Outage Performance for DF Two-Way Relaying with Co-Channel Interference over Nakagami-*m* Fading

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Abstract

In this paper, we investigate the outage performance of a two-way decode-and-forward relaying network in an interference-limited Nakagami-*m* fading environment. More specifically, assuming the presence of Nakagami-*m* faded multiple co-channel interferers at the source/destination terminals, the closed-form approximate expression for the outage probability is derived by using moment-based estimators attaining the appropriate Nakagami-*m* fading parameter. Simulation results demonstrate that our analytical result is in excellent agreement with the Monte Carlo simulation.

Keywords: Two-way relaying, outage probability, decode-and-forward, co-channel interference, Nakagami-*m* fading

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1. Introduction

Relaying technologies can improve throughout and increase communication range. They have emerged as an effective means for exploiting spatial diversity [1,2]. Channel capacity is increased [3] and full diversity gain can be achieved [4] by sharing antennas amongst users via relaying. The capacity of relay channels was first studied in [5] where Cover et al. considered the classical three-node relay network and derived the channel capacity. Two protocols for one-way relay networks, known as decode-and-forward (DF) and amplify-and-forward (AF) relaying, were proposed in [6]. Due to the capacity loss of the pre-log factor of 1/2 [7] in half-duplex relaying, two-way relaying has been introduced, e.g., [8-10]. Until now, the performance analysis and different transmission schemes for AF and DF two-way relaying network have been well investigated in the literature. When a network coding approach [11] is applied to relay networks, two-way DF [8] and AF [9] relaying schemes were proposed. It has been illustrated in [10] that both DF and AF two-way relaying protocols can fully recover the spectral efficiency loss. For this reason, two-way relaying networks have attracted much attention in wireless communications. The rate performance of two-way relaying network has been extensively studied in recent years. The achievable rate regions for half-duplex two-way relaying network were studied in [12,13]. In [14], the exact outage probabilities for a three-node two-way relaying network using AF and DF schemes were presented and an adaptive AF/DF scheme was proposed to achieve the optimal outage performance. The two-way relaying technology was combined with small cell [15,16,17] technology and Multiple-Input Multiple-Output (MIMO) [18] technology.

The co-channel interference is inevitable in wireless communications. The performance analysis of one-way relaying network has turned the focus to interference-limited channels [19-21]. One-way relaying system with noisy relay and interference-limited destination was examined and the closed-form outage probabilities were derived for both DF and AF protocols [19]. One-way relaying system with multiple interferers over Rayleigh fading channels was studied in [20]. The exact outage probability of the DF one-way relaying system with unequal-power interferers using opportunistic relay selection was provided in [21]. A DF one-way relaying network using opportunistic relaying selection was investigated in [22], where the outage-optimal relay selection was proposed and the closed-form outage probabilities were derived in a multi-cell environment. A DF two-way relaying network with co-channel interferences was investigated in [23], where a tight approximate expression of the average symbol error rate was derived in closed-form. In [24], the exact symbol error probability of two-way DF relaying network in the presence of a finite number of co-channel interferes and noise at the relay and the source codes in Rayleigh fading environment was studied. The interference limits were considered in cognitive femtocells system [25].

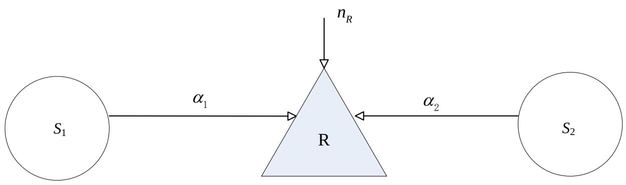
On the other hand, the performance of the relaying network based on the Nakagami-*m* fading channels has been investigated recently. In[26-28], the performance of two-way interference-limited AF relaying systems with over Nakagami-m fading channels was investiaged. In [29], the outage performance of dual-hop DF cooperative systems in the interference-limited Nakagami-*m* fading environment was investigated. The symbol error probability of a two-way relay-based communication system with opportunistic relay selection in Nakagami-*m* fading environments was studied in [30]. In this letter, we consider an interference-limited Nakagami-m fading environment in the investigation of the outage performance of a DF two-way relaying network with multiple interferers.

The rest of this paper is organized as follows. The system model is described in Section 2. In Section 3, we investigate the outage probability of the DF two-way relaying system with multiple interferers in Nakagami-m fading environment. In Section 4, some numerical results are given to verify our analysis. Finally, Section 5 concludes the paper.

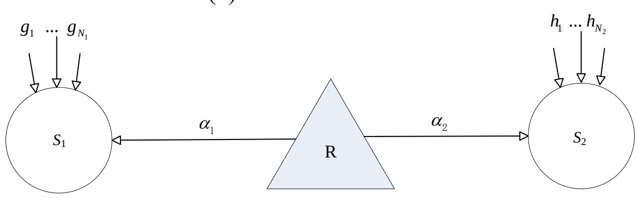
Notations-we denote $P\{B\}$ as the probability of a random event B, while $E\{B\}$ returns the expected value of the input random variable or event. $F_B(x)$ and $f_B(x)$ are, respectively, the cumulative density function and the probability density function of B. $\binom{x}{y}$ represents the binomial coefficient, whereas $\Gamma(n,x)=\int_x^{+\infty} t^{n-1}e^{-t}dt$ and $\Gamma(n)=\int_0^{+\infty} t^{n-1}e^{-t}dt$ are the upper Gamma and the Euler Gamma functions, respectively.

2. System Model

The two-way relaying system model with co-channel interference is shown in **Fig. 1**, where two mobile terminals, S_1 and S_2, at the edges of two different cells exchange message with the aid of a relay node R, assuming that the direct path between them is broken. The source nodes, S_1 and S_2, are at the cell-edges and suffer from interference from other mobile/relay nodes in adjacent cells, while the relay node R is free from interference. We assume that interference is the dominating factor limiting the performance. The noises at S_1 and S_2 are ignored, whilst R is noise-limited. The forward and backward channels are reciprocal, with α_1 denoting the channel between S_1 and R, and α_2 denoting the channel between S_2 and R. We assume that S_1, S_2 and R are all equipped with one antenna only. The DF protocol is used at the relay. The DF two-way relaying strategy consists of two equal time slots.



(a) The first time slot



(b) The second time slot

Fig. 1. The two-way relaying system model with co-channel interference

In the first time slot, S_1 and S_2 send their messages, x_1 and x_2, to R, and R has the following received signal:

$$y_R = \alpha_1 x_1 + \alpha_2 x_2 + n_R \tag{1}$$

where n_R is the complex Gaussian noise with zero mean and variance of σ_R^2. It is assumed that

α_1 and α_2 are independent Nakagami-m fading channels, respectively having fading parameter m_1 and m_2 and satisfying $\Omega_1 = E\{|\alpha_1|^2\}$ and $\Omega_2 = E\{|\alpha_2|^2\}$. We also denote the transmit power at S_1 and S_2 by $P_1 = E\{|x_1|^2\}$ and $P_2 = E\{|x_2|^2\}$, respectively.

In the second time slot, both x_1 and x_2 are decoded successfully. The relay R combines the decoded symbols using physical layer network coding, obtains x_R and broadcasts it to S_1 and S_2 [31]. Therefore, after two time slots, S_1 obtains

$$y_1 = \alpha_1 x_R + \sum_{i=1}^{N_1} g_i s_1^{(i)} + n_1 \tag{2}$$

where the contribution from N_1 interference signals $\{s_1^{(i)}\}_{i=1}^{N_1}$ is considered. The channels between the interferers and S_1 are $\{g_i\}$. They are assumed to be independent Nakagami-m fading satisfying $E\{|g_i|^2\} = \Omega_{iI}$ and have fading parameter m_{iI}, for $i = 1,2,\ldots,N_1$. The received signal by S_2 is

$$y_2 = \alpha_2 x_R + \sum_{j=1}^{N_2} h_j s_2^{(j)} + n_2 \tag{3}$$

where $\{s_2^{(j)}\}_{j=1}^{N_2}$ are the interference signals. The channels between the interferers and S_2 are $\{h_j\}$. They are independent Nakagami-m fading with $E\{|h_j|^2\} = \Omega_{jI}$ and have fading parameter m_{jI}, for $j = 1,2,\ldots,N_2$. Furthermore, we assume that the influence of the interference at S_1 and S_2 are dominant and therefore the effect of n_1 and n_2 are neglected. The transmit power of R is given by $P_R = E\{|x_R|^2\}$. The interference power at S_1 and S_2 are $P_1^i = E\{|s_1^{(i)}|^2\}$ and $P_2^j = E\{|s_2^{(j)}|^2\}$.

We define the following signal-to-noise ratios (SNR):

$$\text{SNR at } R \text{ from } S_1\text{: } \gamma_{S_1R} = \frac{P_1 |\alpha_1|^2}{\sigma_R^2} \tag{4}$$

$$\text{SNR at } R \text{ from } S_2\text{: } \gamma_{S_2R} = \frac{P_2 |\alpha_2|^2}{\sigma_R^2} \tag{5}$$

$$\text{The sum-SNR at } R\text{: } \gamma_{MAC} = \frac{P_1 |\alpha_1|^2 + P_2 |\alpha_2|^2}{\sigma_R^2} \tag{6}$$

We also define the signal-to-interference ratios:

$$\text{Signal-to-interference ratio at } S_1\text{: } \gamma_{RS_1} = \frac{P_R |\alpha_1|^2}{|\bar{g}|^2} \tag{7}$$

$$\text{Signal-to-interference ratio at } S_2\text{: } \gamma_{RS_2} = \frac{P_R |\alpha_2|^2}{|\bar{h}|^2} \tag{8}$$

where $|\bar{g}|^2 = \sum_{i=1}^{N_1} |g_i|^2 P_1^i$ and $|\bar{h}|^2 = \sum_{j=1}^{N_2} |h_j|^2 P_2^j$.

3. Outage Probability Analysis

In this section, we investigate the outage probability for the two-way relaying network. Firstly we denote the transmission rates from S_1 to S_2 and from S_2 to S_1 by R_1 and R_2, respectively. According to the rate region for the two-way relaying network in [32], an outage event exactly occurred when

$$\begin{aligned} &R_1 > \min\{\frac{1}{2}\log(1+\gamma_{S_1R}), \frac{1}{2}\log(1+\gamma_{RS_2})\} \quad \text{or} \\ &R_2 > \min\{\frac{1}{2}\log(1+\gamma_{S_2R}), \frac{1}{2}\log(1+\gamma_{RS_1})\} \quad \text{or} \\ &R_1 + R_2 > \frac{1}{2}\log(1+\gamma_{MAC}) \end{aligned} \tag{9}$$

Our main result is given in the following conclusion.

Conclusion: Assuming that $\bar{\gamma}_1 = \frac{P_1\Omega_1}{\sigma_R^2}$, $\bar{\gamma}_2 = \frac{P_2\Omega_2}{\sigma_R^2}$, $\bar{\gamma}_{I1} = \frac{P_1}{P_R\sigma_R^2}P_{I1}\Omega_{I1}$, $\bar{\gamma}_{I2} = \frac{P_2}{P_R\sigma_R^2}P_{I2}\Omega_{I2}$, $\Omega_{I1} = \sum_{i=1}^{N_1}\Omega_{iI}$, $m_{I1} = \sum_{i=1}^{N_1} m_{iI}$, $\Omega_{I2} = \sum_{j=1}^{N_2}\Omega_{jI}$, $m_{I2} = \sum_{j=1}^{N_2} m_{jI}$, $\lambda = \frac{C(\beta)}{C(1-\beta)}$, $\lambda_1 = \frac{C(1)}{C(1-\beta)}$, $\lambda_2 = \frac{C(1)}{C(\beta)}$ .If the interferers have similar power at S_1 and S_2, i.e., $P_1^i = P_1^j = P_{I1}$ and $P_2^i = P_2^j = P_{I2}$, $\forall i \neq j$, the outage probability P_{out} is given by

$$\begin{aligned} P_{out} &= 1 - \psi + e^{-d_1}\sum_{p=0}^{m_2-1}\frac{1}{p!}(\frac{m_2}{\bar{\gamma}_2})^p\{e^{-\frac{m_{I1}\lambda}{\bar{\gamma}_{I1}}}\delta[(C(\beta))^s F_1(\lambda) - F_4(\lambda)] \\ &-e^{-\frac{m_{I2}(\lambda_2-1)}{\bar{\gamma}_{I2}}}[\frac{m_{I2}^{m_{I2}}}{\Gamma(m_{I2})\bar{\gamma}_{I2}^{-m_{I2}}}\sum_{l=0}^{m_1-1}\frac{1}{l!}(\frac{m_1}{\bar{\gamma}_1})^l(-F_5(\lambda_2-1)+F_7(\lambda_2-1)) + \delta(-(C(\beta))^s F_2(\lambda_2-1)+F_6(\lambda_2-1))] \\ &+e^{-\frac{m_{I1}\lambda}{\bar{\gamma}_{I1}}-\frac{m_{I2}(\lambda_2-1)}{\bar{\gamma}_{I2}}}[\frac{m_{I2}^{m_{I2}}}{\Gamma(m_{I2})\bar{\gamma}_{I2}^{-m_{I2}}}\sum_{l=0}^{m_1-1}\frac{1}{l!}(\frac{m_1}{\bar{\gamma}_1})^l(-F_1(\lambda)F_5(\lambda_2-1)+F_1(\lambda)F_7(\lambda_2-1)+F_{10}(\lambda)-F_{11}(\lambda)) \\ &\qquad + \delta(-(C(\beta))^s F_1(\lambda)F_2(\lambda_2-1)+F_1(\lambda)F_6(\lambda_2-1)-F_8(\lambda)+F_9(\lambda))]\} \\ &+e^{-d_2}\sum_{p=0}^{m_2-1}\frac{1}{p!}(\frac{m_2}{\bar{\gamma}_2})^p\{e^{-\frac{m_{I2}\lambda^{-1}}{\bar{\gamma}_{I2}}}[\sum_{l=0}^{m_1-1}\frac{1}{l!}(\frac{m_1}{\bar{\gamma}_1})^l((C(1)-C(1-\beta))^l C(1-\beta)^p F_2(\lambda^{-1}) - F_5(\lambda^{-1})) \\ &\qquad +\delta(-(C(1)-C(1-\beta))^s F_2(\lambda^{-1})+F_6(\lambda^{-1}))] \\ &-e^{-\frac{m_{I1}(\lambda_1-1)}{\bar{\gamma}_{I1}}}[\sum_{l=0}^{m_1-1}\frac{1}{l!}(\frac{m_1}{\bar{\gamma}_1})^l(-(C(1)-C(1-\beta))^l C(1-\beta)^p F_1(\lambda_1-1)+F_3(\lambda_1-1)) \\ &\qquad +\delta[(C(1)-C(1-\beta))^s F_1(\lambda_1-1)-F_4(\lambda_1-1)] \\ &+e^{-\frac{m_{I1}(\lambda_1-1)}{\bar{\gamma}_{I1}}-\frac{m_{I2}\lambda^{-1}}{\bar{\gamma}_{I2}}}\sum_{l=0}^{m_1-1}\frac{1}{l!}(\frac{m_1}{\bar{\gamma}_1})^l[-(C(1)-C(1-\beta))^l C(1-\beta)^p F_1(\lambda_1-1)F_2(\lambda^{-1})+F_3(\lambda_1-1)F_2(\lambda^{-1}) \\ &\qquad +F_1(\lambda_1-1)F_{12}(\lambda^{-1})-F_{10}(\lambda_1-1)-F_{13}(\lambda_1-1)+F_{11}(\lambda_1-1)] \\ &\qquad +\delta[(C(1)-C(\beta))^s F_1(\lambda_1-1)F_2(\lambda^{-1})-F_1(\lambda_1-1)F_{14}(\lambda^{-1})+F_8(\lambda_1-1)-F_9(\lambda_1-1)]\} \end{aligned} \tag{10}$$

In (10), the parameters are

$$\psi=\frac{\Gamma(m_1,m_1(C(1)-C(1-\beta))/\bar{\gamma}_1)}{\Gamma(m_1)}\frac{\Gamma(m_2,m_2C(1-\beta)/\bar{\gamma}_2)}{\Gamma(m_2)}$$

$$-\exp(-\frac{m_2C(1)}{\bar{\gamma}_2})\frac{m_1^{m_1}}{\Gamma(m_1)\bar{\gamma}_1^{m_1}}\sum_{p=0}^{m_2-1}\frac{m_2^p}{p!\bar{\gamma}_2^p}\sum_{j=0}^{p}\frac{\binom{p}{j}(-1)^jC(1)^{p-j}}{(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})^{p+m_1}}\Gamma(j+m_1,(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})(C(1)-C(1-\beta))),$$

$$+\exp(-\frac{m_2C(1)}{\bar{\gamma}_2})\frac{m_1^{m_1}}{\Gamma(m_1)\bar{\gamma}_1^{m_1}}\sum_{p=0}^{m_2-1}\frac{m_2^p}{p!\bar{\gamma}_2^p}\sum_{j=0}^{p}\frac{\binom{p}{j}(-1)^jC(1)^{p-j}}{(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})^{p+m_1}}\Gamma(j+m_1,(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(\beta))$$

$$d_1=\frac{m_1C(\beta)}{\bar{\gamma}_1}+\frac{m_2(C(1)-C(\beta))}{\bar{\gamma}_2},\quad d_2=\frac{m_2C(1-\beta)}{\bar{\gamma}_2}+\frac{m_1(C(1)-C(1-\beta))}{\bar{\gamma}_1},$$

$$\delta=\frac{m_1^{m_1}}{\Gamma(m_1)\bar{\gamma}_1^{m_1}}\sum_{j=0}^{p}\frac{\binom{p}{j}(-1)^jC(1)^{p-j}\Gamma(j+m_1)}{(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})^{j+m_1}}\sum_{s=0}^{j+m_1-1}\frac{1}{s!}(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})^s,$$

$$F_1(x)=\sum_{f=0}^{m_{I1}-1}\frac{1}{f!}(\frac{m_{I1}x}{\bar{\gamma}_{I1}})^f,\ F_2(x)=\sum_{h=0}^{m_{I2}-1}\frac{1}{h!}(\frac{m_{I2}x}{\bar{\gamma}_{I2}})^h,$$

$$F_3(x)=\frac{m_{I1}^{m_{I1}}C(1-\beta)^{l+p}}{\Gamma(m_{I1})\bar{\gamma}_{I1}^{m_{I1}}}\frac{\Gamma(l+m_{I1})}{(\frac{m_{I1}}{\bar{\gamma}_{I1}}+\frac{m_1}{\bar{\gamma}_1}C(1-\beta))^{l+m_{I1}}}\sum_{i=0}^{l+m_{I1}-1}\frac{1}{i!}(\frac{m_{I1}}{\bar{\gamma}_{I1}}+\frac{m_1}{\bar{\gamma}_1}C(1-\beta))^ix^i,$$

$$F_4(x)=\frac{m_{I1}^{m_{I1}}C(1-\beta)^s}{\Gamma(m_{I1})\bar{\gamma}_{I1}^{m_{I1}}}\frac{\Gamma(s+m_{I1})}{(\frac{m_{I1}}{\bar{\gamma}_{I1}}+(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(1-\beta))^{s+m_{I1}}}\sum_{n=0}^{s+m_{I1}-1}\frac{1}{n!}(\frac{m_{I1}}{\bar{\gamma}_{I1}}+(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(1-\beta))^nx^n,$$

$$F_5(x)=\frac{m_{I2}^{m_{I2}}}{\Gamma(m_{I2})\bar{\gamma}_{I2}^{m_{I2}}}\sum_{i=0}^{l}\frac{\binom{l}{i}(-1)^iC(1)^{l-i}C(\beta)^i\Gamma(i+p+m_{I2})}{(\frac{m_{I2}}{\bar{\gamma}_{I2}}+(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(\beta))^{i+p+m_{I2}}}\sum_{t=0}^{i+p+m_{I2}-1}\frac{1}{t!}(\frac{m_{I2}}{\bar{\gamma}_{I2}}+(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(\beta))^tx^t,$$

$$F_6(x)\frac{m_{I2}^{m_{I2}}}{\Gamma(m_{I2})\bar{\gamma}_{I2}^{m_{I2}}}\sum_{n=0}^{s}\frac{\binom{s}{n}(-1)^nC(1)^{s-n}C(\beta)^n}{(\frac{m_{I2}}{\bar{\gamma}_{I2}}+(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(\beta))^{n+m_{I2}}}\sum_{k=0}^{n+m_{I2}-1}\frac{1}{k!}(\frac{m_{I2}}{\bar{\gamma}_{I2}}+(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(\beta))^kx^k,$$

$$F_7(x)=\frac{C(\beta)^{p+l}\Gamma(p+m_{I2})}{(\frac{m_2C(\beta)}{\bar{\gamma}_2}+\frac{m_{I2}}{\bar{\gamma}_{I2}})^{p+m_{I2}}}\sum_{j=0}^{p}\frac{1}{j!}(\frac{m_2C(\beta)}{\bar{\gamma}_2}+\frac{m_{I2}}{\bar{\gamma}_{I2}})^jx^j,$$

$$F_8(x)\frac{m_{I1}^{m_{I1}}}{\Gamma(m_{I1})\bar{\gamma}_{I1}^{m_{I1}}}\frac{m_{I2}^{m_{I2}}}{\Gamma(m_{I2})\bar{\gamma}_{I2}^{m_{I2}}}\sum_{n=0}^{s}\frac{\binom{s}{n}(-1)^n C(1)^{s-n}C(\beta)^n\Gamma(n+m_{I2})}{(\frac{m_{I2}}{\bar{\gamma}_{I2}}-\frac{m_1}{\bar{\gamma}_1}+\frac{m_2}{\bar{\gamma}_2})^{n+m_{I2}}}\sum_{k=0}^{n+m_{I2}-1}\frac{1}{k!}(\frac{m_{I2}}{\bar{\gamma}_{I2}}-\frac{m_1}{\bar{\gamma}_1}+\frac{m_2}{\bar{\gamma}_2})^k ,$$

$$\sum_{a=0}^{k}\frac{\binom{k}{a}(-1)^a\lambda_2^{k-a}\lambda^{-a}\Gamma(a+m_{I1})}{(\frac{m_{I1}}{\bar{\gamma}_{I1}}-\frac{m_{I2}}{\bar{\gamma}_{I2}\lambda}+\frac{m_1}{\bar{\gamma}_1\lambda}-\frac{m_2}{\bar{\gamma}_2\lambda})^{a+m_{I1}}}\sum_{b=0}^{a}\frac{1}{b!}(\frac{m_{I1}}{\bar{\gamma}_{I1}}-\frac{m_{I2}}{\bar{\gamma}_{I2}\lambda}+\frac{m_1}{\bar{\gamma}_1\lambda}-\frac{m_2}{\bar{\gamma}_2\lambda})^b x^b$$

$$F_9(x)\frac{m_{I1}^{m_{I1}}}{\Gamma(m_{I1})\bar{\gamma}_{I1}^{m_{I1}}}\sum_{h=0}^{m_{I2}-1}\frac{1}{h!}(\frac{m_{I2}}{\bar{\gamma}_{I2}})^h\sum_{b=0}^{h}\frac{\binom{h}{b}\lambda_2^{h-b}(-\lambda^{-1})^b\Gamma(s+b+m_{I1})}{(\frac{m_{I1}}{\bar{\gamma}_{I1}}-\frac{m_{I2}}{\bar{\gamma}_{I2}\lambda}+(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(1-\beta))^{s+p+m_{I1}}} ,$$

$$\sum_{q=0}^{s+b+m_{I1}-1}\frac{1}{q!}(\frac{m_{I1}}{\bar{\gamma}_{I1}}-\frac{m_{I2}}{\bar{\gamma}_{I2}\lambda}+(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(1-\beta))^q\lambda^q$$

$$F_{10}(x)=\sum_{i=0}^{l}\frac{\binom{l}{i}(-1)^i C(1)^{l-i}C(\beta)^i\Gamma(i+p+m_{I2})}{(\frac{m_{I2}}{\bar{\gamma}_{I2}}+(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(\beta))^{i+p+m_{I2}}}\sum_{c=0}^{i+p+m_{I2}-1}\frac{1}{c!}(\frac{m_{I2}}{\bar{\gamma}_{I2}}+(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(\beta))^c ,$$

$$\sum_{d=0}^{c}\frac{\binom{c}{d}\lambda_2^{c-d}(-\lambda^{-1})^d\Gamma(d+m_{I1})}{(\frac{m_{I1}}{\bar{\gamma}_{I1}}-\frac{m_{I2}}{\bar{\gamma}_{I2}\lambda}+(-\frac{m_1}{\bar{\gamma}_1}+\frac{m_2}{\bar{\gamma}_2})C(1-\beta))^{d+m_{I1}}}\sum_{q=0}^{d+m_{I1}-1}\frac{1}{q!}(\frac{m_{I1}}{\bar{\gamma}_{I1}}-\frac{m_{I2}}{\bar{\gamma}_{I2}\lambda}+(-\frac{m_1}{\bar{\gamma}_1}+\frac{m_2}{\bar{\gamma}_2})C(1-\beta))^q x^q$$

$$F_{11}(x)=\frac{m_{I1}^{m_{I1}}C(1-\beta)^l C(\beta)^p}{\Gamma(m_{I1})\bar{\gamma}_{I1}^{m_{I1}}}\frac{\Gamma(p+m_{I2})}{(\frac{m_{I2}}{\bar{\gamma}_{I2}}+\frac{m_2}{\bar{\gamma}_2}C(\beta))^{p+m_{I2}}}\sum_{j=0}^{p+m_{I2}-1}\frac{1}{j!}(\frac{m_{I2}}{\bar{\gamma}_{I2}}+\frac{m_2}{\bar{\gamma}_2}C(\beta))^j ,$$

$$\sum_{s=0}^{j}\frac{\binom{s}{j}(-1)^s\lambda_2^{s-j}\lambda^{-1})^s\Gamma(l+s+m_{I1})}{(\frac{m_{I1}}{\bar{\gamma}_{I1}}-\frac{m_{I2}}{\bar{\gamma}_{I2}\lambda}+(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(1-\beta))^{l+s+m_{I1}}}\sum_{n=0}^{l+s+m_{I1}-1}\frac{1}{n!}(\frac{m_{I1}}{\bar{\gamma}_{I1}}-\frac{m_{I2}}{\bar{\gamma}_{I2}\lambda}+(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(1-\beta))^n x^n$$

$$F_{12}(x)=\frac{m_{I2}^{m_{I2}}}{\Gamma(m_{I2})\bar{\gamma}_{I2}^{m_{I2}}}\sum_{i=0}^{l}\frac{\binom{l}{i}(-1)^i C(1)^{l-i}C(\beta)^i\Gamma(i+p+m_{I2})}{(\frac{m_{I2}}{\bar{\gamma}_{I2}}+(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(\beta))^{i+p+m_{I2}}}\sum_{t=0}^{i+p+m_{I2}-1}\frac{1}{t!}(\frac{m_{I2}}{\bar{\gamma}_{I2}}+(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2})C(\beta))^t x^t ,$$

$$F_{13}(x)=\frac{m_{I2}^{m_{I2}}}{\Gamma(m_{I2})\gamma_{I2}^{-m_{I2}}}\sum_{i=0}^{l}\frac{\binom{l}{i}(-1)^i C(1)^{l-i}C(\beta)^i\Gamma(i+p+m_{I2})}{(\frac{m_{I2}}{\gamma_{I2}}+(\frac{m_1}{\gamma_1}-\frac{m_2}{\gamma_2})C(\beta))^{i+p+m_{I2}}}\sum_{c=0}^{i+p+m_{I2}-1}\frac{1}{c!}(\frac{m_{I2}}{\gamma_{I2}}+(\frac{m_1}{\gamma_1}-\frac{m_2}{\gamma_2})C(\beta))^c ,$$

$$\sum_{d=0}^{c}\frac{\binom{c}{d}\lambda_2^{c-d}(-\lambda^{-1})^d\Gamma(d+m_{I1})}{(\frac{m_{I1}}{\gamma_{I1}}-\frac{m_{I2}}{\gamma_{I2}\lambda}+(-\frac{m_1}{\gamma_1}+\frac{m_2}{\gamma_2})C(1-\beta))^{d+m_{I1}}}\sum_{q=0}^{d+m_{I1}-1}\frac{1}{q!}(\frac{m_{I1}}{\gamma_{I1}}-\frac{m_{I2}}{\gamma_{I2}\lambda}+(-\frac{m_1}{\gamma_1}+\frac{m_2}{\gamma_2})C(1-\beta))^q x^q$$

$$F_{14}(x)=\frac{m_{I2}^{m_{I2}}}{\Gamma(m_{I2})\gamma_{I2}^{-m_{I2}}}\sum_{n=0}^{s}\frac{\binom{s}{n}(-1)^n C(1)^{s-n}C(\beta)^n\Gamma(n+m_{I1})}{(\frac{m_{I2}}{\gamma_{I2}}+(-\frac{m_1}{\gamma_1}+\frac{m_2}{\gamma_2})C(\beta))^{n+m_{I1}}}\sum_{k=0}^{n+m_{I1}-1}\frac{1}{k!}(\frac{m_{I2}}{\gamma_{I2}}+(-\frac{m_1}{\gamma_1}+\frac{m_2}{\gamma_2})C(\beta))^k x^k \tag{11}$$

Proof: See Appendix.

4. Numerical Results

Here, we present the numerical result to validate the analytical result of the outage probability. **Fig. 2** portrays the outage probability of DF two-way relaying network for different R_2 and by setting P_1=P_2, $m_1=2$, $\Omega_1=1.5$, $m_2=2$, and $\Omega_2=2$. In the simulation, we set the transmission rates by R_1=0.7, $P_1^i=P_1^j=P_{I1}=1$, $P_2^i=P_2^j=P_{I2}=1$, $\{m_{iI}\}_{i=1}^2=\{2,\ 2\}$, $\{\Omega_{iI}\}_{i=1}^2=\{1.8,\ 2\}$, $\{m_{jI}\}_{j=1}^2=\{2,\ 2\}$, $\{\Omega_{jI}\}_{j=1}^2=\{1.8,\ 2\}$, P_R=30dB, N_1=N_2=2. It is clearly observed that the approximate result (10) matches the Monte Carlo result perfectly.

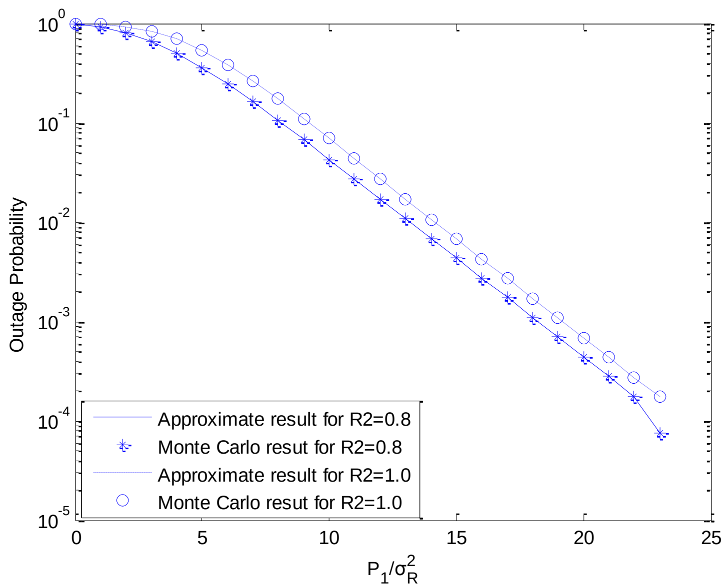


Fig. 2. Outage probability of DF two-way relaying system for different R_2

5. Conclusion

Assuming a two-way DF relaying system with Nakagami-*m* fading multiple co-channel interferers at the source/terminal nodes and a noisy relay, an approximate expression for the outage probability was derived. In all the comparisons, an excellent match between the approximate and simulation result has been observed.

APPENDIX

Proof

We define the function $C(x) \overset{\Delta}{=} 2^{2xR} - 1$ with $R = R_1 + R_2$. Then, (9) is recast as

$$\{\gamma_{S_1R} < C(\beta) \text{ or } \gamma_{RS_1} < C(1-\beta) \text{ or } \gamma_{S_2R} < C(1-\beta) \text{ or } \gamma_{RS_2} < C(\beta) \text{ or } \gamma_{MAC} < C(1)\} \quad (12)$$

where $\beta = R_1 / R$, for $0 \le \beta \le 1$. Therefore, the outage probability is given by

$$P_{out} = P\{Z_1 < C(\beta) \text{ or } Z_1 < \beta_1 C(1-\beta) \text{ or } Z_2 < C(1-\beta) \text{ or } Z_2 < \beta_2 C(\beta) \text{ or } Z_1 + Z_2 < C(1)\} \quad (13)$$

where $\beta_1 = \frac{P_1}{P_R \sigma_R^2} \left|\bar{g}\right|^2$, $\beta_2 = \frac{P_2}{P_R \sigma_R^2} \left|\bar{h}\right|^2$, $Z_1 = \frac{P_1 |\alpha_1|^2}{\sigma_R^2}$ and $Z_2 = \frac{P_2 |\alpha_2|^2}{\sigma_R^2}$. From (13), we see that P_{out} is affected by the cumulative density functions (CDFs) of Z_1, Z_2, β_1 and β_2. It is easily derived that

$$C(\beta) + C(1-\beta) \le C(1) \qquad 0 \le \beta \le 1 \quad (14)$$

Therefore, we obtain the expressions of P_{out} for different cases:

$$P_{out}^{(1)} = P\{Z_1 < C(\beta) \text{ or } Z_2 < C(1-\beta) \text{ or } Z_1 + Z_2 < C(1)\} \qquad \beta_1 \le \frac{C(\beta)}{C(1-\beta)}, \beta_2 \le \frac{C(1-\beta)}{C(\beta)} \quad (15)$$

$$\begin{gathered} P_{out}^{(2)} = P\{Z_1 < C(\beta) \text{ or } Z_2 < \beta_2 C(\beta) \text{ or } Z_1 + Z_2 < C(1)\} \\ \beta_1 \le \frac{C(\beta)}{C(1-\beta)}, \frac{C(1-\beta)}{C(\beta)} < \beta_2 \le \frac{C(1)}{C(\beta)} - 1 \end{gathered} \quad (16)$$

$$P_{out}^{(3)} = P\{Z_1 < C(\beta) \text{ or } Z_2 < \beta_2 C(\beta)\} \qquad \beta_1 \le \frac{C(\beta)}{C(1-\beta)}, \beta_2 > \frac{C(1)}{C(\beta)} - 1 \quad (17)$$

$$\begin{gathered} P_{out}^{(4)} = P\{Z_1 < \beta_1 C(1-\beta) \text{ or } Z_2 < C(1-\beta) \text{ or } Z_1 + Z_2 < C(1)\} \\ \frac{C(\beta)}{C(1-\beta)} < \beta_1 \le \frac{C(1)}{C(1-\beta)} - 1, \beta_2 \le \frac{C(1-\beta)}{C(\beta)} \end{gathered} \quad (18)$$

$$P_{out}^{(5)} = P\{Z_1 < \beta_1 C(1-\beta) \text{ or } Z_2 < C(1-\beta)\} \qquad \beta_1 > \frac{C(1)}{C(1-\beta)} - 1, \beta_2 \le \frac{C(1-\beta)}{C(\beta)} \quad (19)$$

$$\begin{gathered} P_{out}^{(6)} = P\{Z_1 < \beta_1 C(1-\beta) \text{ or } Z_2 < \beta_2 C(\beta) \text{ or } Z_1 + Z_2 < C(1)\} \\ \beta_1 > \frac{C(1)}{C(1-\beta)} - 1, \beta_2 > \frac{C(1-\beta)}{C(\beta)}, \beta_1 C(1-\beta) + \beta_2 C(\beta) \le C(1) \end{gathered} \quad (20)$$

$$P_{out}^{(7)} = P\{Z_1 < \beta_1 C(1-\beta) \text{ or } Z_2 < \beta_2 C(\beta)\}$$
$$\beta_1 > \frac{C(\beta)}{C(1-\beta)}, \beta_2 > \frac{C(1-\beta)}{C(\beta)}, \beta_1 C(1-\beta) + \beta_2 C(\beta) \le C(1) \tag{21}$$

and

$$\begin{aligned} P_{out} &= P_{out}^{(1)} F_{\bar{\beta}_1}(\lambda) F_{\bar{\beta}_2}(\lambda^{-1}) + \int_0^{\lambda}\int_{\lambda^{-1}}^{\lambda_2 - 1} P_{out}^{(2)} f_{\bar{\beta}_2}(\beta_2) d\beta_2 f_{\bar{\beta}_1}(\beta_1) d\beta_1 \\ &+ \int_0^{\lambda}\int_{\lambda_2-1}^{\infty} P_{out}^{(3)} f_{\bar{\beta}_2}(\beta_2) d\beta_2 f_{\bar{\beta}_1}(\beta_1) d\beta_1 + \int_{\lambda}^{\lambda_1-1}\int_0^{\lambda^{-1}} P_{out}^{(4)} f_{\bar{\beta}_2}(\beta_2) d\beta_2 f_{\bar{\beta}_1}(\beta_1) d\beta_1 \\ &+ \int_{\lambda_1-1}^{\infty}\int_0^{\lambda^{-1}} P_{out}^{(5)} f_{\bar{\beta}_2}(\beta_2) d\beta_2 f_{\bar{\beta}_1}(\beta_1) d\beta_1 + \int_{\lambda}^{\lambda_1-1}\int_{\lambda^{-1}}^{\lambda_2 - \frac{\beta_1}{\lambda}} P_{out}^{(6)} f_{\bar{\beta}_2}(\beta_2) d\beta_2 f_{\bar{\beta}_1}(\beta_1) d\beta_1 \\ &+ \int_{\lambda}^{\infty}\int_{\lambda^{-1}}^{\infty} P_{out}^{(7)} f_{\bar{\beta}_2}(\beta_2) d\beta_2 f_{\bar{\beta}_1}(\beta_1) d\beta_1 - \int_{\lambda}^{\lambda_1-1}\int_{\lambda^{-1}}^{\lambda_2 - \frac{\beta_1}{\lambda}} P_{out}^{(7)} f_{\bar{\beta}_2}(\beta_2) d\beta_2 f_{\bar{\beta}_1}(\beta_1) d\beta_1 \end{aligned} \tag{22}$$

where $F_{\bar{\beta}_1}(x)$, $F_{\bar{\beta}_2}(x)$, $f_{\bar{\beta}_1}(x)$, $f_{\bar{\beta}_2}(x)$ denote the CDFs and the probability density function (PDF)s for β_1 and β_2 respectively. With $Z_1 = \frac{P_1 |\alpha_1|^2}{\sigma_R^2}$, $Z_2 = \frac{P_2 |\alpha_2|^2}{\sigma_R^2}$, the CDFs of Z_1 and Z_2 are, respectively, given by

$$F_{Z_1}(x) = 1 - \frac{\Gamma(m_1, m_1 x / \bar{\gamma}_1)}{\Gamma(m_1)} \qquad x \ge 0 \tag{23}$$

where $\bar{\gamma}_1 = \frac{P_1 \Omega_1}{\sigma_R^2}$, and

$$F_{Z_2}(x) = 1 - \frac{\Gamma(m_2, m_2 x / \bar{\gamma}_2)}{\Gamma(m_2)} \qquad x \ge 0 \tag{24}$$

where $\bar{\gamma}_2 = \frac{P_2 \Omega_2}{\sigma_R^2}$, and the PDFs of Z_1 and Z_2 are, respectively, given by

$$f_{Z_1}(x) = \frac{m_1^{m_1} x^{m_1 - 1}}{\Gamma(m_1)} e^{-\frac{m_1 x}{\bar{\gamma}_1}} \qquad x \ge 0 \tag{25}$$

$$f_{Z_2}(x) = \frac{m_2^{m_2} x^{m_2 - 1}}{\Gamma(m_2)} e^{-\frac{m_2 x}{\bar{\gamma}_2}} \qquad x \ge 0 \tag{26}$$

Following (15)-(21), we have

$$P_{out}^{(1)} = G_1(C(1-\beta), C(\beta)) \tag{27}$$
$$P_{out}^{(2)} = G_1(\beta_2 C(\beta), C(\beta)) \tag{28}$$
$$P_{out}^{(3)} = G_2(C(\beta), \beta_2 C(\beta)) \tag{29}$$
$$P_{out}^{(4)} = G_1(C(1-\beta), \beta_1 C(1-\beta)) \tag{30}$$
$$P_{out}^{(5)} = G_2(\beta_1 C(1-\beta), C(1-\beta)) \tag{31}$$
$$P_{out}^{(6)} = G_1(\beta_2 C(\beta), \beta_1 C(1-\beta)) \tag{32}$$
$$P_{out}^{(7)} = G_2(\beta_1 C(1-\beta), \beta_2 C(\beta)) \tag{33}$$

where

$$G_1(x,y) = 1-\psi(x,y) \tag{34}$$

$$G_2(x,y) = 1-\frac{\Gamma(m_1, m_1 x/\bar{\gamma}_1)}{\Gamma(m_1)}\frac{\Gamma(m_2, m_2 x/\bar{\gamma}_2)}{\Gamma(m_2)} \tag{35}$$

and $\psi(x,y)$ is

$$\begin{aligned}\psi(x,y) =& \frac{\Gamma(m_1, m_1(C(1)-y)/\bar{\gamma}_1)}{\Gamma(m_1)}\frac{\Gamma(m_2, m_2 y/\bar{\gamma}_2)}{\Gamma(m_2)} \\ &-\exp\left(-\frac{m_2 C(1)}{\bar{\gamma}_2}\right)\frac{m_1^{m_1}}{\Gamma(m_1)\bar{\gamma}_1^{m_1}}\sum_{p=0}^{m_2}\frac{m_2^p}{p!\bar{\gamma}_2^p}\sum_{j=0}^{p}\frac{\binom{p}{j}(-1)^j C(1)^{p-j}}{\left(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2}\right)^{p+m_1}}\Gamma\left(j+m_1,\left(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2}\right)(C(1)-y)\right) \\ &+\exp\left(-\frac{m_2 C(1)}{\bar{\gamma}_2}\right)\frac{m_1^{m_1}}{\Gamma(m_1)\bar{\gamma}_1^{m_1}}\sum_{p=0}^{m_2-1}\frac{m_2^p}{p!\bar{\gamma}_2^p}\sum_{j=0}^{p}\frac{\binom{p}{j}(-1)^j C(1)^{p-j}}{\left(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2}\right)^{p+m_1}}\Gamma\left(j+m_1,\left(\frac{m_1}{\bar{\gamma}_1}-\frac{m_2}{\bar{\gamma}_2}\right)x\right)\end{aligned} \tag{36}$$

According to the definitions $\beta_1 = \frac{P_1}{P_R\sigma_R^2}\left|\bar{g}\right|^2$, $\beta_2 = \frac{P_2}{P_R\sigma_R^2}\left|\bar{h}\right|^2$ and the CDFs of $\left|\bar{g}\right|^2$ and $\left|\bar{h}\right|^2$ in [33], the CDFs and PDFs of β_1 and β_2 are given by

$$F_{\bar{\beta}_1}(x) = 1-\frac{\Gamma(m_{I1}, m_{I1}x/\bar{\gamma}_{I1})}{\Gamma(m_{I1})} \qquad x\geq 0 \tag{37}$$

$$F_{\bar{\beta}_2}(x) = 1-\frac{\Gamma(m_{I2}, m_{I2}x/\bar{\gamma}_{I2})}{\Gamma(m_{I2})} \qquad x\geq 0 \tag{38}$$

$$f_{\bar{\beta}_1}(x) = \frac{m_{I1}^{m_{I1}}x^{m_{I1}-1}}{\Gamma(m_{I1})}e^{-\frac{m_{I1}x}{\bar{\gamma}_{I1}}} \qquad x\geq 0 \tag{39}$$

$$f_{\bar{\beta}_2}(x) = \frac{m_{I2}^{m_{I2}}x^{m_{I2}-1}}{\Gamma(m_{I2})}e^{-\frac{m_{I2}x}{\bar{\gamma}_{I2}}} \qquad x\geq 0 \tag{40}$$

in which $\bar{\gamma}_{I1} = \frac{P_1}{P_R\sigma_R^2}P_{I1}\Omega_{I1}$, $\bar{\gamma}_{I2} = \frac{P_2}{P_R\sigma_R^2}P_{I2}\Omega_{I2}$. Without loss of generality, hereafter we assume that no power control is used, i.e., $P_1^i = P_{I1}, P_2^j = P_{I2}$. In order to render (39) and (40) an accurate approximation, the required parameters m_{I1}, m_{I2}, Ω_{I1} and Ω_{I2} must be calculated. To this end, we shall use moment-based estimators [34] for the computation of such parameters. Firstly, let $\phi_1 = \sum_{i=1}^{N_1}\left|g_i\right|^2$, $\phi_2 = \sum_{j=1}^{N_2}\left|h_j\right|^2$. Then, moment-based estimators can be written from the exact moments of ϕ_1 and ϕ_2, i.e., $\Omega_{I1} = E\{\phi_1\}$, $\Omega_{I2} = E\{\phi_2\}$, $m_{I1} = \sum_{i=1}^{N_1} m_{iI}$, $m_{I2} = \sum_{j=1}^{N_2} m_{jI}$, where Ω_{I1} and Ω_{21} are easily attained as $\Omega_{I1} = \sum_{i=1}^{N_1}\Omega_{iI}$ and

$\Omega_{I2} = \sum_{j=1}^{N_2} \Omega_{jI}$ .Substituting (27)-(33), (37)-(40) into (22) and simplifying the result gives the desired result (10).

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