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# Performance analysis of DS/CDMA systems with shadowing and flat fading

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**Abstract**

A new method is developed for evaluating the error probability ($P_e$) for direct sequence, code division multiple access (DS/CDMA) wireless systems that includes the effects of shadowing and fading. The method is based on saddle point integration (SPI) of the test statistic's moment generating function (MGF) in the complex plane. The SPI method is applicable to both ideal and wireless channels. For wireless channels, a Padé approximation (PA) of the MGF, which is derived from the moments of the channel's shadowing and fading distributions, allows efficient evaluation of the $P_e$. The SPI method can be used to model independent channels using separate shadowing and fading moments for each individual channel. The relative error between the probability density function (PDF) of the composite variate representing log-normal shadowing and Rayleigh fading and the PDF found from the inverse Laplace transform of the PA is negligible. Results show that log-normal shadowing increases the $P_e$ by 100–1000% compared to channels exhibiting fading only. © 2001 Elsevier Science B.V. All rights reserved.

*Keywords:* DS/CDMA; Shadowing; Fading; Saddle point integration; Numerical contour integration; Padé approximation

## 1. Introduction

Much research effort has been directed towards the performance evaluation of direct sequence, code division multiple access (DS/CDMA) communication systems during the past two decades. Methods for computing the error probability, $P_e$, for DS/CDMA systems have been proposed for both ideal channels [13,14,16,18], and fading channels [3,4]. Recently, DS/CDMA models have been improved to include the effects of channel coding and multiuser receivers [10–12]. It is well known that wireless channels are affected by shadowing, which is a long-term variation in the mean envelope averaged over several wavelengths, in addition to fading [17]. Due to the mathematical complexity, previous methods for computing the $P_e$ for wireless channels have not included the effects of both shadowing and fading. In this paper, we develop a new method for evaluating error probabilities for DS/CDMA wireless systems including the effects of shadowing as well as flat fading. In the process, we also present the method for ideal channels.

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Saddle point integration (SPI) is used to efficiently evaluate chip-asynchronous, DS/CDMA error probabilities. SPI is based on numerical contour integration of the test statistic's moment generating function (MGF) in the complex plane. The SPI method has been used to compute the error probability resulting from intersymbol and cochannel interference [6], radar detection probabilities [8], and $K$-distributions [5]. SPI is superior to the characteristic function method presented in [3] because it is less susceptible to roundoff error due to the integrand oscillations, and this property is particularly valuable for automated system modeling tools.

We use Padé approximations (PAs) [1,2] to model the effects of shadowing and flat fading channels. The unconditioned MGF, averaged over the shadowing and fading distributions, is approximated by its PA. This PA is determined from the moments of the shadowing and fading distributions. In this work, we consider mean envelope, log-normal shadowing as well as Rayleigh and Ricean fading. However, the model is applicable to any channel given the exact moments of the shadowing and fading distributions. The SPI method is completely general and does not place any restrictions on the channel statistics. Independent channels can be modeled using separate shadowing and fading moments for each individual channel. As a result, one can model different types of channels simultaneously such as Rayleigh fading with shadowing and Ricean fading without shadowing.

Previous results in the literature have considered the average $P_e$ based on the statistics of the source, channel, and additive white Gaussian noise (AWGN). However, the systems engineer must also determine the worst case $P_e$ when analyzing a wireless communication system for a particular environment. For the reverse link from the mobile station (MS) to the base station (BS), we compare the average and worst case $P_e$ given rectangular chips where the average $P_e$ is determined by modeling the multiple access interference (MAI) sources with asynchronous chips while the worst case $P_e$ is found assuming synchronous chips for the MAI sources. This analysis does not apply to the forward link from the BS to the MS in cellular DS/CDMA, which is also synchronous, because the separate information sequences are spread at the BS with orthogonal, Walsh–Hadamard sequences prior to transmission.

This paper is organized as follows. In Section 2, we present the chip-asynchronous DS/CDMA system model. The SPI method is derived for random signature sequences for ideal channels in Section 3 and wireless channels with shadowing and fading in Section 4. Finally in Section 5, we present numerical results which evaluate the error probabilities for all channel models.

## 2. System model

Consider $l = 0, 1, \ldots, L$ co-channel, DS/CDMA sources where each source transmits with a periodic code of length/period $N$. For a chip period of $T_c$, the resulting symbol rate is $1/T$ with $T = NT_c$. The baseband signal transmitted by the $l$th source is

$$s_l(t) = a_l \sum_{k=-\infty}^{\infty} i_l[k] h_l(t - kT), \tag{1}$$

where $a_l$ is the transmitted signal amplitude, $i_l[k] \in \{+1, -1\}$ is the equally likely, information symbol modulated using binary phase shift keying (BPSK), and $h_l(t)$ is the chip sequence

$$h_l(t) = \sum_{n=0}^{N-1} b_l[n] p(t - nT_c). \tag{2}$$

The signature sequence, $\mathbf{b_l} = [b_l[0], \ldots, b_l[N-1]]^{\mathrm{T}}$, $b_l[k] \in \{+1, -1\}$, specifies the pseudo-noise (PN) sequence employed by the $l$th transmitter to spread the information symbol. The chip waveform, $p(t)$, is supported on the interval $[0, T_c]$ and has normalized energy, $\int_0^{T_c} p^2(t)\,\mathrm{d}t = 1$.

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