Power Splitting and Source-Relay Selection in Energy Harvesting Wireless Network

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Abstract
This paper investigates the performance of an energy-harvesting (EH) relay network, where multiple sources communicate with a destination via multiple EH decode-and-forward (DF) relays. The EH relays all equip with a power splitter to divide the received signal power into two parts, which are used for signal processing and information forwarding, respectively. The power splitting ratio depicts the trade-off between the relaying energy and decoding energy. We propose an optimal power splitting and joint source-relay selection (OPS-JSRS) scheme where the optimal power-splitting ratio is obtained and the best source-relay pair is selected to transmit the message. For the purpose of comparison, we present the optimal power splitting and round-robin (OPS-RR) and the traditional power splitting and joint source-relay selection (TPS-JSRS) schemes. The exact and asymptotic closed-form expressions of outage probability for OPS-RR, TPS-JSRS and OPS-JSRS schemes are derived over Rayleigh fading channels. Numerical results show that the outage probability of OPS-JSRS scheme is lower than that of OPS-RR and TPS-JSRS schemes, explaining that the proposed OPS-JSRS scheme outperforms TPS-JSRS and OPS-RR schemes. Additionally, the outage probability performance of OPS-JSRS scheme can be improved by increasing the number of sources and/or relays.

Keywords Energy harvesting · Power splitting · Source-relay selection · Outage probability
1 Introduction

Recently, wireless cooperative communications have attracted a large number of researchers’ attention because it can reduce channel fading loss and improve the transmission reliability [1–5]. Typically, the relaying protocols include decode-and-forward (DF) and amplify-and-forward (AF) [6]. Specifically, in the AF protocol, the relay simply amplifies and forwards the received signals to destination, which suffers from noise propagation problems. By contrast, in the DF protocol, the relay decodes the received messages first and then forwards the re-encoded symbols to destination. In the past few years, the best single relay selection has been drawing an increasing attention in the cooperative communications [7–9]. Furthermore, the multiple relay selection scheme is proposed to improve the security and reliability of the relay network [10, 11].

Energy harvesting (EH), which can extract energy from ambient energy sources, is emerging as an efficient technology to extend the lifetime and improve energy efficiency of the wireless devices, and has been widely used in the wireless communications [12–14]. Unlike traditional EH technology, simultaneous wireless information and power transfer (SWIPT) transmits both the information and energy to destination [15].

SWIPT has two protocols, namely time-switching (TS) protocol and power-splitting (PS) protocol [16]. In the PS protocol, the received signal power is divided into two parts, which are used to process information and forward signals, respectively. By contrast, TS protocol divides the time slot into two components. In the first time slot, the devices harvest energy from the received RF signals. And in the second time slot, the devices transmit messages with the harvested energy [17].

As a further development, the combination of EH and cooperative communications has regarded as a hot topic [18–20]. In [18], the authors studied the secrecy performance of a three-step two-way energy harvesting DF relay network. The closed-form intercept probability expression was derived over $k - u$ shadowed fading. [19] presented an energy aware relay selection scheme in the EH cognitive radio network for enhancing the security and reliability of the system. In [20], the outage probability performance was investigated in a energy harvesting wireless body area network. An optimal relay selection scheme was proposed to improve the system performance.

In addition, there is also some literature devoted to the power allocation problem in EH relay networks [21–24]. [21] proposed an optimal power allocation scheme for EH cooperative wireless network and derived the closed-form optimal power allocation factor. In [22], the authors formulated a power allocation problem by maximizing the energy efficiency. The closed-form solution is obtained with the aid of nonlinear fractional programming. Additionally, [23] provided a power allocation scheme for maximizing the energy efficiency by obtaining the optimal transmission power of a source in terms of consumed energy fraction. In [24], the authors investigated the data rate and energy efficiency of a EH two-way relay network. The rate and energy efficiency tradeoff algorithm was proposed to achieve the optimal power allocation. Presently, a few studies have focused on the joint power allocation and relay selection for EH relay networks [25, 26]. In [25], the authors formulated an outage probability minimization problem under the constraints of total transmit power for a two-way AF relay network. [26] investigated a relay selection scheme for EH AF relay networks and solved the joint optimization of relay selection and power splitting.

Multiuser scheduling, which can improve the system diversity and against channel fading, has been studied in recent years [7, 12, 27–29]. More specifically, [27] proposed a best
source relay selection schemes in a multiuser multi-relay network to improve the system throughput. [28] and [29] studied the multiuser scheduling scheme in the EH multiuser system.

Motivated by above observation, in this paper, we jointly consider the power splitting and source-relay selection to improve the outage probability performance in an EH DF relay network. The main contributions of this paper can be summarized as follows:

- We propose an optimal power splitting and joint source-relay selection (OPS-JSRS) scheme for an EH DF relay network. In the proposed OPS-JSRS scheme, the expression of optimal power-splitting ratio is obtained, and the best source-relay pair maximizing the main link capacity is selected to transmit messages. For comparison, we present the optimal power splitting and round robin (OPS-RR) and traditional power splitting and joint source-relay selection (TPS-JSRS) schemes.
- We derive the exact and asymptotic closed-form outage probability expressions of OPS-JSRS, OPS-RR and TPS-JSRS schemes over Rayleigh fading channels. The numerical results show that the OPS-JSRS scheme outperforms OPS-RR and TPS-JSRS schemes in terms of outage probability.
- Differing from [25] and [26], where the AF is considered, we consider DF relaying protocol in this paper. This paper investigates the power splitting and source-relay selection, whereas [18] and [19] only consider the relay selection and did not optimize the power splitting.

The rest of this paper is organized as follows. Section 2 presents the system model of a multi-source multi-relay network. In Section 3, we propose the OPS-JSRS scheme. For the purpose of comparison, the OPS-RR and TPS-JSRS schemes are introduced. The exact closed-form outage probability expressions of OPS-JSRS, OPS-RR and TPS-JSRS schemes are derived. And in Section 4, we obtain the asymptotic closed-form outage probability expressions of OPS-JSRS, OPS-RR and TPS-JSRS schemes. Next, we give the numerical results of the three schemes in Section 5. Finally, we conclude the paper in Section 6.

2 System Model

As shown in Fig. 1, this paper presents a multi-source multi-relay system, where M sources, represent by \( S_m, m \in \{1, 2, \ldots, M\} \), communicate with one destination D with the help of N EH relays, denote by \( R_n, n \in \{1, 2, \ldots, N\} \). Assuming that all nodes have only one antenna and there is no direct link between \( S_m \) and D. All relays equip with a power splitter. Figure 2 shows a block diagram of an EH relay \( R_n \), where power splitter divides the received signal power into two parts, which are respectively used for signal processing and information forwarding.

Without loss of generality, let \( P \) denote the transmit power of source \( S_m \). The power-splitting ratio (PSR) of EH relay \( R_n \) is represented by \( \rho_n \) (0 \(<\) \( \rho_n \leq 1 \)), which refers to the ratio of the harvested energy to total received energy of the relay \( R_n \). We assume that all links are independent and non-identically distributed (i.n.i.d.) quasi-static Rayleigh fading. For notational convenience, let \( h_{SmR_n} \) and \( h_{RnD} \) denote the fading coefficient of the channel spanning from \( S_m \) to \( R_n \) and \( R_n \) to D, respectively. The \( |h_{SmR_n}|^2 \) and \( |h_{RnD}|^2 \) obey the exponentially distribution.
with respective means of $\sigma^2_{SmRn}$ and $\sigma^2_{RnD}$. Therefore, the probability distribution functions (PDFs) of $|h_{SmRn}|^2$ and $|h_{RnD}|^2$ can be expressed as

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

(1)

and

$$f_{|h_{RnD}|^2}(x) = \frac{1}{\sigma^2_{RnD}} \exp\left(-\frac{x}{\sigma^2_{RnD}}\right).$$

(2)

In the first time slot $T$, a source is selected to transmit signals to the relay $R_n$, and then $R_n$ divides the received signal power into two components according to the PSR $\rho_n$. Without loss of generality, we consider the source $S_m$ is selected to transmit $x_m$ ($E[|x_m|^2] = 1$) with a transmit power of $P$ to the relay $R_n$. Therefore, the signal received at the $R_n$ can be obtained as

$$y_{SmRn} = h_{SmRn} \sqrt{P} x_m + n_{SmRn},$$

(3)

where $n_{SmRn}$ is the additive white Gaussian noise (AWGN) at $R_n$ and its variance is $N_0$. As aforementioned, the relay $R_n$ divides the total energy received from source signal $x_m$ into two parts. The fraction $\rho_n$ of the received total signals energy is used for information forwarding, and the remaining fraction $1 - \rho_n$ is used for information decoding. Therefore, we can express the harvested energy at the relay $R_n$ in the first slot $T$ as

$$E_n = \rho_n \eta P |h_{SmRn}|^2 T,$$

(4)
where η is an energy conversion efficiency of the energy harvester. Hence, the transmission power used for information relaying during the following time slot of the relay \( R_n \) can be expressed as

\[
P'_n = \rho_n \eta |h_{SmRn}|^2.
\]  

As mentioned above, the relay \( R_n \) uses the remaining fraction \( 1 - \rho_n \) of received total energy to process the information. Therefore, the power for information processing of \( R_n \) can be obtained as

\[
P''_n = (1 - \rho_n) |h_{SmRn}|^2.
\]  

Therefore, the channel capacity between \( S_m \) and \( R_n \) can be expressed as

\[
C_{SmRn} = \frac{1}{2} \log \left( 1 + (1 - \rho_n) \eta |h_{SmRn}|^2 \right),
\]  

where \( \gamma = \frac{P}{N_0} \).

If the EH relay \( R_n \) decodes the received message \( x_m \) successfully, it then forwards the re-encoded symbols to \( D \) using the same codewords as the \( S_m \) [7, 30, 31]. Therefore, the signal received at \( D \) can be written as

\[
y_{RnD} = h_{RnD} \sqrt{P'_n x_m + n_{RnD}},
\]  

where \( n_{RnD} \) is AWGN at \( D \) with variance \( N_0 \) and \( P'_n \) is the transmit power of \( R_n \). The channel capacity from \( R_n \) to \( D \) can be given by

\[
C_{RnD} = \frac{1}{2} \log \left( 1 + \rho_n \eta |h_{SmRn}|^2 |h_{RnD}|^2 \right).
\]  

It has been shown in [7, 30, 31], the overall channel capacity is the minimum of the channel capacity from \( S_m \) to relay \( R_n \) and that from relay \( R_n \) to \( D \). Therefore, the overall channel capacity from \( S_m \) via an EH relay \( R_n \) to \( D \) as

\[
C_{SmRnD} = \min(C_{SmRn}, C_{RnD}).
\]  

3 Power Splitting and Joint Source-Relay Selection

In this section, we propose OPS-JSRS scheme in which the optimal PSR of the relay \( R_n \) is obtained by maximizing the overall channel capacity from \( S_m \) to \( D \) and a best source-relay pair is selected to transmit messages. For the purpose of comparison, we present the TPS-JSRS and OPS-RR schemes. Exact closed-form outage probability expressions of the OPS-RR, OPS-JSRS and TPS-JSRS schemes are derived over Rayleigh fading channels.

3.1 TPS-JSRS Scheme

In this subsection, we present the TPS-JSRS scheme and derive its closed-form outage probability expression. In TPS-JSRS scheme, the PSR \( \rho_n \) is not optimized and varies from 0 to 1. Meanwhile, we select the best source-relay pair by maximizing the overall
channel capacity from $S_m$ to $D$. Therefore, the best source-relay pair selection criterion can be expressed as

$$\left( S_{m^*}, R_{n^*} \right) = \arg \max_{1 \leq m \leq M} \max_{1 \leq n \leq N} C_{SmRnD},$$  \hspace{1cm} (11)$$

where $C_{SmRnD}$ is given by (10).

Following, the outage probability of the TPS-JSRS scheme is analyzed. An outage event occurs when the overall channel capacity is lower than a predefined date rate $R$ [7]. Thus, the outage probability of the TPS-JSRS scheme can be expressed as (12), shown on the top of the following page,

$$P_{\text{out,TPS-JSRS}} = \Pr \left( \max_{1 \leq m \leq M} \max_{1 \leq n \leq N} C_{SmRnD} < R \right) = \Pr \left( \max_{1 \leq m \leq M} \min_{1 \leq n \leq N} \left[ \min((1 - \rho_n) |h_{SmRn}|^2, \rho_n \eta |h_{SmRn}|^2 |h_{RnD}|^2) \right] < \beta \right)$$

$$= \prod_{n=1}^{N} \left[ \prod_{m=1}^{M} \left( 1 - \Pr \left( (1 - \rho_n) |h_{SmRn}|^2 > \beta, \rho_n \eta |h_{SmRn}|^2 |h_{RnD}|^2 > \beta \right) \right) \right]$$

(12)

where $\beta = (2^R - 1) \gamma$, and $|h_{S_m R_n}|^2 = \max_{1 \leq m \leq M} |h_{SmRn}|^2$.

For notational convenience, we define $P_{\text{out,1}}$ as

$$P_{\text{out,1}}^{\text{TPS-JSRS}} = \Pr \left( \begin{array}{c}
(1 - \rho_n) |h_{SmRn}|^2 > \beta, \\
\rho_n \eta |h_{SmRn}|^2 |h_{RnD}|^2 > \beta 
\end{array} \right).$$  \hspace{1cm} (13)$$

According to Appendix A, $P_{\text{out,1}}^{\text{TPS-JSRS}}$ can be obtained as

$$P_{\text{out,1}}^{\text{TPS-JSRS}} = \sum_{i=1}^{M} \exp \left( -\frac{a}{\sigma_{S_{i}}^2} \right) - \sum_{i=1}^{M} \frac{\beta E(x_{i})}{\sigma_{S_{i}}^2 \sigma_{R}^2 \sigma_{D}^2 \sigma_{\eta}^2}$$

$$+ \sum_{i=1}^{M} \sum_{u=2}^{M} \frac{(-1)^{u} \rho_{u}}{\sigma_{S_{i}}^2 \sigma_{R}^2 \sigma_{D}^2 \sigma_{\eta}^2} \Phi_{1,\mu}$$

$$+ \sum_{i=1}^{M} \sum_{k=1}^{M} \frac{(-1)^{i} \rho_{i}}{\sigma_{S_{k}}^2} \exp(-ab)$$

$$- \sum_{i=1}^{M} \sum_{k=1}^{M} \frac{(-1)^{i} \rho_{i} \rho_{k}}{\sigma_{S_{i}}^2 \sigma_{R}^2 \sigma_{D}^2 \sigma_{\eta}^2} E_{i}(ab)$$

$$+ \sum_{i=1}^{M} \sum_{k=1}^{M} \sum_{u=2}^{M} \frac{(-1)^{i} \rho_{i} \rho_{u}}{\sigma_{S_{i}}^2 \sigma_{R}^2 \sigma_{D}^2 \sigma_{\eta}^2} \Phi_{2,\mu}$$

where

\[ \Phi_{1,\mu} = \frac{1}{\mu} \int_{0}^{\mu} \Phi_{1}(x) \, dx \]

\[ \Phi_{2,\mu} = \frac{1}{\mu} \int_{0}^{\mu} \Phi_{2}(x) \, dx \]

\[ E_{i}(ab) = \frac{1}{\mu} \int_{0}^{\mu} E_{i}(x) \, dx \]

\[ \Phi_{1}(x) = \frac{1}{\sqrt{2\pi}} \int_{0}^{x} e^{-\frac{y^2}{2}} \, dy \]

\[ \Phi_{2}(x) = \frac{1}{\sqrt{2\pi}} \int_{0}^{x} y e^{-\frac{y^2}{2}} \, dy \]
and

\[
\Phi_{2,u} = \frac{1}{\alpha^u} \sum_{k=0}^{u-2} \frac{(-1)^k b^k}{(u-1)(u-2)\cdots(u-k+1)} \exp(-ab) + (-1)^u \frac{b^{u-1}}{(u-1)!} E_i(-ab).
\]  

(16)

Substituting \( P_{out}^{TPS-JSRS} \) from (14) into (12), the outage probability of TPS-JSRS \( P_{out}^{TPS-JSRS} \) can be obtained.

### 3.2 OPS-RR Scheme

This subsection presents an optimal power splitting and round-robin (OPS-RR) scheme and derive the closed-form outage probability expression of OPS-RR scheme over Rayleigh fading channels. As mentioned above, the relay \( R_n \) divides the received signal power into two parts. The fraction \( \rho_n \) of the received total energy is used to forward the re-encoded signals to \( D \) during the following time slot, and the remaining fraction \( 1-\rho_n \) of the total energy is used to process information. In this scheme, the optimal PSR \( \rho_n \) of the relay \( R_n \) is obtained by maximizing the channel capacity from \( S_m \) to \( D \). This differs from the TPS-JSRS scheme, which does not optimize the PSR \( \rho_n \). Therefore, the optimal PSR \( \rho_n \) can be obtained as

\[
\rho_n^* = \frac{1}{1 + \frac{1}{\rho_n^2} h_{RnD}^2}.
\]  

(19)

We can obtain the optimal PSR \( \rho_n \) when \( 1-\rho_n \) equals \( \rho_n^* h_{rd}^2 \) as

\[
\rho_n^* = \min(C_{SmRn}, C_{RnD}),
\]  

(17)

where \( C_{SmRn} \) and \( C_{RnD} \) are given by (7) and (9), respectively. Combining (7), (9) and (17) yields

\[
\rho_n^* = \arg \max_{0 \leq \rho_n \leq 1} \min(1 - \rho_n, \rho_n^2 h_{RnD}^2).
\]  

(18)

Substituting \( \rho_n^* \) from (19) into (10), the overall channel capacity from \( S_m \) to \( D \) via EH relay \( R_n \) can be rewritten as

\[
C_{SmRnD}^* = \frac{1}{2} \log \left( 1 + \frac{\gamma^2 h_{SmRn}^2 h_{RnD}^2}{h_{RnD}^2 + \frac{1}{\eta} h_{RnD}^2} \right).
\]  

(20)

Next, we select a source-relay pair to transmit the messages. In the OPS-RR scheme, each source and the relay is given the equal chance to transmit information. That is to say, there are \( M \times N \) source-destination pairs take turns in accessing the channel. Without loss of generality, the source \( S_m \) and the relay \( R_n \) are chosen. Therefore, the outage probability of OPS-RR scheme from \( S_m \) to \( D \) via the relay \( R_n \) can be expressed as
Substituting $C^*_\text{SmRnD}$ from (20) into (21) gives

$$P_{\text{out}, \text{SmRn}}^{\text{OPS–RR}} = \Pr\left( \frac{1}{2} \log \left( 1 + \frac{\gamma h_{\text{SmRn}} |h_{\text{RnD}}|^2}{1 + \eta |h_{\text{RnD}}|^2} \right) < R \right),$$

which is further simplified to

$$P_{\text{out}, \text{SmRn}}^{\text{OPS–RR}} = \Pr\left( |h_{\text{SmRn}}|^2 < \frac{\alpha}{|h_{\text{RnD}}|^2} + \alpha \eta \right),$$

where $\alpha = \frac{\gamma^{3/2} - 1}{\gamma}$. Notice that $|h_{\text{SmRn}}|^2$ and $|h_{\text{RnD}}|^2$ follow exponential distributions with means of $\sigma^2_{\text{SmRn}}$ and $\sigma^2_{\text{RnD}}$. Denoting $X = |h_{\text{SmRn}}|^2$ and $Y = |h_{\text{RnD}}|^2$, the $P_{\text{out}, \text{SmRn}}^{\text{OPS–RR}}$ can be rewritten as (24), shown on next page,

$$P_{\text{out}, \text{SmRn}}^{\text{OPS–RR}} = \int_0^\infty f_Y(y) F_X\left( \frac{\alpha}{\gamma} + \alpha \eta \right) dy = \int_0^\infty \frac{1}{|h_{\text{RnD}}|^2} \exp\left( -\frac{y}{|h_{\text{RnD}}|^2} \right) \left[ 1 - \exp\left( -\frac{\alpha}{\sigma^2_{\text{SmRn}}} - \frac{\alpha \eta}{\sigma^2_{\text{SmRn}}} \right) \right] dy$$

$$= 1 - \exp\left( -\frac{\alpha}{\sigma^2_{\text{SmRn}}} \right) \int_0^\infty \frac{1}{|h_{\text{RnD}}|^2} \exp\left( -\frac{y}{|h_{\text{RnD}}|^2} \right) \left[ 1 - \exp\left( -\frac{\alpha \eta}{\sigma^2_{\text{SmRn}}} \right) \right] dy$$

$$= 1 - \exp\left( -\frac{\alpha}{\sigma^2_{\text{SmRn}}} \right) \frac{1}{2\sqrt{\pi}} K_1\left( \frac{2\sqrt{\alpha}}{|h_{\text{RnD}}|^2} \right)\sigma^2_{\text{SmRn}}$$

where $K_1(\cdot)$ is the first-order modified Bessel function of second kind as given by (8.432.6) in [32].

Therefore, the outage probability of OPS-RR scheme is the mean of $M \times N$ source-relay pairs’ outage probability [12, 28], yields

$$P_{\text{out}}^{\text{OPS–RR}} = \sum_{m=1}^M \sum_{n=1}^N \frac{1}{M \times N} P_{\text{out}, \text{SmRn}}^{\text{OPS–RR}},$$

where the $P_{\text{out}, \text{SmRn}}^{\text{OPS–RR}}$ is given by (24).

### 3.3 OPS-JSRS Scheme

This subsection proposes an optimal power splitting and joint source-relay selection (OPS-JSRS) scheme. And the closed-form outage probability expression of OPS-JSRS scheme is derived. In OPS-JSRS scheme, the optimal PSR $p_n$ is obtained by maximizing the overall channel capacity from $S_m$ to $D$ via an EH relay $R_n$, which is same as OPS-RR scheme. Therefore, the optimal PSR of OPS-JSRS scheme is equal to that of OPS-RR scheme and is given by (19). Furthermore, the overall channel capacity $C^*_\text{SmRnD}$ from $S_m$ to $D$ via EH relay $R_n$ of OPS-JSRS scheme is given by (20).

In the OPS-JSRS scheme, a source-relay pair having the maximal overall channel capacity of $C^*_\text{SmRnD}$ is chosen to transmit messages. Therefore, the source-relay pair selection criterion for the OPS-JSRS scheme can be defined as

$$p_n = \max_{0 < p < 1} c(p, \hat{c}, \gamma, \eta, \sigma^2_{\text{RnD}}, \sigma^2_{\text{SmRn}}).$$
Therefore, the overall channel capacity of OPS-JSRS scheme can be expressed as
\[
C_{\text{OPS-JSRS}} = \max_{1 \leq m \leq M, 1 \leq n \leq N} C^*_{\text{SmRnD}}
\]  
(27)

where \(C^*_{\text{SmRnD}}\) is given by (20).

Next, we present an outage probability analysis of OPS-JSRS scheme. As mentioned above, an outage event occurs when the overall channel capacity \(C_{\text{OPS-JSRS}}\) drops below a predefined data rate \(R\). Hence, we can obtain the outage probability of the OPS-JSRS scheme as
\[
P_{\text{OPS-JSRS}} = \Pr\left( C_{\text{OPS-JSRS}} < R \right) = \Pr\left( \max_{1 \leq m \leq M, 1 \leq n \leq N} C^*_{\text{SmRnD}} < R \right),
\]  
(28)

where \(C^*_{\text{SmRnD}}\) is given by (20). Substituting \(C^*_{\text{SmRnD}}\) from (20) into (28), the \(P_{\text{OPS-JSRS}}\) can be rewritten as
\[
P_{\text{OPS-JSRS}} = \Pr\left[ \max_{1 \leq m \leq M} \frac{1}{2} \log\left( 1 + \frac{\eta |h_{\text{SmRnD}}|^2}{1 + \eta |h_{\text{RnD}}|^2} \right) < R \right]
\]  
(29)

According to Appendix B, \(P_{\text{OPS-JSRS}}\) can be obtained as (30), given at the top of next page.

\[
P_{\text{OPS-JSRS}} = \prod_{n=1}^{N} \left[ 1 + \sum_{j=1}^{2^M-1} (-1)^{|A_j|} \exp\left( - \sum_{S_m \in A_j} \frac{\eta}{\sigma^2_{\text{SmD}}} \right) \int_0^\infty \frac{1}{\sigma^2_{\text{RnD}}} \exp\left( - \frac{\gamma}{\sigma^2_{\text{RnD}}} - \sum_{S_m \in A_j} \frac{\alpha}{\sigma^2_{\text{SmD}}} \right) dy \right]^{-\frac{1}{2}} 
\]  
(30)

4 Asymptotic Outage Probability Analysis

To obtain more insights, this section analyze the asymptotic outage probability in the high SNR region with \(\gamma \to \infty\).
4.1 TPS-JSRS Scheme

In the high SNR region, the asymptotic outage probability of TPS-JSRS scheme can be expressed as

\[ P_{\text{out}}^{\text{TPS-JSRS}, \infty} = \left( 1 - \Phi_1^{\infty} - \Phi_2^{\infty} \right)^N, \]  

(31)

where

\[ \Phi_1^{\infty} = \sum_{i=1}^{M} \int_0^{\infty} \frac{1}{\sigma_{\text{Sho}}^2} \exp\left(-\frac{x}{\sigma_{\text{Sho}}^2}\right) \exp\left(-\frac{\beta}{\sigma_{\text{RoD}}^2 \rho_n^b}\right) dx \]

(32)

and

\[ \Phi_2^{\infty} = \sum_{i=1}^{M} \frac{1}{\sigma_{\text{Sho}}^2} \int_0^{\infty} \sum_{k=1}^{2^{M-1}-1} (-1)^{|D_k|} \exp\left(-\sum_{Sm \in D_k} \frac{x}{\sigma_{\text{Sho}}^2} \right) \exp\left(-\frac{\beta}{\sigma_{\text{RoD}}^2 \rho_n^b}\right) dx \]

(33)

Substituting (32) and (33) into (31), the asymptotic outage probability of the TPS-JSRS scheme can be obtained.

4.2 OPS-RR Scheme

When \( \gamma \to \infty \), the asymptotic outage probability of OPS-RR scheme can be obtained as

\[ P_{\text{out}}^{\text{OPS-RR}, \infty} = \sum_{m=1}^{M} \frac{1}{N} \sum_{n=1}^{N} \Pr\left( \left| h_{\text{SmRn}} \right|^2 < \frac{\alpha}{\left| h_{\text{RnD}} \right|^2} \right). \]  

(34)

Similar to the derivation of (30), (33) can be obtained as (34).

\[ P_{\text{out}}^{\text{OPS-RR}, \infty} = \sum_{m=1}^{M} \frac{1}{N} \sum_{n=1}^{N} \Pr\left( \left| h_{\text{SmRn}} \right|^2 < \frac{\alpha}{\left| h_{\text{RnD}} \right|^2} \right) \]

(35)
4.3 OPS-JSRS Scheme

In the high SNR region, the asymptotic outage probability of OPS-JSRS scheme can be obtained as

\[
P_{\text{out}}^{\text{OPS-JSRS, } \infty} = \prod_{n=1}^{N} \Pr\left(\left| h_{SmR_{n}} \right|^2 < \frac{\alpha}{\left|h_{RnD} \right|^2} \right).
\]

(36)

Similar to (29), the \( P_{\text{out}}^{\text{OPS-JSRS, } \infty} \) can be derived as

\[
P_{\text{out}}^{\text{OPS-JSRS, } \infty} = \prod_{n=1}^{N} \int_{0}^{\infty} \frac{1}{\sigma_{\text{RnD}}^2} \exp\left(-\frac{y}{\sigma_{\text{RnD}}^2}\right) dy \times \left[ 1 + \sum_{j=1}^{2^M-1} (-1)^{|A_j|} \exp\left(-\sum_{Sm \in A_j} \frac{\alpha}{\sigma_{SmR_{n}}^2} \right) \right].
\]

(37)

5 Numerical Results and Discussions

In this section, we present the numerical and simulation results for OPS-RR, OPS-JSRS and TPS-JSRS schemes in terms of their outage probability. All the numerical results are based on the above-mentioned analysis. We assume that the transmission links between any two nodes of Fig. 1 are Rayleigh fading channels. Following the existing literature [17–19], we assume that all relays have the same power splitting ratio \( \rho_n = \rho \). The average channel gains of \( \sigma_{SmR_{n}}^2 = \sigma_{RnD}^2 = 1 \), the energy conversion efficiency of \( \eta = 0.5 \), \( \rho_n = 0.5 \) are used. It can be seen from Figs. 3, 4, 5, 6, 7, 8 and 9, the theoretical outage probability...
curves match well with the simulation results, indicating the correctness of our outage probability analysis.

Figure 3 shows the theoretical and simulated outage probability versus power splitting ratio $\rho$ of the OPS-JSRS and TPS-JSRS schemes with $\text{SNR}=10\text{dB}$, $R = 1\text{bit/s/Hz}$, $\eta = 0.5$ and $M = N = 4$. The power splitting ratio $\rho$ of TPS-JSRS scheme is not optimized and varies from 0 to 1, while in the OPS-JSRS scheme, an optimized $\rho$ is given by (19). As shown in Fig. 3, with the increase of $\rho$, the outage probability curve of TPS-JSRS scheme first decreases and then rises, illustrating that the outage probability of TPS-JSRS scheme can be minimized by optimizing $\rho$. It can also be seen from Fig. 3, outage probability of TPS-JSRS scheme is higher than that of OPS-JSRS scheme, explaining the superiority of the proposed power splitting scheme.

Figure 4 illustrates the theoretical and simulated outage probability versus SNR of the OPS-JSRS as well as TPS-JSRS and OPS-RR schemes for different number of sources of $M = 4$ and $M = 8$ with $R = 1\text{bit/s/Hz}$, $\eta = 0.5$ and $N = 4$. As shown from Fig. 4, with
the SNR increases, outage probabilities of OPS-JSRS as well as TPS-JSRS and OPS-RR schemes decrease, that means the outage probability performance can be improved by increasing the SNR. One can also observe from Fig. 4 that the outage probability of OPS-JSRS scheme is lower than that of OPS-RR scheme and TPS-JSRS scheme. Moreover, with the increase of the number of sources from $M = 4$ to $M = 8$, the outage probability of OPS-JSRS decreases while that of OPS-RR scheme remains unchanged, demonstrating that the OPS-JSRS scheme outperforms OPS-RR scheme in terms of outage probability and the outage advantage becomes more significant as the number of sources increases. Additionally, the outage performance of proposed OPS-JSRS scheme can be improved by increasing the number of sources.

Figure 5 depicts the theoretical and simulated outage probability versus SNR of the OPS-JSRS as well as TPS-JSRS and OPS-RR schemes for different data rates with $\eta = 0.5$ and $M = N = 4$, where t. represents the theoretical results and s. denotes the simulated results.

Figure 6 Outage probability versus SNR of the OPS-JSRS as well as TPS-JSRS and OPS-RR schemes for different data rates with $\eta = 0.5$ and $M = N = 4$, where t. represents the theoretical results and s. denotes the simulated results.
SNR region, the outage probability of the proposed OPS-JSRS scheme is lower than that of OPS-RR scheme and TPS-JSRS scheme. That means the proposed OPS-JSRS scheme is better than OPS-RR scheme and TPS-JSRS scheme in terms of outage probability. It also appears from Fig. 5 that with the increasing of the number of EH relays from $N = 4$ to $N = 8$, the outage probability of OPS-JSRS scheme decreases, implying that the outage probability performance of proposed OPS-JSRS scheme can be greatly improved by increasing the number of EH relays.

In Figure 6, we present the theoretical and simulated outage probability versus SNR of OPS-JSRS as well as TPS-JSRS and OPS-RR schemes for different data rates with $R = 1$ bit/s/Hz and $R = 0.5$ bit/s/Hz with $\eta = 0.5$ and $M = N = 4$. As shown in Fig. 6, with the data rate decreases from $R = 1$ bit/s/Hz to $R = 0.5$ bit/s/Hz, outage probabilities of OPS-JSRS, TPS-JSRS and OPS-RR schemes decrease. That is to say, outage probability performances of OPS-JSRS, TPS-JSRS and OPS-RR schemes can be enhanced by decreasing the data rate. One can also observe from Fig. 6 the OPS-JSRS scheme is better than the OPS-RR scheme and
TPS-JSRS scheme in terms of outage probability whatever \( R = 1 \text{bit/s/Hz} \) or \( R = 0.5 \text{bit/s/Hz} \), verifying the superiority of proposed OPS-JSRS scheme.

Figure 7 shows the theoretical and simulated outage probability versus SNR of the OPS-JSRS as well as TPS-JSRS and OPS-RR schemes for different energy conversion efficiency \( \eta = 0.4 \) and \( \eta = 0.8 \) with \( R = 1 \text{bit/s/Hz} \) and \( M = N = 4 \). It can be seen from Fig. 7, as the energy conversion efficiency increases from \( \eta = 0.4 \) to \( \eta = 0.8 \), outage probabilities of OPS-JSRS, TPS-JSRS and OPS-RR schemes decrease. Due to the fact that with the increase of \( \eta \), the relay converts more energy from received RF signals for information relaying, which leads to a lower outage probability. Figure 7 also demonstrates that the OPS-JSRS scheme outperforms OPS-RR scheme and TPS-JSRS scheme in terms of outage probability.

Figure 8 illustrates the theoretical and simulated outage probability versus energy conversion efficiency \( \eta \) of the OPS-JSRS as well as TPS-JSRS and OPS-RR schemes for different data rates of \( R = 1 \text{bit/s/Hz} \) and \( R = 0.5 \text{bit/s/Hz} \) with \( \text{SNR}=10 \) and \( M = N = 4 \). It can be seen from Fig. 8, as the increase of \( \eta \) from 0 to 1, outage probabilities of OPS-JSRS, TPS-JSRS and OPS-RR schemes decrease, demonstrating that outage probabilities of OPS-JSRS, TPS-JSRS and OPS-RR schemes are affected by \( \eta \). In other words, the higher energy conversion efficiency, the better outage probability performance.

Figure 9 shows the exact and asymptotic outage probability versus SNR of the OPS-JSRS as well as TPS-JSRS and OPS-RR schemes with \( R = 1 \text{bit/s/Hz} \), \( \eta = 0.5 \) and \( N = 4 \). It can be seen from Fig. 9, the asymptotic outage probability curves of OPS-JSRS, TPS-JSRS and OPS-RR schemes match the exact ones very well in the high SNR region.

6 Conclusions

In this paper, we proposed an optimal power splitting and joint source-relay selection (OPS-JSRS) scheme in energy harvesting DF relay system. In the OPS-JSRS scheme, a source and relay pair maximizing the main link capacity was selected to transmit the messages. For the purpose of comparison, we presented the traditional power splitting and joint source-relay (TPS-JSRS) and the optimal power splitting and round robin (OPS-RR) schemes. We derived the exact and asymptotic closed-form outage probability expressions of OPS-JSRS, TPS-JSRS and OPS-RR schemes. Numerical results shown that the outage probability of OPS-JSRS scheme is lower than that of TPS-JSRS scheme and OPS-RR scheme, indicating that the proposed OPS-JSRS scheme outperforms TPS-JSRS and OPS-RR schemes in terms of outage probability performance. Additionally, the outage probability performance of OPS-JSRS schemes can be improved by increasing the number of sources and/or relays.

Appendix

Derivation of (14)

Notice that \( h_{SmRn}^2 \) follows exponential distributions with the mean of \( \sigma_{SmRn}^2 \). Thus, the cumulative density function (CDF) of \( h_{SmRn}^2 \) can be expressed as

\[
F[h_{SmRn}^2(x)] = \prod_{m=1}^{M} \left[1 - \exp\left(-\frac{x}{\sigma_{SmRn}^2}\right)\right].
\]

Therefore, the PDF of \( h_{SmRn}^2 \) can be obtained as
\[ f \left| h_{Sm^* R_n} \right|^2 (x) = \sum_{i=1}^{M} \frac{1}{\sigma_{SiR_n}^2} \exp \left( -\frac{x}{\sigma_{SiR_n}^2} \right) \exp \left( -\frac{\beta}{\sigma_{RoD}^2 \rho_n \eta x} \right) \times \prod_{m=1, m \neq i}^{M} \left[ 1 - \exp \left( -\frac{x}{\sigma_{SmR_n}^2} \right) \right]. \]  

(39)

Denoting \( X = \left| h_{Sm^* R_n} \right|^2 \), the \( P_{TPS-JSRS}^{out,1} \) can be rewritten as

\[ P_{TPS-JSRS}^{out,1} = \Pr \left( X > a, \left| h_{RoD} \right|^2 > \frac{\beta}{\rho_n \eta x} \right) \]

\[ = \int_{a}^{\infty} \exp \left( -\frac{\beta}{\sigma_{RoD}^2 \rho_n \eta x} \right) \sum_{i=1}^{M} \frac{1}{\sigma_{SiR_n}^2} \exp \left( -\frac{x}{\sigma_{SiR_n}^2} \right) \times \prod_{m=1, m \neq i}^{M} \left[ 1 - \exp \left( -\frac{x}{\sigma_{SmR_n}^2} \right) \right] dx, \]

(40)

where \( a = \frac{2^M - 1}{(1-\rho_n)^2} \). The term \( \prod_{m=1, m \neq i}^{M} \left[ 1 - \exp \left( -\frac{x}{\sigma_{SmR_n}^2} \right) \right] \) can be expanded as

\[ \prod_{m=1, m \neq i}^{M} 2^{M-1} - 1 \]

\[ = 1 + \sum_{k=1}^{M-1} (-1)^{D_k} \exp \left( -\sum_{Sm \in D_k} \frac{x}{\sigma_{SmR_n}^2} \right), \]

(41)

where \( D_k \) represents the \( k \)-th nonempty subset of \( M \) sources, \( |D_k| \) represents the number of elements in set \( D_k \). Thus, the \( P_{TPS-JSRS}^{out,1} \) can be rewritten as

\[ P_{TPS-JSRS}^{out,1} = \Phi_1 + \Phi_2 \]

(42)

where

\[ \Phi_1 = \sum_{i=1}^{M} \int_{a}^{\infty} \frac{1}{\sigma_{SiR_n}^2} \exp \left( -\frac{x}{\sigma_{SiR_n}^2} \right) \exp \left( -\frac{\beta}{\sigma_{RoD}^2 \rho_n \eta x} \right) dx, \]

(43)

and

\[ \Phi_2 = \sum_{i=1}^{M} \frac{1}{\sigma_{SmR_n}^2} \int_{a}^{\infty} \sum_{k=1}^{2^M - 1} (-1)^{D_k} \exp \left( -\sum_{Sm \in D_k} \frac{x}{\sigma_{SmR_n}^2} \right) \exp \left( -\frac{\beta}{\sigma_{RoD}^2 \rho_n \eta x} \right) dx. \]

(44)

Using the Maclaurin series expansion, we have

\[ \exp \left( -\frac{\beta}{\sigma_{RoD}^2 \rho_n \eta x} \right) = \sum_{u=0}^{\infty} \frac{(-1)^u \beta^u}{u! \sigma_{RoD}^{2u} \rho_n^u \eta^u x^u}. \]

(45)

Substituting (45) into (43), we can obtain the \( \Phi_1 \) as (46) at the top of following page, where \( Ei(x) = \int_{x}^{\infty} \frac{e^{-t}}{t} dt \)
\[
\Phi_1 = \sum_{i=1}^{M} \frac{1}{\sigma_{S_iR_n}^2} \int_{a}^{\infty} \exp(-\frac{x}{\sigma_{S_iR_n}^2})dx - \sum_{i=1}^{M} \frac{\beta}{\sigma_{S_iR_n}^2 \sigma_{R_nD}^2 \rho_n \eta} \int_{a}^{\infty} \frac{1}{x} \exp(-\frac{x}{\sigma_{S_iR_n}^2})dx \\
+ \sum_{i=1}^{M} \frac{1}{\sigma_{S_iR_n}^2} \sum_{m=2}^{\infty} \frac{(-1)^m \beta^m}{a! \sigma_{R_nD}^2 \rho_n \eta^m} \Phi_{1,u} \\
= \sum_{i=1}^{M} \exp(-\frac{a}{\sigma_{S_iR_n}^2}) - \sum_{i=1}^{M} \frac{\beta}{\sigma_{S_iR_n}^2 \sigma_{R_nD}^2 \rho_n \eta} Ei(\frac{a}{\sigma_{S_iR_n}^2}) + \sum_{i=1}^{M} \frac{1}{\sigma_{S_iR_n}^2} \sum_{m=2}^{\infty} \frac{(-1)^m \beta^m}{a! \sigma_{R_nD}^2 \rho_n \eta^m} \Phi_{1,u} \tag{46}
\]

and
\[
\Phi_{1,u} = \int_{a}^{\infty} \frac{1}{x} \exp(-\frac{x}{\sigma_{S_iR_n}^2})dx \\
= \frac{1}{\alpha^{\alpha-1}} \sum_{k=0}^{n-2} \frac{(-1)^k \alpha^k}{\sigma_{S_iR_n}^2 \sigma_{R_nD}^2 \rho_n \eta} \exp(-\frac{a}{\sigma_{S_iR_n}^2}) \\
+ (-1)^n \frac{1}{(n-1)! \sigma_{S_iR_n}^2} Ei(-\frac{a}{\sigma_{S_iR_n}^2}) \tag{47}
\]

Similarly, substituting (45) into (44), we can obtain the \(\Phi_2\) as
\[
\Phi_2 = \sum_{i=1}^{M} \sum_{k=1}^{M-1} \frac{(-1)^n \alpha_n}{\sigma_{S_iR_n}^2} \exp(-\alpha \mu) \\
- \sum_{i=1}^{M} \sum_{k=1}^{M-1} \frac{(-1)^n \alpha_n}{\sigma_{R_nD}^2 \rho_n \eta} \mu \exp(-\alpha \mu) \\
+ \sum_{i=1}^{M} \sum_{k=1}^{M-1} \sum_{m=2}^{\infty} \frac{(-1)^n \alpha_n}{\sigma_{S_iR_n}^2} \frac{\beta^m}{a! \sigma_{R_nD}^2 \rho_n \eta^m} \Phi_{2,u} \tag{48}
\]

where \(b = \frac{1}{\sigma_{S_iR_n}^2} + \sum_{S_i \in D_{a,b}} \frac{1}{\sigma_{S_{iD}}^2}\) and
\[
\Phi_{2,u} = \int_{a}^{\infty} \frac{1}{x} \exp(-\beta x)dx \\
= \frac{1}{\alpha^{\alpha-1}} \sum_{k=0}^{n-2} \frac{(-1)^k \alpha^k b^k}{(n-1)(n-2)...(n-k+1)} \exp(-\alpha \mu) \\
+ (-1)^n \frac{\beta^{n-1}}{(n-1)!} \mu \exp(-\alpha \mu) \tag{49}
\]

Substituting (46) and (48) into (42), \(P_{out,1}^{TPS-JSRS}\) can be obtained as (14).

**Derivation of (30)**

Denoting \(Y = |h_{R_nD}|^2\), the \(P_{out}^{OPS-JSRS}\) can be rewritten as
\[
P_{out}^{OPS-JSRS} = \prod_{n=1}^{N} \int_{0}^{\infty} \exp\left(-\frac{y}{\sigma_{R_nD}^2}\right) F_{h_{S_iR_n}}\left(\frac{\sigma_{S_iR_n}^2}{\sigma_{R_nD}^2} + \alpha \eta \right) dy \\
= \prod_{n=1}^{N} \int_{0}^{\infty} \frac{1}{\sigma_{R_nD}^2} \exp\left(-\frac{\sigma_{S_iR_n}^2}{\sigma_{R_nD}^2}\right) \times \prod_{m=1}^{M} \left[1 - \exp\left(-\frac{a}{\sigma_{S_{iD}}^2} - \frac{\alpha \eta}{\sigma_{S_{iD}}^2}\right)\right] dy \tag{50}
\]

The term \(\prod_{m=1}^{M} \left[1 - \exp\left(-\frac{a}{\sigma_{S_{iD}}^2} - \frac{\alpha \eta}{\sigma_{S_{iD}}^2}\right)\right]\) can be expanded as
where $A_j$ represents the j-th nonempty subset of $M$ sources, $|A_j|$ represents the number of elements in set $A_j$. Substituting (51) into (50), we can obtain the outage probability of OPS-JSRS scheme $P_{\text{out}}^{\text{OPS-JSRS}}$ as (30).

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Code availability The data that support the findings of this study are available from the corresponding author upon request.

Declarations

Conflicts of interest The authors declare that they have no conflicts of interest

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