Relay Selection Schemes in Threshold DF Cooperative Systems With Wireless Power Transfer

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Abstract

In this work, a dual-hop cooperative wireless energy harvesting system, in which there are a Source-Destination (S-D) pair and several relay candidates is considered. all relay candidates adopt threshold decode-and-forward (DF) relaying scheme to decide whether to aid S-D pair information transmission or not. We assumed that these relay candidates and S are all equipped with single receiving antenna while D is equipped multiple receiving antenna and adopts generalized selection combining scheme to achieve receiving diversity gain. We also consider that relay candidates and S can harvest energy from D with finite energy storage capacity under time switching scheme. Three kinds of best relay selection (RS) schemes based threshold (TH) D-F relay scheme, that is, the TH optimal source-relay link, the TH optimal relay-destination link, and the TH optimal source-relay-destination link, are proposed and studied. Closed-form analytical expressions for the outage probability over the three proposed RS schemes are derived and verified by

Monte-Carol simulations.
Keywords:
Cooperative system; decode-and-forward; generalized selection combining; relay selection; outage probability; wireless power transfer

1. Introduction

Over last few years, large quantities of research works focus on prolonging the network lifetime, which is a crucial challenge to realize efficient wireless communications. In the view of the theoretical aspects and practical implementation aspects, energy harvesting (EH) becomes an attractive complementary technology to provide convenient and perpetual energy supplies [1]-[3]. Compared conventional battery or grid power-operated communications, more unique features like self-sustainable capability, without requiring battery replacement, easy and fast deployment and reduction of carbon footprint could be provided by EH [4]. There are four EH sources, that is, thermoelectric power, solar/light, mechanical motion and electromagnetic radiation. In particular, harvesting from electromagnetic radiation plays a more critical role for the broadcast nature of wireless communications [5]-[6].

Based on the above research results, cooperative communication considering EH technology has gained much interests to overcome the space limitation, improve the network throughput and reliability, and promise perpetual network lifetime. [7]-[10] have studied the ambient EH for two-hop cooperative communications. The joint time allocation problem under two-hop relay network with EH source is investigated in [7]. Considering EH constraints, the authors of [8] maximized the throughput of a cooperative network. The impact of the EH at the relay on the outage performance of a dual-hop threshold amplify-and-forward (AF)/decode-and-forward (DF) system was studied in [9], in which there is only one relay serving for the information forwarding between the source and the destination. [10] conducted stability analysis for a non-cooperative protocol and orthogonal DF scheme in EH network.

In order to improve the energy efficiency and service quality with lower complexity for multiple relay-assisted networks, relay selection (RS) acts as an essential tool [11]-[14]. [12] investigated the RS problem in full-duplex two-way EH relay networks. Under a given energy transfer constraint, [13] studied the optimal trade-off between a maximum capacity and minimum outage probability (OP) with a relay selection policy. Volunteer EH node can serve as AF relays when they have sufficient energy for transmissions in [14]. More specifically, three relay selection schemes, that is, optimal source-relay link (OSRL) scheme, optimal relay-destination link (ORDL) scheme, and optimal source-relay-destination link (OSRDL) scheme have been studied in [15]-[17].

Moreover, diversity combining scheme has been adopted in various system to combat the effect of channel fading with multiple path fading [18]-[19]. Diversity combining techniques like maximum-ratio combining (MRC), selection combining (SC) and generalized selection combining (GSC) are proposed to increase the overall signal-to-noise-ratio (SNR) effectively at the receiver and then enhance important system performance consequently. In particular, MRC could offer better performance at the cost of high implementation complexity because all paths information needed to be estimated and combined, while SC provides poorer performance but a lower implementation complexity with only one path will be selected. Compared with MRC and SC, GSC is able to trade-off the system performance and implementation complexity, which only a subset of receive antennas are selected and combined to process the received signal.

Compared to previous works, one can see that GSC has not been fully studied in EH systems. Thus, we consider a dual-hop cooperative system with a destination (D) equipped with multiple receive antennas to adopt GSC. Moreover, the source (S) and multiple relay candidates ($R_n, 1 \leq n \leq N, N \geq 1$) are equipped with finite energy storage for EH. Compared to previous relay selection schemes, we combining threshold DF relaying scheme with three best RS schemes, OSRL, ORDL and OSRDL, which named as threshold (TH)-OSRL, TH-ORDL and TH-OSRDL, respectively, in this paper.

As MRC and SC schemes are the special cases of GSC scheme and threshold DF relaying scheme can degrade to common DF relaying scheme via setting the relay threshold to 0, one can see that, compared with the beforementioned works, the considered system in our work is more practical and reasonable, leading to comprehensive and unified analytical models for potential applications in practice.

The main contributions of this paper are summarized as follows:

- Three modified RS schemes, TH-OSRL, TH-ORDL and TH-OSRDL, are proposed for dual-hop cooperative EH systems by exploiting the benefits of the traditional DF threshold relaying scheme;

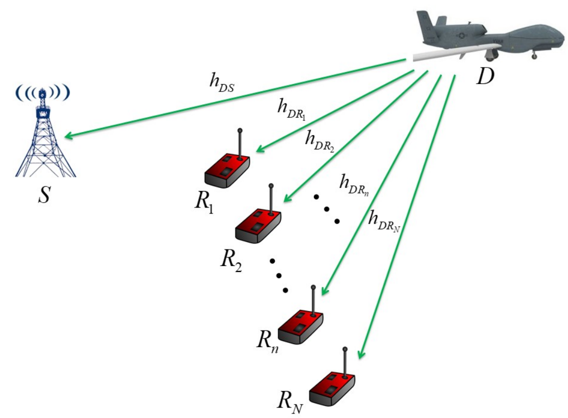
- We derive the closed-form analytical expression for each $S-R_n$ link in EH communication network while considering S harvests energy from D with finite energy storage.

- We also derive the closed-form analytical expression for the OP of R_m-D $(1 \leq m \leq M \leq N)$ link while considering GSC at D and EH relays with finite storage.
- We derive the closed-form analytical expressions for the OP of the considered system under TH-OSRL, TH-ORDL and TH-OSRDL schemes, respectively.

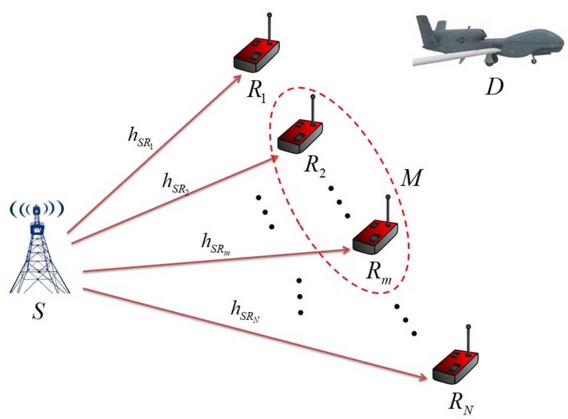
The rest of this paper is organized as follows. In Section II, the considered cooperative EH communication system is introduced. In Section III, the closed-form analytical expressions for single source-to-relay link and relay-to-destination link are derived, respectively. In Section IV, TH-OSRL, TH-ORDL and TH-OSRDL schemes are proposed and discussed, respectively. The outage performance of the considered system with three different RS schemes are respectively investigated by deriving closed-form analytical expressions. In Section V, we present simulation and numerical results for the OP under three RS schemes and compared them. Finally, some remarks of this paper are concluded in Section VI.

2. System model

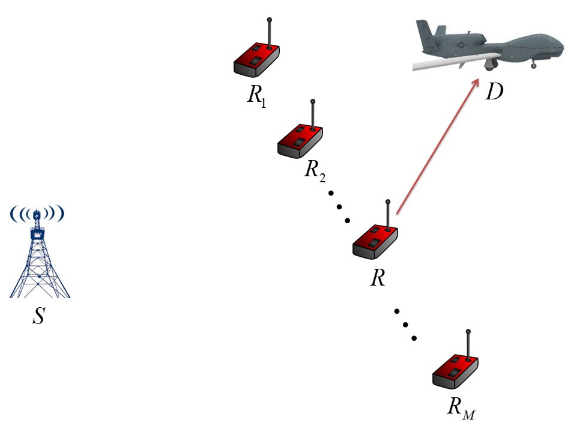
In this paper, we consider a dual-hop cooperative communication system with EH nodes. All terminals are equipped with a single transmitting antenna while D is equipped with N_D $(N_D \geq 1)$ receiving antennas. GSC is adopted at D to process the multiple copies of the received signals from R, which means that D can combine N_G $(1 \leq N_G \leq N_D)$ strongest receive antennas from perfect channel state information (CSI) estimation by the pilot



(a) Wireless energy transferring



(b) Data transmission over $S-R_n$ link



(c) Data transmission over $R-D$ link

Figure 1: Cooperative System Model

signal transmitted by R. A conditional relay scheme is considered in this work: S-D link based threshold DF relaying scheme. It is assumed that each terminal operates in a half-duplex mode. In this work, we considered three relay selection schemes to select a best relay R.

Similar to [11], the information transmission process can be divided into three phases: 1) D broadcasts energy via wireless signals to charge S and relays; 2) S broadcasts the information to each relay by using the harvested energy. Under $S - R_n$ link based threshold DF relaying scheme, R_n adopts their instantaneous SNR of the received signal at its information receiver as an indication of the reliability of the relay detection. If the SNR is larger than a predefined threshold (γ_0), the probability of an error at the relay is small. Hence the selected relays R_m, $(m = 1, 2, ..., M \leq N)$ can forwards the signal after recoding; 3) R_m participates in the optimal relay selection process to select the best relay R. Finally, R will forward the information to D with the harvested energy while the other relays remain silent.

We also consider three kinds of relay selection schemes based the threshold DF relaying scheme discussed above: 1) TH-ORDL: S delivers a pilot signal to R_m and obtains the feedback information form R_m, and then S selects the forwarding relay which has the best S-R link. 2) TH-OSRL: R_m delivers a pilot signal to D and D selects the forwarding relay which has the best R-D link. 3) TH-OSRDL: Pilot signals including the received SNR over S-R_m link and R_m-D link are sent to D to let D find the forwarding relay with the best S-R-D link.

In this work, we assumed that all links experience independent and identically Rayleigh fading, namely, $|h_{ij}|^2$, $(i, j \in \{S, R_n, R_m, D\})$. Thus it is easy to have the PDF of $|h_{ij}|^2$ as [21]

$$f_{|h_{ij}|^2}(x) = \frac{1}{h_{ij}} \exp\left(-\frac{x}{h_{ij}}\right), \tag{1}$$

where h_{ij} are the expectation of channel power gain of $|h_{ij}|^2$.

Thus, in the EH process, the energy harvested by S and R_n with time slot T_1 can be respectively written as [11]

$$E_i = P_D T_1 |h_{Di}|^2, \tag{2}$$

where E_i, $(i \in \{S, R_n\})$ is the harvest energy at node i, P_D is the transmit power at node D.

After the information transmission process, the received signals at R_n and D are given by

$$y_{R_n} = \sqrt{P_S} h_{SR_n} s + n_{R_n} \tag{3}$$

and

$$y_{R_m D} = \sqrt{P_{R_m}} h_{R_m D} s_{R_m} + n_D, \tag{4}$$

respectively, where P_S and P_{R_m} are the transmit power at node S and R_m, s and s_{R_m} denote the transmitted symbols from S and R_m, n_i, $(i \in \{R_n, D\})$ denotes the independent complex Gaussian noise at R_n and D. In this work, to simplify the analysis, we assume that n_i are with zero means and a same variances, N_0.

Considering that S and R_n harvest energy with a limit energy storage capacity, B_i, $(i \in \{S, R_n\})$, we can divide the transmit power at S and R_n into two situations: 1) S and R_n transmit the information with its maximum available power B_i; 2) S and R_n transmit the information with its harvested energy E_i, which can be expressed as

$$P_S = \min\left\{\frac{B_S}{T_2}, \frac{E_S}{T_2}\right\} = \min\left\{\frac{B_S}{T_2}, \frac{P_D T_1 |h_{DS}|^2}{T_2}\right\} \tag{5}$$

and

$$P_{R_m} = \min\left\{\frac{B_{R_m}}{T_3}, \frac{E_{R_m}}{T_3}\right\} = \min\left\{\frac{B_{R_m}}{T_3}, \frac{P_D T_1 |h_{DR_m}|^2}{T_3}\right\}, \tag{6}$$

respectively, where T_2 is the transmission time slot from S to R_n and T_3 is the transmission time slot from relays to the destination.

Therefore, the SNR of the received signal at R_n and D can be written as

$$\gamma_{SR_n} = \frac{P_S |h_{SR_n}|^2}{N_0} \tag{7}$$

and

$$\gamma_{R_m D} = \sum_{i=1}^{N_G} \gamma_{R_m D}^i = \frac{P_R}{N_0} \sum_{i=1}^{N_G} \left|h_{R_m D}^i\right|^2, \tag{8}$$

respectively.

In the following, we let $H_{R_m D} = \sum\limits_{i=1}^{N_G} \left|h_{R_m D}^i\right|^2$, where $\left|h_{R_m D}^1\right|^2 \geq \left|h_{R_m D}^2\right|^2 \geq \cdots \geq \left|h_{R_m D}^i\right|^2 \geq \cdots \geq \left|h_{R_m D}^{N_D}\right|^2$.

Thus, the PDF of $H_{R_m D}$ is given by [22]

$$\begin{aligned} f_{H_{R_m D}}(x) = \binom{N_D}{N_G} \Bigg\{ & \frac{x^{N_G - 1}}{h_{R_m D}^{N_G} (N_G - 1)!} e^{-\frac{x}{h_{R_m D}}} + \frac{1}{h_{R_m D}} \\ & \cdot \sum_{n=1}^{N_D - N_G} (-1)^{N_G + n - 1} \binom{N_D - N_G}{n} \left(\frac{N_G}{n}\right)^{N_G - 1} \\ & \times \left[e^{-\frac{x}{h_{R_m D}} - \frac{nx}{N_G h_{R_m D}}} - e^{-\frac{x}{h_{R_m D}}} \sum_{m=0}^{N_G - 2} \frac{1}{m!} \left(-\frac{nx}{N_G h_{R_m D}}\right)^m \right] \Bigg\}. \end{aligned} \tag{9}$$

3. Outage event over each hop

In this section, we will study the outage probabilities for single $S-R_n$ link and R_m-D link.

3.1. Outage Probability over $S-R_n$ link

In this work, the OP for $S-R_n$ is defined as the probability that the instantaneous SNR is below a threshold SNR γ_{th}, which can be denoted as

$$\begin{aligned}
P_{SR_n}(\gamma_{th}) &= \Pr\left\{\gamma_{SR_n} \leq \gamma_{th}\right\} \\
&= \Pr\left\{\frac{P_{SR_n}|h_{SR_n}|^2}{N_0} < \gamma_{th}\right\} \\
&= \Pr\left\{\frac{\min\left\{\frac{B_S}{T_2}, \frac{E_S}{T_2}\right\}|h_{SR_n}|^2}{N_0} < \gamma_{th}\right\} \\
&= \Pr\left\{\min\left\{\gamma_{S1}, \gamma_{S2}\right\} \leq \gamma_{th}\right\} \\
&= 1 - \Pr\left\{\min\left\{\gamma_{S1}, \gamma_{S2}\right\} > \gamma_{th}\right\} \\
&= 1 - \Pr\left\{\gamma_{S1} > \gamma_{th}, \gamma_{S2} > \gamma_{th}\right\}, \qquad (10)
\end{aligned}$$

where γ_{S1} and γ_{S2} can be calculated as

$$\gamma_{S1} = \frac{B_S|h_{SR_n}|^2}{N_0T_2} = \lambda_{S1}|h_{SR_n}|^2 \qquad (11)$$

and

$$\gamma_{S2} = \frac{P_DT_1|h_{DS}|^2|h_{SR_n}|^2}{N_0T_2} = \lambda_{S2}|h_{DS}|^2|h_{SR_n}|^2, \qquad (12)$$

respectively, where $\lambda_{S1} = \frac{B_S}{N_0T_2}$ and $\lambda_{S2} = \frac{P_DT_1}{N_0T_2}$.

Thus, we can re-express $|h_{SR_n}|^2 = \frac{\gamma_{S1}}{\lambda_{S1}} = X_{S1}$ and $|h_{DS}|^2 = \frac{\gamma_{S2}\lambda_{S1}}{\lambda_{S2}\gamma_{S1}} = X_{S2}$. Then, we can form the Jacobian as

$$D_S = \begin{bmatrix} \frac{\partial X_{S1}}{\partial \gamma_{S1}} & \frac{\partial X_{S1}}{\partial \gamma_{S2}} \\ \frac{\partial X_{S2}}{\partial \gamma_{S1}} & \frac{\partial X_{S2}}{\partial \gamma_{S2}} \end{bmatrix} = \begin{bmatrix} \frac{1}{\lambda_{S1}} & 0 \\ -\frac{\gamma_{S2}\lambda_{S1}}{\lambda_{S2}\gamma_{S1}^2} & \frac{\lambda_{S1}}{\lambda_{S2}\gamma_{S1}} \end{bmatrix}. \tag{13}$$

Thus, the absolute value of the determinant of D_S is $|\det D_S| = \frac{1}{\lambda_{S2}\gamma_{S1}}$. Since X_{S1} and X_{S2} are independent channel, we can obtain the joint PDF of γ_{S1} and γ_{S2} as

$$f_{\gamma_{S1},\gamma_{S2}}(\gamma_{S1},\gamma_{S2}) = \frac{1}{\lambda_{S2}\gamma_{S1}} f_{X_{S1},X_{S2}}\left(\frac{\gamma_{S1}}{\lambda_{S1}}, \frac{\gamma_{S2}\lambda_{S1}}{\lambda_{S2}\gamma_{S1}}\right) = \frac{e^{-\frac{\gamma_{S1}}{\lambda_{S1}h_{SR_n}}} e^{-\frac{\gamma_{S2}\lambda_{S1}}{\lambda_{S2}\gamma_{S1}h_{DS}}}}{\lambda_{S2}\gamma_{S1}h_{SR_n}h_{DS}}. \tag{14}$$

By setting $a_1 = \frac{1}{\lambda_{S2}h_{SR_n}h_{DS}}$, $a_2 = \frac{1}{\lambda_{S1}h_{SR_n}}$ and $a_3 = \frac{\lambda_{S1}}{\lambda_{S2}h_{DS}}$, we can obtain $P_{SR_n}(\gamma_{th})$ as

$$\begin{aligned} P_{SR_n}(\gamma_{th}) &= 1 - \int_{\gamma_{th}}^{\infty}\int_{\gamma_{th}}^{\infty} \frac{a_1}{\gamma_{S1}} e^{-a_2\gamma_{S1} - \frac{a_3\gamma_{S2}}{\gamma_{S1}}} d\gamma_{S2} d\gamma_{S1} \\ &= 1 - \frac{a_1}{a_3}\int_{\gamma_{th}}^{\infty} e^{-a_2\gamma_{S1} - \frac{a_3\gamma_{th}}{\gamma_{S1}}} d\gamma_{S1} \\ &= 1 - \frac{a_1}{a_3}\left[\int_0^{\infty} e^{-a_2\gamma_{S1} - \frac{a_3\gamma_{th}}{\gamma_{S1}}} d\gamma_{S1} - \int_0^{\gamma_{th}} e^{-a_2\gamma_{S1} - \frac{a_3\gamma_{th}}{\gamma_{S1}}} d\gamma_{S1}\right] \end{aligned} \tag{15}$$

Using [23, Eq. (3.471.9)] and Chebyshev-Gauss quadrature which is given as $\int_{-1}^{+1} \frac{f(x)}{\sqrt{1-x^2}}dx \approx \sum_{i=1}^{S} w_i f(x_i)$ with $w_i = \pi/S$ and $x_i = \cos\left(\frac{2i-1}{2S}\pi\right)$, we can re-express $P_{SR_n}(\gamma_{th})$ as

$$\begin{aligned} P_{SR_n}(\gamma_{th}) &= 1 - \frac{a_1}{a_3}\left[\sqrt{\frac{4a_3\gamma_{th}}{a_2}}K_1\left(2\sqrt{a_2a_3\gamma_{th}}\right) - \frac{\gamma_{th}}{2}\int_{-1}^{1} e^{-\frac{a_2\gamma_{th}(t+1)}{2}-\frac{2a_3}{t+1}}dt\right] \\ &= 1 - \frac{a_1}{a_3}\left[\sqrt{\frac{4a_3\gamma_{th}}{a_2}}K_1\left(2\sqrt{a_2a_3\gamma_{th}}\right) - \frac{\gamma_{th}}{2}\sum_{g=1}^{G} W_g\sqrt{1-\xi_g^2}e^{-\frac{a_2\gamma_{th}(\xi_g+1)}{2}-\frac{2a_3}{\xi_g+1}}\right], \end{aligned} \tag{16}$$

where $W_g = \pi/G$, $\xi_g = \cos\left(\frac{2g-1}{2G}\pi\right)$.

3.2. Outage Probability $R_m - D$ Link

In this section, we will investigate the OP for $R_m - D$ link, the process of which is similar with the one presented in subsection A.

Since we consider that D is equipped with multiple receiving antennas and adopts GSC scheme, the OP for $R_m - D$ link is defined as

$$\begin{aligned} P_{R_mD}(\gamma_{th}) &= \Pr\left\{\gamma_{R_mD} \le \gamma_{th}\right\} = \Pr\left\{\frac{P_{R_m}H_{R_mD}}{N_0} \le \gamma_{th}\right\} \\ &= \Pr\left\{\frac{\min\left\{\frac{B_{R_m}}{T_3}, \frac{E_{R_m}}{T_3}\right\}H_{R_mD}}{N_0} \le \gamma_{th}\right\} \\ &= 1 - \Pr\left\{\gamma_{R1} > \gamma_{th}, \gamma_{R2} > \gamma_{th}\right\}, \end{aligned} \tag{17}$$

where γ_{R1} and γ_{R2} can be expressed as

$$\gamma_{R1} = \frac{B_{R_m}H_{R_mD}}{N_0T_3} = \lambda_{R1}H_{R_mD} \tag{18}$$

and

$$\gamma_{R2} = \frac{P_DT_1|h_{DR_m}|^2H_{R_mD}}{N_0T_3} = \lambda_{R2}|h_{DR_m}|^2H_{R_mD}, \tag{19}$$

respectively, where $\lambda_{R1} = \frac{B_{R_m}}{N_0 T_3}$ and $\lambda_{R2} = \frac{P_D T_1}{N_0 T_3}$.

Similar to the subsection A, we set $X_{R1} = H_{R_m D}$ and $X_{R2} = |h_{DR_m}|^2$. Then, we can obtain the joint PDF of γ_{R1} and γ_{R2} as

$$\begin{aligned}
&f_{\gamma_{R1},\gamma_{R2}}(\gamma_{R1},\gamma_{R2}) = \frac{1}{\lambda_{R2}\gamma_{R1}} f_{X_{R1},X_{R2}}\left(\frac{\gamma_{R1}}{\lambda_{R1}}, \frac{\gamma_{R2}\lambda_{R1}}{\lambda_{R2}\gamma_{R1}}\right) \\
&= \frac{1}{\lambda_{R2}\gamma_{R1} h_{DR_m}} e^{-\frac{\gamma_{R2}\lambda_{R1}}{\lambda_{R2}\gamma_{R1} h_{DR_m}}} \binom{N_D}{N_G} \left\{ \frac{\gamma_{R1}^{N_G-1}}{\lambda_{R1}^{N_G-1} h_{R_m D}^{N_G} (N_G-1)!} e^{-\frac{\gamma_{R1}}{h_{R_m D}\lambda_{R1}}} \right. \\
&\quad + \frac{1}{h_{R_m D}} \sum_{n=1}^{N_D-N_G} (-1)^{N_G+n-1} \binom{N_D-N_G}{n} \left(\frac{N_G}{n}\right)^{N_G-1} \\
&\quad \left. \times \left[e^{-\frac{\gamma_{R1}}{h_{R_m D}\lambda_{R1}} - \frac{n\gamma_{R1}}{h_{R_m D}\lambda_{R1} N_G}} - e^{-\frac{\gamma_{R1}}{h_{R_m D}\lambda_{R1}}} \sum_{m=0}^{N_G-2} \frac{1}{m!} \left(-\frac{n\gamma_{R1}}{h_{R_m D}\lambda_{R1} N_G}\right)^m \right] \right\}.
\end{aligned} \tag{20}$$

By setting $b_1 = \frac{1}{\lambda_{R2} h_{DR_m}} \binom{N_D}{N_G}$, $b_2 = \frac{\lambda_{R1}}{\lambda_{R2} h_{DR_m}}$, $b_3 = \lambda_{R1}^{N_G-1} h_{R_m D}^{N_G} (N_G-1)!$, $b_4 = \frac{1}{h_{R_m D}\lambda_{R1}}$, $b_5 = \frac{1}{h_{R_m D}\lambda_{R1} N_G}$ and $\Xi = \frac{1}{h_{R_m D}} (-1)^{N_G+n-1} \binom{N_D-N_G}{n} \left(\frac{N_G}{n}\right)^{N_G-1}$, we can obtain $P_{R_m D}(\gamma_{th})$ as

$$\begin{aligned}
P_{R_m D}(\gamma_{th}) &= 1 - \int_{\gamma_{th}}^{\infty}\int_{\gamma_{th}}^{\infty} \frac{b_1}{\gamma_{R1}} e^{-\frac{b_2\gamma_{R2}}{\gamma_{R1}}} \Bigg\{ \frac{\gamma_{R1}^{N_G-1}}{b_3} e^{-b_4\gamma_{R1}} \\
&+ \sum_{n=1}^{N_D-N_G} \Xi \left[e^{-b_4\gamma_{R1}-nb_5\gamma_{R1}} - e^{-b_4\gamma_{R1}} \sum_{m=0}^{N_G-2} \frac{1}{m!}(-nb_5\gamma_{R1})^m \right] \Bigg\} d\gamma_{R2} d\gamma_{R1} \\
&= 1 - \frac{b_1}{b_2} \left\{ \underbrace{\int_{\gamma_{th}}^{\infty} \frac{\gamma_{R1}^{N_G-1}}{b_3} e^{-\frac{b_2\gamma_{th}}{\gamma_{R1}}-b_4\gamma_{R1}} d\gamma_{R1}}_{I_1} + \sum_{n=1}^{N_D-N_G} \Xi \left[\underbrace{\int_{\gamma_{th}}^{\infty} e^{-\frac{b_2\gamma_{th}}{\gamma_{R1}}-b_4\gamma_{R1}-nb_5\gamma_{R1}} d\gamma_{R1}}_{I_2} \right.\right. \\
&\left.\left. - \sum_{m=0}^{N_G-2} \frac{(-nb_5)^m}{m!} \underbrace{\int_{\gamma_{th}}^{\infty} \gamma_{R1}^m e^{-\frac{b_2\gamma_{th}}{\gamma_{R1}}-b_4\gamma_{R1}} d\gamma_{R1}}_{I_3} \right] \right\}. \qquad (21)
\end{aligned}$$

Using [23, Eq. (8.407)] and Chebyshev-Gauss quadrature, we can re-express I_1as

$$\begin{aligned}
I_1 &= \int_0^{\infty} \frac{\gamma_{R1}^{N_G-1}}{b_3} e^{-\frac{b_2\gamma_{th}}{\gamma_{R1}}-b_4\gamma_{R1}} d\gamma_{R1} - \int_0^{\gamma_{th}} \frac{\gamma_{R1}^{N_G-1}}{b_3} e^{-\frac{b_2\gamma_{th}}{\gamma_{R1}}-b_4\gamma_{R1}} d\gamma_{R1} \\
&= \frac{2}{b_3}\left(\frac{b_2\gamma_{th}}{b_4}\right)^{\frac{N_G}{2}} K_{N_G}\left(2\sqrt{b_2 b_4 \gamma_{th}}\right) - \frac{\gamma_{th}}{2b_3} \int_{-1}^{1} \left[\frac{\gamma_{th}(t+1)}{2}\right]^{N_G-1} e^{-\frac{2b_2}{(t+1)}-\frac{b_4\gamma_{th}(t+1)}{2}} dt \\
&= \frac{2}{b_3}\left(\frac{b_2\gamma_{th}}{b_4}\right)^{\frac{N_G}{2}} K_{N_G}\left(2\sqrt{b_2 b_4 \gamma_{th}}\right) - \frac{\gamma_{th}}{2b_3} \sum_{i=1}^{I} W_i \sqrt{1-\phi_i^2} \left[\frac{\gamma_{th}(\phi_i+1)}{2}\right]^{N_G-1} \\
&\quad \times e^{-\frac{2b_2}{(\phi_i+1)}-\frac{b_4\gamma_{th}(\phi_i+1)}{2}}, \qquad (22)
\end{aligned}$$

where $W_i = \pi/I$ and $\phi_i = \cos\left(\frac{2i-1}{2I}\pi\right)$.

Similarly, we can express I_2 and I_3 as

$$
\begin{aligned}
I_2 &= \int\limits_0^{\infty} e^{-\frac{b_2\gamma_{th}}{\gamma_{R1}}-b_4\gamma_{R1}-nb_5\gamma_{R1}} d\gamma_{R1} - \int\limits_0^{\gamma_{th}} e^{-\frac{b_2\gamma_{th}}{\gamma_{R1}}-b_4\gamma_{R1}-nb_5\gamma_{R1}} d\gamma_{R1} \\
&= 2\sqrt{\frac{b_2\gamma_{th}}{b_4+nb_5}} K_1\left(2\sqrt{b_2\left(b_4+nb_5\right)\gamma_{th}}\right) - \frac{\gamma_{th}}{2}\sum_{j=1}^{J} W_j\sqrt{1-\tau_j^2} e^{-\frac{2b_2}{\left(\tau_j+1\right)}} \\
&\quad \times e^{-\frac{(b_4+nb_5)\gamma_{th}\left(\tau_j+1\right)}{2}}
\end{aligned} \tag{23}
$$

and

$$
\begin{aligned}
I_3 &= \int\limits_0^{\infty} \gamma_{R1}^m e^{-\frac{b_2\gamma_{th}}{\gamma_{R1}}-b_4\gamma_{R1}} d\gamma_{R1} - \int\limits_0^{\gamma_{th}} \gamma_{R1}^m e^{-\frac{b_2\gamma_{th}}{\gamma_{R1}}-b_4\gamma_{R1}} d\gamma_{R1} \\
&= 2\left(\frac{b_2\gamma_{th}}{b_4}\right)^{\frac{m+1}{2}} K_{m+1}\left(2\sqrt{b_2b_4\gamma_{th}}\right) - \frac{\gamma_{th}}{2}\sum_{k=1}^{K} W_k\sqrt{1-\mu_k^2}\left[\frac{\gamma_{th}\left(\mu_k+1\right)}{2}\right]^m \\
&\quad \times e^{-\frac{2b_2}{(\mu_k+1)}-\frac{b_4\gamma_{th}(\mu_k+1)}{2}},
\end{aligned} \tag{24}
$$

respectively, where $W_j = \pi/J$, $\tau_j = \cos\left(\frac{2j-1}{2J}\pi\right)$, $W_k = \pi/K$ and $\mu_k = \cos\left(\frac{2k-1}{2K}\pi\right)$.

4. OP under Three RS Schemes Combined with Threshold DF Relaying Scheme

In this section, we will discuss three types of RS methods combined with threshold DF relaying scheme for the considered dual-hop cooperative EH network.

4.1. Threshold DF Relaying Scheme

Under threshold DF relaying scheme, R_n can participate the best relay selection process only when its instantaneous SNR of the received signal over $S-R_n$ link is larger than a predefined threshold, γ_0, which means the probability of an error at R_n is small. Otherwise, R_n remains silent.

Although the transmitting power varies at any time slot, there is only one S with single transmit antenna causing to same transmitting power for any $S-R_n$ link. Thus, we only need to compare instantaneous channel gain to select the relay candidates. Thus, in this work, we assume the SNR of $S-R_n$ link can be expressed as $\gamma_S = \frac{P|h_{SR_n}|^2}{N_0}$ with the same transmit power P while we adopt the DF relaying scheme. Thus, the probability that R_n could forward information successfully can be expressed as

$$P_F = \Pr\left\{\gamma_S > \gamma_0\right\} = 1 - \Pr\left\{\gamma_S \le \gamma_0\right\} = \exp\left(-\lambda_S \gamma_0\right), \tag{25}$$

where $\lambda_S = \frac{N_0}{P}$.

Assuming the number of the relays that can forward information successfully is M. Then, $\Pr\{M = i\}$, $(0 \le M = i \le N)$ can be denoted as

$$\Pr\{M = i\} = \binom{N}{i} (1 - P_F)^{N-i} {P_F}^i. \tag{26}$$

4.2. TH-OSRL scheme

Under OSRL scheme, the candidate with the best $S-R_m$ link is selected as the forwarding relay. However, under the DF threshold relay scheming, the SNR of the best relay should also larger than the predefined threshold γ_0. Therefore, the received SNR at the best relay with M relaying candidates is

$$\gamma_{SR}^M = \max_{m=1,\ldots,M \le N} \left\{\gamma_{SR_m} | \gamma_S > \gamma_0\right\}, \tag{27}$$

where $\gamma_S = \frac{P|h_{SR_m}|^2}{N_0} = \lambda_S |h_{SR_m}|^2 = \lambda_S X_{S1}$.

Thus, the OP over the $S-R$ link with M relaying candidates can be expressed as $P_{SR}^M(\gamma_{th}) = \Pr\left\{\gamma_{SR}^M \le \gamma_{th}\right\}$. Accordingly, the total OP over

$S-R$ link can be expressed as

$$P_{SR}^{OSRL}\left(\gamma_{th}\right)=\sum_{i=0}^{N}\Pr\left\{M=i\right\}P_{SR}^{M}\left(\gamma_{th}\right). \tag{28}$$

Then, we will calculate the OP for a single $S-R_m$ link first, which can be calculated as

$$\begin{aligned}
P_{SR_m}^{\gamma_0}\left(\gamma_{th}\right) &= \Pr\left\{\gamma_{SR_m}\leq\gamma_{th}\left|\gamma_S>\gamma_0\right.\right\}\\
&= \Pr\left\{\frac{\min\left\{\frac{B_S}{T_2},\frac{E_S}{T_2}\right\}\left|h_{SR_m}\right|^2}{N_0}\leq\gamma_{th}\left|\gamma_S>\gamma_0\right.\right\}\\
&= \Pr\left\{\min\left\{\gamma_{S1},\gamma_{S2}\right\}\leq\gamma_{th}\left|\gamma_S>\gamma_0\right.\right\}\\
&= 1-\Pr\left\{\min\left\{\gamma_{S1},\gamma_{S2}\right\}>\gamma_{th}\left|\gamma_S>\gamma_0\right.\right\}\\
&= 1-\Pr\left\{\gamma_{S1}>\gamma_{th},\gamma_{S2}>\gamma_{th}\left|\gamma_S>\gamma_0\right.\right\}\\
&= 1-\frac{\Pr\left\{\gamma_{S1}>\gamma_{th},\gamma_{S2}>\gamma_{th},\gamma_S>\gamma_0\right\}}{\Pr\left\{\gamma_S>\gamma_0\right\}}.
\end{aligned} \tag{29}$$

According to some previous assumptions, $\gamma_{S1}=\lambda_{S1}X_{S1}$, $\gamma_{S2}=\lambda_{S2}X_{S1}X_{S2}$, $\gamma_S=\lambda_S X_{S1}$, $X_{S1}=\frac{\gamma_{S1}}{\lambda_{S1}}$, $X_{S2}=\frac{\gamma_{S2}\lambda_{S1}}{\lambda_{S2}\gamma_{S1}}$, we can obtain $\Pr\left\{\gamma_{S1}>\gamma_{th},\gamma_{S2}>\gamma_{th},\gamma_S>\gamma_0\right\}$ as

$$\begin{aligned}
&\Pr\left\{\gamma_{S1}>\gamma_{th},\gamma_{S2}>\gamma_{th},\gamma_S>\gamma_0\right\}\\
&= \Pr\left\{\lambda_{S1}X_{S1}>\gamma_{th},\lambda_{S2}X_{S1}X_{S2}>\gamma_{th},\lambda_S X_{S1}>\gamma_0\right\}\\
&= \Pr\left\{X_{S1}>\frac{\gamma_{th}}{\lambda_{S1}},X_{S1}>\frac{\gamma_{th}}{\lambda_{S2}X_{S2}},X_{S1}>\frac{\gamma_0}{\lambda_S}\right\}\\
&= \Pr\left\{X_{S1}>\max\left\{\frac{\gamma_{th}}{\lambda_{S1}},\frac{\gamma_{th}}{\lambda_{S2}X_{S2}},\frac{\gamma_0}{\lambda_S}\right\}\right\}\\
&= 1-\Pr\left\{X_{S1}\leq\max\left\{\frac{\gamma_{th}}{\lambda_{S1}},\frac{\gamma_{th}}{\lambda_{S2}X_{S2}},\frac{\gamma_0}{\lambda_S}\right\}\right\}.
\end{aligned} \tag{30}$$

Since $\frac{\gamma_{th}}{\lambda_{S1}}$ and $\frac{\gamma_{th}}{\lambda_{S1}}$ are both constants, we denote $C = \max\left\{\frac{\gamma_{th}}{\lambda_{S1}}, \frac{\gamma_0}{\lambda_S}\right\}$ to simplify the equation. Thus, $\Pr\{\gamma_{S1} > \gamma_{th}, \gamma_{S2} > \gamma_{th}, \gamma_S > \gamma_0\}$ can be re-expressed as

$$\begin{aligned}\Pr\{\gamma_{S1} > \gamma_{th}, \gamma_{S2} > \gamma_{th}, \gamma_S > \gamma_0\} &= 1 - \Pr\left\{X_{S1} \le \max\left\{\frac{\gamma_{th}}{\lambda_{S2}X_{S2}}, C\right\}\right\} \\ &= 1 - F_{X_{S1}}\left(\max\left\{\frac{\gamma_{th}}{\lambda_{S2}X_{S2}}, C\right\}\right) \\ &= e^{-\frac{\max\left\{\frac{\gamma_{th}}{\lambda_{S2}X_{S2}}, C\right\}}{h_{SR_m}}}. \end{aligned} \tag{31}$$

As $\Pr\{\gamma_S > \gamma_0\} = P_F$, we can express $P_{SR_m}^{\gamma_0}(\gamma_{th})$ as

$$P_{SR_m}^{\gamma_0}(\gamma_{th}) = 1 - P_F^{-1} e^{-\frac{\max\left\{\frac{\gamma_{th}}{\lambda_{S2}X_{S2}}, C\right\}}{h_{SR_m}}}. \tag{32}$$

Considering i.i.d Rayleigh fading channel, we can obtain that $P_{SR}^M(\gamma_{th})$ as

$$\begin{aligned}P_{SR}^M(\gamma_{th}) = \prod_{m=1,\dots,M\le N}^{M} P_{SR_m}^{\gamma_0}(\gamma_{th}) &= \left[1 - P_F^{-1} e^{-\frac{\max\left\{\frac{\gamma_{th}}{\lambda_{S2}X_{S2}}, C\right\}}{h_{SR_m}}}\right]^M \\ &= \sum_{k=0}^{M} \binom{M}{k} (-1)^k {P_F}^{-k} e^{-k\frac{\max\left\{\frac{\gamma_{th}}{\lambda_{S2}X_{S2}}, C\right\}}{h_{SR_m}}}. \end{aligned} \tag{33}$$

Then, using the distribution of X_{S2}, we can re-express $P_{SR}^M(\gamma_{th})$ as

$$P_{SR}^M(\gamma_{th}) = \sum_{k=0}^{M} \binom{M}{k} (-1)^k {P_F}^{-k} \underbrace{\int_0^\infty e^{-k\frac{\max\left\{\frac{\gamma_{th}}{\lambda_{S2}x}, C\right\}}{h_{SR_m}}} f_{X_{S2}}(x)\, dx}_{I_4}, \tag{34}$$

where I can be calculated as

$$\begin{aligned} I_4 &= \int\limits_{\gamma_{th}/\lambda_{S2}C}^{\infty} e^{-\frac{kC}{h_{SR_m}}} f_{X_{S2}}(x)\,dx + \int\limits_{0}^{\gamma_{th}/\lambda_{S2}C} e^{-\frac{k\gamma_{th}}{\lambda_{S2}h_{SR_m}x}} f_{X_{S2}}(x)\,dx \\ &= \int\limits_{\gamma_{th}/\lambda_{S2}C}^{\infty} e^{-\frac{kC}{h_{SR_m}}} \frac{1}{h_{DS}} e^{-\frac{x}{h_{DS}}}\,dx + \int\limits_{0}^{\gamma_{th}/\lambda_{S2}C} e^{-\frac{k\gamma_{th}}{\lambda_{S2}h_{SR_m}x}} \frac{1}{h_{DS}} e^{-\frac{x}{h_{DS}}}\,dx. \end{aligned} \tag{35}$$

Using Chebyshev-Gauss quadrature in the second integral, I_4 can be rewritten as

$$\begin{aligned} I_4 &= e^{-\frac{kC}{h_{SR_m}}} e^{-\frac{\gamma_{th}}{h_{DS}\lambda_{S2}C}} + c_1 \int\limits_{-1}^{1} e^{-\frac{c_2 k}{(t+1)} - c_3(t+1)}dt \\ &= e^{-\frac{kC}{h_{SR_m}}} e^{-\frac{\gamma_{th}}{h_{DS}\lambda_{S2}C}} + \sum_{i=1}^{L} W_l \sqrt{1-\varepsilon_l^2}\, c_1 e^{-\frac{c_2 k}{(\varepsilon_l+1)} - c_3(\varepsilon_l+1)}, \end{aligned} \tag{36}$$

where $W_l = \pi/L$, $\varepsilon_l = \cos\left(\frac{2l-1}{2L}\pi\right)$, $c_1 = \frac{\gamma_{th}}{2\lambda_{S2}Ch_{DS}}$, $c_2 = \frac{2C}{h_{SR_m}}$ and $c_3 = \frac{\gamma_{th}}{2\lambda_{S2}Ch_{DS}}$.

So, we can obtain $P_{SR}^{M}(\gamma_{th})$ and $P_{SR}^{OSRL}(\gamma_{th})$ accordingly. Finally, the OP of the considered system under TH-OSRL scheme can be obtained by using (21) and (28), which can be expressed as

$$\begin{aligned} P_{OSRL}(\gamma_{th}) &= 1 - \left[1 - P_{SR}^{OSRL}(\gamma_{th})\right]\left[1 - P_{R_mD}(\gamma_{th})\right] \\ &= P_{SR}^{OSRL}(\gamma_{th}) + P_{R_mD}(\gamma_{th}) - P_{SR}^{OSRL}(\gamma_{th})\, P_{R_mD}(\gamma_{th}). \end{aligned} \tag{37}$$

4.3. TH-ORDL scheme

Under TH-ORDL scheme, the candidate with the best link between the forwarding relays and D is selected as the best relay. Thus, the SNR of the $R-D$ link with M relaying candidates should satisfy

$$\gamma_{RD} = \max_{m=1,\dots,M\le N} \left\{\gamma_{R_mD}\right\}. \tag{38}$$

The OP over the $R-D$ link with M relaying candidates can be expressed as

$$\Pr\left\{\gamma_{RD} \le \gamma_{th}\right\} = \Pr\left\{\max_{m=1,\ldots,M \le N}\left\{\gamma_{R_m D}\right\} \le \gamma_{th}\right\} = \prod_{m=1}^{M} P_{R_m D}\left(\gamma_{th}\right), \quad (39)$$

where $P_{R_m D}\left(\gamma_{th}\right)$ has been obtained in (21).

Similarly, the OP of the considered system under this case can be expressed as

$$\begin{aligned} P_{ORDL}\left(\gamma_{th}\right) &= 1 - \left[1 - \Pr\left\{\gamma_{RD} \le \gamma_{th}\right\}\right]\left[1 - \Pr\left\{\gamma_{SR} \le \gamma_{th}\left|\gamma_S > \gamma_0\right.\right\}\right] \\ &= \Pr\left\{\gamma_{RD} \le \gamma_{th}\right\} + \Pr\left\{\gamma_{SR} \le \gamma_{th}\left|\gamma_S > \gamma_0\right.\right\} \\ &\quad - \Pr\left\{\gamma_{RD} \le \gamma_{th}\right\}\Pr\left\{\gamma_{SR} \le \gamma_{th}\left|\gamma_S > \gamma_0\right.\right\}, \end{aligned} \quad (40)$$

where $\Pr\left\{\gamma_{SR} \le \gamma_{th}\left|\gamma_S > \gamma_0\right.\right\} = P_{SR_m}^{\gamma_0}\left(\gamma_{th}\right) = P_{SR}^{\gamma_0}\left(\gamma_{th}\right)$ is shown in (32). Then, considering the distribution of X_{S2}, we can re-express $P_{SR}^{\gamma_0}\left(\gamma_{th}\right)$ as

$$\begin{aligned} P_{SR}^{\gamma_0}\left(\gamma_{th}\right) &= 1 - \int_0^\infty \frac{e^{-\frac{\max\left\{\frac{\gamma_{th}}{\lambda_{S2}x}, C\right\}}{h_{SR}}}}{P_F} f_{X_{S2}}\left(x\right)dx \\ &= 1 - {P_F}^{-1}\left[\int_{\gamma_{th}/\lambda_{S2}C}^{\infty} \frac{1}{h_{DS}} e^{-\frac{C}{h_{SR}} - \frac{x}{h_{DS}}}dx + \int_0^{\gamma_{th}/\lambda_{S2}C} \frac{1}{h_{DS}}\, e^{-\frac{\gamma_{th}}{\lambda_{S2}h_{SR}x} - \frac{x}{h_{DS}}}\right]dx \\ &= 1 - {P_F}^{-1}\left\{\exp\left(-\frac{C}{h_{SR}}\right)\exp\left(-\frac{\gamma_{th}}{h_{DS}\lambda_{S2}C}\right)\right. \\ &\quad \left. + \sum_{i=1}^{Q} W_q\sqrt{1-\kappa_q^2}\,c_1\exp\left[-\frac{c_2}{\left(\kappa_q+1\right)} - c_3\left(\kappa_q+1\right)\right]\right., \end{aligned} \quad (41)$$

where $W_q = \pi/Q$ and $\kappa_q = \cos\left(\frac{2q-1}{2Q}\pi\right)$.

Thus, we can obtain the OP of the considered system under TH-ORDL scheme by substituting (41) and (21) into (40).

4.4. TH-OSRDL scheme

Under TH-OSRDL scheme, the equivalent end-to-end SNR of the received signal at D with M relaying candidates satisfies

$$\gamma_{SRD}^{M} = \max_{m=1,\ldots,M\leq N} \left\{ \min \left\{ \gamma_{SR_m} \left| \gamma_S > \gamma_0 \right. , \gamma_{R_m D} \right\} \right\}. \tag{42}$$

The OP under TH-OSRDL scheme with M relaying candidates can be expressed as $P_{SRD}^{M}(\gamma_{th}) = \Pr\left\{\gamma_{SRD}^{M} \leq \gamma_{th}\right\}$. Thus, the total OP under this scheme can be expressed as

$$P_{SRD}^{OSRDL}(\gamma_{th}) = \sum_{i=0}^{N} \Pr\{M = i\} P_{SRD}^{M}(\gamma_{th}). \tag{43}$$

In order to obtain $P_{SRD}^{M}(\gamma_{th})$, we should calculate the OP for single $S-R_m-D$ link first. It can be denoted as $P_{SR_mD}(\gamma_{th})$, which could be calculated as

$$\begin{aligned} P_{SR_mD}(\gamma_{th}) &= \Pr\left\{\min\left\{\gamma_{SR_m} \left| \gamma_S > \gamma_0 \right., \gamma_{R_mD}\right\} \leq \gamma_{th}\right\} \\ &= 1 - \left[1 - P_{SR_m}^{\gamma_0}(\gamma_{th})\right]\left[1 - P_{R_mD}(\gamma_{th})\right]. \end{aligned} \tag{44}$$

Thus, using (21) and (32), we can obtain $P_{SR_mD}(\gamma_{th})$ as

$$\begin{aligned} P_{SR_mD}(\gamma_{th}) = 1 - P_F^{-1} e^{-\frac{\max\left\{\frac{\gamma_{th}}{\lambda_{S2}\chi_{S2}}, C\right\}}{h_{SR_m}}} &\left\{ \frac{b_1}{b_2} \left\{ \frac{2}{b_3} \left(\frac{b_2\gamma_{th}}{b_4}\right)^{\frac{N_G}{2}} K_{N_G}\left(\sqrt{4b_2b_4\gamma_{th}}\right) e^{-b_4\gamma_{th}} \right.\right. \\ &+ \sum_{n=1}^{N_D-N_G} \Xi \left[\sqrt{\frac{4b_2\gamma_{th}}{(b_4+nb_5)}} K_1\left(\sqrt{4b_2(b_4+nb_5)\gamma_{th}}\right) e^{-(b_4+nb_5)\gamma_{th}} \right. \\ &\left.\left.\left. - \sum_{m=0}^{N_G-2} \frac{(-nb_5)^m}{m!} 2\left(\frac{b_2\gamma_{th}}{b_4}\right)^{\frac{m+1}{2}} K_{m+1}\left(\sqrt{4b_2b_4\gamma_{th}}\right) e^{-b_4\gamma_{th}} \right] \right\} \right\}. \end{aligned} \tag{45}$$

According to (42) and considering i.i.d Rayleigh fading channel, we can obtain $P_{SRD}^{M}\left(\gamma_{th}\right)$ as

$$\begin{aligned}
P_{SRD}^{M}\left(\gamma_{th}\right) &= \prod_{m=1}^{M}\left\{1-\left[1-P_{R_mD}\left(\gamma_{th}\right)\right].\, P_F^{-1}e^{-\frac{\max\left\{\frac{\gamma_{th}}{\lambda_{S2}X_{S2}},C\right\}}{h_{SR_m}}}\right\} \\
&= \sum_{k=0}^{M}\binom{M}{k}(-1)^k P_F{}^{-k}\left(1-P_{R_mD}\left(\gamma_{th}\right)\right)^k P_F^{-1}e^{-k\frac{\max\left\{\frac{\gamma_{th}}{\lambda_{S2}X_{S2}},C\right\}}{h_{SR_m}}}.
\end{aligned} \tag{46}$$

Thus, considering the distribution of X_{R1}, we can re-express $P_{SRD}^{M}\left(\gamma_{th}\right)$ as

$$\begin{aligned}
P_{SRD}^{M}\left(\gamma_{th}\right) &= \sum_{k=0}^{M}\binom{M}{k}(-1)^k P_F{}^{-k}\left(1-P_{R_mD}\left(\gamma_{th}\right)\right)^k \\
&\quad \cdot \int_{0}^{\infty} e^{-k\frac{\max\left\{\frac{\gamma_{th}}{\lambda_{S2}x},C\right\}}{h_{SR_m}}} f_{X_{R1}}(x)\,dx \\
&= \sum_{k=0}^{M}\binom{M}{k}(-1)^k P_F{}^{-k}\left(1-P_{R_mD}\left(\gamma_{th}\right)\right)^k I_4,
\end{aligned} \tag{47}$$

where I_4 was obtained in (36).

Finally, we can obtain the OP of the considered system under TH-OSRDL scheme by inserting (47) into (43).

5. Numerical results

In this section, numerical results are obtained by running 10^5 trials of Monte Carlo simulations to validate our proposed analysis models of the OP for the considered system. The main parameters adopted here are set as: $T_1 = 400$ s, $T_2 = 200$ s, $T_3 = 300$ s, $B_{R_m} = B_S = 500$ mAh $\times 3.0$ V, $P_D = 10$ dB, $P = 3$ dB, $N = 6$, $N_D = 9$, $N_G = 5$, $\gamma_0 = 0.5$ dB, $h_{DR} = h_{DR_n} = 5$ dB, $h_{DS} = 5$ dB, $h_{RD} = h_{R_mD} = 5$ dB, $h_{SR} = h_{SR_n} = 5$ dB and $N_0 = 1$.

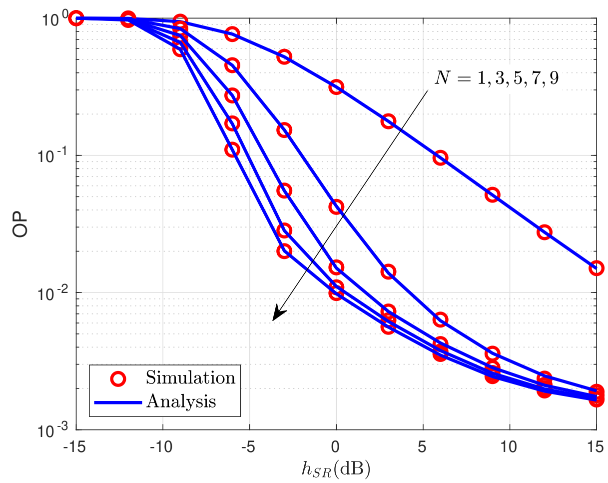


Figure 2: OP versus h_{SR} for various N.

5.1. TH-OSRL

In this subsection, the best relay is selected by TH-OSRL scheme. As depicted in Fig. 2, the outage performance can be significantly improved by increasing N, which means higher diversity gain. However, the improvement becomes weak in the higher N field, since the OP for R-D link is not influenced by N. We can also see that there is a floor existing for OP lines in high h_SR region because the OP of R-D link leads to a low bound of the overall OP of the considered system in high h_SR region.

5.2. TH-OSRL

In this subsection, the best relay is selected by using TH-ORDL scheme. In Fig. 3, we show the lines of the OP versus h_{RD} for various N_D. It is clear that a significant decrease in the OP is obtained as the number N_D increases for fixed N_G because of the increasing available diversity path. Moreover, there is also a floor existing for the OP lines in high h_RD region as same

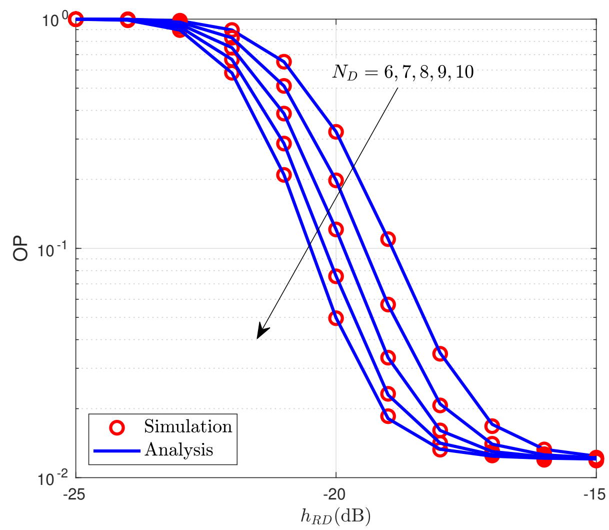


Figure 3: OP versus h_{RD} for various N_D.

as the ones in Fig. 2, because the outage performance over S-R link mainly decides the OP of the objective system in high h_{RD} region.

5.3. TH-OSRDL

In this subsection, the best relay is selected by TH-OSRDL scheme. Fig. 4 shows the impact of P_D for various P on OP. High P leads to more available candidates participating in the best relay selection process and then reduces OP accordingly. However, the improvement is more obvious in lower P field, because almost all relays could engage the best relay selection process, when P increases to certain value. We can see that increasing P_D could also improve the system performance. It is obvious that high P_D means more harvest energy at S and relays and high transmit power accordingly. But we can also see the floor exists in high P_D, since S and R could only transmit signal with the maximum power decided by the energy storage capacity when

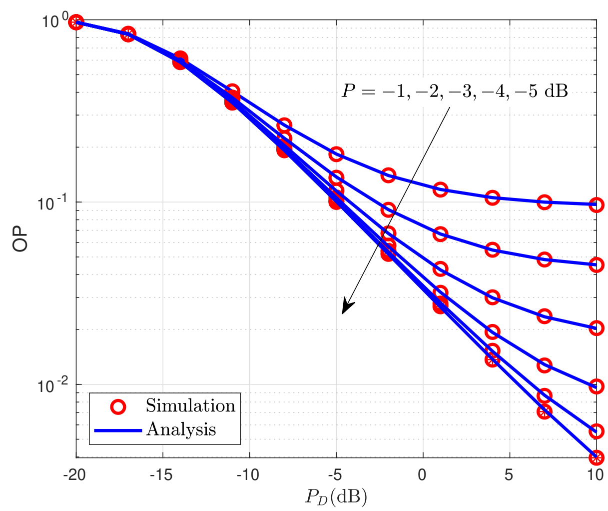


Figure 4: OP versus P_D for various P.

the harvesting energy exceeds the capacity.

5.4. Comparisons among TH-OSRL, TH-ORDL, TH-OSRDL Schemes

In this subsection, we compare the outage performance under TH-OSRL, TH-ORDL, TH-OSRDL schemes. As shown in Fig. 5, OP can be improved by decreasing γ_0 in high γ_0 region under TH-OSRDL scheme to maintain more relay candidates, while it only makes a little sense in low γ_0 region under TH-OSRL and TH-OSRDL schemes. However, since S-R link exhibits a significant contribution on the system performance, we can see that OP decreases under TH-ORDL scheme with increasing γ_0, while OP only decreases under TH-OSRL in high γ_0 region. Moreover, the OP under these three schemes with a small γ_{th} outperforms the one with a high γ_{th}.

Fig. 6 plots the OP versus N_G for various $\eta_1 = \frac{T_1}{T_2}$ and $\eta_2 = \frac{T_1}{T_3}$. We can observe that OP can be improved by decreasing T_2 under three relay selec-

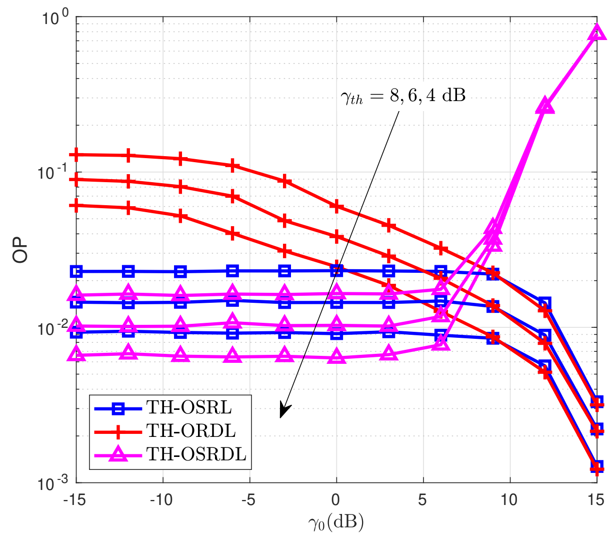


Figure 5: OP versus γ_0 for various γ_{th}.

tion schemes while T_3 only affects the system performance under TH-OSRL scheme. The reason is that R-D link mainly decides the OP of the considered system under good channel condition. The number of the combined receive antennas only make a difference under TH-OSRL scheme, because the diversity gain does not play the main role under high quality of channel condition.

Obviously, TH-OSRDL scheme outperforms TH-OSRL and TH-ORDL schemes in the same communication environments. Because the two other schemes only utilize the CSI of partial links while TH-OSRDL scheme exploits the CSI of the end-to-end S-R_m-D link to select the best forwarding relay. Moreover, TH-OSRL scheme outperforms TH-ORDL scheme sometimes because the threshold DF relay reduces the diversity gain at D with less forwarding candidates, while TH-OSRL scheme exhibits same outage

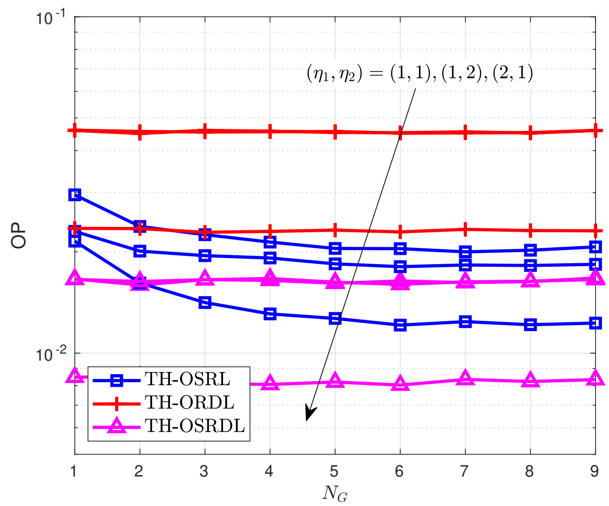


Figure 6: OP versus N_G for various (η_1, η_2) with $\gamma_0 = 3$ dB, $\gamma_{th} = 5$ dB.

performance with OSRL scheme in most cases.

6. Conclusion

In this paper, we have considered a dual-hop cooperative EH system combining with relay selection schemes and threshold DF relaying scheme at relays, and GSC technologies at D. The OP for single S-R_n link and R_m-D link has been characterized. We also derive the overall system OP under three best relay selection schemes based on threshold DF relaying scheme: TH-OSRL, TH-ORDL and TH-OSRDL schemes. Monte-Carlo simulations are used to verify the correctness of the derived closed-form analytic expressions for the OP of the overall system.

By observing the numerical results, we can reach the following conclusions:

1) Threshold DF relaying scheme could improve the system outage performance by increasing γ_0 under TH-OSRL scheme in high γ_0 region while by decreasing γ_0 under TH-OSRDL scheme in high γ_0 region. The OP can be improved as the γ_0 increase under TH-ORDL scheme.

2) The increasing of the number of the receiving antennas acts a more critical role under TH-OSRL scheme. Increasing the number of relay candidates could reduce the OP as well.

3) A low bound of the OP occurs under the TH-OSRL and TH-ORDL schemes, since the quality of the other link decide the final OP in better channel condition.

4) TH-OSRL scheme outperforms TH-ORDL scheme, while TH-OSRDL outperforms TH-ORDL scheme and TH-OSRL scheme in the same communication environments.

5) The transmitting slots over S-R_m link makes more contributions compared with the ones over R-D link, because of the adopted threshold DF relaying scheme.

7. Acknowledgement

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References

[1] J. Yang and S. Ulukus, Optimal packet scheduling in an energy harvesting communication system, IEEE Trans. Commun. 60 (1) (2012) 220-230.

[2] H. Zhang, S. Huang, C. Jiang, et al., Energy efficient user association and power allocation in millimeter wave based ultra dense networks with energy harvesting base stations, IEEE J. Sel. Areas Commun. 35 (9) (2017) 1936-1947.

[3] G. Pan, J. Ye and Z. Ding, Secure hybrid VLC-RF systems with light energy harvesting, IEEE Trans. Commun. 65 (10) (2017) 4348-4359.

[4] M. Ku, W. Li, Y. Chen and K. J. Ray Liu, Advances in energy harvesting communications: Past, present, and future challenges, IEEE Commun. Surveys Tuts. 18 (2) (2016) 1384-1412.

[5] G. Pan, H. Lei, Y. Yuan and Z. Ding, Performance analysis and optimization for SWIPT wireless sensor networks, IEEE Trans. Commun. 65 (5) (2017) 2291-2302.

[6] H. Zhang, J. Du, J. Cheng, etc., Incomplete CSI based resource optimization in SWIPT enabled heterogeneous networks: A non-cooperative game theoretic approach, IEEE Trans. Wireless Commun. 17 (3) (2018) 1882-1892.

[7] Y. Luo, J. Zhang, and K. B. Letaief, Optimal scheduling and power allocation for two-hop energy harvesting communication systems, IEEE Trans. Wireless Commun. 12 (9) (2013) 4729-4741.

[8] C. Huang, R. Zhang, and S. Cui, Throughput maximization for the Gaussian relay channel with energy harvesting constraints, IEEE J. Sel. Areas Commun. 31 (8) (2013) 1469-1479.

[9] G Pan, C. Tang, Outage performance on threshold AF and DF relaying schemes in simultaneous wireless information and power transfer systems, AEU-International Journal of Electronics and Communications 71 (2017) 175-180.

[10] I. Krikidis, T. Charalambous, and J. S. Thompson, Stability analysis and power optimization for energy harvesting cooperative networks, IEEE Signal Process. Lett. 19 (1) (2012) 20-23.

[11] J. Ye, H. Lei, Y. Liu, G. Pan, D. B. da Costa, Q. Ni, Z. Ding, Cooperative communications with wireless energy harvesting over Nakagami-m fading channels, IEEE Trans. Commun. 65 (12) (2017) 5149-5164.

[12] D. Wang, R. Zhang, X. Cheng, L. Yang and C. Chen, Relay selection in full-duplex energy-harvesting two-way relay networks, IEEE Trans. Green Commun. Netw. 1 (2) (2017) 182-191.

[13] D. S. Michalopoulos, H. A. Suraweera and R. Schober, Relay selection for simultaneous information transmission and wireless energy transfer: A tradeoff perspective, IEEE J. Sel. Areas Commun. 33 (8) (2015) 1578-1594.

[14] B. Medepally and N. B. Mehta, Voluntary energy harvesting relays and selection in cooperative wireless networks, IEEE Trans. Wireless Commun. 9 (11) (2010) 3543-3553.

[15] G. Pan, Y. Chen, and Q. Feng, Performance analysis of interference limited cooperative systems with relay selection over independent log-normal fading channels, IET Commun. 8 (10) (2014) 1751-1761.

[16] D. S. Michalopoulos, H. A. Suraweera, G. K. Karagiannidis and R. Schober, Amplify-and-forward relay selection with outdated channel estimates, IEEE Trans. Commun. 60 (5) (2012) 1278-1290.

[17] H. Yu, D. Wang, G. Pan, R. Shi, J. Zhang and Y. Chen, On outage of WPC system with relay selection over Nakagami-m fading channels, IEEE Trans. Veh. Technol. 66 (9) (2017) 8590-8594.

[18] H. Lei, H. Zhang, I. S. Ansari, C. Gao, Y. Guo, G. Pan, K. a. Qaraqe, Secrecy outage performance for SIMO underlay cognitive radio systems with generalized selection combining over Nakagami-m channels, IEEE Trans. Veh. Technol. 65 (12) (2016) 10126-10132.

[19] D. Wang, H. Yu, H. Lei, T. Li, J. Zhang, G. Pan and Y. Chen, Outage of relay simultaneous wireless information and power transfer with GSC and finite storage in Nakagami-m fading, IET Commun. 11 (12) (2017) 1871-1881.

[20] V. A. Aalo and J. Zhang, Performance analysis of maximal ratio combining in the presence of multiple equal-power cochannel interferers in a Nakagami fading channel, IEEE Trans. Veh. Technol. 50 (2) (2001) 497-503.

[21] M. K. Simon, M. S. Alouini, Digital communication over fading channels, 2nd Ed, Wiley Interscience, 2005.

[22] M.-S. Alouini and M. Simon, An MGF-based performance analysis of generalized selection combining over Rayleigh fading channels, IEEE Trans. Commun. 48 (3) (2000) 401-415.

[23] I.S. Gradshteyn and I.M. Ryzhik, Table of integrals, Series and Products, 7th Ed., Academic Press, 2007.