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Relay Selection and Performance Analysis of Wireless Energy Harvesting Networks

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Abstract

We proposed an integrated information relay and wireless power supply assisted RF energy harvesting-based cooperative dual-hope decode-and-forward (DF) relaying communication model. The relay node not only aids the communication between energy constrained source and destination but also supply power to them using time switching (TS) protocol. We also proposed a relay selection protocol where the source is capable of selecting an appropriate relay link on the basis of channel gain condition. The performance of the system in terms of outage probability and achievable ergodic capacity over Rayleigh fading channels are thoroughly analyzed. Closed from analytical expression of outage probability of the considered system is derived and authenticated by the Monte-Carlo simulation result. The results show the impact of the number of relay nodes on outage probability and achievable ergodic capacity. Simulation results also demonstrated the optimum energy harvesting time for which system achieves maximum throughput and minimum outage probability.

Keywords Energy harvesting · DF-relay · WPCN · Outage probability

1 Introduction

In modern wireless communication, significant enhancement in the application of wireless sensor networks (WSNs) ranging from environmental monitoring to human health control and security, further increases the problem of prolonging network lifetime. To address the

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expensive and inconvenient process of changing or recharging batteries, energy harvesting (EH) emerged as a useful technique that can prolong the battery life of wireless devices [1, 2]. In compared to various conventional EH methods, such as solar, thermoelectric effects, wind, vibration, etc., wireless energy harvesting (WEH) has received significant attention due to the controllability and predictability in the harvested energy. In WEH, the antenna of sensor nodes (SNs) receive ambient radio frequency radiation and converts into a direct current (DC) voltage using an appropriate rectifier circuit [3, 4]. Fundamental concepts of EH sensor nodes and its applications are discussed in [5]. The harvested energy is stored in batteries for using at the time of information transmission. This architecture of EH receiver is commonly categorized as power splitting (PS) receiver and time switching (TS) receiver. In a PS receiver, a fraction of power of the received signal is used for EH and the remaining power is used for information processing; whereas in TS, the EH receiver switches between energy harvesting and information processing.

EH is popularly implemented in cooperative relaying networks, where single or multiple intermediate nodes assist to transit the information of source in the direction of destination to extend coverage of wireless networks. Amplify-and-forward (AF) and decode-and-forward (DF) are two commonly used relaying protocols [6]. In the AF protocol, the relay node forwards the received signal towards destination after amplification. On the other hand, in the DF protocol, relay node first decodes the received signal and then forwards the representation of the decoded signal towards the destination. The relay nodes require own energy during forwarding the source signal. Hence, if energy of the relay node is drained out, it will not be able to assist the relaying transmission. Improvement in the joint wireless energy and information transfer techniques are addressed by adopting two network architectures; wireless powered communication networks (WPCNs) and simultaneous wireless information-and-power transfer (SWIPT) [7, 8]. In SWIPT, the directions of data transmission signal and energy harvesting signal are the same, and in WPCN, the directions are opposite. The fundamental performance metrics of the SWIPT in a heterogeneous cellular network are thoughtfully exploited in [9], and an overview of the WPCNs and the techniques of enhancing corresponding performances are studied in [10]. The goal of this paper is to analyze the outage performance of wireless EH DF-relaying-based unidirectional communications in sensor networks.

1.1 Related Works

Several works considering PS and TS-based protocols have been carried out to analyze the performance of AF and DF based EH relay networks. In [11, 12] throughput and outage performances of TS, PS and TS-PS protocol have been analyzed for a WEH in a DF relay network. In [13, 14], the authors have implemented EH to analyze the outage performance of multihop cognitive radio (CR) network, where all the secondary users harvest energy from dedicated power beacon (PB). The authors have considered a battery-assisted EH in two- hop AF relay networks and compared the performance of TS and PS relay protocol in terms of throughput and level of energy consumption in [15]. An AF relaying EH network with time power switching based protocol is also considered to investigate the outage probability and system throughput in [16]. Combining both the WPCN and SWIPT network architectures, authors have developed a DF relay based WEH system model to analyze the optimal system performance in [17]. In [18], the authors have proposed a relay selection protocol of a TS-based dual hop DF relay network where to forward the received signal, the best relay was selected based on the level of harvested energy. In [19], the best relay was selected on the basis of a best end-to-end SNR from source to destination in non identical Rayleigh faded channel. In [20], the source and relays harvest energy from a multi-antenna beacon in SWIPT mode. In [21], both AF and DF schemes of relay selection protocol are used in the multi-hop scenario and evaluated the performance of a secondary network. Outage probability minimization problem is addressed in EH enabled DF relay based CR networks and determined the relay harvesting time, source and relay power [22].

In [23], authors have presented a performance analysis of three power distribution algorithms namely water-filling method, equal power distribution and channel-gain-based power allocation techniques to maximize system throughput of a relay-based wireless EH network. Joint optimization of time and power allocation for maximizing the average throughput of an EH-based relaying cooperative IoT network is presented [24]. One relaying node has been considered which harvests power from renewable energy supply then only charges the IoT nodes. However, outage probability analysis is out of the scope of these articles [23, 24]. Outage performance of a SWIPT-based two-way DF relay network employing PS protocol has been presented in [25]. An optimal PS ratio for information and energy transfer are derived. Authors in [26] have minimized the outage probability of a bidirectional SWIPT-based DF relaying EH network in the context of underlay cognitive radio systems. A TS-based full-duplex EH enabled bidirectional DF relaying network has been considered to analyze the outage performance, average throughput and optimal EH time in [27]. Because of considering only a single relay node between source and destination, implementing a relay node selection technique was not required in [24–27]. Impacts of the position of the relay node on achieving system throughput and outage probability are numerically investigated in [28]. An optimal time for information allocations and energy transmission is also derived.

1.2 Motivation and Contributions

A numerous literatures have optimized cooperative relaying for improving and analyzing the efficiency and performances of WPCN or SWIPT. Recent works have considered the relay node is power constrained in [15, 29] and hybrid access-point (HAP) where both the source and relay are powered considered in [26, 27, 30, 31]. In this paper, similar to [17, 18, 30], both the WPCN and SWIPT are combined in a WEH system where both the source and destination are energy constrained and analyzed the throughput and outage performances of a cooperative dual hope DF relaying protocol. Different from [17, 30, 18], the WPCN can select an appropriate relay channel based on the channel gain quality of $\mathcal{S}$ -to-$\mathcal{R}$ link. A relay selection strategy has been proposed in a CR system to enhance the information transmission from source to destination in [32]. Another relay selection protocol is also proposed in [18]. However, unlike to our article, relay was selected based on the amount of energy harvested at each relay. TS-EH protocol is adopted for EH and information transmission.

Based on the channel gain quality of source to relay nodes, we have implemented a relay selection scheme to forward information from source to destination via a relay node. Unlike [26, 27] TS-based EH and information transmission protocol is applied to unidirectional DF relaying energy harvesting network. To get the practical design insights of a cooperative DF relaying protocol based WEH system, we have derived a closed-form analytical expression of outage probability and ergodic capacity of cooperative DF relaying protocol based WEH system for Rayleigh fading channels. A simulation-based optimal energy harvesting time for minimum outage probability and maximum ergodic capacity are also investigated here. The interplay among various system parameters have been presented to analyze the performances of the proposed WPCN and SWIPT-based WEH system.

The rest of the paper is organized as follows-system model is described in Sect. 2. Problem formulation has been presented in Sect. 3. The results and discussion are explained in Sect. 4. Finally, the conclusion is drawn in Sect. 5.

2 System Model

We considered a wireless network consist of one source, one destination and L number of relay nodes ($\mathcal{R}$) as shown in Fig. 1. Both the source and destination nodes are energy constrained, i.e., they need to harvest energy first from RF signal and then can communicate with each other. It is assumed that there is no direct path from source ($\mathcal{S}$) to destination ($\mathcal{D}$). Hence, source communicates to the destination via ($R_i, i = 1, 2, \ldots, L$) one of the intermediate relay nodes. The relay is selected depending on the channel gain quality from source to relay. The relay nodes are connected with a huge battery and continuously able to communicate with source and destination. Source communicates to a destination in half duplex mode.

It is assumed that the channel coefficients $\mathcal{S}$-to-$\mathcal{R}$ (h_{SR_i}), $\mathcal{R}$-to-$\mathcal{D}$ (h_{R_iD}) and $\mathcal{R}$-to-$\mathcal{S}$ (h_{R_iS}) are Rayleigh faded and statistically independent. Therefore, the channel gains $|h_{SR_i}|^2$, $|h_{R_iD}|^2$ and $|h_{R_iS}|^2$ are exponential distributed with mean λ_z, λ_x and λ_y. The average powers of the respective channel are $|h_{SR_i}|^2 = \frac{a_{SR}G_SG_R}{d_{SR}^m}$, $|h_{RD}|^2 = \frac{a_{RD}G_RG_D}{d_{RD}^m}$, $|h_{RS}|^2 = \frac{a_{RS}G_RG_S}{d_{SR}^m}$. d_{SR} and d_{RD} are the distance from $\mathcal{S}$-to-$\mathcal{R}$ and $\mathcal{R}$-to-$\mathcal{D}$ respectively. The antenna gains at $\mathcal{S}$, $\mathcal{R}$ and $\mathcal{D}$ are symbolized by G_S, G_R and G_D. Path loss exponent is m. The parameters a_{SR}, a_{RD} and a_{RS} depend on the average channel attenuation and antenna characteristics. Let total time of a data packet transmission from source to destination is T. The $\mathcal{S}$ harvests energy from RF signal of relays during αT time where α is fraction of EH time ($0 < \alpha < 1$) and the remaining time is equally allotted for data transmission to relay and reception from relay. So, the transmission and reception time is $(1 - \alpha)\frac{T}{2}$.

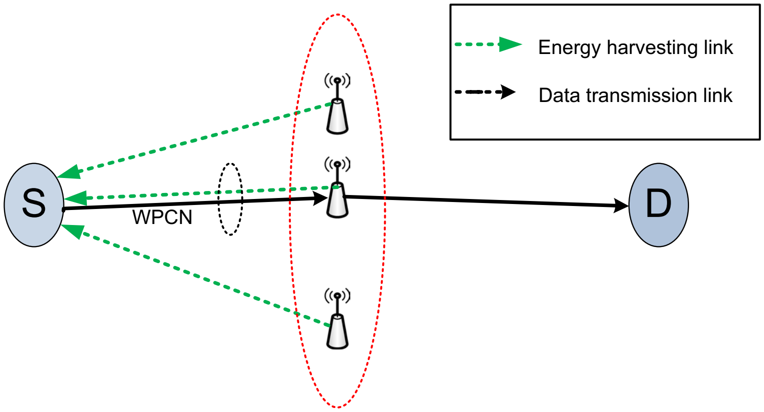


Fig. 1 Dual-hop wireless energy harvesting network

3 Problem Formulation

We assume that all relays are powered by external batteries and sending RF signal for energy harvesting to source. The source received all the RF signal coming from L number of relay nodes. Considering η as efficiency of harvesting circuit, $(0 < \eta < 1)$ and P_{t_i} as the transmitted power of ith relay node, the receiver of source extract energy from RF signals during αT time is expressed as

$$E_S = \eta \sum_{i=1}^{L} P_{t_i} |h_{R_i,S}|^2 \alpha T \tag{1}$$

Destination node also harvest energy during αT (if required) which is given by $E_D = \eta \sum_{i=1}^{L} P_{t_i} |h_{R_iD}|^2 \alpha T$. Destination node uses E_D energy to received the information. On the other hand, E_S in (1) is used to transmit information from source to destination via relay node during $\frac{(1-\alpha)T}{2}$ time. Hence, P_S, the transmit power of source is expressed as

$$P_S = \frac{E_S}{\frac{(1-\alpha)T}{2}} = \eta \sum_{i=1}^{L} P_{t_i} |h_{R_i,S}|^2 \frac{2\alpha}{1-\alpha} \tag{2}$$

The received signal at relay and destination are given by,

$$y_{R_i} = \sqrt{P_S} h_{SR_i} S_s(n) + n_{R_i} \tag{3}$$

$$y_D = \sqrt{P_{t_i}} h_{R_iD} S_d(n) + n_D \tag{4}$$

where P_S is the transmit power of source extracted from harvested energy. P_{t_i} is the transmit power of relay supplied from external power supply. $S_s(n)$ and $S_d(n)$ are considered as nth normalized information symbol transmitted from source and relay respectively. $n_{R_i} \sim \mathcal{N}(0, \sigma^2_{R_i})$ and $n_D \sim \mathcal{N}(0, \sigma^2_D)$ are the additive white Gaussian noise (AWGN) at relay and destination nodes respectively.

There is L number of different paths from $\mathcal{S}$-to-$\mathcal{R}$. The source selects the best path based on the channel gain quality from $\mathcal{S}$-to-$\mathcal{R}$ (h_{SR_i}).

$$i^* = arg \quad max|h_{SR_i}|^2 \tag{5}$$

where i^* is the selected relay index $i^* \epsilon (1, L)$. SNR at the selected ith relay node is expressed as

$$\begin{aligned} \gamma_R &= \frac{P_s\left\{\max\left\{|h_{SR_i}|^2\right\}\right\}}{N_0} \\ &= \frac{\left\{\eta \sum_{i=1}^{L} P_{t_i} |h_{R_iS}|^2 \frac{2\alpha}{1-\alpha}\right\}\left\{\max\left\{|h_{SR_i}|^2\right\}\right\}}{N_0} \\ &= \frac{\left\{\sum_{i=1}^{L} P_{t_i}{}' |h_{R_iS}|^2\right\}\left\{\max\left\{|h_{SR_i}|^2\right\}\right\}}{N_0} \end{aligned} \tag{6}$$

where $P_{t_i}{}' = \eta P_{t_i}\frac{2\alpha}{1-\alpha}$. The primary aim of this article is to analyse the performance of the proposed WEH-based network in terms of outage probability. Outage probability of a system is defined as the probability that a network is unable to realize a minimum predefined threshold SNR. Channel gain quality between transmitter and receiver is one of the major reasons for the outage.To evaluate $\mathcal{S}$-to-$\mathcal{D}$ outage probability, first, we need to find outage probabilities of $\mathcal{S}$-to-$\mathcal{R}$ link and $\mathcal{R}$-to-$\mathcal{D}$ link. Then we can derive end-to-end outage probability from them. The $\mathcal{S}$-to-$\mathcal{R}$ link is in outage when SNR at the relay node is less than γ_{th}, a predefined threshold SNR.

Proposition 1 *The CDF of SNR at relay i.e.* $F_{\gamma_R}(\gamma_{th})$ *using* (6) *is given by*

$$\begin{aligned} F_{\gamma_R}(\gamma_{th}) &= \mathcal{P}_r\{\gamma_R < \gamma_{th}\} \\ &= \mathcal{P}_r\left\{ \frac{\left\{P'_{t_i}|h_{R_iS}|^2\right\}\left\{\max\left\{|h_{SR_i}|^2\right\}\right\}}{N_0} < \gamma_{th} \right\} \\ &= \frac{1}{\Gamma(L)\left(P'_{t_i}\lambda_y\right)^L}\sum_{l=0}^{L}(-1)^l\binom{L}{l}2\left(l\frac{w}{\lambda_x}P'_{t_i}\lambda_y\right)^{L/2}K_L\left(2\sqrt{\frac{lw}{\lambda_x\lambda_y P'_{t_i}}}\right) \end{aligned} \tag{7}$$

Proof Please see Appendix A.1

The ergodic capacity of the source to the selected relay link is given by

$$C_r = \left\{log_2(1+\gamma_R)\right\} \tag{8}$$

After received data at relay, relay node forwards data to destination using external power supply. γ_D, the SNR at destination node is given by

$$\gamma_D = \frac{P_{t_i}|h_{R_iD}|^2}{N_0} \tag{9}$$

The CDF of SNR at destination is given by

$$\begin{aligned} F_{\gamma_D}(\gamma_{th}) &= \mathcal{P}_r\{\gamma_D < \gamma_{th}\} \\ &= \mathcal{P}_r\left\{ \frac{P_{t_i}|h_{R_iD}|^2}{N_0} < \gamma_{th} \right\} \\ &= P_r\left\{ |h_{R_iD}|^2 < \frac{\gamma_{th}N_0}{P_{t_i}} \right\} \\ &= 1 - e^{-\frac{\gamma_{th}N_0}{\lambda_x P_{t_i}}} \end{aligned} \tag{10}$$

The ergodic capacity of the relay to destination link is given by,

$$C_d = \left\{log_2(1+\gamma_D)\right\} \tag{11}$$

The network outage occurs when end-to-end SNR is lesser than SNR threshold. The outage probability of the network is given by,

$$\mathcal{O} = \mathcal{P}_r\{min(\gamma_R, \gamma_D) < \gamma_{th}\} \tag{12}$$

As the best relay has used external power for data transmission from relay to destination, γ_R and γ_D are independent random variable. So, we can write

$$\begin{aligned} \mathcal{O} &= 1 - \left\{1 - \mathcal{P}_r(\gamma_R < \gamma_{th})\right\}\left\{1 - \mathcal{P}_r(\gamma_D < \gamma_{th})\right\} \\ &= 1 - \left\{1 - F_{\gamma_R}(\gamma_{th})\right\}\left\{1 - F_{\gamma_D}(\gamma_{th})\right\} \end{aligned} \tag{13}$$

By using (7) and (10), we can get closed form expression for outage probability as

$$\begin{aligned} &\mathcal{O} = 1 - e^{-\frac{\gamma_{th} N_0}{\lambda_x P_{t_i}}} \\ &\left\{1 - \frac{1}{\Gamma(L)\left(P'_{t_i}\lambda_y\right)^L}\sum_{l=0}^{L}(-1)^l\binom{L}{l}2\left(l\frac{w}{\lambda_x}P'_{t_i}\lambda_y\right)^{L/2}K_L\left(2\sqrt{\frac{lw}{\lambda_x\lambda_y P'_{t_i}}}\right)\right\} \end{aligned} \tag{14}$$

The end-to-end ergodic capacity of network is given by [33]

$$\mathrm{C} = \min\left\{\mathrm{C_r}, \mathrm{C_d}\right\} \tag{15}$$

The total time required to transmit source to destination is T. Here, α is reserve for energy harvesting and rest for communication. Hence, the effective time fraction for transmission or reception is $\frac{(1-\alpha)T}{2}$. Hence, the throughput is given by,

$$\tau = \frac{(1-\alpha)T}{2}C = \frac{(1-\alpha)T}{2}min\left\{C_r, C_d\right\} \tag{16}$$

4 Results and Discussion

In this section, we have investigated and validated the accuracy of the derived analytical expressions of outage probability and throughput through a simulation process. Matlab software is used for performing simulation process, and following important parameters are considered for this analysis $\eta = 0.8, N_0 = 10^{-5}W, d_{SR} = d_{RD} = 2m, G_S = G_R = 10, a_{SR} = a_{RD}, = a_{RS} = 0.16.$ The simulation results are obtained through 10^5 independent Monte Carlo trials.

The variation of outage probability of relay network with respect to threshold SNR has been depicted in Fig. 2 for a different number of relay nodes and transmitting power. It is observed that outage probability degrades with the increase of interference threshold level. This is because the probability of CDF expressed through (7) and (10) enhance as threshold SNR gets a higher value. However, system performance in terms of outage probability improves along with the increase of relay nodes. Whenever the number of relay nodes increases (from two to four), the source harvests more amount of energy that is utilised to transmit source signal. The outage probability is also influenced by the transmitted power level of the relay nodes. More transmission power of relay nodes helps the source to harvest more energy, and the SNR gets improves whenever the harvested energy is used for signal transmission. Hence, the outage probability degrades, or network performance improves.

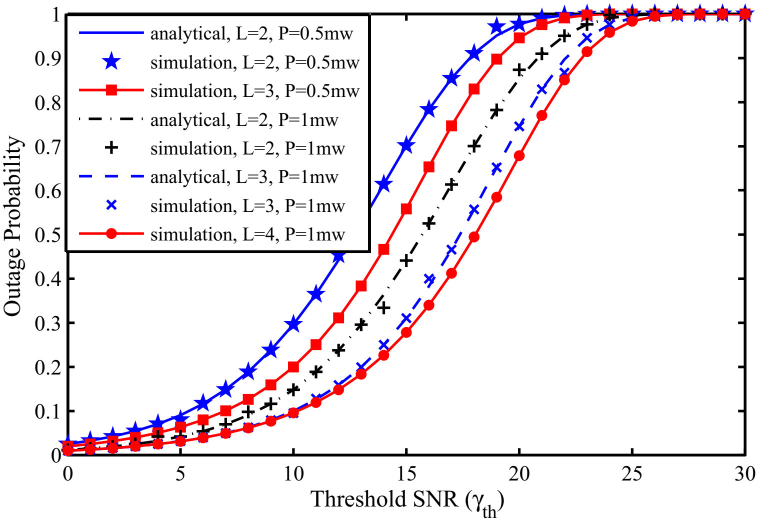
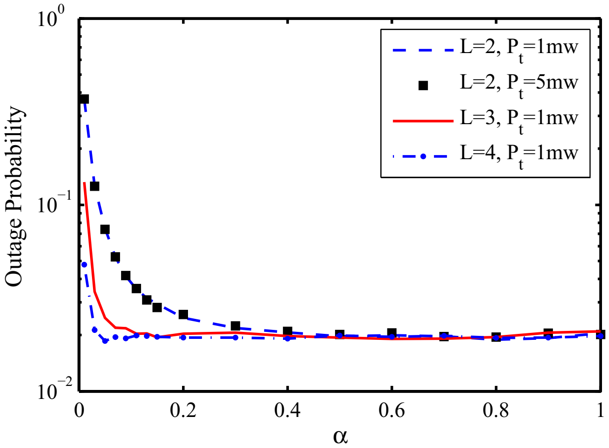


Fig. 2 Relation between outage probability and γ_{th}

In Fig. 3, variation of outage probability is analyzed with respect to fraction of EH time (α), the function of EH time. It is observed that when $\alpha < 0.2$, outage probability of the system improves sharply. Increasing α indicates an enhancement in EH time span and source become capable to harvest more amount of energy which is used for information transmission to relay node with a higher SNR. Hence, outage probability reduces. The system is said to be in the outage if minimum between γ_R and γ_D is below the threshold SNR (see (12)). When $\alpha > 0.2$ (for $L > 2$), SNR improvement is observed from source to relay, however, no improvement is observed in the $\mathcal{R}$-to-$\mathcal{D}$ link. Therefore, outage probability becomes saturated when the number of relay node increases. Outage performance further improves as more energy is harvested at the destination, and outage saturates quickly. For instance, saturation starts from $\alpha = 0.3$ for $L = 2$, however, $\alpha = 0.1$ for $L = 3$.

Fig. 3 Variation of outage probability with α and number of relay nodes



In Fig. 3, the outage probability becomes saturated after a specific value of α. However, the throughput performance of the system shows different characteristic under the variation of α. The relation between achievable system throughput and α for different number of relay nodes and their power transmission level has been depicted in Fig. 4. Unlike outage and α relationship as shown in Fig. 3, throughput achieves a maximum level and then starts to degrade. The value of α at which maximum throughput is achieved is called optimum α. Effect of amount of energy harvested power is observed before optimum α and after optimum α, the impact of reduction in information transmission time span (when α increases) is observed. However, outage performance does not depend on the information transmission time span, hence, outage probability becomes saturated which is shown in Fig. 3. It is noticeable that there is (Fig. 4) no effect of relay transmission power on optimal α. However, lower optimal α is observed if number of relay node increases.

The relation between outage probability and α when the system is targeting a minimum throughput (C_{th}) has been presented in Fig. 5 for different number of relay nodes and their transmission power. In this figure, the system is called in outage if any one of the following condition is satisfied i.e., (1) $SNR < \gamma_{th}$ and (2) system throughput $< C_{th}$. We considered $C_{th} = 3bps/Hz$ for simulation. Similar to Fig. 3, when α starts to increase from zero, outage probability reduces as the source can harvest more energy which is utilized during information transmission. For a particular C_{th}, the α at which outage probability is minimum is known as optimal α. When α starts to increase beyond the optimal value, the probability of achieving C_{th} reduces due to the reduction of information transmission time. The optimal value of α reduces as the number of relay nodes increases.

In the previous figure we have seen that the system outage probability achieves an optimal value for a particular α. Figure 6 depicts the optimal outage probability as a function of relay nodes transmitting power for various throughput threshold, C_{th}. We considered two relay nodes for the simulation. For a specific value of C_{th}, L, and P_t, first we find the outage probability by varying the α (similar as Fig. 5) and then minimum (Optimal) outage probability is plotted with respect to transmitted power of relay nodes in Fig. 6. Minimum outage probability

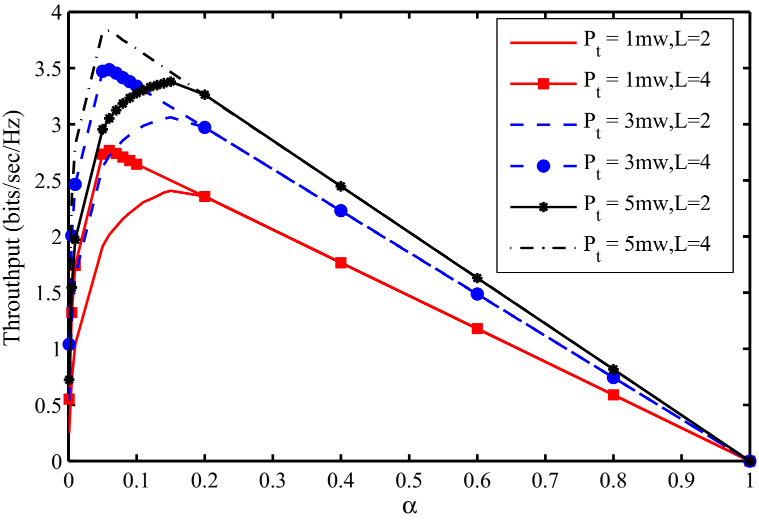


Fig. 4 Variation of throughput with α

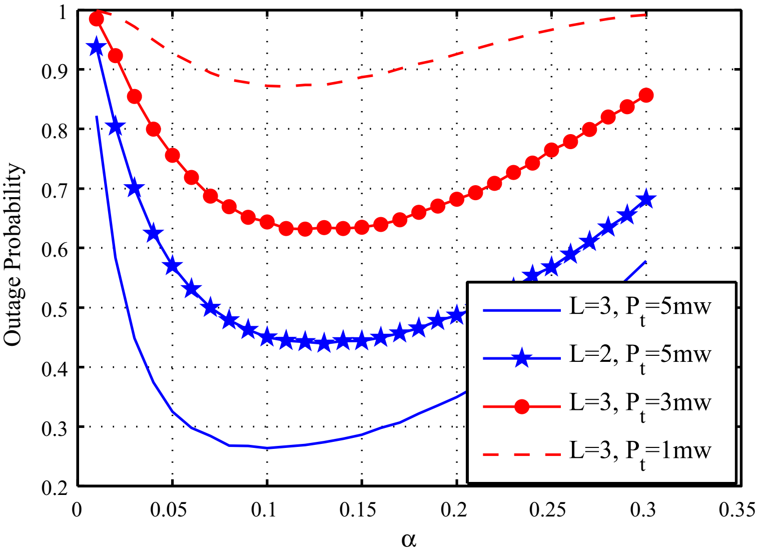


Fig. 5 Relation of system outage probability with α

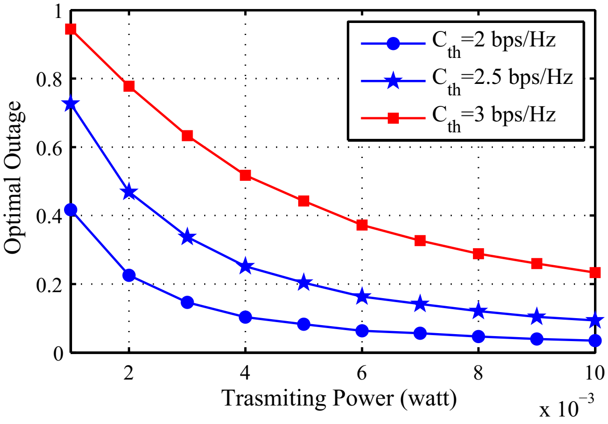


Fig. 6 Variation of optimal outage probability with relay transmitted power for different threshold throughput

can be estimated using this figure. For instance, the minimum achievable system outage probability is approximately 20% when $L = 2, C_{th} = 2bps/Hz$ and $P_t = 2mw$. The improvement in optimal outage probability is observed when P_t increases as $\mathcal{S}$ can harvest more energy for information transmission. However, as expected, the outage probability increases when C_{th} is comparable high.

5 Conclusions

In this paper, the performance of a relay selection protocol for a cooperative dual-hop DF relaying EH network has been analyzed. The source is capable of selecting best relay link on the basis of $\mathcal{S}$-to-$\mathcal{R}$ channel condition. We derived a closed-form analytical expression for outage probability and achievable throughput of the system considering Rayleigh fading channels. We also presented the impact of the transmission power of relay nodes on the network performance in terms of outage probability and throughput. After performing an extensive simulation, we have captured an optimal value of α for maximum system throughput and found a minimum achievable outage probability. The present work can be extended through obtaining an analytical expression of an optimal α and optimal system outage probability.

Appendix 1

Proof of Proposition 1 in (7)

Assume $P'_{t_i}|h_{R_iS}|^2 = Y$ and $\max\{|h_{SR_i}|^2\} = Z$. CDF of Y is given by [34]

$$F_Y(y) = \frac{\Gamma\left(L, \frac{y}{P'_{t_i}\lambda_y}\right)}{N_0} \tag{17}$$

And PDF of Y is given by [34]

$$f_Y(y) = \frac{y^{L-1}e^{-\frac{y}{P'_{t_i}\lambda_y}}}{\Gamma(L)\left(P'_{t_i}\lambda_y\right)^L} \tag{18}$$

CDF of Z is given by [21]

$$\begin{aligned} F_Z(z) &= \left(1 - e^{-\frac{z}{\lambda_x}}\right)^L \\ &= \sum_{i=0}^{L} (-1)^l \binom{L}{l} e^{-l\frac{z}{\lambda_x}} \end{aligned} \tag{19}$$

The CDF of SNR at relay i.e. $F_{\gamma_R}(\gamma_{th})$ using (6) is given by

$$\begin{aligned} F_{\gamma_R}(\gamma_{th}) &= \mathcal{P}_r\left\{ \frac{\left\{ \eta \sum_{i=1}^{L} P'_{t_i} |h_{R_iS}|^2 \frac{2\alpha}{1-\alpha} \right\} \left\{ \max\left\{ |h_{SR_i}|^2 \right\} \right\}}{N_0} < \gamma_{th} \right\} \\ &= \mathcal{P}_r\{YZ \leq w\} \\ &= \mathcal{P}_r\left\{ Z \leq \left. \frac{w}{y} \right|_{Y=y} \right\} \\ &= \int_0^\infty F_Z\left(\frac{w}{y}\right) f_Y(y)dy \\ &= \int_0^\infty \sum_{l=0}^{L} (-1)^l \tbinom{L}{l} e^{-l\frac{w}{\lambda_{xy}}} \frac{y^{L-1} e^{-\frac{y}{P'_{t_i}\lambda_y}}}{\Gamma(L)\left(P'_{t_i}\lambda_y\right)^L} dy \\ &= \frac{1}{\Gamma(L)\left(P'_{t_i}\lambda_y\right)^L} \sum_{l=0}^{L} (-1)^l \tbinom{L}{l} \int_0^\infty e^{-l\frac{w}{\lambda_{xy}}} y^{L-1} e^{-\frac{y}{P'_{t_i}\lambda_y}} dy \\ &= \frac{1}{\Gamma(L)\left(P'_{t_i}\lambda_y\right)^L} \sum_{l=0}^{L} (-1)^l \tbinom{L}{l} \int_0^\infty y^{L-1} e^{-\left(\frac{y}{P'_{t_i}\lambda_y} + l\frac{w}{\lambda_{xy}}\right)} dy \\ &= \frac{1}{\Gamma(L)\left(P'_{t_i}\lambda_y\right)^L} \sum_{l=0}^{L} (-1)^l \tbinom{L}{l} 2\left(l\frac{w}{\lambda_x} P'_{t_i}\lambda_y \right)^L / 2K_L\left(2\sqrt{l\frac{w}{\lambda_x\lambda_y P'_{t_i}}} \right) \end{aligned} \tag{20}$$

where $\int_0^\infty x^{\nu-1} e^{-\frac{\beta}{x}-\gamma x} dx = 2\left(\frac{\beta}{\gamma}\right)^{\frac{\nu}{2}} K_\nu\left(2\sqrt{\beta\gamma}\right)$ [35, §3.471.9] is used and $K_\nu(.)$ is the νth order modified Bessel function of the second kind.

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