Time-Switching Energy Harvesting Relay Optimizing Considering Decoding Cost

Wanqiu Hu[1], Yanxin Yao[1], Zhengwei Ni[2(✉)], Rajshekhar V. Bhat[3], and Mehul Motani[4]

[1] Key Laboratory of the Ministry of Education for Optoelectronic Measurement Technology and Instrument, Advanced Equipment Intelligent Perception and Control, Beijing International Cooperation Base for Science and Technology, Beijing Information Science and Technology University, Beijing 100190, China
1302566503@qq.com, yanxin_buaa@126.com

[2] Zhejiang Gongshang University, Zhejiang 310018, China
nzw_hk@hotmail.com

[3] Indian Institute of Technology Dharwad, Dharwad, India
rajshekhar.bhat@iitdh.ac.in

[4] National University of Singapore, Singapore, Singapore
motani@nus.edu.sg

Abstract. Energy harvesting (EH) from natural and man-made sources is of prime importance for enabling the Internet of Things (IoT) networks. Although, energy harvesting relays in a relay network, which form building blocks of an IoT network, have been considered in the literature, most of the studies do not account for the processing costs, such as the decoding cost in a decode-and-forward (DF) relay. However, it is known that the decoding cost amounts to a significant fraction of the circuit power required for receiving a codeword. Hence, in this work, we are motivated to consider an EH-DF relay with the decoding cost and maximize the average number of bits relayed by it with a time-switching architecture. To achieve this, we first propose a *time-switching* frame structure consisting of three phases: (i) an energy harvesting phase, (ii) a reception phase and, (iii) a transmission phase. We obtain optimal length of each of the above phases and communication rates that maximize the average number of bits relayed. We consider two EH scenarios, (a) when the radio frequency (RF) energy, to be harvested by the relay, is transmitted from a dedicated transmitter, and (ii) when the energy is harvested at the rely from the ambient environment. By exploiting the convexity of the optimization problem, we derive analytical optimum solutions under the above two scenarios and provide numerical simulations for verifying our theoretical analysis.

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1 Introduction

Recent days, communication systems with energy harvesting (EH) functions become more and more popular with the rapid development of Internet of things. The harvested energy could complement the scarce energy in mobile situation or out of cable line area. The study on energy harvesting system optimization is very important to improve the energy utilization efficiency or their performance indices of communicate systems.

There are energy harvesting optimization for various communication network such as Wireless sensor network [4], cellular network, internet of things [5] and cognitive network [6]. There are energy harvesting optimization for different scenarios such as point to point system, relay system [1], cooperative system [7], cognitive radio system [8] and multiple antenna system [9]. And also there are energy harvesting optimization for various communication objectives such as outrage probability [2,10], packet drop rate [11], energy efficiency and secure communication [12] and so on.

For relay systems, [7] studies the scenario when both source node (SN) and relay node (RN) have limited energy storage, and SN harvests energy form RF signals of the SN. For different harvesting efficiency and channel conditions, closed-form optimal solutions for the joint SN and RN power allocation are derived to maximize the overall throughput. [13] uses a generalized iterative directional water-filling algorithm to solve the sum-rate maximization problem under half-duplex and full-duplex channels with energy harvesting nodes under any relaying strategy, namely amplify-and-forward, decode-and-forward, compress-and-forward and compute-and-forward. [14] propose two schemes: (1) jointly optimal power and time fraction (TF) allocation, (2) optimal power allocation with fixed TF for a three-node DF half-duplex relaying system. [15] drives the delay-limited and delay-tolerant throughput for a DF single-way and two-way relaying networks with time switching relaying protocol.

Most literature for the energy harvesting relay mainly consider the transmission and receiving energy, such as in [7], but rarely discuss the information decoding energy which is the main energy cost for DF scheme [16]. Our paper mainly focuses on this novel aspect when the information decoding energy is taken into account. The papers [17] considers the decoding cost and the effect of decoding model on energy harvesting receiver. There has not been a study on their effect on the relay system.

In this paper, we study the problem of optimizing time fraction and receiving rate for an EH relay system whose energy comes from the dedicated transmitter and ambient environment for transferring more information from dedicated transmitter to destination. The frame structure is determined as three phase: harvesting, receiving information and transmitting information. The time fraction or ratio of these operations are to determined. The average transmitting rate for the relay is known, while the receiving rate related to the decoding energy is to be optimized. We discuss the single block case when energy is forbidden to flow among blocks. We consider the energy comes from dedicated receiver only and could come both from dedicated transmitter and ambient environment. For all the cases, we give the optimum time fraction for three operation phases and receiving rate. Finally, numerical results are provided to validate the accuracy of the analysis. The main contributions of the paper are

- We formulate the information transferring and energy usage model for the energy harvesting relay considering the decoding cost.
- We give the solutions for single block case when energy is from dedicated transmitter and from both dedicated transmitter and ambient environment, and analyze the solution difference between them.

2 System Model

We consider an end-to-end communication with an EH relay as shown in Fig. 1. The relay extracts the information contained in the signals sent by the transmitter, and then transmits it to the receiver in DF mode. We hope to transmit as most data as possible to the receiver. The energy source of the transmitter and receiver could be seen as infinite, while the energy of the relay is only from energy harvesting. Apparently, the bottle neck of the system is the EH relay which has limited harvested energy from the RF signals of both the dedicated transmitter and ambient RF sources. Both extracting information (decoding) and transmitting information (forward) need energy to run the corresponding circuits.

Solar energy is generally from 1 uW to 100 mW in a small-sized solar cell across day (approximate area of 10 cm^2). There are many models to be used for the system. Because the energy harvesting equipment is generally used in small energy scale applications, for purpose of simplicity and low cost, we design the structure of the relay as simple as possible. There is only one antenna shared by the energy harvesting, transmitting and receiving functions or periods with a time-switching on-off controlling the antenna to receive or transmit signals. We consider a "Harvest-Receive-Transmit" time-switching architecture in this paper. The harvested energy which is generally from 1 uW to 100 mW in a small-sized device needs to be stored in storage elements for later operation use. We assume the battery cannot be charged and discharged simultaneously. This assumption is both practical and without loss of generality.

The system consists of energy harvesting unit, decoding unit, transmitting unit, battery and data buffer. The energy harvesting unit harvest energy from RF signals of dedicated transmitter and ambient transmitters, and then store the energy in batteries for later transmitting or receiving freely. In the information receiving period, information is extracted from the received signals in the decoder unit using the energy drawn from the batteries. Then the information is stored in the buffer for later transmitting. In the information transmitting

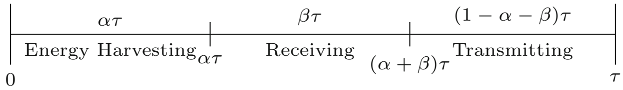

Fig. 1. The communication block structure at the relay

period, the information in the buffer is transmitted using the energy discharged from batteries or supercapacities.

Generally, the information is organized in a block or frame to process. In order to simplify model, we consider an average transmitting and receiving rate and channel condition when transferring information. So we could represent many parameters for the transmitting and receiving as constants during the block, such as the maximum signal power p_m, channel capacity C, the power gain of channel h, transmitting power p_t. A frame is divided into three parts as shown in Fig. 1. Assume the time length of a frame is τ.

- Over the time duration $[0, \alpha\tau), \alpha \in [0, 1]$, switcher connects to the EH circuit and all the signals received are used for harvesting energy. To make the receiver harvest the largest amount of energy, the transmitter should always transmit the symbol with the largest energy. Denote $p_{\rm m} = \max_x p(x)$ where the maximum is over all possible values of $x \in \mathcal{X}$ and e is the energy harvested outside the bands used for transmission.
- Over the time duration $[\alpha\tau, (\alpha + \beta)\tau), \alpha + \beta \in [0, 1]$, switcher connects to the information extracting circuit. From [19], we adopt the following model: for a fixed channel capacity C [3], the energy consumed for decoding a codeword with rate R per channel is a non-decreasing convex function of R, i.e., $h(R) = \mathcal{E}_{\rm D}(\frac{C}{C-R})$, where $\mathcal{E}_{\rm D}(0) = 0$ [19]. $\frac{C}{C-R}\log(\frac{C}{C-R})$ and $(\frac{C}{C-R})^2 \log^3(\frac{C}{C-R})$ are two common seen instances for $\mathcal{E}_{\rm D}(\frac{C}{C-R})$ [19]. All the other factors are 'hidden' in this function. The total number of bits decoded by the relay in this phase are $I_R = \beta\tau R$ and stored in the buffer for later transmission. In this phase, no energy is harvested. The total number of bits decoded by the relay in this phase are $I_R = \beta\tau R$ and stored in the buffer for later transmission. In this phase, no energy is harvested.
- Over the time duration $[(\alpha + \beta)\tau, \tau]$, switcher connects to the transmitting circuit and the information decoding is transmitted from the relay to the receiver. For transmission over an additive white Gaussian noise (AWGN) channel with power gain h, and unit received noise power spectral density, we consider the average rate as $Wlog(1 + hp_t)$ bits per channel symbol during the block.

  The may be several specific forms for characterizing the decoding energy consumption. For example, for LDPC codes on the binary erasure channel (BEC), [18] shows that for any $\theta > 0$, there exists a code with code rate of at least R, with complexity per input node per iteration scaling like $log\theta$, to make decoding iterations to converge. The iteration rounds scale like θ. So the total complexity of decoder per channel use scales like $\theta log\theta$ [19].

3 Transmission Over a Single Block from Transmitter Only

For a single block transmission, the optimization problem to maximize the amount of information relayed can be formulated as

$$
\begin{aligned}
\text{(P1)} \quad & \max_{\alpha, \beta, \gamma, R} I_R, \\
\text{s.t.} \quad & I_R \le I_T \\
& \beta \mathcal{E}_{\rm D}\left(\tfrac{C}{C-R}\right) + \gamma p_t \le \alpha p_m \\
& 0 \le \alpha \le 1 \\
& 0 \le \beta \le 1 \\
& 0 \le \gamma \le 1 \\
& \alpha + \beta + \gamma = 1 \\
& 0 \le R \le C.
\end{aligned} \tag{1}
$$

We assume that the average transmitting rate for the frame is known at the start of the frame, which is representing with a constant channel power gain and a fixed p_t, by optimizing R, α, β, γ. The second constraint follows because γ is time duration for transmission. To solve (P1), we first give two useful lemmas.

Lemma 1. *To be optimal, the first constraint in (1) must hold with equality, i.e.,*

$$\beta \tau R = log(1 + hp_t)(1 - \alpha - \beta)\tau. \tag{2}$$

Proof. If the equality in (2) does not hold, we can increase β to make the equality hold. When α, R, p_t are fixed, increasing β means increase the value of the objective function.

Lemma 2. *To be optimal, the third sub-equation in (1) must hold with equality. i.e.,*

$$\beta \mathcal{E}_{\rm D}\left(\frac{C}{C-R}\right) + (1 - \alpha - \beta)p_t = \alpha p_m. \tag{3}$$

Proof. If the equality in (3) does not hold, we can increase R to make the equality hold since $\mathcal{E}_D(R)$ is a non-decreasing function of R. When α, β, p_t are fixed, increasing R means increasing the value of the objective function.

Based on Lemma 1 and Lemma 2, we can express α and β in terms of R and p_t.

$$\alpha = 1 - \beta - \frac{\beta R}{log(1 + hp_t)} \tag{4}$$

$$\beta = \frac{p_m log(1 + hp_t)}{R(p_m + p_t) + (p_m + \mathcal{E}_D)log(1 + hp_t)} \tag{5}$$

Express β and the objective function in (1) in terms of R and p_t, we can rewrite the objective function of problem (P1) as $\mathcal{O}_1(R) = \beta R\,\tau$.

Take the derivative of $\mathcal{O}_1(R)$ with respect to R, we have $\frac{\partial \mathcal{O}_1}{\partial R} = p_m \tau log(1+hp_t)\mathcal{P}_1(R)$, where $\mathcal{P}_1(R) = \frac{R}{R(p_m+p_t)+(\mathcal{E}_D+p_m)log(1+hp_t)}$. For the decoding instances $\theta \log \theta$ common seen in literature, we could further derive following theorem.

Theorem 1. $\frac{\partial \mathcal{P}_1(R)}{\partial R}|_{R\to 0} > 0$. $\frac{\partial \mathcal{P}_1(R)}{\partial R}|_{R\to C} \to -\infty$. $\frac{\partial^2 \mathcal{O}_1(R)}{\partial R^2} \le 0$.

Proof. Assume $T(x) = log(1+hx)$. $\frac{\partial \mathcal{O}_1}{\partial R} = p_m log(1+hp_t)\mathcal{P}_1(R)$, where $\mathcal{P}_1(R) = \frac{R}{R(p_m+p_t)+(\mathcal{E}_D+p_m)T(p_t)}$.
We could derive $\frac{\partial \mathcal{P}_1(R)}{\partial R} = \frac{T(p_t-p_c)(\mathcal{E}_D(\theta)+p_m)-T(p_t)\frac{\partial \mathcal{E}(\theta)}{\partial \theta}\frac{R}{(C-R)^2}}{[R(p_m+p_t)+(\mathcal{E}_D+p_m)T(p_t)]^2}$, and $\frac{\partial^2 \mathcal{P}_1(R)}{\partial R^2} = -RT(p_t)\frac{\frac{\partial^2 \mathcal{E}(\theta)}{\partial \theta^2}\frac{1}{(C-R)^4}+2\frac{\partial \mathcal{E}(\theta)}{\partial \theta}\frac{1}{(C-R)^3}}{[R(p_m+p_t)+(\mathcal{E}_D+p_m)T(p_t)]^4}$.

When $\mathcal{E}_\mathrm{D}(\theta) = \theta \log \theta$, we could derive $\frac{\partial \mathcal{E}_D(\theta)}{\partial \theta} = log\theta + \frac{1}{ln2}$, and $\frac{\partial^2 \mathcal{E}_D(\theta)}{\partial \theta^2} = \frac{1}{ln2\theta}$.

For $\mathcal{E}_\mathrm{D}(\theta) = \theta \log \theta$, when $R \to 0$ and $\theta \to 1$, we could see the numerator of $\frac{\partial P_1(R)}{\partial R}$ is positive finite while the denominator is positive finite.

So $\frac{\partial P_1(R)}{\partial R}|_{R\to 0} > 0$. When $R \to C$ and $\theta \to +\infty$, $\frac{\partial P_1(R)}{\partial R} \to B\frac{\theta log\theta - (log\theta + \frac{1}{ln2})(\frac{\theta}{C})^2 C(1-\frac{1}{\theta})}{\theta^2 log^2\theta} \to -A\frac{1}{log\theta} \to -\infty$, where A, B are positive parameters. $\frac{\partial^2 \mathcal{P}_1(R)}{\partial R^2}$ could easily be seen as non-positive for $R \in [0, C]$.

So there is a single R^* maximizing $\mathcal{O}_1(R)$. We will get the optimum $\alpha^*, \beta^*, \gamma^*$ according to

$$\gamma^* = \frac{R^*(p_m\tau + e)}{(p_m+p_t)R^*\tau + T(p_t)\tau(p_m + \mathcal{E}_\mathrm{D}(\frac{C}{C-R^*}))}, \tag{6}$$

$$\beta^* = \frac{T(p_t)(p_m\tau + e)}{(p_m+p_t)R^*\tau + T(p_t)\tau(p_m + \mathcal{E}_\mathrm{D}(\frac{C}{C-R^*}))}, \tag{7}$$

$$\alpha^* = 1 - \beta^* - \gamma^*. \tag{8}$$

We could easily find that when e increases, both β and γ will increase, and α will decrease. When α decreases to zero, the energy harvested from ambient environment is enough for the relay, whose value is $\tilde{e}$,

$$\tilde{e} = \frac{\tau\Big(p_t R^* + T(p_t)\mathcal{E}_\mathrm{D}(\frac{C}{C-R^*})\Big)}{T(p_t) + R^*} \tag{9}$$

which is derived from $\beta + \gamma = 1$. Then we have the lemma.

Lemma 3. *The optimal solution for (P2) is* $\frac{\partial \mathcal{P}_1(R)}{\partial R} = 0$, α^*, β^* *and* γ^* *could be obtained with* (6), (7) *and* (8) *when* $e \le \tilde{e}$; *otherwise,* α^*, β^* *and* γ^* *could be obtained with* (6), (7) *and* (8) *with* $e = \tilde{e}$, *when* $e > \tilde{e}$.

Remark 1. Intuitively, the energy harvesting period becomes smaller due to the increase of e to allow for more time for receiving and transmitting. When α becomes zero, the energy harvested from ambient environment is enough and β and γ are constant values given by (6) and (7) with $e = \tilde{e}$.

4 Transmission over Single Block: Energy Harvested from Transmitter and Ambient RF Sources

In this section, we consider the case when the receiver harvests energy from both the transmitter and other RF sources. Then the energy harvested are not merely controlled by energy extraction from transmitter. We then maximized the information to destination by jointly choosing optimal α, β, γ, R. p_t is known in assumption. The corresponding optimization problem is given by (P2).

$$\begin{aligned} \text{(P2)} \quad & \max_{\alpha, \beta, \gamma, R} I_R, \\ \text{s.t.} \quad & I_R \leq I_T, \\ & \beta \mathcal{E}_{\rm D}\left(\frac{C}{C-R}\right) + \gamma p_t \leq \alpha p_{\rm m} + e \\ & 0 \leq \alpha \leq 1 \\ & 0 \leq \beta \leq 1 \\ & 0 \leq \gamma \leq 1 \\ & \alpha + \beta + \gamma = 1 \\ & 0 \leq R \leq C. \end{aligned} \tag{10}$$

We could derive

$$\alpha = 1 - \beta - \frac{\beta R}{log(1 + hp_t)}. \tag{11}$$

$$\beta = \frac{(p_m \tau + e) log(1 + hp_t)}{R(p_m + p_t)\tau + (p_m + \mathcal{E}_D) log(1 + hp_t)\tau}. \tag{12}$$

Express α, β and the objective function in (10) in terms of R and p_t, we can rewrite the objective of problem (P2) as $\mathcal{O}_2(R) = \beta R \tau$. Take the derivative of $\mathcal{O}_2(R)$ with respect to R, we have $\frac{\partial \mathcal{O}_2}{\partial R} = (p_m \tau + e) log(1 + hp_t) \mathcal{P}_2(R)$, where $\mathcal{P}_2(R) = \mathcal{P}_1(R)$. According to Theorem 1, we could derive $\frac{\partial \mathcal{P}_2(R)}{\partial R}|_{R \to 0} > 0$. $\frac{\partial \mathcal{P}_2(R)}{\partial R}|_{R \to C} \to -\infty$. $\frac{\partial^2 \mathcal{O}_2(R)}{\partial R^2} \leq 0$. So there is a single R^* maximizing $\mathcal{O}_2(R)$. We will get the optimum α, β, γ according to (11), (12), (10).

We could easily find that when e increases, both β and γ will increase, and α will decrease. This indicates that the energy harvesting period become smaller due to e to allow for more time for receiving and transmitting.

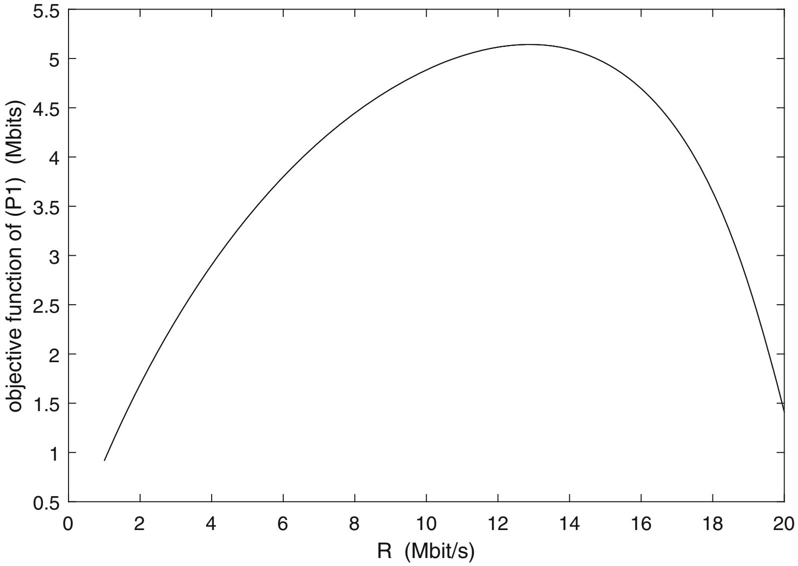

Fig. 2. The objective function value of (P1) versus R

5 Numerical Results

5.1 Energy from Dedicated Transmitter only

Firstly, we focus on the optimization results when energy is from dedicated transmitter only.

We originally assume that $\mathcal{E}_D(\theta) = 10^{-3} \times \theta log_2 \theta\,\text{W}$, $T(p_t) = Blog_2(1 + p_t h')\,\text{bit/s}$, $B = 10^6\,\text{Hz}$, $C = 21\,\text{Mbit/s}$, $N_0 = 10^{-15}\,\text{W/Hz}$, $\tau = 1\,\text{s}$, $h' = \frac{1}{N_0 W} = 10^9$. As the coefficients at the front in $T(p_t)$ and $\mathcal{E}_D(\theta)$ do not affect the convexity property of the functions, Theorem 1 still holds.

In the following simulation, we adopt energy unit as mW and bit rate unit as Mbit/s. Then we have $\mathcal{E}_D(\theta) = \frac{C}{C-R} log_2\left(\frac{C}{C-R}\right)\,\text{mW}$, $T(p_t) = log_2(1 + p_t h)\,\text{Mbit/s}$, where p_t represent x energy unit, $h = 10^6$, C, R and $T(P_t)$ are bit rate with unit Mbit/s.

We assume $C = 21\,\text{Mbit/s}$, According to $P_1(R^*) = 0$, the numerical result for optimum R^* could be obtained at $12.88\,\text{Mbit/s}$.

In order to verify we plot the objective function of (P1) versus R in Fig. 2. We could easily get the optimum $R^* = 12.88\,\text{Mbit/s}$. When $p_m = 8\,\text{mW}$, $p_t = 7\,\text{mW}$, we could give the optimum α, β and γ in Fig. 3 at $e = 0$.

5.2 Energy from Dedicated Transmitter and Ambient Environment

Now we consider the case when the energy comes from the dedicated transmitter and ambient environment both.

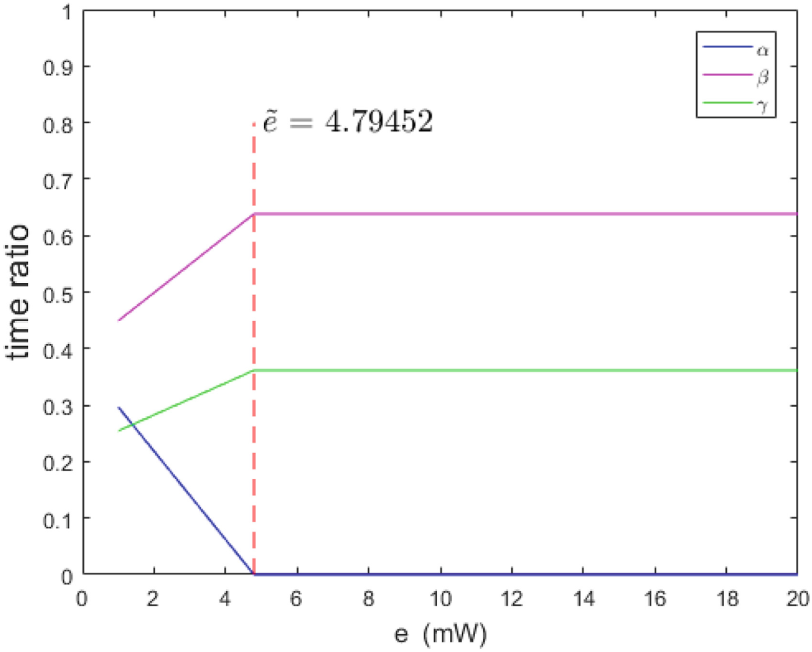

Fig. 3. The value of α, β, γ versus e

When $p_m = 8\,\text{mW}$, $p_t = 7\,\text{mW}$, with $R^* = 12.88\,\text{Mbit/s}$, We present the variation of optimum α, β and γ versus e in Fig. 3. $\tilde{e}$ is computed to be $4.79\,\text{mW}$ in this case. We can see that β and γ increase with e, but α decreases with e over $e \leq \tilde{e}$; for $e > \tilde{e}$, both α and β no longer vary, but remain the same as when $e = \tilde{e}$. The numerical results are given by solving (P2).

From these figures, we see the numerical results coincide with the theoretical analysis.

From these figures, we could see the numerical results coincide well with the theoretical analysis for the single block case.

6 Conclusion

This paper formulates the information transferring and energy usage model for the energy harvesting relay considering the decoding cost and give the unique solution for single block case when energy is from dedicated transmitter. When energy is harvested from both dedicated transmitter and ambient environment, energy saturation will occur when harvested energy from ambient environment is large enough. There is a threshold for it when α become zero all the time. Simulations verify the theoretical analysis and give the performance of the system.

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