig. 4 shows how the BER varies with the relative power of the transmitter of interest. It is seen that the BER increases when the power of the transmitter of interest decreases relative to that of the others. This is reminiscent of the far-near problem, where, if all the transmitters have equal signal power, the performance of the transmitter of interest will degrade as its distance from the receiver increases. These results substantiate why it is necessary to control the power levels of the various transmitters in multi-user wireless communication systems.

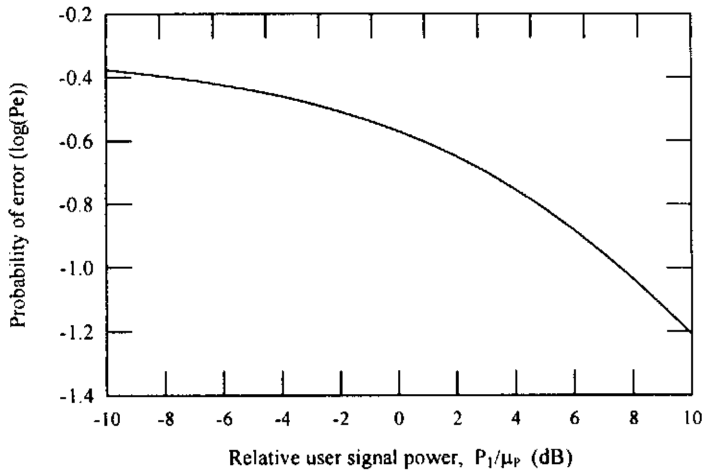

Figure 4: Variation of probability of error versus relative transmitter of interest signal power with K = 25 and L = 10.

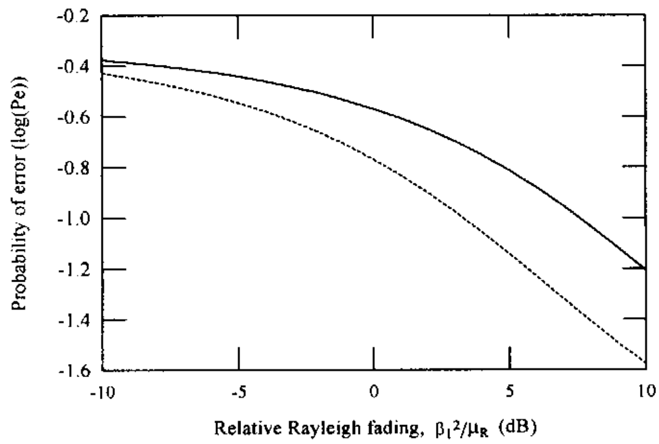

Figure 5: Variation of probability of error versus relative transmitter of interest fading factor with L = 10 for K = 10 (-----------) and K = 25 (———).

Fig. 5 shows the variation of the BER with the fading factor of the transmitter of interest relative to that of the others. In this study, the fading factor represents the gain of the respective path. It is seen that the probability of error increases with increase in the fading factor of the transmitter of interest relative to that of the others. It can also be seen that it increases with the number of users. Fig. 6 shows the variation of BER with the number of chips per bit. It is seen that the BER decreases with the number of chips. This is also reflected in the results obtained by Morrow (1998). The explanation is that higher number of chips imply more codes available to the users. The performance of the system increases with the distance between the different codes in use among the available codes. Therefore, if more codes remain unused, the distance between the codes in use increases. The smallest distance occurs when all the available codes are used. Hence, if the number of users remains constant, the performance of the system increases with the number of chips, and this is the trend observed in Fig. 6. Although not presented in this report, investigations on the variation of the probability of error with the variance of the transmitter signal powers as well as with the variance of the Rayleigh fading factor at low number of users gave inconsistent results. The behaviour is therefore still under investigation.

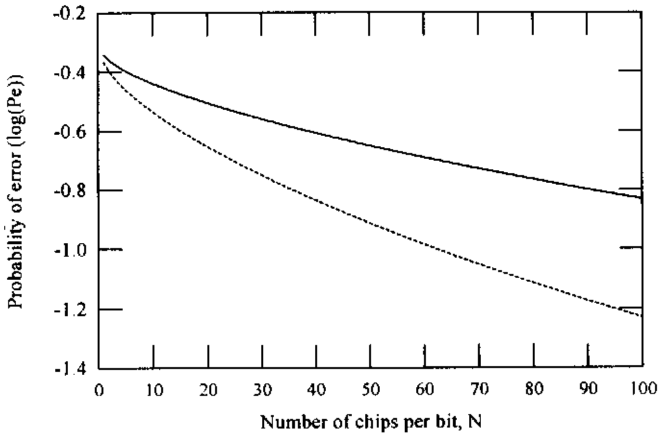

Figure 6: Variation of probability of error versus number of chips, N with L= 10 for K = 10 (-----------) and K = 25 (———).

CONCLUSION

In this paper the error performance of a DS-CDMA system has been analyzed using the simplified improved gaussian approximation method. The performance of the system has been found to decrease with both the multipath and multiaccess interference. It has also been found to increase with the ratio of the signal energy to the channel noise, with the signal power of the transmitter of interest relative to that of the other transmitters, with the fading factor of the transmitter of interest relative to that of the other transmitters, and with the number of chips per bit. The variation of the probability of error with the variance of both the transmitter signal power and the fading factor did not produce conclusive results and is still under investigation.

The poor performance of the initial CDMA systems as characterised in this report explains why efforts were taken to combat multipath interference through equalization and the use of the rake receiver, why various interference cancellation schemes were developed to combat multiaccess interference, why efficient power control methods were developed to overcome the far-near problem, and why good codes were developed to utilize their good features in communication. The improvements in the performance of CDMA-based systems as a result of these efforts has made CDMA a prime contender for future communication applications over the traditional FDMA and TDMA schemes. The communication systems of the future are aimed at real-time multimedia services using very high transmission speeds in highly mobile environments. Our future research will therefore focus on communication systems having problems associated with such operating requirements and environments.

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