Outage Performance on Threshold AF and DF Relaying Schemes in Simultaneous Wireless Information and Power Transfer Systems

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Abstract

In the work, a dual-hop cooperative simultaneous wireless information and power transfer (SWIPT) system, in where there are a Source-Destination ($S-D$) pair and a relay node (R), is considered. R adopts threshold amplify-and-forward (AF)/decode-and-forward (DF) relaying schemes to decide whether to aid $S-D$ pair's information transmission not. The effect of SWIPT on the outage performance has been investigated and the closed-form analytical expressions for outage probability have been derived under threshold AF and DF schemes, respectively, which are verified by Monte-Carlo simulations.

Keywords:

Simultaneous wireless information and power transfer; amplify-and-forward; decode-and-forward; outage probability

1. Introduction

Nowadays, energy budget is a crucial limitation factor on mobile terminals' lifetime and performance, which are usually equipped with rechargeable batteries. As a promising solution for this problem, simultaneous wireless information and power transfer (SWIPT) technology was proposed for future wireless communications [1]-[2]. Under SWIPT transmission scheme, the radio-frequency (RF) signals radiated by the transmitters, which are used for information delivery, can also be regarded as a viable source of energy. At the receiver, the received RF signal can be split into two portions: one for information decoding and the other for energy harvesting, by using power splitting method [3]-[5].

Plenty of attentions have been paid on power control, resource scheduling and transmission schemes design in SWIPT systems [6]-[16]. [6] investigated multiple-input-multiple-output (MIMO) communications under energy harvesting (EH) constraints with partial channel state information (CSI). The authors of [7] proposed an optimal and the low complexity suboptimal energy efficient power allocation algorithms for MIMO SWIPT systems with covariance CSI feedback. In [8], the authors proposed a robust beamforming design for the multi-antenna SWIPT systems to maximize the worst-case harvested energy for the energy-harvesting receiver (ER), as well as to guarantee that the rate at the IR is above a threshold. In a MIMO SWIPT system, the authors of [9] derived closed-form expressions for the energy shortage and data outage probability under the three cases for the CSI knowledge at the transmitter: no CSI, and imperfect CSI in case of time-division duplexing and frequency-division duplexing communications. In a power splitting (PS)-

based multiple-input single-output (MISO) interference channel for SWIPT, the total transmission power was minimized by joint beamforming and PS under both the SINR and EH constraints in the presence of local CSI [10]. The authors of [11] investigated the joint multicast transmit beamforming and receive power splitting problem for MISO SWIPT systems and minimized the transmit power subject to signal-to-noise ratio (SNR) and EH constraints at each receiver, in both scenarios of perfect and imperfect CSI at the transmitter. In [12], two robust joint beamforming and power splitting designs were developed for a downlink MISO SWIPT system to minimize the transmission power under both the SINR and EH constraints per user. In a MIMO SWIPT system, a robust secure transmission scheme was proposed and investigated to maximize the worst-case secrecy rate under transmitting power constraint and EH constraint while considering channel uncertainties [13]. In [14], a robust artificial noise-aided secure transmission design was proposed for MIMO SWIPT systems, while considering the worst-case channel uncertainties model. In a MISO SWIPT system, the harvested energy by the ERs was maximized while maintaining the SINR threshold at the IR [16].

Inspired from the above observations, in this work, a cooperation group including a Source-Destination ($S - D$) pair, and a relay node, R , is considered. Threshold amplify-and-forward (AF) and decode-and-forward (DF) relaying schemes have been considered at R to process and forward the received signals to D . The effect of SWIPT on the outage performance has been studied under both threshold DF/AF relaying schemes, respectively, by setting up the analytical models. The closed-form analytical expressions

have been derived for threshold AF/DF relaying schemes.

However, most of the existed works related to SWIPT systems [3]-[16] are limited to single-hop scenarios and the effect on SWIPT technology on the performance of cooperative systems has not been investigated yet.

The rest of the paper is structured as follows. In Section 2, the system model is introduced. The outage performance is studied for threshold AF and DF schemes, respectively, as well as deriving the closed-form analytical expressions for the outage probability of the considered system, in Section 3. The proposed analytical models are evaluated by Monte-Carlo simulations in Section 4. Finally, the paper is concluded in Section 5.

2. System model

In this section, the simplest cooperation group including a Source-Destination ($S - D$) pair, and a relay node, R , is considered. All links experience independent and identically Rayleigh fading. It is assumed that each terminal has a single antenna and operates in a half-duplex mode.

R adopts power splitting method to coordinate the processes of informa-

Figure 1: Diagram of cooperative SWIPT system model

tion decoding and energy harvesting from the received signal [17]. Specifi-

cally, the received signal at R is split to the information decoder (ID) and the energy harvester (EH) by a power splitter, which divides an (ρ) portion of the signal power to the ID, and the remaining portion $(0 \leq \rho \leq 1)$ of power to the EH.

The information transmission process can be divided into two phases: 1) S broadcasts the information to R and D ; 2) R adopts its instantaneous SNR of the received signal at its IR as an indication of the reliability of the relay detection. If the SNR is larger than a predefined threshold, the probability of an error at the relay is small under DF scheme or the quality of the received signal is good enough under AF scheme. Hence R forwards the signal after recoding under DF scheme or amplifying under AF. Otherwise, R remains silent.

In Phase 1, the downlink received signals at the IR of R and D are given by

$$y_R = \sqrt{\rho} \left(\sqrt{P_S} h_{SR} s + n_R \right) + z_R \quad (1-a)$$

$$y_{D1} = \sqrt{P_S} h_{SD} s + n_D, \quad (1-b)$$

respectively, where P_i ($i \in \{S, R\}$) is the transmitting power at node i , s denotes the transmitted symbols from BS, h_{ij} ($i, j \in \{S, D, R\}$) is the link channel gain between node i and j , n_i ($i \in \{D, R\}$) denotes the independent complex Gaussian noise at the IR of R and D . In this work, to simplify the analysis, we assume that and are with zero means and a same variances, N_0 . z_R is the signal processing noise by the ID at R , which can also be modeled as additional white Gaussian noise with zero means and variances σ^2 .

Therefore, the SNR of the received signal at IR of R and D can be written

as

$$\gamma_R = \frac{\rho P_S |h_{SR}|^2}{\rho N_0 + \sigma^2} \quad (2-a)$$

$$\gamma_{D1} = \frac{P_S |h_{SD}|^2}{N_0}. \quad (2-b)$$

The probability density function (PDF) of $|h_{SR}|^2$ and $|h_{SD}|^2$ can be given as

$$f_{|h_{SR}|^2}(x) = \frac{1}{h_1} \exp\left(-\frac{x}{h_1}\right) \quad (3-a)$$

$$f_{|h_{SD}|^2}(x) = \frac{1}{h_2} \exp\left(-\frac{x}{h_2}\right), \quad (3-b)$$

respectively, where h_1 and h_2 are the expectation of channel power gain $|h_{SR}|^2$ and $|h_{SD}|^2$, respectively.

Further, we can obtain $\gamma_R \sim \text{Exp}(\lambda_{SR})$ and $\gamma_{D1} \sim \text{Exp}(\lambda_{SD})$, where $\lambda_{SR} = \frac{\rho N_0 + \sigma^2}{h_1 \rho P_S}$ and $\lambda_{SD} = \frac{N_0}{h_2 P_S}$.

3. Outage analysis

3.1. DF scheme

In the second phase, if R decides to forward the detected symbol, s_R , to D after regenerating, the received signal at D is

$$y_{D2} = \sqrt{P_R} h_{RD} s_R + n_D. \quad (4)$$

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

$$\gamma_{D2} = \frac{P_R |h_{RD}|^2}{N_0}. \quad (5)$$

The PDF of $|h_{RD}|^2$ can be written as $f_{|h_{RD}|^2}(x) = \frac{1}{h_3} \exp\left(-\frac{x}{h_3}\right)$, where h_3 is the expectation of channel power gain $|h_{RD}|^2$. Then, we can also obtain

$\gamma_{D2} \sim \text{Exp}(\lambda_{RD})$, where $\lambda_{RD} = \frac{N_0}{h_3 P_R}$.

In this work, we assume that D adopts SC scheme to combine y_{D1} and y_{D2} as the final received signal. Then, we have $\gamma_D = \begin{cases} \gamma_{D1} & \text{if } \gamma_{SR} \leq \gamma_{\text{th}} \\ \max\{\gamma_{D1}, \gamma_{D2}\} & \text{else} \end{cases}$.

The outage probability for the considered system using threshold can be expressed as

$$\begin{aligned} \text{Pr}_{\text{out}}(\gamma_{\text{th}}) &= \text{Pr}\{\gamma_{SR} > \gamma_{\text{th}}\} \text{Pr}\{\gamma_D \leq \gamma_{\text{th}} | \gamma_{SR} > \gamma_{\text{th}}\} \\ &\quad + \text{Pr}\{\gamma_{SR} \leq \gamma_{\text{th}}\} \text{Pr}\{\gamma_{D1} \leq \gamma_{\text{th}}\}, \end{aligned} \quad (6)$$

where γ_D denotes the SNR of the output signal at the combiner of D , which can be written as $\gamma_D = \max\{\gamma_{D1}, \gamma_{D2}\}$.

In the following, we derive the terms in (6), respectively.

The probability that the SNR of the $S - R$ link γ_{SR} is below the threshold can be given as

$$\text{Pr}\{\gamma_{SR} \leq \gamma_{\text{th}}\} = \int_0^{\gamma_{\text{th}}} \lambda_{SR} \exp(-\lambda_{SR}x) dx = 1 - \exp(-\lambda_{SR}\gamma_{\text{th}}). \quad (7)$$

Similarly, we can obtain the probability that the SNR of the $S - D$ link is below the threshold as

$$\text{Pr}\{\gamma_{SD} \leq \gamma_{\text{th}}\} = \int_0^{\gamma_{\text{th}}} \lambda_{SD} \exp(-\lambda_{SD}x) dx = 1 - \exp(-\lambda_{SD}\gamma_{\text{th}}). \quad (8)$$

The probability that the SNR of the combined signal at D , γ_D , is below the threshold can be given as

$$\begin{aligned} \text{Pr}\{\gamma_D \leq \gamma_{\text{th}} | \gamma_{SR} > \gamma_{\text{th}}\} &= \text{Pr}\{\gamma_D \leq \gamma_{\text{th}}\} \\ &= \text{Pr}\{\max\{\gamma_{D1}, \gamma_{D2}\} \leq \gamma_{\text{th}}\} \end{aligned}$$

$$= [1 - \exp(-\lambda_{SD}\gamma_{\text{th}})] [1 - \exp(-\lambda_{RD}\gamma_{\text{th}})]. \quad (9)$$

Therefore, SOP can be obtained by substituting (7), (8) and (9) into (6) as

$$\begin{aligned} \Pr_{\text{out}}(\gamma_{\text{th}}) &= \exp(-\lambda_{SR}\gamma_{\text{th}}) \cdot [1 - \exp(-\lambda_{SD}\gamma_{\text{th}})] [1 - \exp(-\lambda_{RD}\gamma_{\text{th}})] \\ &+ [1 - \exp(-\lambda_{SR}\gamma_{\text{th}})] \cdot [1 - \exp(-\lambda_{SD}\gamma_{\text{th}})]. \end{aligned} \quad (10)$$

3.2. AF scheme

In the second phase, if R decides to forward the detected symbol, s_R , to D after amplifying, the received signal at D can be written as

$$\begin{aligned} y_{D2} &= Gh_{RD}y_R + n_D \\ &= Gh_{RD} \left[\sqrt{\rho} \left(\sqrt{P_S}h_{SR}s + n_R \right) + z_R \right] + n_D \\ &= \frac{\sqrt{P_S}}{\sqrt{P_S|h_{SR}|^2 + N_0}} h_{RD} \left[\sqrt{\rho} \left(\sqrt{P_S}h_{SR}s + n_R \right) + z_R \right] + n_D \\ &= \frac{P_S\sqrt{\rho}}{\sqrt{P_S|h_{SR}|^2 + N_0}} h_{RD}h_{SR}s + \frac{\sqrt{P_S}h_{RD}}{\sqrt{P_S|h_{SR}|^2 + N_0}} (\sqrt{\rho}n_R + z_R) + n_D, \end{aligned} \quad (11)$$

where $G = \frac{\sqrt{P_S}}{\sqrt{P_S|h_{SR}|^2 + N_0}}$ is the amplifying factor at R .

As the noise terms n_R , n_D and z_R are independent, y_{D2} can be rewritten as

$$y_{D2} = \frac{P_S\sqrt{\rho}}{\sqrt{P_S|h_{SR}|^2 + N_0}} h_{RD}h_{SR}s + n'_D, \quad (12)$$

where $n'_D = \frac{\sqrt{P_S}h_{RD}}{\sqrt{P_S|h_{SR}|^2 + N_0}} (\sqrt{\rho}n_R + z_R) + n_D$ is the equivalent noise, which is a zero-mean, complex Gaussian random variable with variance

$$N_0' = \frac{P_S|h_{RD}|^2}{P_S|h_{SR}|^2 + N_0} (\rho N_0 + \sigma^2) + N_0. \quad (13)$$

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

$$\begin{aligned}
\gamma_{D2} &= \frac{P_S^2 \rho |h_{SR}|^2 |h_{RD}|^2}{N_0' (P_S |h_{SR}|^2 + N_0)} \\
&= \frac{\frac{P_S^2 \rho |h_{SR}|^2 |h_{RD}|^2}{P_S |h_{SR}|^2 + N_0}}{\frac{P_S |h_{RD}|^2}{P_S |h_{SR}|^2 + N_0} (\rho N_0 + \sigma^2) + N_0} \\
&= \frac{\rho \frac{P_S^2}{N_0^2} |h_{SR}|^2 |h_{RD}|^2}{\frac{P_S (\rho N_0 + \sigma^2)}{N_0^2} |h_{RD}|^2 + \frac{P_S}{N_0} |h_{SR}|^2 + 1}. \tag{14}
\end{aligned}$$

At high SNR, the constant 1 in the denominator in (14) can be omitted and the effective SNR of the received signal at D can be approximated as

$$\begin{aligned}
\gamma_{D2} &\approx \frac{\rho \frac{P_S^2}{N_0^2} |h_{SR}|^2 |h_{RD}|^2}{\frac{P_S (\rho N_0 + \sigma^2)}{N_0^2} |h_{RD}|^2 + \frac{P_S}{N_0} |h_{SR}|^2} \\
&= \frac{\rho \frac{P_S}{N_0}}{\frac{(\rho N_0 + \sigma^2)}{N_0} \frac{1}{|h_{SR}|^2} + \frac{1}{|h_{RD}|^2}} \\
&= \frac{1}{\frac{a}{b} \frac{1}{|h_{SR}|^2} + \frac{1}{b} \frac{1}{|h_{RD}|^2}}, \tag{15}
\end{aligned}$$

where $a = \frac{(\rho N_0 + \sigma^2)}{N_0}$ and $b = \rho \frac{P_S}{N_0}$.

As $|h_{SR}|^2$ and $|h_{SD}|^2$ are exponentially distributed with parameters h_1^{-1} and h_3^{-1} , respectively, we can obtain the PDF of $\frac{a}{b} \frac{1}{|h_{SR}|^2}$ and $\frac{1}{b} \frac{1}{|h_{RD}|^2}$ as

$$f_1(x) = \frac{a}{b h_1 x^2} \exp\left(-\frac{a}{b h_1 x}\right) \tag{16-a}$$

$$f_2(x) = \frac{1}{b h_3 x^2} \exp\left(-\frac{1}{b h_3 x}\right), \tag{16-b}$$

respectively.

Using Eq. (3.471.9) in [18] and the symmetry property of the modified

Bessel function (as shown by Eq. (8.486.16) in [18]), the moment generating function (MGF) of $Y_1 = \frac{a}{b|h_{SR}|^2}$ and $Y_2 = \frac{1}{b|h_{RD}|^2}$ can be given as

$$M_{Y_1}(s) = 2\sqrt{\frac{as}{bh_1}} K_1\left(2\sqrt{\frac{as}{bh_1}}\right) \quad (17-a)$$

$$M_{Y_2}(s) = 2\sqrt{\frac{s}{bh_3}} K_1\left(2\sqrt{\frac{s}{bh_3}}\right), \quad (17-b)$$

where $K_1(\cdot)$ is the first order modified Bessel function of the second kind defined in [19].

Then, the MGF of $Y = Y_1 + Y_2 = \frac{a}{b|h_{SR}|^2} + \frac{1}{b|h_{RD}|^2}$ can be given as

$$M_Y(s) = M_{Y_1}(s) M_{Y_2}(s) = 4s\sqrt{\frac{a}{b^2h_1h_3}} K_1\left(2\sqrt{\frac{as}{bh_1}}\right) K_1\left(2\sqrt{\frac{s}{bh_3}}\right). \quad (18)$$

The CDF of γ_{D2} , $P_{\gamma_{D2}}(z)$ can be given as

$$\begin{aligned} P_{\gamma_{D2}}(x) &= \Pr\{\gamma_{D2} < x\} \\ &= \Pr\left\{\frac{1}{\gamma_{D2}} > \frac{1}{x}\right\} \\ &= \Pr\left\{Y > \frac{1}{x}\right\} \\ &= 1 - \Pr\left\{Y < \frac{1}{x}\right\} \\ &= 1 - P_Y\left(\frac{1}{x}\right), \end{aligned} \quad (19)$$

where $P_Y(\cdot)$ is the CDF of Y .

Using the differentiation property of Laplace transform, $P_Y(\cdot)$ can be obtained as

$$P_Y(y) = \mathcal{L}^{-1}\left(\frac{M_Y(s)}{s}\right), \quad (20)$$

where $\mathcal{L}^{-1}(\cdot)$ denotes the inverse Laplace transform.

Substituting (18) in (19) and (20) and using Eq. (3.16.13.4) in [20], we have

$$\begin{aligned} P_{\gamma_{D2}}(x) &\approx 1 - \mathcal{L}^{-1} \left(4 \sqrt{\frac{a}{b^2 h_1 h_3}} K_1 \left(2 \sqrt{\frac{as}{bh_1}} \right) K_1 \left(2 \sqrt{\frac{s}{bh_3}} \right) \right) \Big|_{y=\frac{1}{x}} \\ &= 1 - 2 \sqrt{\frac{a}{b^2 h_1 h_3}} \cdot x \exp \left(- \left(\frac{a}{h_1} + \frac{1}{h_3} \right) \frac{x}{b} \right) K_1 \left(2 \sqrt{\frac{a}{h_1 h_3}} \cdot \frac{x}{b} \right). \end{aligned} \quad (21)$$

Therefore, under AF scheme the probability that the SNR of the combined signal at D , γ_D , is below the threshold can be given as

$$\begin{aligned} \Pr \{ \gamma_D \leq \gamma_{\text{th}} | \gamma_r > \gamma_{\text{th}} \} &= \Pr \{ \gamma_D \leq \gamma_{\text{th}} \} \\ &= \Pr \{ \max \{ \gamma_{D1}, \gamma_{D2} \} \leq \gamma_{\text{th}} \} \\ &= \Pr \{ \gamma_{D1} \leq \gamma_{\text{th}} \} \Pr \{ \gamma_{D2} \leq \gamma_{\text{th}} \} \\ &\approx [1 - \exp(-\lambda_{SD} \gamma_{\text{th}})] \\ &\cdot \left[1 - 2 \sqrt{\frac{a}{b^2 h_1 h_3}} \cdot \gamma_{\text{th}} \exp \left(- \left(\frac{a}{h_1} + \frac{1}{h_3} \right) \frac{\gamma_{\text{th}}}{b} \right) K_1 \left(2 \sqrt{\frac{a}{h_1 h_3}} \cdot \frac{\gamma_{\text{th}}}{b} \right) \right]. \end{aligned} \quad (22)$$

Thus, SOP can be obtained by substituting (7), (8) and (22) into (6) as

$$\begin{aligned} \Pr_{\text{out}}(\gamma_{\text{th}}) &= \exp(-\lambda_{SR} \gamma_{\text{th}}) \cdot [1 - \exp(-\lambda_{SD} \gamma_{\text{th}})] \\ &\cdot \left[1 - 2 \sqrt{\frac{a}{b^2 h_1 h_3}} \cdot \gamma_{\text{th}} \exp \left(- \left(\frac{a}{h_1} + \frac{1}{h_3} \right) \frac{\gamma_{\text{th}}}{b} \right) K_1 \left(2 \sqrt{\frac{a}{h_1 h_3}} \cdot \frac{\gamma_{\text{th}}}{b} \right) \right] \\ &+ [1 - \exp(-\lambda_{SR} \gamma_{\text{th}})] \cdot [1 - \exp(-\lambda_{SD} \gamma_{\text{th}})]. \end{aligned} \quad (23)$$

4. Numerical and simulation results

To confirm our proposed model, in this section, we compare simulation and analysis results for SOP under both AF and DF schemes. Unless otherwise explicitly specified, the main parameters adopted in this work are set as $P_s = P_R = 1$, $N_0 = 0.01$, $\gamma_{\text{th}} = 0$ dB, $\rho = 0.5$, $h_1 = h_2 = h_3 = 1$.

In Fig. 2, SOP curves for $h_2 = h_3 = 1$, and $\rho = 0.1, 0.3, 0.5, 0.7$ and 0.9 under AF and DF schemes are presented. Clearly, the SOP for a lower ρ outperforms the one for a higher ρ . This is because that a lower ρ means a lower portion of the received signal power is split to the ID at the relay, resulting in a higher received SNR at the relay, which leads to a higher capacity. Moreover, SOP gets worse when h_3/h_1 increases because increasing h_3/h_1 means $S - R$ link gets worse, resulting in an increasing outage probability over $S - R$ link.

In Fig. 3, SOP curves for $h_1 = h_3 = 1$, and $\gamma_{\text{th}} = 0, 1, 2$ and 3 under AF and DF schemes are depicted. It is obvious that the SOP for a lower γ_{th} outperforms the one for a higher γ_{th} . Because that a lower γ_{th} means a lower probability that the SNR at each receiver falls below the threshold. Further, SOP gets worse when h_1/h_2 increases because increasing h_1/h_2 means $S - D$ link gets worse, resulting in a lower diversity gain at D .

In Fig. 4, SOP curves for $h_1 = h_2$, and $h_1 = 1, 2, 3$ and 4 under AF and DF schemes are depicted. One can see that the SOP for a lower h_1 outperforms the one for a higher h_1 . Because that a lower h_1 means a lower probability that the SNR at each receiver falls below the threshold. It can also be observed that SOP gets worse when h_1/h_3 increases because

(a) AF

(b) DF

Figure 2: SOP for various ρ

(a) AF

(b) DF

Figure 3: SOP for various γ_{th}

(a) AF

(b) DF

Figure 4: SOP for various h_1

increasing h_1/h_3 means $R - D$ link gets worse, resulting in an increasing outage probability over $R - D$ link.

As shown in Figs. 2-4, it is clear that SOP under DF outperforms the one under AF. It is because of the decoding gain at R .

5. Conclusions

In this paper, the outage performance of a dual-hop cooperative simultaneous wireless information and power transfer (SWIPT) system was investigated under threshold AF and DF schemes. The closed-form analytical expressions for outage probability under threshold AF and DF schemes have been derived and verified through Monte-Carlo simulations.

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