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Outage probability of dual-hop cooperative communication networks over the Nakagami-*m* fading channel with RF energy harvesting

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Abstract

Cooperative communication systems with wireless power transfer are being investigated for future advanced wireless networks. In this research, we propose applying a wireless power transfer to dual-hop cooperative communication systems, in which a relay node harvests the energy from the radiofrequency in order to forward the received signal, and a source node can communicate with a destination node directly or through the selected relay nodes. The system performance is evaluated by an outage probability that is calculated over independent and identically distributed (i.i.d) Nakagami-m distributions in two scenarios, i.e., integer m and arbitrary m. Furthermore, the closed forms of the outage probability expressions are derived in the case of both the amplify-and-forward (AF) and decode-and-forward (DF) protocols. The Monte Carlo method is utilized to simulate the system with the aims of evaluating the system performance and verifying the theoretical analysis. The numerical results highlight that the proposed calculation method and the closed form of the outage probability are accurate. We also compare the system performance of both the AF and DF protocols and show the effect of parameter m on the performance of the system.

Keywords Dual-hop cooperative communication · Energy harvesting · Arbitrary m parameter · Closed-form of outage probability

1 Introduction

Cooperative communication has been recognized as an efficient way to extend the coverage of wireless networks. Two relaying protocols commonly used for cooperative networks are the amplify-and-forward (AF) and decode-and-forward (DF) [1, 2]. In the AF protocol, a relay node amplifies the signals received from the source and then forwards the amplified signals to the destination, whereas in the DF protocol, the signal is detected, decoded, re-encoded, and remodulated before being forwarded to the destination. In case there are multiple available relay nodes, a relay selection protocol, i.e., partial relay selection or full relay selection [3, 4], is applied to select the best relay node based on the channel state information (CSI).

On the other hand, radiofrequency (RF) energy transfer and harvest techniques have become alternative methods for supplying power to devices in next-generation wireless networks [5]. These techniques appear to be a promising solution for energy-constrained wireless networks such as wireless sensor networks and biomedical wireless body area networks. The devices in energy-constrained wireless networks have a limited lifetime, which greatly confines the network performance. In response to the growth in wireless communications and networking technologies, the authors in [14] proposed an efficient algorithm for advanced scalable media-based smart big data on intelligent cloud computing systems. In addition, the authors in [15] proposed a new method to collect and manage data from sensors in a smart building that operates in the Internet of Things (IoT) environment.

According to state-of-the-art research, a relay node can be supplied by energy harvesting (EH) around radio terminals. We believe that many other applications of the

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EH technique are still waiting to be disclosed. In recent years, the EH technique has attracted increasing interest from researchers. In particular, the combination of relaying protocols with energy harvesting has been proposed for several systems, which is expressed as follows.

The downlink hybrid information and energy transfer with a massive MIMO system is considered in [6]; in this letter, the authors consider simultaneously sending the information and energy to the information users and energy users, respectively. The problem is solved by obtaining the asymptotically optimal power allocation from the information users. Vahidnia et al. considered a system equipped with multiple-antenna transceivers and exchanged information through a relay-assisted network by using a single-carrier communication scheme [7]. The relay nodes harvest energy from the surrounding environment and utilize this energy to forward their received messages to the destinations. This process uses a harvest-then-forward scheme.

On the other hand, Do et al. derived an accurate outage probability expression in the closed form of a dual-hop DF relaying network with a time switching-based relaying mechanism. In this work, the authors assumed that a direct link is not available [8]. The DF protocol in the cooperative communication network with energy harvesting relays is also investigated in [9]. In this article, the authors proposed a method to select the best relay to forward a signal to destinations. The proposed method was investigated in two operation schemes: power splitting (PS) and time switching (TS) at the relays.

Chen [10] studied EH AF relaying networks in the case where a channel suffers from interference and Nakagami-m fading. The results showed that the TS is more sensitive to EH than the PS under the same channel settings. Dong et al. considered the nonlinear effects of RF EH circuits on the performance of wireless powered relays with AF protocols. They assumed that the channels have a Nakagami-m distribution [11]. Moreover, the partial relaying system and wireless power transfer have been studied over Rayleigh fading channels in [12], and the relation between the EH duration and communication duration has been discussed in nonorthogonal multiple access (NOMA) relay systems by the authors in [13]. NOMA has become significantly popular in both academia and industry due to its high spectral efficiency and the support of multiple connections in wireless cellular networks. Our members also optimized the duration of EH for downlink NOMA full-duplex relay systems [16].

As mentioned above, the previous studies focused on cooperative communication and wireless power transfer networks; however, to the best of our knowledge, these studies do not combine cooperative communication and RF EH in terms of the existing direct link with relay selection schemes over Nakagami-m fading channels. In particular, the analysis based on the arbitrary m parameter is not taken into consideration. Therefore, in this work, we focus on the time switching relaying protocol and propose a relay selection scheme for energy-constrained dual-hop cooperative wireless networks. The performance of the system is evaluated by calculating the outage probability over the system model, which is close to the actual outage probability when the m parameter is set as arbitrary. Moreover, the outage probability is calculated mathematically, and its closed form is derived so that it can be easily applied to many different systems. Our proposed analysis method makes RF EH technology clearer, more attractive, and applicable to future advanced wireless networks.

The contributions of this paper are summarized as follows:

- We propose RF EH to supply power to the relay nodes in dual-hop cooperative communication networks. Partial relay selection is employed at the source node to improve the system performance. The outage probability of the system is calculated mathematically to evaluate the system performance.
- We propose a a method to derive the outage probability in the case where the m parameter of the Nakagami-m distribution is not only an integer but also arbitrary.
- The outage probability is mathematically derived in both the AF and the DF protocols, and then its closed form is proposed.
- The proposed mathematical analysis is validated through simulations.
- Sensitive parameters, such as the number of relays and the value of the m parameter, are discussed based on the performance of the system.

The rest of this paper is organized as follows: Section 2 presents the system model and then characterizes the end-to-end signal-to-noise ratio (SNR). The outage probability expression for the AF and DF protocols is theoretically analyzed in Section 3. Section 4 provides the theoretical analysis and simulation results. Finally, the conclusion is given in Section 5.

Notation In this paper, notations are used as follows: $\frac{n!}{k!(n-k)!} = \binom{n}{k}$ represents the binomial coefficient and $(\cdot)!$ represents the factorial of $(\cdot)$. $\Gamma(\alpha) = \int_0^\infty t^{\alpha-1}e^{-t}dt$, $\Gamma(\alpha, x) = \int_x^\infty t^{\alpha-1}e^{-t}dt$ and $\gamma(\alpha, x) = \int_0^x t^{\alpha-1}e^{-t}dt$ respectively denote the gamma function [17, eq, (8.310.1)], the upper incomplete gamma function [17, eq, (8.350.2)] and the lower incomplete gamma function [17, (8.350.1)]. $E_n(x) = \int_1^\infty \frac{e^{-xt}}{t^n}dt$ represents the exponential integral function. The cumulative distributed function (CDF) and probability density function (PDF) of random variable $\mathcal{X}$ are expressed as $F_{\mathcal{X}}(\cdot)$ and $f_{\mathcal{X}}(\cdot)$, respectively. The $\mathcal{K}_n(\cdot)$ is the second kind of Bessel function with order n.

2 System model

In our research, we investigate a wireless cooperative relay selection system under the condition that EH is implemented at the relay nodes. The system includes one source: S, a set of relays, R_n with $n \in 1, \cdots, N$; and one destination D, as shown in Fig. 1. Each node is equipped with only one antenna and operates in a half-duplex mode. In addition, all relays are grouped into one cluster where each relay node is equipped with an EH receiver and an information decoding (ID) receiver. Furthermore, because both AF and DF protocols are taken into consideration, the relay is controlled on the higher layer [18]. The source communicates with the destination through a direct link and forward link via the best relay, R_b, which is selected by the source based on the channel gains of $S - R_b$ (the first hop). The channel model of all wireless links is assumed to follow the independent and identically distributed (i.i.d) Nakagami-m distribution. While both the source and the destination are commonly powered, the relay nodes are powered by harvesting from the radiofrequency. It is assumed that the channel state information is known at both the transmitter and the receiver sites.

The relay nodes operate in a time switching (TS)[1] scheme [19] to harvest the energy that is transmitted by the source. T denotes the block time, and αT, $0 \leq \alpha \leq 1$, is the fraction of the block time in which the relay node harvests energy from the source. The remaining block time, $(1-\alpha)T$, is used in the communication process, where the first half of the remaining block time, $(1-\alpha)T/2$, receives the signal from the source and the last half, $(1-\alpha)T/2$, forwards the received signal to the destination (Fig. 2).

Let us denote $|h_{\mathrm{SD}}|^2$, $|h_{\mathrm{SR}}|^2$, and $|h_{\mathrm{R}}\mathrm{D}|^2$ as the amplitudes of the channels between $S - D$, $S - R$, and $R - D$, respectively.

In the Nakagami-m distribution, parameter m signifies the fading severity, and a small value of m represents more fading in the channel. The Nakagami-m fading channels between $S - R$, $R - D$, and $S - D$ are also described by variable parameters (m_0, λ_0), (m_1, λ_1), and (m_2, λ_2), respectively. Here, the notation $\lambda_i = \mathrm{E}\{\mathcal{X}\}$ is the mean of variable $\mathcal{X}$ with $i \in \{0, 1, 2\}$ and $\mathcal{X} \subset \{S, R, D\}$. Hence, the probability density function (PDF) and the cumulative distribution function (CDF) of $\mathcal{X}$ are the gamma distributions with parameters $m_i > 0$ and $\lambda_i > 0$ [4, 20].

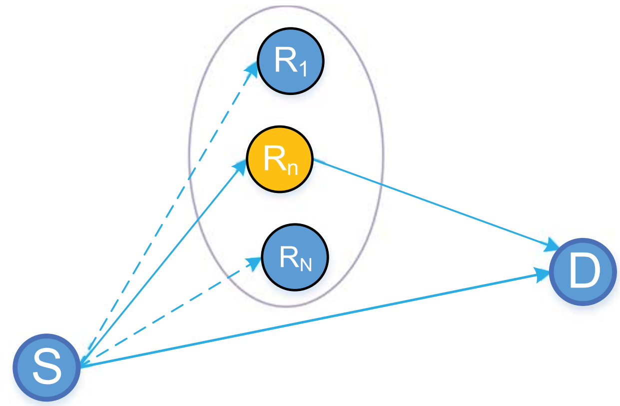

Fig. 1 Wirelessly powered cooperative relay selection networks

$$f_{\mathcal{X}}(x) = \left(\frac{m_i}{\lambda_i}\right)^{m_i} \frac{x^{m_i-1}}{\Gamma(m_i)} \exp\left(-\frac{m_i x}{\lambda_i}\right), \tag{1}$$

$$F_{\mathcal{X}}(x) = \frac{1}{\Gamma(m_i)} \gamma\left(m_i, \frac{m_i x}{\lambda_i}\right). \tag{2}$$

During the broadcasting phase, the received signal at the relay node, $y_{\mathrm{R}}(t)$, and the destination node, $y_{\mathrm{D}}(t)$, can be expressed as:

$$y_{\mathrm{R}}(t) = \sqrt{P_{\mathrm{S}}} h_{\mathrm{SR}} x(t) + n_{\mathrm{R}}(t), \tag{3}$$

$$y_{\mathrm{D}}(t) = \sqrt{P_{\mathrm{S}}} h_{\mathrm{SD}} x(t) + n_{\mathrm{D}}(t), \tag{4}$$

where P_{S} denotes the transmission power from the source, t is the symbol index, $x(t)$ is the sampled and normalized information signal from the source, and $n(t)$ is the additive white Gaussian noise (AWGN) with power spectral density N_0.

From Eq. 3, the harvested energy at the relay node, E_h, during time αT is given by [21].

$$E_h = \frac{\eta P_{\mathrm{S}} |h_{\mathrm{SR}}|^2 \alpha T}{N_0}, \tag{5}$$

where $0 \leq \eta \leq 1$ is the energy conversion efficiency, which depends on the rectification process and the EH circuitry. In this work, the power consumption of the circuit at the relay nodes is assumed to be negligible, and the harvested energy during the EH phase is stored in a supercapacitor and then entirely consumed to forward the source signal to the destination. This is called the harvest-use protocol [22, 23].

In the last half of the communication phase, the best relay, R_n, re-codes (for the DF protocol) or amplifies (for the AF protocol) the signal of the source and then transmits it to the destination for $\frac{1-\alpha}{2}T$ seconds. Hence, the received

[1] The power splitting architecture can be applied directly

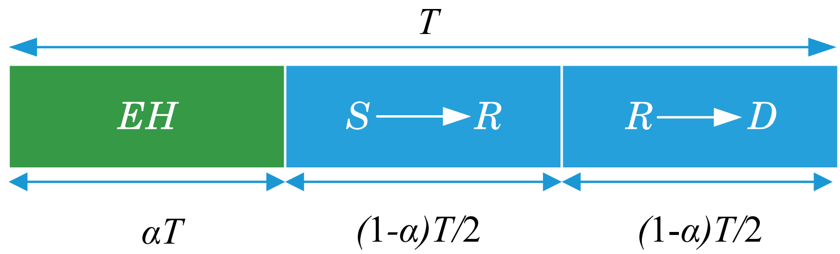

Fig. 2 The time switching protocol of the dual-hop relay system with the EH scheme

signal at the destination of the DF protocol is given as:

$$y_{\mathrm{D}}(t) = \sqrt{P_{\mathrm{R}}} h_{\mathrm{R}_n\mathrm{D}} y_{\mathrm{R}}(t) + n_{\mathrm{D}}(t). \tag{6}$$

In the AF protocol, the signal received at the destination after being amplified and forwarded by the relay node is given by:

$$y_{\mathrm{D}}(t) = G h_{\mathrm{R}_n\mathrm{D}} y_{\mathrm{R}}(t) + n_{\mathrm{D}}(t). \tag{7}$$

To maintain the quality of the forwarded signal, P_{R} is transformed to allow the relaying gain, $G = \sqrt{P_{\mathrm{R}}/P_{\mathrm{S}}|h_{\mathrm{SR}_n}|^2 + \sigma_{\mathrm{R}}^2}$, be constant.

Based on the expressions in Eqs. 3, 4 and 7, we can define the instantaneous signal-to-noise ratio (SNR) for each link. γ_{AB} denotes the instantaneous SNR from node A to node B, with $A \in \{\mathrm{S}, \mathrm{R}_n\}$ and $B \in \{\mathrm{R}_n, \mathrm{D}\}$.

$$\gamma_{\mathrm{SR}_n} = \frac{P_{\mathrm{S}}|h_{\mathrm{SR}_n}|^2}{N_0} = \frac{P_{\mathrm{S}} \max\limits_{i=1,\ldots,N} |h_{1,i}|^2}{N_0}, \tag{8}$$

$$\gamma_{\mathrm{R}_n\mathrm{D}} = \frac{P_{\mathrm{R}}}{N_0}\left|h_{\mathrm{R}_n\mathrm{D}}\right|^2 = \frac{\phi P_{\mathrm{S}} \max\limits_{i=1,\ldots,N} |h_{1,i}|^2 |h_{\mathrm{R}_n\mathrm{D}}|^2}{N_0}, \tag{9}$$

$$\gamma_{\mathrm{SD}} = \frac{P_{\mathrm{S}}|h_{\mathrm{SD}}|^2}{N_0}. \tag{10}$$

In the case of the DF protocol, the end-to-end SNR, γ_{e2e}, is given as follows:

$$\gamma_{\mathrm{e2e}} = \min\left(\gamma_{\mathrm{SR}_n}, \gamma_{\mathrm{R}_n\mathrm{D}}\right). \tag{11}$$

In the case of the AF protocol, the relay amplifies the received signals and forwards them to the destination node. Thus, the end-to-end SNR, γ_{e2e}, is represented by:

$$\gamma_{\mathrm{e2e}} = \frac{\gamma_{\mathrm{SR}_n}\gamma_{\mathrm{R}_n\mathrm{D}}}{\gamma_{\mathrm{SR}_n} + \gamma_{\mathrm{R}_n\mathrm{D}} + 1}. \tag{12}$$

When the bandwidth is normalized, the maximum average mutual information between the source and the destination, i.e., the channel capacity, in each connecting case is given by:

$$C_{\mathrm{SD}} = \log_2(1 + \gamma_{\mathrm{SD}}). \tag{13}$$

$$C_{\mathrm{R}} = \frac{1-\alpha}{2}\log_2(1 + \gamma_{\mathrm{e2e}}). \tag{14}$$

Prefactor $\frac{1-\alpha}{2}$ is accounted for by the communication between the source and the destination via the relay nodes.

3 Outage analysis

Because the outage probability can be considered an essential parameter in analyzing the performance and is commonly used to characterize wireless communication systems, in this section, we derive a closed-form expression for the outage probability. The outage probability is defined as the probability that the channel capacity is less than the determined transmission rate, $C < \mathcal{R}$.

$$\begin{aligned} \mathrm{OP} &= \Pr\left\{\max\left[\log_2(1+\gamma_{\mathrm{SD}}), \frac{1-\alpha}{2}\log_2(1+\gamma_{\mathrm{e2e}})\right] < \mathcal{R}\right\} \\ &= \Pr\left[\log_2(1+\gamma_{\mathrm{SD}}) < \mathcal{R}, \quad \frac{1-\alpha}{2}\log_2(1+\gamma_{\mathrm{e2e}}) < \mathcal{R}\right]. \end{aligned} \tag{15}$$

To solve the above equation, we need to calculate the CDF and PDF of the random variables; thus, we start with the following remark.

Remark 1 (Order statistic) In this model, N relay nodes are used to forward the received signal from the source to the destination. Let $X_1, X_2, \cdots, X_N$ be a sequence of independent random variables, which corresponds to the order statistic.

The link with the largest instantaneous SNR is selected as the best relay and described with the following criterion:

$$X = \max\{X_1, X_2, \cdots, X_N\}. \tag{16}$$

The PDF of X is formed as follows:

$$f_X(x) = N f_{X_i}(x)\left[F_{X_i}(x)\right]^{N-1}. \tag{17}$$

Based on Remark 1, by substituting (1) and (2) into (17) and after some modified operations, we obtain the PDF of X.

$$f_X(x) = \left(\frac{m_1}{\lambda_1}\right)^{m_1} \frac{N x^{m_1-1}}{\Gamma(m_1)^N} \exp\left(-\frac{m_1 x}{\lambda_1}\right)\left[\gamma\left(m_1, \frac{m_1 x}{\lambda_1}\right)\right]^{N-1}. \tag{18}$$

By utilizing the [17, 8.352.4] and the Newton binomial expansion, we can rewrite (18) as the inner sum of the degree of $(m_1 - 1)$.

$$f_X(x) = \sum_{n=0}^{N-1} \binom{N-1}{n} \frac{N x^{m_1-1} (-1)^n}{\Gamma(m_1)^{N-1}} \left(\frac{m_1}{\lambda_1}\right)^{m_1} \times \exp\left(-\frac{m_1 (n+1) x}{\lambda_1}\right) \left(\sum_{k=0}^{m_1-1} \frac{1}{k!} \left(\frac{m_1 x}{\lambda_1}\right)^k \right)^n . \quad (19)$$

The inner sum in Eq. 19 is a polynomial of variable $z = m_1 x/\lambda_1$ with the degree of $(m_1 - 1)$, whose coefficients are $a_k = 1/k!$.

The n^{th} term of this polynomial is a polynomial of degree $n(m_1 - 1)$ [24, Eq:18].

$$\left[\sum_{k=0}^{m_1-1} \left(a_k z^k\right) \right]^n = \sum_{k=0}^{n(m_1-1)} \left(b_k^n z^k\right). \quad (20)$$

where coefficient b_k^n can be recursively calculated [17, 0.314]:

$$b_0^n = 1, b_1^n = n, b_{n(m_1-1)}^n = \left(\frac{1}{(m_1-1)!}\right)^n \quad (21a)$$

$$b_k^n = \frac{1}{k} \sum_{j=1}^{J_0} \frac{j(n+1) - k}{j!} b_{k-j}^n \quad (21b)$$

$$J_0 = \min(k, m_1 - 1), \quad 2 \le k \le n(m_1 - 1) - 1. \quad (21c)$$

To the best of the authors' knowledge, the outage probability expression for the cooperative communication model over Nakagami-m fading channels with arbitrary m parameters has not previously been reported in any literature. Additionally, no paper has been published regarding the proposed system model that employs the EH technique. We propose the outage probability expression with an arbitrary m parameter with the following propositions.

3.1 DF protocol with EH

Proposition 1 *The outage probability of the relaying network that applies EH and the DF protocol over the Nakagami-m fading channel with an arbitrary m parameter is given by:*

$$OP_{DF} = \frac{1}{\Gamma(m_0)} \gamma\left(m_0, \frac{m_0 \gamma_{direct}}{\lambda_0 P_S}\right) \mathbb{J}(a, b). \quad (22)$$

The $\mathbb{J}(a, b)$ can be separated into two parts, $\mathbb{J}(a, b) = \mathbb{J}_1 + \mathbb{J}_2$, which are expressed in Eqs. 23 *and* 24.

$$\mathbb{J}_1 = \sum_{k=0}^{\mathcal{N}_t} \frac{N c_k}{\Gamma(m_1)} \left(\frac{m_1}{\lambda_1}\right)^{N m_1} \left(\frac{N m_1}{\lambda_1}\right)^{-N m_1 - k} \Gamma\left(N m_1 + k, \frac{a N m_1}{\lambda_1}\right). \quad (23)$$

and

$$\mathbb{J}_2 = \sum_{k=0}^{\mathcal{N}_t} \sum_{j=0}^{\mathcal{N}_t} \sum_{t=0}^{\mathcal{N}_t} \frac{(-1)^t N c_k}{t! \Gamma(m_2 + j + 1) \Gamma(m_1)} \left(\frac{m_2 b}{\lambda_2}\right)^{m_2+j+t} \left(\frac{m_1}{\lambda_1}\right)^{N m_1} \times \underbrace{\int_a^\infty x^v \exp\left(-\frac{N m_1 x}{\lambda_1}\right) dx}_{\Delta(x)}, \quad (24)$$

where

$$\Delta(x) = \left(\frac{N m_1}{\lambda_1}\right)^{-v-1} \Gamma\left(v + 1, \frac{a N m_1}{\lambda_1}\right), \text{ if } v \ge 0 \quad (25)$$

$$= \left(\frac{1}{a}\right)^{v-1} E_v\left(\frac{a N m_1}{\lambda_1}\right), \quad \text{if } v < 0 \quad (26)$$

with $v = N m_1 + k - m_2 - j - t - 1$.

The approximation of $\mathbb{J}(a, b)$ is given as:

$$\mathbb{J}(a, b) \le \sum_{k=0}^{\mathcal{N}_t} \sum_{j=0}^{\mathcal{N}_t} \frac{1}{\Gamma(m_1)} \left(\frac{m_1}{\lambda_1}\right)^{N m_1} \left(\frac{m_2 b}{\lambda_2}\right)^{m_2+j} \frac{2 c_k N}{\Gamma(m_2 + j + 1)} \times \left(\frac{m_2 b \lambda_1}{N m_1 \lambda_2}\right)^{\frac{N m_1 + k - m_2 - j}{2}} \mathcal{K}_{N m_1 + k - m_2 - j}\left(2\sqrt{\frac{N m_1 m_2 b}{\lambda_1 \lambda_2}}\right), \quad (27)$$

with $\mathcal{N}_t \in \{1; \infty\}$

Proof Because the direct link is independent of the forward link and by substituting (8), (9), and (10) into (15), we obtain:

$$OP = \underbrace{\Pr\left(\gamma_{SD} < 2^{\mathcal{R}} - 1\right)}_{\mathcal{O}_1} \underbrace{\Pr\left(\min\left(\gamma_{SR_n}, \gamma_{R_n D}\right) < 2^{\frac{2\mathcal{R}}{1-\alpha}} - 1\right)}_{\mathbb{J}(a,b)}. \quad (28)$$

The signal received at the destination via the direct link is unaffected by the EH process; thus, the OP of the direct link can be illustrated as follows:

$$\mathcal{O}_1 = \Pr\left(\gamma_{SD} < \frac{\gamma_{direct} \sigma_D^2}{P_S}\right) = \frac{1}{\Gamma(m_0)} \gamma\left(m_0, \frac{m_0 \gamma_{direct} \sigma_D^2}{\lambda_0 P_S}\right), \quad (29)$$

where $\gamma_{direct} = 2^{\mathcal{R}} - 1$. The term $\mathbb{J}(a, b)$ is described in the Appendix. □

3.2 AF protocol with EH

Proposition 2 *The outage probability of the relaying network that applies EH and the AF protocol over the Nakagami-m fading channel with an arbitrary m parameter is given by:*

$$OP = \frac{1}{\Gamma(m_0)} \gamma\left(m_0, \frac{m_0 \gamma_0}{\lambda_0 P_S}\right) \mathbb{P}(x), \tag{30}$$

where

$$\mathbb{P}(x) = \sum_{k=0}^{N} \frac{N c_k}{\Gamma(m_1)\Gamma(m_2)} \left(\frac{m_1}{\lambda_1}\right)^{N m_1} \left(\mathbb{B}_1(x) - \mathbb{B}_2(x)\right). \tag{31}$$

and

$$\mathbb{B}_1(x) = \Gamma(m_2) \left(\frac{N m_1}{\lambda_1}\right)^{-N m_1 - k} \Gamma\left(N m_1 + k, \frac{N m_1 \gamma_{th}}{\lambda_1 P_S}\right), \tag{32}$$

$$\begin{aligned}\mathbb{B}_2(x) &= \sum_{j=0}^{N} \sum_{i=0}^{N m_1 + k - 1} \binom{N m_1 + k - 1}{i} \frac{\Gamma(m_2) (\phi \gamma_{th})^i}{\Gamma(m_2 + j + 1) \phi P_S} \\ &\times \exp\left(-\frac{N m_1 \gamma_{th}}{\lambda_1 P_S}\right) \left(\frac{1}{\phi P_S}\right)^{N m_1 + k - 1} \left(\frac{m_2 \gamma_{th}}{\lambda_2}\right)^{j + m_2} \\ &\times 2 \left(\frac{m_2 \gamma_{th} \lambda_1 \phi P_S}{\lambda_2 N m_1}\right)^{\frac{v}{2}} \mathcal{K}_v\left(2\sqrt{\frac{N m_1 m_2 \gamma_{th}}{\lambda_2 \lambda_1 \phi P_S}}\right).\end{aligned} \tag{33}$$

Proof From Eqs. 12 and 15, the outage probability expression of the AF protocol is rewritten based on the CDF of the SNR over the direct link and the forward link as follows:

$$\begin{aligned}\mathrm{OP_{AF}} &= \Pr(\gamma_{\mathrm{SD}} < \gamma_0) \Pr\left(\frac{\gamma_{\mathrm{SR}} \gamma_{\mathrm{RD}}}{\gamma_{\mathrm{SR}} + \gamma_{\mathrm{RD}} + 1} < \gamma_{\mathrm{th}}\right) \\ &\simeq \underbrace{\Pr(\gamma_{\mathrm{SD}} < \gamma_0)}_{Q_1(x)} \underbrace{\Pr\left(\frac{\gamma_{\mathrm{SR}} \gamma_{\mathrm{RD}}}{\gamma_{\mathrm{SR}} + \gamma_{\mathrm{RD}}} < \gamma_{\mathrm{th}}\right)}_{Q_2(x)}.\end{aligned} \tag{34}$$

where $\gamma_{\mathrm{th}} = 2^{\frac{2\mathcal{R}}{1-\alpha}} - 1$ and $\gamma_0 = 2^{\mathcal{R}} - 1$.

The first part of the probability, $Q_1(x)$, is calculated as in Eq. 29. It is the CDF of the SNR over the direct link, in which the communication channel from the source to the destination exists only in the first phase.

We can rewrite the second part of the probability, $Q_2(x)$, as follows:

$$\begin{aligned}Q_2(x) &= \Pr\left(\frac{P_{\mathrm{S}}|h_{1i}|^2 \delta P_{\mathrm{S}}|h_{1i}|^2|h_2|^2}{P_{\mathrm{S}}|h_{1i}|^2 + \delta P_{\mathrm{S}}|h_{1i}|^2|h_2|^2} < \gamma_{\mathrm{th}}\right) \\ &= \Pr\left(\frac{|h_{1i}|^2|h_2|^2}{1 + \delta|h_2|^2} < \frac{\gamma_{\mathrm{th}}}{\delta P_{\mathrm{S}}}\right),\end{aligned} \tag{35}$$

where $\delta = \frac{2\alpha\eta}{1-\alpha}$.

Furthermore, Eq. 35 is rewritten as:

$$\begin{aligned}Q_2(x) &= \Pr\left(\frac{XY}{1 + \delta Y} < \frac{\gamma_{\mathrm{th}}}{\delta P_{\mathrm{S}}}\right) \\ &= \int_0^{\frac{\gamma_{\mathrm{th}}}{P_{\mathrm{S}}}} \underbrace{\Pr\left(Y \geq \frac{\gamma_{\mathrm{th}}}{\delta P_{\mathrm{S}} x - \delta \gamma_{\mathrm{th}}}\right)}_{=1} f_X(x)\, dx \\ &+ \int_{\frac{\gamma_{\mathrm{th}}}{P_{\mathrm{S}}}}^{\infty} \Pr\left(Y < \frac{\gamma_{\mathrm{th}}}{\delta P_{\mathrm{S}} x - \delta \gamma_{\mathrm{th}}}\right) f_X(x)\, dx.\end{aligned} \tag{36}$$

Substituting (2) into (36) and after some algebraic manipulations, we obtain (37).

$$\begin{aligned}Q_2(x) &= \int_0^{\frac{\gamma_{\mathrm{th}}}{P_{\mathrm{S}}}} f_X(x)\, dx \\ &+ \int_{\frac{\gamma_{\mathrm{th}}}{P_{\mathrm{S}}}}^{\infty} \left\{1 - \frac{1}{\Gamma(m_2)} \Gamma\left[m_2, \left(\frac{\beta_2 \gamma_{\mathrm{th}}}{\delta P_{\mathrm{S}} x - \delta \gamma_{\mathrm{th}}}\right)\right]\right\} f_X(x)\, dx \\ &= \underbrace{\int_0^{\frac{\gamma_{\mathrm{th}}}{P_{\mathrm{S}}}} f_X(x)\, dx + \int_{\frac{\gamma_{\mathrm{th}}}{P_{\mathrm{S}}}}^{\infty} f_X(x)\, dx}_{=1} - \int_{\frac{\gamma_{\mathrm{th}}}{P_{\mathrm{S}}}}^{\infty} \frac{1}{\Gamma(m_2)} \Gamma \\ &\times \left[m_2, \left(\frac{\beta_2 \gamma_{\mathrm{th}}}{\delta P_{\mathrm{S}} x - \delta \gamma_{\mathrm{th}}}\right)\right] f_X(x)\, dx.\end{aligned} \tag{37}$$

From Eq. 37, we have:

$$Q_2(x) = 1 - \frac{1}{\Gamma(m_2)} \int_{\frac{\gamma_{\mathrm{th}}}{P_{\mathrm{S}}}}^{\infty} \Gamma\left[m_2, \left(\frac{\beta_2 \gamma_{\mathrm{th}}}{\delta P_{\mathrm{S}} x - \delta \gamma_{\mathrm{th}}}\right)\right] f_X(x)\, dx, \tag{38}$$

where $\beta_2 = \frac{m_2}{\lambda_2}$.

Substituting (44) into (38), we obtain the CDF of the relaying branch, as in Eq. 39.

$$F_{\gamma_R}(\gamma) = 1 - \sum_{k=0}^{N} \frac{N c_k}{\Gamma(m_1)\Gamma(m_2)} \left(\frac{m_1}{\lambda_1}\right)^{N m_1} \times \underbrace{\int_{\frac{\gamma_{th}}{P_S}}^{\infty} \left[\Gamma(m_2) - \gamma\left(m_2, \frac{\beta_2 \gamma_{th}}{\phi P_S x - \phi \gamma_{th}}\right)\right] x^{N m_1 + k - 1} \exp\left(-\frac{N m_1 x}{\lambda_1}\right) dx}_{\mathbb{B}_1(x) - \mathbb{B}_2(x)}. \tag{39}$$

In Eq. 39, we have $\mathbb{B}_1(x)$ and $\mathbb{B}_2(x)$. Note that to obtain $\mathbb{B}_2(x)$, we change the variable $u = \phi P_S x - \phi \gamma_{th}$ and execute the binomial expansion, which leads to Eq. 40.

$$\mathbb{B}_2(x) = \sum_{j=0}^{N} \sum_{i=0}^{N m_1 + k - 1} \binom{N m_1 + k - 1}{i} \frac{\Gamma(m_2)(\phi \gamma_{th})^i}{\Gamma(m_2 + j + 1)} \times \exp\left(-\frac{N m_1 \gamma_{th}}{\lambda_1 P_S}\right) \frac{(\beta_2 \gamma_{th})^{j + m_2}}{\phi P_S} \left(\frac{1}{\phi P_S}\right)^{N m_1 + k - 1} \times \int_0^{\infty} u^{N m_1 + k - i - j - m_2 - 1} \exp\left(-\frac{\beta_2 \gamma_{th}}{u} - \frac{N m_1 u}{\lambda_1 \phi P_S}\right) du. \tag{40}$$

Finally, by applying [17, 3.471.9], we obtain $\mathbb{B}_2(x)$, as in Eq. 33. □

4 Simulation results

In this section, the outage probability of the AF and DF protocols obtained in our analysis shown in Section 3 is verified by comparing to the outage probability obtained through Monte Carlo simulations. We assume that $\mathcal{R} = 1$ bit/s/Hz, $\eta = 1$ (perfect current converter), P_S is constant, and $\alpha = 0.3$. The effect of parameter N is investigated in the specific scenario; however, in the other scenario, N is set as 2.

The distance from S to D is normalized to the unit value. Moreover, all channels are identical independent distributions (i.i.d.). For the sake of simplicity, the average channel gains are set as $\lambda_{1i} = \lambda_{2j} = \lambda_0 = 1$.

Figure 3 illustrates the outage probability versus the average transmission power of the S. To reduce complexity, we choose $[m_{SR}\, m_{RD}\, m_{SD}] = [2\,2\,2]$, where m_{SR}, m_{RD}, and m_{SD} are the distribution parameters of the links S-R, R-D, and S-D, respectively. From Fig. 3, it is clear that the performance of the DF protocol is better than the performance of the AF protocol. This result can be explained by the fact that the SNR of the AF protocol is always less than the SNR of the DF protocol due to the noise retained after the first hop. On the other hand, the system performance is improved when the number of relay nodes increases. This is because the system can select the channel whose quality is the best; thus, the SNR and the amount of harvested energy are improved. In this result, we also recognize that the proposed theoretical analysis results perfectly match the simulation results in the case of integral m, which confirms the correctness of the proposed analysis approach.

Figure 4 demonstrates the outage probability with respect to different m parameters, while the other parameters are as mentioned above. In this figure, the comparison of the outage probability based on the AF and DF protocols is

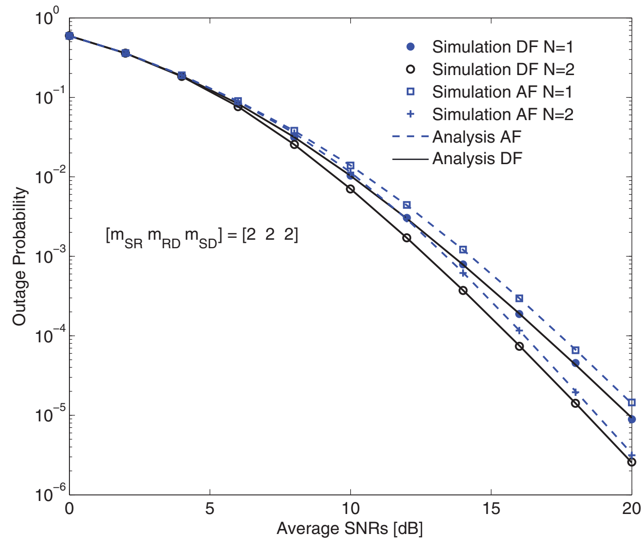

Fig. 3 The comparison of the outage probability of the AF and DF protocols vs. average the SNRs

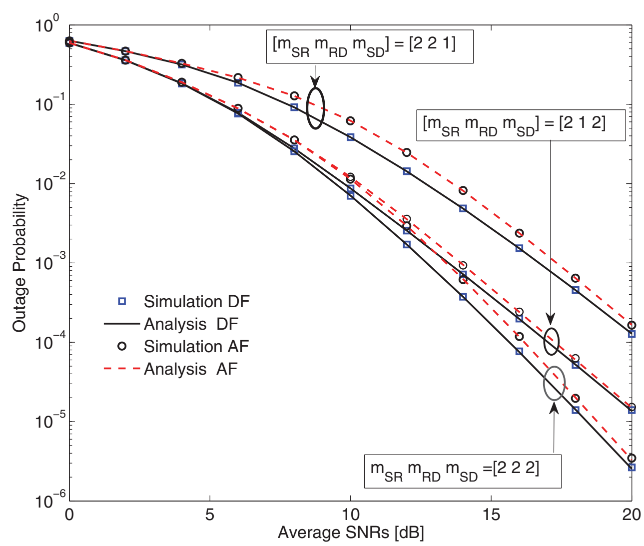

Fig. 4 The outage probability with different values of parameter m

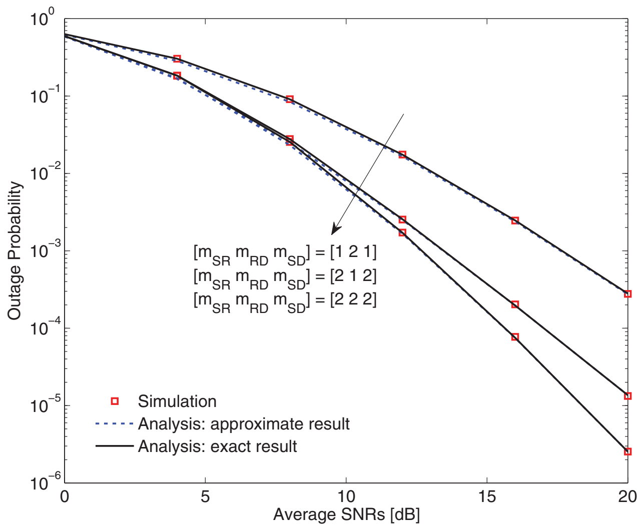

Fig. 5 The exact and approximate outage probabilities with different values of parameter m

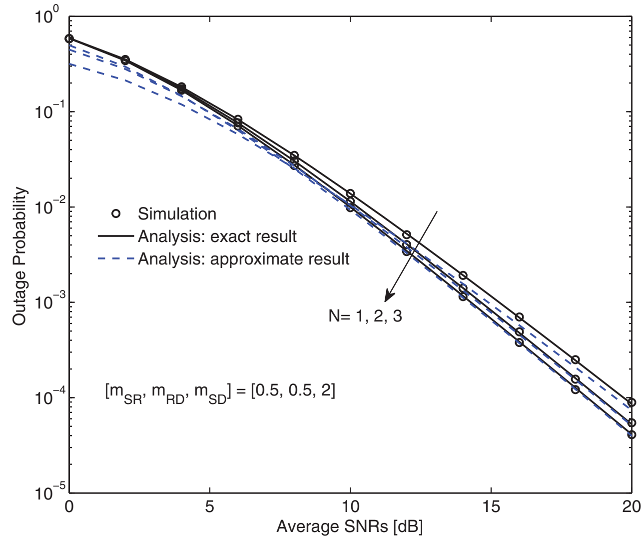

Fig. 6 The exact and approximate outage probabilities with different numbers of relays and arbitrary m

also illustrated. Moreover, excellent agreement between the analytical result and simulation result is also observed. When the parameter m is increased, the outage probability decreases because of the decrease in fading. Moreover, the fading of the forward link depends on both links between S-R and R-D; therefore, the outage probability of $[m_{SR}\, m_{RD}] = [2\,2]$ is smaller than that of $[m_{SR}\, m_{RD}] = [2\,1]$. In addition, when the quality of the direct link is better than that of the forward link, parameter m of the forward link does not affect the system performance, which is a reason why the outage probability of case $[m_{SD}] = [2]$ is lower than the outage probability of case $[m_{SD}] = [1]$.

Figure 5 presents the exact and approximate outage probabilities versus the SNR with an integral m parameter. The results in Fig. 5 show that as the value of parameter m increases, the system performance is improved. The reason is that parameter m represents a channel gain between the transmitter and the receiver; thus, the higher parameter m is, the better the system performance. Moreover, from this figure, we can observe that the approximate outage probability is very close to the exact probability, especially in the high SNR region. These results indicate that the proposed closed form of the outage probability expression can be used to evaluate the performance of the system.

Figure 6 demonstrates the outage probability of the system versus the SNR in the case of arbitrary parameter m and different numbers of relays. As shown in Fig. 6, the gaps between the exact and approximate outage probabilities are small, especially in the high SNR region. Obviously, the small gap between them comes from the approximate operation in Eq. 47, and the gap becomes smaller in the high SNR region because the SNR was assumed to be high in this approximate operation. On the other hand, in the case of a small value of m in the forward link, $m_{\mathrm{SR}} = m_{\mathrm{RD}} = 0.5$; although we increase the number of relays, the outage probabilities of the system are improved slightly.

Figure 7 describes the outage probability versus the SNR with different arbitrary m parameters. As explained above, the outage probability decreases as parameter m increases. It is clear that the communication environment plays an important role in the quality of the network. In particular, in the case of an increase in the m_{SD} value, the outage performance is improved significantly because of the enhanced direct link. Finally, this figure also shows an agreement between the analytical and simulation results.

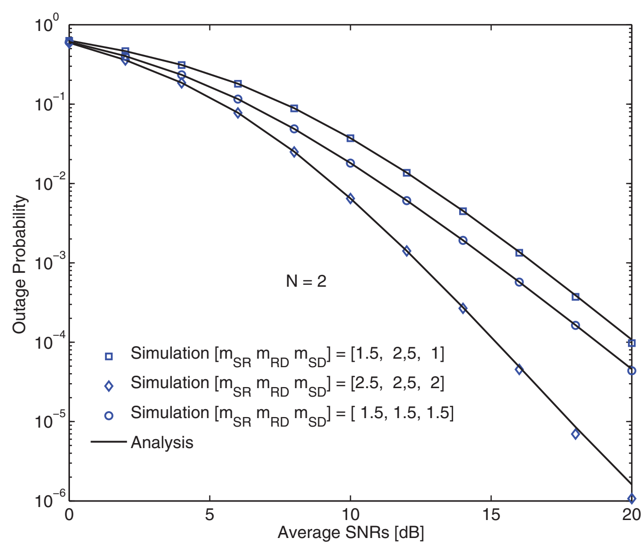

Fig. 7 The outage probability with several arbitrary m parameters

5 Conclusions

In this paper, we consider a partial relay selection scheme for the EH dual-hop cooperative communication network and investigate its performance through the outage probability. The main results of this work are summarized as follows. (i) We derive a PDF of the order statistic for the equivalent instantaneous SNR in the case of both the AF and the DF protocols, and then the derived PDF is utilized to calculate the outage probability. (ii) A closed-form expression of the outage probability with the Nakagami-m distribution is proposed based on both integer and arbitrary m parameters. (iii) Our proposed derivation method is confirmed with the Monte Carlo simulation, and the significant match in both the theoretical and simulation results verifies our proposed analysis method. (iv) The performance of the system is evaluated based on different values of parameter m, and an increase in parameter m improves the system performance. (v) The effect of the number of relays is also discussed; the higher the number of relays is, the better the system performance is, especially for a large value of parameter m.

For the next steps, it could be interesting to discuss the effect of the time duration for EH on the system performance. Additionally, investigating the impact of the nonlinear EH model on our proposed system is left for future work.

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Appendix: The proof of term $\mathbb{J}(a, b)$

Combining (8), (9), and (11), function $\mathbb{J}(a, b)$ can be rewritten as:

$$\begin{aligned}\mathbb{J}(a,b) &= 1-\Pr\left(\gamma_{\mathrm{SR}}>\gamma_{\mathrm{th}},\ \gamma_{\mathrm{RD}}>\gamma_{\mathrm{th}}\right)\\ &= 1-\Pr\left(X>a,\ XY>b\right),\end{aligned} \tag{41}$$

where $\gamma_{\mathrm{th}} = 2^{\frac{2\mathcal{R}}{1-\alpha}} - 1$; $a = \frac{\gamma_{\mathrm{th}}}{P_{\mathrm{S}}}$, *and* $b = \frac{(1-\alpha)\gamma_{\mathrm{th}}}{2\alpha\eta P_{\mathrm{S}}}$.

The expansion of the incomplete gamma function by a series development is applied for $\gamma(m, z)$ [25, Eq. 5].

$$\gamma(m,z) = e^{-z}\sum_{k=0}^{\infty}\frac{\Gamma(m)\, z^{m+k}}{\Gamma(m+k+1)}. \tag{42}$$

From Eq. 42, it is clear that when the Nakagami-m fading parameter is not an integer, the CDF can be expressed as a single infinity series of incomplete gamma functions.

Substituting (42) into (18) and after some algebraic manipulations, we obtain the PDF of the instantaneous SNR over the first hop.

$$\begin{aligned}f_X(x) &= \left(\frac{m_1}{\lambda_1}\right)^{Nm_1}\frac{Nx^{Nm_1-1}}{\Gamma(m_1)}\exp\left(-\frac{Nm_1x}{\lambda_1}\right)\\ &\times\left[\sum_{k=0}^{\infty}\left(\frac{m_1}{\lambda_1}\right)^k\frac{x^k}{\Gamma(m_1+k+1)}\right]^{N-1}.\end{aligned} \tag{43}$$

Based on [17, 0.314], Eq. 43 is rewritten as:

$$f_X(x) = \sum_{k=0}^{\infty}c_k\left(\frac{m_1}{\lambda_1}\right)^{Nm_1}\frac{Nx^{Nm_1+k-1}}{\Gamma(m_1)}\exp\left(-\frac{Nm_1x}{\lambda_1}\right), \tag{44}$$

where c_k is defined as

$$c_0 = \left[\frac{1}{\Gamma(m_1+1)}\right]^{N-1}, \quad \text{for } k=0, \tag{45a}$$

$$c_k = \sum_{\ell=1}^{k}\frac{\Gamma(m_1+1)}{k}\left(\frac{m_1}{\lambda_1}\right)^{\ell}\frac{(\ell N-k)\,c_{k-\ell}}{\Gamma(m_1+\ell+1)}, \text{ for } k\geq 1. \tag{45b}$$

The CDF and PDF of the individual links are already obtained by Eqs. 2 and 44; consequently, the CDF of link S-R-D can be derived as:

$$\begin{aligned}\mathbb{J}(a,b) &= 1-\int_a^{\infty}\left[1-F_Y\left(\frac{b}{x}\right)\right]f_X(x)\,dx\\ &= 1-\left[\int_a^{\infty}f_X(x)\,dx-\int_a^{\infty}F_Y\left(\frac{b}{x}\right)f_X(x)\,dx\right],\end{aligned} \tag{46}$$

where $b = \frac{(1-\alpha)\gamma_{\mathrm{th}}}{2\alpha\eta P_{\mathrm{S}}}$ and $a = \frac{\gamma_{\mathrm{th}}}{P_{\mathrm{S}}}$.

With high transmission power, parameter a can be approximated as $a = \frac{\gamma_{\mathrm{th}}}{P_{\mathrm{S}}\to\infty} \approx 0$. Hence, $\mathbb{J}(a, b)$ is changed.

$$\begin{aligned}\mathbb{J}(a,b) &\leq \sum_{k=0}^{\mathcal{N}_t}\sum_{j=0}^{\mathcal{N}_t}\left(\frac{m_1}{\lambda_1}\right)^{Nm_1}\left(\frac{m_2b}{\lambda_2}\right)^{m_2+j}\frac{c_k}{\Gamma(m_2+j+1)}\\ &\times\frac{N}{\Gamma(m_1)}\int_0^{\infty}x^v\exp\left(-\frac{m_2b}{\lambda_2x}-\frac{Nm_1x}{\lambda_1}\right)dx.\end{aligned} \tag{47}$$

with $v = Nm_1 + k - m_2 - j - 1$.

Applying [17, Eq:3.471.9], we have

$$\begin{aligned}&\int_0^{\infty}x^v\exp\left(-\frac{m_2b}{\lambda_2x}-\frac{Nm_1x}{\lambda_1}\right)dx = \\ &2\left(\frac{m_2b\lambda_1}{Nm_1\lambda_2}\right)^{\frac{Nm_1+k-m_2-j}{2}}\mathcal{K}_{Nm_1+k-m_2-j}\left(2\sqrt{\frac{Nm_1m_2b}{\lambda_1\lambda_2}}\right),\end{aligned} \tag{48}$$

and then the approximation of $\mathbb{J}(a, b)$ in Eq. 47 is changed, as in Eq. 27.

To analyze the exact outage probability expression, Eqs. 2 and 44 are substituted into Eq. 46, and we obtain function $\mathbb{J}(a,b)$.

$$\mathbb{J}(a,b) = \underbrace{1-\sum_{k=0}^{\infty}\left(\frac{m_1}{\lambda_1}\right)^{Nm_1}\frac{c_k N}{\Gamma(m_1)}\int_a^{\infty} x^{Nm_1+k-1}\exp\left(-\frac{Nm_1 x}{\lambda_1}\right)dx}_{\mathbb{J}_1} \\ +\underbrace{\sum_{k=0}^{\infty}\left(\frac{m_1}{\lambda_1}\right)^{Nm_1}\frac{Nc_k}{\Gamma(m_1)}\int_a^{\infty} F_Y\left(\frac{b}{x}\right)x^{Nm_1+k-1}\exp\left(-\frac{Nm_1 x}{\lambda_1}\right)dx}_{\mathbb{J}_2}. \quad (49)$$

To calculate $\mathbb{J}_1$, [17, 3.351.2] can be used, while to calculate $\mathbb{J}_2$, the variable x is replaced with $x = au$, and then we obtain (24). Finally, we consider the system model in the two cases of index power $\upsilon \geq 0$ and $\upsilon < 0$, in which [17, 3.351.2] is used for the case $\upsilon \geq 0$ and the exponential integral function is used for the case $\upsilon < 0$. We completely prove the proposition 1 here.

References

1. Laneman JN, Tse DN, Wornell GW (2004) Cooperative diversity in wireless networks: efficient protocols and outage behavior. IEEE Trans Inf Theory 50(12):3062–3080
2. Bletsas A, Shin H, Win MZ (2007) Cooperative communications with outage-optimal opportunistic relaying. IEEE Trans. Commun. 6(9):3450–3460
3. Duy TT, Duong TQ, Benevides da Costa D, Bao VNQ, Elkashlan M (2015) Proactive relay selection with joint impact of hardware impairment and co-channel interference. IEEE Trans Commun 63(5):1594–1606
4. Duong TQ, Bao VNQ, Zepernick H-J (2009) On the performance of selection decode-and-forward relay networks over Nakagami-m fading channels. IEEE Commun Lett 13(3):172–174
5. Lu X, Wang P, Niyato D, Kim DI, Han Z (2015) Wireless networks with RF energy harvesting: a contemporary survey. IEEE Commun Tutorials 17(2):757–789
6. Zhao L, Wang X, Zheng K (2016) Downlink hybrid information and energy transfer with massive MIMO. IEEE Commun Mag 15(2):1390–1322
7. Vahidnia R, Anpalagan A, Mirzaei J (2016) Diversity combining in bi-directional relay networks with energy harvesting nodes. IET Commun 10(2):207–211
8. Do NT, Bao VNQ, An B (2015) A relay selection protocol for wireless energy harvesting relay networks. Proc 2015 12th Adv Tech Commun (ATC) 10(2):243–247
9. Son PN, Kong HY, Anpalagan A (2016) Exact outage analysis of a decode-and-forward cooperative communication network with Nth best energy harvesting relay selection. Ann Telecommun 71(5-6):251–263
10. Chen Y (2016) Energy-harvesting AF relaying in the presence of interference and Nakagami-fading. IEEE Trans Commun 15(2):1008–1017
11. Dong Y, Hossain M, Cheng J (2016) Performance of wireless powered amplify and forward relaying over Nakagami-*m* fading channels with nonlinear energy harvester. IEEE Commun Lett 20(4):672–675
12. Hoang TM, Duy TT, Bao VNQ (2016) On the performance of non-linear wirelessly powered partial relay selection networks over rayleigh fading channels. Proc 2016 3rd Nat Found Science and Tech Dev Conf (NICS) 10(2):6–11
13. Hoang TM, Tan NT, Hoang NH, Hiep PT (2018) Performance analysis of decode-and-forward partial relay selection in noma systems with rf energy harvesting. Wireless Networks, pp 1–11. https://doi.org/10.1007/s11 276–018–1746–8
14. Psannis KE, Stergiou C, Gupta BB (2018) Advanced media-based smart big data on intelligent cloud systems. IEEE Trans Sustain Comput 4(1):77–87
15. Plageras AP, Psannis KE, Stergiou C, Wang H, Gupta BB (2018) Efficient IoT-based sensor big data collection–processing and analysis in smart buildings. Futur Gener Comput Syst 82:349–357
16. Hoang TM, Son VV, Dinh NC, Hiep PT (2018) Optimizing duration of energy harvesting for downlink noma full-duplex over Nakagami-m fading channel. Int J Electron Commun. (AEÜ) 95:199–206
17. Zwillinger D (2014) Table of integrals, series, and products. Elsevier
18. Bao VNQ, Kong HY (2010) Performance analysis of decode-and-forward relaying with partial relay selection for multihop transmission over Rayleigh fading channels. J Commun Netw 12(5):433–441
19. Nasir AA, Zhou X, Durrani S, Kennedy RA (2013) Relaying protocols for wireless energy harvesting and information processing. IEEE Trans Wirel Commun 12(7):3622–3636
20. Senaratne D, Tellambura C (2010) Unified exact performance analysis of two-hop amplify-and-forward relaying in Nakagami *m* fading. IEEE Trans Veh Technol 59(3):1529–1534
21. Krikidis I, Timotheou S, Sasaki S (2012) RF Energy transfer for cooperative networks: data relaying or energy harvesting? IEEE Commun Lett 16(11):1772–1775
22. Sudevalayam S, Kulkarni P (2011) Energy harvesting sensor nodes: survey and implications. IEEE Commun Surv Tuts 13(3):443–461
23. Krikidis I, Zheng G, Ottersten B (2013) Harvest-use cooperative networks with half/full-duplex relaying. In: Wirel Commun and Netw Conf (WCNC). IEEE, pp 4256–4260
24. Fedele G (1996) N-Branch diversity reception of mary DPSK signals in slow and non selective Nakagami *m* fading. IEEE Trans Commun Technol 7(2):119–123
25. Hung C-C, Chiang C-T, Yen N-Y, Wu R-C (2010) Outage probability of multiuser transmit antenna selection/maximal-ratio combining systems over arbitrary Nakagami-*m* fading channels. IET Commun 4(1):63–68