On the Performance of Non-linear Wirelessly Powered Partial Relay Selection Networks over Rayleigh Fading Channels

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Abstract—**In this paper, we propose a partial relay selection protocol using decode-and-forward non-linear energy harvesting model. For performance evaluation, we derive an analytical expression of outage probability for the proposed protocol over Rayleigh fading channels. Monte Carlo simulations are then performed to verify the theoretical results. The results present the efficiency of the relay selection method. Moreover, from the results obtained, the optimal value of the time switching is also investigated.**

Index Terms—**Non-linear energy harvester, partial relay selection, cooperative communication.**

I. INTRODUCTION

Cooperative communication using relays has been recognized as an efficient way to extend coverage of wireless networks. Two relaying protocols commonly used for cooperative networks are amplify-and-forward (AF) and decode-and-forward (DF) [1], [2]. In the AF protocol, the relay amplifies the received signals from the source and then forwards the amplified signal to the destination. In the DF protocol, the relay decodes the source signal, re-encodes and then forwards the encoded signal to the destination. Once there are multiple relays available, relay selection protocols such as partial selection [3], [4] or full selection [3], can be used. In [5]–[7], the best relay selection systems are introduced to obtain full diversity gain in multi relay scenarios. However, since best relay selection (BRS) is typically based on the instantaneous end to end signal to noise ratio (SNR), a signaling overhead is required for channel state information (CSI) acquisition and feedback. To reduce the required amount of CSI for relay selection, partial relay selection (PRS) has been proposed [3]. Conventionally, the relay nodes use their own energy to relay the signal. As a result, their energy can rapidly drain out, leading to drastically reduce the network's lifetime.

Recently, harvesting energy from ambient environment has become a promising solution for energy-constrained electronic devices, which are conventionally supported by limited power sources such as battery. In some special applications, charging battery is too expensive or even impossible, e.g., sensor network working under toxic environment and body-area network. In addition to some natural energy sources such as solar and wind, radio frequency (RF) signal can be also utilized as an effective source for energy harvesting (EH).

Compared with other kinds of sources, RF-based energy harvesting, also called wireless energy transfer, has some unique advantages. Since it is an active energy supply way, RF energy harvesting can provide more reliable energy flow to guarantee the performance of system. Wireless communication with EH nodes has recently drawn signicant research attention [8], [9]. In particular, the authors in [10] first considered the rate-energy tradeoff model. Then, energy harvesting in the single input-multiple output (SIMO) networks was investigated in [11]. The joint wireless information and energy transfer in a two-user multiple input-multiple output orthogonal frequency division multiplexing (MIMO-OFDM) interference channel was considered in [12], [13]. In order to use energy effectively, the authors of [14] proposed a scheme for opportunistic wireless energy harvesting in cognitive radio networks.

Besides point-to-point communication systems, the MIMO-OFDM relaying protocol was proposed in [15], where the relay nodes have energy-constrained and all relays transmit concurrently and sequentially over orthogonal channels. Works [16]–[21] addressed energy harvesting in cooperative communication relaying. In the article [16], the authors considered the relay node having an the packet power arrival buffer for forwarding messages in second phase. The optimal relay node selection depending on the channel SNR and the amount of harvested energy stored by the nodes was proposed in [17]. Indeed, [17] proposed offline and online (realtime) joint relay selection and source-relay transmit power allocation schemes that maximize the end to end system throughput over a finite number of transmission intervals.

However, the implementation of this work in practice is very difficult. In [22], the throughput maximization problem for the orthogonal relay channel with EH source and relay nodes was studied, where a deterministic EH model under the Gaussian relay channel is assumed. In order to exploit spatial diversity, [23] proposed a relay selection method, which shows that the performance gain not only depends on the amount of harvested energy but also depends on the number relay nodes. But in [23], the authors assumed that processing arrival energy is static and ergodic.

In most literature above, the total harvested energy at relay is formulated as a linear model. But, in practice, energy harvesting circuits usually comprise diodes, inductors and capacitors, which have responsive non-linear outputs leading causal saturation threshold. Besides, energy arrived at the relay also changes. In practice, EH circuits usually result in a non-linear end-to-end wireless power transfer [24]. Hence, the conventional linear EH model cannot properly model the power dependent EH efficiency, which leads to a mismatch for

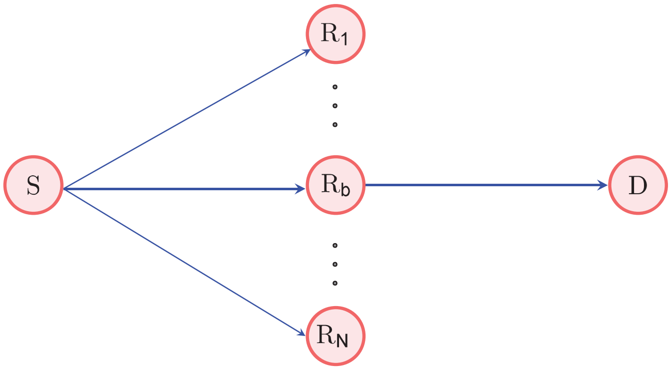

Fig. 1. Wirelessly powered partial selection relaying Networks.

resource allocation. In addition, the system outage probability (OP) expression is not in closed-form.

In this paper, we address the above issues by considering a practical parametric non-linear EH harvesting model with partial relay selection and verify its accuracy with measurement data versus OP. The relay with non-linear energy harvester is solely powered by the harvested energy from the RF signals of the source node. As a result, the transmit power of the relay depends both on the transmit power of the source and the saturation threshold of the energy harvested. Specifically, closed-form expressions for the outage probability is derived using the statistical characteristic of the SNR. We apply the joint probability properties to obtain an analytical expression for the distribution of the received SNR. To assess the system performance, we also derive the analytical expression of OP. The main contributions of the paper are summarized as follows:

- We study the non-linear energy harvesting model for partial relay selection with decode-and-forward relaying.
- We derive the analytical expression of the system outage probability and investigate the effect of the key channel and system parameters on the system performance.

The rest of this paper is organized as follows. Section II describes the system model and presents the proposed relay selection protocol. The derivation of the system outage probability is presented in Section III and Section IV. Section V shows simulation results to verify the theoretical analysis. Finally, the conclusions are given in Section VI.

II. SYSTEM MODEL

We consider a decode-and-forward (DF) relaying communication system, where a source node, denoted by S, communicates with a destination node, denoted by D, in the presence of N relays, denoted by R_n with $n = 1, 2, \ldots, N$, as shown in Fig. 1. All nodes are equipped with a single antenna and operates in a half-duplex mode. We assume that all relays have no fixed power supply and then powered by wireless power transfer from the source.

There is no direct link from S $\rightarrow$ D due to far distance or deep shadow-fading. We assume that all wireless links exhibit frequency non-selective Rayleigh block fading, i.e., channel coefficients are constant during one block time T and independent and identically distributed (i.i.d.) from one slot to the next. In addition, we assume that the CSI is available at any terminals in the network.

Let us denote h_{SR_n} and $h_{\mathsf{R}_n\mathsf{D}}$ as channel coefficients of the $\mathsf{S} \rightarrow \mathsf{R}_n$ and $\mathsf{R}_n \rightarrow \mathsf{D}$ link, respectively. Under Rayleigh fading channels, channel gains, i.e., $|h_{\mathsf{SR}_n}|^2$ and $|h_{\mathsf{R}_n\mathsf{D}}|^2$, are exponential random variables (RVs) with $\lambda_{1,n}$ and $\lambda_{2,n}$, respectively. Since all relays are assumed to be grouped in one cluster by node geographical proximity based clustering algorithms [25], we can have $\lambda_{1,n} = \lambda_1$ and $\lambda_{2,n} = \lambda_2$ $\forall n$.

Under time switching (TS) energy harvesting model [20][1], the communication from the source to the destination is separated into three consecutive time slots including energy transmission, information transmission and information reception. For the given total block duration T, the corresponding duration for each time slot are $(1-\alpha)T$, $(1-\alpha)T/2$, and $(1-\alpha)T/2$ with $0 \leq \alpha \leq 1$.

In the first time-slot, all relays wirelessly harvest energy from the source and convert into a voltage of direct current (DC) by using appropriate circuits. The received signal at relay R_n, denoted by y_{R_n}, due to the source transmission is given by

$$y_{\mathsf{R}_n} = \sqrt{P_{\mathsf{S}}} h_{\mathsf{SR}_n} s + n, \tag{1}$$

where P_{S} is the average transmitted power of the source, s is the transmitted signal, and n is the baseband additive white Gaussian noise (AWGN) with variance N_0.

Using partial relay selection [26], [27], the relay having the best harvest energy will be the decoder in the second timeslot and the forwarder in the third timeslot. Denoting R_b as the selected relay, we have

$$\mathsf{R}_b = \arg\max_{n=1,2,\ldots,N} \gamma_{\mathsf{SR}_n}, \tag{2}$$

where $\gamma_{\mathsf{SR}_n} = P_{\mathsf{S}}|h_{\mathsf{SR}_n}|^2/N_0$ denotes the instantaneous SNR of the $\mathsf{S} \rightarrow \mathsf{R}_n$ link.

The harvested energy of the selected relay in an amount of time αT is given as [20]

$$E_h = \alpha T \eta P_{\mathsf{S}} \max_{n=1,\ldots,N} |h_{\mathsf{SR}_n}|^2, \tag{3}$$

where $0 < \eta \leq 1$ is the energy conversion efficiency, which depends on the rectification process and the energy harvesting circuitry.

Assuming that all harvested energy during the first timeslot is totally used to forward the source data towards the destination, the transmit power of the selected relay can be written as

$$P_{\mathsf{R}} = \frac{2\alpha\eta P_{\mathsf{S}}}{1-\alpha} \max_{n=1,\ldots,N} |h_{\mathsf{SR}_n}|^2. \tag{4}$$

In this paper, we adopt the non-linear energy harvesting model as shown in Fig. 2. Such a model is able to capture the joint effect of the non-linear phenomena caused by hardware

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[1] The proposed analysis approach can be applied for the power spitting energy harvesting model.

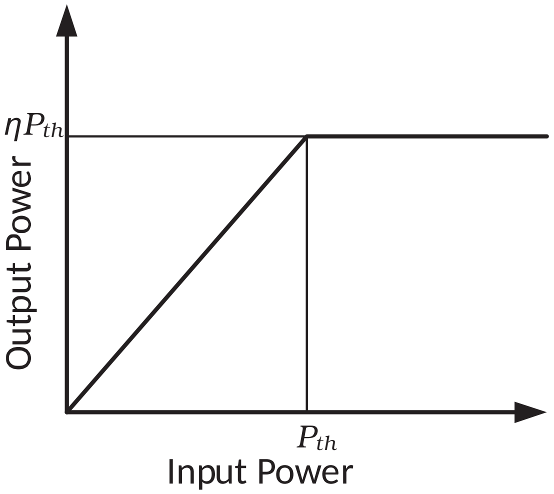

Fig. 2. Characteristic non-linear output.

constraints including circuit sensitivity limitations and current leakage. In particular, the energy harvester will output a constant power denoted by ηP_{th}, when the input power is beyond the threshold P_{th}. Hence, the transmit power of the selected relay is re-written as follows:

$$\begin{aligned} P_{\mathsf{R}} =& \frac{2\alpha\eta}{1-\alpha}\min(P_{\mathsf{S}}|h_{\mathsf{SR}_b}|^2, P_{\mathrm{th}}) \\ =& \begin{cases} \frac{2\alpha\eta}{1-\alpha}P_{\mathsf{S}}|h_{\mathsf{SR}_b}|^2, & P_{\mathsf{S}}|h_{\mathsf{SR}_b}|^2 \le P_{\mathrm{th}} \\ \frac{2\alpha\eta}{1-\alpha}P_{\mathrm{th}}, & P_{\mathsf{S}}|h_{\mathsf{SR}_b}|^2 > P_{\mathrm{th}} \end{cases}. \end{aligned} \tag{5}$$

From (5), the instantaneous SNR of the second hop is given as

$$\gamma_{\mathsf{R}_b\mathsf{D}} = \begin{cases} \frac{2\alpha\eta}{(1-\alpha)N_0}P_{\mathsf{S}}|h_{\mathsf{SR}_b}|^2|h_{\mathsf{R}_b\mathsf{D}}|^2, & P_{\mathsf{S}}|h_{\mathsf{SR}_b}|^2 \le P_{\mathrm{th}} \\ \frac{2\alpha\eta}{(1-\alpha N_0}P_{\mathrm{th}}|h_{\mathsf{SR}_b}|^2, & P_{\mathsf{S}}|h_{\mathsf{SR}_b}|^2 > P_{\mathrm{th}} \end{cases}. \tag{6}$$

For DF relaying, the instantaneous end-to-end SNR received at the destination, γ_Σ, can be written as [28], [29]

$$\gamma_\Sigma = \min(\gamma_{\mathsf{SR}_b}, \gamma_{\mathsf{R}_b\mathsf{D}}). \tag{7}$$

III. OUTAGE ANALYSIS

In this section, we will derive the system outage probability over Rayleigh fading channels. The system outage probability is mathematically defined as

$$\mathrm{OP} = \Pr\left[\frac{1-\alpha}{2}\log_2(1+\gamma_\Sigma) < \mathcal{R}\right], \tag{8}$$

where $\mathcal{R}$ denotes the target rate and γ_Σ is the end-to-end SNR. It is noted that the pre-factor of $\frac{1-\alpha}{2}$ is due to the three consecutive time slots for communication between the source and the destination. Combining (7) and (8), the system outage probability can be re-expressed as follows:

$$\begin{aligned} \mathrm{OP} &= \Pr[\min(\gamma_{\mathsf{SR}_b}, \gamma_{\mathsf{R}_b\mathsf{D}}) \le \gamma_{\mathrm{th}}] \\ &= 1 - \Pr[\min(\gamma_{\mathsf{SR}_b}, \gamma_{\mathsf{R}_b\mathsf{D}}) > \gamma_{\mathrm{th}}], \end{aligned} \tag{9}$$

where $\gamma_{\mathrm{th}} = 2^{2\mathcal{R}/(1-\alpha)} - 1$.

The analytical expression for OP over Rayleigh fading is given in the following Theorem.

Theorem 1. *The outage probability of wirelessly powered partial relay selection networks under non-linear energy harvesting model can be expressed as*

$$\mathrm{OP} = 1 - (\mathcal{I}_1 + \mathcal{I}_2) \tag{10}$$

with

$$\begin{aligned} \mathcal{I}_1 =& \delta(\gamma_{\mathrm{th}} - P_{\mathrm{th}}) \\ & \times \sum_{n=1}^{N}(-1)^{n-1}\binom{N}{n}\sum_{t=0}^{N_t}\frac{(-1)^t}{t!}\left(\frac{\gamma_{\mathrm{th}}N_0}{\lambda_2\phi P_{\mathsf{S}}}\right)^t\left(\frac{n}{\lambda_1}\right)^t \\ & \times \left[\Gamma\left(1-t, \frac{n\gamma_{\mathrm{th}}N_0}{\lambda_1 P_{\mathsf{S}}}\right) - \Gamma\left(1-t, \frac{nP_{\mathrm{th}}N_0}{\lambda_1 P_{\mathsf{S}}}\right)\right] \end{aligned} \tag{11}$$

and

$$\mathcal{I}_2 = \begin{cases} \sum\limits_{n=1}^{N}(-1)^{n-1}\binom{N}{n}\exp\left(-\frac{n\gamma_{\mathrm{th}}N_0}{\lambda_1 P_{\mathsf{S}}} - \frac{\gamma_{\mathrm{th}}N_0}{\lambda_2\phi P_{\mathrm{th}}}\right), & P_{\mathrm{th}} \le \gamma_{\mathrm{th}} \\ \sum\limits_{n=1}^{N}(-1)^{n-1}\binom{N}{n}\exp\left(-\frac{n\gamma_{\mathrm{th}}N_0}{\lambda_1 P_{\mathsf{S}}} - \frac{\gamma_{\mathrm{th}}N_0}{\lambda_2\phi P_{\mathrm{th}}}\right), & P_{\mathrm{th}} > \gamma_{\mathrm{th}} \end{cases} \tag{12}$$

where $\delta(x)$ is the step function and $N_t \in [1,\infty)$ denotes the number of truncated terms.

Proof. We start the proof by rewriting OP as

$$\begin{aligned} \mathrm{OP} = 1 - & \underbrace{\Pr[\min(P_{\mathsf{S}}X, P_s\phi XY) > \gamma_{\mathrm{th}}, P_{\mathsf{S}}X < P_{\mathrm{th}}]}_{\mathcal{I}_1} \\ & - \underbrace{\Pr[\min(P_{\mathsf{S}}X, \phi P_{\mathrm{th}}Y) > \gamma_{\mathrm{th}}, P_sX \ge P_{\mathrm{th}}]}_{\mathcal{I}_2}, \end{aligned} \tag{13}$$

where $X = \max_{n=1,\ldots,N}|h_{\mathsf{SR}_n}|^2$ and $Y = |h_{\mathsf{R}_b\mathsf{D}}|^2$.

Using conditional probability, $\mathcal{I}_1$ is rewritten as

$$\mathcal{I}_1 = \begin{cases} 0, & P_{\mathrm{th}} \le \gamma_{\mathrm{th}} \\ \int\limits_{\frac{\gamma_{\mathrm{th}}N_0}{P_{\mathsf{S}}}}^{\frac{P_{\mathrm{th}}N_0}{P_{\mathsf{S}}}} f_X(x)\int\limits_{\frac{\gamma_{\mathrm{th}}N_0}{\phi P_{\mathsf{S}}x}}^{\infty} f_Y(y)dxdy, & P_{\mathrm{th}} > \gamma_{\mathrm{th}}. \end{cases} \tag{14}$$

To obtain $\mathcal{I}_1$ in closed-form expression, we need the PDF of X and Y. Since $X = \max_{n=1,\ldots,N}|h_{\mathsf{SR}_n}|^2$ and assuming that all links in the first hop are independent, the CDF of γ_{SR_b} is given as [26]

$$F_X(x) = \prod_{n=1}^{N}\left[1 - \exp\left(-\frac{x}{\lambda_1}\right)\right], \tag{15}$$

leading to PDF of X thanks to the binomial expansion [30, (1.111)] as

$$f_X(x) = \sum_{n=1}^{N}(-1)^{n-1}\binom{N}{n}\frac{n}{\lambda_1}\exp\left(-\frac{nx}{\lambda_1}\right). \tag{16}$$

Over Rayleigh fading channel, the PDF of Y is of the form

$$f_Y(y) = \frac{1}{\lambda_2}\exp\left(-\frac{y}{\lambda_2}\right). \tag{17}$$

Substituting (16) and (17) into (14) gives

$$\mathcal{I}_1 = \begin{cases} 0, & P_{\rm th} \leq \gamma_{\rm th} \\ \Theta \int\limits_{\frac{\gamma_{\rm th} N_0}{P_{\sf S}}}^{\frac{P_{\rm th} N_0}{P_{\sf S}}} \exp\left(-\frac{nx}{\lambda_1} - \frac{\gamma_{\rm th} N_0}{\phi P_{\sf S} x}\right) dx, & P_{\rm th} \leq \gamma_{\rm th} \end{cases}, \tag{18}$$

where

$$\Theta = \sum_{n=1}^{N} (-1)^{n-1} \binom{N}{n} \frac{n}{\lambda_1}. \tag{19}$$

Applying the Taylor expansion, i.e.,

$$\exp\left(-\frac{\gamma_{\rm th} N_0}{\phi P_{\sf S} x}\right) = \sum_{t=0}^{\infty} \frac{(-1)^t}{t} \left(\frac{\gamma_{\rm th} N_0}{\phi P_{\sf S} x}\right)^t, \tag{20}$$

and then making a change of variable, i.e., $x = y + \frac{\gamma_{\rm th}}{N_0} P_{\sf S}$, we have

$$\mathcal{I}_1 = \sum_{t=0}^{\infty} \sum_{n=1}^{N} \frac{(-1)^t}{t!} (-1)^{n-1} \binom{N}{n} \frac{n}{\lambda_1} \left(\frac{\gamma_{\rm th} N_0}{\lambda_2 \phi P_{\rm th}}\right)^t e^{-\frac{n \gamma_{\rm th} N_0}{\lambda_1 P_{\sf S}}} \times \int\limits_{0}^{\frac{P_{\rm th} N_0}{P_{\sf S}} - \frac{\gamma_{\rm th} N_0}{P_{\sf S}}} \frac{e^{-\frac{ny}{\lambda_x}}}{\left(y + \frac{\gamma_{\rm th} N_0}{P_{\sf S}}\right)^t} dy. \tag{21}$$

With the help of the identity [30, (3.462.17)], we obtain the desired result for (21) as shown in (11), where $\Gamma(a, x)$ is the upper incomplete Gamma function [30, (8.350)].

For $\mathcal{I}_2$, it is noted that since $P_{\sf S} |h_{{\sf SR}_b}|^2 > P_{\rm th}$, the output of the energy harvester is saturated leading to the fact that $\gamma_{{\sf SR}_b} = \frac{P_{\sf S} |h_{{\sf SR}_b}|^2}{N_0}$ and $\gamma_{{\sf R}_b {\sf D}} = \frac{2\alpha\eta P_{\rm th} |h_{{\sf R}_b D}|^2}{(1-\alpha) N_0}$ are independent. As a result, $\mathcal{I}_2$ is written as

$$\mathcal{I}_2 = \begin{cases} \int\limits_{\frac{\gamma_{\rm th}}{N_0} P_{\sf S}}^{\infty} f_X(x) \int\limits_{\frac{\gamma_{\rm th}}{N_0} \phi P_{\rm th}}^{\infty} f_Y(y) dx dy, & P_{\rm th} \leq \gamma_{\rm th} \\ \int\limits_{\frac{P_{\rm th}}{N_0} P_{\sf S}}^{\infty} f_X(x) \int\limits_{\frac{\gamma_{\rm th}}{N_0} \phi P_{\rm th}}^{\infty} f_Y(y) dx dy, & P_{\rm th} > \gamma_{\rm th}. \end{cases} \tag{22}$$

Substituting (16) and (17) into (14) yields the closed-form expression for $\mathcal{I}_2$ as shown in (12). Having $\mathcal{I}_1$ and $\mathcal{I}_2$ at hands, we can obtain the system OP at (8).

□

IV. THROUGHPUT

The throughput is determined by evaluating the outage probability, OP, at a fixed source transmission rate, i.e., $\mathcal{R}$ bits/sec/Hz. Let $\mathcal{R}$ be a fixed transmission rate that the source need to satisfy such that $\mathcal{R} = \log_2(1 + \gamma_{\rm th})$, where $\gamma_{\rm th}$ is the threshold value of SNR for correct data detection. For delay-limited transmission, the system throughput is given by

$$\tau = (1 - {\rm OP}) \mathcal{R} \frac{(1-\alpha) T/2}{T} = \frac{\mathcal{R}}{2} (1-\alpha)(1 - {\rm OP}). \tag{23}$$

The factor 1/2 accounts for the fact that two transmission phases are involved in the communication between the source to destination.

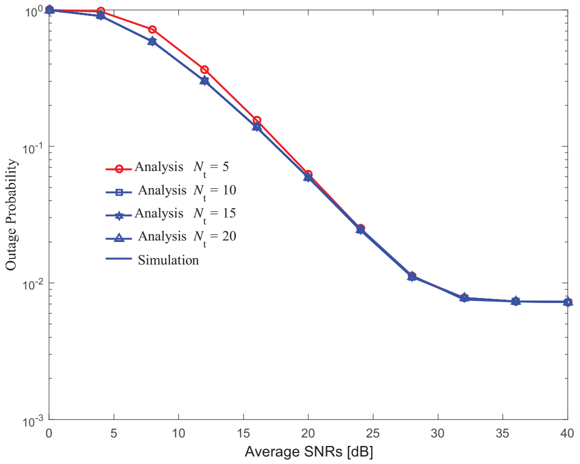

Fig. 3. Convergence of OP with truncated dominant terms, $\alpha = 0.3$, $N = 3$ and $P_{\rm th} = 30$ [dB]

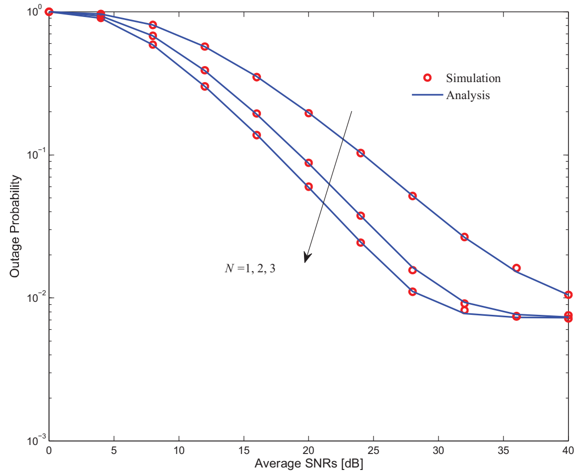

Fig. 4. Outage probability versus the transmit power of the source at different values of the number of relays N with $\alpha = 0.3$ and $P_{\rm th} = 30$ dB.

V. SIMULATION RESULTS

In this section, Monte-Carlo simulations are presented to verify our derivations. For illustrative purpose, the system settings are set as follows: $\mathcal{R} = 1$ and $\eta = 1$. In addition, we set $\lambda_1 = 1$ and $\lambda_2 = 1$.

We first investigated the impact of the number dominant terms $N_{\rm t}$ on the accuracy of the system outage probability. We increase $N_{\rm t}$ from 5 to 20. It can be seen that increasing $N_{\rm t}$ will improve the OP accuracy. For example, $N_{\rm t} \geq 10$ has been found sufficiently to provide accurate OP as compared with simulation results in all range of SNRs.

Fig. 4 shows the system outage probability as a function of the average transmit power of the source. For low SNRs, i.e., $P_{\sf S} \leq 30$ dB, increasing the average transmit power of the source will decrease the system outage probability. However,

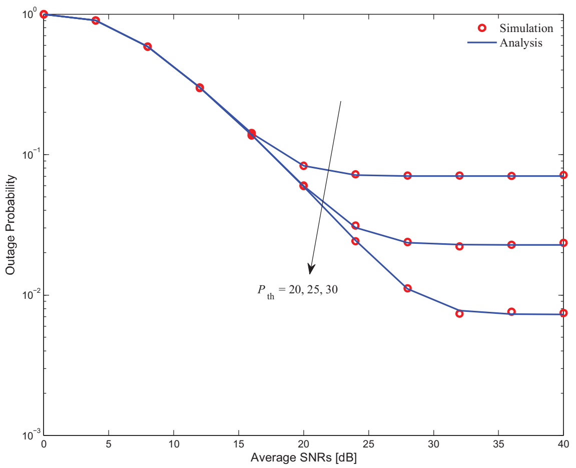

Fig. 5. Outage probability versus the transmit power of the source at different values of the saturation threshold with $N = 3$ and $\alpha = 0.3$.

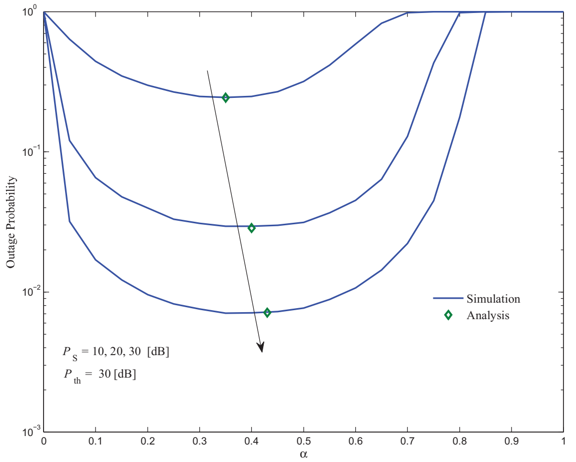

Fig. 6. Outage probability versus the time switching, α, with $N = 3$.

it is saturated at a certain level of P_S, i.e., $P_S \le 30$ dB, which is determined by $P_{\rm th}$. Fig. 4 also confirms the advantage of partial relay selection at low SNR regime but not high SNR regime. In particular, increasing the number of relays will not improve the system outage probability at the high SNR regime.

In Fig. 5, we investigate the system outage probability for different values of the saturation threshold, i.e, $P_{\rm th} = 20, 25, 30$ dB. As expected, the increase of $P_{\rm th}$ will significant improve the system performance at high SNRs. We also see that the analysis results are in excellent agreement with the simulation ones confirming the correctness of the proposed analysis approach. In Fig. 6 and 7, we study the effect of α on the system performance. We can see that there exists an optimal value of α, denoted as $\alpha_{\rm opt}$, which minimizes the system outage probability. Mathematically speaking, $\alpha_{\rm opt}$ can be obtained by solving the optimal problem as follows:

$$\begin{array}{l} \alpha_{\rm opt} = \arg \min\limits_{\alpha} \mathrm{OP}\left(\alpha\right) \\ \mathrm{subject\,to}\ 0 < \alpha < 1 \end{array}. \tag{24}$$

With the current form of OP in (8), it is very difficult to obtain the closed form expression for $\alpha_{\rm opt}$. Observing from the results in Fig. 6 and 7, we can see that $\alpha_{\rm opt}$ tends to increase when the number of relays, N, or the average transmit power of the source, P_S, increases.

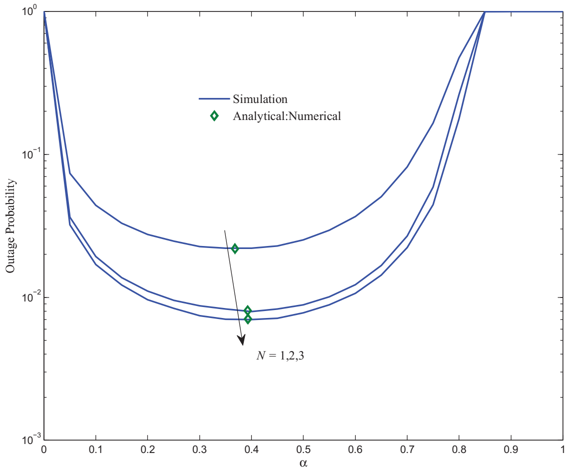

Fig. 7. Outage probability versus the time switching, α, with $N = 1, 2, 3$, $P_{\rm th} = 30$ [dB] and $P_S = 30$ [dB].

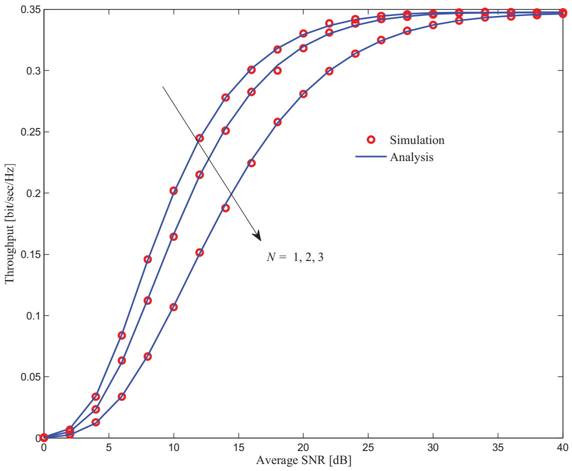

Fig. 8. Throughput versus the average SNR, $P_{\rm th} = 30$ [dB], $P_S = 10$ [dB].

In Fig. 8, we show the throughput versus SNR using TS. We can observe that the throughput is better when increasing the number of relays. As illustrated, the analytical results are in good agreement with the Monte Carlo simulation, which validates our derivations.

As show in Fig. 9, the energy harvesting ratio α increases from 0.1 to 0.8, the throughput of system increases at first

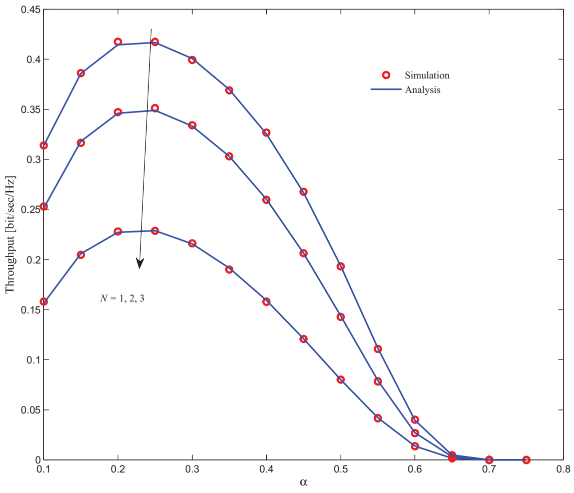

Fig. 9. Throughput versus the TS, α, $P_{\rm th} = 30$ [dB], $P_{\rm S} = 10$ [dB].

until $\alpha_0 = 0.1$ reaches the optimal value where the throughput gets its maximum, and thereafter decreases from the maximum to zero. We can see that the optimal value of the system throughput is not a function of relays.

VI. CONCLUSIONS

In this paper, we have investigated the effect of non-linear energy harvesting model on the performance of wirelessly powered partial relay selection networks. We have obtained the closed-form expression for the system outage probability over Rayleigh fading channels. Numerical results shown that the simulation and theoretical results are in good agreement.

VII. ACKNOWLEDGMENT

This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 102.04-2014.32.

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