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Outage analysis in wireless channels with multiple interferers subject to shadowing and fading using a compound pdf model

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Abstract

Wireless communication systems are subject to short term and long term fading of the channel. Instead of the commonly used Nakagami-lognormal model to account for the conditions existing in these shadowed fading channels, a compound probability density function (pdf) model is used to evaluate the performance of wireless systems. While the Nakagami-lognormal lacks a closed form solution to the pdf of the received power in shadowed fading channels, the compound pdf has an analytical expression for the pdf of the received signal power. The synergy between these two models for the analysis of wireless systems is explored by calculating the bit error rate in a DPSK modem as well as the outage probability in a wireless system in a shadowed fading channel. This is followed by the computation of the outage probability in the general case where both the desired and cochannels are subject to shadowing and fading. The analyses were carried out for both fixed number of cochannels and random number of cochannels. Results demonstrate the usefulness of the compound pdf model for the performance analyses of wireless systems in shadowed fading channels.

Key words: Fading. Shadowing. Shadowed fading channels. Outage Probability. Nakagami-lognormal. Suzuki. Compound fading. Compound pdf

1. Introduction

In wireless communication systems, the received signal is likely to suffer from the damaging effects of the channel in the form of short term fading and long term fading, also known as shadowing [1]–[3]. While short term fading arises from the existence of multiple paths between transmitted and receiver, shadowing is the result of the topographical elements such as tall buildings, trees and other structures in the transmission path. Several statistical distributions have been used to model the envelope of the signal under short term fading conditions. Of these, the Nakagami distribution provides significant flexibility to model variations in signal strengths whether the fading is severe or weak [3]. Long term fading has been generally modeled using the lognormal distribution [1]. Since both short term and long term fading conditions coexist in wireless systems, it is necessary to have models that can simultaneously take these into account. The Suzuki and the Nakagami-lognormal models available in literature accomplish this goal [4,5]. While the former takes short term fading as Rayleigh and long term fading as lognormal, the latter takes short term fading as Nakagami and long term fading as lognormal. One of the major shortcomings of these two models is the absence of any closed form solution to the received signal power in the shadowed fading channels leading to serious difficulties in assessing the performances of wireless systems. These are compounded by the fact that the wireless systems are also subject to the unwelcome effects of cochannel interference (CCI) arising from other channels operating at the same frequency located away from the desired channel [6]-[10]. These cochannels are also subject to both short and long term fading and it is necessary to incorporate these effects in assessing the performance of the wireless systems.

Outage probabilities have been calculated by treating the interferers to be either Nakagami distributed or lognormal distributed [10]-[13]. The absence of a closed form expression for the received signal in the presence of short and long term fading, has hindered the calculation of the outages under these conditions. Recently, a new model was proposed which provided a closed form solution to the received signal power in shadowed fading channels [14]-[16]. The error rates for the BPSK modem in the shadowed fading channels were evaluated in one case [14]. In the other case, the outage probabilities in shadowed fading channels were evaluated with the cochannels undergoing only short term fading [15]. The compound pdf model is used in this work to calculate the outage probabilities when both the desired signal and interferers undergo fading and shadowing simultaneously.

The compound pdf and its relationship to the Nakagami-lognormal are reviewed first. This is followed by the analysis of outage in shadowed fading channels. A discussion of the results is given at the end.

2. Compound pdf model for the shadowed fading channel and relationship to Nakagami-lognormal

The short term fading observed in wireless systems can be modeled using the Nakagami distribution. The probability density function of the envelope of the signal is expressed as

$$f_X(x) = \frac{2m^m x^{2m-1} e^{-\frac{m}{y}x^2}}{\Gamma(m)\, y^m}, \qquad x > 0 \tag{1}$$

where m is the Nakagami parameter [1]-[3]. The effects of fading on wireless channels are measured in terms of m, with severe fading occurring when m is small and weak fading occurring when m is large. In the absence of any shadowing or long term fading, the average power of the received signal, expressed in terms of y of eqn. (1), is deterministic. When shadowing is present, y is random and the expression for the density function envelope needs to be expressed in conditional form as [1]

$$f_{X|Y}(x|y) = \frac{2m^m x^{2m-1} e^{-\frac{m}{y}x^2}}{\Gamma(m)\, y^m}. \tag{2}$$

The pdf of the envelope in a shadowed short term fading channel becomes

$$f_X^{SL}(x) = \int_0^\infty f_{X|Y}(x|y) f_Y(y)\, dy \tag{3}$$

where $f_Y(y)$ is the pdf of the power. The superscript SL of $f_X^{SL}(x)$ indicates that the envelope pdf accounts for both short term and long term fading. The Nakagami-lognormal pdf is obtained by taking $f_Y(y)$ to be a lognormal $f_Y^L(y)$ given by

$$f_Y^L(y) = \frac{K}{y\sqrt{2\pi\sigma^2}} e^{-\frac{[10\ \log_{10} y - \mu]^2}{2\sigma^2}} \tag{4}$$

resulting in

$$f_{X}^{NL}\left(x\right)=\int_{0}^{\infty}\frac{2m^{m}x^{2m-1}e^{-\frac{m}{y}x^{2}}}{\Gamma\left(m\right)y^{m}}\frac{K}{y\sqrt{2\pi\sigma^{2}}}e^{-\frac{\left[10\ \log_{10}y-\mu\right]^{2}}{2\sigma^{2}}}dy\,. \tag{5}$$

The superscript NL of $f_{X}^{NL}\left(x\right)$ indicates the Nakagami-lognormal pdf [1,5]. In eqn. (4), both σ and μ are in decibel (dB) units and represent the standard deviation and mean respectively. K is equal to $\left[\frac{10}{\log_{e}10}\right]$. Equation (5) does not lead to a closed form expression for the pdf, thus making its application to the performance evaluation of wireless systems computationally tedious. Instead of using the lognormal pdf of eqn. (4), one can use the gamma pdf to describe the long term fading [14]-[21]. This means that $f_{Y}\left(y\right)$ is a gamma pdf $f_{Y}^{G}\left(y\right)$ given by

$$f_{Y}^{G}\left(y\right)=\frac{y^{M-1}e^{-\frac{y}{y_{0}}}}{\Gamma\left(M\right)y_{0}^{M}},\quad y>0,M>0 \tag{6}$$

with $\left\langle Y\right\rangle=y_{0}M$ where <.> is the statistical average. The density function of the signal envelope in shadowed fading channels becomes

$$f_{X}^{C}\left(x\right)=\frac{2b}{\Gamma\left(m\right)\Gamma\left(M\right)}\left(\frac{bx}{2}\right)^{M+m-1}K_{M-m}\left(bx\right),\qquad x>0,\ m>0.5,\ M>0 \tag{7}$$

where $K_{M-m}\left(\ \right)$ is the modified Bessel function [14] of order (M-m) and $b=2\sqrt{\frac{m}{y_{0}}}$. The level of shadowing is measured in term of M. The superscript C of $f_{X}^{C}\left(x\right)$ indicates that it is a compound pdf incorporating both short term fading and shadowing [14,15]. Use of the gamma distribution can be justified on the premise that it is a very versatile distribution and it can approximate to several distributions including lognormal and Gaussian [17]-[21]. It must be mentioned that the similarities between lognormal and gamma distributions were explored and suggested by other researchers, specifically by Ohta and Kozumi in 1969 [22] and Clark and Karp in 1970 [23]. Some aspects of the compound fading model given in eqn. (7) were explored by this author where the error rates for the BPSK modem [14] and the outage probabilities in shadowed fading channels (cochannels being Nakagami) were evaluated [15].

Equation (7) can model pure short term fading when $\left(M \to \infty\right)$ and for various values of M and m, the amount of fading (AF) given by [1,3]

$$AF = \frac{\left\langle X^4 \right\rangle - \left\langle X^2 \right\rangle^2}{\left\langle X^2 \right\rangle^2} = \frac{\left\langle X^4 \right\rangle}{\left\langle X^2 \right\rangle^2} - 1 = \frac{1}{m} + \frac{1}{M} + \frac{1}{mM} > 0 \qquad (8)$$

allowing it to vary from zero (no fading/no shadowing) to infinity (severe fading, severe shadowing or both). Thus, eqn. (7) provides a closed form expression to model fading and shadowing simultaneously, offering a significant advantage over the Suzuki (Rayleigh-lognormal) and Nakagami-lognormal models [1,4,5].

Before describing the effects of CCI on the performance of the wireless systems, it is appropriate to establish that there is a reasonable and sufficient synergy between the Nakagami-lognormal and the compound pdf. First, the error rates of DPSK in shadowed fading channels are evaluated using both the Nakagami-lognormal and the compound pdf. The error rate of DPSK in a Nakagami channel is given by [1]

$$p\left(e|y\right)=\frac{1}{2}m^{m}\left[\frac{1}{m+y}\right]^{m}. \tag{9}$$

The conditioning reflects the existence of shadowing in the channels. The parameter y is the signal-to-noise ratio which accounts for shadowing having, either the lognormal distribution $f_{Y}^{L}\left(y\right)$ of eqn. (4) or the gamma distribution $f_{Y}^{G}\left(y\right)$ of eqn. (6). The bit error rate in shadowed fading channels can be obtained by removing the conditioning as

$$p\left(e\right)=\int_{0}^{\infty}p\left(e|y\right)f_{Y}\left(y\right)dy \tag{10}$$

where $f\left(y\right)$ is either eqn. (4) or eqn. (6). The relationships between the parameters of the gamma pdf and the lognormal have been derived and are available in literature as given below [15,22,23].

$$\sigma\left(dB\right)=K\sqrt{\psi'\left(M\right)} \tag{11}$$

$$\mu\left(dB\right)=K\left[\log_{e}\left(\frac{Z_{av}}{M}\right)+\psi\left(M\right)\right]. \tag{12}$$

In eqns. (11) and (12), $\psi(\ )$ and $\psi'(\ )$ are the digamma and trigamma functions respectively [24]. The parameter Z_{av} is the signal-to-noise ratio, expressed as the average value of a gamma random variable having a pdf in eqn. (6) as

$$Z_{av}=\left\langle Y\right\rangle=y_{0}M\ . \tag{13}$$

The bit error rates are plotted as a function of the average signal-to-noise ratio in Fig. 1. It shows that for the shadowing typically observed in wireless channels (σ = 2 to 12 dB), the agreements between the error rates computed using the compound pdf and the Nakagami-lognormal are very excellent.

Next, the outage probability in the absence of any CCI was calculated using both models. Outage occurs when the signal-to-noise ratio fails to reach a threshold that is determined by the specific modulation format, multiple access scheme used, etc [1,2,7]. If Z_T is the threshold, the outage in the absence of any CCI can be expressed as

$$P_{out} = \int_0^{\sqrt{Z_T}} f_X^C(x) dx \tag{14}$$

where $f_X^C(x)$ is the pdf of the envelope given in eqn. (7). The outage probability in terms of the compound pdf model can be expressed by using eqn. (7) in eqn. (14) leading to

$$\begin{aligned} P_{out}^C = & \frac{\Gamma(M-m)\left(\frac{Z_T b^2}{4}\right)^m}{\Gamma(M)\Gamma(m+1)} {}_1F_2\left(m, [1-M+m, 1+m], \frac{Z_T b^2}{4}\right) \\ & + \frac{\Gamma(m-M)\left(\frac{Z_T b^2}{4}\right)^M}{\Gamma(M+1)\Gamma(m)} {}_1F_2\left(M, [1-m+M, 1+M], \frac{Z_T b^2}{4}\right) \end{aligned} . \tag{15}$$

In eqn. (15), ${}_1F_2(\;)$ is the hypergeometric function [24]. The average signal-to-noise ratio Z$_{\text{av}}$ is equal to $\left[\frac{4Mm}{b^2}\right]$.The outage probability under the Nakagami lognormal model was evaluated as

$$\begin{aligned} P_{out}^{NL} &= \int_0^{\sqrt{Z_T}} f_X^{NL}(x)\, dx \\ &= \int_0^{\sqrt{Z_T}} \int_0^{\infty} \frac{2m^m x^{2m-1} e^{-\frac{m}{y}x^2}}{\Gamma(m)\, y^m} \frac{K}{y\sqrt{2\pi\sigma^2}} e^{-\frac{[10 \log_{10} y - \mu]^2}{2\sigma^2}} dy\, dx \end{aligned} . \tag{16}$$

Eqn. (16) can be simplified to

$$P_{out}^{NL} = \int_0^{\infty} P\left(\frac{mZ_T}{y}, m\right) \frac{K}{y\sqrt{2\pi\sigma^2}} e^{-\frac{[10 \log_{10} y - \mu]^2}{2\sigma^2}} dy . \tag{17}$$

In eqn. (17), $P(,)$ is the incomplete gamma function [24]. Equations (15) and (17) can be evaluated using MATLAB (The Mathworks, Natick, MA, USA). The results of this study are shown in Figure 2. A value of $Z_T = 5\,dB$ was used as the threshold. For a set of parameters of the compound pdf, the corresponding values of μ and σ for the Nakagami-lognormal pdf were computed from eqns. (11) and (12). The values of σ are indicated in the figure caption. It seen that the outages for the Nakagami-lognormal and the compound pdf model are relatively close [15].

3. Outage in presence of a fixed number of shadowed fading cochannels

Having shown that there is considerable synergy between the Nakagami-lognormal and compound pdf in modeling shadowed fading channels, the compound pdf model was applied to the computation of outage probabilities when the cochannels also underwent fading and shadowing along with the desired channel. Most of the existing work on the outage probability calculations has been undertaken by treating the interfering channels to be either Nakagami or lognormal while the desired signal channel has been considered to be Nakagami or Nakagami-lognormal. Recently, the outage probability was evaluated for the desired channel which is modeled using a compound pdf with the interferers being Nakagami distributed [15]. However, the cochannels will also be undergoing fading and shadowing simultaneously and it is essential to incorporate this aspect of the cochannels in the computation of the outage probabilities. This task, the performance analysis of wireless systems where the desired channel and the interfering channels operate in shadowed fading channels, is undertaken here.

We will assume that there are N cochannels operating in the same frequency band as the desired signal [25]. Each of these is considered to be a shadowed fading channel undergoing Nakagami fading and gamma shadowing, described in terms of a pdf similar to the one in eqn. (7). It is assumed that all the cochannels are independent and identically distributed. If W_i is the power of each of these channels at the receiver, we can write the expression for the pdf of the interfering power of the i$^{\text{th}}$ cochannel $f_{W_i}\left(w_i\right)$, as

$$f_{W_i}\left(w_i \middle| w_a\right)=\left(\frac{\nu}{w_a}\right)^{\nu}\frac{w_i^{\nu\text{-}1}}{\Gamma\left(\nu\right)}\exp\left(-\frac{\nu}{w_a}w_i\right), \qquad w_i>0,\nu>0,w_a>0 \tag{18}$$

where w_a is the average power (in each cochannel) and ν is the Nakagami parameter of the interfering component. The conditioning in eqn. (18) indicates the existence of shadowing where w_a is gamma distributed with a density function given by

$$f\left(w_a\right)=\frac{\left[w_a\right]^{M_1-1}e^{-\frac{w_a}{\Omega}}}{\Gamma\left(M_1\right)\Omega^{M_1}} \tag{19}$$

with $\left\langle w_a\right\rangle=M_1\Omega$. The parameter M_1 is the order of the gamma density function and is related to the lognormal fading parameters existing in the cochannels similar to the descriptions in eqn. (11) and (12). If *W* is the total interference power from all the *N* independent identically distributed channels, the pdf of W, $f_W\left(w\middle|w_a\right)$ becomes

$$f_W\left(w\middle|w_a\right)=\left(\frac{\nu}{w_a}\right)^{N\nu}\frac{w^{N\nu\text{-}1}}{\Gamma\left(N\nu\right)}e^{\left(-\frac{\nu}{w_a}w\right)}, \quad w>0,\nu>0,w_a>0\,. \tag{20}$$

The conditioning of the pdf in eqn. (20) once again accounts for the existence of shadowing in the cochannels. Using eqn. (19) for the density function of the shadowing component, the density function $f_W\left(w\right)$ can be obtained as

$$\begin{aligned} f_W\left(w\right) &= \int_0^{\infty} f_W\left(w\middle|w_a\right) f_{W_a}\left(w_a\right) dw_a \\ &= \int_0^{\infty} \left(\frac{\nu}{w_a}\right)^{N_1} \frac{w^{N_1\text{-}1}}{\Gamma\left(N_1\right)} e^{\left(\text{-}\frac{\nu}{w_a}w\right)} \frac{\left[w_a\right]^{M_1-1} e^{-\frac{w_a}{\Omega}}}{\Gamma\left(M_1\right)\Omega^{M_1}} dw_a \end{aligned} \qquad (21)$$

where $N_1 = N\nu$. Equation (21) simplifies to

$$f_W\left(w\right) = \frac{2w^{\frac{M_1+N_1}{2}-1}}{\Gamma\left(N_1\right)\Gamma\left(M_1\right)} \left(\frac{\nu}{\Omega}\right)^{\frac{M_1+N_1}{2}} K_{M_1-N_1}\left(2\sqrt{\frac{\nu w}{\Omega}}\right), \quad M_1 > 0, N_1 > 0, w > 0\,. \qquad (22)$$

The cumulative distribution function of the interference power $F_W\left(w\right)$ becomes

$$\begin{aligned} F_W\left(w\right) = &\frac{\Gamma\left(M_1-N_1\right)\left(\frac{\nu w}{\Omega}\right)^{N_1}}{\Gamma\left(M_1\right)\Gamma\left(N_1+1\right)} {}_1F_2\left(N_1,\left[1-M_1+N_1,1+N_1\right],\frac{\nu w}{\Omega}\right) \\ &+ \frac{\Gamma\left(N_1-M_1\right)\left(\frac{\nu w}{\Omega}\right)^{M_1}}{\Gamma\left(N_1\right)\Gamma\left(M_1+1\right)} {}_1F_2\left(M_1,\left[1-N_1+M_1,1+M_1\right],\frac{\nu w}{\Omega}\right) \end{aligned} \qquad (23)$$

The outage probability in presence of N interferers can be written as [10]-[13], [25]

$$P_{outN} = 1 - \int_{\sqrt{Z_T}}^{\infty} f_x^C\left(x\right)\left[\int_0^{\frac{x^2}{q}} f_W\left(w\right) dw\right] dx\,. \qquad (24)$$

In eqn. (24), q is the system protection ratio which depends on the modulation technique as well as the performance levels required [6]-[9], [25]. The signal-to-interference ratio (SIR), *R* is given by

$$R = \frac{Z_{av}}{\langle w_a \rangle} = \frac{Z_{av}}{M_1 \Omega}. \tag{25}$$

The practical values of q are in the range of 15-20 dB, the higher the value of q, the better the performance. Equation (24) can be written in terms of *R*, *q*, and Z_{av} as

$$P_{outN} = 1 - \int_{\sqrt{Z_T}}^{\infty} \frac{2b}{\Gamma(M)\Gamma(m)} \left(\frac{bx}{2}\right)^{M+m\text{-}1} K_{M\text{-}m}(bx)\xi(x)\,dx \tag{26}$$

where

$$\begin{aligned}\xi(x) = & \frac{\Gamma(M_1 - N_1)\left(\frac{\nu x^2 M_1 R}{Z_{av} q}\right)^{N_1}}{\Gamma(M_1)\Gamma(N_1+1)} {}_1F_2\left(N_1, [1 - M_1 + N_1, 1 + N_1], \frac{\nu x^2 M_1 R}{Z_{av} q}\right) \\ & + \frac{\Gamma(N_1 - M_1)\left(\frac{\nu x^2 M_1 R}{Z_{av} q}\right)^{M_1}}{\Gamma(N_1)\Gamma(M_1+1)} {}_1F_2\left(M_1, [1 - N_1 + M_1, 1 + M_1], \frac{\nu x^2 M_1 R}{Z_{av} q}\right)\end{aligned}. \tag{27}$$

The outage probability given in eqn. (26) was evaluated for different values of M, m, ν, M_1 and N. The value of q was fixed at 17 dB. An average signal-to-noise ratio of 10 dB (Z_{av}) was chosen. The threshold (Z_T) was chosen to be 5 dB. The results are plotted in Figure 3. They show the effects of fading and shadowing, resulting in ‘floors’ of outage probabilities. Higher values of M correspond to negligible shadowing in the desired channel and the outage floors are lower in these cases compared to those when M is small (high shadowing). These observations are consistent with the results expected in shadowed fading channels.

4. Outage in presence of a random number of shadowed fading cochannels

Generally, the number of interfering channels may not be fixed and it is likely to be random [7,8], [25]. It is possible to extend the results to the case where the number of cochannels is random. The average outage probability can now be expressed as

$$P_{out}^{av} = \sum_{N=0}^{L} PoutN * P\left(N\right) \tag{28}$$

where P_{outN} is the outage in eqn. (26) for N=0,1,2,..L and P(N) is the probability that the number of interfering channels is N [7,8], [25]. This probability P(N) is determined by the number of voice channels (N_s) and the blocking probability B. It can be expressed as

$$P\left(N\right) = \begin{pmatrix} L \\ N \end{pmatrix} B^{\frac{N}{N_s}} \left(1 - B^{\frac{N}{N_s}}\right)^{L-N} . \tag{29}$$

Equation (28) can now be evaluated using eqns. (27) and (29) with maximum value of N being 6. Outage probabilities in random number of cochannels were evaluated for N_s =10 and B=0.02 for several values of M, m, ν, and M_1. The results are shown in Figure 4. The values of q, Z_{av} and Z_T were the same as the ones used for the case of fixed number of cochannels. Once again, the results are consistent with the outage probabilities evaluated by other researchers [7,8], [25].

5. Concluding remarks

A simple model for the shadowed fading channels is used to compute the outage probabilities in wireless communication channels. This model, namely the compound pdf, can replace with the Nakagami-lognormal model used to take shadowing and fading into account. The equivalence of the compound model and the Nakagami model is demonstrated through the computation of the error probabilities of the DPSK modem in shadowed fading channels using the compound pdf and the Nakagami-lognormal pdf. Outage probabilities in wireless channels (in the absence of CCI) in shadowed fading channels are also similarly computed. These studies showed that the results using the two models are close enough and that the compound pdf is reasonably sufficient to describe flat fading and shadowing. The compound pdf is used to calculate the outage probabilities in cases where both the desired signal and the cochannels undergo flat fading (Nakagami) and shadowing simultaneously. The availability of a closed form expression for the envelope or the power of the signal under shadowed fading channels makes the compound pdf computationally efficient in the analysis of the performance of wireless communication systems.

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Figure Captions

Figure 1 The error probabilities in shadowed fading channels are shown for the compound pdf and the Nakagami-lognormal pdf.

(a) $M=0.35; m=0.90; \sigma = 13$dB

(b) $M=0.63; m=0.75; \sigma = 8.0$dB

(c) $M=4.00; m=0.98; \sigma = 2.3$dB

(d) $M=2.00; m=1.25; \sigma = 3.4$dB

Figure 2 Outage probabilities in shadowed fading channels (no cochannel interference) are shown for the compound pdf and the Nakagami-lognormal pdf.

(a) $M = 0.38; m=0.9; \sigma =12.3$ dB

(b) $M = 0.67; m=0.75; \sigma =7.6$ dB

(c) $M=2; m=1.2; \sigma =3.6$ dB

(d) $M=6; m=1.3; \sigma =1.8$ dB

Figure 3 Outage probabilities in shadowed fading channels in presence of fixed number of CCI channels undergoing fading and shadowing.

(a) $M= 1.5$, $m =1.1$, $N= 4$, $\nu = 0.75$, $M_1= 0.35$

(b) $M=1.5$, $m =1.1$, $N=2$, $\nu =0.75$, $M_1=0.35$

(c) $M=3.75$, $m =1.8$, $N=3$, $\nu =1.1$, $M_1=0.5$

(d) $M=10.75$, $m =2.0$, $N=1$, $\nu =0.75$, $M_1=0.35$

(e) $M=8.75$, $m = 2.5$, $N= 1$, $\nu =0.75$, $M_1=1.5$

Figure 4 Outage probabilities in shadowed fading channels in presence of random number of CCI channels undergoing fading and shadowing.

(a) $M=2.65,m=.75$, $\nu=0.85$, $M_1=0.5$

(b) $M=2.65,m=1,0$, $\nu=0.85$, $M_1=0.5$

(c) $M=2.65, m=5, \nu=0.85, M_1=0.5$

(d) $M=8.5, m=5, \nu=0.85, M_1=0.5$

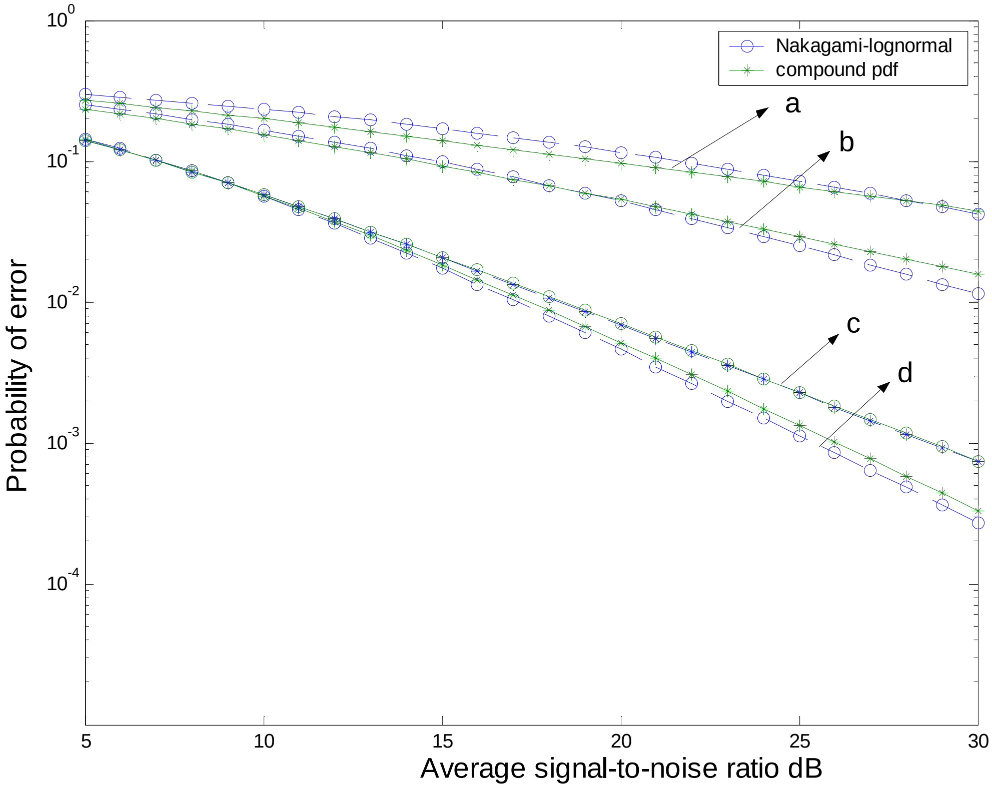

Figure 1 The error probabilities in shadowed fading channels are shown for the compound pdf and the Nakagami-lognormal pdf.

(a) M=0.35; m=0.90; σ = 13dB
(e) M=0.63; m=0.75; σ = 8.0dB
(f) M=4.00; m=0.98; σ = 2.3dB
(g) M=2.00; m=1.25; σ = 3.4dB

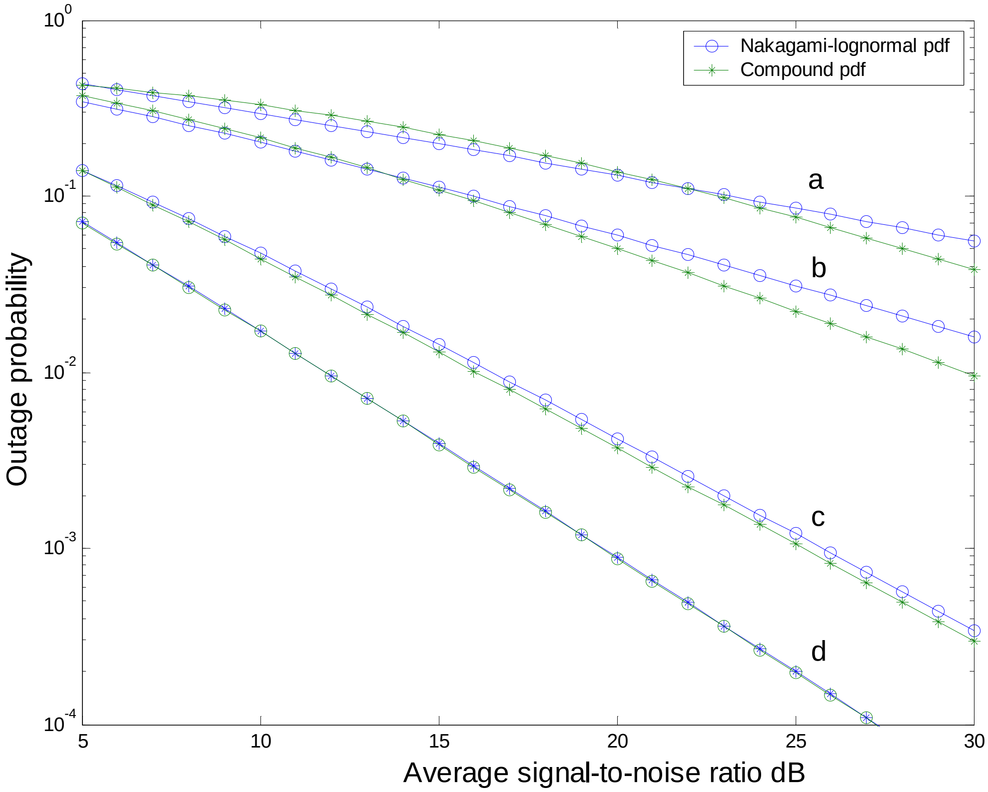

Figure 2 Outage probabilities in shadowed fading channels (no cochannel interference) are shown for the compound pdf and the Nakagami-lognormal pdf.

(a) M = 0.38; m=0.9; σ =12.3 dB

(b) M = 0.67; m=0.75; σ =7.6 dB

(b) M=2; m=1.2; σ =3.6 dB

(c) M=6; m=1.3; σ =1.8 dB

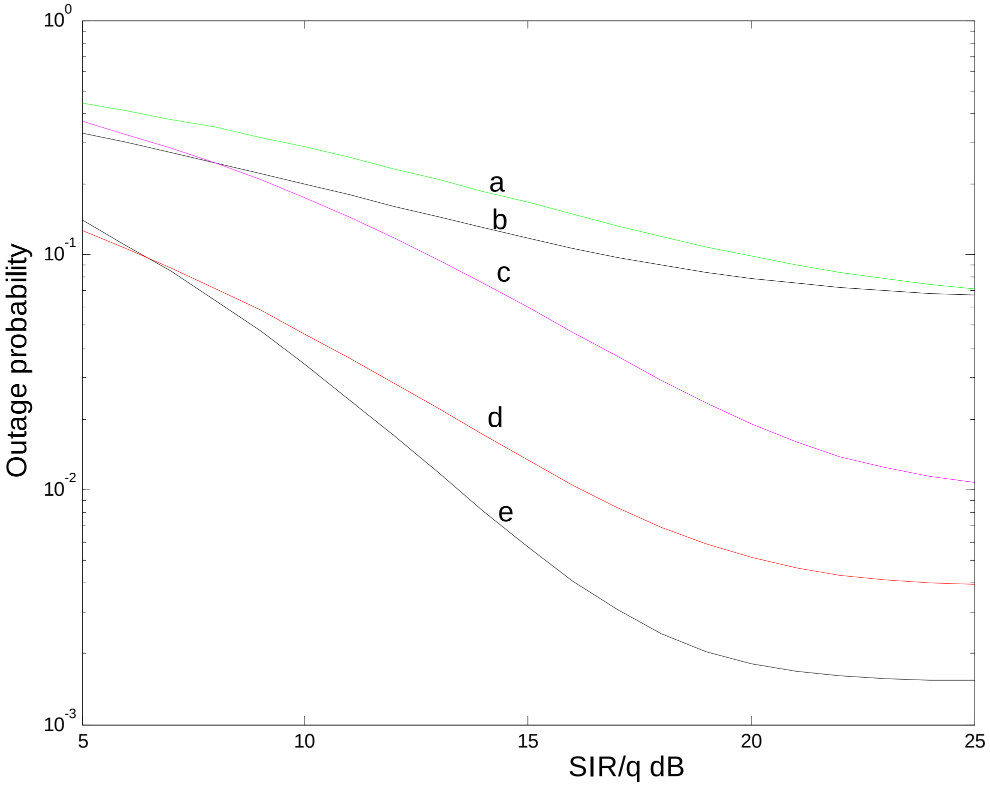

Figure 3 Outage probabilities in shadowed fading channels in presence of fixed number of CCI channels undergoing fading and shadowing.

(a) M= 1.5, m =1.1, N= 4, ν = 0.75, M_1= 0.35
(f) M=1.5, m =1.1, N=2, ν =0.75, M_1=0.35
(g) M=3.75, m =1.8, N=3, ν =1.1, M_1=0.5
(h) M=10.75, m =2.0, N=1, ν =0.75, M_1=0.35
(i) M=8.75, m = 2.5, N= 1, ν =0.75, M_1=1.5

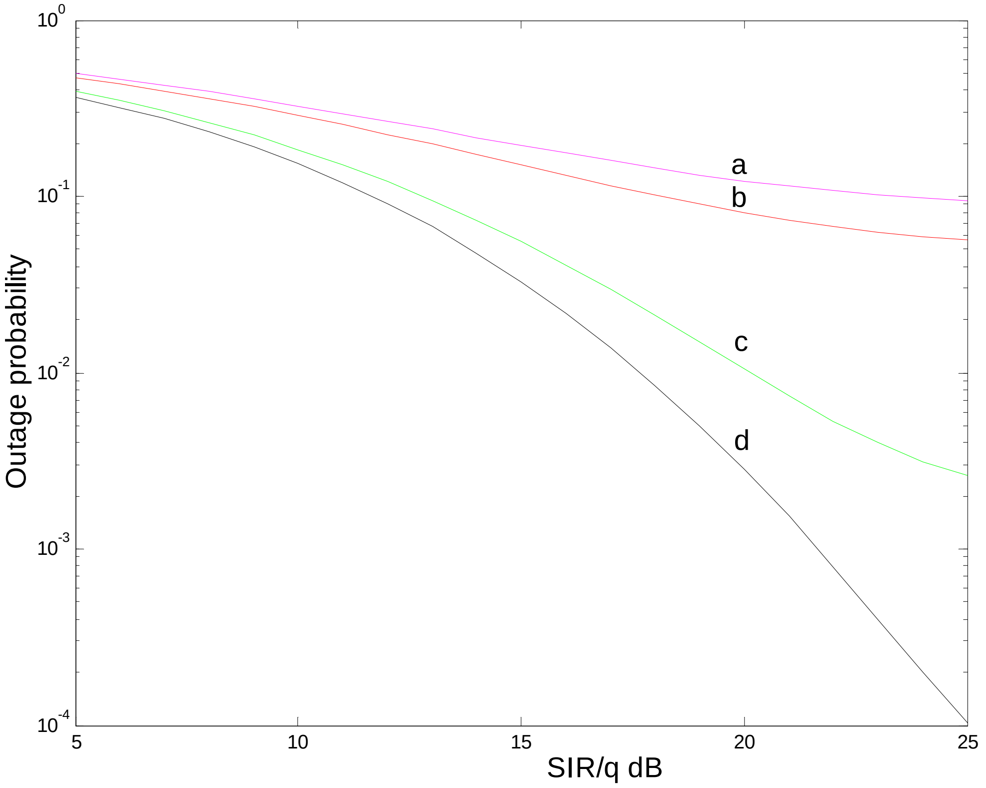

Figure 4 Outage probabilities in shadowed fading channels in presence of random number of CCI channels undergoing fading and shadowing.

(e) M=2.65,m=.75, ν=0.85, M_1=0.5
(f) M=2.65,m=1,0, ν=0.85, M_1=0.5
(g) M=2.65,m=5,ν=0.85, M_1=0.5
(h) M=8.5,m=5, ν=0.85, M_1=0.5