Outage Analysis of Dual-Hop Amplify-and-Forward Relaying Systems with Co-Channel Interferers

Daniel Benevides da Costa

Resumo— **Este artigo investiga o desempenho de *outage* de sistemas cooperativos amplifica-e-encaminha (AF) de dois saltos em um ambiente de desvanecimento Nakagami-*m* limitado por interferência. Mais especificamente, assumindo a presença de múltiplos interferentes Nakagami-*m* no *relay* AF e um terminal destino ruidoso, aproximações simples e em forma fechada para a probabilidade de *outage* fim-a-fim são obtidas. Com esse propósito, estimadores baseados em momentos são empregados para se determinar apropriadamente os parâmetros de desvanecimento Nakagami-*m* requeridos nas formulações. Resultados de simulação são apresentados com o intuito de mostrar a precisão das aproximações propostas.**

Palavras-Chave— **Métodos de aproximação, interferência co-canal, comunicações cooperativas, probabilidade de *outage*, desvanecimento Nakagami-*m*.**

Abstract— **In this paper, the outage performance of dual-hop amplify-and-forward (AF) cooperative systems in an interference-limited Nakagami-*m* fading environment is investigated. More specifically, assuming the presence of Nakagami-*m* faded multiple co-channel interferers at the AF relay and a noisy destination, simple accurate closed-form approximations for the end-to-end outage probability are derived. To this end, moment-based estimators are used to attain the appropriate Nakagami-*m* fading parameters. Simulation results are presented in order to confirm the accuracy of the proposed approximations.**

Keywords— **Approximate methods, co-channel interference, cooperative communications, outage probability, Nakagami-*m* fading.**

I. INTRODUCTION

Along the last years, cooperative diversity has received great attention from the wireless communications community due to its numerous benefits over direct transmission systems, such as good scalability, increased connectivity, robustness to channel impairments, and energy efficiency [1]–[3]. The basic idea is that mobile users relay signals for each other to emulate an antenna array and exploit the benefits of spatial diversity. On the other hand, in light of the demand for and advent of new wireless communication services is constantly increasing, frequency reuse has proved to be a practical strategy for an efficient use of the radio spectrum. However, as well known, frequency reuse gives rise to the so called cochannel interference (CCI).

Depending on the nature and complexity of the relaying technique, cooperative diversity networks can be broadly categorized as either nonregenerative or regenerative. In the former, the relays simply amplify and forward (AF) the received signal, while in the latter the relays decode, encode, and then forward the received signal to the destination node. The AF mode puts less processing burden on the relays and, hence, is often preferable when complexity and/or latency issues are of importance. This paper primarily focuses on AF relaying systems.

Despite the importance of analyzing the performance of dual-hop cooperative networks in the presence of CCIs, few works have investigated these kinds of systems [4]–[11]. A pioneering work in this regard [4] examined the end-to-end performance of multiuser AF cooperative networks assuming that the relay-destination link suffered from CCI. Results in terms of average sum-throughput showed that significant gains can be attained over direct transmission and over AF relaying systems without reuse by tuning the number of interfering relays and the target signal-to-noise ratio (SNR) between the relay and destination. In [5], the effect of multiuser interference in AF schemes was investigated in which asymptotic analysis showed that interference limits the diversity gain of the system. In [6], opportunistic relaying with reactive channel sensing was evaluated. In [7], considering that the destination is corrupted by a number of CCIs while the relay is only perturbed by an additive white Gaussian noise (AWGN), the outage probability performance was investigated assuming either AF or decode-and-forward (DF) relays. In addition, in that work the diversity order was also addressed. In [8], the outage probability and the average bit error rate (BER) of the AF protocol with interference at the relay were studied. In [9], a lower bound for the outage probability of dual-hop systems with multiple interferers and using AF relays was derived. More recently, [10], [11] investigated the outage probability of dual-hop AF relay systems using an approach rather different from [9]. Common to the works in [4]–[11] is that they considered Rayleigh fading channels.

In this paper, differently from previous works, we consider an interference-limited Nakagami-*m* fading environment[1] in the investigation of the outage performance of dual-hop AF cooperative systems. In our analysis, we assume the presence of Nakagami-*m* faded multiple co-channel interferers at the AF relay and a noisy destination. This scenario finds applicability in frequency-division relay systems, where the relay and destination terminals experience different interference patterns. Owing to the computational intractability inherent to the outage probability exact analysis, a simple accurate closed-form approximate expression for the outage probability is derived. Our approach relies on moment estimators and employs multinomial expansion to obtain the required moments

D. B. da Costa is with the Federal University of Ceara - Campus Sobral, CE, Brazil (email: danielbcosta@ieee.org). This work is supported by the FUNCAP (Grant No. BP1-0031-00090.01.00/10).

[1]It is well known that Nakagami-m fading covers a wide range of fading scenarios that are typical in realistic wireless relay applications via the m parameter, which includes the Rayleigh fading ($m = 1$) as a special case.

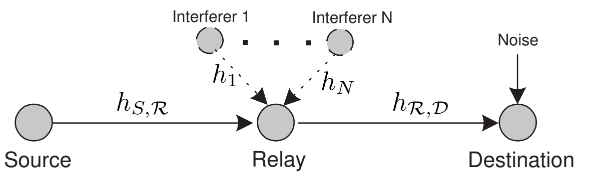

Fig. 1. A dual-hop AF cooperative network with the presence of Nakagami-*m* faded multiple co-channel interferers at the relay and a noisy destination.

in their estimators. All will be observed, the simplicity of our formulations provides much better computational efficiency than the exact solution, in which this latter is indeed rather intricate and difficult to evaluate especially when the number of interference signals increases. On the other hand, our approximate expression is obtained instantaneously, regardless the number of interference signals considered. This is an advantage when compared with Monte Carlo simulation, since that in the latter case, although results are reliable, the plotting time can be excessive and increases as the number of interference signals is higher.

Throughout this paper, $f_W(\cdot)$ and $F_W(\cdot)$ denote the probability density function (PDF) and cumulative distribution function (CDF) of a random variable (RV) W, respectively, whereas $\tilde{F}_W(\cdot)$ represents the complementary CDF of W. The operator $E[\cdot]$ stands for expectation, $\Pr(\cdot)$ symbolized probability, $\Gamma(\cdot)$ and $\Gamma(\cdot,\cdot)$ denote the Gamma function [12, Eq. (8.310.1)] and the incomplete Gamma function [12, Eq. (8.350.2)], respectively, and $K_x(\cdot)$ is the x-order modified Bessel function of second kind [13, Eq. (9.6.22)].

II. System and Channel Models

We consider a dual-hop non-regenerative cooperative system where a source node S communicates, using two time slots, with a destination node D through the help of an AF relay $\mathcal{R}$,as illustrated in Fig. 1. All nodes are equipped with single antennas. Also, due to the presence of obstacles, the source has no direct link with the destination. We assume that $\mathcal{R}$ operates in an interference-limited Nakagami-*m* fading environment in which N independent but not necessarily identically distributed interferes, each one with an average power P_i, with fading coefficient $\{h_i\}_{i=1}^N$ satisfying $E[|h_i|^2] = \Omega_{i\mathrm{I}}$, and with Nakagami-*m* fading parameter $m_{i\mathrm{I}}$, are added to the signal transmitted from the source. Consequently, in the first time slot the received signal at $\mathcal{R}$ can be expressed as

$$y_{\mathcal{R}} = \sqrt{P_S} h_{S,\mathcal{R}} s_0 + \sum_{i=1}^{N} \sqrt{P_i} h_i s_i, \tag{1}$$

where P_S stands for the transmit power of the source, $h_{S,\mathcal{R}}$ represents the fading coefficient of the Nakagami-*m* channel between S and $\mathcal{R}$, having fading parameter m_1 and satisfying $E[|h_{S,\mathcal{R}}|^2] = \Omega_1$, and, s_0 and s_i denote the transmitted and interfering symbols, respectively, which are mutually independent with zero mean and unit variance.

Assuming the interference at D is negligible, in the second time slot the relaying node forwards $y_{\mathcal{R}}$ to the destination after multiplying it with a gain G. Hence, the received signal at D is given by

$$\begin{aligned} y_D &= h_{\mathcal{R},D}\, G y_{\mathcal{R}} + n_D \\ &= h_{\mathcal{R},D}\, G \left(\sqrt{P_S} h_{S,\mathcal{R}} s_0 + \sum_{i=1}^{N} \sqrt{P_i} h_i s_i \right) + n_D, \end{aligned} \tag{2}$$

where $h_{\mathcal{R},D}$ denotes the fading coefficient of the Nakagami-*m* channel between $\mathcal{R}$ and D, having fading parameter m_2 and satisfying $E[|h_{\mathcal{R},D}|^2] = \Omega_2$, and n_D represents the AWGN component with zero mean and average power $E[|n_D|^2] = \sigma_D^2$. Consequently, the instantaneous end-to-end signal-to-interference-plus-noise ratio (SINR) can be expressed as

$$\gamma_{\text{end}} = \frac{G^2 P_S |h_{S,\mathcal{R}}|^2 |h_{\mathcal{R},D}|^2}{G^2 |h_{\mathcal{R},D}|^2 \left(\sum_{i=1}^{N} P_i |h_i|^2 \right) + \sigma_D^2}. \tag{3}$$

Note from (3) that the choice of the relay gain affects the determination of the instantaneous end-to-end SINR. Considering a channel state information (CSI)-assisted relay, i.e., a variable gain relay, the gain G can be written as

$$G^2 = \frac{P_{\mathcal{R}}}{P_S |h_{S,\mathcal{R}}|^2 + \sum_{i=1}^{N} P_i |h_i|^2}, \tag{4}$$

where $P_{\mathcal{R}}$ denotes the power of the transmitted signal at the output of the relay. From (4), it can be noticed that the CSI-assisted relay requires a continuous estimate of the channel fading coefficient which may make this choice of gain not always feasible from a practical point of view. For this reason, herein we are interested in studying the outage performance of interference-limited relaying systems of another class of non-regenerative systems, namely, those with fixed-gain relays. By definition, these relays introduce fixed gains to the received signal regardless of the fading amplitude on the first hop. More specifically, in this paper we consider another type of fixed-gain relays, namely, semi-blind relays[2], in which the relay gain can written as

$$G^2 = \frac{P_{\mathcal{R}}}{P_S \Omega_1 + \sum_{i=1}^{N} P_i \Omega_{i\mathrm{I}}}. \tag{5}$$

By substituting (5) into (3) and after some algebraic manipulations, (3) can be rewritten as

$$\gamma_{\text{end}} = \frac{P_S |h_{S,\mathcal{R}}|^2 P_{\mathcal{R}} |h_{\mathcal{R},D}|^2 / \sigma_D^2}{\frac{P_{\mathcal{R}} |h_{\mathcal{R},D}|^2}{\sigma_D^2} \sum_{i=1}^{N} P_i |h_i|^2 + P_S \Omega_1 + \sum_{i=1}^{N} P_i \Omega_{i\mathrm{I}}}. \tag{6}$$

Now, let $\gamma_1 = P_S |h_{S,\mathcal{R}}|^2$, $\gamma_2 = P_{\mathcal{R}} |h_{\mathcal{R},D}|^2 / \sigma_D^2$, $\gamma_{\text{Int}} = \sum_{i=1}^{N} P_i |h_i|^2$, and $C = P_S \Omega_1 + \sum_{i=1}^{N} P_i \Omega_{i\mathrm{I}}$. Then, (6) can be reexpressed in a more concise form as

$$\gamma_{\text{end}} = \frac{\gamma_1 \gamma_2}{\gamma_2 \gamma_{\text{Int}} + C}. \tag{7}$$

As all the channels undergo Nakagami-*m* fading, the PDF and CDF of γ_1, γ_2, and $\gamma_i = P_i |h_i|^2$ can be written as [15]

$$f_\varphi(\varphi) = \frac{m^m \varphi^{m-1}}{\Gamma(m) \bar{\gamma}^m} \exp\left(-\frac{m\varphi}{\bar{\gamma}} \right), \tag{8a}$$

[2]The readers are referred to [14] for further details about this class of relays.

$$F_{\varphi}(\varphi) = 1 - \Gamma(m, m\varphi/\bar{\gamma})/\Gamma(m), \tag{8b}$$

where: (a) when $\varphi = \gamma_1$, $m \triangleq m_1$ and $\bar{\gamma} \triangleq \bar{\gamma}_1 = E[P_S|h_{S,\mathcal{R}}|^2] = P_S\Omega_1$; (b) when $\varphi = \gamma_2$, $m \triangleq m_2$ and $\bar{\gamma} \triangleq \bar{\gamma}_2 = E[P_{\mathcal{R}}|h_{\mathcal{R},D}|^2/\sigma_D^2] = P_{\mathcal{R}}\Omega_2/\sigma_D^2$, and (c) when $\varphi = \gamma_{i\mathrm{I}}$, $m \triangleq m_{i\mathrm{I}}$ and $\bar{\gamma} \triangleq \bar{\gamma}_{i\mathrm{I}} = E[P_i|h_i|^2] = P_i\Omega_{i\mathrm{I}}$. Hereafter, it is also assumed that the fading coefficients $|h_{S,\mathcal{R}}|$, $|h_{\mathcal{R},D}|$, and $\{|h_i|\}_{i=1}^N$ are independent and non-identically distributed (i.n.i.d.) Nakagami-*m* RVs.

III. Outage Probability Analysis

The outage probability, P_{out}, is defined as the probability that the received signal falls below a given threshold γ_{th}. This threshold is a protection value for the SINR, above which the quality of service is deemed satisfactory. Specifically, in AF interference-limited relaying systems with semi-blind relays, such metric can be expressed as

$$\begin{aligned}
P_{\text{out}} &= \Pr\left(\gamma_{\text{end}} \leq \gamma_{\text{th}}\right) \\
&= \Pr\left(\frac{\gamma_1\gamma_2}{\gamma_2\gamma_{\text{Int}} + C} \leq \gamma_{\text{th}}\right) \\
&= \Pr\left(\gamma_1 \leq \gamma_{\text{th}}\gamma_{\text{Int}} + \frac{C\gamma_{\text{th}}}{\gamma_2}\right) \\
&= \int_0^\infty \int_0^\infty \Pr\left(\gamma_1 \leq \frac{\gamma_{\text{th}}(yz + C)}{y}\right) f_{\gamma_2}(y) f_{\gamma_{\text{Int}}}(z)\,dy\,dz \\
&= 1 - \int_0^\infty \int_0^\infty \Pr\left(\gamma_1 \geq \frac{\gamma_{\text{th}}(yz + C)}{y}\right) \\
&\quad \times f_{\gamma_2}(y) f_{\gamma_{\text{Int}}}(z)\,dy\,dz.
\end{aligned} \tag{9}$$

In order to assess (9), the complementary CDF of γ_1 and the PDFs of γ_2 and γ_{Int} are required. In one hand, the PDF of γ_2 can be easily attained from (8a) by performing the appropriate substitutions. In addition, assuming integer values of m_1 in (8b), based on [12, Eq. (8.352.2)] and relying on the binomial theorem given in [12, Eq. (1.111)], the complementary CDF of γ_1, evaluated at $\gamma_{\text{th}}(yz + C)/y$, can be written as

$$\begin{aligned}
\tilde{F}_{\gamma_1}\left(\frac{\gamma_{\text{th}}(yz + C)}{y}\right) &= \exp\left(-\frac{m_1\gamma_{\text{th}}}{\bar{\gamma}_1}\left(z + \frac{C}{y}\right)\right) \\
&\times \sum_{l=0}^{m_1-1}\sum_{\eta=0}^{l}\binom{l}{\eta}\frac{1}{l!}\left(\frac{m_1}{\bar{\gamma}_1}\right)^l z^{l-\eta}\left(\frac{C}{y}\right)^\eta.
\end{aligned} \tag{10}$$

On the other hand, differently from $f_{\gamma_2}(\cdot)$ and $\tilde{F}_{\gamma_1}(\cdot)$, the exact computation of $f_{\gamma_{\text{Int}}}(\cdot)$ is rather intricate since it involves the sum of RVs (i.e., interfering signals). One of the possible solutions for this PDF relies on the evaluation of multifold integrals or integral of the product of moment generating functions (MGFs), certainly non-attractive approaches as the number of interfering signals increases. More specifically, by performing the convolution approach, the PDF of γ_{Int} can be calculated as [16]

$$\begin{aligned}
f_{\gamma_{\text{Int}}}(z) = \int_0^z \int_0^{z-\gamma_{N\mathrm{I}}} \cdots \int_0^{z-\sum_{i=3}^N \gamma_{i\mathrm{I}}} f_{\gamma_{1\mathrm{I}}}\left(z - \sum_{i=2}^N \gamma_{i\mathrm{I}}\right) \\
\times \prod_{i=2}^N f_{\gamma_{i\mathrm{I}}}(\gamma_{i\mathrm{I}})\,d\gamma_{2\mathrm{I}} \ldots d\gamma_{(N-1)\mathrm{I}}\,d\gamma_{N\mathrm{I}}.
\end{aligned} \tag{11}$$

Then, by substituting appropriately (11), (10), and (8a) into (9), P_{out} is derived in terms of multifold integrals. However, owing to this fact, tests performed by the authors revealed that beyond three interfering signals, the exact solution for P_{out} becomes computationally impracticable. For instance, for three interference signals using MATHEMATICA a plot takes more than one hour and beyond this the results may not converge. Therefore, it is certainly of interest to find some simple accurate approximations that can be used in order to circumvent this.

A. Approximated Analysis

In [17], a highly accurate approximation for the sum of i.n.i.d Nakagami-*m* RVs was derived. Relying on the idea employed in [17], herein we propose to approximate the PDF of γ_{Int} given in (11) by the PDF of a single Gamma RV, i.e.,

$$f_{\gamma_{\text{Int}}}(z) \approx \frac{m_{\mathrm{I}}^{m_{\mathrm{I}}} z^{m_{\mathrm{I}}-1}}{\Gamma(m_{\mathrm{I}})\bar{\gamma}_{\mathrm{I}}^{m_{\mathrm{I}}}} \exp\left(-\frac{m_{\mathrm{I}}\, z}{\bar{\gamma}_{\mathrm{I}}}\right), \tag{12}$$

in which $\bar{\gamma}_{\mathrm{I}} = P_{\mathrm{I}}\,\Omega_{\mathrm{I}}$. Without loss of generality, hereafter we assume that no power control is used, i.e., $P_i = P_{\mathrm{I}}$. Now, in order to render (12) an accurate approximation, the required parameters m_{I} and Ω_{I} must be calculated. To this end, we shall use moment-based estimators [18] for the computation of such parameters. Firstly, let $\Phi = \sum_{i=1}^N |h_i|^2$. Then, moment-based estimators can be written from the exact moments of Φ, i.e.,

$$\Omega_{\mathrm{I}} = E[\Phi], \tag{13a}$$

$$m_{\mathrm{I}} = \frac{\Omega_{\mathrm{I}}^2}{E[\Phi^2] - \Omega_{\mathrm{I}}^2}, \tag{13b}$$

where Ω_{I} is easily attained as $\Omega_{\mathrm{I}} = \sum_{i=1}^N \Omega_{i\mathrm{I}}$. By its turn, to achieve the exact moment $E[\Phi^2]$, required for the calculation of m_{I}, we make use of a multinomial expansion [16] so that the exact moments of Φ can be written in terms of the individual moments of the summands as

$$\begin{aligned}
E[\Phi^n] = \sum_{n_1=0}^{n}\sum_{n_2=0}^{n_1}\cdots\sum_{n_{N-1}=0}^{n_{N-2}}\binom{n}{n_1}\binom{n_1}{n_2}\cdots\binom{n_{N-2}}{n_{N-1}} \\
\times E\left[|h_1|^{2(n-n_1)}\right]E\left[|h_2|^{2(n_1-n_2)}\right]\ldots E\left[|h_N|^{2(n_{N-1})}\right],
\end{aligned} \tag{14}$$

where [18]

$$E\left[|h_i|^n\right] = \frac{\Gamma(m_{i\mathrm{I}} + (n/2))}{\Gamma(m_{i\mathrm{I}})}\left(\frac{\Omega_{i\mathrm{I}}}{m_{i\mathrm{I}}}\right)^{\frac{n}{2}}. \tag{15}$$

Finally, by substituting (12), (10), and (8a) into (9) and solving the required integrals, an accurate closed-form approximation for P_{out} of dual-hop AF cooperative systems in an interference-limited Nakagami-*m* fading environment can derived, after some algebraic manipulations, as (16), given at the top of the next page.

It is noteworthy that our approach is very simple and highly precise, with the determination of the appropriate parameters being done straightforwardly. In addition, as P_{out} is given in a closed-form fashion, its evaluation is instantaneous regardless of the number of interfering signals, in contrast with the exact

$$P_{\text{out}} \approx 1 - \frac{2 m_{\text{I}}^{m_{\text{I}}} m_2^{m_2}}{\Gamma(m_{\text{I}})\Gamma(m_2)\bar{\gamma}_{\text{I}}^{m_{\text{I}}}\bar{\gamma}_2^{m_2}} \sum_{l=0}^{m_1-1}\sum_{\eta=0}^{l}\binom{l}{\eta}\frac{C^{\eta}}{l!}\left(\frac{m_1\gamma_{\text{th}}}{\bar{\gamma}_1}\right)^{l}\Gamma(m_{\text{I}}+l-\eta)\left(\frac{\bar{\gamma}_1\bar{\gamma}_{\text{I}}}{m_{\text{I}}\bar{\gamma}_1+m_1\bar{\gamma}_{\text{I}}\gamma_{\text{th}}}\right)^{m_{\text{I}}+l-\eta}$$
$$\times\left(\frac{m_2\bar{\gamma}_1}{C m_1\bar{\gamma}_2\gamma_{\text{th}}}\right)^{\frac{1}{2}(-m_2+\eta)} K_{-m_2+\eta}\left(2\sqrt{\frac{C m_1 m_2\gamma_{\text{th}}}{\bar{\gamma}_1\bar{\gamma}_2}}\right). \tag{16}$$

solutions, which, in general, involve multifold integrals or integral of the product of MGFs.

B. Remarks

As aforementioned, the trick part of the approximated analysis is based on the idea employed in [17]. As far as the author is aware, this is the first time in the literature that such idea has been employed for the performance analysis of cooperative diversity systems, particularly in interference-limited relaying scenarios. Note that if, in one hand, the proposed approach is not novel, on the other hand, its applicability in interference-limited relaying scenarios is totally new in the sense that it has never been used before for analyzing these kinds of systems.

In addition, it should be noticed that the statistics of the sum of interfering signals arises as the bottleneck for the performance analysis of interference-limited cooperative systems and this paper points out a new way to efficiently solve this inconvenience, i.e., by employing moment-based estimators to attain the required moments of the respective estimators. In this sense, our approximate formulations appear as useful tools for evaluating the outage probability in interference-limited relaying scenarios because of this evaluation is performed instantaneously, regardless the number of interference signals.

Finally, it is also noteworthy this is the first time that the end-to-end performance of interference-limited AF relaying scenarios has been investigated in a Nakagami-*m* environment.

IV. Numerical Plots and Simulations

In this Section, with the purpose of showing how our proposed approximate expression yields remarkable results, some representative examples are plotted for P_{out} and checked against Monte Carlo simulation results. Note the excellent adjustment between the approximate curves and simulation results, with the difference between such curves being imperceptible.

Fig. 2 portrays P_{out} of dual-hop DF relaying systems for different number of interfering signals ($N = 1, \ldots, 6$) and by setting $m_1 = 2$, $\Omega_1 = 1.5$, $m_2 = 3$, and $\Omega_2 = 2$. The transmit powers have been normalized to unity. For comparison purposes, we also plotted the case with $N = 1$, in which the approximate formulation reduces to the exact one, and the case with no interfering signals. The parameters of the interference channels have been set as $\{\Omega_{i\text{I}}\}_{i=1}^{N} = \{1.8, 2.2, 2.2, 2.5, 3.2, 3.2\}$ and $\{m_{i\text{I}}\}_{i=1}^{N} = \{1.5, 2, 2, 2.5, 3, 3\}$. For each value of N, Table I depicts the parameters estimated for the respective approximate curves. As can be observed, an improvement of the performance is noticed as N decreases. As the x-axis of Fig. 2 represents the outage threshold, which means as the threshold tends to infinity, the outage probability naturally tends to 1 regardless of the number of interferers. However, from Fig. 2 it can also be noticed that when the threshold is not large enough, the outage probability increases with the number of interferers and does not converge to a fixed value. Exhaustive tests have been carried out by the author and, in all of them, the proposed approximation proves to be an excellent tool for substituting the computationally intricate formulation inherent to the exact solution.

	m_{I}	Ω_{I}
$N=2$	3.4935	4
$N=3$	5.4914	6.2
$N=4$	7.9674	8.7
$N=5$	10.9662	11.9
$N=6$	13.9655	15.1

TABELA I

Values of the parameters required for the approximate curves of Fig. 2.

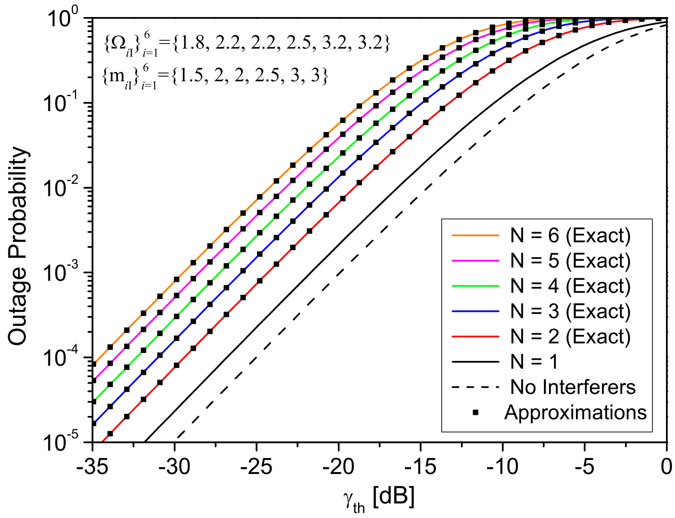

Fig. 2. Outage probability versus γ_{th} of dual-hop AF relaying systems for different number of interfering signals and links' parameters $m_1 = 2$, $\Omega_1 = 1.5$, $m_2 = 3$, and $\Omega_2 = 2$.

V. Conclusions

Assuming a dual-hop DF relaying system with Nakagami-*m* faded multiple co-channel interferers at the AF relay and a noisy destination, a simple accurate approximate expression for the outage probability was derived. In all the comparisons, an excellent match between the approximate and simulation results has been observed. As far as the author is aware, this is the first time that the Nakagami-*m* fading model is used in the performance analysis of dual-hop cooperative systems subject to CCIs.

ACKNOWLEDGMENT

Prof. Daniel Benevides da Costa would like to thank the financial support by the Ceará Council of Scientific and Technological Development (FUNCAP) under Grant no. BP1-0031-00090.01.00/10.

REFERÊNCIAS

[1] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[2] S. Ikki and M. H. Ahmed, "Performance analysis of cooperative diversity wireless networks over Nakagami-*m* fading channel," *IEEE Commun. Lett.*, vol. 11, no. 4, pp. 334–336, Apr. 2007.

[3] D. B. da Costa and Sonia Aïssa, "End-to-end performance of dual-hop semi-blind relaying systems with partial relay selection," *IEEE Trans. Wireless Commun.*, vol. 8, no. 8, pp. 4306–4315, Aug. 2009.

[4] A. Agustin and J. Vidal, "Amplify-and-forward cooperation under interference-limited spatial reuse of the relay slot," *IEEE Trans. Wireless Commun.*, vol. 7, no. 5, pp. 1952–1962, May 2008.

[5] I. Krikidis, J. S. Thompson, S. McLaughlin, and N. Goertz, "Max-min relay selection for legacy amplify-and-forward systems with interference," *IEEE Trans. Wireless Commun.*, vol. 8, no. 6, pp. 3016–3027, Jun. 2009.

[6] A. Bletsas, A. G. Dimitriou, and J. N. Sahalo, "Interference-limited opportunistic relaying with reactive sensing," *IEEE Trans. Wireless Commun.*, vol. 9, no. 1, pp. 14–20, Jan. 2010.

[7] C. Zhong, S. Jin, and K.-K. Wong, "Dual-hop systems with noisy relay and interference-limited destination," *IEEE Trans. Commun.*, vol. 58, no. 3, pp. 764–768, Mar. 2010.

[8] H. A. Suraweera, H. K. Garg, and A. Nallanathan, "Performance analysis of two hop amplify-and-forward systems with interference at the relay," *IEEE Commun. Lett.*, vol. 14, no. 8, pp. 692–694, Aug. 2010.

[9] S. S. Ikki and S. Aïssa, "Performance analysis of dual-hop relaying systems in the presence of co-channel interference," *in Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, Dec. 2010, Miami, Florida, USA.

[10] D. Lee, and J. H. Lee, "Outage probability for dual-hop relaying systems with multiple interferers over Rayleigh fading channels," *IEEE Trans. Veh. Technol.*, vol. 60, no. 1, pp. 333–338, Jan. 2011.

[11] A. M. Cvetkovic, G. T. Dordevic, and M. C. Stefanovic, "Performance of interference-limited dual-hop non-regenerative relays over Rayleigh fading channels," *IET Commun.*, vol. 5, no. 2, pp. 135–140, Feb. 2011.

[12] I. S. Gradshteyn and I. M. Ryzhik, *Table of Integrals, Series, and Products*, 7th ed., San Diego, CA: Academic, 2007.

[13] M. Abramowitz and I. A. Stegun, *Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables*. New York, 1972.

[14] M. O. Hasna and M.-S. Alouini, "A performance study of dual-hop transmissions with fixed gain relays," *IEEE Trans. Wireless Commun.*, vol. 3, no. 6, pp. 1963–1968, Nov. 2004.

[15] M. K. Simon and M. -S. Alouini, *Digital Communication Over Fading Channels*, 2nd ed., John Wiley & Sons, 2005.

[16] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*. McGraw-Hill, 2002, 4th Ed.

[17] J. C. S. Santos Filho and M. D. Yacoub, "Nakagami-*m* approximation to the sum of M non-identical independent Nakagami-*m* variates," *IET Electron. Lett.*, vol. 40, no. 15, pp. 951–952, Jul. 2004.

[18] M. Nakagami, "The m-distribution - A general formula of intensity distribution of rapid fading," in *Statistical Methods in Radio Wave Prop.*, Ed. Elmsford, Pergamon, 1960.