Research on Interference Energy Harvesting Based on SWIPT Relay System

Jianxiong Li[1,2], Ke Zhao[1,2], Xianguo Li[1,2](✉), Xuelong Ding[1,2], and Weiguang Shi[1,2]

[1] School of Electronics and Information Engineering, Tianjin Polytechnic University,
Tianjin 300387, China
{lijianxiong,lixianguo,shiweiguang}@tjpu.edu.cn,
1140350591@qq.com, 1206737984@qq.com

[2] Tianjin Key Laboratory of Optoelectronic Detection Technology and Systems,
Tianjin 300387, China

Abstract. Simultaneous wireless information and power transfer (SWIPT) is a promising communication solution for energy-constrained wireless network. In the practical environment, the interference often results in a loss of the system rate, but it also brings energy at the same time. This paper proposes the scheme of interference energy harvesting (IEH) which can compensate for the loss of the SWIPT relay system rate caused by the interference. Based on the existing two operation strategies, time switching (TS) and power splitting (PS), we investigate the effect of IEH on the relay system rate. The interference energy is divided among subsequent transmission blocks, which can reduce the duration of energy harvesting (EH) slots. In addition, the optimal points are investigated in the different interference factors and interference power. The results show that IEH can effectively improve the relay system performance under an interference channel.

Keywords: SWIPT · Relay system · Interference energy harvesting (IEH)

1 Introduction

In recent years, energy harvesting (EH) has become a potential solution to prolong the lifetime of energy-constrained wireless network [1]. Besides other commonly used energy sources such as solar and wind, ubiquitous radio frequency (RF) signals have become another available source for wireless power transfer (WPT). So, simultaneous wireless information and power transfer (SWIPT) has drawn a great deal of attention. It can provide green energy [2] and information for the energy-constrained users simultaneously.

SWIPT first was introduced by Varshney [3]. In [3], the fundamental tradeoff between the information transmission rate and power transfer has been investigated. Two practical receiver operation strategies, time switching (TS) and power splitting (PS), have been presented in [4]. In [5], Liu et al. studied the optimal switching strategy of EH/information decoding (ID) mode under a single-input-single-output (SISO) channel subject to the time-varying interference.

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Wireless relay communication system has been widely used, because it can extend the coverage of communication [6]. The relay system based on SWIPT has also attracted the attention of scholars. In [7], Krikidis et al. studied an amplify-and-forward (AF) relay system based on TS strategy. The goal was to design the optimal TS factor which minimized the probability of interruption. In [8], the AF and decode-and-forward (DF) SISO relay system based on TS strategy was discussed, and the optimal TS factor was designed to maximize the system throughput. A low complexity algorithm of the resource allocation for DF relay system was presented in [9], but it did not involve harvesting the interference energy.

In this paper, we focus on the SISO relay system based on TS or PS operation strategy and propose the scheme of interference energy harvesting (IEH). During the strong interference, the signal-to-noise ratio (SNR) sharply drops so that the information transmission (IT) is interrupted. Generally, the relay system does not operate until the end of the interference which results in a decrease of the system rate. In order to alleviate the problem, we propose the IEH scheme that the relay harvests the interference energy and then evenly divides the harvested interference energy among the subsequent transmission blocks. IEH can reduce the duration of EH slots so as to compensate for the loss of the system rate caused by the interference and improve the system performance under an interference channel. Of course, it is assumed that the channel state information (CSI) is perfectly known at the relay.

2 System Model

This paper considers a wireless relay system including a transmitter (Tx), a relay and a receiver (Rx). The Tx and the Rx are active without energy limit, while the relay is passive. The Tx and the Rx are equipped with single antenna, and the relay is equipped with double antennas. The relay works in the AF mode and employs TS or PS strategy. The link from the Tx to the relay is referred to as the downlink with channel gain $h > 0$, and the link from the relay to the Rx is referred to as the uplink with channel gain $g > 0$.

2.1 Time Switching Relay System Model

The relay system model based on TS is shown in Fig. 1. At the Tx side, the baseband signal is expressed as x, and $\mathrm{E}[|x|^2] = 1$, where $\mathrm{E}[\cdot]$ and $|\cdot|$ denote the mathematical expectation and absolute value, respectively. The RF band signal is expressed as $\sqrt{P}x$ with the average transmit power P. At the relay side, the noise n_A is a circularly symmetric complex Gaussian random variable [5], i.e. $n_A \sim CN(0, \sigma_A^2)$. y_r is the signal received by the relay. The fraction of time that the relay operates in the EH mode is defined as $\alpha \in [0, 1]$. The AF power P_r from the harvested energy in the EH mode is used to amplify the information signal y_r' to x_r, where y_r' is equal to y_r in the IT mode. At the Rx side, the received signal is expressed as y. Similarly, the noise $n_R \sim CN(0, \sigma_R^2)$ is introduced.

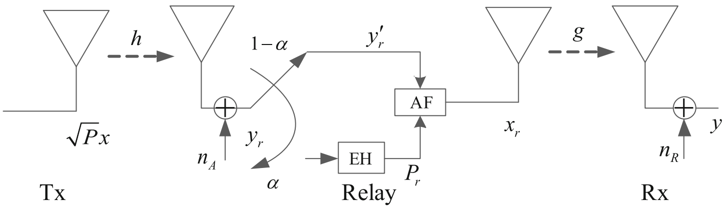

Fig. 1. Time switching relay system model

2.2 Power Splitting Relay System Model

The relay system model based on PS is shown in Fig. 2. Unlike the TS relay model, due to the use of the power splitter, new noise n_P is introduced at the relay. The fraction of energy harvested by the relay in the EH mode is defined as $\rho \in [0, 1]$.

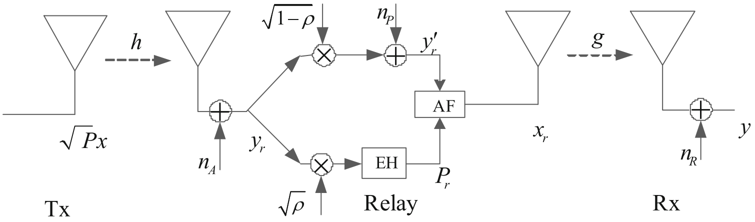

Fig. 2. Power splitting relay system model

2.3 Allocation of Blocks

As shown in Fig. 3, the TS relay system is taken as an example to illustrate the allocation of blocks. The interference lasts for mT blocks and its energy is harvested by the relay. Subsequently, a block of T is split into an EH slot and an IT slot. The relay harvests energy in the EH slot and transmits information in the IT slot. The energy harvested from the interference is evenly divided among n subsequent EH slots. New variable $\xi = m/n$ is introduced and defined as the interference factor.

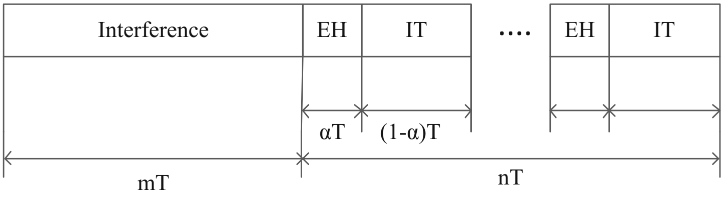

Fig. 3. Allocation of blocks

The average power of the interference is defined as P_I, and the energy harvested from the interference is expressed as $E_I = \eta P_I mT$, where η indicates the energy conversion efficiency. Therefore, the energy of each EH slot from the harvested interference energy can be expressed as

$$E_I' = \frac{\eta P_I mT}{n} = \eta \xi P_I T. \tag{1}$$

3 Problem Formulation

3.1 Time Switching Model

Frist, we consider the TS relay system shown in Fig. 1. Through the downlink, the signal y_r received by the relay is expressed as

$$y_r = \sqrt{hP}x + n_A. \tag{2}$$

The average AF power of the relay is

$$P_r = \frac{E_{EH} + E_I'}{(1-\alpha)T}, \tag{3}$$

where E_{EH} denotes the energy harvested in the EH slot and can be expressed as

$$E_{EH} = \eta hP\alpha T. \tag{4}$$

By substituting (1) and (4) into (3), we obtain

$$P_r = \frac{\eta hP\alpha T + \eta\xi P_I T}{(1-\alpha)T} = \frac{\eta(h\alpha P + \xi P_I)}{1-\alpha}. \tag{5}$$

Then, the signal x_r transmitted by the relay can be expressed as

$$x_r = \sqrt{\frac{P_r}{hP + \sigma_A^2}}(\sqrt{hP}x + n_A). \tag{6}$$

Through the uplink, the signal y received by the Rx can be expressed as

$$y = \sqrt{g}x_r + n_R = \sqrt{\frac{gP_r}{hP + \sigma_A^2}}(\sqrt{hP}x + n_A) + n_R. \tag{7}$$

Thus, the SNR of the signal y is obtained as

$$SNR = \frac{hg\eta P(h\alpha P + \xi P_I)}{g\eta(h\alpha P + \xi P_I)\sigma_A^2 + (1-\alpha)(hP + \sigma_A^2)\sigma_R^2}. \tag{8}$$

The system rate is given by

$$R_{TS} = \frac{1-\alpha}{1+\xi} \cdot \log_2\left(1 + \frac{hg\eta P(h\alpha P + \xi P_I)}{g\eta(h\alpha P + \xi P_I)\sigma_A^2 + (1-\alpha)(hP + \sigma_A^2)\sigma_R^2}\right). \tag{9}$$

Then, we consider the following optimization problem (P1),

$$\begin{aligned} (\text{P1}) \ \max_{\alpha} \quad & R_{TS} \\ s.t. \quad & 0 < \alpha < 1\,. \end{aligned}$$

Problem (P1) can be solved by the extremum method. With the first derivative $R'_{TS}(\alpha) = 0$, the extreme point can be obtained as $\alpha = \alpha^*$. At the same time, we verify whether the second derivative $R''_{TS}(\alpha^*)$ is less than zero. If $R''_{TS}(\alpha^*) < 0$, it can be determined that α^* is the maximum point, i.e., the optimal point. The maximum system rate at the optimal point α^* is defined as R^*_{TS}.

3.2 Power Splitting Model

Through the downlink, the signal y_r received by the relay shown in Fig. 2 is expressed as (2). The signal y'_r is expressed as

$$y'_r = \sqrt{1-\rho}(\sqrt{hP}x + n_A) + n_P. \tag{10}$$

The average AF power of the relay is

$$P_r = \frac{E_{EH} + E'_I}{T}, \tag{11}$$

where E_{EH} in (11) is the harvested energy by the relay in a block and expressed as

$$E_{EH} = \eta h \rho P T. \tag{12}$$

Substituting (12) and (1) into (11), we obtain

$$P_r = \frac{\eta h \rho P T + \eta \xi P_I T}{T} = \eta(h\rho P + \xi P_I). \tag{13}$$

Then, the signal x_r can be expressed as

$$x_r = \sqrt{\frac{P_r}{(1-\rho)(hP + \sigma_A^2) + \sigma_P^2}} \cdot [\sqrt{1-\rho}(\sqrt{hP}x + n_A) + n_P]. \tag{14}$$

Through the uplink, the signal y received by the Rx can be expressed as

$$y = \sqrt{\frac{gP_r}{(1-\rho)(hP+\sigma_A^2)+\sigma_P^2}} \cdot [\sqrt{1-\rho}(\sqrt{hP}x + n_A) + n_P] + n_R. \tag{15}$$

Thus, the SNR of the received signal y is obtained as

$$SNR = \frac{(1-\rho)hgP}{(1-\rho)g\sigma_A^2 + g\sigma_P^2 + \frac{\left[(1-\rho)(hP+\sigma_A^2)+\sigma_P^2\right]\sigma_R^2}{\eta(h\rho P + \xi P_I)}}. \tag{16}$$

The system rate is given by

$$R_{PS} = \frac{1}{1+\xi} \cdot \log_2\left(1 + \frac{(1-\rho)hgP}{(1-\rho)g\sigma_A^2 + g\sigma_P^2 + \frac{\left[(1-\rho)(hP+\sigma_A^2)+\sigma_P^2\right]\sigma_R^2}{\eta(h\rho P + \xi P_I)}}\right). \tag{17}$$

Then, we consider the following optimization problem (P2),

$$\begin{aligned} \text{(P2)}\ \max_{\rho} \quad & R_{PS} \\ s.t. \quad & 0 < \rho < 1\,. \end{aligned}$$

The solution method of (P2) is the same as that of (P1), and the optimal point is $\rho = \rho^*$. The maximum systen rate at the optimal point ρ^* is defined as R_{PS}^*.

4 Simulation Results

Unless otherwise specified, the simulation parameters are set as follows: $h = 1$, $g = 1$, $P = 200$, $P_I = 100$, $\xi = 0.1$, and the noise power is set to be $\sigma_A^2 = \sigma_R^2 = \sigma_P^2 = 1$. For convenience, the energy conversion efficiency is set to be $\eta = 1$.

4.1 The Effect of IEH on the System Rate

The relay system rates based on TS and PS are shown in Figs. 4 and 5, respectively.

As shown in Fig. 4, the relay system rate based on TS with IEH is higher than that without IEH in [8]. Furthermore, the optimal point α^* with IEH is smaller than that without IEH, since the harvested interference energy reduces the duration of the EH slot. Therefore, the duration of the IT slot increases, and the system rate naturally rises. The same conclusions can be obtained by analyzing Fig. 5. Compared with [10], the system performance based on PS is improved effectively.

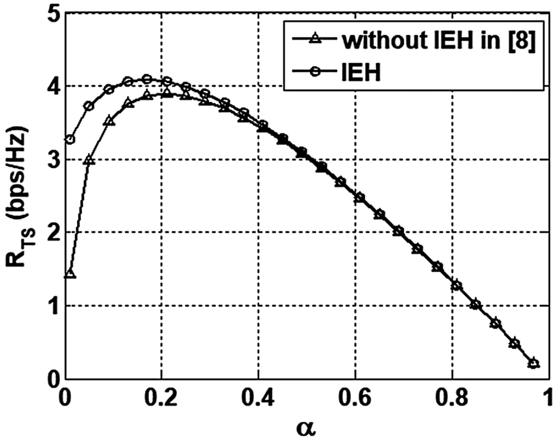

Fig. 4. The system rate based on TS

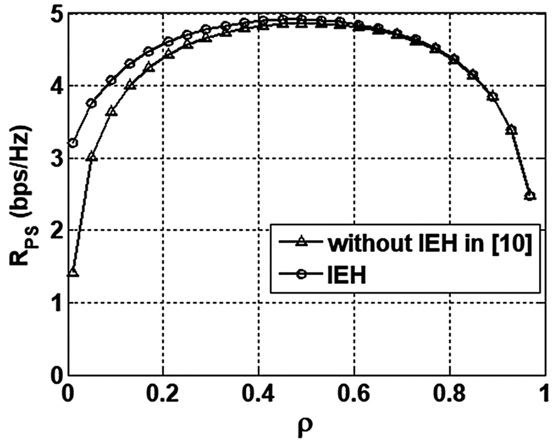

Fig. 5. The system rate based on PS

4.2 The Effect of the Interference Power on the Optimal Points

The optimal points α^* and ρ^* in the different interference power are shown in Figs. 6 and 7, respectively. They decrease gradually with the increase of the interference power, since the stronger interference can supply more energy. Hence fewer resources are allocated for EH and more resources are allocated for IT. In other words, the optimal point decreases and the system rate increases. As such, IEH reduces more loss of the system rate caused by the interference if the interference power is larger.

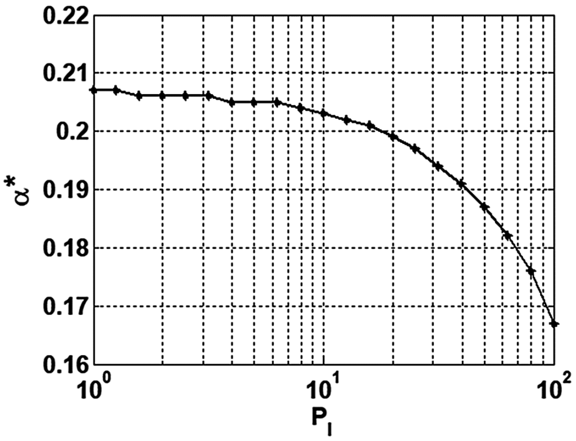

Fig. 6. The optimal point α^* in the different interference power

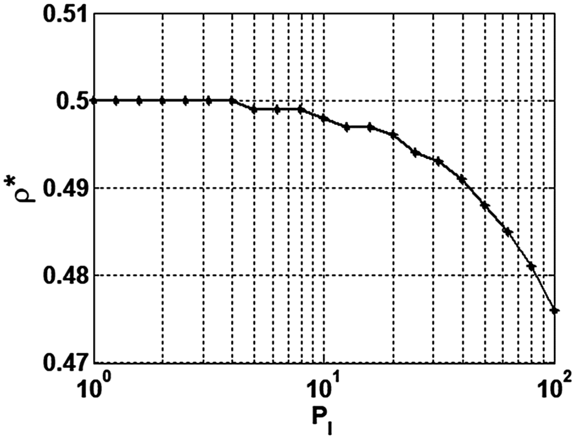

Fig. 7. The optimal point ρ^* in the different interference power

4.3 The Effect of the Interference Factor on the Optimal Points and the Corresponding Maximum System Rates

When other parameters are fixed, the optimal points α^*, ρ^* and the corresponding maximum system rates in the different interference factors are shown in Figs. 8 and 9, respectively. With the increase of ξ, the optimal points and the maximum system rates decrease simultaneously.

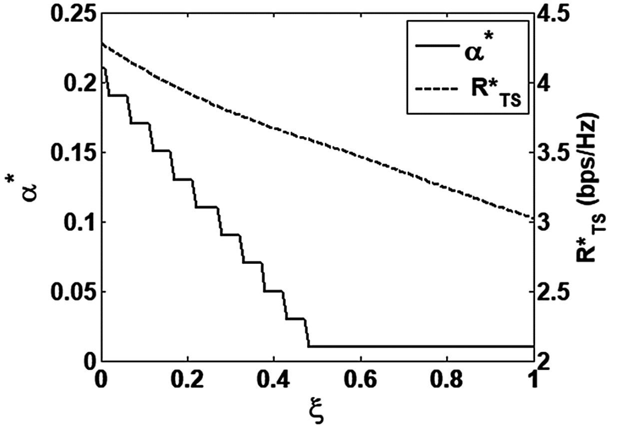

Fig. 8. The optimal point α^* and the maximum system rate R^*_{TS} in the different interference factors

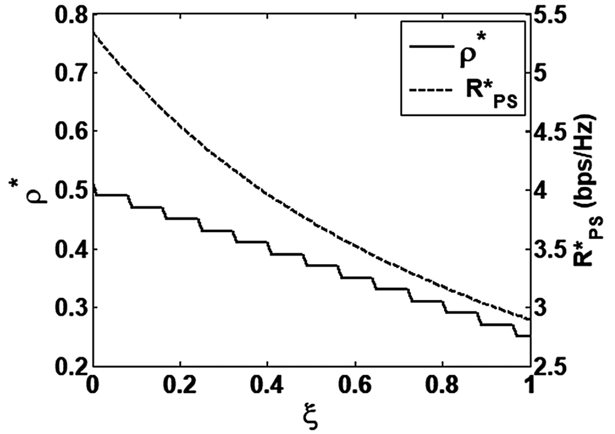

Fig. 9. The optimal point ρ^* and the maximum system rate R^*_{PS} in the different interference factors

5 Conclusion

This paper proposes the scheme of IEH based on SWIPT relay system. The optimal points α^* and ρ^* are investigated in the different interference power and interference factors. For the relays based on TS or PS operation strategy, the simulation results show that IEH can compensate for the loss of the system rate caused by the interference and effectively improve the system performance.

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