Price-Based Power Allocation in Energy Harvesting Wireless Cooperative Networks: A Stackelberg Game Approach

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Abstract. In this letter, a wireless cooperative network is considered, in which multiple source-destination pairs communicate with each other via an energy harvesting relay. We propose a price-based power allocation scheme to distribute the harvested energy among the multiple users. We model the interaction between the relay and the destinations as a Stackelberg game and then study the joint utility maximization of the relay and the destination. The Stackelberg equilibriums for the proposed game are characterized. Simulation results show the effectiveness of the proposed algorithm in comparison with the uniform pricing algorithm.

Keywords: Stackelberg game · Wireless power transfer · Price · Power allocation

1 Introduction

With rapid growth of wireless services in recent years, issues in energy consumption become increasingly critical for wireless communication systems. Therefor energy harvesting, a technique to collect energy from the environment, has recently received considerable attention as a sustainable solution to overcoming the bottleneck of energy constrained wireless networks [1]. Unlike conventional energy harvesting techniques rely on external energy sources such as solar and wind [2], ambient radio signal can also be a practicable source since radio signal carries energy as well as information at the same time, so that wireless signals can be used as a means for the delivery of information and power simultaneously [3]. The work [4] investigated the optimal information/energy beamforming strategy to achieve the maximum harvested energy for multi-user MISO SWIPT system with separated information/energy receivers. SWIPT for relay system and multiple access channel was consider in [5]. The problem in such energy harvesting networks is that practical circuits cannot realize energy harvesting and data detection from wireless signals at the same time. In [6], the authors introduced a general receive architecture, in which the circuits for energy harvesting and signal detection are operated in a time sharing or power splitting manner. The

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performance difference between power splitting and time sharing is studied in broadcasting scenarios in [7]. In a power splitting scheme, the received signal is split with an adjustable power splitting ratio to enable simultaneous energy harvesting and information decoding.

In this paper, we consider a general wireless cooperative network, where multiple source-destination pairs communicate with each other via an energy harvesting relay. Specifically, the cooperative transmission consists of two time slots of duration $\frac{T}{2}$. In the first slot, multiple sources deliver their information to the relay via orthogonal channels. At the end of the first phase, the relay splits the signals sent from the i-th source into two streams, one for detection and the other for energy harvesting. Then in the second phase, the relaying transmissions are power by the energy harvested at the relay. The relay's strategies to distribute the harvested energy among the multiple users are investigated in [8], e.g., the noncooperative individual transmission strategy and the equal allocation scheme. In this letter, we propose a new price-based power allocation scheme, where the relay price the destinations to control the transmission power under the total transmit power constraint. The relay will choose a suitable price to maximize its revenue from the destinations. The destination will choose an optimal power to maximize its utility after the relay set prices for them. A Stackelberg game is formulated to model the strategy between the relay and the destinations and we study the Stackelberg equilibriums for the proposed power allocation game.

Notations: Boldface capital and lowercase letters denote matrices and vectors, respectively. The inequalities for vectors are defined element-wise, i.e., $\boldsymbol{x} \preceq \boldsymbol{y}$ represents $x_i \leq y_i, \forall i$, where x_i and y_i are the i-th elements of the vector $\boldsymbol{x}$ and $\boldsymbol{y}$, respectively. The superscript T denotes the transpose operation of a vector.

2 System Model and Problem Formulation

Consider an energy harvesting communication scenario, where N source nodes (S_i, for $i = 1, ..., N$) intended to communicate with their respective destination nodes (D_i, for $i = 1, ..., N$) through an intermediate relay node (R). Each node is equipped with a single antenna. For simplicity, we assume that channel state information (CSI) of each link is perfectly known to the relay. Further, the relay nodes are operate in the half-duplex mode with two transmission phases. Among the various energy harvesting relaying models, we focus on power splitting. Let θ_i denote the power splitting coefficient for S_i at R. At the end of the first phase, R harvests the following amount of energy from S_i:

$$E_i = \eta P_{S_i} h_{i,j} \theta_i \frac{T}{2}, \tag{1}$$

where η denotes the energy harvesting efficiency factor, P_{S_i} denotes the transmission power at S_i, h_i denotes the channel power gain between S_i and R.

Then the total power reserved at the relay at the end of the first phase is:

$$P_R = \sum_{i=1}^{N} \frac{E_i}{\frac{T}{2}} = \sum_{i=1}^{N} \eta P_{S_i} h_i \theta_i \frac{T}{2}, \tag{2}$$

Assuming that the battery is sufficiently large, the relay can accumulate a significant amount of power for relaying transmission. We focus on the strategy to distribute the harvested energy among the multiple users. The strategy between the relay and the multiple users is modeled as a Stackelberg game. The relay is the leader in this game. It choose a price on per transmission power for each destination to maximize its own revenue. Then the destinations will decide the transmit power to maximize their utilities based on the assigned power price.

Let λ_i denotes the price paid to R on per transmission power for D_i. The total revenue of the relay can be expressed as:

$$U_R = \sum_{i=1}^{N} \lambda_i p_i, \tag{3}$$

where p_i denotes the transmission power allocated to D_i at the relay. Let $\boldsymbol{\lambda} = [\lambda_1, \lambda_2, \cdots, \lambda_N]^T$. The problem of the relay is formulated as:

$$\begin{aligned} \max_{\boldsymbol{\lambda} \succeq 0} \quad & U_R = \sum_{i=1}^{N} \lambda_i p_i, \\ \text{s.t.} \quad & \sum_{i=1}^{N} p_i \leq P_R, \\ & p_i \geq 0. \end{aligned} \tag{4}$$

The data rate D_i can achieve is $R_{D_i} = \frac{1}{2}\log_2(1 + \frac{p_i g_i}{\sigma_i^2})$, where p_i denotes the channel power gain between R and D_i, and σ_i^2 denotes the background noise at D_i. Without loss of generality, it is assumed for convenience that $\sigma_i^2 = \sigma^2, \forall i$. The utility for D_i can be defined as:

$$U_{D_i} = \frac{1}{2}\omega_i \log_2(1 + \frac{p_i g_i}{\sigma^2}) - \lambda_i p_i, \tag{5}$$

where ω_i denotes the equivalent utility per unit data valuation contributing to D_i's utility. Let $\mathbf{p} = [p_1, p_2, \cdots, p_N]^T$. The problem for D_i is formulated as:

$$\max_{p_i \geq 0} \quad U_{D_i} = \frac{1}{2}\omega_i \log_2(1 + \frac{p_i g_i}{\sigma^2}) - \lambda_i p_i. \tag{6}$$

The problem (4) and (6) together form a Stackelberg game in which R is the leader. The objective is to find the Stackelberg Equilibrium (SE) point(s).

3 Optimal Price-Based Power Allocation Algorithm

For the proposed Stackelberg game, the SE is defined as follows.

Definition 1: Let $\boldsymbol{\lambda}^*$ be a solution for problem (4) and p_i^* be a solution for problem (6) of $D_i(i = 1, ..., N)$. The point $(\boldsymbol{\lambda}^*, \mathbf{p}^*)$ is a SE for the addressed game if for any $(\boldsymbol{\lambda}, \mathbf{p})$ with $\boldsymbol{\lambda} \succeq 0$ and $\mathbf{p} \succeq 0$, the following conditions are satisfied:

$$U_R(\boldsymbol{\lambda}^*, \mathbf{p}^*) \geq U_R(\boldsymbol{\lambda}, \mathbf{p}^*), \tag{7}$$

$$U_{D_i}(p_i^*, \mathbf{p}_{-i}^*, \boldsymbol{\lambda}^*) \geq U_{D_i}(p_i, \mathbf{p}_{-i}^*, \boldsymbol{\lambda}^*), \forall i. \tag{8}$$

The SE can be obtained as follows: For a given $\boldsymbol{\lambda}$, problem (6) is solved first. Then, the optimal price of problem (4) can be obtained with the optimal power allocated strategy p_i^*.

Recall problem (6), it is observed that the objective function is a concave function with the allocated power p_i, and the constraint is affine. Thus, problem (6) is a convex optimization problem. Therefore, we can solve the problem by using the KKT conditions.

Lemma 1: For a given price λ_i, the optimal solution for problem (8) is given by:

$$p_i^* = (\frac{\frac{1}{2}\omega_i}{\lambda_i} - \frac{\sigma^2}{g_i})^+, \forall i, \tag{9}$$

where $(\cdot)^+ \triangleq max(\cdot, 0)$.

From (9), the power allocated to D_i is zero if the price for D_i is too high, i.e., $\lambda_i \geq \frac{\frac{1}{2}\omega_i g_i}{\sigma^2}$. This means that D_i will be removed from the game. Substituting (9) into problem (4):

$$\begin{aligned} \max_{\boldsymbol{\lambda} \succeq 0} \quad & \sum_{i=1}^{N} (\frac{1}{2}\omega_i - \frac{\lambda_i \sigma^2}{g_i})^+, \\ \text{s.t.} \quad & \sum_{i=1}^{N} (\frac{\frac{1}{2}\omega_i}{\lambda_i} - \frac{\sigma^2}{g_i})^+ \leq P_R. \end{aligned} \tag{10}$$

Assume P_R is large enough so that all the destinations are involved, i.e., $\lambda_i < \frac{\frac{1}{2}\omega_i g_i}{\sigma^2}, \forall i$. Then problem (10) can be transformed to the following form:

$$\begin{aligned} \min_{\boldsymbol{\lambda} \succeq 0} \quad & \sum_{i=1}^{N} \frac{\lambda_i \sigma^2}{g_i}, \\ \text{s.t.} \quad & \sum_{i=1}^{N} \frac{\frac{1}{2}\omega_i}{\lambda_i} \leq P_R + \sum_{i=1}^{N} \frac{\sigma^2}{g_i}. \end{aligned} \tag{11}$$

Obviously, this problem is convex. Next, we will give the optimal solution to problem (11).

It is observed that problem (11) is a convex optimization problem. Thus, there is no duality gap between this problem and its dual optimization problem. Therefor, problem (11) can be solved by its dual problem.

The Lagrangian function of problem (11) is given as:

$$\begin{aligned} L(\boldsymbol{\lambda}, \alpha, \boldsymbol{\beta}) \quad &= \sum_{i=1}^{N} \frac{\lambda_i \sigma^2}{g_i} + \alpha(\sum_{i=1}^{N} \frac{\frac{1}{2}\omega_i}{\lambda_i} - P_R - \sum_{i=1}^{N} \frac{\sigma^2}{g_i}) \\ &- \sum_{i=1}^{N} \beta_i \lambda_i, \end{aligned} \tag{12}$$

where α and β_i are non-negative dual variables associated with the constrains $\sum_{i=1}^{N} \frac{\frac{1}{2}\omega_i}{\lambda_i} \leq P_R + \sum_{i=1}^{N} \frac{\sigma^2}{g_i}$ and $\lambda_i \geq 0$.

The dual objective is then defined as $G(\boldsymbol{\lambda}, \alpha, \boldsymbol{\beta}) = \max_{\boldsymbol{\lambda} \succeq 0} L(\boldsymbol{\lambda}, \alpha, \boldsymbol{\beta})$, and the dual optimization problem is given by $\min_{\alpha \geq 0, \boldsymbol{\beta} \succeq 0} G(\boldsymbol{\lambda}, \alpha, \boldsymbol{\beta})$. Then, KKT conditions are given as follows:

$$\frac{\partial L(\boldsymbol{\lambda}, \alpha, \boldsymbol{\beta})}{\partial \lambda_i} = \frac{\sigma^2}{g_i} - \alpha \frac{\frac{1}{2}\omega_i}{\lambda_i^2} - \beta_i = 0, \forall i, \tag{13}$$

$$\alpha(\sum_{i=1}^{N} \frac{\frac{1}{2}\omega_i}{\lambda_i} - P_R - \sum_{i=1}^{N} \frac{\sigma^2}{g_i}) = 0, \tag{14}$$

$$\alpha \geq 0, \beta_i \geq 0, \lambda_i \geq 0, \beta_i \lambda_i = 0, \forall i, \tag{15}$$

$$\sum_{i=1}^{N} \frac{\frac{1}{2}\omega_i}{\lambda_i} - P_R - \sum_{i=1}^{N} \frac{\sigma^2}{g_i} \leq 0. \tag{16}$$

From (13), we have:

$$\lambda_i^2 = \alpha \frac{\frac{1}{2}\omega_i}{\frac{\sigma^2}{g_i} - \beta_i}, \forall i. \tag{17}$$

Lemma 2: $\beta_i = 0, \forall i$.

Proof: We prove it by contradiction. Assume that $\beta_i \neq 0$ for any arbitrary i. Then, from $\beta_i \lambda_i = 0$ in (15), we have $\lambda_i = 0$. Substituting it into (17), we have $\alpha = 0$ since $\omega_i > 0$. Then, from (17), it follows that $\lambda_i = 0, \forall i$, which contradicts (16), and thus we have $\beta_i = 0, \forall i$. ■

Lemma 3: $\sum_{i=1}^{N} \frac{\frac{1}{2}\omega_i}{\lambda_i} - P_R - \sum_{i=1}^{N} \frac{\sigma^2}{g_i} = 0$.

Proof: We prove it by contradiction. Assume that $\sum_{i=1}^{N} \frac{\frac{1}{2}\omega_i}{\lambda_i} - P_R - \sum_{i=1}^{N} \frac{\sigma^2}{g_i} \neq 0$. Then from (14), we have $\alpha = 0$. Then, from (17), it follows that $\lambda_i = 0, \forall i$, which contradicts (16), and thus we have $\sum_{i=1}^{N} \frac{\frac{1}{2}\omega_i}{\lambda_i} - P_R - \sum_{i=1}^{N} \frac{\sigma^2}{g_i} = 0$. ■

According to Lemma 2, (17) can be rewritten as $\lambda_i = \sqrt{\frac{\frac{1}{2}\omega_i g_i \alpha}{\sigma^2}}, \forall i$. Substituting it into (16) and according to Lemma 3, we have $\sqrt{\alpha} = \frac{\sum_{i=1}^{N}\sqrt{\frac{\frac{1}{2}\omega_i\sigma^2}{g_i}}}{P_R + \sum_{i=1}^{N}\frac{\sigma^2}{g_i}}$. Thus, we have:

$$\lambda_i = \sqrt{\frac{\frac{1}{2}\omega_i g_i}{\sigma^2}} \frac{\sum_{i=1}^{N}\sqrt{\frac{\frac{1}{2}\omega_i\sigma^2}{g_i}}}{P_R + \sum_{i=1}^{N}\frac{\sigma^2}{g_i}}, \forall i. \tag{18}$$

With the results obtained above, we give the optimal solution for problem (11) by the following proposition.

Proposition 3: The optimal solution to problem (11) is given by

$$\lambda_i^* = \sqrt{\frac{\frac{1}{2}\omega_i g_i}{\sigma^2}} \frac{\sum_{i=1}^{N}\sqrt{\frac{\frac{1}{2}\omega_i\sigma^2}{g_i}}}{P_R + \sum_{i=1}^{N}\frac{\sigma^2}{g_i}}, \forall i \in \{1, 2, \cdots, N\}. \tag{19}$$

Now, we relate the optimal solution of problem (11) to that of the original problem (10) in the following proposition.

Proposition 4: The power prices given by (19) are the optimal solutions of problem (10) if and only if $P_R > \frac{\sum_{i=1}^{N}\sqrt{\frac{\frac{1}{2}\omega_i\sigma^2}{g_i}}}{\min_i \sqrt{\frac{\frac{1}{2}\omega_i g_i}{\sigma^2}}} - \sum_{i=1}^{N}\frac{\sigma^2}{g_i}$.

Proof: Sufficiency Part: It is observed that the price vector $\boldsymbol{\lambda}^*$ given by (19) is the optimal solution of problem (10) if $\lambda_i < \frac{\frac{1}{2}\omega_i g_i}{\sigma^2}, \forall i \in \{1, 2, \cdots, N\}$. Substituting (19) into these inequalities yields $\sqrt{\frac{\frac{1}{2}\omega_i g_i}{\sigma^2}} \frac{\sum_{i=1}^{N}\sqrt{\frac{\frac{1}{2}\omega_i\sigma^2}{g_i}}}{P_R + \sum_{i=1}^{N}\frac{\sigma^2}{g_i}} < \frac{\frac{1}{2}\omega_i g_i}{\sigma^2}, \forall i \in \{1, 2, \cdots, N\}$. Thus, it follows that $P_R > \frac{\sum_{i=1}^{N}\sqrt{\frac{\frac{1}{2}\omega_i\sigma^2}{g_i}}}{\sqrt{\frac{\frac{1}{2}\omega_i g_i}{\sigma^2}}} - \sum_{i=1}^{N}\frac{\sigma^2}{g_i}, \forall i \in \{1, 2, \cdots, N\}$. Furthermore, the inequalities given above can be compactly written as:

$$P_R > \frac{\sum_{i=1}^{N}\sqrt{\frac{\frac{1}{2}\omega_i\sigma^2}{g_i}}}{\min_i \sqrt{\frac{\frac{1}{2}\omega_i g_i}{\sigma^2}}} - \sum_{i=1}^{N}\frac{\sigma^2}{g_i}. \tag{20}$$

Necessity Part: We prove it by contradiction. Assuming that destinations are sorted by the following order: $\frac{\frac{1}{2}\omega_1 g_1}{\sigma^2} > \cdots > \frac{\frac{1}{2}\omega_{N-1} g_{N-1}}{\sigma^2} > \frac{\frac{1}{2}\omega_N g_N}{\sigma^2}$. Then, in Proposition 4, the condition becomes:

$$P_R > T_N, T_N = \frac{\sum_{i=1}^{N} \sqrt{\frac{\frac{1}{2}\omega_i \sigma^2}{g_i}}}{\sqrt{\frac{\frac{1}{2}\omega_N g_N}{\sigma^2}}} - \sum_{i=1}^{N} \frac{\sigma^2}{g_i}. \tag{21}$$

Now, suppose $T_{N-1} < P_R \leq T_N$, where T_{N-1} is a threshold shown later in (24). Suppose that $\boldsymbol{\lambda}^*$ given by (19) is still optimal for Problem (10) with $T_{N-1} < P_R < T_N$. Then, since $P_R \leq T_N$, from (19) it follows that $\lambda_N^* \geq \frac{\frac{1}{2}\omega_N g_N}{\sigma^2}$ and thus $(\frac{\frac{1}{2}\omega_N}{\lambda_N} - \frac{\sigma^2}{g_N})^+ = 0$. From Problem (10) it then follows that $\lambda_1^*, \cdots, \lambda_{N-1}^*$ is the optimal solution of the following problem:

$$\begin{aligned} \max_{\boldsymbol{\lambda} \succeq 0} \quad & \sum_{i=1}^{N-1} (\frac{1}{2}\omega_i - \frac{\lambda_i \sigma^2}{g_i})^+, \\ \text{s.t.} \quad & \sum_{i=1}^{N-1} (\frac{\frac{1}{2}\omega_i}{\lambda_i} - \frac{\sigma^2}{g_i})^+ \leq P_R. \end{aligned} \tag{22}$$

This problem is similar to Problem (10). Thus, from the proof of the previous sufficiency part, we can show that the optimal solution for this problem is given by:

$$\lambda_i^* = \sqrt{\frac{\frac{1}{2}\omega_i g_i}{\sigma^2}} \frac{\sum_{i=1}^{N-1} \sqrt{\frac{\frac{1}{2}\omega_i \sigma^2}{g_i}}}{P_R + \sum_{i=1}^{N-1} \frac{\sigma^2}{g_i}}, \forall i \in \{1, 2, \cdots, N-1\}, \tag{23}$$

if $P_R > T_{N-1}$, where T_{N-1} is obtained as the threshold for P_R above which $\lambda_i^* < \frac{\frac{1}{2}\omega_i g_i}{\sigma^2}$ holds $\forall i \in \{1, 2, \cdots, N-1\}$, i.e.,

$$T_{N-1} = \frac{\sum_{i=1}^{N-1} \sqrt{\frac{\frac{1}{2}\omega_i \sigma^2}{g_i}}}{\sqrt{\frac{\frac{1}{2}\omega_{N-1} g_{N-1}}{\sigma^2}}} - \sum_{i=1}^{N-1} \frac{\sigma^2}{g_i}. \tag{24}$$

Obviously, the optimal power price solution in (23) for the above problem is different from that given by (19). Thus, this contradicts with our presumption that $\boldsymbol{\lambda}^*$ is optimal for Problem (10) with $T_{N-1} < P_R \leq T_N$. ■

Therefore, the optimal solution of problem (10) can be given by the following theorem.

Theorem 1: Assuming that all the destinations are sorted in the order $\frac{\frac{1}{2}\omega_1 g_1}{\sigma^2} > \cdots > \frac{\frac{1}{2}\omega_{N-1} g_{N-1}}{\sigma^2} > \frac{\frac{1}{2}\omega_N g_N}{\sigma^2}$, the optimal solution for problem (10) is given by:

$$\boldsymbol{\lambda}^* = \begin{cases} q_N[\sqrt{\frac{\frac{1}{2}\omega_1 g_1}{\sigma^2}}, \sqrt{\frac{\frac{1}{2}\omega_2 g_2}{\sigma^2}}, \cdots, \sqrt{\frac{\frac{1}{2}\omega_N g_N}{\sigma^2}}]^T, \\ \qquad\qquad\qquad\qquad\qquad\qquad \text{if} \quad P_R > T_N \\ q_{N-1}[\sqrt{\frac{\frac{1}{2}\omega_1 g_1}{\sigma^2}}, \cdots, \sqrt{\frac{\frac{1}{2}\omega_{N-1} g_{N-1}}{\sigma^2}}, \infty]^T, \\ \qquad\qquad\qquad\qquad\qquad\qquad \text{if } T_N \geq P_R > T_{N-1} \\ \qquad\qquad\qquad\qquad\qquad\qquad \vdots \\ q_1[\sqrt{\frac{\frac{1}{2}\omega_1 g_1}{\sigma^2}}, \infty, \cdots, \infty]^T, \\ \qquad\qquad\qquad\qquad\qquad\qquad \text{if} \quad T_2 \geq P_R > T_1 \end{cases} \tag{25}$$

where $q_K = \frac{\sum_{i=1}^K \sqrt{\frac{\frac{1}{2}\omega_i \sigma^2}{g_i}}}{P_R + \sum_{i=1}^K \frac{\sigma^2}{g_i}}$ and $T_K = \frac{\sum_{i=1}^K \sqrt{\frac{\frac{1}{2}\omega_i \sigma^2}{g_i}}}{\sqrt{\frac{\frac{1}{2}\omega_K g_K}{\sigma^2}}} - \sum_{i=1}^K \frac{\sigma^2}{g_i}, \forall K \in \{1, 2, \cdots, N\}$.

Proof: If $P_R > T_N$, the optimal $\boldsymbol{\lambda}^*$ is readily obtained by Proposition 3. For other intervals of P_R, e.g., $T_{N-1} < P_R \leq T_N$, the proof of the optimality for the corresponding $\boldsymbol{\lambda}^*$ can be obtained similarly as Proposition 3. ∎

Now, the proposed Stackelberg game is completely solved. And the SE for this game is then given by the following proposition.

Proposition 5: The SE for the Stackelberg game formulated in problem (4) and (6) is $(\boldsymbol{\lambda}^*, \mathbf{p}^*)$, where $\boldsymbol{\lambda}^*$ is given by (25), and $\mathbf{p}^*$ is given by (9).

4 Simulation Results

In this section, computer simulations will be carried out to evaluate the performance of the proposed power allocation protocol described in the previous sections. For simplicity, we assume that the variance of the noise is 1, and the payoff factors $\omega_i, \forall i$ are all equal to 2.

An wireless cooperative network with one energy harvesting relay and three user pairs is considered. Without loss of generality, the channel power gains are chosen as follows: $g_1 = 10, g_2 = 1, g_3 = 0.1$.

Now, we compare the system performance obtained by the price-based power allocation algorithm with the uniform pricing algorithm proposed in [9]. In Fig. 1, we present the total income of the relay versus the total energy harvested at it. It is observed that the revenue of the relay increases as P_R increases in both tow algorithms. This is because that the pricing strategies for the relay increases as the available energy increases. And for the same available power P_R, the revenues of the relay under the price-based power allocation algorithm are more than the uniform pricing algorithm. In addition, when P_R is sufficiently small, the revenues of the relay under the tow pricing schemes are identical. It is because that when P_R is very small, there is only one destination active in this game, and thus the proposed price-based algorithm is same as the uniform pricing scheme.

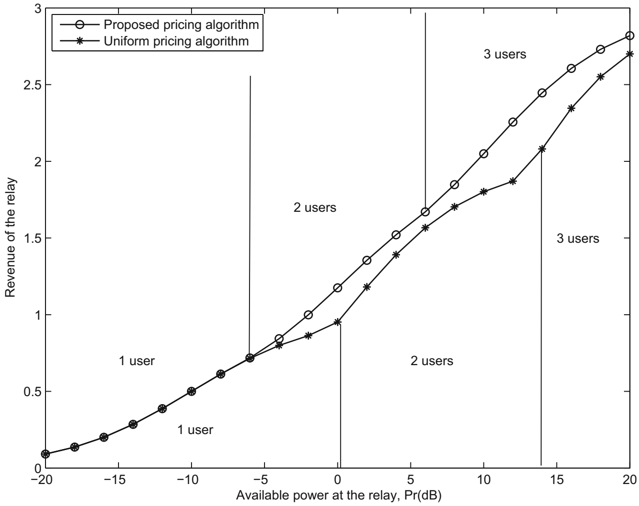

Fig. 1. Revenue of the relay vs. P_R

5 Conclusions

In this letter, we have studied a power allocation strategies for a cooperative network in which multiple user pairs communicate with each other via an energy harvesting relay. And we propose a price-based power allocation scheme to distribute the harvested energy among the multiple users. The Stackelberg game model is adopted to investigate the joint utility maximization of the relay and the destination, closed-form solutions are obtained for the strategy proposed. Compared with the uniform pricing algorithm, simulation results show that the proposed price-based algorithm improves the revenue of the relay for all the available power P_R.

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