Block-Wise Time-Switching Energy Harvesting Protocol for Wireless-Powered AF Relays

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***Abstract*—We consider wireless-powered amplify-and-forward relaying in cooperative communications and propose block-wise time-switching based energy harvesting protocol to implement wireless energy harvesting (EH) and information transmission (IT) at the energy constrained relay node. The time-switching EH protocol switches the relay operation between EH and IT such that during EH, relay harvests energy through the received radio-frequency signal from the source and during IT, the relay receives information signal from the source and uses the harvested energy to amplify and forward source signal to the destination. In our proposed block-wise time-switching EH protocol, the whole transmission block time is used for either EH or IT. The attractive feature of our proposed protocol is that the relay transmits at preset fixed transmit power and no channel state information is required either by the source or relay node. We derive exact expression of the analytical throughput for the proposed protocol and verify it through simulation. In addition, we show that our proposed protocol outperforms the existing time-switching EH protocol because it allows efficient use of resources by intelligently switching between EH and IT in an online fashion.**

***Index Terms*—Wireless energy harvesting, wireless communications, amplify-and-forward, throughput.**

I. Introduction

Recently, wireless energy harvesting (EH) through radio frequency (RF) signals to power nodes in future wireless networks has received much attention [1], [2]. The basic concept of simultaneous wireless information and power transfer (SWIPT) was first proposed in [3] and a more comprehensive receiver architecture and the corresponding rate-energy tradeoff was then developed in [4]. Later, the concept of SWIPT was extended to two-user multiple-input-multiple-output [5], orthogonal frequency division multiplexing [6], and cooperative relaying [7]–[9] based systems.

In cooperative relaying networks, relay node assists in the transmission of the source information to the destination. However, due to limited power supply, a relay node may need to rely on external charging mechanism in order to remain active in the network [7], [8]. Consequently, EH in such networks is an alternate way to enable information relaying. Recently, EH through RF signals in wireless relaying networks is considered in [7]–[10]. Specifically, [10] considered multi-user and multi-hop systems to study SWIPT while assuming that the relay node is able to decode the information and extract power simultaneously. However, as explained in [4], this may not hold in practice. In [9], outage performance of an amplify-and-forward (AF) relaying network under EH constraints was studied, while assuming perfect channel knowledge for the relay-to-destination link at the relay transmitter. In [7], the power allocation strategies and outage performance of decode-and-forward (DF) relaying network under EH constraints were analyzed. The studies in [9] and [7] do not analyze analytical expressions for the achievable throughput at the destination node. Recently, the authors in [8] investigated the throughput performance of an AF relaying network under EH constraints and proposed EH time-duration to be a fixed percentage of the transmission block time. However, fixed time-duration EH protocol in [8] may result in non-efficient use of resources. This is because the harvested energy in each block is not controllable and depends on the fading channel quality. If the channel is in deep fade, the harvested energy will be small, resulting in outage at the destination due to insufficient relaying power. On the other hand, if the channel is strong, the harvested energy will be large, which although guarantees a successful relay transmission but is a waste of energy. In this paper, we address the non-efficient resource usage of the protocol in [8] without increasing the system complexity. The main contributions of this work are summarized below:

- We propose a new block-wise time-switching EH protocol for energy-constrained AF relaying network where relay transmits with a preset fixed value of transmit power. Considering block-wise transmission over quasi-static fading channels, a whole block is either used for EH or information transmission (IT). Specifically, the relay continues to harvest energy from the RF signal transmitted by the source node until it has harvested sufficient energy to be able to transmit the source information in the next block with the fixed preset transmit power. Given there could be extra harvested energy at the end of an EH block prior to an IT block, we allow storage of extra harvested energy for future use.
- We derive an exact analytical expression of the achievable throughput for the proposed protocol. Using the derived expression, we determine the throughput performance as a function of relay transmit power and the noise power. Specifically, the relay transmit power is an important and controllable parameter that can be optimally chosen for the best throughput performance.
- Our simulations results show that the proposed protocol outperforms the existing fixed time-duration EH protocol in the literature. This is because the proposed protocol allows efficient use of resources since it intelligently tracks the level of the harvested energy to switch between EH and IT in an online fashion. This benefit comes

The work of A. A. Nasir, X. Zhou, and S. Durrani was supported under Australian Research Council's Discovery Projects funding scheme (project number DP140101133).

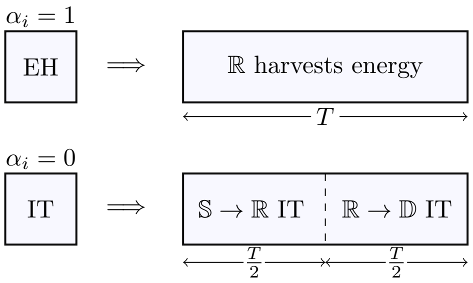

Fig. 1. Illustration of EH and IT blocks.

with no increase in the complexity as it does not require channel state information at the source or relay.

II. System Model and Assumptions

We consider a wireless AF relaying scenario with one source node, $\mathbb{S}$, one destination node, $\mathbb{D}$, and one *energy constrained* relay node $\mathbb{R}$. We assume that the destination is out-of-direct-communication-range with the source node. Thus, the intermediate relay node assists in the transmission of the source messages to the destination.

A. Channel Assumptions

We assume that the $\mathbb{S} \to \mathbb{R}$ and $\mathbb{R} \to \mathbb{D}$ channel links are composed of large scale path loss and statistically independent small-scale Rayleigh fading. The $\mathbb{S} \to \mathbb{R}$ and $\mathbb{R} \to \mathbb{D}$ fading channel gains, denoted by h and g, respectively, are modeled as quasi-static and frequency non-selective parameters. Consequently, the complex fading channel coefficients h and g are circular symmetric complex Gaussian random variables with zero mean and unit variance, which are assumed to be constant over a *block time* of T seconds and independent and identically distributed from one block to the next [4], [7], [9]. We do not assume any knowledge about channel state information at the source and relay nodes.

B. Relay Receiver

We assume that the relay receiver has two circuits to perform EH and IT separately and the receiver adopts the time-switching strategy [8], i.e., the relay switches its operation between EH and IT. During EH, relay harvests energy through the received RF signal from the source for the block time T and during IT, the relay receives information signal from the source and uses the harvested energy to amplify and forward source signal to the destination with a preset fixed transmission power P_r. During IT, as indicated in Fig. 1, half of the time, $\frac{T}{2}$, is used for $\mathbb{S} - \mathbb{R}$ IT and the remaining half time, $\frac{T}{2}$, is used for $\mathbb{R} - \mathbb{D}$ IT. We use a binary variable α_i to indicate the relay operation during the ith transmission block, such that, if the block is used for EH, $\alpha_i = 1$ and if the block is used for IT, $\alpha_i = 0$. The relay checks the level of harvested energy at the start of each block. If the harvested energy is sufficient for IT, the relay sends 1 bit to the source and destination nodes to indicate IT for that block. In this work, for the sake of tractability, we assume that this control channel information is error free.

We assume that the processing power required by the transmit/receive circuitry at the relay is negligible as compared to the power used for signal transmission from the relay to the destination. This assumption is justifiable in practical systems when the transmission distances are large, such that the transmission energy is the dominant source of energy consumption [4], [11]. For the purpose of exposition, we also assume that the energy storage device has an infinite capacity [12].

C. Received Signal Model

The received signal at the relay node, $y_{r,i}$ is given by

$$y_{r,i} = \frac{1}{\sqrt{d_1^m}} \sqrt{P_s} h_i s_i + n_{r,i}, \tag{1}$$

where i is the block index, h_i is the $\mathbb{S} \to \mathbb{R}$ fading channel gain, d_1 is the source to relay distance, P_s is the source transmission power, m is the path loss exponent, $n_{r,i}$ is the additive white Gaussian noise (AWGN) at the relay node, s_i is either an energy signal (during EH block) or an information signal (during IT block) from the source, such that $\mathbb{E}\{|s_i|^2\} = 1$, where $\mathbb{E}\{\cdot\}$ is the expectation operator and $|\cdot|$ is the absolute value operator.

The AF relay first harvests sufficient energy to be able to transmit with preset power P_r during IT block. Thus, during IT block, the AF relay amplifies the received signal and forwards it to the destination. The signal transmitted by the relay, $x_{r,i}$, is given by

$$x_{r,i} = \frac{\sqrt{P_r} y_{r,i}}{\sqrt{\frac{P_s |h_i|^2}{d_1^m} + \sigma_{n_r}^2}}, \tag{2}$$

where $\sigma_{n_r}^2$ is the variance of the AWGN at the relay node and the factor in the denominator, $\sqrt{\frac{P_s|h_i|^2}{d_1^m} + \sigma_{n_r}^2}$ is the power constraint factor at the relay. Note that an AF relay can obtain the power constraint factor, $\sqrt{\frac{P_s|h_i|^2}{d_1^m} + \sigma_{n_r}^2}$, from the power of the received signal, $y_{r,i}$, and does not necessarily require source to relay channel estimation.

Following [8], the received signal at the destination during the ith block, y_i is given by

$$y_{d,i} = \frac{1}{\sqrt{d_2^m}} g_i x_{r,i} + n_{d,i} \tag{3a}$$

$$= \underbrace{\frac{\sqrt{P_r P_s} h_i g_i s_i}{\sqrt{d_2^m}\sqrt{P_s|h_i|^2 + d_1^m \sigma_{n_r}^2}}}_{\text{signal part}} + \underbrace{\frac{\sqrt{P_r d_1^m} g_i n_{r,i}}{\sqrt{d_2^m}\sqrt{P_s|h_i|^2 + d_1^m \sigma_{n_r}^2}} + n_{d,i}}_{\text{overall noise}}, \tag{3b}$$

where (3b) follows from (3a) by substituting $x_{r,i}$ from (2) into (3a), g_i is the $\mathbb{R} \to \mathbb{D}$ fading channel gain, d_2 is $\mathbb{R} \to \mathbb{D}$ distance, and $n_{d,i}$ is the AWGN at the destination node.

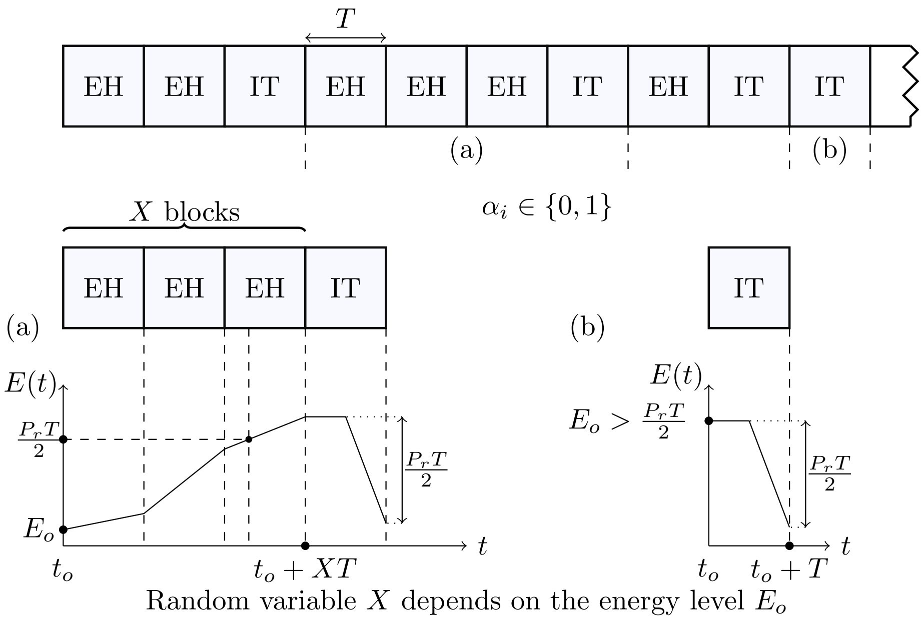

Fig. 2. Illustration of the proposed block-wise time-switching based EH protocol with different possible EH-IT patterns. (a) $X = 3$ EH blocks before an IT block, (b) $X = 0$ (a single IT block).

Using (3), the signal-to-noise-ratio (SNR) at the $\mathbb{D}$, $\gamma_{d,i} = \frac{\mathbb{E}_{s_i}\{|\text{signal part in(3b)}|^2\}}{\mathbb{E}_{n_{r,i},n_{d,i}}\{|\text{overall noise in (3b)}|^2\}}$, is given by

$$\gamma_{d,i} = \frac{\frac{P_s P_r |h_i|^2 |g_i|^2}{d_2^m (P_s |h_i|^2 + d_1^m \sigma_{n_r}^2)}}{\frac{P_r |g_i|^2 d_1^m \sigma_{n_r}^2}{d_2^m (P_s |h_i|^2 + d_1^m \sigma_{n_r}^2)} + \sigma_{n_d}^2}$$
$$= \frac{P_s P_r |h_i|^2 |g_i|^2}{P_r |g_i|^2 d_1^m \sigma_{n_r}^2 + d_2^m \sigma_{n_d}^2 (P_s |h_i|^2 + d_1^m \sigma_{n_r}^2)}, \quad (4)$$

where $\sigma_{n_d}^2$ is the AWGN variance at the destination node.

The ith block will suffer from outage if SNR, $\gamma_{d,i}$, is less than the threshold SNR, γ_o. Thus, the outage indicator, $I_{o,i}$ is given by

$$I_{o,i} = \mathbb{1}(\gamma_{d,i} < \gamma_o), \quad (5)$$

where $\mathbb{1}(\cdot)$ is an indicator function which is equal to 1 if its argument is true and 0 otherwise.

D. Figure of Merit

We use the *throughput efficiency* as the figure of merit. It is defined as the fraction of the total time used for successful information transmission, on average, where successful transmission implies the successful decoding of the source message at the destination. Note that we use the terms throughput efficiency and throughput interchangeably in the paper.

III. Proposed Block-wise Time-switching EH Relaying Protocol

In this section, we describe our proposed block-wise time-switching EH relaying protocol and derive exact analytical expression for the achievable throughput. By block-wise time-switching, we imply that each block is dedicated either for EH ($\alpha_i = 1$) or IT ($\alpha_i = 0$). Let us define $E_i(0)$ and $E_i(T)$ as the level of harvested energy at the start and end of the ith block, respectively. The proposed protocol works as follows.

The relay checks the level of harvested energy at the start of each block, i.e., $E_i(0)$ for the ith block. If $E_i(0) > \frac{P_r T}{2}$, the block is used for IT, otherwise it is used for EH. Note that $\frac{P_r T}{2}$ is the required energy to forward the source information to the destination with the fixed transmit power P_r. This is because relay has to transmit the source information for $T/2$ time with the power P_r (see Fig. 1).

Given there could be extra harvested energy at the end of an EH block prior to an IT block, we propose to store extra harvested energy for future use. Consequently, the number of EH blocks prior to an IT block will depend on the accumulated harvested energy and the quality of the source-to-relay channel.

For convenience, let us define a term, *EH-IT pattern*, as a pattern of blocks which either consists of a single IT block or contains a sequence of EH blocks followed by an IT block and let us define a symbol E_o as the available harvested energy at the start of any EH-IT pattern. As illustrated in Fig. 2, there can be two possible types of EH-IT patterns where t_o is the EH-IT pattern start time. (i) EH-IT pattern containing X successive EH blocks before an IT block, where X is a discrete random variable which depends on E_o. Note that an EH-IT pattern having a large E_o is more likely to have a small number of X blocks. (ii) EH-IT pattern containing a single IT block because $E_i(0) > \frac{P_r T}{2}$. In Fig. 2(a), the desired energy level is shown to be achieved somewhere in the middle of the third EH block and the EH-IT pattern contains $X = 3$ EH blocks before an IT block. Note that since the harvested energy during X EH blocks can exceed $\frac{P_r T}{2}$ and IT block only consumes $\frac{P_r T}{2}$ energy, E_o can have a value greater than

0.

A. Energy Analysis

Using (1), the total harvested energy during an EH block, denoted by $E_i^{0\to T}$, is given by

$$E_i^{0\to T}=\frac{\eta P_s|h_i|^2}{d_1^m}T, \tag{6}$$

where $0<\eta<1$ is energy harvesting efficiency. The value of α_i and $E_i(T)$ for the ith block is given by

$$\alpha_i=\begin{cases}1, & E_i(0)<\frac{P_rT}{2}\\ 0, & E_i(0)>\frac{P_rT}{2}\end{cases} \tag{7}$$

$$E_i(T)=\begin{cases}E_i(0)+E_i^{0\to T}=E_i(0)+\frac{\eta P_s|h_i|^2}{d_1^m}T, & \alpha_i=1\\ E_i(0)-\frac{P_rT}{2}, & \alpha_i=0\end{cases} \tag{8}$$

B. Throughput Analysis

Given that $\frac{T}{2}$ is the effective communication time within the block of time T seconds, the throughput, τ_i is given by

$$\tau_i=(1-I_{o,i})(1-\alpha_i)\frac{T/2}{T}=\frac{(1-I_{o,i})(1-\alpha_i)}{2}, \tag{9}$$

where the outage indicator, $I_{o,i}$, and EH time, α_i are defined in (5) and (7), respectively.

In order to determine the analytical throughput expression for our proposed protocol, we need to determine the distribution of E_o and the conditional distribution of $\bar{X}\triangleq X-1$, given the value of E_o, where $\bar{X}$ denotes the number of EH blocks that arrive within the energy interval $\left(E_o,\frac{P_rT}{2}\right]$. These are given in the lemmas below.

Lemma 1: The available harvested energy available at the start of any EH-IT pattern, E_o, is exponentially distributed with mean ρ and the probability density function (PDF)

$$f_{E_o}(\epsilon)=\frac{1}{\rho}e^{-\frac{\epsilon}{\rho}},\quad \epsilon>0 \tag{10}$$

where $\rho\triangleq\frac{\eta P_sT}{d_1^m}$.

Proof: Lemma 1 can be proved by following the memoryless property of the exponential distribution [13, Ch. 2]. Due to space limitation, the proof is not provided here. Please refer to [14] for the proof. ■

Lemma 2: Given the value of E_o, if $E_o<\frac{P_rT}{2}$, $\bar{X}\triangleq X-1$ is a Poisson random variable with parameter λ_p and the probability mass function (PMF) of $\bar{X}$ is given by the Poisson PMF,

$$p_{\bar{X}|E_o}(\bar{x}|E_o)=\frac{\lambda_p^{\bar{x}}\ e^{-\lambda_p}}{\bar{x}!},\quad E_o<\frac{P_rT}{2} \tag{11}$$

where $\lambda_p\triangleq\mathbb{E}\left\{\bar{X}|E_o\right\}=\frac{1}{\rho}\left(\frac{P_rT}{2}-E_o\right)$ and $\bar{X}\in\{0,1,2,\ldots\}$. If $E_o\geq\frac{P_rT}{2}$, $X=0$, i.e., it is a constant.

Proof: Since $|h_i|^2$ is exponentially distributed with the PDF $f_{|h_i|^2}(z)\triangleq e^{-z}$, the harvested energy per block interval, $E_i^{0\to T}=\frac{\eta P_s|h_i|^2}{d_1^m}T$ in (6), is exponentially distributed with parameter $\frac{1}{\rho}$, i.e., $f_{E_i^{0\to T}}(\epsilon)=\frac{1}{\rho}e^{-\frac{\epsilon}{\rho}}$. Note that $\bar{X}=X-1$ denotes the number of EH blocks that arrive within the energy interval $\left(E_o,\frac{P_rT}{2}\right]$. Since the energy harvested per EH block, $E_i^{0\to T}$, is exponentially distributed, the number of EH blocks required to harvest the required energy, $\frac{P_rT}{2}-E_o$, follows a Poisson random variable with parameter $\frac{1}{\rho}\left(\frac{P_rT}{2}-E_o\right)$ [13, Ch. 2]. Consequently, $\bar{X}$, given E_o, is a Poisson random variable with the Poisson PMF defined in (11) [13, Theorem 2.2.4]. ■

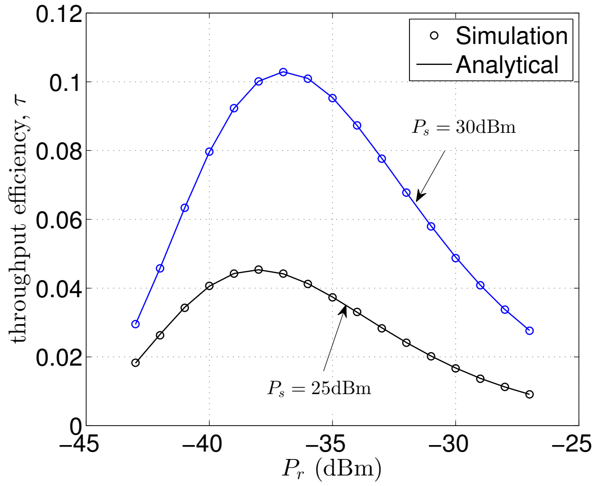

Fig. 3. Throughput efficiency, τ with respect to the preset relay power, P_r, for the proposed protocol.

Using Lemmas 1 and 2, we can derive the analytical throughput result for the proposed protocol, which is given in Theorem 1 below.

Theorem 1: The throughput for the proposed block-wise time-switching EH Protocol is given by

$$\tau=\frac{e^{-\frac{a+d}{c}}uK_1(u)}{2\left(1+\frac{P_rd_1^m}{2\eta P_s}\right)}, \tag{12}$$

where $a\triangleq P_sd_2^m\sigma_{n_d}^2\gamma_o$, $b\triangleq d_1^md_2^m\sigma_{n_r}^2\sigma_{n_d}^2\gamma_o$, $c\triangleq P_sP_r$, $d\triangleq P_rd_1^m\sigma_{n_r}^2\gamma_o$, $u\triangleq\sqrt{\frac{4(ad+bc)}{c^2}}$, and $K_1(\cdot)$ is the first-order modified Bessel function of the second kind [15].

Proof: The proof is given in Appendix A ■

IV. Numerical Results and Discussion

In this section, we present numerical results to demonstrate the performance of the proposed protocol as a function of the system parameters. We set the path loss exponent, $m=3$, and the energy conversion efficiency, $\eta=0.5$. Unless otherwise stated, we set the source power $P_s=30$ dBm, threshold SNR, $\gamma_o=10$ dB, the distances, $d_1=200$ and $d_2=50$ meters, and the noise variances at the relay and the destination nodes, $\sigma_n^2\triangleq\sigma_{n_r}^2=\sigma_{n_d}^2=-100$ dBm respectively.

A. Verification of Analytical Result

First, we present simulation results to verify the derived analytical throughput in Theorem 1. In the simulations, the

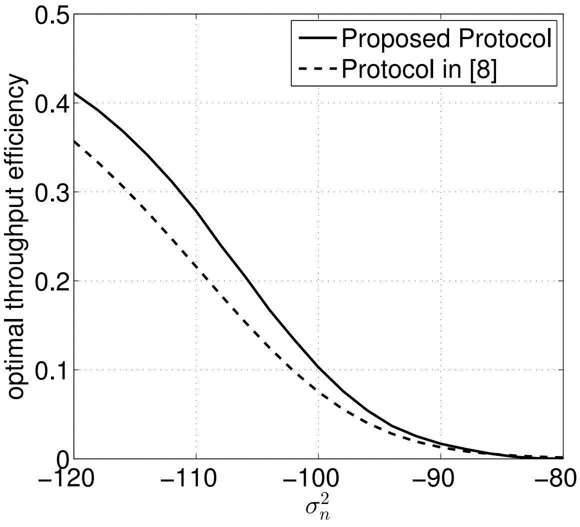

Fig. 4. Optimal throughput efficiency versus noise variance, σ_n^2, for the proposed protocol and the fixed time-duration EH protocol in [8].

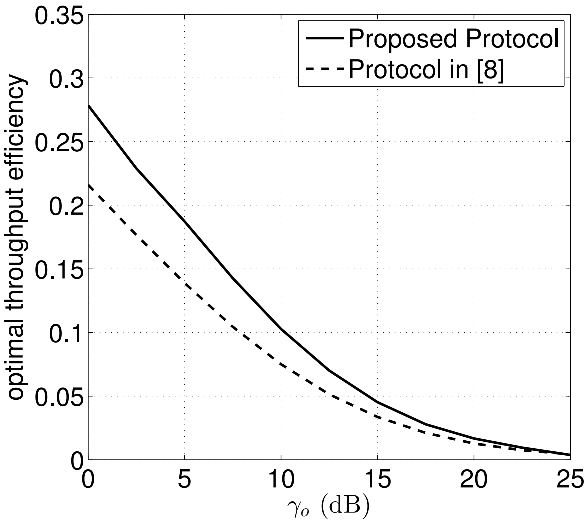

Fig. 5. Optimal throughput efficiency versus detection threshold SNR, γ_o for the proposed protocol and the fixed time-duration EH protocol in [8].

throughput is evaluated by averaging out the block throughput τ_i over a 100,000 blocks, while generating independent fading channels, h_i and g_i, for each block. Fig. 3 plots the analytical and simulation based throughput, τ versus relay power, P_r, for our proposed protocol. In Fig. 3, the analytical results for AF relaying are plotted by numerically evaluating the throughput derived in Theorem 1. The simulation results match perfectly with the analytical results for different values of source power, $P_s = \{25, 30\}$ dBm. This validates the result in Theorem 1.

It can be seen from Fig. 3 that the throughput can vary significantly with P_r. In order to achieve the maximum throughput, we have to choose the optimal relay transmission power. Given the complexity of the expression in Theorem 1, it seems intractable to find the closed-form expression for the optimal relay power, P_r, which would maximize the throughput, τ. However, such an optimization can be done offline for the given system parameters. In the following subsection, we adopt the maximum throughput for some optimal preset relay power P_r as the figure of merit and refer to it as the *optimal throughput*.

B. Performance of the Proposed Protocol vs Existing Protocol

Figs. 4 and 5 plot the optimal throughput for the proposed and the existing protocol [8] as a function of noise variance, σ_n^2, and SNR threshold, γ_o, respectively. The protocol in [8] considers fixed time-duration EH where the optimal time-duration for EH is used to plot the optimal throughput result. We can see from Figs. 4 and 5 that the proposed protocol outperforms the existing time-switching protocol in [8] for a wide range of noise variance ($\sigma_n^2 \in (-120, -90)$ dBm) and wide range of threshold SNR ($\gamma_o \in (0, 20)$ dBs). Particularly, in order to achieve optimal throughput efficiency of 0.2, the proposed protocol outperforms the existing protocol in [8] by approximately 3 dB margin. This performance improvement for the proposed protocols is due to the more efficient use of resources and can be intuitively explained as follows. With the fixed time-duration EH protocol in [8], the harvested energy in each block is uncontrollable and depends on the quality of the $\mathbb{S}\rightarrow\mathbb{R}$ fading channel. When the $\mathbb{S}\rightarrow\mathbb{R}$ channel is in deep fade, the harvested energy for the relay transmission will be very small which may result in outage at the destination due to insufficient relaying power, P_r. When the $\mathbb{S}\rightarrow\mathbb{R}$ channel is very strong, the harvested energy will be very large, which although guarantees a successful transmission but results in the waste of energy. On the other hand, the proposed protocol adapts the EH time-duration to meet a preset relaying power which can be carefully chosen to achieve throughput efficient performance.

It must be noted that the performance improvement of the proposed protocols comes at a marginal expense that the relay needs to alert the source and destination nodes for IT by sending a single bit at the start of the block, which is a negligible overhead as compared to the amount of data being communicated. Moreover, from an implementation complexity perspective, there is no difference between the proposed protocol and the protocol in [8]. The proposed protocol varies EH time-duration to meet a fixed P_r, while the protocol in [8] varies P_r to meet fixed EH time-duration. Consequently, for the proposed protocol, while the relay has to monitor its available energy to decide between EH or IT block, the relay always transmits at the same power P_r, which eases the hardware design at the relay. On the other hand, the variable transmission power for the protocol in [8] increases hardware complexity and may require a large dynamic range of the power amplifier at the relay.

V. Conclusions

In this paper, we have proposed a block-wise time-switching-based protocol for EH and IT in AF relaying. The proposed protocol switches the relay operation between EH and IT such that during EH block, relay harvests energy through the received RF signal from the source and during IT block, the relay receives information signal from the source and uses the harvested energy to amplify and forward source signal to the destination. The relay decides its operation between EH and IT based on the available harvested energy and source-to-relay channel quality. The attractive feature of the proposed protocol is that the relay transmits at preset fixed transmit power and no channel state information is required either by the source or the relay node. We also derived the analytical expression for the achievable throughput of the proposed protocol and verified it by comparing with simulation results. Finally, it has been shown through simulations that the proposed protocol outperforms the existing protocol for a wide range of noise variance and threshold SNR.

Appendix A
Proof of Theorem 1 in (12)

This appendix derives the analytical expression for the throughput τ, in (12). Note that in the block throughput expression $\tau_i = \frac{(1-I_{o,i})R(1-\alpha_i)}{2}$, given in (9), block outage indicator, $I_{o,i}$, is independent of the EH time, α_i. This is because $I_{o,i}$ depends on the fading channels, h_i and g_i, of the current block. However, α_i depends on the accumulated harvested energy at the start of the block, $E_i(0)$ (see (7)), which in turn depends on the $\mathbb{S}-\mathbb{R}$ fading channels of the previous blocks, i.e., $\{h_{i-1}, h_{i-2}, \ldots\}$. Thus, throughput, τ, is given by

$$\tau = \frac{1}{2}\ \mathbb{E}_{h_i,g_i}\{1-I_{o,i}\}\ \ \mathbb{E}_{\mathbf{h}\setminus h_i}\{1-\alpha_i\}. \tag{A.1}$$

where $\mathbf{h} \triangleq \{h_i, h_{i-1}, h_{i-2}, \ldots\}$.

Let us first calculate the first expectation in (A.1), i.e., $\mathbb{E}_{h_i,g_i}\{1-I_{o,i}\}$. Substituting $\gamma_{d,i}$ from (4) into (5) and using the notations, a, b, c, d, defined below (12), the outage indicator, $I_{o,i}$, is given by

$$\begin{aligned} I_{o,i} &= \mathbb{1}\left((c|h_i|^2-d)|g_i|^2 < (a|h_i|^2+b)\right) \\ &= \begin{cases} \mathbb{1}\left(|g_i|^2 < \frac{a|h_i|^2+b}{c|h_i|^2-d}\right), & |h_i|^2 > d/c \\ \mathbb{1}\left(|g_i|^2 > \frac{a|h_i|^2+b}{c|h_i|^2-d}\right) = 1, & |h_i|^2 < d/c. \end{cases} \end{aligned} \tag{A.2}$$

As mentioned in Section II, $|g_i|^2$ is an exponential random variable with unit mean, i.e., $\mathbb{E}_{g_i}\left\{\mathbb{1}(|g_i|^2 < z)\right\} \triangleq (1-e^{-z})\,\mathbb{1}(z)$, thus, $\mathbb{E}_{g_i}\{1-I_{o,i}\}$ is given by

$$\begin{aligned} \mathbb{E}_{g_i}\{1-I_{o,i}\} &= \begin{cases} e^{-\frac{a|h_i|^2+b}{c|h_i|^2-d}}, & |h_i|^2 > d/c \\ 0, & |h_i|^2 < d/c \end{cases} \\ &= e^{-\frac{a|h_i|^2+b}{c|h_i|^2-d}}\,\mathbb{1}\left(|h_i|^2 > d/c\right). \end{aligned} \tag{A.3}$$

Using (A.3) and the fact that $|h_i|^2$ is an exponential random variable with unit mean, i.e., $\mathbb{E}_{h_i}\left\{\mathbb{1}(|h_i|^2 > z)\right\} \triangleq e^{-z}\mathbb{1}(z)$, $\mathbb{E}_{h_i,g_i}\{1-I_{o,i}\}$ is given by

$$\begin{aligned} \mathbb{E}_{h_i,g_i}\{1-I_{o,i}\} &= \frac{1}{\lambda_h}\int_{d/c}^{\infty} e^{-\left(\frac{az+b}{(cz-d)\lambda_g}+\frac{z}{\lambda_h}\right)}dz \\ &= e^{-\left(\frac{a}{c\lambda_g}+\frac{d}{c\lambda_h}\right)}uK_1(u). \end{aligned} \tag{A.4}$$

The second expectation, $\mathbb{E}_{\mathbf{h}\setminus h_i}\{1-\alpha_i\}$ is the expected value that any block is an IT block. From the general EH-IT pattern (a), given in Fig. 2, probability of any block being IT block can be written as

$$\mathbb{E}_{\mathbf{h}\setminus h_i}\{1-\alpha_i\} = \frac{1}{\mathbb{E}_{\bar{X}}\{X+1\}}, \tag{A.5}$$

where $\bar{X} \triangleq X-1$. Using $f_{E_o}(\epsilon)$ and $p_{\bar{X}|E_o}(\bar{x}|E_o)$ from (10) and (11), respectively, $\mathbb{E}_{\bar{X}}\{X\}$ is given by

$$\begin{aligned} \mathbb{E}_{\bar{X}}\{X\} &= \mathbb{E}_{E_o}\left\{\mathbb{E}_{\bar{X}|E_o}\{X|E_o\}\right\} \\ &= \int_{\epsilon=0}^{P_rT/2} \mathbb{E}_{\bar{X}|E_o}\{\bar{X}+1|E_o\}\, f_{E_o}(\epsilon)d\epsilon + \int_{\epsilon=P_rT/2}^{\infty} 0 d\epsilon \end{aligned} \tag{A.6a}$$

$$\begin{aligned} &= \int_{\epsilon=0}^{P_rT/2} \left(\frac{1}{\rho}\left(\frac{P_rT}{2}-\epsilon\right)+1\right) f_{E_o}(\epsilon)d\epsilon \\ &= \frac{P_r d_1^m}{2\eta P_s \lambda_h}. \end{aligned} \tag{A.6b}$$

Substituting (A.4), (A.5), and (A.6b) into (A.1), we can obtain the analytical throughput expression as given in (12). This completes the proof for Theorem 1.

References

[1] X. Lu, P. Wang, D. Niyato, D. I. Kim, and Z. Han, "Wireless networks with RF energy harvesting: A contemporary survey," *IEEE Commun. Surveys Tuts.*, 2014.

[2] D. Gunduz, K. Stamatiou, N. Michelusi, and M. Zorzi, "Designing intelligent energy harvesting communication systems," *IEEE Commun. Mag.*, vol. 52, no. 1, pp. 210–216, Jan. 2014.

[3] L. R. Varshney, "Transporting information and energy simultaneously," in *Proc. IEEE ISIT*, 2008.

[4] X. Zhou, R. Zhang, and C. K. Ho, "Wireless information and power transfer: Architecture design and rate-energy tradeoff," *IEEE Trans. Commun.*, vol. 61, no. 11, pp. 4757–4767, Nov. 2013.

[5] J. Park and B. Clerckx, "Joint wireless information and energy transfer in a two-user MIMO interference channel," *IEEE Trans. Commun.*, vol. 12, no. 8, pp. 4210–4221, Aug. 2013.

[6] D. W. K. Ng, E. S. Lo, and R. Schober, "Energy-efficient resource allocation in multiuser OFDM systems with wireless information and power transfer," in *Proc IEEE WCNC*, Apr. 2013, pp. 3823–3828.

[7] Z. Ding, S. M. Perlaza, I. Esnaola, and H. V. Poor, "Power allocation strategies in energy harvesting wireless cooperative networks," *IEEE Trans. Wireless Commun.*, vol. 13, no. 2, pp. 846–860, Feb 2014.

[8] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Relaying protocols for wireless energy harvesting and information processing," *IEEE Trans. Wireless Commun.*, vol. 12, no. 7, pp. 3622–3636, Jul. 2013.

[9] I. Krikidis, S. Timotheou, and S. Sasaki, "RF energy transfer for cooperative networks: Data relaying or energy harvesting?" *IEEE Commun. Lett.*, vol. 16, no. 11, pp. 1772–1775, Nov. 2012.

[10] A. M. Fouladgar and O. Simeone, "On the transfer of information and energy in multi-user systems," *IEEE Commun. Lett.*, vol. 16, no. 11, pp. 1733–1737, Nov. 2012.

[11] B. Medepally and N. B. Mehta, "Voluntary energy harvesting relays and selection in cooperative wireless networks," *IEEE Trans. Wireless Commun.*, vol. 9, no. 11, pp. 3543–3553, Nov. 2010.

[12] J. Xu and R. Zhang, "Throughput optimal policies for energy harvesting wireless transmitters with non-ideal circuit power," *IEEE J. Sel. Area. Comm.*, vol. 32, no. 2, pp. 322–332, Feb. 2014.

[13] R. G. Gallager, *Discrete Stochastic Processes*. Kluwer, 1996.

[14] A. A. Nasir, X. Zhou, S. Durrani, and R. A. Kennedy, "Wireless-powered relays in cooperative communications: Time-switching relaying protocols and throughput analysis," *ArXiv Technical Report*, 2014. [Online]. Available: http://arxiv.org/abs/1310.7648

[15] I. S. Gradshteyn and I. M. Ryzhik, *Table of integrals, series, and products*, 4, Ed. Academic Press, Inc., 1980.