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Research Article

Outage Probability of Dual-Hop Multiple Antenna Relay Systems with Interference at the Relay and Destination

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This paper analyzes the outage performance of a dual-hop relaying system in which the relay is equipped with multiple antennas, while the source and destination have a single antenna. New exact closed-form expressions for the outage probability of both the amplify-and-forward (AF) and the decode-and-forward (DF) relaying systems are derived, assuming that the relay and destination are impaired by cochannel interferers and additive white Gaussian noise (AWGN). Numerical results are presented to verify the theoretical analysis.

1. Introduction

Relaying methodologies such as amplify-and-forward (AF) and decode-and-forward (DF) have received considerable interest by virtue of improving the range and link reliability in fading wireless channels. Meanwhile, the more aggressive frequency reuse strategy results in increasingly complex interference environment. Several recent works have studied the impact of cochannel interference (CCI) on the outage performance of the relaying system when the relay or/and destination are subjected to single or multiple cochannel interferers. In [1], the effect of multiple Rayleigh fading interferers in an AF relay system was investigated and exact expression for outage probability was derived. Reference [2] also studied the outage probability of a fixed gain AF relaying system under the influence of interference at the relay and the destination terminals. However, [1, 2] only considered a single antenna system, which is one common limitation in most of the prior literatures.

Despite the importance of multiple-input multiple-output (MIMO) technology, few papers have studied the performance of multiple antenna relaying systems in the presence of CCI. For example, [3] derived an exact closed-form expression for the outage probability of a dual-hop AF MIMO relay network where the source and destination have multiple antennas and the relay has only one antenna, while [4] addressed the case where only one of the nodes is equipped with multiple antennas and the relay node is subjected to a single interferer, and later [5] extended [4] to systems with arbitrary number of interferers at the relay node, assuming that the relay is subjected to CCI and additive white Gaussian noise (AWGN) while the destination is corrupted by AWGN only. In [6], the outage expressions for different configurations of the multiple antenna relay network with interference in the context of AF relay with fixed gain were derived. Most recently, [7] proposed a two-hop AF relaying scheme considering a system with CCI and thermal noise at both the relay and destination, and [8] investigated the outage probability of an AF relay system in which the source is equipped with multiple transmit antennas and adopts the orthogonal space-time block code to increase the system performance.

Unlike the aforementioned works, this paper aims to analyze the outage performance of a dual-hop multiple antenna relay system with arbitrary number of cochannel interferers at both the relay and the destination along with thermal noise. For the reason of mathematical tractability, we neglect

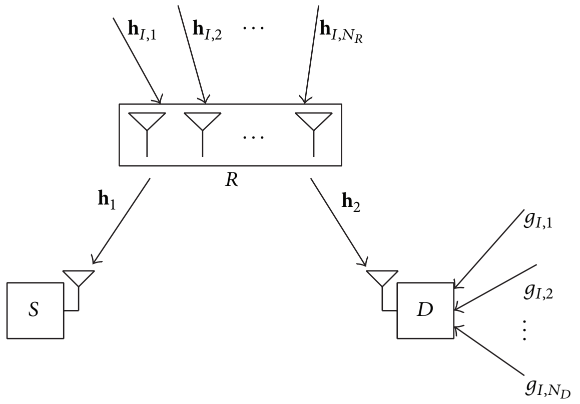

Figure 1: System diagram.

the effect of noise in AF scheme. The main contribution is the derivation of new exact closed-form expressions for the outage probability of the system under consideration employing either an AF or a DF relay.

2. System Models

Consider a dual-hop relaying system, where the source S and destination D have only one antenna while the relay R is equipped with N antennas, as illustrated in Figure 1. It is assumed that both the relay and destination suffer from CCI and AWGN. All the channel coefficients are independent and identically distributed (i.i.d.) complex Gaussian random variables with zero mean and unit variance. Besides, there is no direct link between the source and destination due to obstacles or deep fading.

Each transmission consists of two phases. In the first phase, the source transmits the signal to the relay, and the received vector at the relay is given by

$$\mathbf{y}_r = \mathbf{h}_1 x + \sum_{i=1}^{N_R} \mathbf{h}_{I,i} s_{R,i} + \mathbf{n}_r, \tag{1}$$

where the $N \times 1$ vectors $\mathbf{h}_1$ and $\mathbf{h}_{I,i}$ denote the channel from the source and the ith interferer, respectively. N_R is the number of interferers at the relay node, x is the information symbol satisfying $\mathbb{E}\{|x|^2\} = P_s$, $s_{R,i}$ is the ith interference symbol with $\mathbb{E}\{|s_{R,i}|^2\} = P_{R,i}$, and $\mathbf{n}_r \sim \mathcal{CN}(0, \sigma_r^2 \mathbf{I})$ represents the AWGN at the relay.

In the second phase, an AF relay retransmits a transformed version of the received signal to the destination, and the signal at the destination is expressed as

$$y_d^{\mathrm{AF}} = \mathbf{h}_2 \mathbf{W} \mathbf{y}_r + \sum_{j=1}^{N_D} g_{I,j} s_{D,j} + n_d, \tag{2}$$

where $\mathbf{h}_2 \in \mathbb{C}^{1\times N}$ and $g_{I,j}$ denote the channel from the relay and the jth interferer, respectively. N_D is the number of interferers at the destination, $s_{D,j}$ is the jth interference symbol with $\mathbb{E}\{|s_{D,j}|^2\} = P_{D,j}$, n_d is the AWGN with $\mathbb{E}\{|n_d|^2\} = \sigma_d^2$, and $\mathbf{W}$ is the $N \times N$ transformation matrix and will be specified in the following section.

As a result, the instantaneous signal-to-interference-plus-noise ratio (SINR) experienced at the destination is given by

$$\gamma_d^{\mathrm{AF}} = \frac{\left|\mathbf{h}_2 \mathbf{W} \mathbf{h}_1\right|^2 P_s}{\sum_{i=1}^{N_R} \left|\mathbf{h}_2 \mathbf{W} \mathbf{h}_{I,i}\right|^2 P_{R,i} + \left\|\mathbf{h}_2 \mathbf{W}\right\|^2 \sigma_r^2 + z_d}. \tag{3}$$

Here, $z_d = \sum_{j=1}^{N_D} |g_{I,j}|^2 P_{D,j} + \sigma_d^2$ denotes the undesired interference-plus-noise signal received at the destination. For a given threshold value γ_{th}, the outage probability of the AF relaying system can be mathematically expressed as

$$P_{\mathrm{out}}^{\mathrm{AF}} = P\left(\gamma_d^{\mathrm{AF}} < \gamma_{\mathrm{th}}\right). \tag{4}$$

On the other hand, when the DF protocol is adopted, the relay first decodes the received signal and then forwards the reencoded message s_r to the destination with $\mathbb{E}\{|s_r|^2\} = P_{s_r}$. We consider two cases: (1) the DF relay applies some sort of transformation to the message s_r; (2) the DF relay does not perform any linear diversity combining. In the first case, the received signal at the destination is

$$y_d^{\mathrm{DF},1} = \mathbf{h}_2 \mathbf{W} s_r + \sum_{j=1}^{N_D} g_{I,j} s_{D,j} + n_d, \tag{5}$$

where $\mathbf{W}$ is the $N \times 1$ precoding matrix. The SINR at the destination is given by

$$\gamma_d^{\mathrm{DF},1} = \frac{\left|\mathbf{h}_2 \mathbf{W}\right|^2 P_{s_r}}{\sum_{j=1}^{N_D} \left|g_{I,j}\right|^2 P_{D,j} + \sigma_d^2}. \tag{6}$$

The outage probability of the DF relaying system can be expressed as

$$P_{\mathrm{out}}^{\mathrm{DF},1} = P\left(\gamma_d^{\mathrm{DF},1} < \gamma_{\mathrm{th}}\right). \tag{7}$$

For the second case, the received signal at the destination becomes

$$y_d^{\mathrm{DF},2} = h_2 s_r + \sum_{j=1}^{N_D} g_{I,j} s_{D,j} + n_d. \tag{8}$$

Then, the outage probability of the DF relaying system can be defined as

$$P_{\mathrm{out}}^{\mathrm{DF},2} = P\left(\min\left\{\max\left\{\gamma_{r,k}^{\mathrm{DF},2}\right\}, \gamma_d^{\mathrm{DF},2}\right\} < \gamma_{\mathrm{th}}\right), \tag{9}$$

where $\gamma_{r,k}^{\mathrm{DF},2}$ and $\gamma_d^{\mathrm{DF},2}$ represent the SINR at the kth relay antenna and destination, respectively. Let $h_{1,k}$ and $h_{I,i,k}$ be the kth element of $\mathbf{h}_1$ and $\mathbf{h}_{I,i}$; from (1), the received signal at the kth relay antenna is given by

$$y_{r,k} = h_{1,k} x + \sum_{i=1}^{N_R} h_{I,i,k} s_{R,i} + n_{r,k}. \tag{10}$$

Thus, we have

$$\gamma_{r,k}^{\mathrm{DF},2} = \frac{|h_{1,k}|^2 P_s}{\sum_{i=1}^{N_R} |h_{I,i,k}|^2 P_{R,i} + \sigma_r^2}, \quad k = 1, \ldots, N,$$
$$\gamma_d^{\mathrm{DF},2} = \frac{|h_2|^2 P_r}{\sum_{j=1}^{N_D} |g_{I,j}|^2 P_{D,j} + \sigma_d^2}. \tag{11}$$

3. Outage Probability Analysis

In this section, we derive new exact analytical expressions for the outage probability of the considered system. For mathematical tractability, if AF protocol is adopted, the relay and destination are assumed to be interference-limited; that is, the effect of the noise at the relay and destination can be neglected.

3.1. AF Relay Systems. Since the optimal relay precoder matrix is analytically intractable, although performing maximum ratio combining will not minimize CCI, we still use a two-stage relay processing strategy, that is, the maximum ratio combining/maximal ratio transmission (MRC/MRT) scheme [5]. Therefore, the relay transformation matrix $\mathbf{W}$ can be written as $\mathbf{W} = G(\mathbf{h}_2^\dagger \mathbf{h}_1^\dagger / \|\mathbf{h}_2\| \|\mathbf{h}_1\|)$. In order to satisfy the transmit power constraint of the relay, that is, $\mathbb{E}\{\|\mathbf{W}\mathbf{y}_r\|^2\} = P_r$, G can be chosen as

$$G = \sqrt{\frac{P_r}{P_s N + \sum_{i=1}^{N_R} P_{R,i} + \sigma_r^2}}. \tag{12}$$

Substituting $\mathbf{W}$ into (3) and after some derivations, γ_d^{AF} can be expressed as

$$\gamma_d^{\mathrm{AF}} = \frac{\|\mathbf{h}_2\|^2 \|\mathbf{h}_1\|^2 P_s}{\|\mathbf{h}_2\|^2 \sum_{i=1}^{N_R} \left(|\mathbf{h}_1^\dagger \mathbf{h}_{I,i}|^2 / \|\mathbf{h}_1\|^2 \right) P_{R,i} + \|\mathbf{h}_2\|^2 \sigma_r^2 + z_d (1/G^2)}. \tag{13}$$

For notational convenience, we define $\gamma_1 = (P_s/\sigma_r^2)\|\mathbf{h}_1\|^2$, $\gamma_2 = (P_r/\sigma_d^2)\|\mathbf{h}_2\|^2$, $\gamma_R = \sum_{i=1}^{N_R} (P_{R,i}/\sigma_r^2) h_{R,i}$, $h_{R,i} = |\mathbf{h}_1^\dagger \mathbf{h}_{I,i}|^2 / \|\mathbf{h}_1\|^2$ and $\gamma_D = \sum_{j=1}^{N_D} (P_{D,j}/\sigma_d^2) |g_{I,j}|^2$. Since the relay and destination are interference-limited, γ_d^{AF} can be further derived as

$$\gamma_d^{\mathrm{AF}} = \frac{\gamma_1 \gamma_2}{\gamma_2 \gamma_R + C \gamma_D}, \tag{14}$$

where the constant $C = (P_s/\sigma_r^2)N + \sum_{i=1}^{N_R} (P_{R,i}/\sigma_r^2) + 1$.

To evaluate the outage performance, the probability density function (PDF) of γ_1, γ_2, γ_R, and γ_D is required. It is easy to observe that γ_1 and γ_2 are i.i.d. random variables with PDF

$$f_{\gamma_i}(\gamma) = \frac{1}{\rho_i^N (N-1)!} \gamma^{N-1} e^{-\gamma/\rho_i} U(\gamma), \tag{15}$$

where $\rho_1 = P_s/\sigma_r^2$, $\rho_2 = P_r/\sigma_d^2$, and $U(\cdot)$ is the unit-step function.

Given that $\{h_{R,i}\}_{i=1}^{N_R}$ are i.i.d. exponential random variables with unit variance, then, γ_R follows the hyperexponential distribution with PDF [1, 5] as

$$f_{\gamma_R}(\gamma) = \sum_{m=1}^{\varrho(\mathcal{A})} \sum_{n=1}^{\tau_m(\mathcal{A})} \mathcal{X}_{m,n}(\mathcal{A}) \frac{\rho_{R,[m]}^{-n}}{(n-1)!} \gamma^{n-1} e^{-\gamma/\rho_{R,[m]}} U(\gamma), \tag{16}$$

where $\mathcal{A} = \mathrm{diag}(\rho_{R,1}, \ldots, \rho_{R,N_R})$, $\rho_{R,i} = P_{R,i}/\sigma_r^2$, $\varrho(\mathcal{A})$ denotes the number of distinct diagonal elements of $\mathcal{A}$, $\{\rho_{R,[m]}\}$ are the distinct diagonal elements in decreasing order, $\tau_m(\mathcal{A})$ is the multiplicity of $\rho_{R,[m]}$, and $\mathcal{X}_{m,n}(\mathcal{A})$ is the (m,n)th characteristic coefficient of $\mathcal{A}$. Similarly, the PDF of γ_D is given by

$$f_{\gamma_D}(\gamma) = \sum_{m=1}^{\varrho(\mathcal{B})} \sum_{n=1}^{\tau_m(\mathcal{B})} \mathcal{X}_{m,n}(\mathcal{B}) \frac{\rho_{D,[m]}^{-n}}{(n-1)!} \gamma^{n-1} e^{-\gamma/\rho_{D,[m]}} U(\gamma), \tag{17}$$

where $\mathcal{B} = \mathrm{diag}(\rho_{D,1}, \ldots, \rho_{D,N_D})$, $\rho_{D,j} = P_{D,j}/\sigma_d^2$, $\varrho(\mathcal{B})$, $\tau_m(\mathcal{B})$, and $\mathcal{X}_{m,n}(\mathcal{B})$ are defined the same as (16).

Combining (4) with (14) and using the PDF of γ_1 given by (15), $P_{\mathrm{out}}^{\mathrm{AF}}$ can be formulated as (18), where the last equality of (18) is obtained by using the binomial expansion

$$\begin{aligned}
P_{\mathrm{out}}^{\mathrm{AF}} &= P\left(\gamma_1 < \gamma_{\mathrm{th}}\gamma_R + \gamma_{\mathrm{th}} C \frac{\gamma_D}{\gamma_2}\right) \\
&= 1 - \sum_{p=0}^{N-1} \frac{1}{p!} \iiint_0^\infty \left(\frac{\gamma_{\mathrm{th}}\gamma_R}{\rho_1} + \frac{\gamma_{\mathrm{th}} C}{\rho_1}\frac{\gamma_D}{\gamma_2}\right)^p \\
&\qquad \times e^{-(\gamma_{\mathrm{th}}/\rho_1)\gamma_R} e^{-(\gamma_{\mathrm{th}} C/\rho_1)(\gamma_D/\gamma_2)} f_{\gamma_2}(\gamma_2) \\
&\qquad \times f_{\gamma_R}(\gamma_R) f_{\gamma_D}(\gamma_D)\, d\gamma_2\, d\gamma_R\, d\gamma_D \\
&= 1 - \sum_{p=0}^{N-1} \sum_{q=0}^{p} \frac{1}{p!} \binom{p}{q} \left(\frac{\gamma_{\mathrm{th}}}{\rho_1}\right)^p C^q \\
&\quad \times \underbrace{\int_0^\infty \gamma_R^{p-q} e^{-(\gamma_{\mathrm{th}}/\rho_1)\gamma_R} f_{\gamma_R}(\gamma_R)\, d\gamma_R}_{I_1} \\
&\quad \times \underbrace{\iint_0^\infty \left(\frac{\gamma_D}{\gamma_2}\right)^q e^{-(\gamma_{\mathrm{th}} C/\rho_1)(\gamma_D/\gamma_2)} f_{\gamma_2}(\gamma_2) f_{\gamma_D}(\gamma_D)\, d\gamma_2\, d\gamma_D}_{I_2}.
\end{aligned} \tag{18}$$

Substituting the PDF of γ_R given by (16) into I_1, with the help of [9, Equation (3.351.3)], I_1 can be derived as

$$I_1 = \sum_{m=1}^{\varrho(\mathscr{A})} \sum_{n=1}^{\tau_m(\mathscr{A})} \mathscr{X}_{m,n}(\mathscr{A}) \rho_{R,[m]}^{-n} \frac{(\alpha-1)!}{(n-1)!} \left(\frac{\gamma_{\text{th}}}{\rho_1} + \frac{1}{\rho_{R,[m]}} \right)^{-\alpha}, \tag{19}$$

where $\alpha = n + p - q$.

To calculate the integral of I_2, we first substitute the PDF of γ_2 given by (15) into I_2 and then use the integral identity [9, Equation (3.471.9)] to obtain

$$I_2 = \frac{2}{\rho_2^N (N-1)!} \int_0^\infty \gamma_D^q \left(\frac{\gamma_{\text{th}} C \rho_2 \gamma_D}{\rho_1} \right)^{(N-q)/2} \times K_{N-q}\left(2\sqrt{\frac{\gamma_{\text{th}} C \gamma_D}{\rho_1 \rho_2}} \right) f_{\gamma_D}(\gamma_D)\, d\gamma_D, \tag{20}$$

where $K_n(z)$ is the nth order modified Bessel function of the second kind [9, Equation (8.407)].

Substituting (17) into (20) and using [9, Equation (6.631.3)], after some algebraic manipulation, we get

$$I_2 = \frac{1}{(N-1)!} \left(\frac{\gamma_{\text{th}} C}{\rho_1} \right)^a \rho_2^{-b} \sum_{m=1}^{\varrho(\mathscr{B})} \sum_{n=1}^{\tau_m(\mathscr{B})} \mathscr{X}_{m,n}(\mathscr{B}) \frac{\rho_{D,[m]}^b}{(n-1)!} \times \Gamma(n+N)\Gamma(n+q) \exp\left(\frac{\overline{\rho}_m}{2} \right) W_{-(n+b),(N-q)/2}(\overline{\rho}_m), \tag{21}$$

where $a = (N-q-1)/2$, $b = (N+q-1)/2$, $\overline{\rho}_m = \gamma_{\text{th}} C \rho_{D,[m]} / \rho_1 \rho_2$, and $W_{\lambda,\mu}(z)$ is the Whittaker function defined in [9, Equation (9.222.1)].

Now substituting (19) and (21) into (18), the closed-form expression for the outage probability of the AF relay system can be obtained as

$$\begin{aligned} P_{\text{out}}^{\text{AF}} &= 1 - \frac{1}{(N-1)!} \sum_{p=0}^{N-1} \sum_{q=0}^{p} \frac{1}{p!} \binom{p}{q} \left(\frac{\gamma_{\text{th}}}{\rho_1} \right)^{p+a} \left(\frac{C}{\rho_2} \right)^b \\ &\quad \times \sum_{m=1}^{\varrho(\mathscr{A})} \sum_{n=1}^{\tau_m(\mathscr{A})} \mathscr{X}_{m,n}(\mathscr{A}) \rho_{R,[m]}^{-n} \frac{(\alpha-1)!}{(n-1)!} \left(\frac{\gamma_{\text{th}}}{\rho_1} + \frac{1}{\rho_{R,[m]}} \right)^{-\alpha} \\ &\quad \times \sum_{u=1}^{\varrho(\mathscr{B})} \sum_{v=1}^{\tau_u(\mathscr{B})} \mathscr{X}_{u,v}(\mathscr{B}) \frac{\rho_{D,[u]}^b}{(v-1)!} \Gamma(v+N)\Gamma(v+q) \\ &\quad \times \exp\left(\frac{\overline{\rho}_u}{2} \right) \\ &\quad \times W_{-(v+b),(N-q)/2}(\overline{\rho}_u). \end{aligned} \tag{22}$$

For the case of equal-power interference, that is, $\rho_{R,i} = \rho_R$, $\forall i = 1, \ldots, N_R$, $\rho_{D,j} = \rho_D$, $\forall j = 1, \ldots, N_D$, (22) reduces to

$$\begin{aligned} P_{\text{out}}^{\text{AF}} &= 1 - \frac{1}{(N-1)!} \sum_{p=0}^{N-1} \sum_{q=0}^{p} \frac{1}{p!} \binom{p}{q} \left(\frac{\gamma_{\text{th}}}{\rho_1} \right)^{p+a} \left(\frac{C}{\rho_2} \right)^b \\ &\quad \times \rho_R^{-N_R} \frac{(N_R+p-q-1)!}{(N_R-1)!} \left(\frac{\gamma_{\text{th}}}{\rho_1} + \frac{1}{\rho_R} \right)^{-N_R-p+q} \\ &\quad \times \frac{\rho_D^b}{(N_D-1)!} \Gamma(N_D+N)\Gamma(N_D+q) \exp\left(\frac{\overline{\rho}_u}{2} \right) \\ &\quad \times W_{-(N_D+b),(N-q)/2}(\overline{\rho}_u). \end{aligned} \tag{23}$$

3.2. DF Relay Systems. In the analysis of DF relay channels, the relay and destination are assumed to be interference-and-noise-limited, and the effect of noise is taken into account. We consider two cases, respectively. In the first case, we use the maximal ratio transmission scheme and the relay precoding matrix $\mathbf{W}$ is set to be $\mathbf{W} = G(\mathbf{h}_2^\dagger / \|\mathbf{h}_2\|)$. In order to meet the relay power constraint $\mathbb{E}\{\|\mathbf{W} s_r\|^2\} = P_r$, G can be chosen as $G = \sqrt{P_r / P_{s_r}}$. After some substitutions, (6) becomes

$$\gamma_d^{\text{DF},1} = \frac{\gamma_2}{\gamma_D + 1}. \tag{24}$$

Then,

$$\begin{aligned} P_{\text{out}}^{\text{DF},1} &= P\left(\frac{\gamma_2}{\gamma_D+1} < \gamma_{\text{th}} \right) = P(\gamma_2 < \gamma_{\text{th}}(\gamma_D+1)) \\ &= 1 - \sum_{p=0}^{N-1} \frac{1}{p!} \int_0^\infty \left(\frac{\gamma_{\text{th}}(\gamma_D+1)}{\rho_2} \right)^p e^{-\gamma_{\text{th}}(\gamma_D+1)/\rho_2} \\ &\quad \times f_{\gamma_D}(\gamma_D)\, d\gamma_D \\ &= 1 - \sum_{p=0}^{N-1} \sum_{q=0}^{p} \frac{1}{p!} \binom{p}{q} \left(\frac{\gamma_{\text{th}}}{\rho_2} \right)^p e^{-\gamma_{\text{th}}/\rho_2} I_3, \end{aligned} \tag{25}$$

where $I_3 = \int_0^\infty \gamma_D^{p-q} e^{-(\gamma_{\text{th}}/\rho_2)\gamma_D} f_{\gamma_D}(\gamma_D) d\gamma_D$. Similar to the integral of I_1 in (18), we obtain $P_{\text{out}}^{\text{DF},1}$ as follows:

$$\begin{aligned} P_{\text{out}}^{\text{DF},1} &= 1 - \sum_{p=0}^{N-1} \sum_{q=0}^{p} \frac{1}{p!} \binom{p}{q} \left(\frac{\gamma_{\text{th}}}{\rho_2} \right)^p \\ &\quad \times e^{-\gamma_{\text{th}}/\rho_2} \sum_{m=1}^{\varrho(\mathscr{B})} \sum_{n=1}^{\tau_m(\mathscr{B})} \mathscr{X}_{m,n}(\mathscr{B}) \rho_{D,[m]}^{-n} \\ &\quad \times \frac{(\alpha-1)!}{(n-1)!} \left(\frac{\gamma_{\text{th}}}{\rho_2} + \frac{1}{\rho_{D,[m]}} \right)^{-\alpha}. \end{aligned} \tag{26}$$

For the second case, we first define $\gamma_{1,k} = \rho_1 |h_{1,k}|^2$, $\gamma_2^{\mathrm{DF}} = \rho_2 |h_2|^2$, and $\gamma_{R,k} = \sum_{i=1}^{N_R} \rho_{R,i} |h_{I,i,k}|^2$. As a consequence, the SINR in (11) can be written as

$$\gamma_{r,k}^{\mathrm{DF},2} = \frac{\gamma_{1,k}}{\gamma_{R,k} + 1}, \quad k = 1, \ldots, N,$$
$$\gamma_d^{\mathrm{DF},2} = \frac{\gamma_2^{\mathrm{DF}}}{\gamma_D + 1}. \tag{27}$$

Here, $\gamma_{1,k}$ and γ_2^{DF} are exponentially distributed with parameters ρ_1 and ρ_2, respectively, and $\gamma_{R,k}$ is distributed the same as γ_R defined in (16).

From the definition in (9), considering the mutual independence of $\{\gamma_{r,k}^{\mathrm{DF}}\}_{k=1}^{N}$, and after some simple manipulation, $P_{\mathrm{out}}^{\mathrm{DF},2}$ can be alternatively expressed as

$$P_{\mathrm{out}}^{\mathrm{DF},2} = 1 - \left(1 - \prod_{k=1}^{N} \underbrace{P(\gamma_{r,k}^{\mathrm{DF},2} < \gamma_{\mathrm{th}})}_{P_k}\right) \times \left(1 - P\left(\gamma_d^{\mathrm{DF},2} < \gamma_{\mathrm{th}}\right)\right). \tag{28}$$

By utilizing the known distribution of $\gamma_{1,k}$, it is easy to show that

$$P_k = P\left(\frac{\gamma_{1,k}}{\gamma_{R,k} + 1} < \gamma_{\mathrm{th}}\right) = 1 - \int_0^{\infty} e^{-\gamma_{\mathrm{th}}(\gamma+1)/\rho_1} f_{\gamma_{R,k}}(\gamma)\, d\gamma. \tag{29}$$

Substituting the PDF of $\gamma_{R,k}$ into (29) and using [9, Equation (3.351.3)], we have

$$P_k = 1 - \sum_{m=1}^{\varrho(\mathscr{A})} \sum_{n=1}^{\tau_m(\mathscr{A})} \mathscr{X}_{m,n}(\mathscr{A})\, \rho_{R,[m]}^{-n} \times e^{-\gamma_{\mathrm{th}}/\rho_1} \left(\frac{\gamma_{\mathrm{th}}}{\rho_1} + \frac{1}{\rho_{R,[m]}}\right)^{-n}. \tag{30}$$

Likewise, using the PDF of γ_2^{DF} and γ_D, we obtain

$$P\left(\gamma_d^{\mathrm{DF},2} < \gamma_{\mathrm{th}}\right) = P\left(\frac{\gamma_2^{\mathrm{DF}}}{\gamma_D + 1} < \gamma_{\mathrm{th}}\right) = 1 - \sum_{m=1}^{\varrho(\mathscr{B})} \sum_{n=1}^{\tau_m(\mathscr{B})} \mathscr{X}_{m,n}(\mathscr{B})\, \rho_{D,[m]}^{-n} e^{-\gamma_{\mathrm{th}}/\rho_2} \times \left(\frac{\gamma_{\mathrm{th}}}{\rho_2} + \frac{1}{\rho_{D,[m]}}\right)^{-n}. \tag{31}$$

Finally, substituting (30) and (31) into (28), we can obtain the closed-form expression for the outage probability of the DF relay system.

4. Numerical Results

In this section, we present some numerical results to verify the theoretical analysis. In Figures 2, 4, and 5, $N = 2$, $N_R = N_D = 2$, $\rho_1 = \rho_2$, $\mathbb{E}\{\gamma_R\} = \mathbb{E}\{\gamma_D\}$, $\rho_{R,[1]}/\rho_{R,[2]} = \rho_{D,[1]}/\rho_{D,[2]} = 1$, and the signal-to-interference ratio (SIR) is defined as $\eta = \rho_1/(\sum_{i=1}^{N_R} \rho_{R,i} + \sum_{j=1}^{N_D} \rho_{D,j})$.

Figure 2 shows the outage probability of the dual-hop AF relaying system with the MRC/MRT scheme for different η. It is clear that all the analytical results are in exact agreement with the simulation results. Also, it is observed that in the high SNR range there is a floor effect, due to the impact of cochannel interference.

Figure 3 examines the impact of interference power distribution on the outage probability of the AF relaying system.

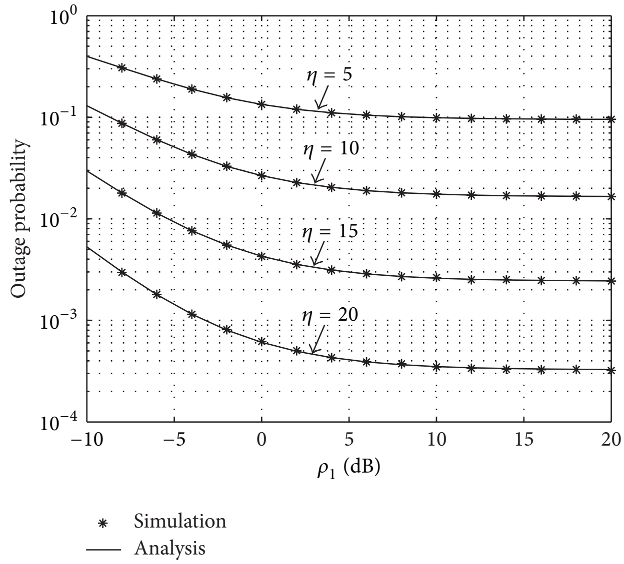

Figure 2: Outage probability of the AF relaying system versus SNR ($\gamma_{\mathrm{th}} = 0$ dB).

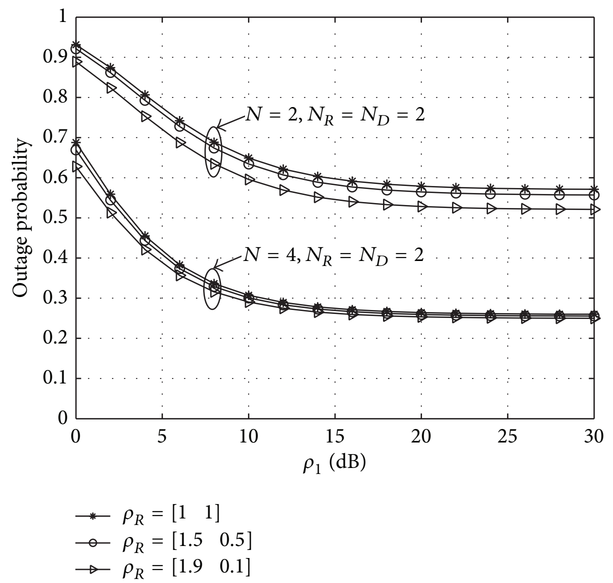

Figure 3: Impact of interference power distribution on the outage performance of the AF relaying system ($\rho_2 = 0$ dB, $\rho_D = \rho_R$, $\gamma_{\mathrm{th}} = 0$ dB).

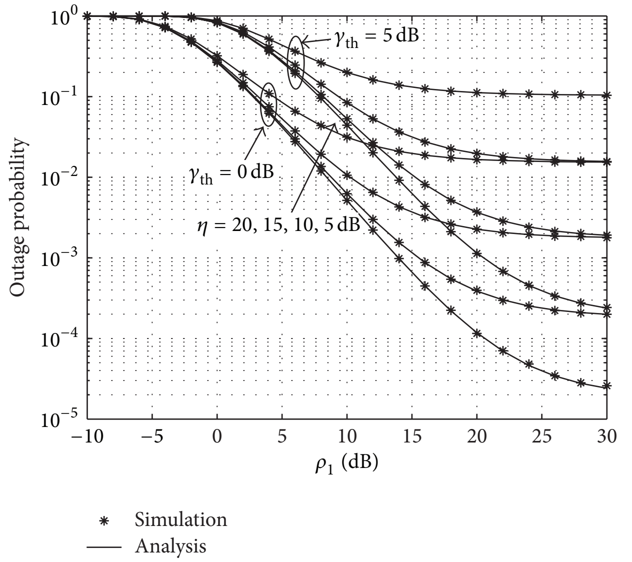

Figure 4: Outage probability of the DF relaying system with MRT versus SNR.

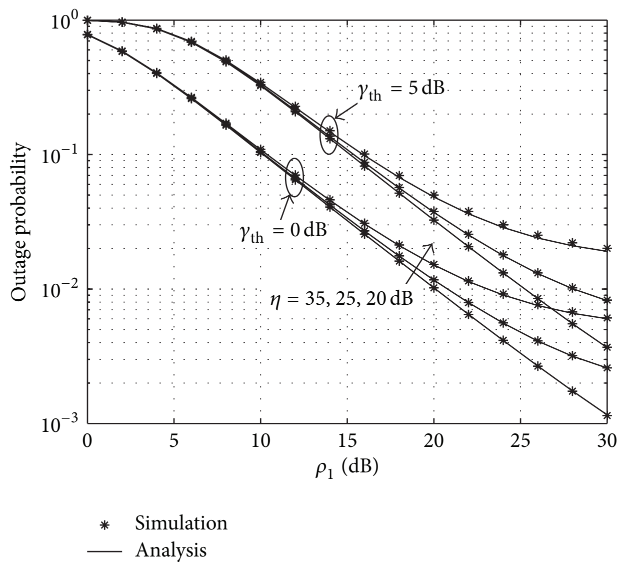

Figure 5: Outage probability of the DF relaying system without MRT versus SNR.

As illustrated, the equal interference power case yields the worst outage performance.

Figure 4 illustrates the outage probability of the dual-hop DF relaying system when maximal ratio transmission scheme is used at the relay. Also, it is clear that all the simulation results match the analytical results very well. As a result of the cochannel interference, the curves converge to a floor in the very high SNR range under the constraints of SIR η. The effect of threshold value γ_{th} is also depicted, and we see that increasing γ_{th} deteriorates the system performance as expected.

Figure 5 shows the outage probability of the DF relaying system without adopting any linear diversity combining

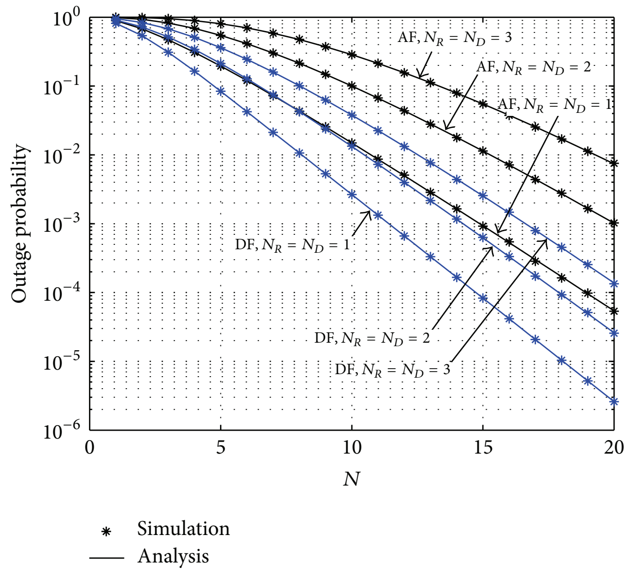

Figure 6: Comparison of AF relaying system with MRC/MRT and DF relaying system with MRT versus N ($\rho_1 = \rho_2 = 0$ dB, $\rho_{R,i} = \rho_{D,j} = 0$ dB, $\forall i, j$, $\gamma_{th} = 0$ dB).

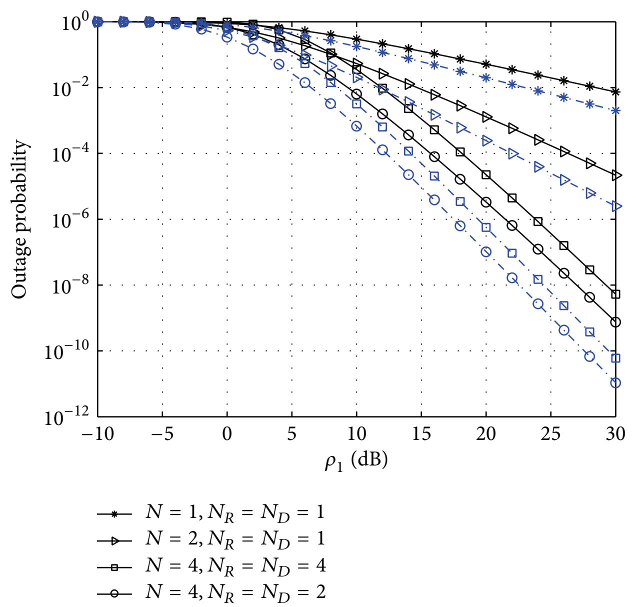

Figure 7: Comparison of AF relaying system with MRC/MRT and DF relaying system with MRT versus SNR ($\rho_1 = \rho_2$, $\rho_{R,i} = \rho_{D,j} = 0$ dB, $\forall i, j$, $\gamma_{th} = 0$ dB).

schemes for different η. From Figures 4 and 5, it is obvious that the DF relaying system can benefit from linear diversity combining scheme which has the capability of improving SINR.

Figure 6 compares the outage probability of the AF relaying system and DF relaying system as a function of the number of relay antennas N. We observe that increasing N reduces the outage probability significantly, while increasing the number of interferers N_R and N_D degrades the outage performance.

Figure 7 compares the analytical results of AF relaying system with MRC/MRT scheme and DF relaying system with MRT scheme, using (22) and (26), respectively. The solid line denotes AF while the dashdot refers to DF. Because the DF relay fully decodes the source message x and the noise at the relay is not amplified and forwarded to the destination, the outage performance of DF relaying system is superior to the AF system.

5. Conclusion

We investigated the outage performance of a dual-hop multiple antenna relaying system by taking into account the interference and noise at both the relay and destination. New exact closed-form expressions for the outage probability of the system employing AF and DF protocols were derived, which paved a fast and efficient way for understanding the effects of multiple antennas and interference on the system performance.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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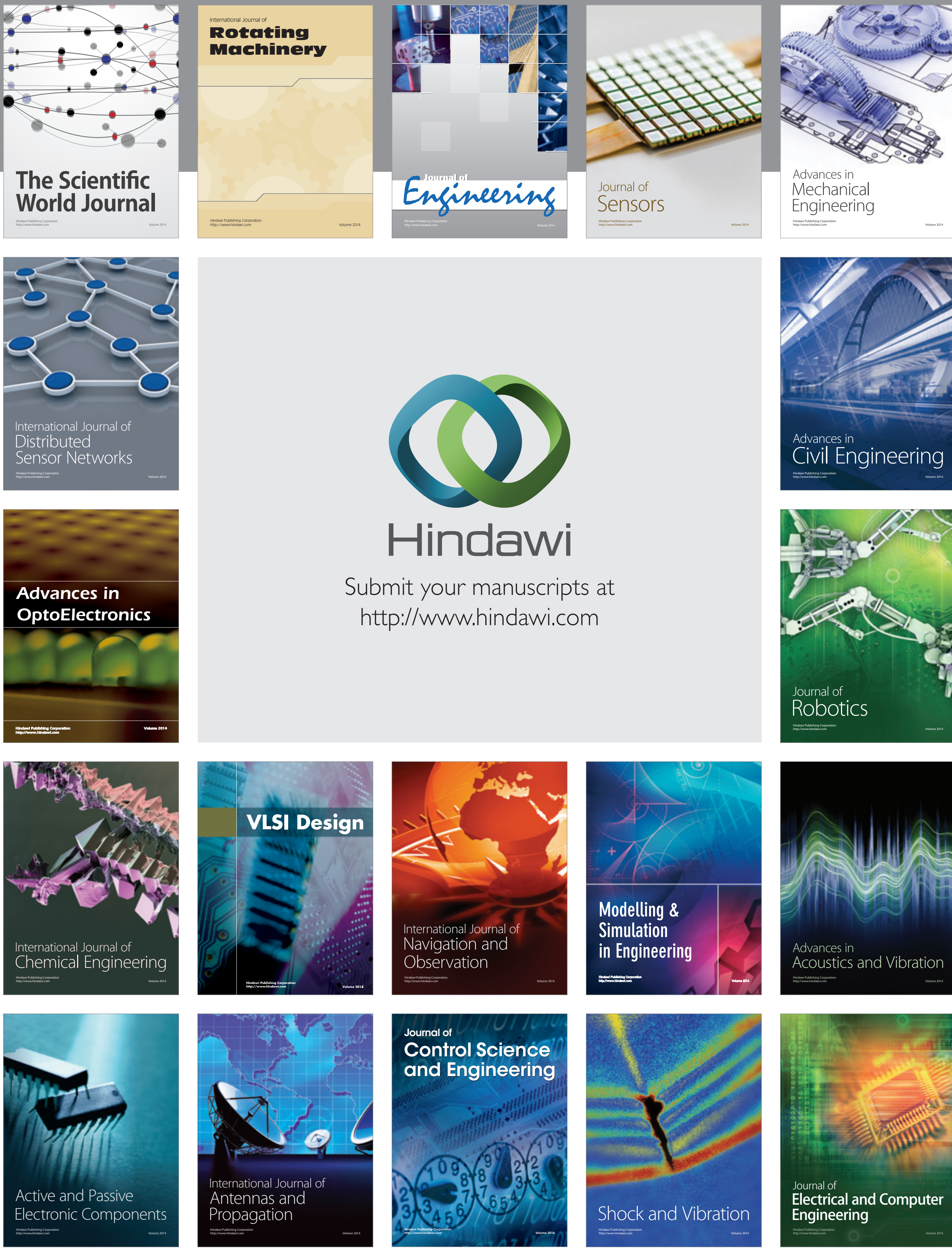
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