PERFORMANCE ANALYSIS OF RF ENERGY HARVESTING COOPERATIVE COMMUNICATION NETWORKS WITH DF SCHEME

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Abstract

Wireless energy transfer cooperative communication systems are analyzed in this paper. In these systems, a source node can communicate with a destination node directly or via the selected relay nodes, while relay nodes harvest energy from radio frequency for forwarding the received signal. In addition, the decode and forward (DF) protocol is applied to relay nodes, and selection combination technique is employed at the destination in order to select the best relay node. The system performance is presented by outage probability expressions over independent and identically distributed (i.i.d) Nakagami-m channel model. The theoretical analysis and the closed-form expression of outage probability are derived and compared with Monte-Carlo simulations. The simulation results are similar to the theoretical analysis results, it verifies our proposed derivation method.

Index terms

Cooperative communication, Energy harvesting, Nakagami-m, Outage probability, decode and forward scheme, wireless energy transfer.

1. Introduction

Radio frequency (RF) energy transfer and harvest techniques become alternative methods to supply the power for devices in the next generation wireless networks [1]. These techniques appear as a promising solution for energy-constrained wireless networks such as wireless sensor networks, biomedical wireless body area network and so on. The devices in energy-constrained wireless networks have limited lifetime which largely confines the network performance. According to the state - of - art researches, the relay node can be supplied by energy harvesting (EH) from around radio terminals. We believe that many other applications of EH technique are still waiting to be disclosed. In recent years, the EH technique has attract more and more interest of

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researchers. Specially, the combination of relaying protocols with energy harvesting has been proposed to a number of systems.

The downlink hybrid information and energy transfer with massive MIMO system is considered in [2], in this letter the authors considered simultaneously sending information and energy to information users and energy users respectively. The problem is solved by obtaining the asymptotically optimal power allocation of information users. Vahidnia et al. considered the transceivers are equipped with multiple antennas and exchanges information through the relay-assisted network by using a single-carrier communication scheme [3]. The relay nodes harvest energy from the surrounding environment and utilize this energy to forward their received messages to destinations, this process uses a harvest-then-forward scheme.

On the other hand, Do et al. derived outage probability expression that is accurate in closed-form of the dual-hop decode-and- forward (DF) relaying network with time switching-based relaying mechanism. In this work, the authors assumed that the direct link is not available [4]. The DF protocol in the cooperative communication network with energy harvesting relays is also investigated in [5]. In this article, the authors proposed selection method of the best relay to forward signal to destinations. The proposed method was investigated in two operation schemes: power splitting (PS) and time switching (TS) at the relays.

Chen in [6] has studied EH amplify-and-forward (AF) relaying networks in case the channel is suffered from interference and Nakagami-m fading, the result showed that the TS is more sensitive to EH than the PS under the same channel settings. Dong et. al. considered non-linear of RF EH circuits on the performance of wireless powered relay with AF protocol. They have assumed that the channels have distribution of Nakagami-m [7]. Moreover, the partial relaying system and wireless power transfer have been studied over Rayleigh fading channels in [8] and the relation between the EH duration and communication duration has been discussed in non-orthogonal multiple access (NOMA) relay systems by our members in [9]. Our members also optimized the duration of EH for downlink NOMA full-duplex relay systems [10].

As mentioned above, the previous researches focused on the cooperative communication and wireless transfer networks, however, according to the best of our knowledge, these studies do not combine cooperative communication and energy harvesting RF in term of exiting direct link with relay selection schemes over Nakagami-m fading channels.

The main target of this work is to focus on the performance analysis of the energy harvesting relay-aided cooperative network with selected relaying in terms of outage probability. Specially, we analyze performance of system over Nakagami-m fading channel. The contributions of this paper is in summary as follows:

- To determine the closed-form expression of outage probability over Nakagami-m channels for wireless cooperative communication networks with direct link.
- To evaluate system performance with different number of relay nodes and/or dif-

ferent m factor.

- To verify the theoretical analysis by Monte - Carlo simulations.

The rest of this paper is organized as follows: Section 2 presents the system model and characterizes the end-to-end signal-to-noise ratio (SNR). The outage probability is theoretically analyzed in Section 3. Section 4 compares theoretical and simulation results to verify the theoretical analysis. 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 $(\cdot)$. $\Gamma(\alpha) = \int_0^\infty t^{\alpha-1}e^{-t}dt$, and $\Gamma(\alpha, x) = \int_x^\infty t^{\alpha-1}e^{-t}dt$ and $\gamma(\alpha, x) = \int_0^x t^{\alpha-1}e^{-t}dt$ denote the gamma function [11, eq, (8.310.1)], the upper incomplete gamma function [11, eq, (8.350.2)] and the lower incomplete gamma function [11, (8.350.1)], respectively. $E_n(x) = \int_1^\infty \frac{e^{-xt}}{t^n}dt$ represent 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 other n.

2. System Model

The wireless cooperative relaying selection system over condition that EH is produced at the relay nodes, as shown in Fig. *1*. The source node S communicates with the destination node D through the direct link and multiple relay nodes R_n with $n \in 1, \cdots, N$ in order to forward signal to the destination.

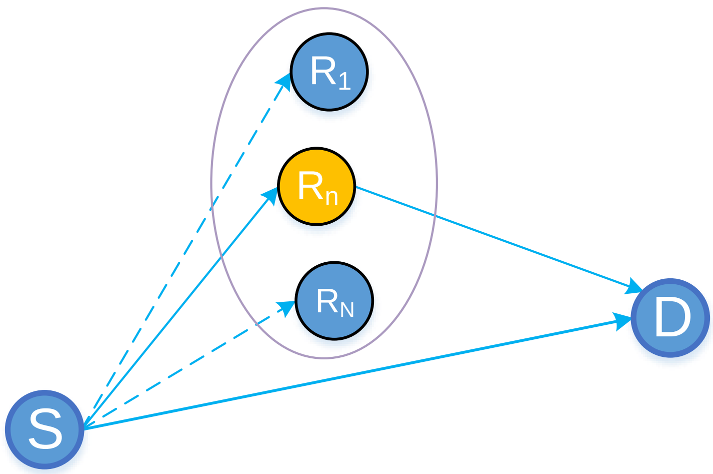

Fig. 1. *Wirelessly powered cooperative selection networks.*

The source node and the destination node are powered commonly, whereas the relay nodes are powered by harvesting energy from the source. Each relay node is equipped

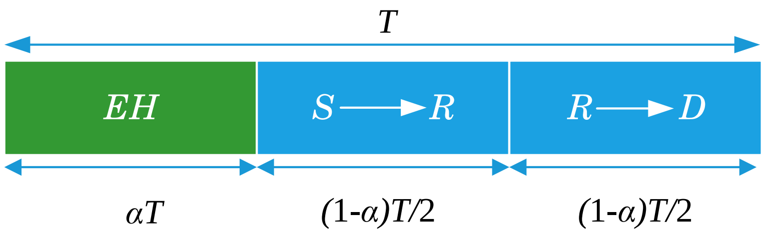

Fig. 2. The protocol of dual hops relaying system with EH relay.

with an EH receiver and an information decode (ID) receiver. We assume that the EH and ID receivers operate at the same frequency.

We assume that all the relay nodes are operated with DF protocol and grouped into one cluster, which is set up at higher layers [12], and each node is equipped with single-antenna and operates in half-duplex mode.

The $|h_{\mathrm{SD}}|^2$, $|h_{\mathrm{SR}_n}|^2$ and $|h_{\mathrm{R}_n\mathrm{D}}|^2$ denote the amplitudes of the fading channel links between the source to the destination, the source to the cooperative nodes and the cooperative nodes to the destination, respectively. We assume that channel state information (CSI) is available at the receiver nodes, but is not available at the transmitter nodes.

The operation of the relay is depicted in Fig. 2. According to the time switching relay (TSR) protocol [13], after selecting the link from the S to the best relay (R_b), the transmission period T is spitted into two time slots[1] for EH and information transmission. Specifically, a time duration αT is used for EH[2]. The remaining time duration, $(1-\alpha)T$, is once again divided into two equal time subslots. The first half, $(1-\alpha)T/2$, is used for information transmission from the S to the relay, and the second half, $(1-\alpha)T/2$, is used for information transmission from the relay to the D. It should be noted that we only consider $0 \leq \alpha < 1$. In the case of $\alpha = 1$, the relay harvests energy in the whole time, the signal is not forwarded to the D, thus this case is not considered in this paper. Moreover, in the proposed system, because the harvest-use (HU) architecture is applied, the relay does not need batteries to store the harvested energy.

In the Nakagami-m distribution, the parameter m signifies the fading severity and the smaller values of m represents more fading in the channel, which is also modeled as Nakagami-m variable with parameters m_0, λ_0; m_1, λ_1 and m_2, λ_2, respectively. Therefore, notation $\lambda_{\mathcal{A}} = \mathrm{E}\{\mathcal{X}\}$ is the mean of variable $\mathcal{X}$ where $\mathcal{A} \in \{0, 1, 2\}$ and $\mathcal{X} \subset \{X, Y, Z\}$. Hence, the probability density function (PDF) and the cumulative distribution function (CDF) of $\mathcal{X}$ are the Gamma distribution with the parameters

[1] In this system, we use the time division multiple access (TDMA) scheme.

[2] Power splitting protocol can also be applied in this system.

$m_{\mathcal{A}} > 0$ and $\lambda_{\mathcal{A}} > 0$ [14], [15].

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

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

Now, we analyze the harvested energy at the relay and describe its baseband received signal. 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

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

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

where P_{S} is transmit power of the source, t is the symbol index, $x(t)$ is the sampled and normalized information signal from the source, $n(t)$ is the baseband additive white Gaussian noise (AWGN) due to the receiver.

From (3), we have harvested energy at the relay node, E_h, during the time αT given by [16].

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

where N_0 is the power spectral density of the additive white Gaussian noise (AWGN) at each node and $0 \le \eta \le 1$ is the energy conversion efficiency, which depends on the rectification process and the EH circuitry. In this work, the circuit power consumption at the relay nodes is assumed to be negligible. The harvested energy during the EH phase is stored in a supercapacitor and then wholly consumed by the relay node to forward the source signal to the destination. It is called the harvest-use architecture, and opposes the harvest-store-use architecture [17], [18].

In the relaying phase, the best relay R_n re-codes the signal of the source and then transmits to the destination for $\frac{1-\alpha}{2}T$ second. Hence the received signal at the destination of DF protocol is given as

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

Since the main aim of this paper is to investigate performance of the system, based on the expressions (3), (4) and (6), we can define the instantaneous signal-to-noise ratio (SNR) for each link as following.

$$
\begin{aligned}
\gamma_{\mathrm{SR}_n} =& \frac{P_{\mathrm{S}}|h_{\mathrm{SR}_n}|^2}{N_0} = \frac{P_{\mathrm{S}} \max\limits_{i=1,\ldots,N} |h_{1,i}|^2}{N_0}, & (7)\\
\gamma_{\mathrm{R}_n\mathrm{D}} =& \frac{P_{\mathrm{R}}}{N_0}|h_{\mathrm{R}_n\mathrm{D}}|^2 = \frac{\phi P_{\mathrm{S}} \max\limits_{i=1,\ldots,N} |h_{1,i}|^2 |h_{\mathrm{R}_n\mathrm{D}}|^2}{N_0}, & (8)\\
\gamma_{\mathrm{SD}} =& \frac{P_{\mathrm{S}}|h_{\mathrm{SD}}|^2}{N_0}. & (9)
\end{aligned}
$$

The γ_{AB} is the instantaneous SNR from the node A to the node B, with $A \in \{\mathrm{S}, \mathrm{R}_n\}$ and $B \in \{\mathrm{R}_n, \mathrm{D}\}$.

When the DF cooperation protocol is applied, the end to end SNR, γ_{e2e} is derived equivalently as follows.

$$
\gamma_{\mathrm{e2e}} = \min\left(\gamma_{\mathrm{SR}_n}, \gamma_{\mathrm{R}_n\mathrm{D}}\right). \tag{10}
$$

When the bandwidth is normalized, the maximum average mutual information between the source and the destination, i.e. channel capacity, in each connecting case is given by [19], [20]

$$
\begin{aligned}
C_{\mathrm{SD}} &= \log_2\left(1+\gamma_{\mathrm{SD}}\right), & (11)\\
C_{\mathrm{R}} &= \frac{1-\alpha}{2}\log_2\left(1+\gamma_{\mathrm{e2e}}\right), & (12)
\end{aligned}
$$

where the pre-factor $\frac{1-\alpha}{2}$ is accounted for communication between the source node and the destination node via the relay nodes.

3. Outage Analysis

The outage probability can be considered as an essential parameter in order to analyze performance and commonly used to characterize the wireless communication systems. The outage probability is defined as the probability that the channel capacity is less than the determined transmission rate, $C < \mathcal{R}$.

$$
\begin{aligned}
\mathrm{OP} =& \Pr\left\{\max\left[\log_2\left(1+\gamma_{\mathrm{SD}}\right), \frac{1-\alpha}{2}\log_2\left(1+\gamma_{\mathrm{e2e}}\right)\right] < \mathcal{R}\right\}\\
=& \Pr\left[\log_2\left(1+\gamma_{\mathrm{SD}}\right) < \mathcal{R}, \quad \frac{1-\alpha}{2}\log_2\left(1+\gamma_{\mathrm{e2e}}\right) < \mathcal{R}\right]. \qquad (13)
\end{aligned}
$$

When the link having the largest instantaneous SNR is selected as the best relay and described by [20], [21]

$$
X = \max\left\{X_1, X_2, \cdots, X_N\right\}. \tag{14}
$$

The PDF of X is formed as follows.

$$f_X\left(x\right) = N f_{X_i}\left(x\right)\left[F_{X_i}\left(x\right)\right]^{N-1}. \tag{15}$$

Substituting (1) and (2) into (15) and after some modified operations, we have the PDF of X.

$$f_X(x) = \left(\frac{m_1}{\lambda_1}\right)^{m_1}\frac{N x^{m_1-1}}{\Gamma(m_1)^N}\exp\left(-\frac{m_1 x}{\lambda_1}\right)\left[\gamma\left(m_1, \frac{m_1 x}{\lambda_1}\right)\right]^{N-1}, \tag{16}$$

when m reaches to the restricted integral values, Fedele [22] showed that the PDF of $f_X(x)$ (16) can be rewritten in terms of a finite series expansion given by [22, Eq: 18]. By utilizing the [11, 8.352.4], and the Newton binomial expansion, we can rewrite (16) to be the inner sum of degree of $(m_1 - 1)$.

$$\begin{aligned} f_X(x) = &\sum_{n=0}^{N-1}\binom{N-1}{n}\frac{N x^{m_1-1}(-1)^n}{\Gamma(m_1)^{N-1}}\left(\frac{m_1}{\lambda_1}\right)^{m_1} \\ &\times \exp\left(-\frac{m_1\left(n+1\right)x}{\lambda_1}\right)\left(\sum_{k=0}^{m_1-1}\frac{1}{k!}\left(\frac{m_1 x}{\lambda_1}\right)^k\right)^n. \end{aligned} \tag{17}$$

The inner sum in (17) is a polynomial of variable $z = m_1 x/\lambda_1$ with degree of $(m_1 - 1)$, whose coefficients are $a_k = 1/k!$.

The n^{th} term of this polynomial is a polynomial of degree $n\left(m_1 - 1\right)$ [22, Eq: 18].

$$\left[\sum_{k=0}^{m_1-1}\left(a_k z^k\right)\right]^n = \sum_{k=0}^{n(m_1-1)}\left(b_k^n z^k\right). \tag{18}$$

where the coefficient b_k^n can be recursively calculated [11, 0.314]:

$$b_0^n = 1, b_1^n = n, b_{n(m_1-1)}^n = \left(\frac{1}{(m_1-1)!}\right)^n \tag{19a}$$

$$b_k^n = \frac{1}{k}\sum_{j=1}^{J_0}\frac{j\left(n+1\right)-k}{j!}b_{k-j}^n \tag{19b}$$

$$J_0 = \min\left(k,\, m_1 - 1\right), \quad 2 \le k \le n\left(m_1 - 1\right) - 1. \tag{19c}$$

Proposition 1. *The outage probability of the relaying network that applies EH using the DF protocol over Nakagami-m fading channels can be expressed as follows:*

$$\mathrm{OP_{DF}} = \frac{1}{\Gamma\left(m_0\right)}\gamma\left(m_0, \frac{m_0\gamma_{\text{direct}}}{\lambda_0 P_{\mathrm{S}}}\right)\mathcal{I}\left(a, \phi\right), \tag{20}$$

where $\mathcal{I}(a,\phi)$ is approximate term as in (21) *or accurate term as in* (22).

$$\mathcal{I}(a,\phi) \le 1-\left\{\sum_{n=0}^{N-1}\sum_{k=0}^{n(m_1-1)}\sum_{t=0}^{m_2-1}\frac{(-1)^n N b_k^n}{t!\Gamma(m_1)^{N-1}}\left(\frac{m_2\phi}{\lambda_2}\right)^t\binom{N-1}{n}\left(\frac{m_1}{\lambda_1}\right)^{m_1+k}\right. \\ \left.\times\ 2\left(\frac{m_2\lambda_1\phi}{\lambda_2 m_1(n+1)}\right)^{\frac{m_1+k-t}{2}}\mathcal{K}_{m_1+k-t}\left(2\sqrt{\frac{m_1 m_2\phi(1+n)}{\lambda_1\lambda_2}}\right)\right\}. \tag{21}$$

$$\mathcal{I}(a,\phi) = 1-\sum_{n=0}^{N-1}\sum_{k=0}^{n(m_1-1)}\sum_{t=0}^{m_2-1}\frac{1}{t!}\binom{N-1}{n}\left(\frac{m_1}{\lambda_1}\right)^{m_1+k}\left(\frac{m_2\phi}{\lambda_2}\right)^t\frac{(-1)^n b_k^n N}{\Gamma(m_1)^{N-1}} \\ \times\sum_{\ell=0}^{\infty}\frac{(-1)^\ell}{\ell!}\left(\frac{m_2\phi}{\lambda_2}\right)^\ell\Psi(x). \tag{22}$$

where

$$\Psi(x) = \begin{cases} \left(\dfrac{m_1(1+n)}{\lambda_1}\right)^{m_1-k+t+\ell}\Gamma\left(m_1+k-t-\ell,\ \dfrac{m_1(1+n)\gamma_{\text{th}}}{\lambda_1 P_{\text{S}}}\right), \\ \textit{with}\ \ m_1+k-t-\ell>1, & \text{(23a)} \\ \dfrac{(-1)^{q+1}}{q!}\left(\dfrac{m_1(1+n)}{\lambda_1}\right)^q \text{Ei}\left(-\dfrac{m_1(1+n)\gamma_{\text{th}}}{\lambda_1 P_{\text{S}}}\right)+\dfrac{\exp\left(-\frac{m_1(1+n)\gamma_{\text{th}}}{\lambda_1 P_{\text{S}}}\right)}{\left(\frac{\gamma_{\text{th}}}{P_{\text{S}}}\right)^q}\widetilde{\sum}, \\ \textit{with}\ \widetilde{\sum} = \displaystyle\sum_{j=0}^{q-1}\frac{(-1)^j\left(\frac{m_1(1+n)}{\lambda_1}\right)^j\left(\frac{\gamma_{\text{th}}}{P_{\text{S}}}\right)^j}{q(q-1)\cdots(q-j)},\ q = m_1+k-t-\ell<1. & \text{(23b)} \end{cases}$$

Proof: We rewrite (13) to become an independent product of two probability components, and let $X = \max\limits_{i=1,\dots,N}|h_{1,i}|^2$, $Y = |h_{\text{R}_n\text{D}}|^2$ and $Z = |h_{\text{SD}}|^2$ be the random variables Gamma distribution, which are modeled as $X \sim \mathcal{G}(m_1, \beta_1)$, $Y \sim \mathcal{G}(m_2, \beta_2)$ and $Z \sim \mathcal{G}(m_0, \beta_0)$, respectively.

Substituting (17) and (2) into (20), we get $\mathcal{I}(a,\phi)$ that is showed by the equations (24a).

$$\mathcal{I}(a,\phi) = 1-\left\{\sum_{k=0}^{n(m_1-1)}\sum_{t=0}^{m_2-1}\frac{1}{t!}\sum_{n=0}^{N-1}\binom{N-1}{n}\left(\frac{m_1}{\lambda_1}\right)^{m_1+k}\left(\frac{\phi m_2}{\lambda_2}\right)^t\frac{N(-1)^n b_k^n}{\Gamma(m_1)^{N-1}}\right\}\mathbb{J}(x) \tag{24a}$$

$$\text{where } \mathbb{J}(x) = \int_a^\infty x^{m_1+k-t-1}\exp\left(-\frac{\phi m_2}{x\lambda_2}-\frac{m_1(n+1)x}{\lambda_1}\right)dx. \tag{24b}$$

In the case of high transmit power, i.e $a = \frac{\gamma_{\rm th} N_0}{P_{\rm S \to \infty}} \to 0$, by applying [11, 3.471.9], we obtain $\mathcal{I}(a, \phi)$ as in (21), and then by replacing back (21) into (20), we obtain the approximation of outage probability expression as in (24b). However, this approximation is unsuitable for low transmit power which is basically applied for EH system. To obtain the closed-form of the outage probability expression for general case of transmit power, the exponential function is expanded by Taylor algorithm: $\exp\left(-\frac{a}{x}\right) = \sum\limits_{t=0}^{\infty} \frac{(-1)^t}{t!}\left(\frac{a}{x}\right)^t$. Therefore, the $\mathbb{J}(x)$ in (24b) is rewritten as

$$\mathbb{J}(x) = \sum_{\ell=0}^{\infty} \frac{(-1)^{\ell}}{\ell!}\left(\frac{m_2 \phi}{\lambda_2}\right)^{\ell} \underbrace{\int\limits_{a}^{\infty} x^{m_1+k-t-\ell-1} \exp\left(-\frac{m_1(1+n)x}{\lambda_1}\right) dx}_{\Psi(x)}. \tag{25}$$

Finally, by applying [11, Eq:3.351.211, Eq:3.351.4] for the integral term in (25), we have the $\Psi(x)$ that is given in (23a) and (23b). The proof of Proposition is completed. ■

4. Simulation Results

In this section, we show the Monte - Carlo simulation results and compare them with our theoretical analysis. We assume that the $\mathcal{R}$ is fixed as 1 bit/s/Hz, $\eta = 1$ (perfect current converter), $P_{\rm S}$ is constant, and $\alpha = 0.3$. The distance from S to D is normalized to unit value. We also assume that the relay node cluster is at the middle of the source and the destination. Moreover, all channels are identical independent distribution (i.i.d). For the sake of simplicity, the average channel gains are set as $\lambda_{1i} = \lambda_{2j} = \lambda_0 = 1$.

Fig. *3* illustrates the outage probability versus the average transmit power of the S. In order to reduce complexity, we choose $[m_1\, m_2\, m_3] = [2\,2\,2]$, where m_1, m_2, m_3 are the distribution parameters of the links S-R, R-D and S-D, respectively. The number of relays is changed within [1,5]. The result in Fig. *3* shows that the channel gain is increased by increasing the number of relays. The reason is, the selected best relay provides the best channel from the source to the relay in order to achieve better decoding performance as well as higher RF EH from the source in the first phase. Furthermore, it is clear that the theoretical analysis is perfect match with the simulation, it confirms the correctness of the proposed analysis approach.

Fig. *4* demonstrates the outage probability of the EH cooperative communication system with respect to the different parameters m, while other parameters are set to be the same as in Fig. *3*. In this figure, the excellent agreement between the analytical result and simulation result is also observed. When the parameter m is increased, the outage probability decreases. It is explained that the other diversity is improved by the $d = \min(\mathrm{m_x}, \mathrm{m_y})$, and then the system performance is improved significantly. In addition, when the quality of direct link is better than that of the forward link, the parameter m of forward link unaffects the system performance. The reason of this state

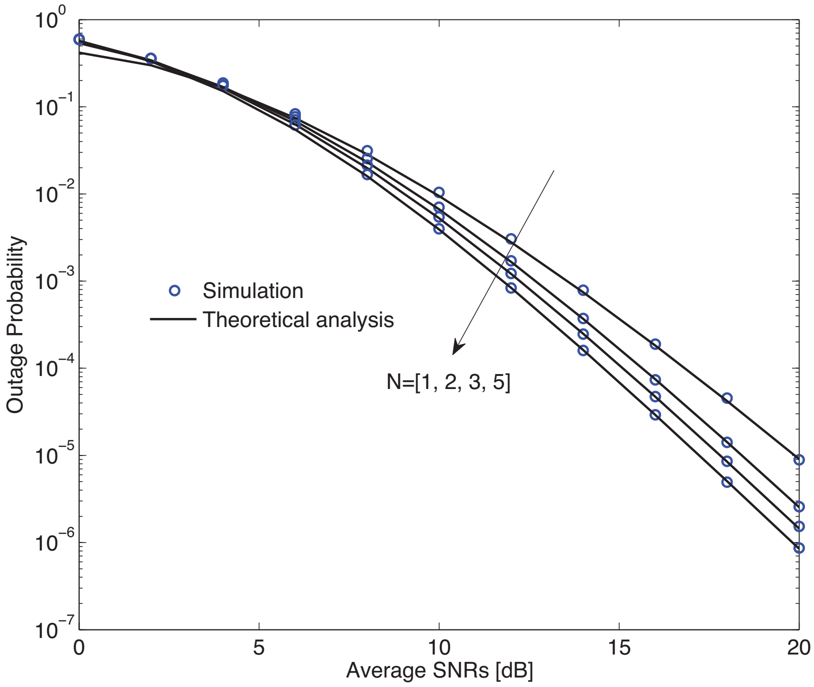

Fig. 3. The effect of relay numbers on the system performance.

is that the SNR threshold for demodulation of the destination depends on the SNR of the direct link.

5. Conclusions

In this paper, we derive the PDF of the order statistic for the equivalent instantaneous SNR of the EH cooperative communication with DF protocol. The derived PDF is then utilized to calculate the outage probability, especially the asymptotic and approximate outage probability. The system performance is analyzed based on different parameter m, channel gain and number of relay nodes. Our derivations are confirmed by Monte - Carlo simulations, the significant match of both theoretical and simulation results verifies our proposed analysis method.

The expansion method for incomplete Gamma function provided in this paper can be applied, and then save time for future investigations on EH DF relay systems. The derived equations also can be integrated with Matlab or Mathematica as an useful function to evaluate another system. Moreover, the results provided in this paper can play an important role in the design of practical wireless networks.

However, the system performance was theoretically analyzed while assuming the duration time for EH is fixed. The investigation of effect and optimization of duration

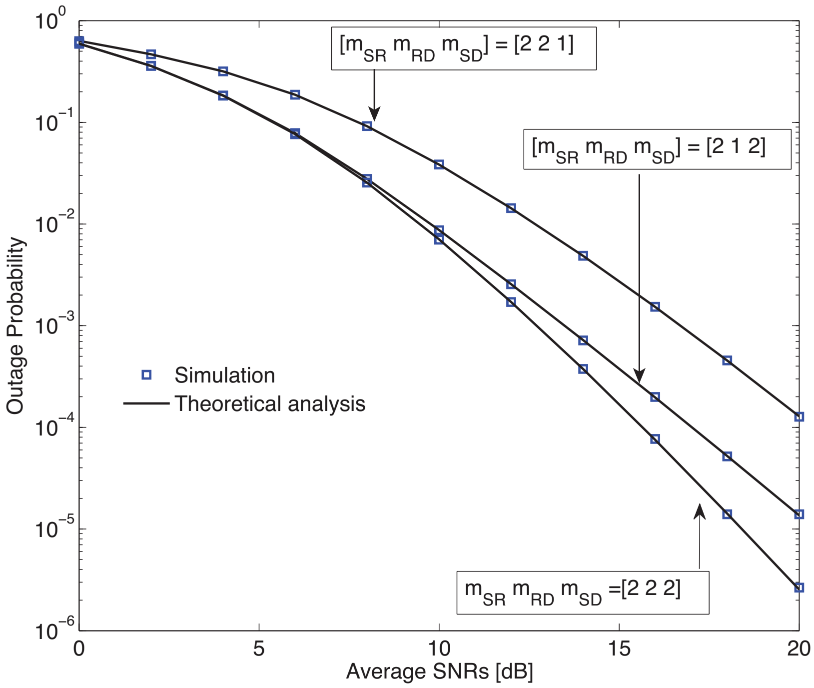

Fig. 4. The outage probability with different values of parameter m.

time for EH is left for the future work.

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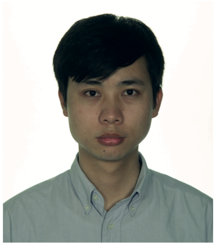

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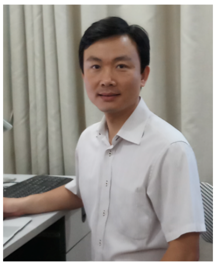

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PHÂN TÍCH HIỆU NĂNG HỆ THỐNG HỢP TÁC GIẢI MÃ CHUYỂN TIẾP ỨNG DỤNG THU THẬP NĂNG LƯỢNG VÔ TUYẾN

Tóm tắt

Bài báo phân tích hoạt động truyền tải thông tin và năng lượng đồng thời cho mạng truyền thông hợp tác. Trong hệ thống này, một nút nguồn truyền thông tin tới một nút đích thông qua đường truyền trực tiếp hoặc thông qua nút chuyển tiếp được lựa chọn. Giao thức giải mã và chuyển tiếp (DF: decode and forward) được sử dụng tại nút chuyển tiếp, và kĩ thuật lựa chọn kết hợp (SC: selection combination) được áp dụng tại nút nguồn để lựa chọn nút chuyển tiếp tốt nhất. Phẩm chất hệ thống được đánh giá qua xác suất dừng trên kênh có phân bố Nakagami-m. Phân tích giải tích và các phương trình gần đúng được đề xuất, tính toán và so sánh với mô phỏng Monte-Carlo. Kết quả mô phỏng tương đồng với kết quả tính toán, điều này chứng minh tính chính xác của phương pháp tính toán của chúng tôi.