Power Allocation for Uplink Multi-user Energy Harvesting Relay Systems with Sleep Mode

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***Abstract*—Contributing to both energy-deficiency alleviation and carbon footprint reduction, energy harvesting (EH) and sleep mode (SM) are deemed to be promising techniques these days. Different from existing researches, this paper considers uplink multi-user relay systems which adopt these two kinds of technologies. The relay in our system is an EH node with random charging rate while the base station (BS) is supplied by power grid and users work with traditional rechargeable batteries. We propose a novel power allocation scheme with which the system can minimize the total energy consumption. After formulating a joint optimization problem, we put forward a heuristic algorithm and successfully decrease the computational complexity. Firstly, by fixing the transmission time, we transform the problem into a convex optimization problem. Secondly, the shortest transmission time can be obtained by the method of bisection. The simulation results show that the proposed scheme can effectively bring a lower energy consumption, and we further validate that a combination of EH and SM plays a significant role in energy saving.**

Keywords*—energy harvesting; sleep mode; power allocation; heuristic algorithm

I. INTRODUCTION

As consciousness for environment protections is increasing, energy conservation has become a hot issue in both industry and academia. Energy harvesting (EH) nodes are able to recharge their energy storage with the source which can be considered as zero carbon emission (such as solar, thermoelectric and so on) . Therefore, EH nodes serve as a promising alternative to traditional communication devices.

Recently, there has been considerable interest in EH technology [2]-[10]. In [2], [3] and [4], a point-to-point communication scenario has been taken into account. [2] and [3] aim at throughput maximization and find out that better system performance can be acquired by introducing EH technology. The authors, in [5] and [6], extend single user systems into multi-user ones and propose optimal policies that can minimize the transmitting time and enhance the energy efficiency, respectively. Along with the advancement of research, relay systems have been brought to attention. Researchers in [7], [8] and [9] apply the EH technology to the two-hop relay system. Also, each of them manages to obtain a unique resource allocation scheme with which system performance can be improved effectively. Further, reference [10] puts forward joint relay selection and power allocation schemes of a system which consists of an EH source node, several amplify-and-forward (AF) EH relays and single receiver. Different from one user relay systems mentioned above, we come up with a power allocation scheme which is applicable to uplink multi-user EH relay systems. Specially, because the randomness of the arrival of harvested renewable energy is inevitable, the base station and users should still be supplied by stable power source. Only in this way can the communication quality be guaranteed. Hence, in this paper, we assume only the relay node can be charged with harvested energy at a random rate while the base station is supplied by power grid and users work with traditional rechargeable batteries.

Sleep mode, on the other hand, is designed to cut down the operational energy consumption by periodically switching off some hardware components and circuits when the device is idle [11]. And the authors, in [12], demonstrate that sleep mode is reasonable and valid for orthogonal frequency division multiple access (OFDMA) networks. Since deploying sleep mode is an effective way to save energy, in our research, we combine it with EH technology.

In order to promote system performance and decrease energy consumption, our research focuses on an optimized power allocation scheme for uplink multi-user EH relay systems with sleep mode. The remainder of this paper is organized as follows. The system model is described in Section II. In Section III, optimization problem description is established. Next, we analyze the problem and propose a heuristic algorithm to obtain the solution in Section IV. In Section V, experimental results are presented to validate that the algorithm can reduce the system consumption effectively. Finally, we conclude this paper in Section VI.

II. SYSTEM MODEL

As shown in Fig. 1, we consider an uplink multi-user EH relay system with M users, U_i, $i \in \{1, 2, ..., M\}$, one DF relay, R, and one base station, BS. Since we take uplink into consideration, U_i communicates with BS via R. We assume that R is an EH device which is equipped with batteries that can store the harvested energy. In consideration of the fact

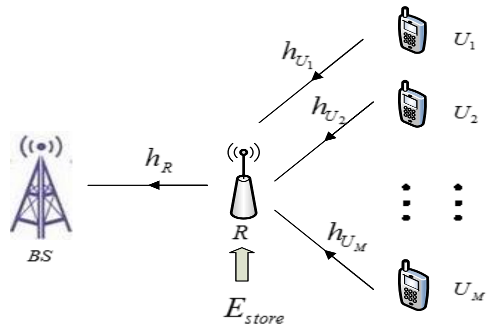

Fig. 1. An Uplink Multi-user EH Relay System Model

that the arrival of harvested energy is unpredictable and the communication quality should be guaranteed, as mentioned previously, we assume only R can be charged with harvested energy. Basically, we need this system to finish transmitting at least B_0 bits in a limited period, T, which means our system has the lower bound of transmission rate.

Meanwhile, all nodes in this system can go to sleep mode to save energy by switching off some hardware components.We suppose that all the nodes in the system have three operating modes: transmitting mode (TM), receiving mode (RM) and sleep mode (SM). Both TM and RM are considered as an active status. In each time interval, one mode of the three would be chosen by each node and the power consumption is shown in TABLE I.

TABLE I
POWER CONSUMPTION

MODE	Ui	R	BS
TM	$P^t_{U_i}$+P^c_U	P^t_R + P^c_R	Undefined
RM	Undefined	P^c_R	P^c_{BS}
SM	P^s_U	P^s_R	P^s_{BS}

where $P^\iota_\dagger$, $\dagger \in \{U_i, R, BS\}$, $\iota \in \{t, s, c\}$ are the different kinds of power. The subscripts, U_i, R and BS, stand for the ith user, relay and base station in proper order, while the meaning of the superscripts, t, c and s, are the transmitting power, the circuit power in TM or RM and the circuit power in SM, respectively.In addition, the conditions that $P^c_{U_i} > P^s_{U_i}$, $P^c_R > P^s_R$, and $P^c_{BS} > P^s_{BS}$ should be met as a result of the off state of some hardwares and circuits.

On the other hand, the transmission is organized in equal time intervals and the duration of each time interval is defined as t_0. According to [13], since the energy harvested batteries cannot charge and discharge simultaneously, we adopt the *save-then-transmit* protocol. In this way, duration t_0 is divided into three timeslots which are shown in Fig. 2 and detailed as the following three steps:

In the first timeslot, R takes a fraction (recorded as save-ratio, $\alpha(0 < \alpha < 1)$ of t_0 to collect harvesting energy and store it in the batteries. Assuming that E_{left} stands for the remaining energy in R's batteries, we define the total energy that reserved after energy harvesting is E_{store}:

$$E_{store} = E_{left} + \alpha\chi T_A \tag{1}$$

where χ is the energy harvesting rate which is the energy

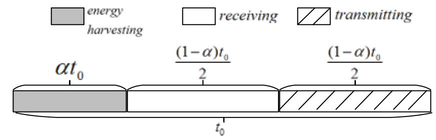

Fig. 2. A Time Interval

stored in unit time. T_A and T_S refer to the period that the system is in active statue (TM and RM)and in idle time (SM), respectively. We have $T = T_A + T_S$.

Considering the situation that all users have similar workloads, we can arguably think that, during the time period T, the discrepancy among users' transmission data volume is narrow. Therefore, we assume that T_A can be equally assigned to M users. Since T_A comprises several time intervals, we have

$$T_A = kMt_0, (k = 1, 2...) \tag{2}$$

The second timeslot is occupied by the process that R receives data, x_{U_i}, from U_i, and then R sends data, x_R, to BS in the last timeslot. As assumed that only one user can send data to R in a timeslot, the received signals can be respectively written as

$$y_{R_i} = h_{U_i} x_{U_i} + n_{R_i} \tag{3}$$

$$y_{BS} = h_R x_R + n_{BS} \tag{4}$$

h_{U_i} is the fading amplitude of the channel between U_i and R while h_R is that between R and BS. h_{U_i} and h_R are generated as independent and identically distributed (i.i.d) Rayleigh random variables. Additive white Gaussian noise (AWGN) signals with zero mean and unit variance are represented by n_{R_i} and n_{BS} (i.i.d), correspondingly.

In order to simplify the calculation, we make the bandwidth of $U_i - R$ links and $R - BS$ link are equal and normalized. Therefore, according to Shannon formula, the data rate at U_i, r_{U_i} and at R, r_R (bps), can be expressed as:

$$r_{U_i} = \log_2(1 + P^t_{U_i} |h_{U_i}|^2) \tag{5}$$

$$r_R = \log_2(1 + P^t_R |h_R|^2) \tag{6}$$

At this point, we have defined the variables in our system model, and then we can get a move on.

III. PROBLEM FORMULATION

In this section, we establish optimization problem description. In the first part, according to [2], a brief retelling about the optimal save-ratio, α, selection is presented. Then, treating the system energy consumption minimization as the objective and taking lower bound of transmission rate and random energy harvesting rate into account, we formulate the optimization problem description in the second part.

A. the optimal save-ratio selection

The optimal save-ratio, α^*, has been deduced in [2] under a certain condition that only the energy harvesting rate's statistical properties are available. The authors assume that the energy harvesting rate, χ, is Gamma-distributed for the reason that a lot of positive random variables can be modeled.

Presuming $\chi \sim \Gamma(k,\theta)$, the optimal save-ratio, α^* , can be calculated by

$$\alpha^* = \frac{1}{W(\theta e^{\psi(k)-1})+1} \tag{7}$$

where $\Gamma(\bullet)$ stands for the gamma function, and $k, \theta > 0$ refer to the shape parameter and the scale parameter, respectively. $W(\bullet)$ denotes the Lambert W function [14]. $\psi(\bullet)$ is the digamma function, which can be shown as following:

$$\psi(x) = \frac{d}{dx}\ln\Gamma(x) \tag{8}$$

Based on (7), the optimization problem description can be established efficiently.

B. the optimization problem description

Since R is supplied by its EH batteries, the total energy consumption of the system in T can be written as:

$$\begin{aligned} E_{sys}(\rho, T_A) = & \underbrace{\frac{T_A(1-\alpha)}{2M}\sum_{i=1}^{M}P_{Ui}^t + T_A P_U^c + T_A P_{BS}^c}_{\mathcal{L}1} \\ & + \underbrace{(T - \frac{T_A}{M})MP_U^s + (T-T_A)P_{BS}^s}_{\mathcal{L}2} \end{aligned} \tag{9}$$

where $\rho = [P_{U1}^t, P_{U2}^t, \ldots\ldots, P_{UM}^t]$. $\mathcal{L}1$ and $\mathcal{L}2$ denote the consumptions during active time and idle time, respectively.

The energy consumption of R is limited to E_{store} which is defined in (1). However, when the energy harvesting rate is unpredictable and only the statistical properties are available, (1) should be transformed into

$$E_{store} = E_{left} + \alpha T_A E[\chi] \tag{10}$$

where $E[\bullet]$ refers to the expectation operator. In particular, we assume that E_{left} can completely prevent the case that the consumption exceeds $\chi\alpha t_0$ in single time interval. And the constraint can be expressed as following:

$$E_R(P_R^t, T_A) = \frac{T_A(1-\alpha)}{2}P_R^t + T_A P_R^c + (T-T_A)P_R^s \le E_{store} \tag{11}$$

During the transmitting time T, the total bits that R sends to BS are supposed to be equal to the sum of the bits that users send to R. And this system need to complete the transmission of B_0 bits in T. Therefore, to meet the requirements, another constraint is

$$\frac{T_A(1-\alpha)}{2} * r_R = \frac{T_A(1-\alpha)}{2M} * \sum_{i=1}^{M} r_{Ui} \ge B_0 \tag{12}$$

When we treat the system energy consumption minimization as the objective, we can formulate the following optimization problem description:

$$\min_{\rho, T_A} \quad E_{sys}(\rho, T_A) \tag{13a}$$

$$s.t. \quad E_R(P_R^t, T_A) \le E_{store} \tag{13b}$$

$$\frac{T_A(1-\alpha)}{2} * r_R = \frac{T_A(1-\alpha)}{2M} * \sum_{i=1}^{M} r_{Ui} \ge B_0 \tag{13c}$$

$$T_A = kMt_0, k = 1, 2 \ldots \left\lfloor \frac{T}{M} \right\rfloor \tag{13d}$$

$$P_{Ui}^t \ge 0, i = 1, 2, \ldots, M \tag{13e}$$

IV. A HEURISTIC POWER ALLOCATION ALGORITHM

In this section, we propose a heuristic algorithm to solve the problem (13). Since the optimization variables consist of a $1 * M$ matrix, ρ, and a number, T_A, the difficulty to solve this problem would be relatively high. By observing the objective function and constraints, we put forward to solve the problem in two stages.

A. a convex optimization problem with a fixed T_A

When we analyze the constraints, problem (13) can be transformed into a convex optimization problem by fixing T_A.

Firstly, the constraint (13b) means the energy consumption of R is limited to E_{store}. Obviously, $E_R(P_R^t, T_A)$ increases with P_R^t when T_A is fixed. Hence, P_R^t should have an upper limit, $P_{R,max}^t$, i.e. if transmission power of R is $P_{R,max}^t$, the energy consumption of it is exactly E_{store}. We have

$$\begin{aligned} & \tfrac{T_A(1-\alpha)}{2}P_{R,\max}^t + T_A P_R^c + (T-T_A)P_R^s = E_{store} \\ => \quad & P_{R,\max}^t = \frac{2E_{store} + 2T_A P_R^c - 2T_A P_R^s - 2TP_R^s}{T_A(1-\alpha)} \end{aligned} \tag{14}$$

Then, substituting (5) and (6) into (13c), we can easily represent P_R^t by $P_{U_i}^t$.

$$\begin{aligned} & \frac{T_A(1-\alpha)}{2} * \log_2(1 + P_R^t |h_R|^2) = \frac{T_A(1-\alpha)}{2M} * \sum_{i=1}^{M} \log_2(1 + P_{Ui}^t |h_{Ui}|^2) \\ & => \quad P_R^t = \frac{\sqrt[M]{\prod_{i=1}^{M}(1 + P_{Ui}^t|h_{Ui}|^2)} - 1}{|h_R|^2} \end{aligned} \tag{15}$$

That is, the transmission power of R should be eventually expressed as

$$\mathcal{P}_R^t = \min\{\frac{\sqrt[M]{\prod_{i=1}^{M}(1 + P_{Ui}^t|h_{Ui}|^2)} - 1}{|h_R|^2}, P_{R,\max}^t\} \tag{16}$$

We get it into $g_1(\rho)$, and a new constraint can be written as

$$g_1(\rho) = \mathcal{P}_R^t \ge \frac{2^{\frac{2B_0}{A(1-\alpha)}} - 1}{|h_R|^2} \tag{17}$$

As $g_1(\rho)$ is the pointwise infimum of a geometric mean function and a constant, $g_1(\rho)$ is concave [15].

Algorithm I: Minimization of transmission time A by the method of bisection

1. Initialization: $T_{A,max} = k_{\max} M$, where $k_{\max} = \left\lfloor \frac{T}{M} \right\rfloor$, $a = 0$, $b = k_{\max}$, $\varepsilon = 1$.
2. Solve the convex optimal problem (14) with $T_{A,max}$, and denote the solution is ρ^*.
3. if $\rho^* < Inf$
4. if $b - a > \varepsilon$
5. $k = \left\lceil \frac{a+b}{2} \right\rceil$,
6. else
7. end up the calculation, and ρ^* is the optimal result.
8. end if
9. Solve the convex optimization problem (14) with $T_A = kM$, then update the result ρ^*.
10. if $\rho^* < Inf$
11. $b = k$,
12. else
13. $a = k$,
14. end if
15. else
16. break out and report errors that the system cannot accomplish the transmit task.
17. end if

Analogously, the other constraint $\frac{T_A}{2M} * \sum_{i=1}^{M} r_{Ui} \geq B_0$, which is recorded as $g_2(\rho)$, is equivalent with

$$g_2(\rho) = \sum_{i=1}^{M} \log_2(1 + P_{Ui}^t |h_{Ui}|^2) \geq \frac{2MB_0}{(1-\alpha)T_A} \tag{18}$$

Apparently, $g_2(\rho)$ is concave too. $f(\rho)$ indicates the objective function. The optimization problem (13) turns into a convex optimization problem of an optimization variable ρ, which is shown below

$$\begin{aligned} \min_{\rho > 0} \quad & f(\rho) = \frac{T_A(1-\alpha)}{2M} \sum_{i=1}^{M} P_{Ui}^t + T_A P_U^c + (T - \frac{T_A}{M}) M P_U^s \\ & \quad + T_A P_{BS}^c + (T - T_A) P_{BS}^s \\ s.t. \quad & g_1(\rho) = \mathcal{P}_R^t \geq \frac{2^{\frac{2B_0}{T_A(1-\alpha)}} - 1}{|h_R|^2} \\ & g_2(\rho) = \sum_{i=1}^{M} \log_2(1 + P_{Ui}^t |h_{Ui}|^2) \geq \frac{2MB_0}{T_A(1-\alpha)} \end{aligned} \tag{19}$$

This problem can be solved by any standard algorithm or solver, e.g. CVX [16].

B. The minimization of T_A

According to the convex optimization problem (19), when T_A is fixed, we can obtain the optimized power allocation ρ^* easily. Moreover, in our assumption, we have $0 \leq T_A \leq T$. Our computational investigation testifies that we can acquire the minimum T_A by simple approaches. In this part, we make efforts to find out T_A by the method of bisection, and the steps are described as Algorithm I.

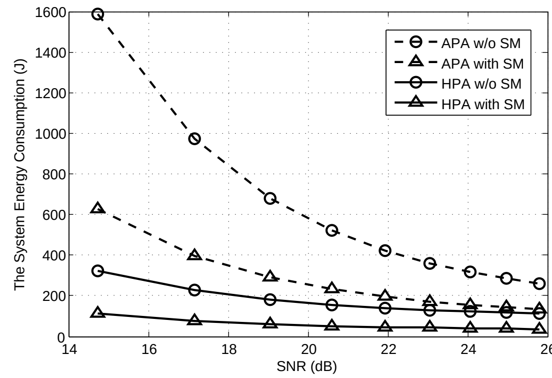

Fig. 3. The System Energy Consumption (J) vs. SNR (dB)

V. Simulation Result

In this section, we evaluate the performance of the proposed heuristic power allocation algorithm. We consider uplink multi-user EH relay systems that all nodes can turn to SM when they are unoccupied. In our system model, we compare the heuristic power allocation algorithm (HPA) with the average power allocation (APA) scheme which means the transmission power of every user is identical and decided by the average signal to noise ratio (SNR). It is assumed that the bandwidth of both the links between the ith user, U_i, and relay, R, and the link between R and base station, BS, is $B = 100kHz$. The transmission time is $T = 1s$ while each time interval is $t_0 = 1ms$, the amount of data is $B_0 = 10kbits$, and the noise power density N_0 is $-174dBm/Hz$.

For all the simulation results, we assume the energy harvesting rate $\chi \sim \Gamma(10, 10)$, i.e. $k = 10, \theta = 10$, and the values of different kinds of power are given in TABLE II.

TABLE II
SIMULATION PARAMETERS

POWER	VALUE	PARAMETERS	VALUE
P_U^c	100 mW	B	100 kHZ
P_U^s	10 mW	T	1 s
P_R^c	1000 mW	t_0	1 ms
P_R^s	500 mW	B_0	10 kbits
P_{BS}^c	2000 mW	N_0	-174 dBm/Hz
P_{BS}^s	500 mW	k, θ	10

A. System Energy Consumption vs SNR

Fig. 3 shows the system energy consumption vs. SNR for the case that the number of users is $M = 64$. The four curves in the diagram from top to bottom stand for conditions that the system adopts neither SM nor the heuristic power allocation algorithm (APA w/o SM), the system adopts SM but works without the heuristic power allocation algorithm (APA with SM), the system works with the proposed heuristic algorithm but without SM (HPA w/o SM) and the system adopts both the heuristic algorithm and SM (HPA with SM), correspondingly. The simulation results prove that this heuristic algorithm can reduce the energy consumption of the system substantially, and in the lower SNR, the effect is more obvious.

In order to obtain a better analysis of the results of HPA algorithm, we put two lines, APA with SM and HPA with

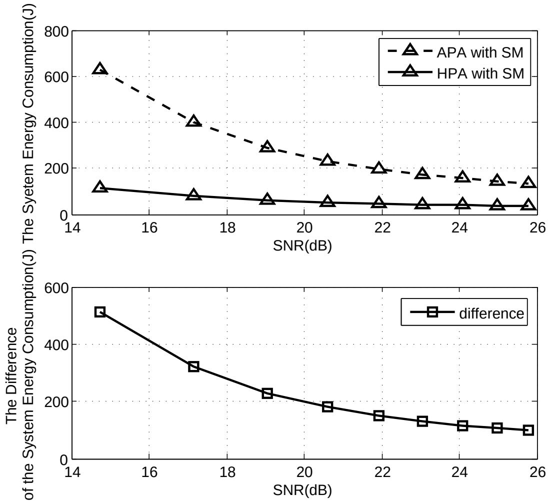

Fig. 4. The Comparison of HPA and APA

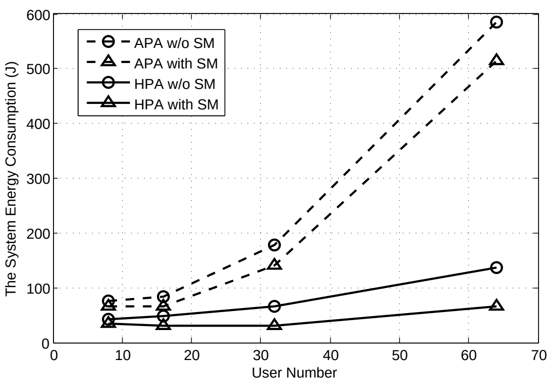

Fig. 5. The System Energy Consumption vs. User Number

SM, in a separate diagram. As it is shown in Fig. 4, the difference between the two lines is calculated at the same time. In detail, when SNR equals to 17.16 dB, the gap of the energy consumptions reaches to 320 J, which is nearly four times lower. And even when the channel SNR rises to 25.80 dB, the difference is 98 J, around one time less.

B. System Energy Consumption vs User number

On the other hand, we fix SNR=20 dB and observe the changing of four lines when the number of users is increasing. Analyzing the simulation result in Fig. 5, we obtain that even though the number of user is various, the consumption reach to the lowest value when both heuristic algorithm and SM are introduced to the system. Besides, when the number of the users increases, the effects of the proposed power allocation scheme and SM are getting more evident.

VI. CONCLUSION

Aiming at minimizing the system energy consumption, we have proposed a power allocation scheme for uplink multi-user energy harvesting relay systems. Basically, we set a lower bound of transmission rate and take random energy harvesting rate in to consideration. After establishing a joint optimization problem, this paper have proposed a heuristic algorithm which make the calculation much easier by solving the problem in two steps. According to the simulation results, we conclude that the scheme we proposed brings a significant reduction in energy consumption. The combination of energy harvesting technology and sleep mode would avail a lot, especially when the system has a lower SNR.

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