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

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

Xiao Jiang, Peng Li and Ruchuan Wang

Abstract—In this paper, we consider an energy-harvesting (EH) relay network composing of multiple sources, a destination and 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, one for information decoding and the remaining for signal relaying. The power splitting ratio (PSR) 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 examine the optimal power splitting and round-robin (OPS-RR) scheme and the traditional power splitting and joint source-relay selection (TPS-JSRS) scheme. The exact and asymptotic closed-form expressions of outage probability for OPS-RR, TPS-JSRS and OPS-JSRS schemes are derived. Numerical results show that OPS-JSRS scheme is better than OPS-RR and TPS-JSRS schemes in terms of outage probability, explaining the superiority of the proposed OPS-JSRS scheme. Additionally, outage probability performance of OPS-JSRS scheme can be improved by increasing the number of sources and relays.

Index Terms—Energy harvesting, power splitting, source-relay selection, outage probability.

I. INTRODUCTION

Recently, wireless cooperative communications have emerged as a promising technology to reduce channel fading loss and improve the transmission reliability [1]-[5]. Typically, relaying protocols can be divided into two types, namely decode-and-forward (DF) and amplify-and-forward (AF) [6]. Specifically, in the AF protocol, the relay simply amplifies and retransmits the received signals to destination, which suffers from noise propagation problems. By contrast, in the DF protocol, the relay decodes source messages from the received signals first and forwards the decoded messages to destination. In the past few years, the best 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].

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Energy harvesting (EH), which can extract energy from surrounding environment, is emerging as an efficient technology to extend the lifetime 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 architectures, they are time-switching (TS) architecture and power-splitting (PS) architecture [16]. PS architecture means that the received signal power is divided into two parts according to the power-splitting ratio, one for energy harvesting and the remaining for information processing. By contrast, TS architecture indicates that the time slot is divided into two components. In the first time slot, the devices harvest energy from RF signals and the harvested energy is used for information transmission in the second time slot [17].

As a further development, the combination of EH and cooperative communications has regarded as a hot topic [18]-[20]. In [18], the authors presented an EH relay system consisting of a source, a destination and multiple EH relays with the existence of eavesdroppers. The relay selection schemes based on DF and AF were proposed to ensure the maximum of security capacity. [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 authors proposed a joint relay-and-antenna selection scheme to minimize the system outage probability in the EH MIMO relay network.

Additionally, there is also some literature devoted to investigating power allocation for EH relay networks [21]-[24]. [21] proposed an optimal power allocation scheme for EH cooperative wireless network and derived the closed-form solutions. 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 presented an energy harvesting relay network consisting of a source, an energy-harvesting relay and a destination, the source and destination transmit the confidential and interference information to relay, respectively. The optimal power allocation between the source and the destination has been obtained to achieve the maximum secrecy rate.

Presently, only 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

Fig. 1. An energy harvesting relay system consisting of multi-source, one destination and multiple energy-harvesting relays.

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. Differing from [25] and [26], where the AF protocol was adopted, 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. Firstly, we propose an optimal power splitting and joint source-relay selection (OPS-JSRS) scheme for an EH DF relay network, which differs from [25] and [26], where the AF protocol was used. This is also different from [18] and [19], which only considered the relay selection and did not optimize the power splitting. The power splitting ratio, which refers to the ratio of the harvested energy to total received energy of the relay, depicts the trade-off between the harvesting energy and decoding energy. In the proposed OPS-JSRS scheme, we derive the expression of optimal power-splitting ratio. Additionally, the optimal power splitting and round robin (OPS-RR) and traditional power splitting and joint source-relay selection (TPS-JSRS) schemes are proposed for comparison. Secondly, we derive the exact and asymptotic closed-form outage probability expressions of OPS-JSRS, OPS-RR and TPS-JSRS schemes. The numerical results show that the OPS-JSRS scheme outperforms OPS-RR and TPS-JSRS schemes in terms of outage probability.

The rest of this paper is organized as follows. Section II presents the system model of a multi-source multi-relay network. In Section III, we propose the OPS-JSRS scheme. For the purpose of comparison, the OPS-RR and TPS-JSRS schemes are introduced. Then the exact closed-form outage probability expressions of OPS-JSRS, OPS-RR and TPS-JSRS schemes are derived. And in Section IV, 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 V. Finally, we conclude the paper in Section VI.

II. SYSTEM MODEL

Fig. 1 presents a multi-source multi-relay system consisting of M sources, represent by S_m , $m \in \{1, 2, \dots, M\}$,

Fig. 2. A block diagram of an EH relay.

a destination D and N EH relays, denote by R_n , $n \in \{1, 2, \dots, N\}$. 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. Fig. 2 shows a block diagram of an EH relay R_n , where power splitter divides the energy of R_n received from source signal into two parts, which are respectively send to energy harvester of R_n for information forwarding and to signal decoder for information processing.

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 ρ_n ($0 \leq \rho_n \leq 1$), which refers to the ratio of the harvested energy to total received energy of the relay R_n . Under Rayleigh fading model, let h_{SmRn} , h_{RnD} denote the fading coefficient of the channel spanning from S_m to R_n and R_n to D , respectively. The $|h_{SmRn}|^2$ and $|h_{RnD}|^2$ obey the exponentially distribution with respective means of σ_{SmRn}^2 and σ_{RnD}^2 . Therefore, the probability distribution functions (PDFs) of $|h_{SmRn}|^2$ and $|h_{RnD}|^2$ can be expressed as

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

and

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

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

$$y_{SmRn} = h_{SmRn} \sqrt{P} x_s + n_{SmRn}, \quad (3)$$

where n_{SmRn} is the additive white Gaussian noise (AWGN) at R_n and its variance is N_0 . As aforementioned, the relay R_{SmRn} divides the total energy received from source signal x_s into two parts. The fraction ρ_n of the total energy received from source signal x_s is collected by energy harvester for information relaying, 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

$$E_n = \rho_n \eta P |h_{SmRn}|^2 T, \quad (4)$$

where η is a 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

$$P_n^t = \rho_n \eta P |h_{SmRn}|^2. \quad (5)$$

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

$$P_n^d = (1 - \rho_n)P|h_{SmRn}|^2. \quad (6)$$

The channel capacity between S_m and R_n can be expressed as

$$C_{SmRn} = \frac{1}{2} \log \left(1 + (1 - \rho_n)\gamma|h_{SmRn}|^2 \right), \quad (7)$$

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

In the second time slot T , an EH relay is selected to forward information. Without loss of generality, we consider the EH relay R_n is selected to forward the information with the power P_n^t to the destination D , the signal received at D can be written as

$$y_{RnD} = h_{RnD} \sqrt{\rho_n \eta P |h_{SmRn}|^2} x_s + n_{RnD}, \quad (8)$$

where n_{RnD} is AWGN at D with variance N_0 . The channel capacity from R_n to D can be given by

$$C_{RnD} = \frac{1}{2} \log \left(1 + \rho_n \gamma \eta |h_{SmRn}|^2 |h_{RnD}|^2 \right). \quad (9)$$

It has been shown in [1], an overall channel capacity from S_m to D via a DF relay is the minimum of the channel capacity from S_m to relay R_n and that from relay R_n to D . Hence, we can obtain the overall channel capacity from S_m via an EH relay R_n to D as

$$C_{SmRnD} = \min(C_{SmRn}, C_{RnD}). \quad (10)$$

III. 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 chosen. In order to compare the proposed power splitting scheme, we examine the TPS-JSRS in which the PSR is not optimized. We also propose OPS-RR scheme to verify the superiority of joint source-relay selection scheme. Exact closed-form outage probability expressions of the OPS-RR, OPS-JSRS and TPS-JSRS schemes are derived over Rayleigh fading channels.

A. 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 ρ_n is not optimized and varies in the interval of $[0, 1]$. Meanwhile, we select the best source-relay pair by maximizing the overall channel capacity from S_m to D . Accordingly, the best source-relay pair selection criterion can be expressed as

$$(S_m^*, R_n^*) = \arg \max_{\substack{1 \leq m \leq M \\ 1 \leq n \leq N}} C_{SmRnD}, \quad (11)$$

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 drops below a predefined data rate R [10]. The outage

probability of the TPS-JSRS scheme can be expressed as (12) at the top of the following page, where $\beta = (2^{2R} - 1)/\gamma$, and $|h_{Sm^*Rn}|^2 = \max_{1 \leq m \leq M} |h_{SmRn}|^2$.

Notice that $|h_{SmRn}|^2$ follows exponential distributions with the mean of σ_{SmRn}^2 . Thus, the cumulative density function (CDF) of $|h_{Sm^*Rn}|^2$ can be expressed as

$$F_{|h_{Sm^*Rn}|^2}(x) = \prod_{m=1}^M [1 - \exp(-\frac{x}{\sigma_{SmRn}^2})]. \quad (13)$$

Therefore, the PDF of $|h_{Sm^*Rn}|^2$ can be obtained as

$$f_{|h_{Sm^*Rn}|^2}(x) = \sum_{i=1}^M \frac{1}{\sigma_{SiRn}^2} \exp(-\frac{x}{\sigma_{SiRn}^2}) \times \prod_{m=1, m \neq i}^M [1 - \exp(-\frac{x}{\sigma_{SmRn}^2})]. \quad (14)$$

Denoting $X = |h_{Sm^*Rn}|^2$, the $P_{out,1}^{\text{TPS-JSRS}}$ can be rewritten as

$$\begin{aligned} P_{out,1}^{\text{TPS-JSRS}} &= \Pr \left(X > a, |h_{RnD}|^2 > \frac{\beta}{\rho_n \eta X} \right) \\ &= \int_a^\infty \exp(-\frac{\beta}{\sigma_{RnD}^2 \rho_n \eta x}) \sum_{i=1}^M \frac{1}{\sigma_{SiRn}^2} \exp(-\frac{x}{\sigma_{SiRn}^2}) \\ &\quad \times \prod_{m=1, m \neq i}^M [1 - \exp(-\frac{x}{\sigma_{SmRn}^2})] dx \end{aligned} \quad (15)$$

where $a = \frac{2^{2R} - 1}{(1 - \rho_n)\gamma}$. Using the binomial formula, we have

$$\begin{aligned} &\prod_{m=1, m \neq i}^M [1 - \exp(-\frac{x}{\sigma_{SmRn}^2})] \\ &= 1 + \sum_{k=1}^{2^{M-1}-1} (-1)^{|D_k|} \exp(-\sum_{Sm \in D_k} \frac{x}{\sigma_{SmRn}^2}) \end{aligned} \quad (16)$$

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 $P_{out,1}^{\text{TPS-JSRS}}$ can be rewritten as

$$P_{out,1}^{\text{TPS-JSRS}} = \Phi_1 + \Phi_2 \quad (17)$$

where

$$\Phi_1 = \sum_{i=1}^M \int_a^\infty \frac{1}{\sigma_{SiRn}^2} \exp(-\frac{x}{\sigma_{SiRn}^2}) \exp(-\frac{\beta}{\sigma_{RnD}^2 \rho_n \eta x}) dx, \quad (18)$$

and

$$\begin{aligned} \Phi_2 &= \sum_{i=1}^M \frac{1}{\sigma_{SiRn}^2} \int_a^\infty \sum_{k=1}^{2^{M-1}-1} (-1)^{|D_k|} \exp(-\sum_{Sm \in D_k} \frac{x}{\sigma_{SmRn}^2}) \\ &\quad \times \exp(-\frac{x}{\sigma_{SiRn}^2}) \exp(-\frac{\beta}{\sigma_{RnD}^2 \rho_n \eta x}) dx \end{aligned} \quad (19)$$

Using the Maclaurin series expansion, we have

$$\exp(-\frac{\beta}{\sigma_{RnD}^2 \rho_n \eta x}) = \sum_{u=0}^\infty \frac{(-1)^u \beta^u}{u! \sigma_{RnD}^{2u} \rho_n^u \eta^u x^u}. \quad (20)$$

Substituting (20) into (18), we can obtain the Φ_1 as (21) at the top of following page, where $Ei(x) = \int_x^\infty \frac{e^{-t}}{t} dt$ and

$$\begin{aligned}
P_{out}^{\text{TPS-JSRS}} &= \Pr \left(\max_{\substack{1 \leq m \leq M \\ 1 \leq n \leq N}} C_{SmRnD} < R \right) = \Pr \left\{ \max_{\substack{1 \leq m \leq M \\ 1 \leq n \leq N}} \left[\min((1 - \rho_n)|h_{SmRn}|^2, \rho_n\eta|h_{SmRn}|^2|h_{RnD}|^2) \right] < \beta \right\} \\
&= \prod_{n=1}^N \Pr \left\{ \min((1 - \rho_n)|h_{SmRn}|^2, \rho_n\eta|h_{SmRn}|^2|h_{RnD}|^2) < \beta \right\} \\
&= \prod_{n=1}^N \left[1 - \underbrace{\Pr \left((1 - \rho_n)|h_{SmRn}|^2 > \beta, \rho_n\eta|h_{SmRn}|^2|h_{RnD}|^2 > \beta \right)}_{P_{out,1}^{\text{TPS-JSRS}}} \right]
\end{aligned} \tag{12}$$

$$\begin{aligned}
\Phi_1 &= \sum_{i=1}^M \frac{1}{\sigma_{SiRn}^2} \int_a^\infty \exp\left(-\frac{x}{\sigma_{SiRn}^2}\right) dx - \sum_{i=1}^M \frac{\beta}{\sigma_{SiRn}^2 \sigma_{RnD}^2 \rho_n \eta} \int_a^\infty \frac{1}{x} \exp\left(-\frac{x}{\sigma_{SiRn}^2}\right) dx + \sum_{i=1}^M \frac{1}{\sigma_{SiRn}^2} \sum_{u=2}^\infty \frac{(-1)^u \beta^u}{u! \sigma_{RnD}^{2u} \rho_n^u \eta^u} \Phi_{1,u} \\
&= \sum_{i=1}^M \exp\left(-\frac{a}{\sigma_{SiRn}^2}\right) - \sum_{i=1}^M \frac{\beta}{\sigma_{SiRn}^2 \sigma_{RnD}^2 \rho_n \eta} Ei\left(\frac{a}{\sigma_{SiRn}^2}\right) + \sum_{i=1}^M \frac{1}{\sigma_{SiRn}^2} \sum_{u=2}^\infty \frac{(-1)^u \beta^u}{u! \sigma_{RnD}^{2u} \rho_n^u \eta^u} \Phi_{1,u}
\end{aligned} \tag{21}$$

$$\begin{aligned}
\Phi_{1,u} &= \int_a^\infty \frac{1}{x^u} \exp\left(-\frac{x}{\sigma_{SiRn}^2}\right) dx \\
&= \frac{1}{a^{u-1}} \sum_{k=0}^{u-2} \frac{(-1)^k a^k}{\sigma_{SiRn}^{2k} (u-1)(u-2)\cdots(u-k+1)} \exp\left(-\frac{a}{\sigma_{SiRn}^2}\right) \\
&\quad + (-1)^u \frac{1}{(u-1)! \sigma_{SiRn}^{2(u-1)}} Ei\left(-\frac{a}{\sigma_{SiRn}^2}\right)
\end{aligned} \tag{22}$$

Similarly, substituting (20) into (19), we can obtain the Φ_2 as

$$\begin{aligned}
\Phi_2 &= \sum_{i=1}^M \sum_{k=1}^{2^{M-1}-1} \frac{(-1)^{|D_k|}}{b \sigma_{SiRn}^2} \exp(-ab) \\
&\quad - \sum_{i=1}^M \sum_{k=1}^{2^{M-1}-1} \frac{(-1)^{|D_k|} \beta Ei(ab)}{\rho_n \eta \sigma_{RnD}^2 \sigma_{SiRn}^2} \\
&\quad + \sum_{i=1}^M \sum_{k=1}^{2^{M-1}-1} \sum_{u=2}^\infty \frac{(-1)^{|D_k|+u} \beta^u}{\sigma_{SiRn}^2 u! \sigma_{RnD}^{2u} \rho_n^u \eta^u} \Phi_{2,u}
\end{aligned} \tag{23}$$

where $b = \frac{1}{\sigma_{SiRn}^2} + \sum_{Sm \in D_k} \frac{1}{\sigma_{SmRn}^2}$ and

$$\begin{aligned}
\Phi_{2,u} &= \int_a^\infty \frac{1}{x^u} \exp(-bx) dx \\
&= \frac{1}{a^{u-1}} \sum_{k=0}^{u-2} \frac{(-1)^k a^k b^k}{(u-1)(u-2)\cdots(u-k+1)} \exp(-ab) \\
&\quad + (-1)^u \frac{b^{u-1}}{(u-1)!} Ei(-ab)
\end{aligned} \tag{24}$$

Substituting (21) and (23) into (17), we can obtain the closed-form expression of $P_{out,1}^{\text{TPS-JSRS}}$ as

$$\begin{aligned}
P_{out,1}^{\text{TPS-JSRS}} &= \sum_{i=1}^M \exp\left(-\frac{a}{\sigma_{SiRn}^2}\right) - \sum_{i=1}^M \frac{\beta Ei\left(\frac{a}{\sigma_{SiRn}^2}\right)}{\sigma_{SiRn}^2 \sigma_{RnD}^2 \rho_n \eta} \\
&\quad + \sum_{i=1}^M \sum_{u=2}^\infty \frac{(-1)^u \beta^u}{u! \sigma_{RnD}^{2u} \rho_n^u \eta^u} \Phi_{1,u} \\
&\quad + \sum_{i=1}^M \sum_{k=1}^{2^{M-1}-1} \frac{(-1)^{|D_k|}}{b \sigma_{SiRn}^2} \exp(-ab) \\
&\quad - \sum_{i=1}^M \sum_{k=1}^{2^{M-1}-1} \frac{(-1)^{|D_k|} \beta}{\rho_n \eta \sigma_{RnD}^2 \sigma_{SiRn}^2} Ei(ab) \\
&\quad + \sum_{i=1}^M \sum_{k=1}^{2^{M-1}-1} \sum_{u=2}^\infty \frac{(-1)^{|D_k|+u} \beta^u}{\sigma_{SiRn}^2 u! \sigma_{RnD}^{2u} \rho_n^u \eta^u} \Phi_{2,u}
\end{aligned} \tag{25}$$

where $\Phi_{1,u}$ and $\Phi_{2,u}$ are given by (22) and (24), respectively. Substituting $P_{out,1}^{\text{TPS-JSRS}}$ from (25) into (12), the outage probability of TPS - JSRS $P_{out}^{\text{TPS-JSRS}}$ can be obtained.

B. 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 total energy of received source signal x_s into two parts. The fraction ρ_n of the received total energy is collected by energy harvester for information forwarding during the following time slot, and the remaining fraction $1-\rho_n$ of the total energy is used for information decoding. In this scheme, the optimal PSR ρ_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 ρ_n . Therefore, the optimal PSR ρ_n can be obtained as

$$\rho_n^* = \max_{0 \leq \rho_n \leq 1} C_{SmRnD} = \max_{0 \leq \rho_n \leq 1} \min(C_{SmRn}, C_{RnD}), \tag{26}$$

where C_{SmRn} and C_{RnD} are given by (7) and (9), respectively. Combining (7), (9) and (26) yields

$$\rho_n^* = \arg \max_{0 \leq \rho_n \leq 1} \min(1 - \rho_n, \rho_n \eta |h_{RnD}|^2). \tag{27}$$

We can obtain the optimal PSR ρ_n when $1-\rho_n$ equals $\rho_n \eta |h_{nd}|^2$ as

$$\rho_n^* = \frac{1}{1 + \eta |h_{RnD}|^2}. \tag{28}$$

Substituting ρ_n^* from (28) into (10), the overall channel capacity from S_m to D via EH relay R_n can be rewritten as

$$C_{SmRnD}^* = \frac{1}{2} \log\left(1 + \frac{\gamma \eta |h_{SmRn}|^2 |h_{RnD}|^2}{1 + \eta |h_{RnD}|^2}\right). \tag{29}$$

Following, a source-relay pair is chosen to transmit the message. In the OPS-RR scheme, each source and the relay is given the equal chance to transmit information. To be specific,

$M \times N$ different source-relay pairs comprised of M sources and N relays 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

$$P_{out,SmRn}^{OPS-RR} = \Pr(C_{SmRnD}^* < R). \quad (30)$$

Substituting C_{SmRnD}^* from (29) into (30) gives

$$P_{out,SmRn}^{OPS-RR} = \Pr\left(\frac{1}{2} \log\left(1 + \frac{\gamma\eta|h_{SmRn}|^2|h_{RnD}|^2}{1 + \eta|h_{RnD}|^2}\right) < R\right), \quad (31)$$

which is further simplified to

$$P_{out,SmRn}^{OPS-RR} = \Pr(|h_{SmRn}|^2 < \frac{\alpha}{|h_{RnD}|^2} + \alpha\eta), \quad (32)$$

where $\alpha = \frac{2^{2R}-1}{\gamma\eta}$. Notice that $|h_{SmRn}|^2$ and $|h_{RnD}|^2$ follow exponential distributions with means of σ_{SmRn}^2 and σ_{RnD}^2 . Denoting $X = |h_{SmRn}|^2$ and $Y = |h_{RnD}|^2$, the $P_{out,SmRn}^{OPS-RR}$ can be rewritten as (33) at the top of the following page, where $K_1(\cdot)$ is the first-order modified Bessel function of second kind as given by (8.432.6) in [29].

As mentioned above, the OPS-RR scheme gives each source and relay the equal chance to be selected for information transmission. Therefore, the outage probability of OPS-RR scheme is the mean of $M \times N$ source-relay pairs' outage probability, yields

$$P_{out}^{OPS-RR} = \sum_{m=1}^M \sum_{n=1}^N \frac{1}{M \times N} P_{out,SmRn}^{OPS-RR}. \quad (34)$$

where the $P_{out,SmRn}^{OPS-RR}$ is given by (33).

C. 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 ρ_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 (28). Furthermore, the overall channel capacity C_{SmRnD}^* from S_m to D via EH relay R_n of OPS-JSRS scheme is given by (29).

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

$$\begin{aligned} (S_m^*, R_n^*) &= \arg \max_{\substack{1 \leq m \leq M \\ 1 \leq n \leq N}} C_{SmRnD}^* \\ &= \arg \max_{\substack{1 \leq m \leq M \\ 1 \leq n \leq N}} \frac{|h_{SmRn}|^2|h_{RnD}|^2}{1 + \eta|h_{RnD}|^2} \end{aligned} \quad (35)$$

Therefore, the overall channel capacity of OPS-JSRS scheme can be expressed as

$$C^{OPS-JSRS} = \max_{\substack{1 \leq m \leq M \\ 1 \leq n \leq N}} C_{SmRnD}^*, \quad (36)$$

where C_{SmRnD}^* is given by (29).

The following present an outage probability analysis of OPS-JSRS scheme. As mentioned above, an outage event occurs when the overall channel capacity $C^{OPS-JSRS}$ drops below a predefined data rate R . Hence, we can obtain the outage probability of the OPS-JSRS scheme as

$$\begin{aligned} P_{out}^{OPS-JSRS} &= \Pr(C^{OPS-JSRS} < R) \\ &= \Pr\left(\max_{\substack{1 \leq m \leq M \\ 1 \leq n \leq N}} C_{SmRnD}^* < R\right), \end{aligned} \quad (37)$$

where C_{SmRnD}^* is given by (29). Substituting C_{SmRnD}^* from (29) into (37), the $P_{out}^{OPS-JSRS}$ can be rewritten as

$$\begin{aligned} P_{out}^{OPS-JSRS} &= \Pr\left[\max_{\substack{1 \leq m \leq M \\ 1 \leq n \leq N}} \frac{1}{2} \log\left(1 + \frac{\gamma\eta|h_{SmRn}|^2|h_{RnD}|^2}{1 + \eta|h_{RnD}|^2}\right) < R\right] \\ &= \prod_{n=1}^N \Pr\left[\max_{1 \leq m \leq M} \frac{1}{2} \log\left(1 + \frac{\gamma\eta|h_{SmRn}|^2|h_{RnD}|^2}{1 + \eta|h_{RnD}|^2}\right) < R\right] \\ &= \prod_{n=1}^N \Pr(|h_{Sm^*Rn}|^2 < \frac{\alpha}{|h_{RnD}|^2} + \alpha\eta) \end{aligned} \quad (38)$$

where $|h_{Sm^*Rn}|^2 = \max_{1 \leq m \leq M} |h_{SmRn}|^2$. Notice that $|h_{SmRn}|^2$ follows exponential distributions with mean of σ_{SmRn}^2 . Thus, CDF of $|h_{Sm^*Rn}|^2$ can be expressed as

$$F_{|h_{Sm^*Rn}|^2}(x) = \prod_{m=1}^M [1 - \exp(-\frac{x}{\sigma_{SmRn}^2})] \quad (39)$$

Denoting $Y = |h_{RnD}|^2$, the $P_{out}^{OPS-JSRS}$ can be rewritten as

$$\begin{aligned} P_{out}^{OPS-JSRS} &= \prod_{n=1}^N \int_0^\infty f_Y(y) F_{|h_{Sm^*Rn}|^2}(\frac{\alpha}{y} + \alpha\eta) dy \\ &= \prod_{n=1}^N \int_0^\infty \frac{1}{\sigma_{RnD}^2} \exp(-\frac{y}{\sigma_{RnD}^2}) \\ &\quad \times \prod_{m=1}^M [1 - \exp(-\frac{\alpha}{\sigma_{SmRn}^2 y} - \frac{\alpha\eta}{\sigma_{SmRn}^2})] dy \end{aligned} \quad (40)$$

Using the binomial formula, we have

$$\begin{aligned} &\prod_{m=1}^M [1 - \exp(-\frac{\alpha}{\sigma_{SmRn}^2 y} - \frac{\alpha\eta}{\sigma_{SmRn}^2})] \\ &= 1 + \sum_{j=1}^{2^M-1} (-1)^{|A_j|} \exp(-\sum_{Sm \in A_j} (\frac{\alpha}{\sigma_{SmRn}^2 y} + \frac{\alpha\eta}{\sigma_{SmRn}^2})) \end{aligned} \quad (41)$$

where A_j represents the j -th nonempty subset of M sources, $|A_j|$ represents the number of elements in set A_j . Substituting (41) into (40), we can obtain the outage probability of OPS-JSRS scheme $P_{out}^{OPS-JSRS}$ as (42) at the top of the following page.

IV. ASYMPTOTIC OUTAGE PROBABILITY ANALYSIS

To obtain more insights, in this section we analyze the asymptotic outage probability in the high SNR region with $\gamma \rightarrow \infty$.

$$\begin{aligned}
P_{out,SmRn}^{OPS-RR} &= \int_0^\infty f_Y(y) F_X\left(\frac{\alpha}{y} + \alpha\eta\right) dy = \int_0^\infty \frac{1}{\sigma_{RnD}^2} \exp\left(-\frac{y}{\sigma_{RnD}^2}\right) \left[1 - \exp\left(-\frac{\alpha}{\sigma_{SmRn}^2 y} - \frac{\alpha\eta}{\sigma_{SmRn}^2}\right)\right] dy \\
&= 1 - \exp\left(-\frac{\alpha\eta}{\sigma_{SmRn}^2}\right) \int_0^\infty \frac{1}{\sigma_{RnD}^2} \exp\left(-\frac{y}{\sigma_{RnD}^2} - \frac{\alpha}{\sigma_{SmRn}^2 y}\right) dy \\
&= 1 - \exp\left(-\frac{\alpha\eta}{\sigma_{SmRn}^2}\right) \frac{2\sqrt{\alpha}}{\sigma_{RnD} \sigma_{SmRn}} K_1\left(\frac{2\sqrt{\alpha}}{\sigma_{RnD} \sigma_{SmRn}}\right)
\end{aligned} \tag{33}$$

$$\begin{aligned}
P_{out}^{OPS-JSRS} &= \prod_{n=1}^N \int_0^\infty \frac{1}{\sigma_{RnD}^2} \exp\left(-\frac{y}{\sigma_{RnD}^2}\right) \left[1 + \sum_{j=1}^{2^M-1} (-1)^{|A_j|} \exp\left(-\sum_{Sm \in A_j} \left(\frac{\alpha}{\sigma_{SmRn}^2 y} + \frac{\alpha\eta}{\sigma_{SmRn}^2}\right)\right)\right] dy \\
&= \prod_{n=1}^N \left[1 + \sum_{j=1}^{2^M-1} (-1)^{|A_j|} \exp\left(-\sum_{Sm \in A_j} \frac{\alpha\eta}{\sigma_{SmRn}^2}\right) \int_0^\infty \frac{1}{\sigma_{RnD}^2} \exp\left(-\frac{y}{\sigma_{RnD}^2} - \sum_{Sm \in A_j} \frac{\alpha}{\sigma_{SmRn}^2 y}\right) dy\right] \\
&= \prod_{n=1}^N \left[1 + \sum_{j=1}^{2^M-1} (-1)^{|A_j|} \exp\left(-\sum_{Sm \in A_j} \frac{\alpha\eta}{\sigma_{SmRn}^2}\right) \frac{2}{\sigma_{RnD}} \sqrt{\sum_{Sm \in A_j} \frac{\alpha}{\sigma_{SmRn}^2}} K_1\left(\frac{2}{\sigma_{RnD}} \sqrt{\sum_{Sm \in A_j} \frac{\alpha}{\sigma_{SmRn}^2}}\right)\right]
\end{aligned} \tag{42}$$

A. TPS-JSRS Scheme

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

$$P_{out}^{TPS-JSRS,\infty} = (1 - \Phi_1^\infty - \Phi_2^\infty)^N, \tag{43}$$

where

$$\begin{aligned}
\Phi_1^\infty &= \sum_{i=1}^M \int_0^\infty \frac{1}{\sigma_{SiRn}^2} \exp\left(-\frac{x}{\sigma_{SiRn}^2}\right) \exp\left(-\frac{\beta}{\sigma_{RnD}^2 \rho_n \eta x}\right) dx \\
&= \sum_{i=1}^M 2\sqrt{\frac{\beta}{\sigma_{SiRn}^2 \sigma_{RnD}^2 \rho_n \eta}} K_1\left(2\sqrt{\frac{\beta}{\sigma_{SiRn}^2 \sigma_{RnD}^2 \rho_n \eta}}\right),
\end{aligned} \tag{44}$$

and

$$\begin{aligned}
\Phi_2^\infty &= \sum_{i=1}^M \frac{1}{\sigma_{SiRn}^2} \int_0^\infty \sum_{k=1}^{2^{M-1}-1} (-1)^{|D_k|} \\
&\quad \times \exp\left(-\sum_{Sm \in D_k} \frac{x}{\sigma_{SmRn}^2} - \frac{x}{\sigma_{SiRn}^2} - \frac{\beta}{\sigma_{RnD}^2 \rho_n \eta x}\right) dx \\
&= \sum_{i=1}^M \frac{1}{\sigma_{SiRn}^2} \sum_{k=1}^{2^{M-1}-1} (-1)^{|D_k|} \\
&\quad \times 2\sqrt{\frac{\beta}{\sigma_{SiRn}^2 \sigma_{RnD}^2 \rho_n \eta}} K_1\left(2\sqrt{\frac{\beta}{\sigma_{SiRn}^2 \sigma_{RnD}^2 \rho_n \eta}}\right)
\end{aligned} \tag{45}$$

Substituting (44) and (45) into (43), the asymptotic outage probability of the TPS-JSRS scheme can be obtained.

B. OPS-RR Scheme

When $\gamma \rightarrow \infty$, the asymptotic outage probability of OPS-RR scheme can be obtained as

$$P_{out}^{OPS-RR,\infty} = \sum_{m=1}^M \sum_{n=1}^N \frac{1}{M \times N} \Pr(|h_{SmRn}|^2 < \frac{\alpha}{|h_{RnD}|^2}). \tag{46}$$

Similar to the derivation of (33), (46) can be obtained as (47).

$$\begin{aligned}
P_{out}^{OPS-RR,\infty} &= \sum_{m=1}^M \sum_{n=1}^N \frac{1}{M \times N} \int_0^\infty \frac{1}{\sigma_{RnD}^2} \exp\left(-\frac{y}{\sigma_{RnD}^2}\right) \\
&\quad \times \left[1 - \exp\left(-\frac{\alpha}{\sigma_{SmRn}^2 y}\right)\right] dy \\
&= \sum_{m=1}^M \sum_{n=1}^N \frac{1}{M \times N} \\
&\quad - \sum_{m=1}^M \sum_{n=1}^N \frac{1}{M \times N} \frac{2\sqrt{\alpha}}{\sigma_{RnD} \sigma_{SmRn}} K_1\left(\frac{2\sqrt{\alpha}}{\sigma_{RnD} \sigma_{SmRn}}\right)
\end{aligned} \tag{47}$$

C. OPS-JSRS Scheme

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

$$P_{out}^{OPS-JSRS,\infty} = \prod_{n=1}^N \Pr(|h_{Sm^*Rn}|^2 < \frac{\alpha}{|h_{RnD}|^2}). \tag{48}$$

Similar to (42), the $P_{out}^{OPS-JSRS,\infty}$ can be derived as

$$\begin{aligned}
P_{out}^{OPS-JSRS,\infty} &= \prod_{n=1}^N \int_0^\infty \frac{1}{\sigma_{RnD}^2} \exp\left(-\frac{y}{\sigma_{RnD}^2}\right) \\
&\quad \times \left[1 + \sum_{j=1}^{2^M-1} (-1)^{|A_j|} \exp\left(-\sum_{Sm \in A_j} \frac{\alpha}{\sigma_{SmRn}^2 y}\right)\right] dy \\
&= \prod_{n=1}^N \left[1 + \sum_{j=1}^{2^M-1} (-1)^{|A_j|} \right. \\
&\quad \times \left. \frac{2}{\sigma_{RnD}} \sqrt{\sum_{Sm \in A_j} \frac{\alpha}{\sigma_{SmRn}^2}} K_1\left(\frac{2}{\sigma_{RnD}} \sqrt{\sum_{Sm \in A_j} \frac{\alpha}{\sigma_{SmRn}^2}}\right)\right]
\end{aligned} \tag{49}$$

V. 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 $\rho_n = \rho$, and the average channel gains of $\sigma_{SmRn}^2 = \sigma_{RnD}^2 = 1$, the energy conversion efficiency of $\eta = 0.5$, $\rho_n = 0.5$ are used.

Fig. 3 shows the theoretical and simulated outage probability versus power splitting ratio ρ of the OPS-JSRS and TPS-JSRS schemes with SNR=10dB, $R = 1\text{bit/s/Hz}$, $\eta = 0.5$ and $M = N = 4$. The power splitting ratio ρ of TPS-JSRS scheme is not optimized and varies from 0 to 1, while in the OPS-JSRS scheme, an optimized ρ is given by (28). As shown in Fig. 3, with the increase of ρ , 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 ρ . 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.

Fig. 3. Outage probability versus PSR ρ of the OPS-JSRS and TPS-JSRS schemes with SNR=10dB, $R = 1\text{bit/s/Hz}$, $\eta = 0.5$ and $M = N = 4$, where t. and s. represent the theoretical and simulated outage probability results, respectively.

Fig. 4. Outage probability versus SNR of the OPS-JSRS as well as TPS-JSRS and OPS-RR schemes for different number of sources with $R = 1\text{bit/s/Hz}$, $\eta = 0.5$ and $N = 4$, where t. and s. represent the theoretical and simulated outage probability results, respectively.

Fig. 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-

Fig. 5. Outage probability versus SNR of the OPS-JSRS as well as TPS-JSRS and OPS-RR schemes for different number of EH relays with $R = 1\text{bit/s/Hz}$, $\eta = 0.5$ and $M = 4$, where t. and s. represent the theoretical and simulated outage probability results, respectively.

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.

Fig. 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 number of EH relays of $N = 4$ and $N = 8$, we assume the data rate $R = 1\text{bit/s/Hz}$, the energy conversion efficiency $\eta = 0.5$ and the number of sources $M = 4$. It can be seen from Fig. 5, in the whole 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 Fig. 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 of $R = 1\text{bit/s/Hz}$ and $R = 0.5\text{bit/s/Hz}$ with $\eta = 0.5$ and $M = N = 4$. As shown in Fig. 6, with the data rate decreases from $R = 1\text{bit/s/Hz}$ to $R = 0.5\text{bit/s/Hz}$, 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.

Fig. 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. and s. represent the theoretical and simulated outage probability results, respectively.

Fig. 7. Outage probability versus SNR of the OPS-JSRS as well as TPS-JSRS and OPS-RR schemes for different energy conversion efficiency with $R = 1\text{bit/s/Hz}$ and $M = N = 4$, where t. and s. represent the theoretical and simulated outage probability results, respectively.

Fig. 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 η , the relay converts more energy from received RF signals for information relaying, which leads to a lower outage probability. Fig. 7 also demonstrates that the OPS-JSRS scheme outperforms OPS-RR scheme and TPS-JSRS scheme in terms of outage probability.

Fig. 8 illustrates the theoretical and simulated outage probability versus energy conversion efficiency η of the OPS-JSRS

Fig. 8. Outage probability versus energy conversion efficiency η of the OPS-JSRS as well as TPS-JSRS and OPS-RR schemes for different data rates with $\text{SNR}=10$ and $M = N = 4$, where t. and s. represent the theoretical and simulated outage probability results, respectively.

Fig. 9. Exact and asymptotic outage probability versus SNR of the OPS-JSRS as well as TPS-JSRS and OPS-RR schemes for different number of sources with $R = 1\text{bit/s/Hz}$, $\eta = 0.5$ and $N = 4$, where t. and s. represent the theoretical and simulated outage probability results, respectively.

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 η 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 η . In other words, the higher energy conversion efficiency, the better outage probability performance.

Fig. 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.

VI. CONCLUSIONS

In this paper, we proposed an optimal power splitting and joint source-relay selection (OPS-JSRS) scheme in energy harvesting DF relay system consisting of M sources, a destination and N EH relays. In OPS-JSRS scheme, we calculated and derived the expression of the optimal power-splitting ratio (PSR) and selected the best source-relay pair to transmit the messages. For the purpose of comparison, we presented the traditional power splitting and joint source-relay scheme (TPS-JSRS) in which the PSR was not optimized and the optimal power splitting and round robin (OPS-RR) scheme. We derived the exact and asymptotic closed-form outage probability expressions of OPS-JSRS, TPS-JSRS and OPS-RR schemes. Numerical results showed 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 has outage advantage. Additionally, the outage probability performance of OPS-JSRS schemes improves with the increase of the number of sources and relays.

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VII. DATA AVAILABILITY

Not applicable.

VIII. CODE AVAILABILITY

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

IX. CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

Figures

Figure 1

An energy harvesting relay system consisting of multi-source, one destination and multiple energy-harvesting relays.

Figure 2

A block diagram of an EH relay.

Figure 3

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Figure 5

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Figure 6

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Figure 7

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Figure 8

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Figure 9

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