Cooperative Joint Power Splitting and Allocation Approach for Simultaneous Energy Delivery and Data Transfer

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Abstract—**In this paper, we propose to minimize the total energy consumption cost of a simultaneous data transmission and power delivery from different sources. The receiver is designed to simultaneously process information and harvest energy from the received signal through a power splitter. We derive an optimal power allocation and splitting ratios for each source node that minimizes the total power cost while ensuring the required data rates for each link. The solution profits from the variability between the channel gains and data requirements. Numerical simulations allow to analyze the performance of the proposed solution.**

***Index Terms*—Energy harvesting, spectrum access efficiency, power allocation.**

I. INTRODUCTION

With the recent advances in wireless communication performance, deployment of wireless devices in large scale became a promising technology due to their lower costs and facility of deployment compared to wired architecture. In addition to conventional cellular devices, a large number of sensor devices used in different fields to take measurements and send data regularly for processing. But, limited energy resources represents a continuous bottleneck although the evolutions realized in optimizing batteries' life-time and capacity due to difficulty of frequent recharging or replacement of these batteries. Energy harvesting [1], which consists in the ability of collecting energy from the surrounding environment, represents an ideal solution to this problem. Although, the very low energy that can be generated through such technique, the low-power consumption of such devices (sensors) makes it practical in this application.

Harvesting energy from the environment, such as wind and power, has an inherent variability related to the nature of these resources. Hopefully, it was shown that it is possible to gather energy from radio-frequency sources [2] and hence delivering information and power at the same time. What is interesting is that the harmful interference will be no longer non-desired but contrariwise to what we may think, a great source of energy [3], [4]. However, since from practical perspective, it is very challenging to design circuits capable of gathering power and decoding data at the same time, researchers considered time shifting or power splitting ways instead [5]. In fact, with practical assumption [5] investigated the design of the receiver architecture and analyzing the system performance. Further developments are under study to extend this technique to multi-antenna systems, OFDM systems, and cooperative networks.

The authors in [8] considered power splitting for power allocation in wireless cooperative communication. The system's performance was analyzed in terms of outage probability where a relay can harvest energy from different sources. The authors in [4] considered power splitting as well but in a point-to-point half duplex multi-channel communications system. The authors considered the sum rate maximization and derived the power splitting ratio with a suboptimal scheme where a lower bound for the sum rate in hostile jamming. This approach may lead to user starvation since maximizing the sum rate does not imply that both users enjoy good throughput.

In this paper, we propose to optimize the power allocation and splitting ratios for multiple sources serving a common energy harvester receiver such that they minimize their global power consumption while guarantying the required data rate of each of them. Cooperation between users allow to profit from the channels variability between the different sources towards the receiver as well as the different quality of service requirements to minimize the total power consumed while ensuring the delivery of the required data and energy simultaneously. The objective consists in determining the optimal power to use as well as the splitting ratio between signal to be decoded and signal to be harvested for each source. We will show an optimal derivation of the power and splitting ratios through Lagrangian approach.

The rest of this paper is organized as follows. In Section II, we describe the system model then we formulate our power and splitting allocation problem. In Section III, we analyze the optimization problem and derive the analytic solution and present a selection algorithm. Simulation-based analysis is presented in Section IV. Finally, conclusion is presented in Section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a wireless system as in Fig. 1 composed of a set of N powerful nodes denoted by $\{A_1, A_2, ...A_N\}$ communicating with an energy harvester node B with a limited power supply. The node B is capable of decoding information and harvesting energy from the received radio signals simultaneously. By reference to the power transfer, the nodes A_i are called "sources" and node B is called "receiver". No interference between the different sources is assumed as disjoint channels are assigned to each node. We denote by link i the communication channel between the node A_i and the node B with a channel gain h_i. All nodes are equipped with a single antenna.

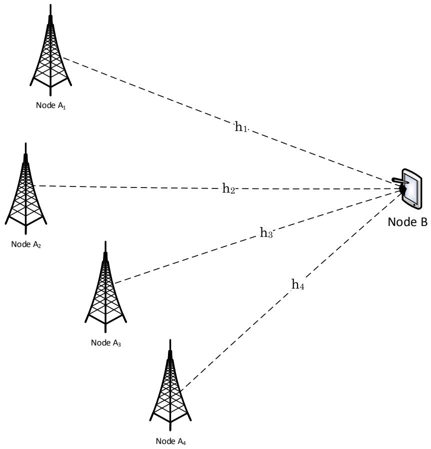

Fig. 1. System Model

We consider the problem of minimizing the total power consumed at the N source nodes $\{A_i\}_{i=1\ldots N}$ needed to ensure in the same time a required data rate $r^{req}_{A_i}$ for each link i from a source A_i towards the node B and simultaneously ensure a needed energy to be harvested at the node B, denoted P_B. The problem is then written as follows:

$$\min_{\rho_i, P_{A_i}} \sum_{i=1}^{N} P_{A_i} \tag{1a}$$

$$\text{S.t} \quad r_{A_i} \geq r^{req}_{A_i}, \quad \forall i \tag{1b}$$

$$P_H \geq P_B \tag{1c}$$

$$P_{A_i} \geq 0, \quad \forall i \tag{1d}$$

$$0 \leq \rho_i \leq 1, \quad \forall i \tag{1e}$$

where P_{A_i} is the power transmitted form each node A_i, and ρ_i represents the splitting ratio for each node A_i that will be used to divide signal used to harvest power from that reserved for data transmission.

r_{A_i}, the data-rate of the transmission from node A_i towards the node B is expressed as

$$r_{A_i} = log_2\left(1 + \frac{(1-\rho_i)P_{A_i}|h_i|^2}{\sigma_i^2}\right), \quad \forall i \tag{2}$$

where σ_i^2 is the noise power for the i-th link.

P_H is the total harvested energy at the node B expressed as

$$P_H = \xi \sum_{i=1}^{N} \rho_i\big(P_{A_i}|h_i|^2 + \sigma_B^2\big) \tag{3}$$

with ξ the harvesting efficiency factor.

III. POWER AND SPLITTING RATIO OPTIMIZATION

The challenge in solving the problem (1) is that unlike the classic power allocation problems, it is not a convex problem due to the non convexity of the rate constraints with regards to the splitting ratio variables (ρ_i). For that, we propose to rewrite the problem as follows:

$$\min_{\rho_i, P_{A_i}} \sum_{i=1}^{N} P_{A_i} \tag{4a}$$

$$\text{S.t} \quad (1-\rho_i)P_{A_i} \geq \bar{P}_{A_i}, \quad \forall i \tag{4b}$$

$$\xi \sum_{i=1}^{N} \rho_i\big(P_{A_i}|h_i|^2 + \sigma_B^2\big) \geq P_B \tag{4c}$$

$$P_{A_i} \geq 0, \quad \forall i \tag{4d}$$

$$0 \leq \rho_i \leq 1, \quad \forall i \tag{4e}$$

$$\tag{4f}$$

where $\bar{P}_{A_i} \triangleq \frac{2^{r^{req}_{A_i}}-1}{|h_i|^2/\sigma_i^2}$ denotes the required minimum power for each source A_i to achieve the required data rate $r^{req}_{A_i}$.

Thus, we end up with a convex minimization problem with non-linear constraints. While the objective function is a common total power minimization, these types of constraints has not been studied before, to the knowledge of the authors.

The Lagrangian function is then written as

$$\begin{aligned}\mathcal{L}(P_{A_i}, \rho_i, \lambda_i, \lambda_R) = &\sum_{i=1}^{N} P_{A_i} \\ &+ \sum_{i=1}^{N} \lambda_i\Big[\bar{P}_{A_i} - (1-\rho_i)P_{A_i}\Big] \\ &+ \lambda_0\Big[P_B - \xi\sum_{i=1}^{N}\rho_i\big(P_{A_i}|h_i|^2 + \sigma_B^2\big)\Big],\end{aligned} \tag{5}$$

where $\{\lambda_i\}_{i=1,\ldots,N}$ and λ_0 are the Lagrangian parameters.

The K.K.T conditions are then derived as follows

$$\frac{\partial \mathcal{L}}{\partial P_{A_i}} = 1 - \lambda_i(1-\rho_i) - \lambda_0\rho_i|h_i|^2 = 0, \ \forall i \tag{6}$$

$$\frac{\partial \mathcal{L}}{\partial \rho_i} = \lambda_i P_{A_i} - \lambda_0(P_{A_i}|h_i|^2 + \sigma_B^2) = 0, \ \forall i \tag{7}$$

$$\lambda_i\Big[\bar{P}_{A_i} - (1-\rho_i)P_{A_i}\Big] = 0, \ \forall i \tag{8}$$

$$\lambda_0\Big[P_B - \xi\sum_{i=1}^{N}\rho_i\big(P_{A_i}|h_i|^2 + \sigma_B^2\big)\Big] = 0 \tag{9}$$

$$\lambda_i \geq 0, \ \forall i \tag{10}$$

$$\lambda_0 \geq 0. \tag{11}$$

The two first K.K.T conditions (6) and (7) allow to obtain closed-form expressions of the allocated power and splitting ratio per node function of the Lagrangian parameters as follows:

$$P_{A_i} = \left[\frac{\lambda_0 \sigma_B^2}{\lambda_i - \lambda_0 |h_i|^2}\right]^+ \qquad (12)$$

$$\rho_i = \left[\frac{\lambda_i - 1}{\lambda_i - \lambda_0 |h_i|^2}\right]_0^1, \qquad (13)$$

where $\left[x\right]_{x^-}^{x^+} = \begin{cases} x & \text{if } x^- \le x \le x^+ \\ x^- & \text{if } x \le x^- \\ x^+ & \text{if } x \ge x^+, \end{cases}$

and $\left[x\right]^+ = \begin{cases} x, & \text{if } x \ge 0 \\ 0, & \text{otherwise.} \end{cases}$

To determine the Lagrangian parameters, we replace (12) and (13) in the inequality constraints (8) and (9).

The $\{\lambda_i\}_{1 \le i \le N}$ can be derived in closed-form function of λ_0 using (8) as follows

$$\lambda_i = \begin{cases} \lambda_0 |h_i|^2 + \sqrt{\frac{\lambda_0 \sigma_B^2 (1 - \lambda_0 |h_i|^2)}{P_{A_i}}}, & \text{if } i \in S \\ 0, & \text{otherwise} \end{cases} \qquad (14)$$

where $S = \left\{1 \le i \le N \text{ and } \frac{1}{|h_i|^2 + \frac{\sigma_B^2}{P_{A_i}}} \le \lambda_0 \le \frac{1}{|h_i|^2}\right\}$ corresponds to the subset of users that will use their power to feed power to the receiver simultaneously to the data transmission while the rest of the users will employ their full power to send data only (i.e., $0 < \rho_i < 1$ if $i \in S$ and $\rho_i = 0$, otherwise.)

λ_0 is determined by solving the equation $f(\lambda_0) = 0$, where the function $f(.)$ is deduced from (9) as follows

$$f(\lambda_0) = \sum_{i \in S} \xi \frac{(\lambda_i - 1)\lambda_i \bar{P}_{A_i}}{(1 - \lambda_0 |h_i|^2)\lambda_0} - P_B \qquad (15)$$

Without loss of generality, we suppose that users are indexed in a decreasing order of their channel gains towards the receiver $|h_i|^2$. The analysis of the function f shows that it is continuous and strictly increasing in each interval $\left[\frac{1}{|h_i|^2}, \frac{1}{|h_{i+1}|^2}\right]$. Thus, existence of λ_0 which nulls this function can be proven easily by a simple sign check at the interval bounds. Then, finding λ_0, if it exists, is done using a subsection algorithm.

The only remaining point to solve the problem is to determine the subset S contributing to the energy harvesting. For that, propose a recursive approach which parses all combinations of selection of the subset of users who will be feeding power in conjunction with data then compute the optimal power and ratio allocation based (12) and (13). The subset requiring the lowest total power to satisfy all requirements is used.

IV. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed scheme. Unless stated differently in a figure's legend, we consider a system with $N = 10$ sources generated randomly in a circle of radius $d_{max} = 1Km$ of the receiver. The channel gains h_i are complex Gaussian with an average proportional to the path loss given by $(d_max/d_i)^\eta$, where d_i is the distance between the source i and the receiver and η is the path-loss exponent set to 3. The noise power per link is set to $\sigma_i^2 = -120\ dBm/Hz$. The data rate requirements r_i^{req} are generated uniformly random in the interval $[r_{min}^{req}, r_{max}^{req}]$ with $r_{min}^{req} = 0\ Mbps/Hz$ and $r_{max}^{req} = 10\ Mbps/Hz$. The receiver's required power is chosen as $P_B = 0.5\ Watts$ and its energy harvesting gain factor is assumed to be $\xi = 0.8$. In the following, we vary the channels average signal-to-noise ratio for the reference distance d_max and apply the proposed algorithm to determine the optimal power and splitting ratios per node. We evaluate the performance in terms of the total additional required power to satisfy the energy harvesting constraint by deducting the total power needed to achieve data-rate requirements only.

In Fig. 2, we observe the effect of the required power to be harvested at the receiver and we plot the average additional user per user as function of the average channels signal-to-noise ratios (SNR) for a reference distance. Obviously, the increase of the required power to be harvested incur an increase of the needed power from the source nodes but as the quality of channels improve, i.e. when average SNR increases, the required additional power for energy harvesting decreases.

In Fig. 3, we observe the effect of the number of source nodes N in the system. Increasing N gives more choices of source nodes to exploit to get power to the receiver which will reduce the total additional required power profiting from variability between links' gains and users' requirements in terms of data-rate.

In Fig. 4, we observe the effect of the source nodes' data-rate requirements by plotting the average additional consumed power for different intervals of the rate requirements. Specifically, we increase the upper-bound of the rate-requirement interval from 10 to 30 $Mbps/Hz$. This increase results in an increase of the additional power needed for energy harvesting. Although, we deducted the power needed for achieving data-rate requirements, an additional power is needed for energy harvesting is noted when the rate requirements increase. This is due to the lesser opportunities left for users to allocate power to be sent to the receiver to be harvested.

In Fig. 5, we focus on the rate requirements distribution, we vary the interval of rate requirements while fixing the average rate required. We note that although source nodes have the same average rate requirement, the additional power is higher when the interval is larger due to the higher variance between the users.

V. CONCLUSION

This paper proposes a power allocation and splitting algorithm for an energy harvesting receiver from multiple sources. The proposed approach profits from channels variability between the different sources and their different requirements in terms of quality of service to minimize the total power usage while meeting the data rate requirements and delivering the needed power. We formulate the problem as a constrained

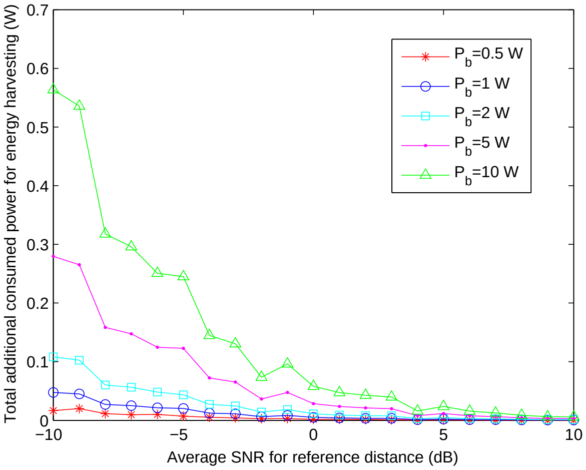

Fig. 2. Additional power cost for different power harvested values.

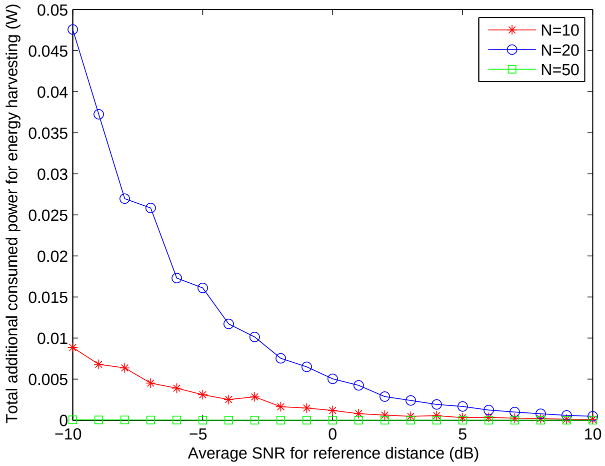

Fig. 3. Additional power cost function of the number of source nodes N in the system.

minimization problem. Then, we derive an optimal solution for the power allocation and splitting ratios using the Lagrangian approach. Numerical simulations allow to analyze the system's performance.

VI. ACKNOWLEDGMENT

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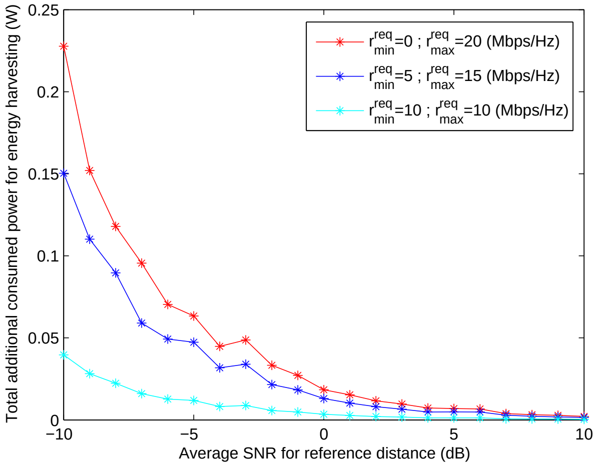

Fig. 4. Additional power cost with different data-rate requirements at the source nodes.

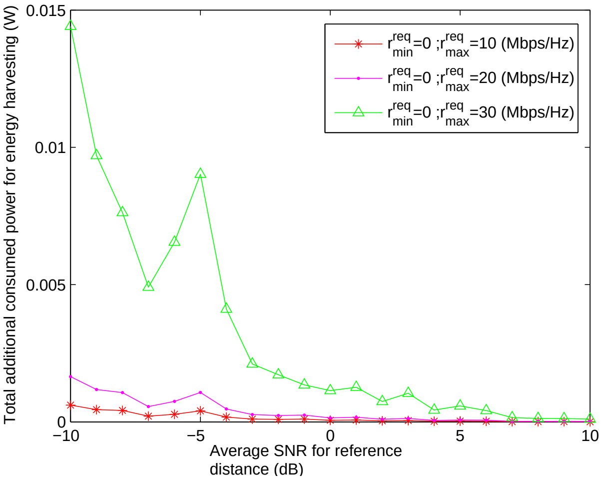

Fig. 5. Additional power cost with different data-rate requirements at the source nodes.

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