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DF Relaying Networks With Randomly Distributed Interferers

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ABSTRACT In this paper, we study a decode-and-forward (DF) relaying network with random interferers, in which the source transmits its message to the destination with the help of N DF relays. We consider the interference-limited environments, where the reception at the relays and the destination are corrupted by random interferers, which are distributed according to a homogeneous Poisson point process. To improve the system performance, relay selection based on received signal-to-interference ratio (SIR) has been employed to select the best relay among N ones. We examine the network performance by deriving the analytical outage probability under Rayleigh fading transmission channels and Nakagami-m fading interference channels. Moreover, we compute the asymptotic expressions of outage probability, and confirm that the system diversity order on SIR is equal to $\frac{2}{\alpha}$, where α denotes the path loss factor. Furthermore, we see that the major limitation of system results from the second hop. Numerical and simulation results are demonstrated to validate the proposed analysis as well.

INDEX TERMS DF relaying networks, random interferers, Poisson point process, outage probability, diversity order.

I. INTRODUCTION

Cooperative relaying has been proved to be an efficient method to extend the network coverage, mitigate shadowing fading and increase transmission reliability without additional transmit power at the sources [1]–[12]. The major performance limitations on wireless networks are noise and interference. As [13] suggested, cooperative relaying networks might be more vulnerable to co-channel interference than noise under certain scenarios, such as high signal-to-interference-plus-noise ratio (SINR) regime. Co-channel interference might weaken the transmission reliability and degrade the system performance, hence extensive literatures have been dedicated to study the statistical models of interference and their impact [14]–[19].

Taking into account the mobility and uncertainty of terminals in wireless networks, a practical communication scenario in which the number and locations of interferers are randomly distributed has been considered. With stochastic geometry, [19] suggested that interferers in an uncertain wireless network were distributed in a plane according to a homogeneous Poisson point process (PPP). By applying stochastic geometry, [20] characterized the random interference with the first two moments, and therefore derived an approximate expression of probability density function (PDF) for the interference modeled under the PPP assumption. And more importantly, [21] provided the Laplace transform function of random interference associated with PPP under independent fading channels.

In recent years, researchers extended the above work to relaying networks in a Poisson field of interferers, and analyzed the system transmission performance by examining the outage probability. For instance, [22] considered the interference at the destination solely, while [23]–[25] analyzed a three-node relaying system with interferers distributed according to PPP at both the relay and the destination. In [26]–[28], multiple-hop relaying communications were studied with the distributions of interferers following PPP. Moreover, [29] studied multiple decode-and-forward (DF) relays networks with interference-limited relays, and it also considered direct link and noise at the destination. However, the results were untraceable and no diversity gain on the system was revealed analytically.

In this paper, we study a DF relaying network with randomly distributed interferers corrupting the reception at both the relays and the destination, where the number and positions of interferers are modeled according to independent PPP. To improve the performance of the proposed system, we aim to achieve the minimum system outage probability. To this end, relay selection based on signal-to-interference ratio (SIR) has been employed. System performance is analyzed by deriving the outage probability under Rayleigh fading transmission channels and Nakagami-m fading interference channels. In order to acquire some insights into the system, we also provide the asymptotic outage probability in the high SIR and the low interferer density regimes respectively. Numerical and simulation results are demonstrated to validate our analysis as well.

The main contributions of our work can be summarized as follows:

- We analyze a DF relaying network degraded by randomly distributed interferers at the relays and the destination, where the number and positions of interferers follow independent PPP. Close-form expressions of outage probability for the proposed system are given.
- We provide new asymptotic expressions of outage probability, which enable us to determine the crucial system parameters in the high SIR regime and evaluate their effects on the system performance.
- Attribute to the asymptotic expressions, we can observe that the system diversity order is equals to $\frac{2}{\alpha}$. Moreover, we can confirm that the system is unable to gain extra system diversity by increasing the number of relays, since the limitation of the second hop.

This paper is organized as follows. Following the introduction, Section II provides a detailed description of a two-hop cooperative relaying system model with multiple fixed DF relays and randomly distributed interferes. Then Section III presents the outage probability analysis, including the analytical outage probability and asymptotic outage probability, and a specific case will be introduced as well. In Section IV, numerical and simulation results are demonstrated to verify our analysis and provide desirable insights on the system performance. Conclusion of our work will be revealed in Section V.

Notations: $X \sim \mathcal{CN}(0, \sigma^2)$ denotes a zero-mean circularly symmetric complex Gaussian random variable (RV) X with variance σ^2. $Y \sim$ Naka$(m, 1)$ denotes a RV Y following Nakagami-m distribution. $\Pr[\cdot]$ denotes the probability.

II. SYSTEM MODEL

As depicted in Fig. 1, we consider a DF relaying network, which comprises one source S, one destination D and multiple DF relays $\{R_n | n = 1, 2 \ldots, N\}$. There are multiple interferers degrading the transmission from the source to the relays

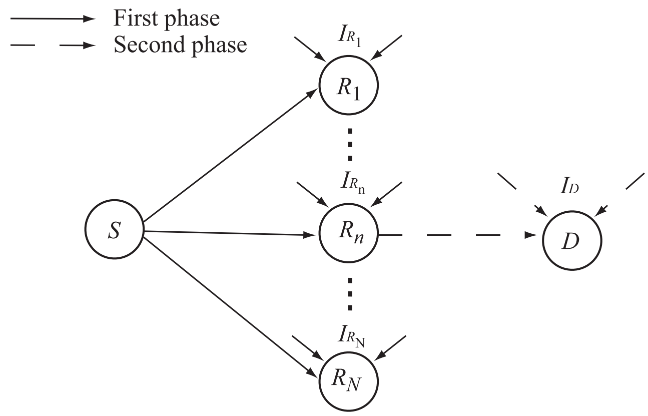

FIGURE 1. Selective DF relaying system model with random interferers.

as well as the transmission from the relays to the destination. We assume that all transmission channels experience independent flat Rayleigh fading. Moreover, we adopt the assumption that interference channels experience independent flat Nakagami-m fading, since the Nakagami-m distribution often offers the best fit to the land-mobile [30]–[32] and indoor-mobile [33] multipath propagation.

During the first time slot, S transmits the normalized signal s. In this work, we consider an interference-limited environment, where noise is negligible with respect to interference, hence we ignore the effect of noise on the proposed system. The signal received at relay R_n can be accordingly expressed by

$$y_{R_n} = \sqrt{P_S} r_{SR_n}^{-\frac{\alpha}{2}} h_{SR_n} s + I_{R_n}, \quad (1)$$

where P_S is the transmit power at the source; r_{SR_n} is the distance from S to R_n; $\alpha \geq 2$ is the exponential path loss factor; $h_{SR_n} \sim \mathcal{CN}(0, 1)$ is the channel fading coefficient for $S \to R_n$ link and I_{R_n} is the aggregated interference at the relay R_n. We assume that the interferers around each relay are randomly distributed in a two-dimensional plane according to independent homogeneous Poisson point process Φ_{R_n} with node density λ_R, and Φ_{R_n} varies from different time slot.[1] Therefore, I_{R_n} can be expressed by

$$I_{R_n} = \sum_{i \in \Phi_{R_n}} \sqrt{P_I} h_{I_i R_n} r_{I_i R_n}^{-\frac{\alpha}{2}} x_{I_i R_n} \quad (2)$$

where P_I is the transmit power at interferers; $h_{I_i R_n} \sim$ Naka$(m, 1)$ is the channel fading coefficient for $I_i \to R_n$ link; $r_{I_i R_n}$ is the distance between interferers I_i and relay R_n and $x_{I_i R_n}$ is the transmit signal from interferer I_i.

Once the received SIR at R_n is above the given threshold γ_{th}, R_n can successfully decode the information. Out of

[1] As noticed in [29] and [34], relays might be interfered by the same source of randomness, and therefore, the correlation of interference degrades the reception at relays significantly. However, according to the analysis from [35], this correlation decreases as the distance between each relay increases. Thus, by independent homogeneous Poisson point process, we assume that the distance between each relay is far enough, hence the correlation of interference is negligible.

the successfully decoding relays, the optimal relay R_{n^*} is selected to forward the information. The signal received at the destination can be accordingly expressed by

$$y_D = \sqrt{P_R} r_{R_{n^*}D}^{-\frac{\alpha}{2}} h_{R_{n^*}D} s + I_D \tag{3}$$

where P_R is the transmit power at relays; $r_{R_{n^*}D}$ is the distance from relay R_{n^*} to D; $h_{R_{n^*}D} \sim \mathcal{CN}(0, 1)$ is the channel fading coefficient for $R_{n^*} \to D$ link and I_D is the aggregated interference at D. We also assume that the interferers around the destination are randomly located according to a homogeneous Poisson point process Φ_D with node density λ_D, and Φ_D varies from different time slot. Therefore, I_D can be expressed by

$$I_D = \sum_{i\in\Phi_D} \sqrt{P_I} h_{I_iD} r_{I_iD}^{-\frac{\alpha}{2}} x_{I_iD} \tag{4}$$

where $h_{I_iD} \sim \text{Naka}(m, 1)$ is the channel fading coefficient for $I_i \to D$ link; r_{I_iD} is the distance from interferer I_i to D and x_{I_iD} is the transmit signal from interferer I_i.

For the simplicity of notation, we use $\omega_n = |h_{SR_n}|^2$ and $\upsilon_n = |h_{R_nD}|^2$ to denote the channel gains of $S \to R_n$ and $R_n \to D$ links, respectively. In addition, we use $\eta_{R_n} = \sum_{i\in\Phi_{R_n}} |h_{I_iR_n}|^2 r_{I_iR_n}^{-\alpha}$ and $\eta_D = \sum_{i\in\Phi_D} |h_{I_iD}|^2 r_{I_iD}^{-\alpha}$ to represent the summed power of interference at R_n and D, respectively. Moreover, we adopt notations that $\rho_1 = \frac{P_S}{P_I}$ and $\rho_2 = \frac{P_R}{P_I}$. Therefore, ρ_1 and ρ_2 represent the source-to-interferer transmit power ratio and the relay-to-interferer transmit power ratio, respectively. Accordingly, the SIR at relay R_n can be obtained as

$$\text{SIR}_{R_n} = \frac{\rho_1 r_{SR_n}^{-\alpha} \omega_n}{\eta_{R_n}} \tag{5}$$

and the SIR at the destination through $S \to R_n \to D$ link is given by

$$\text{SIR}_{R_nD} = \begin{cases} 0, & \text{If } \dfrac{\rho_1 r_{SR_n}^{-\alpha}\omega_n}{\eta_{R_n}} \le \gamma_{th} \\ \dfrac{\rho_2 r_{R_nD}^{-\alpha}\upsilon_n}{\eta_D}, & \text{If } \dfrac{\rho_1 r_{SR_n}^{-\alpha}\omega_n}{\eta_{R_n}} > \gamma_{th} \end{cases}. \tag{6}$$

We denote the set composed of all successfully decoding relays by C and the set including all relays by Ω. To maximizing the received SIR at the destination, the best relay R_{n^*} is selected by

$$n^* = \arg\max_{n\in C} \left(\frac{\rho_2 r_{R_nD}^{-\alpha}\upsilon_n}{\eta_D}\right). \tag{7}$$

III. PERFORMANCE ANALYSIS

The aim of this section is to measure the quality of the proposed communication system in terms of outage performance, thus we derive the analytical and asymptotic expressions of outage probability. In addition, a reduced but practical case is discussed to demonstrate our analysis.

A. EXACT OUTAGE PROBABILITY ANALYSIS

According to the system model and the relay selection criterion in eq. (7), the outage probability for the considered system can be written as

$$P_{out} = \Pr\left[\text{SIR}_{R_{n^*}D} \le \gamma_{th}\right]. \tag{8}$$

The outage probability of this system represents the averaged probability that outage of transmission occurs over different positions of interferers with Poisson distribution. By considering that each relay is influenced by interference following independent PPP Φ_{R_n}, and then applying total probability law, the outage probability can be rewritten as

$$P_{out} = \sum_{l=0}^{N} \sum_{\substack{\forall C\subset\Omega,\\ |C|=l}} \prod_{\forall n\in C} P_{suc,R_n} \times P_{out,C} \times \prod_{\forall m\in(\Omega\setminus C)} P_{out,R_m} \tag{9}$$

where

$$P_{suc,R_n} = \Pr\left[\frac{\rho_1 r_{SR_n}^{-\alpha}\omega_n}{\eta_{R_n}} > \gamma_{th}\right] \tag{10}$$

$$P_{out,R_m} = \Pr\left[\frac{\rho_1 r_{SR_m}^{-\alpha}\omega_m}{\eta_{R_m}} \le \gamma_{th}\right] \tag{11}$$

$$P_{out,C} = \Pr\left[\frac{\max\limits_{\forall n\in C}\left(\rho_2 r_{R_nD}^{-\alpha}\upsilon_n\right)}{\eta_D} \le \gamma_{th}\right] \tag{12}$$

and $|C|$ denotes the cardinal of set C, which represents the number of successfully decoding relays. Here P_{suc,R_n} denotes the success probability of $S \to R_n$ link. P_{out,R_m} and $P_{out,C}$ denote the outage probabilities of $S \to R_n$ link and second hop respectively. The exact close-form expressions for the PDFs of η_{Rn} and η_D are difficult to obtain, except for some approximate approaches, such as [20]. However, by using the result from [36] and applying the PDF of ω_n, $f_{\omega_n}(x) = e^{-x}$, P_{suc,R_n} and P_{out,R_m} can be computed as

$$\begin{aligned} P_{suc,R_n} &= \int_0^\infty \int_{\frac{\gamma_{th} y r_{SR_n}^{\alpha}}{\rho_1}}^\infty f_{\omega_n}(x)dx f_{\eta_{R_n}}(y)dy \\ &= \mathcal{L}_I\left\{\frac{\gamma_{th} y r_{SR_n}^{\alpha}}{\rho_1}\right\} \\ &= \exp\left\{-\lambda_R \pi \mathbb{E}\left[|h|^{\frac{4}{\alpha}}\right]\Gamma\left(1-\frac{2}{\alpha}\right) r_{SR_n}^2 \left(\frac{\gamma_{th}}{\rho_1}\right)^{\frac{2}{\alpha}}\right\} \end{aligned} \tag{13}$$

$$\begin{aligned} P_{out,R_m} &= \int_0^\infty \int_0^{\frac{\gamma_{th} y r_{SR_m}^{\alpha}}{\rho_1}} f_{\omega_m}(x)dx f_{\eta_{R_m}}(y)dy \\ &= 1 - \mathcal{L}_I\left\{\frac{\gamma_{th} y r_{SR_m}^{\alpha}}{\rho_1}\right\} \\ &= 1 - \exp\left\{-\lambda_R \pi \mathbb{E}\left[|h|^{\frac{4}{\alpha}}\right]\Gamma\left(1-\frac{2}{\alpha}\right) r_{SR_m}^2 \left(\frac{\gamma_{th}}{\rho_1}\right)^{\frac{2}{\alpha}}\right\} \end{aligned} \tag{14}$$

where $\mathcal{L}_I(s)$ is the Laplace transform of the interference in an infinite network; $\mathbb{E}\left[|h|^{\frac{4}{\alpha}}\right]$ can be calculated as

$$\mathbb{E}\left[|h|^{\frac{4}{\alpha}}\right] = \int_0^{\infty} x^{\frac{2}{\alpha}} f_{|h|^2}(x)dx = \frac{\Gamma\left(m+\frac{2}{\alpha}\right) m^{-\frac{2}{\alpha}}}{\Gamma(m)} \quad (15)$$

and $f_{|h|^2}(x) = \frac{m^m}{\Gamma(m)} x^{m-1} \exp(-mx)$ is the PDF of interference channel gain $|h_{I_iR_n}|^2$ and $|h_{I_iD}|^2$.

Similarly, by using the PDF of υ_n, $f_{\upsilon_n}(x) = e^{-x}$, we can calculate $P_{out,C}$ as

$$\begin{aligned} P_{out,C} &= \int_0^{\infty}\left[\prod_{\forall n\in C}\int_0^{\frac{\gamma_{th} y r_{R_nD}^{\alpha}}{\rho_2}} f_{\upsilon_n}(x)dx\right] f_{\eta_D}(y)dy. \\ &= \int_0^{\infty}\prod_{\forall n\in C}\left[1-e^{-\frac{\gamma_{th} y r_{R_nD}^{\alpha}}{\rho_2}}\right] f_{\eta_D}(y)dy \\ &= \sum_{k=0}^{|C|}(-1)^k \sum_{\substack{\forall B\subset C,\\ |B|=k}} \exp\left\{-\lambda_D\pi\mathbb{E}\left[|h|^{\frac{4}{\alpha}}\right]\Gamma\left(1-\frac{2}{\alpha}\right)\right. \\ &\quad \left.\times\left(\frac{\gamma_{th}}{\rho_2}\sum_{\forall n\in B} r_{R_nD}^{\alpha}\right)^{\frac{2}{\alpha}}\right\} \end{aligned} \quad (16)$$

where B is a subset of C, and $|B|$ denotes the cardinal of set B.

To conveniently analyze the proposed system and demonstrate the analytical results in a straightforward form, we consider a scenario in which all source-to-relay distances are identical with $r_{SR_n} = r_{SR}$, and all relay-to-destination distances are identical with $r_{R_nD} = r_{RD}$, since relays are placed symmetrically. Moreover, we set m to 1, which is associated to Rayleigh fading interference channels. Accordingly, the outage probability for identical r_{SR} and r_{RD} with Rayleigh fading interference channels is expressed as

$$\begin{aligned} P_{out}^{identical} &= \sum_{l=0}^{N}\binom{N}{l}\underbrace{\prod_{n=1}^{l}\Pr\left[\frac{P_S r_{SR}^{-\alpha}\omega_n}{P_I\eta_{R_n}} > \gamma_{th}\right]}_{J_1} \\ &\quad\times\underbrace{\prod_{m=1}^{N-l}\Pr\left[\frac{P_S r_{SR}^{-\alpha}\omega_m}{P_I\eta_{R_m}} \le \gamma_{th}\right]}_{J_2} \\ &\quad\times\underbrace{\prod_{n=1}^{l}\Pr\left[\frac{P_R r_{RD}^{-\alpha}\upsilon_n}{P_I\eta_D} \le \gamma_{th}\right]}_{J_3}. \end{aligned} \quad (17)$$

By applying the results of eqs. (13), (14) and (16), we can calculate J_1, J_2 and J_3 as follows

$$J_1 = \exp\left[-\frac{l\lambda_R 2\pi^2 r_{SR}^2\left(\frac{\gamma_{th}}{\rho_1}\right)^{\frac{2}{\alpha}}}{\alpha\sin\frac{2\pi}{\alpha}}\right] \quad (18)$$

$$J_2 = \left\{1-\exp\left[-\frac{\lambda_R 2\pi^2 r_{SR}^2\left(\frac{\gamma_{th}}{\rho_1}\right)^{\frac{2}{\alpha}}}{\alpha\sin\frac{2\pi}{\alpha}}\right]\right\}^{N-l} \quad (19)$$

$$J_3 = \sum_{n=0}^{l}\binom{l}{n}(-1)^n\exp\left[\frac{-\lambda_D 2\pi^2 r_{RD}^2\left(\frac{n\gamma_{th}}{\rho_2}\right)^{\frac{2}{\alpha}}}{\alpha\sin\frac{2\pi}{\alpha}}\right]. \quad (20)$$

B. ASYMPTOTIC OUTAGE PROBABILITY ANALYSIS

To acquire some meaningful insights with the crucial network parameters, we aim to investigate the asymptotic behavior of the outage probability for the proposed system in the high SIR and the low interferer density regimes. By using the Taylor expansion method of $e^x \simeq 1+x$ for small value of $|x|$ and omitting the higher order terms, P_{out} can be approximated by

- If $\rho_1 \to \infty$ or $\lambda_R \to 0$,

$$P_{out} \simeq \sum_{k=0}^{N}(-1)^k\sum_{\substack{\forall B\subset\Omega,\\ |B|=k}}\exp\left[-\frac{\lambda_D\pi\Gamma(1-\frac{2}{\alpha})\Gamma(m+\frac{2}{\alpha})m^{-\frac{2}{\alpha}}}{\Gamma(m)}\times\left(\frac{\gamma_{th}}{\rho_2}\sum_{\forall n\in B} r_{R_nD}^{\alpha}\right)^{\frac{2}{\alpha}}\right]. \quad (21)$$

- If $\rho_2 \to \infty$ or $\lambda_D \to 0$,

$$P_{out} \simeq \prod_{n=1}^{N}\left\{1-\exp\left[-\frac{\lambda_R\pi\Gamma(1-\frac{2}{\alpha})\Gamma(m+\frac{2}{\alpha})r_{SR_n}^2 m^{-\frac{2}{\alpha}}}{\Gamma(m)}\times\left(\frac{\gamma_{th}}{\rho_1}\right)^{\frac{2}{\alpha}}\right]\right\}. \quad (22)$$

- If $\rho_1 = \kappa\rho_2$, $\rho_2 \to \infty$ or $\lambda_R = \theta\lambda_D$, $\lambda_D \to 0$

$$P_{out} \simeq \begin{cases} \dfrac{\pi\Gamma\left(1-\frac{2}{\alpha}\right)\Gamma\left(m+\frac{2}{\alpha}\right)m^{-\frac{2}{\alpha}}}{\Gamma(m)} \times\left[\lambda_R r_{SR}^2\left(\frac{\gamma_{th}}{\rho_1}\right)^{\frac{2}{\alpha}}+\lambda_D r_{RD}^2\left(\frac{\gamma_{th}}{\rho_2}\right)^{\frac{2}{\alpha}}\right] & \text{If } N=1 \\ \sum_{n=0}^{N}(-1)^{n+1}\sum_{\substack{\forall B\subset\Omega,\\ |B|=k}}\left(\sum_{\forall n\in B} r_{R_nD}^{\alpha}\right)^{\frac{2}{\alpha}} \times\dfrac{\lambda_D\pi\Gamma\left(1-\frac{2}{\alpha}\right)\Gamma\left(m+\frac{2}{\alpha}\right)m^{-\frac{2}{\alpha}}}{\Gamma(m)}\left(\frac{\gamma_{th}}{\rho_2}\right)^{\frac{2}{\alpha}} & \text{If } N\ge 2 \end{cases}. \quad (23)$$

For the identical r_{SR} and r_{RD} with Rayleigh fading interference channels scenario, we can further simplify the asymptotic expressions for $P_{out}^{identical}$ as eq. (24), as shown at the bottom of the next page.

From the above approximate expressions of outage probability, the following meaningful insights can be achieved accordingly:

Remark 1: As ρ_1 and ρ_2 tend to infinity with $\rho_1 = \kappa\rho_2$, we use ρ_1 as the SIR parameter, and define the system diversity order Δ as

$$\Delta = \lim_{\rho_1 \to \infty} \frac{-\log(P_{out})}{\log(\rho_1)} \tag{25}$$

which is equal to $\frac{2}{\alpha}$. This indicates that the system performance mainly depends on channel condition. Specifically, the diversity gains of system decrease as the path loss factor increases.

Remark 2: According to eqs. (21), (22) and (24), we see that the improvement of either hop may confront the bottleneck results from the other hop. Moreover, the degradation of multiple relay networks mainly results from the interference at the destination, since the performance of the first hop can be significantly improved with the increasing number of relays by obtaining more diversity gains, yet the second hop fails. This is due to the fact that as interferers emerge nearby the destination, it is highly possible that outage of transmission occurs. However, the system can select other optional relays as outage is inevitable at one relay.

Remark 3: As the SIR at the first and second hops tend to infinity or the overall interferer density tends to 0, when $N = 1$, the outage probability is effected by both the first and second hops. However, when the number of relays $N \geq 2$, the second hop becomes the crucial link of the system, which indicates that the second hop is the dominant link of the whole system. This is due to the fact that the interference at the destination has made the second hop a weaker link regarding the whole system, as the first hop is able to gain full diversity while the second hop fails.

IV. NUMERICAL AND SIMULATION RESULTS

In this section, by several numerical and simulation results, we verify the aforementioned analysis results, and evaluate the effects of several important networks parameters on the system performance. We adopt the scenario in which the distance from source to destination is 400 meters and all transmission channels experience flat Rayleigh fading. Unless specified otherwise, the distances from source to relays and the distances from relays to destination are both identical with $r_{SR} = r_{RD} = 200$ meters, and m is set to 1 for interference channels. Besides, λ_R and λ_D are set to 10^{-5}. The simulation performed 10^6 iterations with different interferer position configurations and transmission channel realizations. For each interferer position configuration, the interference nodes are placed according to Poisson point process within a square plane with side length of 10^6 meters, where the relay or destination is placed in the central. Normalized as benchmark, the transmit power at interferers is set to 1. The transmission rate is configured to 1 bit per second per hertz (bps/HZ) and the corresponding SIR threshold γ_{th} is equal to 3.

Fig. 2(a) and 2(b) show how the outage probabilities vary with SIR for $\rho_1 = \rho_2$. Fig. 2(a) corresponds to the scenario in which relays are evenly placed on a straight line between the source and destination, and thus the sum of r_{SR_n} and r_{R_nD} is a constant and set to 400 meters. In addition, we set m to 2. Fig. 2(b) refers to the scenario with $r_{SR_n} = r_{SR}$, $r_{R_nD} = r_{RD}$ and m=1. It can be observed that analytical results approximately match the related simulation results for different N and α, due to the fact that we consider an infinite network in previous analysis. Moreover, the asymptotic results are consistent to the related simulation results in high SIR regime, which confirms our analysis. Furthermore, we see that the increase of the number of relays is able to improve the system performance yet slightly, and the diversity gains are inversely

$$P_{out}^{identical} \simeq \begin{cases} \sum_{n=0}^{N} \binom{N}{n} (-1)^n \exp\left[\dfrac{-\lambda_D 2\pi^2 r_{RD}^2 (\frac{n\gamma_{th}}{\rho_2})^{\frac{2}{\alpha}}}{\alpha \sin\frac{2\pi}{\alpha}}\right], & \text{If } \rho_1 \to \infty, \text{ or } \lambda_R \to 0 \\ \left\{1 - \exp\left[-\dfrac{\lambda_R 2\pi^2 r_{SR}^2 (\frac{\gamma_{th}}{\rho_1})^{\frac{2}{\alpha}}}{\alpha \sin\frac{2\pi}{\alpha}}\right]\right\}^N, & \text{If } \rho_2 \to \infty, \text{ or } \lambda_D \to 0 \\ \dfrac{2\pi^2 \left[\lambda_R r_{SR}^2 (\frac{\gamma_{th}}{\rho_1})^{\frac{2}{\alpha}} + \lambda_D r_{RD}^2 (\frac{\gamma_{th}}{\rho_2})^{\frac{2}{\alpha}}\right]}{\alpha \sin\frac{2\pi}{\alpha}}, & \text{If } \rho_1 = \kappa\rho_2, \rho_2 \to \infty \\ (\text{or } \lambda_R = \theta\lambda_D, \lambda_D \to 0), & N = 1 \\ \dfrac{\lambda_D 2\pi^2 r_{RD}^2 (\frac{\gamma_{th}}{\rho_2})^{\frac{2}{\alpha}}}{\alpha \sin\frac{2\pi}{\alpha}} \sum_{n=1}^{N} \binom{N}{n} (-1)^{n+1} n^{\frac{2}{\alpha}}, & \text{If } \rho_1 = \kappa\rho_2, \rho_2 \to \infty \\ (\text{or } \lambda_R = \theta\lambda_D, \lambda_D \to 0), & N \geq 2 \end{cases} \tag{24}$$

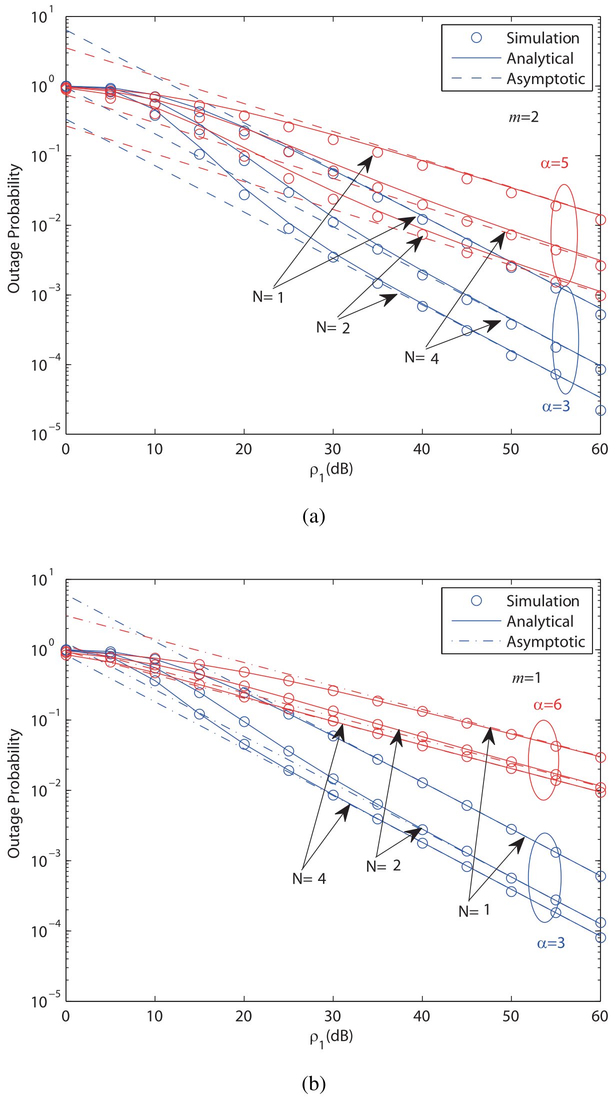

FIGURE 2. Outage probabilities versus SIR $\rho_1 = \rho_2$ for $\lambda_R = \lambda_D = 10^{-5}$. (a) Relays with different distances. (b) Relays with identical distances.

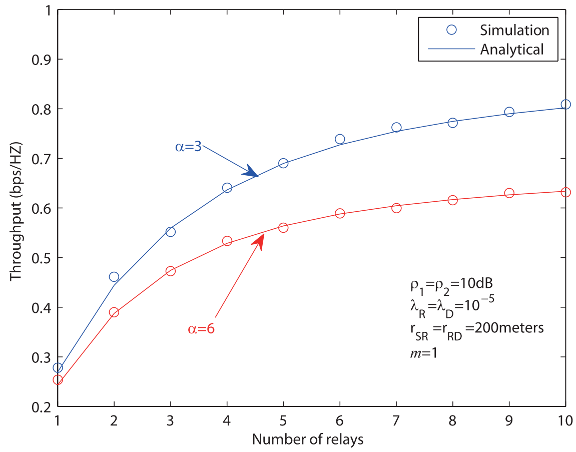

FIGURE 3. Throughput versus relay number, for $\rho_1 = \rho_2 = 10$ dB, $\lambda_R = \lambda_D = 10^{-5}$, m=1 and $r_{SR} = r_{RD} = 200$ meters.

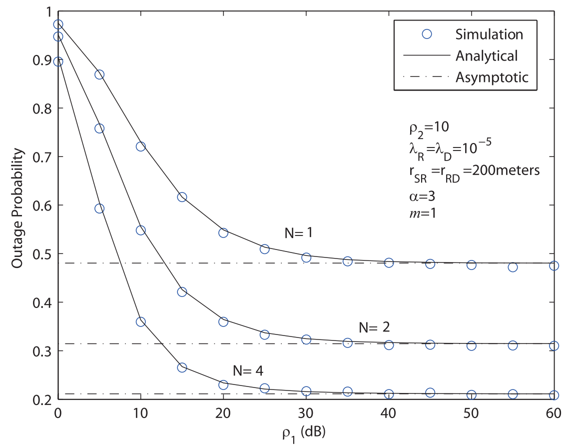

FIGURE 4. Outage probabilities versus source-to-interferer transmit power ratio ρ_1, for $\rho_2 = 10$, $\alpha = 3$, $\lambda_R = \lambda_D = 10^{-5}$, m=1 and $r_{SR} = r_{RD} = 200$ m.

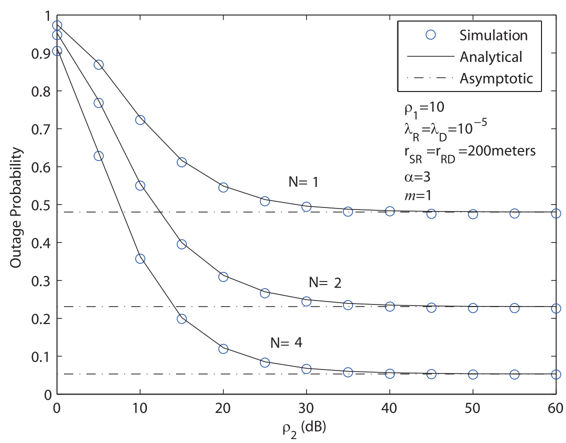

FIGURE 5. Outage probabilities versus relay-to-interferer transmit power ratio ρ_2, for $\rho_1 = 10$, $\alpha = 3$, $\lambda_R = \lambda_D = 10^{-5}$, m=1 and $r_{SR} = r_{RD} = 200$ m.

proportional to the path loss factor α, resulting from the interference at the destination.

Fig. 3 plots the variation of throughput with relay number for $\rho_1 = \rho_2 = 10$ dB, $\lambda_R = \lambda_D = 10^{-5}$, m=1 and $r_{SR} = r_{RD} = 200$ meters. For the unit target data rate, the system throughput is equal to $(1 - P_{out})$. We see that the network throughput increases as the relay number grows. In addition, for smaller value of α, the enhancement is more obvious, since more diversity gain can be obtained, which is consistent to our analysis.

To evaluate each hop individually, Fig. 4 and Fig. 5 plot the variation of outage probabilities with source-to-interferer transmit power ratio ρ_1 and relay-to-interferer transmit power ratio ρ_2 respectively for $\alpha = 3$. As expected, for either $\rho_1 \to \infty$ or $\rho_2 \to \infty$, their exact outage probabilities converge to corresponding asymptotic outage probabilities for different values of N. Moreover, Fig. 6 and Fig. 7 show the outage probabilities versus interferer densities λ_R and λ_D respectively for $\alpha = 3$. We note that for either $\lambda_R \to 0$

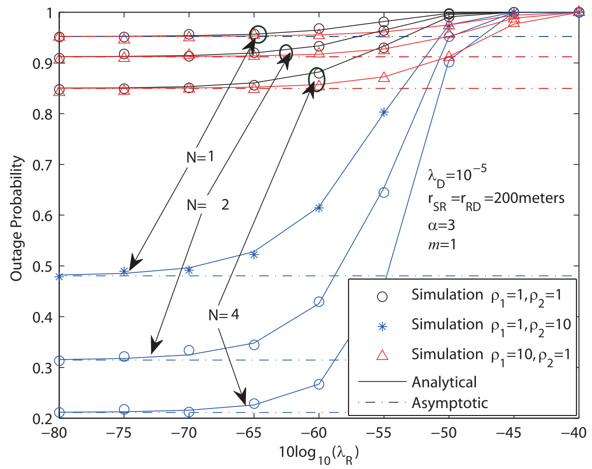

FIGURE 6. Outage probabilities versus interferer density at relays λ_R, for $\lambda_D = 10^{-5}$, $\alpha = 3$, m=1 and $r_{SR} = r_{RD} = 200$ m.

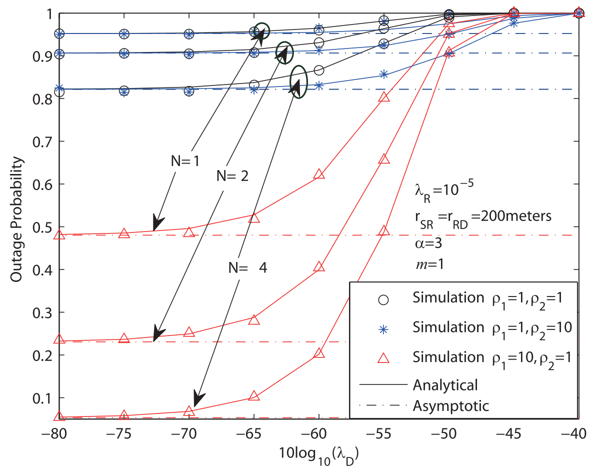

FIGURE 7. Outage probabilities versus interferer density at the destination λ_D, for $\lambda_R = 10^{-5}$, $\alpha = 3$, m=1 and $r_{SR} = r_{RD} = 200$ m.

or $\lambda_D \rightarrow 0$, their exact outage probabilities converge to related asymptotic outage probabilities. From Fig. 4 to Fig. 7, we see that the enhancement of either hop, such as increasing ρ_1 or loweringf down λ_R, may confront the bottleneck results from the other hop. In addition, for $\rho_2 \rightarrow \infty$ or $\lambda_D \rightarrow 0$, augmenting the number of relays can significantly improve the system performance, yet the improvement for the scenario when $\rho_1 \rightarrow \infty$ or $\lambda_R \rightarrow 0$ is much less obvious. This is due to the fact that the interference at the destination degrades the transmission of the second hop, hence it reduces the influence of the number of relays, especially on relay-to-destination links.

Fig. 8 plots the variation of outage probabilities with interferer density $\lambda_R = \lambda_D$ for $\alpha = 3$. As both approximate outage probabilities and numerical results suggested, increasing ρ_1 is unable to fundamentally improve the system performance, which is evident in low interferer density regime. However, the enhancement of ρ_2 can noticeably decrease the outage probability. This indicates that the second hop is

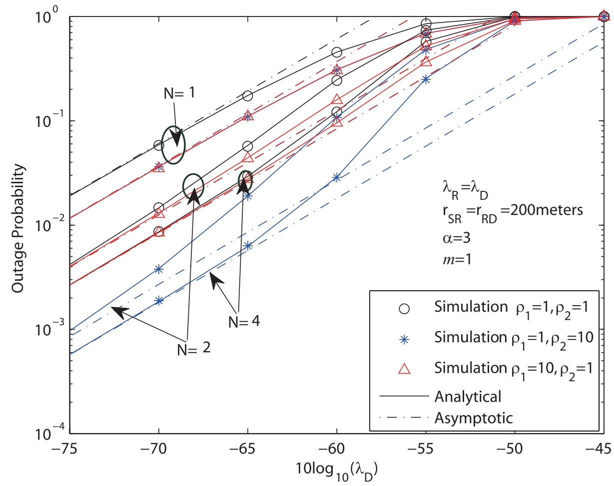

FIGURE 8. Outage probabilities versus interferer density $\lambda_R = \lambda_D$, for $\alpha = 3$, m=1 and $r_{SR} = r_{RD} = 200$ m.

the dominant link of the whole system, which validates our analysis.

V. CONCLUSION

In this work, the performance of a DF relaying network in a Poisson field of interferers has been evaluated. Both analytical and approximate expressions of outage probability for the proposed communications system have been derived under Rayleigh fading transmission channels and Nakagami-m fading interference channels. With the given asymptotic expressions, we can confirm that the system is unable to gain extra system diversity by increasing the number of relays, due to the interference at the destination. Moreover, the improvement of either hop may confront the bottleneck results from the other hop. In addition, in the high SIR or the low interferer density regime, the second hop becomes the dominant hop for the whole system. Numerical and simulation results illustrate the proposed analysis and bring some meaningful insights as well.

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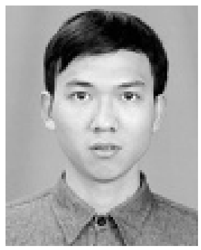

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