Outage Probability Analysis and Power Splitter Designs for SWIPT Relaying Systems With Direct Link

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***Abstract*— This letter investigates the outage performance for simultaneous wireless information and power transfer (SWIPT) relaying systems in the presence of direct link between the source and the destination. For the SWIPT, we employ a power splitter (PS) at the relay, which splits the received signal into the information transmission and the energy harvesting parts. First, we provide an analysis of the outage probability as a closed-form based on a high signal-to-noise ratio approximation. From the analysis, it is recognized that the diversity order of the SWIPT relaying systems equals that of the non-SWIPT cases. The closed-form outage expression also enables us to obtain a simple expression for the PS factor which minimizes the outage probability. Simulation results demonstrate the accuracy of the derived analysis and the efficiency of the proposed PS scheme.**

***Index Terms*— Simultaneous wireless information and power transfer (SWIPT), power splitting (PS), relay.**

I. Introduction

RECENTLY, energy harvesting (EH) has been considered as a promising technology to increase the life time of mobile devices. In particular, simultaneous wireless information and power transfer (SWIPT) [1]–[3] and wireless powered communication networks (WPCN) [4], [5] techniques have received a lot of interest because radio frequency (RF) signals can become a convenient energy source. Meanwhile, relaying systems have been investigated in vast literature, due to its ability of extending cell coverage and improving reliability [6]–[10]. There are several relaying protocols such as decode-and-forward (DF) and amplify-and-forward (AF). The AF relay is considered to be simpler [6]–[8], and thus we focus on the AF relay in this letter.

In [11]–[14], the SWIPT technology was adopted in the relaying systems so that the relay can utilize the energy harvested from the RF signals received from the source. Especially, the authors in [12] analyzed the SWIPT AF relaying systems in terms of the outage probability of the information rate in a power splitting (PS) relay protocol which divides the received RF signal into the EH part and the information transmission part. For the SWIPT in DF relaying systems, [13] optimized transmit power and the PS factor to maximize the information rate. However, the direct link between the source and the destination was ignored in [12] and [13]. The relay channels were also studied for the WPCN in which the source harvests energy from both the relay and an hybrid access point (H-AP), which also acts as a destination [15]. Recently, by adopting the EH relaying protocols, the cooperative WPCN was introduced in [16] where both the source and the relay were wirelessly powered by the H-AP.

Meanwhile, it is well known that the direct link in the relay channels provides a substantial diversity gain as well as a multiplexing gain [9], [10]. Therefore, if the direct link is available, we need to optimize the system considering the direct link. In this letter, by extending the works in [12] which did not consider the direct link channel, we analyze the outage probability of the PS SWIPT relaying systems in the presence of the direct link. To attain more insights from the analysis, we derive the outage probability as a closed-form based on a high signal-to-noise ratio (SNR) approximation and the Riemann sum approaches.

It is worth noting that this closed-form outage analysis provides insights on the SWIPT relaying systems which have not been investigated in the previous works. First, the proposed analysis reveals that the SWIPT relaying helps to achieve higher diversity gain over direct communications between the source and the destination regardless of the EH efficiency and the value of the PS factor at the relay, which implies that deploying an EH relay node between the two end nodes is indeed effective. Second, we can check that a non-negligible shifting gain is still achievable by optimizing the PS factor. To relieve burden for searching the optimal PS factor, we propose a closed-form PS factor selection method by exploiting the proposed outage expression. Finally, through simulation results, we confirm the accuracy of the proposed analysis and the efficiency of the proposed PS factor design.

II. System Model

We consider a point-to-point communication system where a cooperative relay helps data transmission between the source and the destination. We assume that an AF half-duplex relay is adopted and all nodes are equipped with a single antenna. There is no power supply at the relay, and thus the relay operates with the energy harvested from the RF signals from the source. Then, in order to perform the EH and the information processing at the relay at the same time, a PS receiver is employed which splits the received signal power for the information processor and the EH circuit.

Due to the half-duplex property of the relay, the communication occurs over two phases. In the first phase, the source broadcasts the signal x_s with $\mathbb{E}[|x_s|^2] = P_s$ to both the relay and the destination. Then, the received signals at the relay y_r and the destination y_d are respectively given by $y_r = h_1 x_s + n_r$ and $y_0 = h_0 x_s + n_d$, where $h_1 \sim \mathcal{CN}(0, \lambda_1)$ and $h_0 \sim \mathcal{CN}(0, \lambda_0)$ indicate the source-to-relay and source-to-destination channel coefficients, respectively, and $n_r \sim \mathcal{CN}(0, \sigma_r^2)$ and $n_d \sim \mathcal{CN}(0, \sigma_d^2)$ represent the noise at the relay and the destination, respectively. Then, the power splitter

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$$P_{out} = 1 - e^{-\frac{c}{a\lambda_0}} - \frac{1}{\lambda_0\lambda_1}\int_0^{\frac{c}{a}}\int_{\frac{c-ax}{b}}^{\infty} \exp\left(-\left(\frac{my-uxy-fx+g}{(axy+by^2-cy)\lambda_2}+\frac{x}{\lambda_0}+\frac{y}{\lambda_1}\right)\right)dydx \tag{1}$$

at the relay splits the received signal y_r into y_r^E and y_r^I, each of which is utilized in the EH circuit, and the information processor, respectively.

Introducing a PS factor ρ, we can write $y_r^E = \sqrt{\rho}y_r$. Then, the total energy harvested at the relay over the first time slot can be expressed as $E_h \triangleq \mathbb{E}[|y_r^E|^2] = \eta\rho P_s|h_1|^2 T$ [1], where $\eta \in (0, 1]$ is the energy conversion efficiency and T equals the time duration. Since the AF relay uses the same time for data reception and transmission, the total power budget P_r of the relay in the second phase becomes $P_r = \eta\rho P_s|h_1|^2$. In the meantime, the signal y_r^I is represented as $y_r^I = \sqrt{1-\rho}(h_1x_s + n_r) + n_c$, where $n_c \sim \mathcal{CN}(0, \sigma_c^2)$ designates the noise generated in the RF band-to-baseband conversion process. For simplicity, we assume $\sigma_c^2 \gg \sigma_r^2$ as in [1] and $\sigma \triangleq \sigma_c = \sigma_d$. Then, we obtain $y_r^I \simeq \sqrt{1-\rho}h_1x_s + n_c$.

Now, in the second time slot, the relay forwards y_r^I to the destination with power budget P_r. We consider the transmit signal at the relay as $x_r = \kappa y_r^I$, where $\kappa = \sqrt{\frac{P_r}{(1-\rho)|h_1|^2P_s+\sigma^2}}$. Then, the destination receives y_2 from the relay as

$$y_2 = h_2x_r + \tilde{n}_d = \kappa\sqrt{1-\rho}h_1h_2x_s + \kappa h_2n_c + \tilde{n}_d,$$

where $h_2 \sim \mathcal{CN}(0, \lambda_2)$ stands for the relay-to-destination channel and $\tilde{n}_d \sim \mathcal{CN}(0, \sigma^2)$ is the additive Gaussian noise at the destination in the second time slot.

Applying maximum ratio combining to y_0 and y_2 at the destination, we can compute the achievable rate of the SWIPT relaying system as $R = \frac{1}{2}\log_2(1 + \gamma_0 + \gamma_2)$ [9], where $\gamma_0 \triangleq \frac{P_s|h_0|^2}{\sigma^2}$ represents the direct link SNR between the source and the destination and $\gamma_2 \triangleq \frac{P_s\kappa^2(1-\rho)|h_1|^2|h_2|^2}{\kappa^2|h_2|^2\sigma^2+\sigma^2}$ is associated with the source-relay-destination link SNR. Finally, with a certain threshold R_{th}, we obtain the corresponding outage probability as $P_{out} \triangleq P\{R < R_{\text{th}}\}$. In this letter, we aim to analyze the outage probability P_{out} and find the optimal PS factor ρ which minimizes the outage probability.

III. Outage Probability Analysis

In this section, we analyze the outage probability P_{out} for a given PS factor ρ. First, we derive an exact form of the outage probability P_{out} in the following lemma.

Lemma 1: For a given ρ, the outage probability of the SWIPT relaying systems is expressed by (1) at the top of this page, where $a \triangleq \eta\rho P_s$, $b \triangleq \eta\rho(1-\rho)P_s$, $c \triangleq \eta\rho\sigma^2(\tau-1)$, $u \triangleq (1-\rho)P_s$, $m \triangleq \sigma^2(\tau-1)(1-\rho)$, $f \triangleq \sigma^2$, $g \triangleq \frac{\sigma^4(\tau-1)}{P_s}$, and $\tau = 2^{2R_{th}}$.

Proof: Let us define three random variables $X \triangleq |h_0|^2$, $Y \triangleq |h_1|^2$, and $Z \triangleq |h_2|^2$, whose probability density functions (PDF) follow an exponential distribution as $f_X(x) = \frac{1}{\lambda_0}e^{-\frac{x}{\lambda_0}}$, $f_Y(y) = \frac{1}{\lambda_1}e^{-\frac{y}{\lambda_1}}$, and $f_Z(z) = \frac{1}{\lambda_2}e^{-\frac{z}{\lambda_2}}$, respectively. Denoting $M \triangleq aXY + bY^2 - cY$ and $N \triangleq mY - uXY - fX + g$, the outage probability P_{out} can be determined as

$$\begin{aligned} P_{out} &= P\{MZ < N\} \\ &= \begin{cases} P\{Z < \frac{N}{M}\}, & \text{for } M > 0, N > 0, \\ P\{Z > \frac{N}{M}\} = 1, & \text{for } M < 0, N > 0, \quad (2) \\ P\{Z < \frac{N}{M}\} = 0, & \text{for } M > 0, N < 0, \quad (3) \end{cases} \end{aligned}$$

where (2) and (3) come from the facts that $Z \geq 0$ and $\frac{N}{M} < 0$. One can check that there is no such a case where $M < 0$ and $N < 0$ are satisfied simultaneously, since the random variable Y should be negative, which contradicts the fact $Y \geq 0$.

By utilizing the above results, the outage probability can be expressed as

$$\begin{aligned} P_{out} &= \int_0^{\frac{c}{a}}\int_{\frac{c-ax}{b}}^{\infty} P\left\{Z < \frac{my-uxy-fx+g}{axy+by^2-cy}\right\} \\ &\quad\times f_X(x)f_Y(y)dydx \\ &\quad+ \int_0^{\frac{c}{a}}\int_0^{\frac{c-ax}{b}} P\left\{Z > \frac{my-uxy-fx+g}{axy+by^2-cy}\right\} \\ &\quad\times f_X(x)f_Y(y)dydx \\ &= \int_0^{\frac{c}{a}}\int_{\frac{c-ax}{b}}^{\infty}\left(1-\exp\left(-\frac{my-uxy-fx+g}{(axy+by^2-cy)\lambda_2}\right)\right) \\ &\quad\times f_X(x)f_Y(y)dydx \\ &\quad+ \int_0^{\frac{c}{a}}\int_0^{\frac{c-ax}{b}} f_X(x)f_Y(y)dydx, \end{aligned}$$

and we obtain the lemma. ■

It is worth noting that our analysis in Lemma 1 generalizes the previous results in [12] to the relaying systems with direct link. Compared to the analysis in [12], the double-integral form in the exact outage expression (1) is added due to the direct link, and this prevents us from obtaining helpful insights on a system design. Thus, in what follows, we derive a simplified outage expression based on a high SNR approximation, i.e., $P_s \gg \sigma^2$. At high SNR, the source-relay-destination link SNR γ_2 is approximated to

$$\gamma_2 \simeq \frac{\eta\rho(1-\rho)|h_1|^2|h_2|^2}{\eta\rho|h_2|^2+1-\rho}\frac{P_s}{\sigma^2}. \tag{4}$$

Then, substituting (4) into (1) and applying the same argument as in the proof of Lemma 1, we have

$$\begin{aligned} P_{out} &\simeq 1 - e^{-\frac{c}{a\lambda_0}} - \int_0^{\frac{c}{a}} f_X(x) \\ &\quad\times \int_0^{\infty}\frac{e^{\frac{ax-c}{b\lambda_1}}}{b\lambda_1}\exp\left(-\left(\frac{t}{b\lambda_1}+\frac{m-ux}{t\lambda_2}\right)\right)dtdx \quad (5) \end{aligned}$$

where the last equality follows from the change of variable $t \triangleq ax + by - c$. In the meantime, it is true that $\int \exp(-\frac{p}{4x} - qx)dx = \sqrt{\frac{p}{q}}K_1(\sqrt{pq})$ [17], where $K_1(x)$ indicates the first order modified Bessel function of the second kind. Applying the Bessel function, we can rephrase (5) as

$$\begin{aligned} P_{out} &\simeq 1 - e^{-\frac{c}{a\lambda_0}} - \int_0^{\frac{c}{a}} f_X(x) \\ &\quad\times \exp\left(\frac{-(c-ax)}{\lambda_1 b}\right)\sqrt{\frac{4(m-ux)}{\lambda_1\lambda_2 b}}K_1\left(\sqrt{\frac{4(m-ux)}{\lambda_1\lambda_2 b}}\right)dx. \end{aligned} \tag{6}$$

To further simplify (6), we replace the integral in (6) with a Riemann-sum expression as (7)-(9) at the top of the next page, where $\Delta x \triangleq \frac{c}{an} = (1-\rho)\frac{c}{bn}$, (7) comes from the equality

$$P_{out} \simeq 1 - e^{-\frac{c}{a\lambda_0}} - \lim_{n\to\infty} \Delta x \sum_{k=1}^{n} \frac{1}{\lambda_0} e^{-\frac{k\Delta x}{\lambda_0}} e^{-\frac{1-\frac{k}{n}}{\lambda_1}\frac{c}{b}} \sqrt{\frac{4(1-\rho)}{\lambda_2\eta\rho}\frac{(1-\frac{k}{n})}{\lambda_1}\frac{c}{b}} K_1\left(\sqrt{\frac{4(1-\rho)}{\lambda_2\eta\rho}\frac{(1-\frac{k}{n})}{\lambda_1}\frac{c}{b}}\right) \quad (7)$$

$$\simeq 1 - e^{-\frac{c}{a\lambda_0}} - \lim_{n\to\infty} \Delta x \sum_{k=1}^{n} \frac{1}{\lambda_0} e^{-\frac{k\Delta x}{\lambda_0}} \left(1 - \frac{(1-\frac{k}{n})}{\lambda_1}\frac{c}{b}\right)\left(1 + \frac{(1-\rho)}{\lambda_2\eta\rho}\frac{(1-\frac{k}{n})}{\lambda_1}\frac{c}{b}\log\left(\frac{(1-\rho)}{\lambda_2\eta\rho}\frac{(1-\frac{k}{n})}{\lambda_1}\frac{c}{b}\right)\right) \quad (8)$$

$$\simeq \frac{1}{\lambda_0}\lim_{n\to\infty} \Delta x \sum_{k=1}^{n} \left\{\frac{c}{b}\frac{(1-\frac{k}{n})}{\lambda_1} - \frac{c}{b}\frac{(1-\rho)}{\lambda_2\eta\rho}\frac{(1-\frac{k}{n})}{\lambda_1}\log\left(\frac{(1-\rho)}{\lambda_2\eta\rho}\frac{(1-\frac{k}{n})}{\lambda_1}\frac{c}{b}\right)\right\} \quad (9)$$

$m - ux = \frac{1-\rho}{\eta\rho}(c - ax)$, (8) is due to the fact that $\frac{c}{b} \to 0^+$ at high SNR and the well-known approximation $xK_1(x) \simeq 1 + \frac{x^2}{2}\log(\frac{x}{2})$ for $x \ll 1$, and (9) is obtained from the equalities $\lim_{n\to\infty} \Delta x \sum_{k=1}^{n} \frac{1}{\lambda_0}\exp(-\frac{k\Delta x}{\lambda_0}) = \int_0^{\frac{c}{a}} f_X(x)dx = 1 - \exp(-\frac{c}{a\lambda_0})$ with ignoring higher order terms involving $\frac{c^2}{b^2}$. Finally, rewriting (9) as an integral form, the approximated outage probability $\bar{P}_{out}(\rho)$ is expressed as

$$\bar{P}_{out}(\rho) = \frac{(\tau-1)^2}{2\lambda_0}\left(\frac{1}{\text{SNR}}\right)^2\Big(\frac{1}{(1-\rho)\lambda_1} + \frac{1}{2\eta\rho\lambda_1\lambda_2} - \frac{1}{\eta\rho\lambda_1\lambda_2}\Big(\log\Big(\frac{\tau-1}{\eta\lambda_1\lambda_2}\frac{1}{\text{SNR}}\Big) - \log\rho\Big)\Big), \quad (10)$$

where the SNR is defined as $\text{SNR} \triangleq \frac{P_s}{\sigma^2}$.

Note that the diversity order of the conventional non-SWIPT relaying systems equals 2 [6]. A careful examination of equation (10) also reveals that the outage probability of the SWIPT relaying decays with $\bar{P}_{out}(\rho) \propto \frac{\log(\text{SNR})}{\text{SNR}^2}$ at high SNR, which gives rise to a diversity order $d(\rho) = 2$ as

$$d(\rho) \triangleq -\lim_{\text{SNR}\to\infty}\frac{\log \bar{P}_{out}(\rho)}{\log(\text{SNR})} = 2 - \lim_{\text{SNR}\to\infty}\frac{\log\log(\text{SNR})}{\log(\text{SNR})} = 2,$$

which is independent of ρ and η. In addition, by applying similar manipulations in (9), we can show that the diversity order of the SWIPT relay without direct link [12] equals one. Therefore, we conclude that the direct link is important for improving the outage performance in the SWIPT relay systems. These observations will be further verified from numerical results in Section V.

In summary, the above results imply that deploying an EH relay is useful even if the amount of harvested energy is arbitrarily small. Meanwhile, the SWIPT operation at the relay may still cause some shift gain loss compared to the non-SWIPT cases although it achieves the same diversity order. To enhance the shifting gain, we provide an optimization technique for the PS factor ρ in the following section.

IV. PS Factor Optimization

The goal of this section is to identify a simple solution for ρ^* which minimizes the outage probability $P_{out}(\rho)$. One may calculate the optimal ρ^* by solving the following problem:

$$\rho^* = \arg\min_{0\le\rho\le1} P_{out}(\rho). \quad (11)$$

However, such an exhaustive method hardly provides helpful insights as well as an analytical solution.

To resolve the problem, in this section, we adopt the approximated outage expression $\bar{P}_{out}$ in (10) instead of the exact form in Lemma 1. However, the expression in (10) may be still too complicated for an analytical solution. By applying the Taylor series approximation $\log\rho \simeq \rho - 1$ for $0 < \rho < 1$, it is further simplified as

$$\bar{P}_{out}(\rho) \simeq \frac{(\tau-1)^2}{4\lambda_0\lambda_1\lambda_2\eta}\left(\frac{1}{\text{SNR}}\right)^2\left(\frac{\alpha}{1-\rho} - \frac{\beta}{\rho} + 1\right), \quad (12)$$

where $\alpha \triangleq \lambda_2\eta > 0$ and $\beta \triangleq \log(\frac{\sqrt{e}(\tau-1)}{\lambda_1\lambda_2\eta}\frac{1}{\text{SNR}}) < 0$ at high SNR.

The first and second order derivatives of (12) are given as

$$\frac{\partial\bar{P}_{out}(\rho)}{\partial\rho} = k\left(\frac{\alpha}{(1-\rho)^2} + \frac{\beta}{\rho^2}\right)$$

$$\text{and}\quad \frac{\partial^2\bar{P}_{out}(\rho)}{\partial\rho^2} = 2k\left(\frac{\alpha}{(1-\rho)^3} - \frac{\beta}{\rho^3}\right),$$

where $k \triangleq \frac{(\tau-1)^2}{4\lambda_0\lambda_1\lambda_2\eta}(\frac{1}{\text{SNR}})^2 > 0$. Then, we can see that $\bar{P}_{out}(\rho)$ is a convex function with respect to ρ due to the fact that $\frac{\partial^2\bar{P}_{out}(\rho)}{\partial\rho^2} > 0$ for $0 < \rho < 1$, and therefore the solution can be obtained from the zero-gradient condition $\frac{\partial\bar{P}_{out}(\rho)}{\partial\rho} = 0$.

For the case of $|\alpha| = |\beta|$, a solution $\hat{\rho}$ minimizing (12) is simply given by $\hat{\rho} = \frac{1}{2}$. In contrast, if $|\alpha| \neq |\beta|$, we have two different solutions satisfying the zero gradient condition as

$$\rho_1 = \frac{\beta + \sqrt{-\alpha\beta}}{\alpha+\beta} \quad\text{and}\quad \rho_2 = \frac{\beta - \sqrt{-\alpha\beta}}{\alpha+\beta}.$$

One can check that ρ_2 is infeasible, since we have $\rho_2 < \frac{\beta-\sqrt{\alpha\alpha}}{\alpha+\beta} < 0$ for $|\alpha| < |\beta|$ and $\rho_2 > \frac{\beta-\sqrt{\alpha\alpha}}{\alpha+\beta} > 1$ for $|\alpha| > |\beta|$, which contradicts to the condition $0 < \rho_2 < 1$.

Thus, we finally obtain a closed-form PS factor $\hat{\rho}$ as

$$\hat{\rho} = \begin{cases} \dfrac{\beta+\sqrt{-\alpha\beta}}{\alpha+\beta}, & \text{if } |\alpha| \neq |\beta|, \\ \dfrac{1}{2}, & \text{otherwise.} \end{cases} \quad (13)$$

Note that although the above solution may not ensure the optimality in the low SNR regime, simulation results demonstrate that (13) performs well in the medium-to-high SNR ranges.

V. Numerical Results

In this section, we present numerical results to confirm the accuracy of our analysis and the efficiency of the PS factor design. Throughout the simulations, we set the energy conversion efficiency to be $\eta = 0.5$. In Fig. 1, we compare

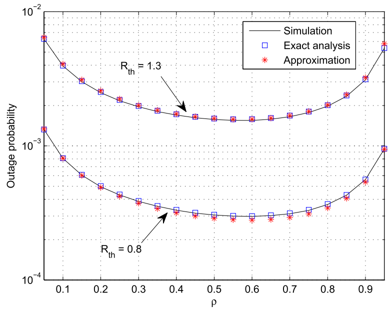

Fig. 1. The outage probability as a function of ρ with SNR = 20 dB, $\lambda_0 = 1$, and $\lambda_1 = \lambda_2 = 5$.

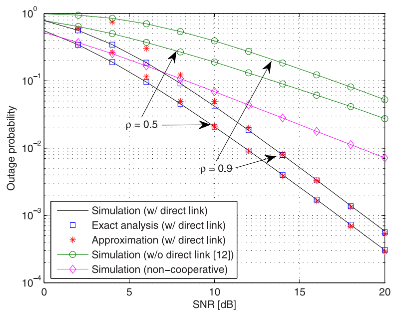

Fig. 2. The outage probability as a function of SNR with $R_{th} = 0.8$, $\lambda_0 = 1$, and $\lambda_1 = \lambda_2 = 5$.

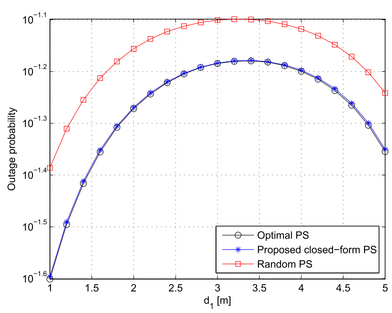

Fig. 3. The outage probability as a function of the distance between the source and the relay with SNR $= 30$ dB and $R_{th} = 0.5$.

our analytical results in (1) and (10) with the numerical simulations. Two threshold values $R_{th} = 0.8$ and 1.3 are considered with the SNR of 20 dB. Also, we set $\lambda_0 = 1$ and $\lambda_1 = \lambda_2 = 5$. From the plot, we can see that our analytical results accurately predict the numerical simulations with reduced complexity.

Fig. 2 exhibits the outage probability as a function of SNR with $\rho = 0.5$ and 0.9, $R_{th} = 0.8$, $\lambda_0 = 1$, and $\lambda_1 = \lambda_2 = 5$. For comparison, we also plot the performance of the conventional PS relaying without direct link [12] and the non-cooperative systems which do not have a relaying node. First of all, we can check that a closed-form outage expression in (10) is fairly accurate for the SNR range higher than 12 dB, and the diversity order of the SWIPT relaying with the direct link exactly equals 2 as expected from our analysis in Section III. Also, it is observed that the direct link signal plays a crucial role to achieve higher diversity order over the conventional scheme in [12] regardless of the PS factor ρ at the relay. By comparing the curves for the SWIPT relaying with direct link and the non-cooperative scheme, we conclude that an EH relay significantly improves the outage probability performance without using extra power at the source node.

In Fig. 3, we compare the outage performance of various PS schemes as a function of the source-to-relay distance d_1. In this figure, it is assumed that the relay is located on the straight line between the source and the destination, i.e., $d_0 = d_1 + d_2$, where $d_0 = 6$ and $d_2 = 6 - d_1$ stand for the distance of the direct link and the relay-to-destination link, respectively. Then, we have $\lambda_0 = 6^{-\phi}$, $\lambda_1 = d_1^{-\phi}$, and $\lambda_2 = (6 - d_1)^{-\phi}$ where $\phi = 2.7$ denotes the pathloss exponent [12]. The optimal and random PS schemes choose ρ optimally with an exhaustive search method as in (11) and randomly with a uniform distribution over [0, 1], respectively. It is shown that the proposed closed-form PS provides a significant performance gain over the random PS scheme and achieves almost identical performance with the optimal PS with reduced complexity.

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