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Optimal Resource Allocation Scheme-Based Time Slot Switching for Point-to-Point SISO SWIPT Systems †

Nivine Guler [1,]* and Ali Gunes [2]

[1] Department of Informatics Engineering, University of Technology Bahrain, Bahrain
[2] Department of Computer Engineering, Istanbul Aydin University, Istanbul, Turkey; aligunes@aydin.edu.tr
* Correspondence: n.guler@utb.edu.bh; Tel.: +973-33361859

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Abstract: This paper presents an optimal resource allocation scheme based on timeslot switching (TS) for point-to-point single-input single-output (SISO) simultaneous wireless information and power transfer (SWIPT) systems aiming at maximizing the average achievable rate. The proposed scheme considers the nonlinear energy harvesting (EH) characteristic and thus the problem is formulated as a nonconvex optimization problem with the presence of binary TS ratio. Hence, solving the problem is done using the time-sharing strong duality theorem and Lagrange dual method. Simulations showed that the proposed scheme improves energy efficiency with respect to different transmission power by 20%, 10%, and 3% for high SNR, medium SNR, and low SNR regions, respectively. Improvement with respect to average energy efficiency versus other system performance metrics has also been noted for the proposed scheme.

Keywords: energy harvesting; information decoding; SWIPT; timeslot switching; SNR

1. Introduction

Energy shortage is considered one of the main issues that faces energy-constrained wireless networks [1]; hence, energy shortage directly affects the network lifetime and performance. Energy harvesting (EH) becomes a promising solution for reducing energy consumption and extending the lifetime of energy-constrained wireless networks where nodes harvest energy from the surrounding environment. The simultaneous wireless information and power transfer (SWIPT) is one of the EH technologies, where energy harvesting is done through the radio frequency (RF) signals since RF signals are able of carrying both information and electromagnetic energy simultaneously. Thus, SWIPT becomes an upsurge of recent research interests due to its higher efficiency compared to transmitting information and power on orthogonal resources, i.e., time or frequency channels [2]. Authors in [3,4] present a trade-off between the amount of the harvested energy and the achievable rate for the SWIPT systems in the frequency selection channel with additive white Gaussian noise (AWGN). TS and power splitting (PS) SWIPT receivers were firstly proposed in [5], and since then, the idea of using TS and PS SWIPT receivers has been adopted in literature. Authors in [6] present multiuser single input single output (SISO) orthogonal frequency-division multiplexing (OFDM) system where the TS and PS ratios are optimized to maximize the weighted sum rate of all receivers. Authors in [7] propose an energy efficiency maximization optimization scheme for the multiuser multi-carrier energy-constrained amplify-and-forward (AF) multi-relay network. Aiming at minimizing the transmission power, the power allocation problem for the multiuser system is studied and the optimal PS ratio is obtained in [8]. Power allocation and subcarrier allocation schemes are presented in [9,10] for energy-efficient in large-scale multiple-antenna SWIPT systems. Most of the proposed SWIPT systems in literature consider the

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linear EH model, where the power conversion efficiency factor of the EH receiver is assumed to be constant. Yet, this assumption is made false in [11] after showing the saturation behavior of the output power of the RF to direct current converter as the input power exceeds certain threshold. In [12–14], a nonlinear EH model is presented to optimize the power split factor to minimize the outage probability for the AF relay system with PS receiver. In this paper, a SISO point-to-point SWIPT communication system with TS receiver is considered where the nonlinear saturation input-output characteristic of EH circuit is modeled, and a simple optimal resource allocation scheme based on the time slot-switching strategy to maximize the average achievable rate for the system is proposed. The paper main contribution is the consideration of the effect of the saturation characteristic of the nonlinear EH model, and the achievable rate in the TS SWIPT system is mathematically formulated where the scheme shows the regions that the receiver can harvest energy or decode information based on the value of SNR. Another contribution is that the proposed resource allocation scheme maximizes the network energy efficiency.

The rest of this paper is organized as follows. Section 2 presents the System Model. Section 3 presents the proposed model. Simulation Results are discussed in Section 4. Section 5 concludes the paper.

2. System Model

We consider a SISO point-to-point SWIPT communication system as shown in Figure 1, where both the receiver and the transmitter have single antenna and Rx is assumed to be energy-limited and could harvest energy from the received signals with a TS scheme. The channel between the transmitter and receiver is subjected to frequency flat and the block Rayleigh fading. The channel coefficient is denoted as h, which is a random variable following the complex Gaussian distribution with zero mean and variance σ^2. The optimal problem is formulated as a nonconvex optimization, which we proved to meet the time-sharing condition and then the problem is solved by using the time-sharing strong duality theorem and Lagrange dual method. Without loss of generality, we assume that each time slot is normalized transmission time. In each time slot, the TS ratio Ʈ is equal to 0 or 1, indicating that the receiver implements EH or ID operations, respectively. The received signal S_R is given in Equation (1) as:

$$S_R = \sqrt{\vartheta P_t} h x + n_i \tag{1}$$

where P_t is the transmit power, x is the data symbol with unity power, i.e., $E[|x|^2] = 1$, where $E[]$ is the mathematical expectation, $n_i \sim CN\,(0, \sigma^2)$ is the channel noise, $\vartheta = d^{-m}$ represents the path loss, d is the distance between the source and the destination nodes, and m represents the pathloss exponent. The achievable rate $\Re$ of the system based on the TS scheme is given in Equation (2) as:

$$\Re(\text{Ʈ}) = \text{Ʈ} \log_2(1 + \frac{\vartheta P_t H}{\sigma^2}), \tag{2}$$

where $H = h^2$ is the channel power gain.

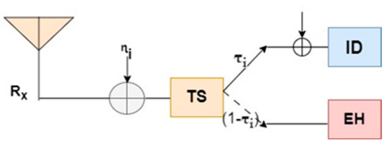

Figure 1. The SISO point-to-point SWIPT system.

We use the piece-wise linear function to model the non- linear saturation input-output characteristic of the EH receive. The harvested power at the EH receiver is given by Equation (3) as:

$$P_h = \begin{cases} \varepsilon \vartheta H P_t, \varepsilon \vartheta H P_t < Pm \\ Pm, \varepsilon \vartheta H P_t \geq Pm \end{cases} \quad (3)$$

where $\varepsilon(0 < \varepsilon < 1)$ is the energy conversion efficiency of the energy harvester in the linear region, Pm is the maximum saturation harvested power of the EH receiver. When the conversion power of the energy receiver, $\varepsilon \vartheta H P_t$ exceeds the saturation output power Pm, the output power of the energy receiver remains unchanged and some of the power is wasted, which means that in such case, the receiver should perform ID instead of EH to avoid waste of the power.

3. An Optimal Resource Allocation Scheme

In this section, we propose an optimal resource allocation scheme based on the simple time slot-switching strategy to achieve the balance between the maximum average achievable rate and the maximum average harvested energy. The harvested energy can be expressed as in Equation (4). The proposed optimal resource allocation scheme maximizes the average achievable rate as given by Equation (5)

$$\mathscr{E}(\mho) = (1 - \mho)P_h \quad (4)$$

$$\max_{\mho} \mathbf{E}[\,\mathfrak{R}(\mho)] \quad (5)$$

$$\text{s.t. } \mathrm{E}[\mathscr{E}(\mho)] \geq \mathscr{E}m,\ \mho \in \{0,1\},$$

where $\mathscr{E}$m is the minimum value of the EH required to maintain the normal operation of the EH receiver. As it is shown in Equation (5), it is a combination of series of nonconvex problem due to the binary aspect of $\mho$, so it is difficult to solve. In addition, the complexity of solving the optimization problem increases with the number of timeslots. Hence, we use the time-sharing strong duality theorem [15]. According to the time-sharing strong duality theorem, the primal problem of Equation (5) has the same optimal solution as its dual problem and can be solved by the Lagrange dual method. The Lagrange function of Equation (5) can be expressed in Equation (6).

$$\boldsymbol{L}(\mho, \boldsymbol{\lambda}) = \mathrm{E}[\boldsymbol{\mathfrak{R}}(\mho)] + \boldsymbol{\lambda}(\mathrm{E}[\mathscr{E}(\mho)] - \mathscr{E}), \quad (6)$$

where $\boldsymbol{\lambda} \geq 0$ is the Lagrange multiplier associated with $\mathrm{E}[\mathscr{E}(\mho)] \geq \mathscr{E}$. Accordingly, the Lagrange dual function is given by Equation (7) and the dual problem is then given by Equation (8).

$$g(\lambda) = \max_{\mho \in \{\mathbf{0},\mathbf{1}\}} \boldsymbol{L}(\mho, \boldsymbol{\lambda}), \quad (7)$$

$$\min \mathbf{g}(\lambda), \quad (8)$$

$$\text{s.t. } \lambda \geq 0.$$

In order to effectively solve Equation (8), first, we decouple the optimization problem in Equation (7) into N parallel subproblems that has the same structure as Equation (7). The kth (k = 1,2,…,N) subproblem is expressed in Equation (9).

$$\max_{\mho \in \{\mathbf{0},\mathbf{1}\}} \boldsymbol{L_k}(\mho), \quad (9)$$

where $\boldsymbol{L_k}(\mho) = \Re(\mho) + \boldsymbol{\lambda}\mathscr{E}(\mho)$. First, we consider the values of $\mho$ = 0,1, and we substitute $\mho$ in Equation (4) and Equation (6). Then, Equation (10) and Equation (11) express the Lagrange functions, respectively.

$$\boldsymbol{L_k}(\mho = \mathbf{0}) = \lambda \boldsymbol{P_h} \quad (10)$$

$$\boldsymbol{L_k}(\mho = \mathbf{1}) = \mathbf{log_2}\left(\mathbf{1} + \frac{\vartheta \boldsymbol{P_t H}}{\boldsymbol{\sigma^2}}\right) \quad (11)$$

Therefore, the optimal solution, Ꚋ*, of Equation (7) is given in Equation (12) as:

$$Ꚋ^* = \begin{cases} \mathbf{1}, \mathbf{\log_2}\left(\mathbf{1} + \frac{\vartheta P_t H}{\sigma^2}\right) > \boldsymbol{\lambda P_h} \\ \mathbf{0}, \boldsymbol{else} \end{cases} \tag{12}$$

Hence, for a given value λ, Ꚋ* can be obtained from (12) according to the channel state in each timeslot. Let λ^* be the optimal dual variable, which is associated with the required minimum harvested energy value ℰm in Equation (5). The optimal dual variable λ^* is found by iterative search until the average energy meets the minimum energy constraint, i.e., ∣ E[ℰ(Ꚋ)] − ℰm ∣≤ δ. The proposed optimal resource allocation scheme is based on the optimal TS strategy according to the channel state in each time in Equation (12). Based on the value of $\boldsymbol{P_h}$ in Equation (3) and Ꚋ* in Equation (12), we define two channel gain functions CG1 and CG2 with respect to the channel power gain in Equations (13) and (14), respectively.

$$\text{CG1(H)} = \mathbf{\log_2}\left(\mathbf{1} + \frac{\vartheta P_t H}{\sigma^2}\right) - \lambda^* \ \boldsymbol{\varepsilon\vartheta H P_t} \tag{13}$$

$$\text{CG2(H)} = \mathbf{\log_2}\left(\mathbf{1} + \frac{\vartheta P_t H}{\sigma^2}\right) - \lambda^* \ \boldsymbol{Pm} \tag{14}$$

As it is seen, Equation (13) is a combination of logarithmic and linear functions, hence, solving it is done by traversing the value of H from 0 until the difference is approximately 10^{-6} and so CG1(H) = 0. Then, we can determine an approximate nonzero H1. Also, λ is found when G1(H) increases in range (0, H1). Since, CG1(0) = 0 and CG1(H1) = 0 when H∈(0, H1), CG1(H) > 0. From Equations (3) and (12), $\mathbf{\log_2}\left(\mathbf{1} + \frac{\vartheta P_t H}{\sigma^2}\right) > \lambda^* \boldsymbol{P_h}$; $\mathbf{\log_2}\left(\mathbf{1} + \frac{\vartheta P_t H}{\sigma^2}\right) > \lambda^* \ \boldsymbol{\varepsilon\vartheta H P_t}$;hence, Ꚋ* = 1. Similarly, CG2(H) is an increasing function, when H∈(H2, ∞), where H2 is a nonzero real root of CG2(H) = 0. Then, when H∈ [H1, H2], Ꚋ* = 0. The optimal TS strategy is given in Equation (15).

$$Ꚋ^* = \begin{cases} \mathbf{1}, \boldsymbol{H < H_1 \ or \ H > H_2} \\ \mathbf{0}, \boldsymbol{H_1 \le H \le H_2} \end{cases} \tag{15}$$

The optimal TS thresholds H*1 and H*2 depend on the optimal dual variable λ^* determined from Equation (5) where E[ℰ(Ꚋ(H))] = ℰm. The average energy collection depends on the probability density function of H, $\boldsymbol{f_H(x)}$, and is given in Equation (16) as:

$$\text{E}[ℰ(Ꚋ(\text{H}))] = \int_{H_1}^{H_{th}} \boldsymbol{\varepsilon\vartheta x P_t f_H(x) d_x} + \int_{H_{th}}^{H_2} \boldsymbol{Pm * f_H(x) d_x} \tag{16}$$

The optimal resource allocation scheme first divides the information block K into k timeslots. For each timeslot, k (1 ≤ k ≤ K), the optimal TS thresholds H*1 and H*2 are found by applying algorithm, and the channel gain Hk is compared to H*1 and H*2. The receiver will switch to ID if Hk < H*1 or Hk > H*2; otherwise, the receiver will perform EH.

4. Simulation Results

In this section, simulation results for the proposed optimal resource allocation scheme is presented. In each timeslot k, the channel obeys the Rayleigh distribution. The distance between the source node and the destination node is d = 5 m, and pathloss exponent m = 2.0, and. The power transmitted, Pt = 1 W, ℰm = 5 mW, Pm = 24 mW, Hth = $^{Pm}/_{\varepsilon\vartheta P_t}$. The energy efficiency with various SNR [5,15,25] is analyzed for different values of transmission power P_t. For verification purposes, the proposed resource allocation scheme is compared with [16] in terms of the energy efficiency (ε_f) of a system which is defined as the ratio of the total achievable rate to the total power consumption as in Equation (17). Hence, the average energy efficiency Êf is given by Equation (18).

$$\varepsilon_f = {}^{\Re(Ꚋ)}\Big/_{(P_t - E[\mathcal{E}(Ꚋ)])} \tag{17}$$

$$\hat{\mathrm{E}}_{\mathrm{f}} = \frac{1}{K}\sum_{\mathrm{ts}=1}^{K} \varepsilon_f(\mathrm{ts}) \quad (18)$$

In Figure 2, as the transmit power increases, the average energy efficiency, Êf, decreases in region where SNR is 15 dB or 25 dB; whereas it stays unchanged when SNR is 5 dB. This is because the receiver of the traditional scheme will waste the power in the nonlinear regions and thus, resulting in bigger gap. The proposed scheme improves the average energy efficiency by 20%, 10%, and 5% when SNR = 25 dB, 15 dB, and 5 dB, respectively.

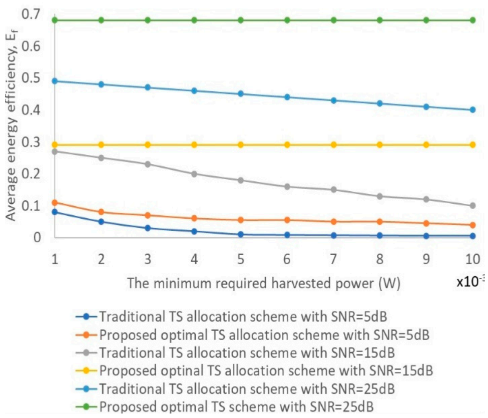

Figure 2. Average energy efficiency versus power.

In Figure 3, as the distance increases, the average energy efficiency decreases. In the intermediate regions where SNR = 15 dB and 25 dB, the gap between the traditional scheme and the proposed scheme becomes obvious due to the saturation characteristic of the EH model. In Figure 4, as the minimum required harvested power increases, the average energy efficiency of the traditional scheme decreases whereas it remains unchanged with the proposed scheme.

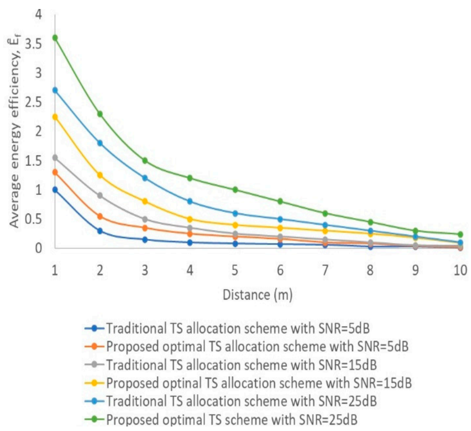

Figure 3. Average energy efficiency versus distance.

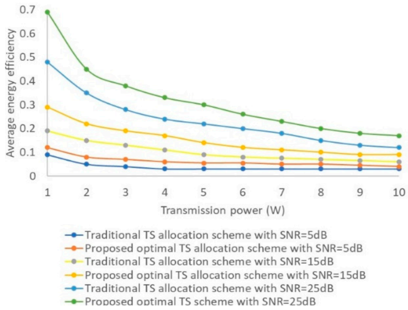

Figure 4. Average energy efficiency versus minimum required harvested energy.

5. Conclusions

In this paper, an optimal resource allocation scheme for point-to-point SISO SWIPT systems with nonlinear EH model is presented. The proposed scheme is based on TS to maximize the average information rate by which the receiver performs information decoding in the regions of either low or high SNR, whereas, switching to energy harvesting is done in the intermediate region. In comparison with the traditional TS resource allocation scheme, the proposed scheme improves energy efficiency with different transmission power by 20%, 10%, and 3% for high SNR, medium SNR, and low SNR regions, respectively. We have also investigated the impact of the minimum required harvested energy on the average energy efficiency performance. It is demonstrated that the average energy efficiency decreases with the increase of the minimum required harvested energy for the traditional TS allocation scheme whereas, it is hardly affected for the proposed scheme.

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