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Outage probability analysis for hybrid TSR-PSR based SWIPT systems over log-normal fading channels

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ABSTRACT

Employing simultaneous information and power transfer (SWIPT) technology in cooperative relaying networks has drawn considerable attention from the research community. We can find several studies that focus on Rayleigh and Nakagami-m fading channels, which are used to model outdoor scenarios. Differing itself from several existing studies, this study is conducted in the context of indoor scenario modelled by log-normal fading channels. Specifically, we investigate a so-called hybrid time switching relaying (TSR)-power splitting relaying (PSR) protocol in an energy-constrained cooperative amplify-and-forward (AF) relaying network. We evaluate the system performance with outage probability (OP) by analytically expressing and simulating it with Monte Carlo method. The impact of power-splitting (PS), time-switching (TS) and signal-to-noise ratio (SNR) on the OP was as well investigated. Subsequently, the system performance of TSR, PSR and hybrid TSR-PSR schemes were compared. The simulation results are relatively accurate because they align well with the theory.

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1. INTRODUCTION

For conventional energy-constrained wireless networks, it is occasionally hard or even impossible to recharge or replace batteries [1], [2]. Instead, we can exploit the natural resources (wind energy, solar energy) by EH modules to keep the networks energized, although with some limitations because of their fluctuating properties [3], [4]. Thereby, the research community has developed the simultaneous information and power transfer (SWIPT) technology to alter the renewable energy with radio frequency (RF), [5]-[8].

Rayleigh fading channels have been utilized for studies about the adaptive relaying protocol of two-hop amplify-and-forward (AF) relaying networks with exceptional throughput performance [9], [10]. Besides, in [11] where the outage probability (OP) of decode-and-forward (DF) PSR system was analyzed, we can see that EH relaying network is more beneficial than conventional networks. Additionally, it is essential to deploy hybrid concepts to study and effectively improve system performance. For example, from the aspect of controlling cooperative multi-agent direct networks, a hybrid system is a mix of discrete-time and continuous-time systems [12]. For cooperative relaying networks, the hybrid concept is employed for either the combination of different relay selection schemes or different relaying protocols. Using hybrid full-duplex (FD) and half-duplex (HD) relay selection scheme, authors in [13], [14] discovered the upper and lower bounds for OP of DF systems. Additionally, we can find a so-called hybridized power-time splitting-based relaying (HPTSR) protocol in [15]-[17] where the OP and maximum throughput were studied. Moreover, in [18], [19], the OP and outage capacity of a so-called joint time allocation and power splitting (JTAPS) scheme over the Rayleigh fading channels were studied concerning the statistical and instantaneous channel state information (CSI). Additionally, in [20], [21], the system performance in terms of the average channel capacity was investigated. We can find some other studies such as [22]-[25], that used the instantaneous CSI to determine the PS factor for a namely dynamic power splitting scheme (DPSS). The OP and throughput for multi-user cooperative relaying networks over Nakagami fading channels were studied in [26], [27]. Last but not least, [28]-[30] investigated the performance of time switching relaying (TSR) and power splitting relaying (PSR) protocols for dual-hop relaying networks in the indoor scenario modelled by log-normal fading channels.

It is noted that several existing studies were conducted mainly over outdoor scenarios which are modelled by Rayleigh and Nakagami-m fading methods. Indeed, there is scarcely recent studies regarding the SWIPT systems for indoor scenarios modelled by log-normal fading channels. Among them, there are papers [28], [29] where the HD AF and DF SWIPT networks were analyzed. Moreover, log-normal fading fits better for modelling shadowing effect from indoor moving objects and human bodies, as mentioned in [31]-[33]. Besides, as in [34], log-normal fading can be employed to model the small-scale fading of indoor ultra-wideband (UWB) communications, and in [35]-[37] to model the short and long-term fading of slowly-varying indoor channels. To overcome all of these constraints, it is essential to deploy cooperative relays for indoor networks, especially for internet of things (IoT) applications [38].

Thereby, in this paper, we study the performance of a hybrid TSR-PSR scheme over log-normal fading channels in a cooperative AF relaying network. We evaluate the system performance in terms of its outage behaviour. It is proven that the proposed hybrid protocol can deliver significantly lower OP than the two separate protocols. Furthermore, we describe the system model in section 2. In section 3, we analyze the performance of the hybrid PSR-TSR AF system over log-normal fading channels. We report the simulation results and discuss them in section 4. The conclusion is in section 5.

2. SYSTEM MODEL

Illustrated in Figure 1(a) (see in appendix) is the system model of a dual-hop network including a base station (BS), a relay (R) and a destination (D). Assumed without direct link, the BS-to-D communication can only be realized via R, with BS's transmission power of P_B. A part of the RF signal that BS sends is harvested by R for relaying task. We denote the BS-to-R, R-to-D distances, respectively, with I_1 and I_2, and according channel coefficients of h_1 and h_2. Additionally, we have two random variables (RVs) $|h_1|^2$and $|h_2|^2$which are independently and identically distributed (i.i.d.) over the block time following the log-normal distribution, respectively, with parameters $LN(\mu_{h1},\sigma_{h1}^2)$ and $LN(\mu_{h2},\sigma_{h2}^2)$. Moreover, we have the mean value of $10\log(|h_i|^2)$ denoted as μ_{hi}, and the standard deviation of $10\log(|\sigma_{hi}|^2)$, $i\in\{1,2\}$, denoted as σ_{hi}^2. BS-to-R and R-to-D have complex Gaussian background noise, n_R and n_D, the former has zero mean and the latter has variance N_0. Last but not least, we have m which is the path-loss exponent.

Considering a hybrid PSR-TSR in Figure 1(b) (see in appendix), we have a two-time-slot block time, T, which is split by TS factor, α_2, to $\alpha_2 T$ and $(1-\alpha_2)T$ given that $\alpha_2\in[0,1]$. In $\alpha_2 T$, R receives signal from BS. We divide this 1st time slot into two segments which are $\sqrt{\alpha_1}$and $\sqrt{1-\alpha_1}$, with the PS factor, α_1, given that $\alpha_1\in[0,1]$. We use the segment $\sqrt{\alpha_1}$ for RF EH, and the segment $\sqrt{1-\alpha_1}$ for receiving information from BS. Then, within the 2nd time slot $(1-\alpha_2)T$, the harvested energy we have at R is used up to decode and forward the signal via the BS-to-D link. Besides, we assume that the processing power of R is neglected because it is relatively small in comparison with the transmission power of R-to-D [11], [39].

3. PERFORMANCE ANALYSIS HYBRID PSR-TSR SCHEME

Within the 1st time block, we have signal transmitted from BS to R for decoding given by (1).

$$y_r=\sqrt{1-\alpha_1}\sqrt{P_B l_1^{-m}}h_1 s_x+n_R, \tag{1}$$

where we normalize the transmitted signal from BS and denote it with $s_x, E=[|s_x|^2]=1$. Then, we have the received signal for EH in the 1st time slot as (2).

$$E = \eta\alpha_2 T\alpha_1 P_B |h_1|^2 l_1^{-m}, \tag{2}$$

where there is the energy conversion efficiency η, $\eta \in (0,1)$.

Within the 2nd time slot, we have signal transmitted from R to D as (3).

$$P_R = E\Big/(1-\alpha_2)T = \alpha_2\eta\alpha_1 P_B |h_1|^2 l_1^{-m}(1-\alpha_2)^{-1}. \tag{3}$$

After the base-band processing and amplifying processes at R, the R transmit signal is

$$s_r = \sqrt{\frac{(1-\alpha_1)P_B P_R}{l_1^m}} G h_1 s_x + \sqrt{P_R} G n_R, \tag{4}$$

where we have the R gain, G of the HD-AF system as (5),

$$G = \left(\sqrt{\frac{(1-\alpha_1)P_B}{l_1^m}}\, h_1^2 + N_0\right)^{-1} \approx \left(\sqrt{\frac{(1-\alpha_1)P_B}{l_1^m}}\, h_1^2\right)^{-1} \tag{5}$$

From (5), we can formulate the received signal at D as (6).

$$y_d = \sqrt{\frac{P_\mathrm{R}}{l_2^m}} h_2 s_r + n_\mathrm{D} = \sqrt{\frac{(1-\alpha_1)P_B P_R}{l_1^m l_2^m}} G h_1 h_2 s_x + \sqrt{\frac{P_R}{l_2^m}} G h_2 n_R + n_D. \tag{6}$$

Consequently, we substitute (3) and (5) into (6) then manipulate it to get the signal-to noise ratio (SNR) at D as (7),

$$\gamma_D = \frac{a_1 |h_1|^2 |h_2|^2}{a_2 |h_2|^2 + a_3}, \tag{7}$$

where $a_1 = \eta\alpha_1\alpha_2(1-\alpha_1)\chi$, $a_2 = \eta\alpha_1\alpha_2 l_1^m$, $a_3 = (1-\alpha_1)(1-\alpha_2)l_1^m l_2^m$, and $\chi = P_S / N_0$.

We evaluate the system performance by analyzing the achievable date rate and the *OP*. Therefore, firstly, we derive the achievable data rate at D as (8).

$$R_D = \frac{1}{2}(1-\alpha_2)\log_2(1+\gamma_D). \tag{8}$$

where we have the HD relaying factor of $1/2$.

The probability that the instantaneous data transmission rate declines below the source transmission rate of $R_0 = (1/2)(1-\alpha_2)\log_2(1+\gamma_0)$ (bits/sec/Hz), with a pre-specified threshold value of γ_0, is named OP. We can obtain the OP at D for the AF hybrid PSR-TSR systems as (9),

$$\mathcal{OP} = \Pr(\gamma_D < \gamma_0), \tag{9}$$

where $\gamma_0 = 2^{2R_0/(1-\alpha_2)} - 1$, and $\Pr(.)$ is the probability function. We can express the OP analytically as (10).

$$OP = 1 - \frac{10}{In(10)\sqrt{8\pi\sigma_{h_1}^2}} \int_{\gamma_0\alpha_2}^{\infty} \frac{1}{x} \varrho\left(\frac{\frac{10}{In(10)} In(\vartheta(x)) - 2\mu_{h2}}{2\sigma_{h_2}}\right) \times exp\left(\frac{\left(\frac{10}{In(10)} In(\vartheta(x)) - 2\mu_{h_2} - \frac{10}{In(10)} in(\alpha_1)\right)^2}{8\mu_{h_1}^2}\right) \tag{10}$$

where $\vartheta(x) = \gamma_0 a_3 / (x - \gamma_0 a_2)$.

Proof:

With (7) and (9), we can formulate the OP for the HD-AF hybrid PSR-TSR network as (11).

$$\mathcal{OP} = \Pr\left(\left|h_2\right|^2 < \frac{a_3\gamma_0}{a_1\left|h_1\right|^2 - a_2\gamma_0}\right). \tag{11}$$

Since $\left|h_2\right|^2$ is always a positive value, we can re-express the probability as (12).

$$OP = \begin{cases} \Pr\left(|h_2|^2 > \frac{\gamma_0\alpha_2}{\alpha_1|h_1|^2-\gamma_0\alpha_3}\right) = 1, |h_1|^2 \geq \frac{\gamma_0\alpha_3}{\alpha_1} \\ \Pr\left(|h_2|^2 < \frac{\gamma_0\alpha_2}{\alpha_1|h_1|^2-\gamma_0\alpha_3}\right), \quad |h_1|^2 < \frac{\gamma_0\alpha_3}{\alpha_1} \end{cases} \tag{12}$$

Thus, we rewrite the OP in (12) as (13).

$$\mathcal{OP} = \int_0^{\gamma_0 a_3/a_1} f_{|h_1|^2}(x)\mathrm{d}x + \int_{\gamma_0 a_3/a_1}^{\infty} f_{|h_1|^2}(x)\Pr\left(\left|h_2\right|^2 \leq \frac{\gamma_0 a_3}{a_1 x - \gamma_0 a_2}\right)\mathrm{d}x. \tag{13}$$

We express the probability density function (PDF), $f_{|h_1|^2}(x)$, and the cumulative distribution function (CDF), $F_{|h_2|^2}(x)$, of the two RVs $\left|h_1\right|^2$, $\left|h_2\right|^2$, respectively, as (14),

$$f_{|h_1|^2}(x) = \frac{10}{\ln(10)x\sqrt{8\pi\sigma_{h_1}^2}}\exp\left(-\frac{\left(\frac{10}{\ln(10)}\ln(x) - 2\mu_{h_1} - \frac{10}{\ln(10)}\ln\left(a_1\right)\right)^2}{8\sigma_{h_1}^2}\right), \tag{14}$$

and

$$F_{|h_2|^2}\big(\vartheta(x)\big) = 1 - \varrho\left(\frac{\frac{10}{In(10)}in\big(\vartheta(x)\big) - 2\mu_{h2}}{2\sigma_{h2}}\right) \tag{15}$$

where following the same in [26], [28], with the Gaussian Q-function, $\varrho(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} exp\left(-\frac{t^2}{2}\right) dt$

Substituting (14) and (15) into (13), we obtain the OP of the HD hybrid PSR-TSR network in (10). This is the end of the proof.

4. RESULTS AND DISCUSSION

In this section, we investigate the impact of the TS factor, the PS factor and SNR on the OP of the hybrid PSR-TSR systems over the log-normal fading channel via the Monte Carlo simulation results of the previously derived expressions. We use the following system parameters in the simulations as shown in Table 1 unless specified otherwise.

Table 1. Parameter setting

Symbol	Value	Symbol	Value
P_B	1 (Walts)	$\sigma_{h1} = \sigma_{h2}$	4(dB)
η	1	$\mu_{h1} = \mu_{h2}$	3(dB)
M	2	$l_1 = l_2$	5(m)
N_0	1	R_0	2(bps/Hz)

Figures 2 and 3 depict the OP of the hybrid PSR-TSR systems versus, respectively, TS factor of α_2, and PS factor of α_1. As in Figure 2, if we fix $\alpha_1 = 0.5$ and vary α_2, we will obtain the lowest curve which yields the best system performance. It is interesting that all the curves in Figure 2 reach their optimal values at $\alpha_2 = 0.25$. On the other hand, as illustrated in Figure 3, for fixed $\alpha_2 = 0.5$ and varied α_1, the curve is the highest indicating the worst system performance. The optimal values for the curves in Figure 3 distributed from $\alpha_1 = 0.7\ to\ 0.9$. Another obvious trait for both figures is that as TS and PS factors approach either zero or one, we have a 100% probability of system shutdown. This is because as $\alpha_2$and α_1 are too small or too large during the 1st time slot, the transmit power from EH process in the 2nd time slot becomes, respectively, insufficient or unnecessarily large leading to poor system capacity [28].

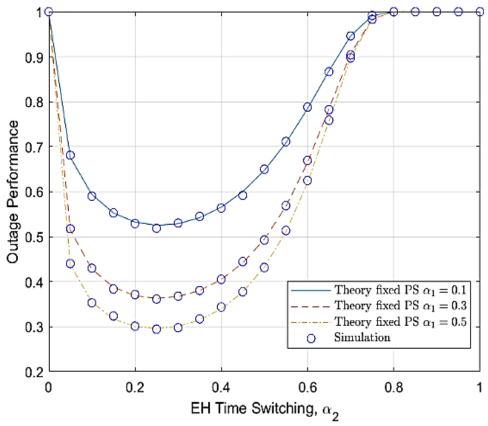

Figure 2. Outage performance versus the EH TS factor, α_2

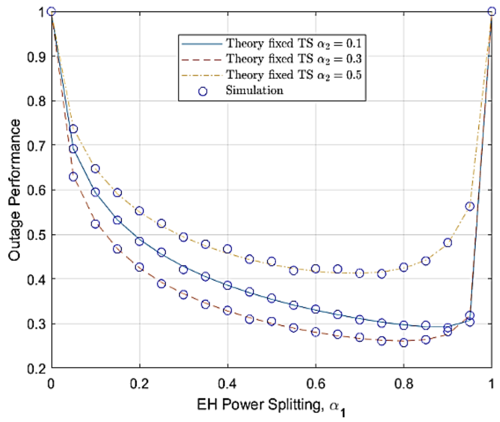

Figure 3. Outage performance versus the EH PS factor, α_1

Besides, Figures 4 and 5 plot the OP versus the SNR, χ, with, respectively, three pairs of EH PS and TS factors, i.e., $(\alpha_2 = 0.3, \alpha_1 = 0.5)$, $(\alpha_2 = 0.3, \alpha_1 = 0.3)$, $(\alpha_2 = 0.5, \alpha_1 = 0.3)$, and two data transmission rates, i.e., $R_0 = 2$ (bps/Hz), and $R_0 = 4$ (bps/Hz). In general, we can see that the OP decreases as the SNR increases. The hybrid PSR-TSR scheme with higher TS factor performs better. Additionally, the OP gets worse as the transmission rate grows because the power for EH and the transmission time decrease in the 2nd slot [11]. Generally speaking, the simulation results and theory agree well with each other. Thereby, we can use the derived expressions for further studies.

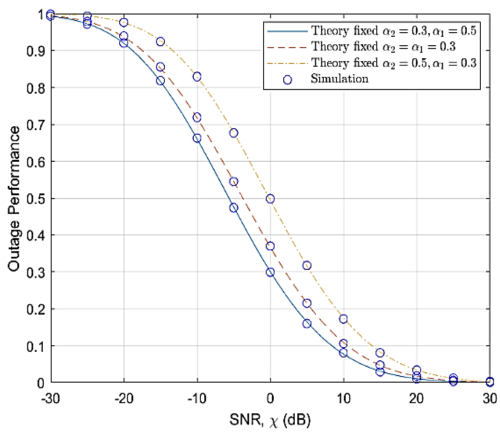

Figure 4. OP versus SNR under various dynamic switching condition

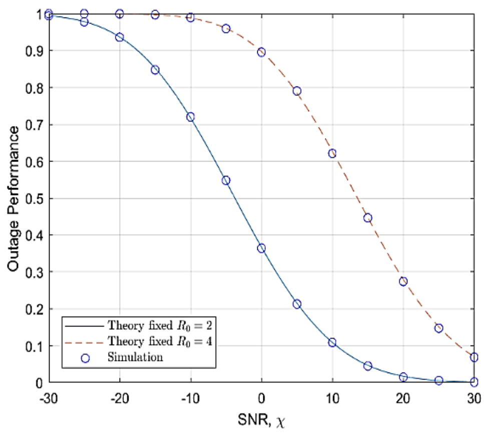

Figure 5. OP versus SNR with various data transmission rate

5. CONCLUSION

To summarize, we study a namely hybrid PSR-TSR protocol employed in a cooperative EH AF relaying network over log-normal fading channels by assessing the analytical expression of the OP. From the simulation results, we are able to conclude that the hybrid PSR-TSR scheme remarkably outperforms the standalone PSR and TSR schemes. Moreover, we prove that the system performance can be raised in association with the increase of EH TS factor and the decrease in data transmission rate.

APPENDIX

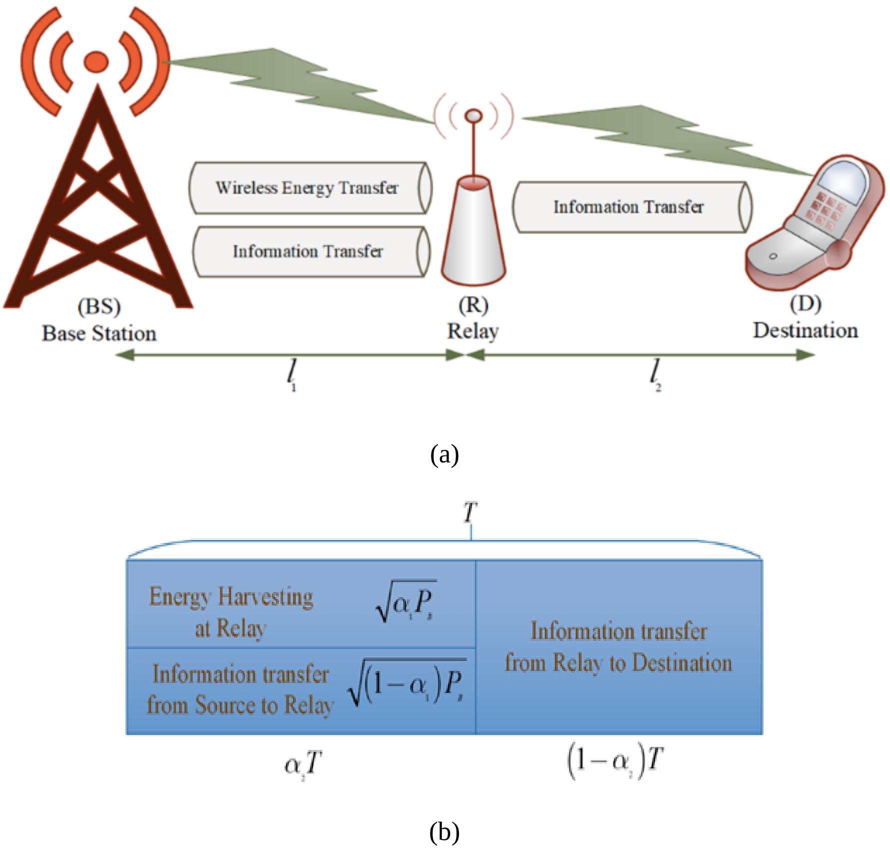

Figure 1. This figure are; (a) system model, (b) hybrid PSR-TSR protocol

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