Single-User and Multiple Access Channels with Energy Harvesting Transmitters and Receivers

Ahmed Arafa Sennur Ulukus
Department of Electrical and Computer Engineering
University of Maryland College Park, MD 20742
arafa@umd.edu *ulukus@umd.edu*

***Abstract*—We consider the effects of decoding costs in energy harvesting communication systems. In our setting, receivers, in addition to transmitters, rely solely on energy harvested from nature, and need to spend some energy in order to decode their intended packets. We model the decoding energy as an increasing convex function of the rate of the incoming data. In this setting, in addition to the traditional *energy causality* constraints at the transmitters, we have the *decoding causality* constraints, where energy spent by the receiver for decoding cannot exceed its harvested energy. We first consider the point-to-point single-user problem where the goal is to maximize the total throughput by a given deadline subject to both energy and decoding causality constraints. We then consider the multiple access channel (MAC) where the transmitters and the receiver harvest energy from nature, and characterize the maximum departure region.**

I. Introduction

Energy harvesting communications offer the promise of energy self-sufficient, energy self-sustaining operation for wireless networks with significantly prolonged lifetimes. Energy harvesting communications have been considered mostly for energy harvesting transmitters, see e.g., [1]–[26], with fewer works on energy harvesting receivers, see e.g., [27]–[30]. In this paper, we consider energy harvesting communications with both energy harvesting transmitters and receivers.

The energy harvested at the transmitters is used for data transmission according to a rate-power relationship, which is concave, monotone increasing in powers. The energy harvested at the receivers is used for decoding costs, which we assume to be convex, monotone increasing in the incoming rate [31], [32]. The transmission energy costs and receiver processing costs could be comparable, especially in short-distance communications, where high rates can be achieved with relatively low powers, and the decoding power could be dominant.

We model the energy needed for decoding at the receivers via *decoding causality* constraints: the energy spent at the receiver for decoding cannot exceed the receiver's harvested energy. We already have the *energy causality* constraints at the transmitter: the energy spent at the transmitter for transmitting data cannot exceed the transmitter's harvested energy. Therefore, for a given transmitter-receiver pair, transmitter powers need now to adapt to both energy harvested at the transmitter and at the receiver; the transmitter must only use powers, and therefore rates, that can be handled/decoded by the receiver.

This work was supported by NSF Grants CNS 13-14733, CCF 14-22111 and CCF 14-22129.

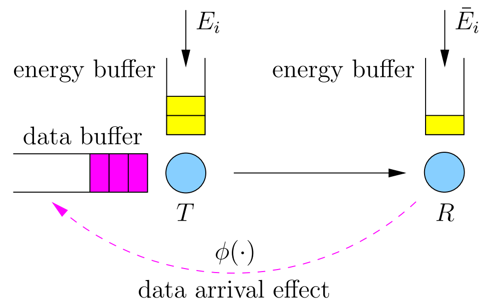

Fig. 1. Single-user channel with an energy harvesting transmitter and receiver.

The most closely related work to ours is [27], where the authors consider a general network with energy harvesting transmitters and receivers, and maximize a general utility function, subject to energy harvesting constraints at all terminals. Reference [27] carries the effects of decoding costs to the objective function. If the objective function is no longer concave after this operation, it uses time-sharing to concavify it, leading to a convex optimization problem, which it then solves by using a generalized water-filling algorithm.

In this paper, we consider a similar problem with a specific utility function (throughput), for two specific network structures (single-user channel and MAC). For the single-user channel, we observe that the decoding costs at the receiver can be interpreted as a *gate keeper* at the front-end of the receiver that lets packets pass only if it has sufficient energy to decode. We show that, we can carry this *gate* effect to the transmitter as a *generalized data arrival constraint*. Therefore, the setting with decoding costs at the receiver is equivalent to a setting with no decoding costs at the receiver, but with a (generalized) data arrival constraint at the transmitter [1]. We also note that the energy harvesting component of the receiver can be separated as a *relay* between the transmitter and the receiver; and again, the problem can be viewed as a setting with no decoding costs at the receiver but with a *virtual relay* with a (generalized) energy arrival constraint [9]–[14].

Next, we consider a two-user MAC with energy harvesting transmitters and receiver, and maximize the departure region. We show that the boundary of this region is achieved by solving a weighted sum rate maximization problem that can be decomposed into an inner and an outer problem. We solve the inner problem using the results of single-user fading problem [3], and the outer problem using a water-filling algorithm.

II. Single-User Channel

As shown in Fig. 1, we have a transmitter and a receiver, both relying on energy harvested from nature. The time is slotted, and at the beginning of time slot $i \in \{1, \dots, N\}$, energies arrive at a given node ready to be used in the same slot. Let $\{E_i\}_{i=1}^N$ and $\{\bar{E}_i\}_{i=1}^N$ denote the energy harvested at each slot for the transmitter and the receiver, respectively, and $\{p_i\}_{i=1}^N$ denote the transmitter's powers. We assume that nodes have infinite rechargeable batteries to store their energies.

Without loss of generality, we assume that the time slot duration is normalized to one time unit. The physical layer is a Gaussian channel with unit noise variance. The objective is to maximize the total amount of data received *and decoded* by the receiver by a given deadline N. Our setting is *offline* in the sense that all energy amounts are known prior to transmission.

The receiver must be able to decode the kth packet by the end of the kth slot. A transmitter transmitting at power p_i in the ith time slot will send at a rate $g(p_i) \triangleq \frac{1}{2}\log_2(1+p_i)$, for which the receiver will spend $\phi(g(p_i))$ amount of power to decode, where ϕ is generally an increasing convex function. In the sequel, we will also focus on the specific cases of linear and exponential functions, where $\phi(r) = ar + b$, with $a \geq 0$ and $b \in \mathbb{R}$, and $\phi(r) = c2^{dr} + e$, with $c, d \geq 0$ and $e \in \mathbb{R}$. Continuing with a general convex increasing function ϕ, we have the following decoding causality constraints:

$$\sum_{i=1}^{k} \phi(g(p_i)) \leq \sum_{i=1}^{k} \bar{E}_i, \qquad k = 1, \dots, N \tag{1}$$

Therefore, the problem is formulated as

$$\begin{aligned} \max_{\mathbf{p} \geq \mathbf{0}} \quad & \sum_{i=1}^{N} g(p_i) \\ \text{s.t.} \quad & \sum_{i=1}^{k} p_i \leq \sum_{i=1}^{k} E_i, \quad \forall k \\ & \sum_{i=1}^{k} \phi(g(p_i)) \leq \sum_{i=1}^{k} \bar{E}_i, \quad \forall k \end{aligned} \tag{2}$$

where $\mathbf{p}$ denotes the vector of powers. Note that the problem above in general is not a convex optimization problem as (1) in general is a non-convex constraint since ϕ is a convex function while g is a concave function [33]. Applying the change of variables $g(p_i) = r_i$, and defining $f \triangleq g^{-1}$ (note that f is a convex function), we have

$$\begin{aligned} \max_{\mathbf{r} \geq \mathbf{0}} \quad & \sum_{i=1}^{N} r_i \\ \text{s.t.} \quad & \sum_{i=1}^{k} f(r_i) \leq \sum_{i=1}^{k} E_i, \quad \forall k \\ & \sum_{i=1}^{k} \phi(r_i) \leq \sum_{i=1}^{k} \bar{E}_i, \quad \forall k \end{aligned} \tag{3}$$

which is now a convex optimization problem that can be solved by standard techniques [33]. We note that the constraints in (1), i.e., $\sum_{i=1}^k \phi(r_i) \leq \sum_{i=1}^k \bar{E}_i$, place upper bounds on the rates of the transmitter by every slot k. This resembles the problem addressed in [1] with data packet arrivals during the communication session. In fact, when $\phi(r) = r$ and $\bar{E}_i = b_i$, where b_i is the amount of data arriving in slot i, these are exactly the data arrival constraints in [1]. A general convex ϕ generalizes this data arrival constraint. We characterize the solution of (3) in the following three lemmas and the theorem. The proofs of these lemmas rely on the convexity of f and ϕ as in [1], and are omitted here due to space limitations.

Lemma 1 *$\{r_i^*\}$ is monotonically increasing.*

Lemma 2 *In the optimal policy, whenever the rate changes at a given time slot, at least one of the following events occur: 1) the transmitter consumes all of its harvested energy in transmission, or 2) the receiver consumes all of its harvested energy in decoding, up to that time slot.*

Lemma 3 *In the optimal policy, by the end of the transmission period, at least one of the following events occur: 1) the transmitter's total power consumption in transmission is equal to its total harvested energy, or 2) the receiver's total power consumption in decoding is equal to its total harvested energy.*

Theorem 1 *Let $\psi \triangleq \phi^{-1}$. A policy is optimal iff it satisfies the following*

$$r_n = \min\left\{ g\left(\frac{\sum_{j=1}^{i_n} E_j - \sum_{j=1}^{i_{n-1}} p_j}{i_n - i_{n-1}}\right), \psi\left(\frac{\sum_{j=1}^{i_n} \bar{E}_j - \sum_{j=1}^{i_{n-1}} p_j}{i_n - i_{n-1}}\right)\right\} \tag{4}$$

where

$$i_n = \arg\min_{i_{n-1} < i \leq N} \left\{ g\left(\frac{\sum_{j=1}^{i} E_j - \sum_{j=1}^{i_{n-1}} p_j}{i - i_{n-1}}\right), \psi\left(\frac{\sum_{j=1}^{i} \bar{E}_j - \sum_{j=1}^{i_{n-1}} p_j}{i - i_{n-1}}\right)\right\} \tag{5}$$

with $i_0 = 0$, and $n = 1, \dots, N$.

Theorem 1 shows that decoding costs at the receiver are similar in effect to having a single-user channel with data arrivals during transmission and no decoding costs. This stems from the fact that the transmitter has to adapt its powers (and rates) in order to meet the decoding requirements at the receiver. Therefore, the receiver's harvested energies and the function ϕ control the amount of data the transmitter can send by any given point in time.

Alternatively, we can view the single-user setting with an energy harvesting receiver, as a two-hop setting with a *virtual relay* between the transmitter and the receiver, with a non-energy harvesting receiver. To this end, we separate the decoding costs of the receiver, which are subject to energy harvesting constraints, as a relay which is subject to energy

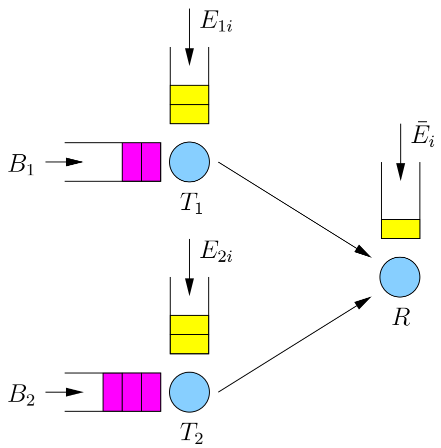

Fig. 2. Two-user MAC with energy harvesting transmitters and receiver.

harvesting constraints in its transmissions, and consider the receiver as fully powered [9]–[14]. The receiver will only receive data if the relay has sufficient energy to forward them. In addition, this energy harvesting virtual relay has no data buffer, thus its incoming data rate equals its outgoing data rate. The rate through this relay is controlled by $\bar{E}_i$ and ϕ. Thus, the decoding function ϕ puts a *generalized energy arrival effect* to this relay, in a similar way that it puts a *generalized data arrival effect* to the transmitter through Theorem 1.

III. Multiple Access Channel

We now consider a two-user Gaussian MAC as shown in Fig. 2. The two transmitters harvest energy in amounts $\{E_{1i}\}_{i=1}^N$ and $\{E_{2i}\}_{i=1}^N$, respectively, and the receiver harvests energy in amounts $\left\{\bar{E}_i\right\}_{i=1}^N$. The received signal is

$$Y = X_1 + X_2 + Z \tag{6}$$

where X_i is the ith transmitter's signal, and Z is the Gaussian noise with zero-mean and unit-variance. The capacity region for this channel is given by [34]: $r_1 \leq g(p_1)$, $r_2 \leq g(p_2)$, $r_1 + r_2 \leq g(p_1 + p_2)$, where p_1 and p_2 are the powers used by the first and the second transmitter, respectively.

In addition to the usual energy harvesting causality constraints on the transmitters, we impose a receiver decoding cost on the sum rate, i.e., the two transmitters can only send at rates whose sum can be decoded at the receiver. This can be the case, for instance, if the receiver employs simultaneous decoding [34]. Let p_{ji} denote the power used by the jth transmitter in time slot i. A policy $\{p_{1i}, p_{2i}\}_{i=1}^N$ is feasible if the following are satisfied

$$\sum_{i=1}^k p_{1i} \leq \sum_{i=1}^k E_{1i}, \quad \sum_{i=1}^k p_{2i} \leq \sum_{i=1}^k E_{2i},$$
$$\sum_{i=1}^k \phi\left(g\left(p_{1i} + p_{2i}\right)\right) \leq \sum_{i=1}^k \bar{E}_i, \quad \forall k \tag{7}$$

Let B_j denote the total departed bits from the jth user by time slot N. Assuming that both transmitters are infinitely backlogged, our aim is to characterize the *maximum departure region*, $\mathcal{D}(N)$, which is the region of (B_1, B_2) the transmitters can depart by time slot N, through a feasible policy. The following lemmas characterize this region [5].

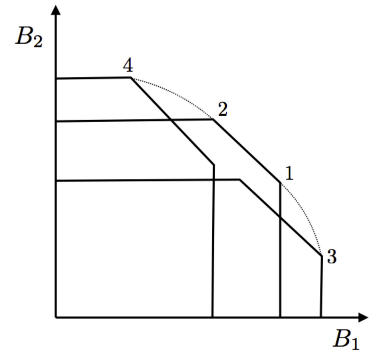

Fig. 3. Departure region of a two-user MAC.

Lemma 4 *The maximum departure region, $\mathcal{D}(N)$, is the union of all (B_1, B_2), over all feasible policies $\{p_{1i}, p_{2i}\}_{i=1}^N$, where for any fixed power policy, (B_1, B_2) satisfy*

$$B_1 \leq \sum_{i=1}^N g(p_{1i}), \ \ B_2 \leq \sum_{i=1}^N g(p_{2i})$$
$$B_1 + B_2 \leq \sum_{i=1}^N g(p_{1i} + p_{2i}) \tag{8}$$

Lemma 5 *$\mathcal{D}(N)$ is a convex region.*

Each point on the boundary of $\mathcal{D}(N)$ can be characterized by solving a weighted sum rate maximization problem subject to feasibility conditions (7). Let μ_1 and μ_2 be the non-negative weights for the first and the second user rates, respectively, and let us examine three cases separately.

A. $\mu_1 = \mu_2$

In this case, the aim is to maximize the sum rate. Let us define $p_i \triangleq p_{1i}+p_{2i}$, and relax the problem by treating the two users as one by adding up their harvested energies to obtain a relaxed problem which is given as in (2) with $E_i = E_{1i}+E_{2i}$. We refer to this problem as the sum rate problem. This is a single-user problem whose solution is given by (4) and (5). Then, we can choose to divide p_i^* in infinitely many ways to get p_{1i} and p_{2i}. For each division choice, we get a different pentagon, but all pentagons share the same dominant face. Our next goal is to get the boundary points of this dominant face, denoted by points 1 and 2 in Fig. 3.

Towards this, let us focus on point 1 without loss of generality. To get a policy that achieves point 1, we need to maximize the rate of the first transmitter, subject to its energy causality constraints, decoding causality at the receiver, and additional constraints from the solution of the sum rate problem. Adding these last set of constraints will force the first transmitter's power to follow a certain pattern that might not be optimal with respect to its single-user rate, but is essential to guarantee that the sum rate of the two transmitters will lie on the maximum dominant face acquired from the sum rate problem. For instance, as we showed in Lemma 2 for a single-user channel, whenever the rate changes, either the transmitter or the receiver consumes all of its harvested energy. Therefore, there might be some instants, where the first transmitter is obligated to deplete its battery in order to keep track with the solution of the sum rate problem.

B. $\mu_1 = 0$ *or* $\mu_2 = 0$

Without loss of generality, we assume $\mu_2 = 0$. The optimization problem for p_{1i}^* becomes a single-user problem, whose solution is given by (4) and (5). From here on, we assume a specific structure for the decoding function ϕ. In particular, we assume that it is exponential with parameters $c = 1$, $d = 2$ and $e = -1$, i.e., $\phi(r) = g^{-1}(r) = 2^{2r} - 1$. Therefore, in order to get point 3 in Fig. 3, we need to solve:

$$\begin{aligned} \max_{\mathbf{p}_2 \geq \mathbf{0}} \quad & \sum_{i=1}^{N} g\left(p_{1i}^* + p_{2i}\right) \\ \text{s.t.} \quad & \sum_{i=1}^{k} p_{2i} \leq \sum_{i=1}^{k} Q_i, \quad \forall k \end{aligned} \tag{9}$$

where p_{1i}^* is the solution of the single-user problem for user 1, and the modified energy levels Q_i are defined as follows

$$\begin{aligned} & Q_i = M_i - M_{i-1}, \\ & M_i = \min\left\{\sum_{j=1}^{i} E_{2j}, \sum_{j=1}^{i} \bar{E}_j - p_{1j}^*\right\}, \quad M_0 = 0 \end{aligned} \tag{10}$$

We observe that (9) is a single-user energy-harvesting maximization problem with fading, whose solution is via directional water-filling of $\{Q_i\}_{i=1}^N$ over the inverse of the fading levels $\{1 + p_{1i}^*\}_{i=1}^N$ as presented in [3].

C. *General* $\mu_1, \mu_2 > 0$

We now aim at characterizing the rest of the region given by the dotted lines in Fig. 3. To do so, we need to solve the weighted sum rate maximization problem for general $\mu_1 \neq \mu_2$ with $\mu_1, \mu_2 > 0$. Without loss of generality, assume $\mu_1 > \mu_2$, and let us define $\mu \triangleq \frac{\mu_2}{\mu_1 - \mu_2}$. We then need to solve the following optimization problem

$$\begin{aligned} \max_{\mathbf{p}_1, \mathbf{p}_2 \geq \mathbf{0}} \quad & \sum_{i=1}^{N} g(p_{1i}) + \mu \sum_{i=1}^{N} g(p_{1i} + p_{2i}) \\ \text{s.t.} \quad & \sum_{i=1}^{k} p_{1i} \leq \sum_{i=1}^{k} E_{1i}, \quad \forall k \\ & \sum_{i=1}^{k} p_{2i} \leq \sum_{i=1}^{k} E_{2i}, \quad \forall k \\ & \sum_{i=1}^{k} p_{1i} + p_{2i} \leq \sum_{i=1}^{k} \bar{E}_i, \quad \forall k \end{aligned} \tag{11}$$

We note that the above problem resembles the one formulated in [16]. In the following, we approach the problem in a similar manner. First, we state a necessary condition of optimality for the above problem. The proof follows through a contradiction argument and is omitted here due to space limitations.

Lemma 6 *In the optimal solution for (11), by the end of the transmission period, at least one of the following occur: 1) both transmitters consume all of their harvested energies in transmission, 2) the receiver consumes all of its harvested energy in decoding.*

We decompose the optimization problem (11) into two nested problems. First we solve for $\mathbf{p}_2$ in terms of $\mathbf{p}_1$, and then solve for $\mathbf{p}_1$. Let us define the following inner problem:

$$\begin{aligned} G(\mathbf{p}_1) \triangleq \max_{\mathbf{p}_2 \geq \mathbf{0}} \quad & \sum_{i=1}^{N} g(p_{1i} + p_{2i}) \\ \text{s.t.} \quad & \sum_{i=1}^{k} p_{2i} \leq Q_i, \quad \forall k \end{aligned} \tag{12}$$

where Q_i is as defined in (10) for the given first user's powers p_{1i}. Then, we have the following lemma.

Lemma 7 $G(\mathbf{p}_1)$ *is a decreasing concave function in* $\mathbf{p}_1$.

Proof: G is a decreasing function of $\mathbf{p}_1$ since the feasible set shrinks with $\mathbf{p}_1$. To show concavity, let us choose two points $\mathbf{p}_1^{(1)}$ and $\mathbf{p}_1^{(2)}$, and take their convex combination $\mathbf{p}_1^\theta = \theta \mathbf{p}_1^{(1)} + (1-\theta)\mathbf{p}_1^{(2)}$ for some $0 \leq \theta \leq 1$. Let $\mathbf{p}_2^{(1)}$ and $\mathbf{p}_2^{(2)}$ denote the solutions of the inner problem (12) at $\mathbf{p}_1^{(1)}$ and $\mathbf{p}_1^{(2)}$, respectively. Now let $\mathbf{p}_2^\theta \triangleq \theta \mathbf{p}_2^{(1)} + (1-\theta)\mathbf{p}_2^{(2)}$, and observe that, from the linearity of the constraint set, $\mathbf{p}_2^\theta$ is feasible with respect to $\mathbf{p}_1^\theta$. Therefore, we have

$$\begin{aligned} G\left(\mathbf{p}_1^\theta\right) & \geq \sum_{i=1}^{N} g\left(p_{1i}^\theta + p_{2i}^\theta\right) \\ & \geq \sum_{i=1}^{N} \theta g\left(p_{1i}^{(1)} + p_{2i}^{(1)}\right) + (1-\theta) g\left(p_{1i}^{(2)} + p_{2i}^{(2)}\right) \\ & = \theta G\left(\mathbf{p}_1^{(1)}\right) + (1-\theta) G\left(\mathbf{p}_1^{(2)}\right) \end{aligned} \tag{13}$$

where the second inequality follows from the concavity of g. ■

Next, we solve the outer problem given by

$$\begin{aligned} \max_{\mathbf{p}_1 \geq \mathbf{0}} \quad & \mu G\left(\mathbf{p}_1\right) + \sum_{i=1}^{N} g(p_{1i}) \\ \text{s.t.} \quad & \sum_{i=1}^{k} p_{1i} \leq \sum_{i=1}^{k} T_i, \quad \forall k \end{aligned} \tag{14}$$

where we define the water levels $T_i = L_i - L_{i-1}$, with $L_i = \min\left\{\sum_{j=1}^{i} E_{1j}, \sum_{j=1}^{i} \bar{E}_j\right\}$, and $L_0 = 0$. The minimum is added to ensure feasibility of the inner problem. Note that, by the results of Lemma 7, the outer problem is a convex optimization problem that can be solved by standard techniques [33]. For instance, a water-filling algorithm similar to the one proposed in [16] converges to the optimal solution.

References

[1] J. Yang and S. Ulukus, "Optimal packet scheduling in an energy harvesting communication system," *IEEE Transactions on Communications*, vol. 60, no. 1, pp. 220–230, January 2012.

[2] K. Tutuncuoglu and A. Yener, "Optimum transmission policies for battery limited energy harvesting nodes," *IEEE Transactions on Wireless Communications*, vol. 11, no. 3, pp. 1180–1189, March 2012.

[3] O. Ozel, K. Tutuncuoglu, J. Yang, S. Ulukus, and A. Yener, "Transmission with energy harvesting nodes in fading wireless channels: Optimal policies," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 8, pp. 1732–1743, September 2011.

[4] C. K. Ho and R. Zhang, "Optimal energy allocation for wireless communications with energy harvesting constraints," *IEEE Transactions on Signal Processing*, vol. 60, no. 9, pp. 4808–4818, September 2012.

[5] J. Yang and S. Ulukus, "Optimal packet scheduling in a multiple access channel with energy harvesting transmitters," *Journal of Communications and Networks*, vol. 14, no. 2, pp. 140–150, April 2012.

[6] J. Yang, O. Ozel, and S. Ulukus, "Broadcasting with an energy harvesting rechargeable transmitter," *IEEE Transactions on Wireless Communications*, vol. 11, no. 2, pp. 571–583, February 2012.

[7] M. A. Antepli, E. Uysal-Biyikoglu, and H. Erkal, "Optimal packet scheduling on an energy harvesting broadcast link," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 8, pp. 1721–1731, September 2011.

[8] O. Ozel, J. Yang, and S. Ulukus, "Optimal broadcast scheduling for an energy harvesting rechargebale transmitter with a finite capacity battery," *IEEE Transactions on Wireless Communications*, vol. 11, no. 6, pp. 2193–2203, June 2012.

[9] D. Gunduz and B. Devillers, "Two-hop communication with energy harvesting," in *IEEE CAMSAP*, December 2011.

[10] C. Huang, R. Zhang, and S. Cui, "Throughput maximization for the Gaussian relay channel with energy harvesting constraints," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 8, pp. 1469–1479, August 2013.

[11] O. Orhan and E. Erkip, "Optimal transmission policies for energy harvesting two-hop networks," in *CISS*, March 2012.

[12] I. Ahmed, A. Ikhlef, R. Schober, and R. K. Mallik, "Power allocation in energy harvesting relay systems," in *IEEE VTC*, May 2012.

[13] Y. Luo, J. Zhang, and K. B. Letaief, "Optimal scheduling and power allocation for two-hop energy harvesting communication systems," *IEEE Transactions on Wireless Communications*, vol. 12, no. 9, pp. 4729–4741, September 2013.

[14] B. Varan and A. Yener, "Two-hop networks with energy harvesting: The (non-)impact of buffer size," in *IEEE GlobalSIP*, December 2013.

[15] B. Gurakan, O. Ozel, J. Yang, and S. Ulukus, "Energy cooperation in energy harvesting communications," *IEEE Transactions on Communications*, vol. 61, no. 12, pp. 4884–4898, December 2013.

[16] B. Gurakan and S. Ulukus, "Energy harvesting diamond channel with energy cooperation," in *IEEE ISIT*, July 2014.

[17] K. Tutuncuoglu and A. Yener, "Optimal power policy for energy harvesting transmitters with inefficient energy storage," in *CISS*, March 2012.

[18] D. Gunduz and B. Devillers, "A general ramework for the optimization of energy harvesting communication systems with battery imperfections," *Journal of Communications and Networks*, vol. 14, no. 2, pp. 130–139, April 2012.

[19] O. Ozel, K. Shahzad, and S. Ulukus, "Optimal energy allocation for energy harvesting transmitters with hybrid energy storage and processing cost," *IEEE Transactions on Signal Processing*, vol. 62, no. 12, pp. 3232–3245, June 2014.

[20] O. Orhan, D. Gunduz, and E. Erkip, "Throughput maximization for an energy harvesting communication system with processing cost," in *IEEE ITW*, September 2012.

[21] J. Xu and R. Zhang, "Throughput optimal policies for energy harvesting wireless transmitters with non-ideal circuit power," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 2, pp. 322–332, February 2014.

[22] O. Orhan, D. Gunduz, and E. Erkip, "Delay-constrained distortion minimization for energy harvesting transmission over a fading channel," in *IEEE ISIT*, July 2013.

[23] M. Gregori and M. Payaró, "Optimal power allocation for a wireless mutli-antenna energy harvesting node with arbitrary input distribution," in *IEEE ICC*, June 2012.

[24] Y. Luo, J. Zhang, and K. B. Letaief, "Training optimization for energy harvesting communication systems," in *IEEE Globecom*, December 2012.

[25] A. Nayyar, T. Basar, D. Teneketzis, and V. V. Veeravalli, "Optimal strategies for communication and remote estimation with an energy harvesting sensor," *IEEE Transactions on Automatic Control*, vol. 58, no. 9, pp. 2246–2260, September 2013.

[26] C. Huang, R. Zhang, and S. Cui, "Optimal power allocation for outage probability minimization in fading channels with energy harvesting constraints," *IEEE Transactions on Wireless Communications*, vol. 13, no. 2, pp. 1074–1087, February 2014.

[27] K. Tutuncuoglu and A. Yener, "Communicating with energy harvesting transmitters and receivers," in *UCSD ITA*, February 2012.

[28] H. Mahdavi-Doost and R. D. Yates, "Energy harvesting receivers: Finite battery capacity," in *IEEE ISIT*, July 2013.

[29] R. D. Yates and H. Mahdavi-Doost, "Energy harvesting receivers: Optimal sampling and decoding policies," in *IEEE GlobalSIP*, December 2013.

[30] H. Mahdavi-Doost and R. D. Yates, "Fading channels in energy-harvesting receivers," in *CISS*, March 2014.

[31] P. Grover, K. Woyach, and A. Sahai, "Towards a communication-theoretic understanding of system-level power consumption," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 8, pp. 1744–1755, September 2011.

[32] J. Rubio, A. Pascual-Iserte, and M. Payaró, "Energy-efficient resource allocation techniques for battery management with energy harvesting nodes: a practical approach," in *European Wireless Conference*, April 2013.

[33] S. P. Boyd and L. Vandenberghe, *Convex Optimization*. Cambridge University Press, 2004.

[34] T. Cover and J. A. Thomas, *Elements of Information Theory*. John Wiley & Sons, 2006.