Hindawi Publishing Corporation
Mobile Information Systems
Volume 2015, Article ID 769286, 8 pages
http://dx.doi.org/10.1155/2015/769286

Research Article

Time Power Switching Based Relaying Protocol in Energy Harvesting Mobile Node: Optimal Throughput Analysis

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Received 9 March 2015; Revised 28 May 2015; Accepted 7 June 2015

Academic Editor: Jose Juan Pazos-Arias

We propose a new protocol for energy harvesting at relay mobile node in wireless communications called energy harvesting cooperative networks (EHCN). In particular, we investigate how the harvested power at relay mobile node affects outage probability and throughput performance. Specifically, we develop outage and throughput performance characterizations in terms of time and power factors in the proposed time power switching based relaying (TPSR) protocol. A simple, highly accurate closed-form formula of outage probability is also derived. It is shown that the optimal throughput of the EHCN is critically dependent on time switching and power splitting factor of the TPSR protocol. In addition, we extend the proposed protocol performance in ideal case of receiver. The tightness of our proposed protocol is determined through Monte Carlo simulation results. Finally, our results provide useful guidelines for the design of the energy harvesting enabled relay mobile node in the EHCN.

1. Introduction

In recent years, energy harvesting through radio frequency (RF) signal has received significant attention in [1–7] as a promising solution to prolonging the lifetime of energy-constrained cooperative networks. Compared with traditional energy supplies such as batteries that have limited operation time and are energy constrained, mobile node with energy harvested from external natural resources such as radio frequency (RF) signal radiation will respond to growing concerns about the high cost of wireless communication networks and inconvenience of replacing or recharging fixed energy supplies [8]. The benefit of this solution lies in the fact that RF signals can be used for information and energy transmission at the same time [6, 9]. In particular, the development of the wireless power transmission brings about the ability to share power, leading to the concept of a new network as the EHCN. Interestingly, mobile devices in the EHCN will combine capability of wireless communication and energy harvesting in order to ensure seamless wireless communication without the need of using external energy sources. As a result, the mobile relay node can harvest energy and processes information simultaneously.

More specifically, the authors in [6] proposed two protocols of an amplify-and-forward (AF) relaying system for energy harvesting and information processing as follows:

(i) Time switching based relaying (TSR) protocol where the receiver switches between information processing and energy harvesting.

(ii) Power splitting based relaying (PSR) protocol where the receiver splits the received signal in two parts for information processing and energy harvesting.

Both protocols have been applied in [7] to calculate the throughput of decode-and-forward (DF) relaying systems. In [9], the authors presented a harvest-then-cooperate (HTC) protocol, in which the relay mobile node harvests energy from the access point (AP) in the downlink and works cooperatively in the uplink for the source's information transmission. Regarding energy harvesting enabled full-duplex relaying system, the authors in [10] studied the outage probability and ergodic capacity for both the amplify-and-forward (AF) and decode-and-forward (DF) protocols.

In addition, the wireless information and power transfer (WIPT) systems for two-way relaying network use the AF scheme, where two sources exchange information via an energy harvesting relay mobile node [11]. The authors in [12] have developed a low-complexity antenna switching technique for WIPT in MIMO (multiple-input multiple-output) channel at relay mobile node and the solutions for WIPT in a multiuser MISO (multiple-input single-output) interference channel are also analyzed in [13].

In this work, the EHCN in [6] has been extended in case of generic energy harvesting protocol. In particular, we propose a time power switching based relaying protocol for determining both time switching and power splitting factors subject to maximized throughput performance. Our proposed protocol can be seen as a general model for energy harvesting enabled relay mobile node in the EHCN.

The rest of this paper is organized as follows. Section 2 introduces the overall system model of energy harvesting enabled mobile node in the EHCN. Section 3 presents the proposed protocols and analytic expression of the achievable throughput. In Section 4, the paper analyzes the throughput performance with an ideal relay receiver. Section 5 addresses the numerical results of the optimal throughput with different values of time switching and power splitting factors. Finally, Section 6 concludes the paper.

2. System Model

We consider a simple EHCN for energy harvesting and information transmission using AF scheme which is shown in Figure 1, where the information is transferred from the source node S (i.e., access point (AP) in WiFi networks) to the destination mobile node D, through an energy-constrained intermediate relay mobile node R. Each mobile node and source is equipped with one single antenna and works in the half-duplex mode. We assume there is no direct link between the source and the destination mobile node. Thus, an intermediate mobile relay assists information transmission between the source and the mobile destination.

Relay Model. We make the following assumptions regarding relay mobile node:

(i) The relay mobile node has no other embedded energy supply and thus needs to first harvest energy from the AP for information processing in the next hop transmission. In practice, harvested power can be stored in batteries and then is supplied as a source of transmitting power in order to forward information from the AP to the destination mobile node.

(ii) The receiver structure of relay mobile node is designed for simultaneous energy harvesting and information processing and it adopts the time power switching based relaying protocol.

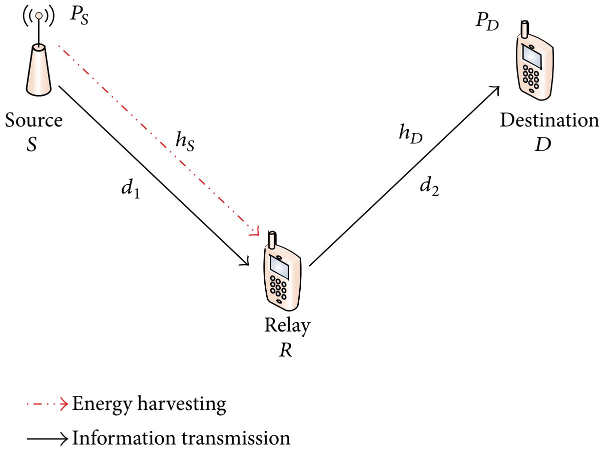

Figure 1: The system model.

Channel Model. We assume that channel state information (CSI) can be obtained thanks to the advanced channel estimation algorithm which was well defined in previous works. Channel model in the EHCN is characterized as flat Rayleigh fading. We denote the distances from the source to the relay and from the relay to the destination mobile node by d_1 and d_2, respectively.

Energy Harvesting Protocol

(i) We propose *time power switching based relaying* (TPSR) protocol for the considered network which is shown in Figure 2. In the TPSR protocol, T denotes the block time in which the information is transmitted from the AP to the destination mobile node and $0 < \alpha < 1$ denotes the fraction of the block time switching in which the first portion of time αT is used for energy harvesting process and information transmission between the AP and the relay mobile node. In context of power splitting, P depicts the total power of the transmitted signal and $0 < \beta < 1$ denotes the fraction of the power splitting ratio in energy harvesting scheme, in which TPSR divides the power of the received signal into two parts, namely, βP and $(1-\beta)P$, with the former being used for energy harvesting and the latter being used for the source to relay information transmission, while αT denotes a time switching ratio of the received signal at the relay mobile node for simultaneous energy harvesting and information transmission between the AP and the relay mobile node, and the remaining block time of $(1 - \alpha)T$ is used for information transmission in the second hop. Specifically, these parameters are designed as in Figure 2.

(ii) In this paper, the WiFi systems following the EHCN technology utilizes amplify-and-forward (AF) relaying protocol at the relay mobile node due to its implementation simplicity.

In the following section, we consider the application of the TPSR protocol for the EHCN, in which the relay mobile node is powered by the energy harvested from source node (i.e., AP). Moreover, we derive a closed-form expression of achievable throughput in different cases of time and power fractions in the proposed TPSR protocol.

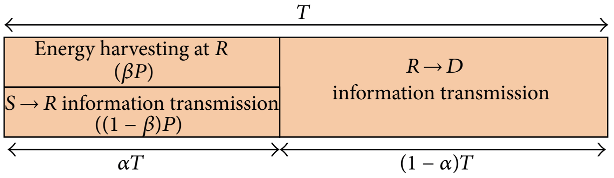

Figure 2: The diagram of the TPSR protocol for energy harvesting and information processing at the relay mobile node.

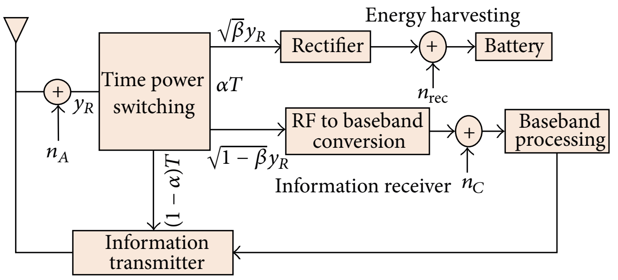

Figure 3: Receiver architecture for the TPSR protocol at the relay mobile node.

3. TPSR in the EHCN

3.1. TPSR Protocol. In the EHCN, relay mobile node scavenges energy from all signals around and assists the communication between the AP and destination mobile node. In this section, we assume a reference system model depicted in Figure 1, in which the harvested energy transferred from the AP is stored in the battery of the relay in the first hop and used for the transmission of relay mobile node in the next hop. To gain further insights into the performance, we will analyze the achievable throughput of the proposed TPSR protocol.

In TPSR protocol, we design two stages, namely, *energy stage* (ES) and *information stage* (IS). Aiming to obtain wireless energy in ES, the power of received signal y_R can be divided into two parts for energy harvesting and information processing in the proposed TPSR protocol. Based on the energy harvesting enabled receiver architecture as shown in Figure 3, the signal received $y_{\rm RE}$ at the input of the energy harvesting receiver is expressed as

$$y_{\rm RE} = \frac{1}{\sqrt{d_1^m}}\sqrt{\beta P_S} h_S x_S + \sqrt{\beta} n_R, \tag{1}$$

where β is the power splitting ratio for energy harvesting, m is the path loss exponent factor, P_S is the transmitted power of the source node, h_S denotes channel coefficient between source and relay mobile node while x_S denotes transmitted signal from source, and $n_R \sim CN(0, \sigma_R^2)$ denotes the total additive white Gaussian noise (AWGN) introduced at the relay mobile node by the receiving antenna and signal band conversion [6].

The energy processing module in the relay mobile node converts incoming signal in (1) to a direct current (DC) signal $i_{\rm DC}$ by a rectifier, which includes a Schottky diode and a low-pass filter (LPF). As illustrated in Figure 3, the direct current signal is used to charge the battery and to supply information transmission [14]. Hence, the energy harvested in the TPSR protocol is given by

$$E_h^{\rm TPSR} = \eta E\{i_{\rm DC}\}\alpha\beta T = \eta \frac{P_S |h_S|^2}{d_1^m}\alpha\beta T, \tag{2}$$

where $E\{\cdot\}$ denotes expectation operation and $0 < \eta \le 1$ depicts the energy harvesting efficiency at the energy receiver and it depends on the rectifier and the energy harvesting circuitry.

In IS of the proposed TPSR protocol, the energy scavenged from the previous stage (i.e., ES) is power supply for information processing in the second hop of the EHCN. Compared with harvesting energy receiver, the received signal at the input of the information processing receiver in the TPSR protocol is written as

$$y_R = \frac{1}{\sqrt{d_1^m}}\sqrt{(1-\beta) P_S} h_S x_S + \sqrt{(1-\beta)} n_R. \tag{3}$$

By applying the AF relaying protocol, the relay amplifies the received messages by a factor G defined as

$$G = \frac{1}{\sqrt{(1-\beta) P_S |h_S|^2 / d_1^m + \sigma_R^2}}. \tag{4}$$

After processing the received signal at relay mobile node, the AF based relay amplifies the source signal and forwards it to the destination mobile node with power of P_R, which depends on the amount of energy harvested during the ES. The received signal at the destination mobile node, y_D, can be expressed as

$$y_D = \frac{\sqrt{P_R} h_D G}{\sqrt{d_2^m}} y_R + n_D, \tag{5}$$

where $n_D \sim CN(0, \sigma_D^2)$ denotes the additive white Gaussian noise (AWGN) introduced at the destination mobile node. Next, by substituting y_R and G from (3) and (4) into (5), y_D can be rewritten as

$$\begin{aligned} y_D = {} & \frac{\sqrt{(1-\beta) P_R P_S} h_S h_D x_S}{\sqrt{(1-\beta) P_S |h_S|^2 d_2^m + d_1^m \sigma_R^2}} \\ & + \frac{\sqrt{P_R d_1^m} h_D n_R}{\sqrt{(1-\beta) P_S |h_S|^2 d_2^m + d_1^m \sigma_R^2}} + n_D. \end{aligned} \tag{6}$$

On the other hand, the relay mobile node transmits the amplified signal using the harvested energy $E_h^{\rm TPSR}$ during energy harvesting time (ES) as a source of power for $(1-\alpha)T$ time, and hence the transmitted power from the relay mobile node P_R is calculated by

$$P_R = \frac{E_h^{\rm TPSR}}{(1-\alpha) T} = \eta \frac{P_S |h_S|^2}{d_1^m} \frac{\alpha\beta}{1-\alpha}. \tag{7}$$

By substituting the transmitted power P_R from (7) into (6), we obtain the received signal at the destination mobile node y_D which is illustrated as

$$y_D = \underbrace{\frac{\sqrt{\eta P_S \left|h_S\right|^2 \alpha\beta\left(1-\beta\right)} P_S h_S h_D x_S}{\sqrt{d_1^m d_2^m \left(1-\alpha\right)}\sqrt{\left(1-\beta\right) P_S \left|h_S\right|^2 + d_1^m \sigma_R^2}}}_{\text{Signal part}} + \underbrace{\frac{\sqrt{\eta P_S \left|h_S\right|^2 \alpha\beta d_1^m} h_D n_R}{\sqrt{d_2^m \left(1-\alpha\right)}\sqrt{\left(1-\beta\right) P_S \left|h_S\right|^2 + d_1^m \sigma_R^2}}}_{\text{Noise part}} + n_D. \tag{8}$$

Next, by calculation of power of signal part and power of noise part, we obtain the end-to-end SNR at the destination as follows:

$$\text{SNR}_D = \frac{\eta\alpha\beta\left(1-\beta\right) P_S \left|h_S\right|^2 \left|h_D\right|^2}{\eta\alpha\beta\left|h_D\right|^2 d_1^m \sigma_R^2 + \left(1-\alpha\right)\left(1-\beta\right) d_1^m d_2^m \sigma_D^2 + \left(1-\alpha\right) d_1^{2m} \sigma_R^2 \sigma_D^2 / P_S \left|h_S\right|^2}. \tag{9}$$

3.2. Throughput Analysis. In this work, we consider the delay-limited transmission mode, where the achievable throughput τ^{TPSR} is determined by evaluating the outage probability $P_{\text{out}}^{\text{TPSR}}$ of the system with a fixed source transmission rate R (bps/Hz). We have $R \triangleq (1/2)\log_2(1+\text{SNR}_0)$ and denote SNR_0 as the threshold signal-to-noise ratio for exact data detection at the destination. Moreover, in order to analyze the outage probability of the TPSR protocol at the destination mobile node, we first obtain the instantaneous mutual information between the relay and the destination mobile node which is given by

$$I_{RD} \triangleq \left(\frac{1}{2}\right)\log_2\left(1+\text{SNR}_D\right), \tag{10}$$

where SNR_D is the signal-to-noise ratio at the destination mobile node, and then we formulate the outage probability of the system as the probability that the instantaneous mutual information I_{RD} is below fixed source transmission rate R. Therefore, the outage probability of the system can be shown as

$$P_{\text{out}}^{\text{TPSR}} = \Pr\left(I_{RD} < R\right) = \Pr\left(\text{SNR}_D < \text{SNR}_0\right), \tag{11}$$

where $\Pr(\cdot)$ is probability operation and the value SNR_0 can be calculated by $\text{SNR}_0 = 2^{2R} - 1$. Specifically, we derive the closed-form SNR_D as the following expression because we can ignore the infinitesimal element with respect to $(1-\alpha)d_1^{2m}\sigma_R^2\sigma_D^2/P_S|h_S|^2 \approx 0$ at high SNR. Therefore, the approximate outage probability $P_{\text{out}}^{\text{TPSR}}$ can be determined by

$$\begin{aligned} &P_{\text{out}}^{\text{TPSR}} \\ &\quad\approx \Pr\left(\frac{\eta\alpha\beta\left(1-\beta\right) P_S \left|h_S\right|^2 \left|h_D\right|^2}{\eta\alpha\beta\left|h_D\right|^2 d_1^m \sigma_R^2 + \left(1-\alpha\right)\left(1-\beta\right) d_1^m d_2^m \sigma_D^2}\right. \\ &\quad\left.< \text{SNR}_0\right) = \Pr\left(\left|h_D\right|^2\right. \\ &\quad\left.< \frac{\left(1-\alpha\right)\left(1-\beta\right) d_1^m d_2^m \sigma_D^2 \text{SNR}_0}{\eta\alpha\beta\left(1-\beta\right) P_S \left|h_S\right|^2 - \eta\alpha\beta d_1^m \sigma_R^2 \text{SNR}_0}\right). \end{aligned} \tag{12}$$

According to (12), we have the following proposition.

Proposition 1. *Let parameters for simplicity be* $\omega \triangleq \eta\alpha\beta d_1^m \sigma_R^2 SNR_0$, $\theta \triangleq (1-\alpha)(1-\beta)d_1^m d_2^m \sigma_D^2 SNR_0$, *and* $\psi \triangleq \eta\alpha\beta(1-\beta)P_S$. *The outage probability of the destination mobile node for the TPSR protocol in the energy harvesting networks is given by*

$$\begin{aligned} &P_{out}^{TPSR} \\ &\quad = Pr\left(\left|h_D\right|^2 < \frac{\theta}{\psi\left|h_S\right|^2 - \omega}\right) \\ &\quad = 1 - \exp\left(-\frac{\omega}{\psi\lambda_{h_S}}\right)\sqrt{\frac{4\theta}{\psi\lambda_{h_S}\lambda_{h_D}}} K_1\left(\sqrt{\frac{4\theta}{\psi\lambda_{h_S}\lambda_{h_D}}}\right), \end{aligned} \tag{13}$$

where λ_{h_S} *and* λ_{h_D} *are the mean of the exponential random variables of* $|h_S|^2$ *and* $|h_D|^2$, *respectively, and* $K_n(\cdot)$ *is the modified Bessel function of the second kind with the order* n *defined in [15].*

Proof. See the Appendix. ☐

The achievable throughput τ^{TPSR} of the TPSR protocol with the fixed rate R at the destination is demonstrated by

$$\begin{aligned} \tau^{\text{TPSR}} &= \left(1 - P_{\text{out}}^{\text{TPSR}}\right) R \frac{\left(1-\alpha\right) T}{T} \\ &= \left(1 - P_{\text{out}}^{\text{TPSR}}\right) R \left(1-\alpha\right). \end{aligned} \tag{14}$$

Therefore, the optimal throughput can be found by simulation due to its complexity, while the tractable expressions of the optimal throughput can be obtained in two special cases as analysis in the next subsection.

3.3. Optimal Throughput Analysis. In this paper, we assume that the CSI can be obtained by channel estimation. In principle, the AP sends a RTS (request-to-send) packet which is compatible with IEEE 802.11 wireless LAN standards. Based on the RTS information, the full CSI can be estimated. On the other hand, the power splitting and time switching factors in the proposed energy harvesting also can be extracted through RTS mechanism. When the relay and destination have the knowledge of h_S and h_D, respectively, maximizing the throughput can be described as

$$\begin{aligned}\tau_{\text{opt}} &= \underset{\alpha,\beta}{\arg\max}\, \tau^{\text{TPSR}} = \underset{\alpha,\beta}{\arg\max}\, R(1-\alpha) \\ &\cdot \left(\exp\left(-\frac{\omega}{\psi\lambda_{h_S}}\right)\sqrt{\frac{4\theta}{\psi\lambda_{h_S}\lambda_{h_D}}}K_1\left(\sqrt{\frac{4\theta}{\psi\lambda_{h_S}\lambda_{h_D}}}\right)\right).\end{aligned} \tag{15}$$

In addition, we adopt the offline store-and-transmit protocol [15]; the relay stores the harvested energy at the fixed level and then forwards information to the destination thanks to its scavenged energy. In particular, the required power P_0 for further information process at the relay can be expressed as

$$P_0 = \frac{\eta\alpha_0\beta_0 P_S|h_S|^2}{d_1^m(1-\alpha)}, \tag{16}$$

where α_0 and β_0 denote time and power allocation coefficients which are known by RTS mechanism.

Interestingly, due to the complexity of the involved expression in (15), we derive the closed-form expression of throughput in case of high SNR (i.e., $\sigma_R^2/P_S \to 0$). By applying the following approximation $e^{-x} \sim 1-x$ and $K_1(x) \sim 1/x$ as $x \to 0$, we obtain new formula of optimal throughput as follows:

$$\begin{aligned}\tau_{\text{opt}} &= \underset{\alpha,\beta}{\arg\max}\, R(1-\alpha)\left(1-\exp\left(-\frac{\omega}{\psi\lambda_{h_S}}\right)\right) \\ &= \underset{\alpha,\beta}{\arg\max}\, R(1-\alpha)\left(1-\frac{\sigma_R^2\text{SNR}_0}{(1-\beta)P_S\lambda_{h_S}}\right).\end{aligned} \tag{17}$$

Next, there are two cases of optimization problems which are considered as the tractable expressions of the optimal throughput after some manipulations.

Case 1. The fixed power allocation and high SNR are as follows:

$$\begin{aligned}\tau_{\text{opt}} &= R\left(1-\frac{P_0}{\eta P_S|h_S|^2\beta_0 + P_0 d_1^m}\right) \\ &\cdot \left(1-\frac{\sigma_R^2\text{SNR}_0}{(1-\beta_0)P_S\lambda_{h_S}}\right).\end{aligned} \tag{18}$$

Case 2. The fixed time allocation and high SNR are as follows:

$$\begin{aligned}\tau_{\text{opt}} &= R(1-\alpha_0) \\ &\cdot \left(1-\frac{\sigma_R^2\text{SNR}_0}{\left(1-P_0(1-\alpha)d_1^m/\alpha\eta P_S|h_S|^2\right)P_S\lambda_{h_S}}\right).\end{aligned} \tag{19}$$

4. Ideal Relay Receiver

In this section, we assume the scenario with an ideal relay receiver at the relay mobile node, where simultaneous energy harvesting and information transmission between the source and the destination mobile node are extracted by the same received signal. Half of the block time, $T/2$, is used to harvest energy and process the information at the relay mobile node. The remaining half, $T/2$, is used for the relay to destination mobile node information transmission [6].

We consider the energy harvesting collected from source node and denote it as E_h^{ideal} given by

$$E_h^{\text{ideal}} = \frac{\eta P_S|h_S|^2}{d_1^m}\left(\frac{T}{2}\right). \tag{20}$$

Similarly, we obtain the received signal y_R' at the input of the ideal receiver as the following expression:

$$y_R' = \frac{1}{\sqrt{d_1^m}}\sqrt{P_S}h_S x_S + n_R. \tag{21}$$

In this ideal case, the relay mobile node amplifies the received signal by a factor G' which is defined by

$$G' = \frac{1}{\sqrt{P_S|h_S|^2/d_1^m + \sigma_R^2}}. \tag{22}$$

Based on principle of ideal receiver, the transmitted power from the relay mobile node P_R' can be given by

$$P_R' = \frac{E_h^{\text{ideal}}}{T/2} = \frac{\eta P_S|h_S|^2}{d_1^m}, \tag{23}$$

where $T/2$ is the communication time from the relay mobile node to the destination mobile node in the block of time T seconds. As a result, substituting the values of P_R', G', and y_R' from (23), (22), and (21) into (6), the received signal at the destination, y_D', is given by

$$\begin{aligned}y_D' &\\ &= \underbrace{\frac{\sqrt{\eta P_S|h_S|^2 P_S}h_S h_D x_S}{\sqrt{d_1^m}\sqrt{P_S|h_S|^2 + d_1^m\sigma_R^2}}}_{\text{Signal part}} + \underbrace{\frac{\sqrt{\eta P_S|h_S|^2 d_1^m}h_D n_R}{\sqrt{d_1^m}\sqrt{P_S|h_S|^2 + d_1^m\sigma_R^2}} + n_D}_{\text{Noise part}}.\end{aligned} \tag{24}$$

In the following, we calculate the SNR at the destination mobile node which is modeled as

$$\text{SNR}_D' = \frac{\eta P_S|h_S|^2|h_D|^2}{\eta d_1^m|h_D|^2\sigma_R^2 + d_1^m\sigma_D^2 + d_1^{2m}\sigma_R^2\sigma_D^2/P_S|h_S|^2}. \tag{25}$$

Similar to the analysis in previous section, the throughput is determined by evaluating the outage probability. Interestingly, the closed-form expression of $P_{\text{out}}^{\text{ideal}}$ can be calculated as $P_{\text{out}}^{\text{TPSR}}$:

$$P_{\text{out}}^{\text{ideal}} = \Pr\left(\left|h_D\right|^2 < \frac{\theta}{\psi\left|h_S\right|^2 - \omega}\right), \tag{26}$$

where $P_{\text{out}}^{\text{ideal}}$ can be calculated as in the Appendix with $\theta \triangleq d_1^m \sigma_D^2 \text{SNR}_0$, $\psi \triangleq \eta P_S$, and $\omega \triangleq \eta d_1^m \sigma_R^2 \text{SNR}_0$. In this case, we also consider the delay-limited transmission mode for evaluating the throughput τ^{ideal} at the destination which is given by

$$\tau^{\text{ideal}} = \left(1 - P_{\text{out}}^{\text{ideal}}\right)\frac{R}{2}. \tag{27}$$

5. Numerical Results

In this section, we present numerical results in order to illustrate the solution to the optimization throughput problems of the AF energy harvesting enabled relaying scheme in the proposed TPSR protocol, namely, the optimal value of throughput τ, optimal value of signal processing time α, and power splitting ratio β.

In these simulations, we set up common parameters as follows: the distances d_1 and d_2 are normalized to be 1 (i.e., $d_1 = d_2 = 1$), the energy harvesting efficiency $\eta = 0.7$, the fixed transmission rate of the source $R = 4$ (bps/Hz), source transmission power $P_S = 2$ (Watt), destination transmission power $P_D = 2$ (Watt), and path loss exponent $m = 2.7$. In all simulations, λ_{h_S} and λ_{h_D} are denoted as the mean values of the exponential random variables $|h_S|^2$ and $|h_D|^2$, respectively, and set to 1. The simulation results depend on the expressions for outage probability in (12) which is evaluated by averaging these calculations over 10^5 random realizations of the Rayleigh fading channels of h_S and h_D.

As observation, Figures 4 and 5 show that simulation results of achievable throughput perfectly match the analytical results for the optimal values range of $0 < \alpha < 1$ and $0 < \beta < 1$ for the TPSR protocol. In this illustration, similar noise variances at the relay and destination mobile nodes are assumed; that is, $\sigma_R^2 = \sigma_D^2 = \sigma^2 = 0.01$. As can be seen from Figure 4, the throughput increases from 0 to 1.25 when α increases from 0.01 to 0.35 but later it starts decreasing as α increases from its optimal value (for $\beta = 0.7$) and the throughput increases from 0 to 0.95 as α increases from 0.01 to 0.45 but then decreases as α increases from its optimal value (for $\beta = 0.3$). In Figure 5, the throughput increases from 0 to 1.25 as β increases from 0.01 to 0.7 but later it starts decreasing as β increases (for $\alpha = 0.3$), and the throughput increases from 0 to 0.84 as β increases from 0.01 to 0.6 but then decreases as β increases from its optimal value (for $\alpha = 0.7$). Interestingly, in the case when value of α increases, we obtain optimal throughput only if β decreases and vice versa. We can explain important results that the value of α is smaller than the optimal value of α which means that there is less time for energy harvesting and more time for information transmission. As a result, less energy is harvested and throughput achieved at the destination mobile node is greater. In contrast, when the value of α is greater than the optimal α, there is more time for energy harvesting but less time for information transmission. Furthermore, when the value of β is smaller than the optimal β, there is less

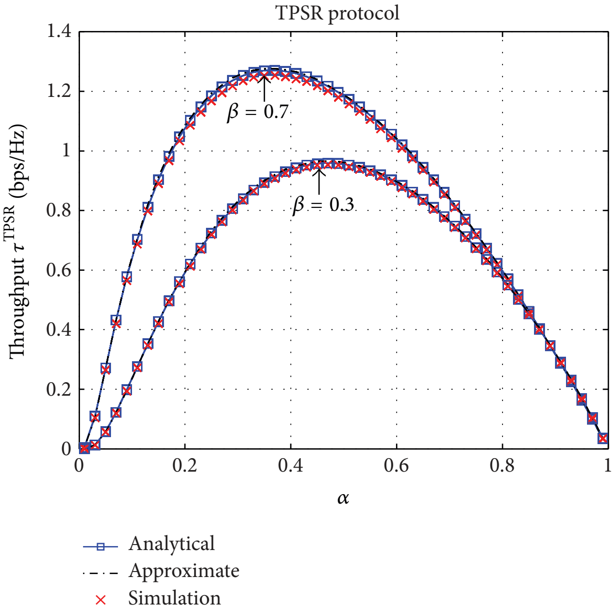

Figure 4: Simulation based and analytical throughput τ at the destination with respect to the fraction of the block time switching.

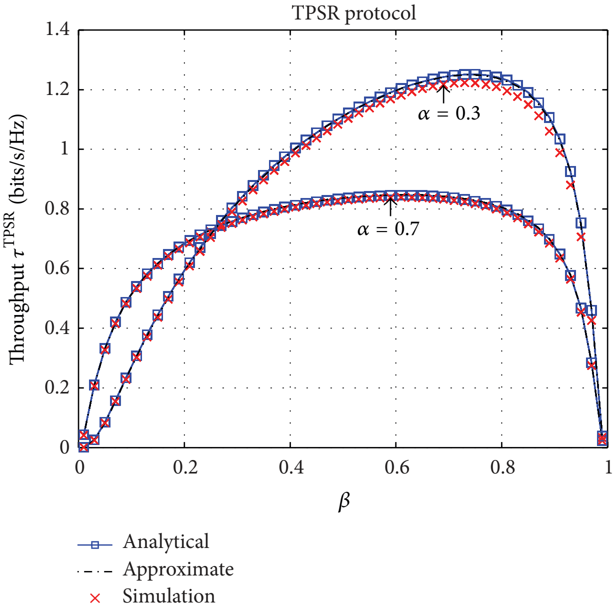

Figure 5: Simulation based and analytical throughput τ at the destination with respect to the fraction of power splitting.

power available for energy harvesting and more power for processing the received signal. Thus, high signal strength is observed at the relay mobile node and results in higher throughput at the destination mobile node. In addition, in case the value of β is greater than the optimal β, more power is wasted on energy harvesting and less power for information transmission from the source to relay mobile node.

For comparison, Figure 6 depicts the optimal throughput τ of the TPSR protocol and the ideal receiver for different values of noise variance σ^2. In fact, the simulation result shows that the throughput in the ideal case always outperforms that in the TPSR case. The optimal throughput roughly remains constant when noise variance changes from −40 dB to −30 dB. In contrast, the system's throughput performance decreases dramatically when a larger number of noise variances occur.

6. Conclusions

This paper proposes TPSR protocol and the design of the receiver architecture for wireless energy harvesting and information transmission in the EHCN. In addition, the outage performance of the AF relaying scheme where the relay mobile node harvests energy from source node through the received RF signal and then uses harvested energy to amplify the information and forward the source signal to the destination mobile node has been derived. For simplicity in computation, we also develop the closed-form expression of the achievable throughput at the destination. More importantly, the optimal values of time switching and power splitting ratio for energy harvesting in the proposed TPSR protocol which are chosen in order to maximize the throughput of the system were also numerically investigated.

Appendix

In the following, we derive the outage probability in (12) which is given by (A.1), where $\theta \triangleq (1-\alpha)(1-\beta)d_1^m\sigma_D^2\mathrm{SNR}_0$, $\psi \triangleq \eta\alpha\beta(1-\beta)P_S$, and $\omega \triangleq \eta\alpha\beta d_1^m\sigma_R^2\mathrm{SNR}_0$:

$$P_{\text{out}}^{\text{TPSR}} = \Pr\left(\left|h_D\right|^2 < \frac{\theta}{\psi\left|h_S\right|^2-\omega}\right). \tag{A.1}$$

It is observed and also can be verified that the factor in the denominator $\psi|h_S|^2 - \omega \neq 0$. Thus, $P_{\text{out}}^{\text{TPSR}}$ is rewritten in two cases as follows:

(i) If $|h_S|^2 > \omega/\psi$

$$P_{\text{out}}^{\text{TPSR}} = \Pr\left(\left|h_D\right|^2 < \frac{\theta}{\psi\left|h_S\right|^2-\omega}\right). \tag{A.2}$$

(ii) If $|h_S|^2 < \omega/\psi$

$$P_{\text{out}}^{\text{TPSR}} = \Pr\left(\left|h_D\right|^2 > \frac{\theta}{\psi\left|h_S\right|^2-\omega}\right) = 1. \tag{A.3}$$

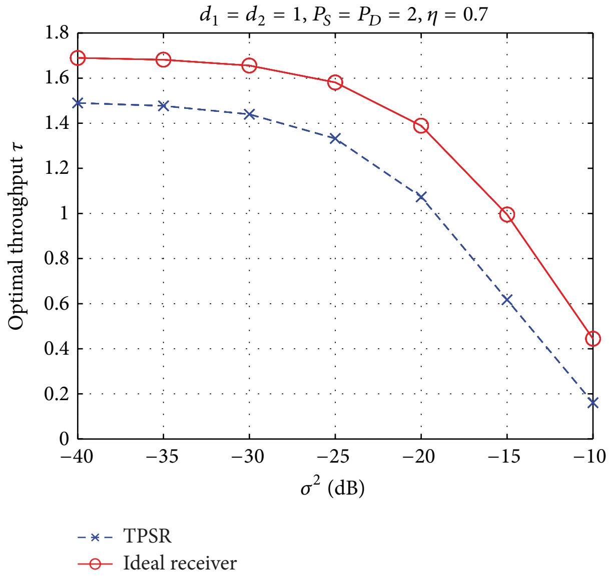

Figure 6: The optimal throughput achieved for the TPSR protocol and the ideal receiver by the different value of noise.

We obtain the equality $\Pr(|h_D|^2 > \theta/(\psi|h_S|^2-\omega)) = 1$ due to the fact that if the value of $|h_S|^2 < \omega/\psi$, with ω/ψ being the factor in denominator, $\psi|h_S|^2 - \omega$ will be a negative number and probability of $|h_D|^2$ being greater than some negative number is always equal to 1. Therefore, $P_{\text{out}}^{\text{TPSR}}$ can be rewritten as

$$\begin{aligned} P_{\text{out}}^{\text{TPSR}} &= \int_0^{\omega/\psi} \Pr\left(\left|h_D\right|^2 > \frac{\theta}{\psi\gamma-\omega}\right) p_{|h_S|^2}(\gamma)\,d\gamma \\ &\quad + \int_{\omega/\psi}^{\infty} \Pr\left(\left|h_D\right|^2 < \frac{\theta}{\psi\gamma-\omega}\right) p_{|h_S|^2}(\gamma)\,d\gamma \\ &= \int_0^{\omega/\psi} p_{|h_S|^2}(\gamma)\,d\gamma \\ &\quad + \int_{\omega/\psi}^{\infty} \Pr\left(1-\exp\left\{-\frac{\theta}{(\psi\gamma-\omega)\lambda_{h_D}}\right\}\right) \\ &\quad \cdot p_{|h_S|^2}(\gamma)\,d\gamma, \end{aligned} \tag{A.4}$$

where γ is the integration variable, $p_{|h_S|^2}(\gamma) \triangleq (1/\lambda_{h_S})e^{-\gamma/\lambda_{h_S}}$ is the probability density function (PDF) of exponential distributed random variable $|h_S|^2$, and $F_{|h_D|^2}(\gamma) \triangleq \Pr(|h_D|^2 < \gamma) = 1 - e^{-\gamma/\lambda_{h_D}}$ is the cumulative distribution function (CDF) of the exponential distributed random variable $|h_D|^2$. Thus, $P_{\text{out}}^{\text{TPSR}}$ can be calculated by

$$\begin{aligned} P_{\text{out}}^{\text{TPSR}} &= 1 \\ &\quad - \frac{1}{\lambda_{h_S}} \int_{\omega/\psi}^{\infty} \exp\left\{-\frac{\gamma}{\lambda_{h_S}} - \frac{\theta}{(\psi\gamma-\omega)\lambda_{h_D}}\right\} d\gamma. \end{aligned} \tag{A.5}$$

Let us define a new integration variable $\mu = \psi\gamma - \omega$. Thus, outage probability is given by [15]

$$\begin{aligned} P_{\text{out}}^{\text{TPSR}} &= 1 - \frac{1}{\psi\lambda_{h_S}} \exp\left(-\frac{\omega}{\psi\lambda_{h_S}}\right) \\ &\quad \cdot \int_{\mu=0}^{\infty} \exp\left(-\frac{\mu}{\psi\lambda_{h_S}} - \frac{\theta}{\mu\lambda_{h_D}}\right) d\mu = 1 \\ &\quad - \exp\left(-\frac{\omega}{\psi\lambda_{h_S}}\right)\sqrt{\frac{4\theta}{\psi\gamma_{h_S}\gamma_{h_D}}}\, K_1\left(\sqrt{\frac{4\theta}{\psi\gamma_{h_S}\gamma_{h_D}}}\right). \end{aligned} \tag{A.6}$$

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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