Outage Analysis of a Dual Relay SWIPT System in Hybrid Forwarding Schemes

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***Abstract*—The outage probability of a dual relay simultaneous wireless information and power transfer (SWIPT) system is investigated in the presence of Rayleigh fading. The message forwarding at the relays is categorized in three schemes. In the first two cases, both the relays are considered to be decode-and-forward (DF) and amplify-and-forward (AF), respectively, whereas in the third case, one of the relays is considered DF and the other as AF. The relaying model considers the source-relay-destination links whereas the direct link between source-destination does not exist. The power splitters at the relaying devices provide energy to the relays by splitting the received signal power into energy harvesting and information transfer parts. The outage probability is investigated using Monte-Carlo simulations and the results for all the three cases are compared. The all-AF forwarding scheme provides the least outage probability among all the three cases. The minimum outage probability is obtained for different values of PS factors for the said case at different transmit powers.**

***Index Terms*—SWIPT, decode-and-forward, amplify-and-forward, relaying, Rayleigh fading, power splitting, energy harvesting, outage probability.**

I. Introduction

Energy harvesting has recently gained importance in communication networks to enhance the lifetime of devices. The phenomena is more pronounced in the Internet-of-Things (IoT) regieme, where devices require connectivity at all times. Different energy harvesting techniques have been proposed in the literature [1]-[6], however, the simultaneous wireless information and power transfer (SWIPT) is one of the most widely used techniques among them. In this technique, a part of the signal power transmitted by the source node is harvested by the relay node, while the remaining power is used for decoding and relaying the source signal in the next time slot. The concept was first proposed by Varshney et al. in [1], which provided a motivation for further research.

A SWIPT receiver with different types of dynamic power splitting (DPS) techniques is presented in [4]. In [5], some of the basic techniques for SWIPT are discussed, keeping in view the practical realizations of the receiver circuit. All these techniques revolve around the basic idea of splitting the signal energy into two parts; for signal decoding and for energy harvesting (EH). The outage probability for a three node model with no direct link between source and destination is investigated in [6], with the relay implementing the two basic SWIPT techniques, i.e., time switching (TS) and power splitting (PS). In [7], the same model is considered and the outage analysis is performed with the relay implementing both the decode-and-forward (DF) and PS technique.

The work in [8] is a further extension of [7], with the relay implementing the amplify-and-forward (AF) protocol. The source-destination direct link is also considered with all the links subject to Rayleigh fading. The outage probability is derived analytically with the relay node implementing PS technique. A SWIPT-based device-to-device cooperative network and a multi-hop cooperative network are studied in [9] and [10], respectively. In [10], the relay harvests the energy from the signal received by the co-channel interferers. Interference-based energy harvesting is also discussed in [11], where the relay node uses DF protocol. The outage probability for a DF SWIPT relaying system in the presence of source-destination direct link with Nakagami fading is studied in [12].

In vehicular networks, SWIPT has been considered as a promising scheme to maximize the battery time of sensors located on the vehicles. The PS for SWIPT over vehicular channels for maximizing the throughput is presented in [13]. In [14], a stochastic model is proposed for the analysis of transmission capacity and energy harvested per unit area. In the aforementioned work, the analytical results are derived for obtaining maximum energy harvested per unit area for different node densities.

In this paper, by extending the approaches in [7] and [8], a two relay SWIPT model is considered. The outage probability at the destination node for three different cases has been investigated. In the first two cases, both the relays use DF protocol and AF protocol, respectively. In the third case, one of the relays uses DF protocol and the other relay uses AF protocol. In either of the three cases, the relays implement PS technique for energy harvesting. Because of the presence of two links, a diversity gain is observed at the destination [15]. The outage analysis is performed at the destination node for all the cases in the presence of Rayleigh fading. The results are discussed with respect to different parameters, such as the power splitting factor, rate threshold, and signal-to-noise ratio (SNR).

The rest of this paper is organized as follows. Section II details the system model. Outage probability is analyzed in Section III, followed by the results in Section IV. Finally, the conclusions are presented in Section V.

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II. System Model

The system model consists of four nodes, i.e., the source (S), the destination (D), and two intermediate relay nodes, R_1 and R_2, as shown in Fig. 1. The source communicates with the destination node through these two intermediate relay nodes. The relays operate with the energy, which is harvested from the signal transmitted by the source node. In this work, all the links are assumed to operate under independent and identically distributed (i.i.d) Rayleigh fading.

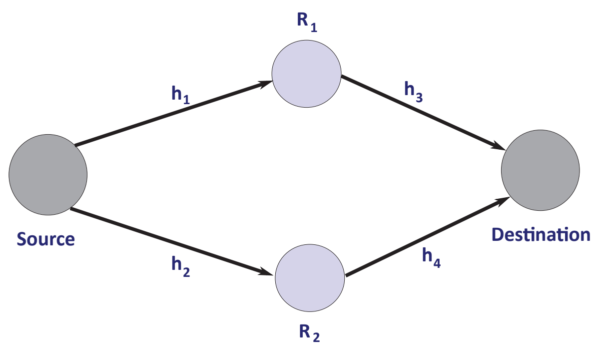

Fig. 1. The system model.

Communication occurs in two time slots due to the half-duplex characteristic of the relay nodes. The signal received during the first time slot at both the relay nodes is given as

$$y_{R_1} = \sqrt{P_t} x h_1 + n_1, \tag{1}$$

and

$$y_{R_2} = \sqrt{P_t} x h_2 + n_2. \tag{2}$$

In (1) and (2), y_{R_1} and y_{R_2} are the signals received at the relay node R_1 and the relay node R_2, respectively, where x is the transmitted symbol with unit energy, $n_1 \sim CN(0, \sigma_1^2)$ and $n_2 \sim CN(0, \sigma_2^2)$ are the white noise random variables, which are complex Gaussian with zero mean and variances σ_1^2 and σ_2^2, respectively. The envelopes of h_1 and h_2 are Rayleigh distributed, i.e., $|h_i| \sim Rayleigh(\lambda_i^2)$ where $i = \{1, 2\}$, whereas their squared envelopes follow exponential distribution.

Since the relays use the power splitting (PS) technique, hence they split the received signal into two parts, i.e.,

$$y_{R_1}^{(E)} = \sqrt{\rho_1} y_{R_1}, \tag{3}$$

$$y_{R_2}^{(E)} = \sqrt{\rho_2} y_{R_2}, \tag{4}$$

and

$$y_{R_1}^{(I)} = \sqrt{1-\rho_1} y_{R_1}, \tag{5}$$

$$y_{R_2}^{(I)} = \sqrt{1-\rho_2} y_{R_2}, \tag{6}$$

where the L_2-norms of $y_{R_1}^{(E)}$ and $y_{R_2}^{(E)}$ are the energy levels that R_1 and R_2 harvest, respectively, whereas $y_{R_1}^{(I)}$ and $y_{R_2}^{(I)}$ are the message parts to be transmitted by the relay nodes to the destination with ρ_1 and ρ_2 as the PS factors of the two relay nodes.

III. Analysis of Outage Probability

The above model is studied using three different cases depending upon the type of protocol that each relay node uses and the outage probability is investigated for each case. The cases are described as follows:

A. Case I

In this case, both the relay nodes R_1 and R_2 shown in Fig. 1 use DF protocol. The relay nodes decode the source message in the first time slot, whereas in the second time slot, both the relays transmit the decoded signal to the destination with power P_{R_1} and P_{R_2}, respectively. The signal received at the destination through R_1 is given by

$$y_D^{(1)} = \sqrt{P_{R_1}} h_3 \hat{x} + n_3, \tag{7}$$

while the received signal through R_2 is given by

$$y_D^{(2)} = \sqrt{P_{R_2}} h_4 \hat{x} + n_3. \tag{8}$$

where $|h_i| \sim Rayleigh(\lambda_i^2)$ with $i = \{3, 4\}$, $P_{R_1} = \eta_1 \rho_1 P_t |h_1|^2$ and $P_{R_2} = \eta_2 \rho_2 P_t |h_2|^2$ denote the transmit powers of R_1 and R_2, respectively, $n_3 \sim CN(0, \sigma_3^2)$ is the additive white Gaussian noise, and η is the energy conversion efficiency of PS. The destination node uses maximum ratio combining (MRC) to combine both copies of the received data signal. Note that MRC is performed only if both relays decode the data. If one of the relays decodes the data, then the destination will not achieve any diversity gain. The relay nodes use the signal represented in (5) and (6) to decode the information part.

The outage probability at the destination node is given by

$$P_{out_1} = \mathbb{P}_r[\gamma < \tau], \tag{9}$$

where τ is the minimum SNR threshold and

$$\gamma = \gamma_1 + \gamma_2, \tag{10}$$

where γ_1 and γ_2 denote the signal-to-noise ratios (SNRs) of R_1-D and the R_2-D links, respectively, given by

$$\gamma_1 = \frac{\eta_1 \rho_1 P_t |h_1|^2 |h_3|^2}{\sigma_3^2}, \tag{11}$$

$$\gamma_2 = \frac{\eta_2 \rho_2 P_t |h_2|^2 |h_4|^2}{\sigma_3^2}. \tag{12}$$

B. Case II

In this case, both R_1 and R_2 use AF protocol. Both the relays transmit the amplified signal to the destination with power P_{R_1} and P_{R_2} calculated in Case I. The signal received at the destination through R_1 is given by

$$y_D^{(1)} = \sqrt{P_{R_1}} h_3 k_1 y_{R_1}^{(I)} + n_3, \tag{13}$$

and through R_2 is given by

$$y_D^{(2)} = \sqrt{P_{R_2}} h_4 k_2 y_{R_2}^{(I)} + n_3, \tag{14}$$

where k_1 and k_2 are the power normalizing factors with $k_i = \sqrt{\frac{P_{R_i}}{(1-\rho_i)P_t|h_i|^2+\sigma_{c_i}^2}}$, $i = \{1,2\}$, for R_1 and R_2, respectively.

Simplifying Eq. (13) and Eq. (14), we get

$$y_D{}^{(1)} = \sqrt{P_t}\phi_1 h_1 h_3 k_1 x + \sqrt{P_{R_1}} h_3 k_1 n_{c_1} + n_3, \quad (15)$$

and

$$y_D{}^{(2)} = \sqrt{P_t}\phi_2 h_2 h_4 k_2 x + \sqrt{P_{R_2}} h_4 k_2 n_{c_2} + n_3, \quad (16)$$

with $\phi_1 \triangleq \sqrt{P_{R_1}(1-\rho_1)}$, $\phi_2 \triangleq \sqrt{P_{R_2}(1-\rho_2)}$, $n_{c_1} \sim CN(0,\sigma_{c_1}^2)$ and $n_{c_2} \sim CN(0,\sigma_{c_2}^2)$ are noises produced due to conversion of RF energy at the relay nodes, respectively. The receiver noises can be ignored due to the fact that $\sigma_{c_1}^2 >> \sigma_1^2$ and $\sigma_{c_2}^2 >> \sigma_2^2$, respectively [8]. The destination node uses MRC to combine both copies of the received data signal.

The outage probability at the destination node is given by

$$P_{out_2} = \mathbb{P}_r[\gamma < \tau], \quad (17)$$

with

$$\gamma = \gamma_3 + \gamma_4, \quad (18)$$

where γ_3 and γ_4 denote the SNRs of R_1-D and the R_2-D link, respectively, given by

$$\gamma_3 = \frac{(1-\rho_1)P_t P_{R_1}|h_1|^2|h_3|^2 {k_1}^2}{P_{R_1}|h_3|^2 {k_1}^2\sigma_{c_1}^2 + \sigma_3^2}, \quad (19)$$

$$\gamma_4 = \frac{(1-\rho_2)P_t P_{R_2}|h_2|^2|h_4|^2 {k_2}^2}{P_{R_2}|h_4|^2 {k_2}^2\sigma_{c_2}^2 + \sigma_3^2}. \quad (20)$$

C. Case III

In this case, R_1 uses AF protocol while R_2 uses DF protocol. The relay R_1's transmission received at the destination during the second time slot is the same as shown in Eq. (15). The DF-relay R_2 if successfully decodes the source signal, transmits the message to the destination. The signal received through R_2 is the same as shown in Eq. (8). The destination node uses MRC only if both links exist to combine both copies of the received data signal. The outage probability at the destination node is given by

$$P_{out_3} = \mathbb{P}_r[\gamma < \tau], \quad (21)$$

where

$$\gamma = \gamma_3 + \gamma_2. \quad (22)$$

IV. Simulation Results and Discussion

The Monte-Carlo simulations are performed and presented in this section to investigate the outage probability of all the three mentioned cases. During the simulations, the parameters with fixed values are $\tau = 5$, $\eta_1 = \eta_2 = 0.75$.

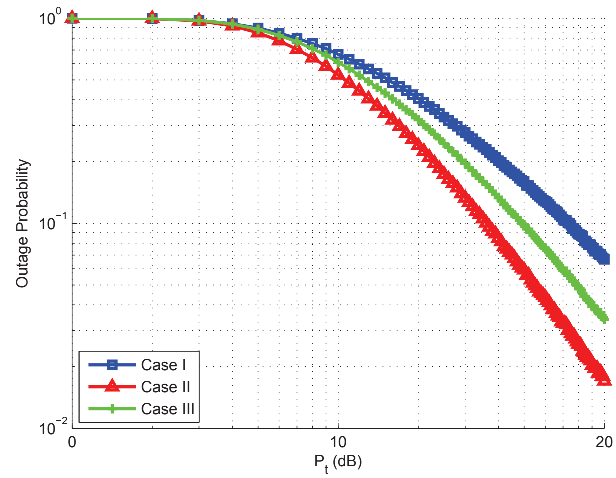

Fig. 2. The outage probability as a function of P_t with $\rho_1 = \rho_2 = 0.5$.

In Fig. 2, the outage probability is plotted as a function of $P_t(dB)$ with $\lambda_i = 1$, $\forall_i = \{1,2,3,4\}$ and all the noise variances are also taken as unity. The curves indicate that in a two relay SWIPT system, the outage probability is least for Case II where both relays implement the AF scheme. This is because AF relays the data to the destination regardless of quality and as a consequence of MRC at the destination, the performance improves. The performance of Case I is worst because the destination receives the copies of message signal only if the relays can decode the message, which may not be the case always.

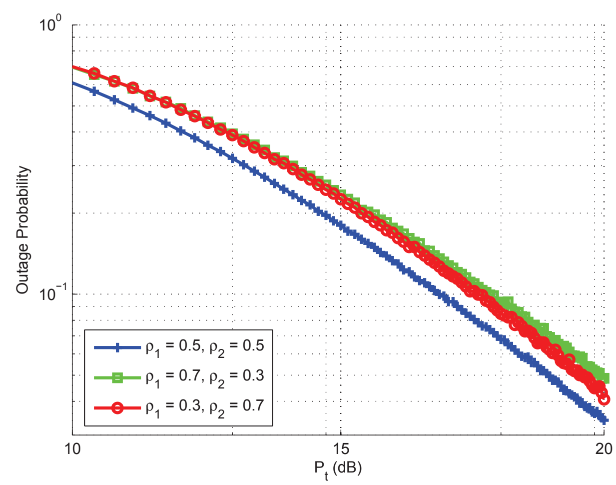

Fig. 3. The outage probability as a function of P_t for Case III.

The results in Fig. 3 are investigated for Case III of hybrid relaying for different values of PS factors. It can be seen from the results that the outage probability is lowest in the scenario when the PS factor for the AF node is equal to the PS factor of the DF node, i.e., ρ_1 should be equal to ρ_2 to achieve minimum outage probability.

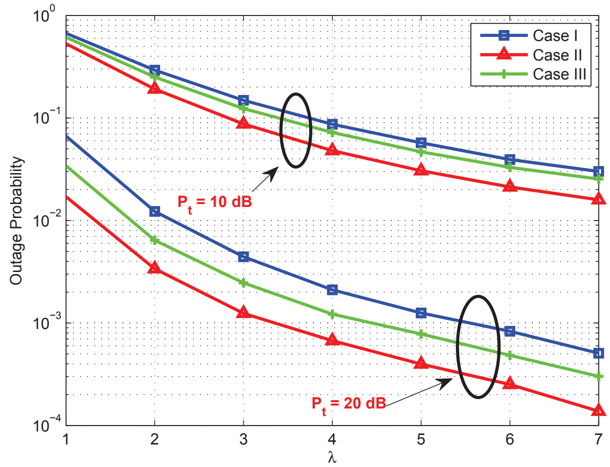

Fig. 4. The outage probability as a function of Rayleigh parameter λ.

In Fig. 4, the outage probability is investigated as a function of Rayleigh parameter with $\lambda = \lambda_i$ for $i = \{1, 2, 3, 4\}$. The curves are obtained for both the low as well as the high transmit powers of the source at $\rho_1 = \rho_2 = 0.5$. It can be seen that the outage probability for Case II is minimum irrespective of the transmit power levels.

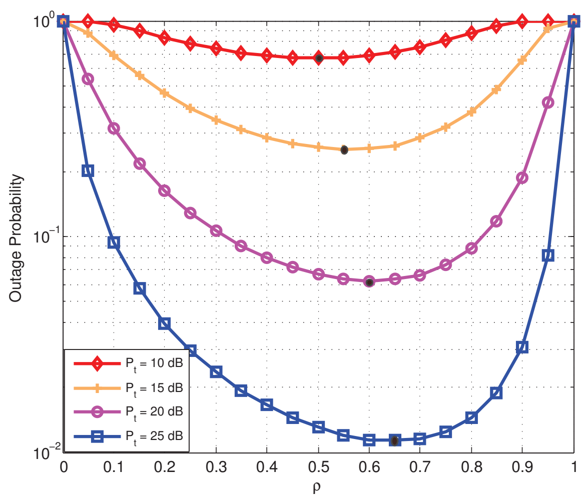

Fig. 5. The outage probability as a function of power splitting factor, ρ. (Case II)

The outage probability for Case II is analyzed against different values of PS factor by assuming $\rho_1 = \rho_2 = \rho$ at different levels of transmit power in Fig. 5. The results show that for different values of P_t, the least outage probability is obtained at a different value of ρ. For $P_t = 10dB$, the minimum outage probability is obtained at $\rho = 0.5$, while for $P_t = 25dB$, the value of ρ is about 0.65. The reason is that when a signal is transmitted with high source transmit power, a low portion of energy is sufficient for signal decoding, (i.e., high ρ) and in this case a very high amount of energy can be harvested which is then used to provide higher power to the relay-destination link. On the other hand, when the signal is transmitted with low power, e.g., $P_t = 10dB$, a major part of it is consumed at the relay for decoding and a small amount of energy is harvested, which when used with relay-destination link weakens the received power at the destination.

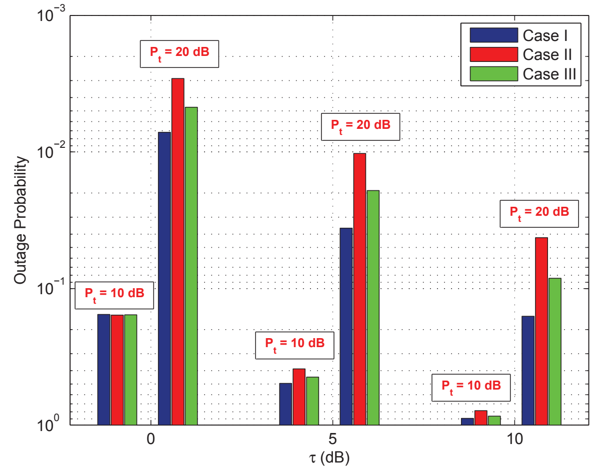

Fig. 6. The outage probability as a function of minimum SNR threshold, τ with $\rho_1 = \rho_2 = 0.5$.

In Fig. 6, the outage probability is plotted versus SNR threshold τ at $P_t = 10dB$ as well as at $P_t = 20dB$. It can be seen that the outage probability for the Case II is minimum for different threshold levels at different transmit powers. It can be seen clearly that at $P_t = 20dB$, the fixed outage probability of 10^{-2} can be achieved only by Case II at the value of $\tau = 0dB$ as well as at $\tau = 5dB$.

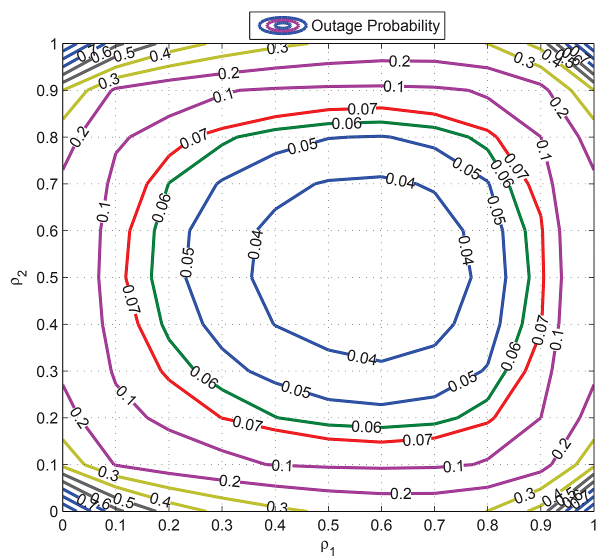

Fig. 7. The contour plot of the outage probability against ρ_1 and ρ_2 for the hybrid forwarding scheme.

In Fig. 7, the contour plot of outage probability is plotted against different values of ρ_1 and ρ_2 at $P_t = 20dB$ for Case III. The figure shows that the same outage probability can be achieved at the different combinations of ρ_1 and ρ_2. It can be seen that for a fixed value of outage probability, the best combinations of ρ_1 and ρ_2 can be chosen to ensure maximum energy harvesting. Furthermore, from a design perspective, the minimum outage probability of the system can be achieved for the values of $0.4 \leq (\rho_1, \rho_2) \leq 0.7$.

V. Conclusion

In this paper, the outage probability of a two relay SWIPT system is analyzed in the presence of Rayleigh fading for three different cases. The results were discussed with respect to different parameters such as the PS factor, P_t, Rayleigh parameter, λ etc., which showed that most often the all-AF mode provides minimum outage probability in SWIPT systems. In the hybrid relay Case, the performance of the system lies in between the other two cases showing the importance of using both the DF and AF protocols at the same time irrespective of the transmit power. The results were also obtained for the optimum value of PS factor at different levels of transmit power for Case II. Moreover, the amount of harvested energy in Case III is better than that in Case II. The future work includes the finding of closed-form solution of outage probability for all the three cases as well as the way of optimizing it through relay selection.

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