Mobile Energy Harvesting Nodes

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***Abstract*— We consider a mobile energy harvesting transmitter where movement is motivated by finding better energy harvesting locations. Movement comes with an energy cost expenditure, and hence there exists a tradeoff between staying at the same location and moving to a new one. On one hand, the transmitter may opt not to move and use all its available energy for transmission; on the other hand, it can choose to move to a potentially better location, spending some of its available energy during the movement process, and yet harvest larger amounts of energy at the new location and achieve higher throughput. In this paper, we characterize this tradeoff by designing throughput-optimal power allocation policies subject to energy causality constraints and moving costs. In our setup, the transmitter moves along a straight line, where two energy sources are located at the opposite ends of the line. We first study the case of a single energy arrival at both sources, and then generalize it to the case of multiple energy arrivals.**

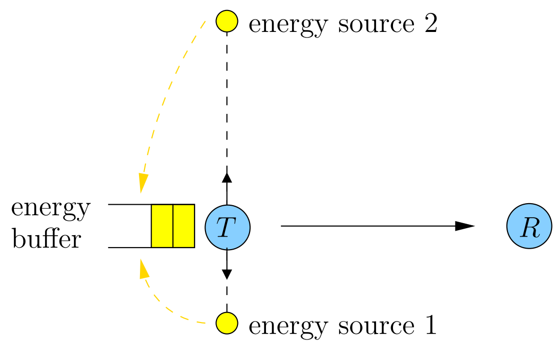

Fig. 1. Mobile energy harvesting node moving along a straight line.

I. Introduction

We consider an energy harvesting single-user channel where the transmitter uses its harvested energy in data transmission and to move to different locations in search for better energy harvesting spots, see Fig. 1. We design optimal power and movement scheduling policies that maximize the throughput by a given deadline subject to energy causality constraints.

Optimal energy management policies in energy harvesting communication networks have been considered extensively in the recent literature. Earlier works [1]–[4] consider the single-user setting with various battery size assumptions, with and without fading. References [5]–[11] extend this to broadcast, multiple access, and interference settings; [12]–[15] consider two-hop and relay channels; and [16], [17] study two-way channels. Energy sharing and energy cooperation concepts are studied in [18]–[20]. Most of the above works focus on transmitter-side energy harvesting.

References [21]–[27] study energy harvesting receivers, where energy harvested at the receiver is spent mainly for sampling and decoding. Other works [28]–[33] study the impact of processing costs, i.e., the power spent for circuitry, on energy harvesting communications. Depending on energy availability and system parameters, the above references show that considering decoding and processing costs can change the characteristics of optimal power policies.

In this paper, we study another aspect of power consumption in energy harvesting sensor nodes, namely, the power consumed in the process of harvesting energy. That is, there is a cost to taking actions to harvest energy. In this paper, we model this cost via the energy consumed in physical movement. We consider an energy harvesting transmitter with the ability to move along a straight line. Two energy sources are located at the opposite ends of the line, and the amount of energy harvested at the transmitter from each source depends on its distance from the two sources. Movement is thus motivated by finding better energy harvesting locations. However, the transmitter incurs a moving cost per unit distance travelled. Therefore, a tradeoff arises between staying in the same position and using all available energy in transmission, and spending some of the available energy to move to another location where it harvests higher energy. In this work, we characterize that tradeoff optimally, by designing throughput-optimal power and movement policies.

We first study the case where each energy source has a single energy arrival, and then generalize that to the case of multiple energy arrivals. Although our problem formulation is non-convex, we are able to solve it optimally for the single energy arrival scenario. For the multiple energy arrivals scenario, we design an iterative algorithm with guaranteed convergence to a local optimal solution of our optimization problem. For each iteration, we first show that given the optimal movement energy expenditure in a given time slot, the movement policy is *greedy;* the transmitter moves to the better location (energy-wise) in that time slot only without considering future time slots. We then find optimal movement energy consumption using a water-filling algorithm.

Related system models are considered in [34], [35] where some devices (energy-rich sources) move through a sensor network and refill the batteries of the sensors with RF radiation.

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II. System Model and Problem Formulation

We consider a single user AWGN channel with an energy harvesting transmitter with moving abilities. The transmitter has the ability to relocate itself to different positions in search for better energy harvesting spots. Movement is along a straight line, and energy is harvested from two energy sources located at the two opposite ends of the line, see Fig. 1. The transmitter's position determines how much energy is harvested from each source: the closer the transmitter is to one source, the larger the amounts of energy it harvests from that source compared to the other[1].

We consider a time-slotted model, where the transmitter is allowed to move during a fixed portion of time at the beginning of each slot, and then starts communicating[2]. Energy arrives in packets of amounts E_{1i} and E_{2i} in slot i at the first and the second energy source, respectively. At the beginning of slot i, the transmitter relocates itself to some position x_i, and harvests energy from both sources simultaneously according to the following relationship [36]–[38]

$$E(i,x_i)=\frac{E_{1i}}{(x_i+r)^\alpha}+\frac{E_{2i}}{(L-x_i+r)^\alpha} \tag{1}$$

where α is the path loss factor, L is the distance between the two energy sources, and $r>0$ is a parameter added to adjust the Friis' free space equation for short distance communication. That is, to keep the harvested energy bounded when the transmitter lies at either ends of the line.

The transmitter incurs moving costs whenever it relocates itself to a different position. We model the total moving cost up to slot k as follows

$$c_m(k)\triangleq\epsilon_m\sum_{i=1}^{k}|x_i-x_{i-1}| \tag{2}$$

where x_0 is the initial position of the transmitter, $\sum_{i=1}^k|x_i-x_{i-1}|$ represents the total distance moved by the transmitter up to slot k, and ϵ_m is the cost of movement in energy per unit distance.

Our goal is to maximize the total number of bits delivered to the receiver by a given deadline N, subject to energy causality constraints and moving costs. Since movement is not cost-free, a tradeoff arises between spending energy to move into better spots (in the sense of energy availability), and staying at the same location and spending all the available energy in communicating. In this paper, we design power and movement policies that capture the optimal tradeoff of this setting. The physical layer is Gaussian with unit noise power. We formulate the problem as follows

$$\begin{aligned}\max_{\boldsymbol{p},\boldsymbol{x}}\quad & \sum_{i=1}^{N}\frac{1}{2}\log(1+p_i)\\ \text{s.t.}\quad & c_m(1)\le E_0\\ & c_m(k+1)+\sum_{i=1}^{k}p_i\le E_0+\sum_{i=1}^{k}E(i,x_i),\quad 1\le k\le N\\ & 0\le x_i\le L,\quad p_i\ge 0,\quad 1\le i\le N\end{aligned} \tag{3}$$

where $c_m(N+1)\triangleq c_m(N)$, and E_0 is the initial energy available at the transmitter. This initial energy enables the transmitter to relocate itself during the first slot (if needed). Note that if the transmitter needs to move in slot $k+1$, then it needs to save some energy by the end of slot k for that purpose. In other words, it should not consume all its energy in transmission by the end of slot k. That is why the energy incurred for moving up to slot $k+1$ is bounded by the residual energy remaining after slot k: $E_0+\sum_{i=1}^k E(i,x_i)-p_i$. We solve problem (3) in the remainder of this paper. We first note the following necessary optimality conditions.

Lemma 1 *In the optimal solution of (3), powers are non-decreasing over time.*

Proof: We show this by contradiction. Assume that at the optimal policy $\{\boldsymbol{p}^*,\boldsymbol{x}^*\}$, there exists a time slot k such that $p_k^*>p_{k+1}^*$. Keeping the movement policy $\boldsymbol{x}^*$ the same, we define another power policy $\tilde{\boldsymbol{p}}$ where only the kth and $k+1$st powers change to $\tilde{p}_k=\tilde{p}_{k+1}=\frac{p_k^*+p_{k+1}^*}{2}$. It is direct to see that $\{\tilde{\boldsymbol{p}},\boldsymbol{x}^*\}$ is a feasible policy. By concavity of the log, this new policy strictly increases the objective function, and hence the original policy $\{\boldsymbol{p}^*,\boldsymbol{x}^*\}$ cannot be optimal. ■

Lemma 2 *In the optimal solution of (3), the transmitter consumes all its harvested energy by the end of communication.*

Proof: We show this by contradiction. If the statement of the lemma were not true, then we can increase the value of p_N until all energy is consumed. This strictly increases the objective function. ■

III. Single Energy Arrival

In this section we study the case where each energy source has only one energy packet arrival. That is, we have only one pair of variables (p,x) to optimize. By Lemma 2, we have

$$p(x)=E_0+\frac{E_1}{(x+r)^\alpha}+\frac{E_2}{(L-x+r)^\alpha}-\epsilon_m|x-x_0| \tag{4}$$

and therefore, by monotonicity of the log, problem (3) becomes

$$\begin{aligned}\max_{x}\quad & \frac{E_1}{(x+r)^\alpha}+\frac{E_2}{(L-x+r)^\alpha}-\epsilon_m|x-x_0|\\ \text{s.t.}\quad & \epsilon_m|x-x_0|\le E_0\\ & 0\le x\le L\end{aligned} \tag{5}$$

Therefore, the problem now reduces to finding the optimal position x^*.

Note that there are two possible movement strategies the transmitter can make: move forward to some $x\ge x_0$, or

[1] In our setting, the transmitter-receiver distance is much larger than the distance between the two energy sources so as to ensure that the transmitter-receiver channel characteristics are not affected by the transmitter's movement.

[2] Without loss of generality, we assume that the remaining portion of the time slot where the transmitter communicates is normalized to one time unit, so that we may use energy and power interchangeably.

move backward to some $x < x_0$. The transmitter chooses the movement strategy that gives the maximum objective function (and hence power/rate). To that end, we next solve the case of moving forward. The problem in this case becomes

$$\begin{aligned} \max_{x} \quad & \frac{E_1}{(x+r)^\alpha} + \frac{E_2}{(L-x+r)^\alpha} - \epsilon_m x \\ \text{s.t.} \quad & x_0 \le x \le \min\left\{\frac{E_0}{\epsilon_m} + x_0, L\right\} \triangleq x_{\max} \end{aligned} \tag{6}$$

Now observe that the objective function is a convex function in x that is maximized over an interval. It then follows that the optimal solution x^* has to be at the boundary of the feasible set [39], i.e.,

$$x^* \in \{x_0, x_{\max}\} \tag{7}$$

Hence, we pick x^* that gives the higher value after substituting in (4), i.e., after comparing $p\left(x_0\right)$ and $p\left(x_{\max}\right)$.

Similarly, the problem in the case of moving backward is given by

$$\begin{aligned} \max_{x} \quad & \frac{E_1}{(x+r)^\alpha} + \frac{E_2}{(L-x+r)^\alpha} + \epsilon_m x \\ \text{s.t.} \quad & x_{\min} \triangleq \max\left\{x_0 - \frac{E_0}{\epsilon_m}, 0\right\} \le x \le x_0 \end{aligned} \tag{8}$$

which again, by convexity of the objective function, yields a solution at the boundary. That is

$$x^* \in \{x_{\min}, x_0\} \tag{9}$$

Hence, we pick x^* that gives the higher value after substituting in (4), i.e., after comparing $p\left(x_0\right)$ and $p\left(x_{\min}\right)$.

Based on the previous analysis, the optimal position in the single energy arrival scenario can only have three possible values: $x^* \in \{x_{\min}, x_0, x_{\max}\}$. This means that if the transmitter decides to move, it moves to the furthest possible distance (forward or backward) allowed by its available initial energy E_0 and the physical length of the straight line L. Therefore, the optimal power is given by

$$p^* = \max\left\{p\left(x_{\min}\right), p\left(x_0\right), p\left(x_{\max}\right)\right\} \tag{10}$$

and x^* is the corresponding maximizing argument.

IV. Multiple Energy Arrivals

In this section we study the multiple energy arrivals setting. We note that problem (3) is not a convex optimization problem due to the convexity of the energy harvesting function $E(i, x_i)$ in (1). We therefore follow a majorization maximization argument to find a local optimal solution for this problem via successive convex optimization. Namely, we approximate $E(i, x_i)$ around some feasible point to get a convex problem, whose solution is then used to (better) approximate $E(i, x_i)$ in the next iteration. Approximate functions should be chosen carefully such that iterations converge to a local optimal solution of the original problem [40], [41]. In particular, in the $(j+1)$st iteration, we solve the following problem

$$\begin{aligned} \max_{\boldsymbol{p},\boldsymbol{x}} \quad & \sum_{i=1}^{N} \frac{1}{2}\log(1+p_i) \\ \text{s.t.} \quad & c_m(1) \le E_0 \\ & c_m(k+1) + \sum_{i=1}^{k} p_i \le E_0 + \sum_{i=1}^{k} f^{(j)}(i, x_i), \quad \forall k \\ & 0 \le x_i \le L, \quad p_i \ge 0, \quad \forall i \end{aligned} \tag{11}$$

where $f^{(j)}(i, x_i)$ is the first order Taylor series approximation of $E(i, x_i)$ around $x_i^{(j)}$, the solution of the approximate problem in the jth iteration. That is, we have

$$f^{(j)}(i, x_i) \triangleq b_i^{(j)} + m_i^{(j)} x_i \tag{12}$$

where

$$\begin{aligned} b_i^{(j)} \triangleq & \frac{E_{1i}}{(x_i^{(j)}+r)^\alpha} + \frac{E_{2i}}{(L-x_i^{(j)}+r)^\alpha} \\ & + \left(\frac{\alpha E_{1i}}{(x_i^{(j)}+r)^{\alpha+1}} - \frac{\alpha E_{2i}}{(L-x_i^{(j)}+r)^{\alpha+1}}\right) x_i^{(j)} \end{aligned} \tag{13}$$

and

$$m_i^{(j)} \triangleq -\frac{\alpha E_{1i}}{(x_i^{(j)}+r)^{\alpha+1}} + \frac{\alpha E_{2i}}{(L-x_i^{(j)}+r)^{\alpha+1}} \tag{14}$$

By convexity of $E(i, x_i)$, it is direct to see that $f^{(j)}(i, x_i)$ satisfies the conditions stated in [40] that guarantee convergence of the iterative solution of problem (11) to a local optimal point of problem (3). Namely, it holds that

$$(1)\ f^{(j)}(i, x_i) \le E(i, x_i),\ \forall x_i \tag{15}$$

$$(2)\ f^{(j)}\left(i, x_i^{(j)}\right) = E\left(i, x_i^{(j)}\right) \tag{16}$$

$$(3)\ \frac{df^{(j)}\left(i, x_i^{(j)}\right)}{dx_i} = \frac{dE\left(i, x_i^{(j)}\right)}{dx_i} \tag{17}$$

We focus on problem (11) in the remainder of this paper. In particular, we introduce some auxiliary variables $\{\delta_i\}$ to denote the amount of energy used for movement in the ith slot. That is, we have

$$\epsilon_m |x_i - x_{i-1}| = \delta_i, \quad \forall i \tag{18}$$

This allows us to rewrite the optimization problem as follows

$$\begin{aligned} \max_{\boldsymbol{p},\boldsymbol{x},\boldsymbol{\delta}} \quad & \sum_{i=1}^{N} \frac{1}{2}\log(1+p_i) \\ \text{s.t.} \quad & \sum_{i=1}^{k} p_i \le E_0 + \sum_{i=1}^{k} b_i^{(j)} + m_i^{(j)} x_i - \sum_{i=1}^{k+1} \delta_i, \quad \forall k \\ & \delta_1 \le E_0 \\ & \epsilon_m |x_i - x_{i-1}| \le \delta_i, \quad \forall i \\ & 0 \le x_i \le L, \quad p_i \ge 0, \quad \delta_i \ge 0, \quad \forall i \end{aligned} \tag{19}$$

where the relaxation of the equality in (18) to an inequality in the above problem does not change the solution. To see this, note that if there exists some slot k such that $\delta_k^* > \epsilon_m |x_k^* - x_{k-1}^*|$, then one can simply decrease the value of δ_k^* until equality holds while keeping the values of x_k^* and x_{k-1}^* the same. This strictly increases the feasible set and thereby potentially increases the objective function. Also note that we set $\delta_{N+1} \triangleq 0$. We now have the following lemma.

Lemma 3 *In the optimal solution of problem (19), if $\delta_i^* > 0$ then the transmitter should move forward (resp. backward) during slot i if $m_i^{(j)}$ is positive (resp. negative). Conversely, if $m_i^{(j)} = 0$, then there exists an optimal policy with $\delta_i^* = 0$.*

Proof: We show this by contradiction. Assume that we have $\delta_i^* > 0$ and $m_i^{(j)} > 0$ but the transmitter moves backward during time slot i, i.e., $x_i^* < x_{i-1}^*$. Now consider the following alternative policy. Let $\delta_i = 0$, i.e., $x_i = x_{i-1}^*$, and let $\delta_{i+1} = \delta_i^* + \delta_{i+1}^*$. Since the cost to move is linear with distance, this new policy reaches the position x_{i+1}^* from x_{i-1}^* with the same cost. At the same time, since $m_i^{(j)} > 0$, this new policy harvests higher energy at slot i, and thereby achieves higher rates. Thus, the transmitter should move forward. The case where $m_i^{(j)} < 0$ implies that the transmitter should move backward can be shown using similar arguments. This proves the first part of the lemma.

To show the second part, note that since $m_i^{(j)} = 0$, moving during slot i does not make the transmitter gain any energy. Hence, by linearity of the moving cost, given any optimal policy with $\delta_i^* > 0$, setting $\delta_i = 0$ and $\delta_{i+1} = \delta_i^* + \delta_{i+1}^*$ in that case makes the transmitter harvest the same amount of energy, and reach x_{i+1}^* with the same moving cost. ■

Lemma 3 indicates that the optimal movement policy can be *greedy*. That is, if the transmitter moves during some time slot i, it moves towards the higher energy location in slot i without considering upcoming slots' energies. Next, we find the optimal greedy policy by decomposing problem (19) into inner and outer problems as follows.

A. Inner Problem

We first fix a feasible choice for $\{\delta_i\}$ and solve an *inner problem* for the pair $\{p_i, x_i\}$. We denote the solution of the inner problem by $R(\boldsymbol{\delta})$. By Lemma 3, once $\boldsymbol{\delta}$ is fixed, the position $\boldsymbol{x}$ is determined according to the sign of $\boldsymbol{m}^{(j)}$. Whence, the power $\boldsymbol{p}$ is found via directional water-filling [3]. Note that the choice of δ_i should be such that it is equal to 0 if $m_i^{(j)} = 0$, according to Lemma 3. In addition, we note that if we have some $\delta_i > 0$ while the greedy movement is not feasible, i.e., moving forward/backward with δ_i energy gets the transmitter outside the straight line boundaries, then surely this δ_i choice is not optimal and needs to change. How to optimally find $\{\delta_i^*\}$ is handled next.

B. Outer Problem

After we solve the inner problem, we find the optimal $\{\delta_i^*\}$ by solving an *outer problem* by maximizing $R(\boldsymbol{\delta})$ over the feasible choices of δ_i. We have the following lemma regarding this problem

Algorithm 1

```
repeat
    Approximate E(i, x_i) around the j − 1st iteration's location solution x_i^(j−1) using (12)-(14), ∀i.
    Fix a feasible movement energy allocation δ.
    repeat
        Solve inner problem for R(δ) as in Section IV-A.
        Solve outer problem for δ* as in Section IV-B.
    until Convergence of movement energy water levels.
until ||(x^(j), p^(j)) − (x^(j−1), p^(j−1))|| is small enough.
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Lemma 4 *$R(\boldsymbol{\delta})$ is a concave function in $\boldsymbol{\delta}$.*

Proof: Let us pick two feasible points $\boldsymbol{\delta}^{(1)}$ and $\boldsymbol{\delta}^{(2)}$ and denote the solutions of the inner problem for these two choices by $\{\boldsymbol{p}^{(1)}, \boldsymbol{x}^{(1)}\}$ and $\{\boldsymbol{p}^{(2)}, \boldsymbol{x}^{(2)}\}$, respectively. Now let $\boldsymbol{\delta}^{\theta} \triangleq \theta\boldsymbol{\delta}^{(1)} + (1-\theta)\boldsymbol{\delta}^{(2)}$ for some $0 \le \theta \le 1$. Next, observe that by linearity of the feasible set, the pair $\boldsymbol{p}^{(\theta)} \triangleq \theta\boldsymbol{p}^{(1)} + (1-\theta)\boldsymbol{p}^{(2)}$ and $\boldsymbol{x}^{(\theta)} \triangleq \theta\boldsymbol{x}^{(1)} + (1-\theta)\boldsymbol{x}^{(2)}$ is feasible in the inner problem for the choice of $\boldsymbol{\delta}^{(\theta)}$. Therefore, we have

$$\begin{aligned} R\left(\boldsymbol{\delta}^{(\theta)}\right) &\ge \sum_{i=1}^{N} \frac{1}{2}\log\left(1+p_i^{(\theta)}\right) \\ &\ge \sum_{i=1}^{N} \frac{\theta}{2}\log\left(1+p_i^{(1)}\right) + \frac{1-\theta}{2}\log\left(1+p_i^{(2)}\right) \\ &= \theta R\left(\boldsymbol{\delta}^{(1)}\right) + (1-\theta) R\left(\boldsymbol{\delta}^{(2)}\right) \end{aligned} \tag{20}$$

where the second inequality follows by concavity of the $\log$. This concludes the proof. ■

We now solve the following outer problem

$$\begin{aligned} \max_{\boldsymbol{\delta}} \quad & R(\boldsymbol{\delta}) \\ \text{s.t.} \quad & \delta_1 \le E_0 \\ & \sum_{i=1}^{k+1} \delta_i \le E_0 + \sum_{i=1}^{k} b_i^{(j)} + \left[m_i^{(j)} L\right]^+, \quad \forall k \\ & \delta_i \ge 0, \quad \forall i \end{aligned} \tag{21}$$

with $\delta_{N+1} \triangleq 0$, and $[y]^+ \triangleq \max(y, 0)$. Note that the term $\left[m_i^{(j)} L\right]^+$ ensures that all the feasible range of $\{\boldsymbol{\delta}\}$ is covered in the outer problem, and that the inner problem is energy-feasible. By Lemma 4, the outer problem is a convex optimization problem [39]. However, not all the available energy should be used in movement, or else we achieve zero throughput. Hence, we follow an iterative water-filling algorithm to solve the outer problem similar to the one proposed in [20], [26] that we summarize next. We add an extra $N+1$st slot where unused energy can be discarded. Initially, each slot is filled up by its own energy arrival and the extra $N+1$st slot is left empty. We allow energy/water to move to the right only if this increases the objective function. Meters are put in between slots to measure the amount of water moving forward. This allows us to pull water back to their sources if this increases

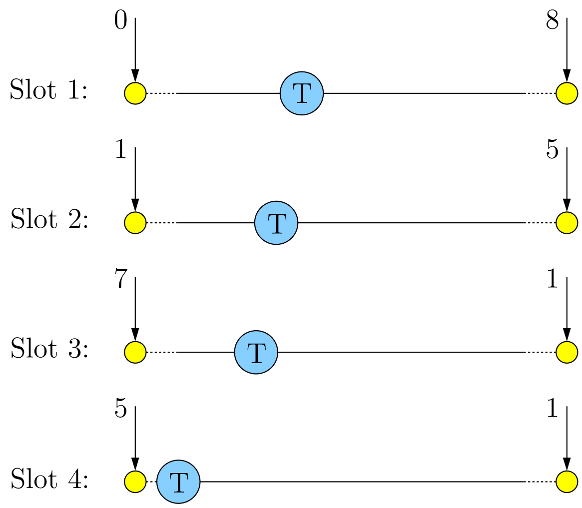

Fig. 2. Optimal transmitter location in a four-slot system.

the objective function. Eventually, all the water in the $N+1$st slot will be discarded but can be pulled back also during the iterations if necessary. Since the objective function increases with each water flow, problem feasibility is maintained during iterations, and by convexity of the problem, iterations converge to the optimal solution. We summarize the multiple energy arrivals solution approach in Algorithm 1.

V. Numerical Results

In this section, we present some numerical examples to further illustrate our results. We consider a system of four time slots. The transmitter has an initial amount of energy of $E_0 = 0.1$ energy units. The length of the straight line between the energy sources is $L = 7$ distance units, and the transmitter is initially positioned at $x_0 = 2.5$. Energies arrive at the two energy sources with amounts $\boldsymbol{E}_1 = [0, 1, 7, 5]$ and $\boldsymbol{E}_2 = [8, 5, 1, 1]$, at the first and the second energy source, respectively. The path loss factor $\alpha = 2.5$, $r = 0.3$, and the movement energy cost per distance $\epsilon_m = 0.5$.

We solve problem (11) by initially approximating the energy-position function at each time slot around x_0. We then do the problem decomposition to solve for $\{\delta_i^*\}$ and $\{p_i^*, x_i^*\}$ as discussed in Sections IV-A and IV-B. Finally, we substitute by $\{x_i^*\}$ in problem (11) and re-iterate until convergence. For this example, it takes 5 iterations to converge to a local optimal solution of problem (3).

In Fig. 2, we plot the results of this example. We show the transmitter's position at different slots in between the two energy sources. Arrows at the sources represent the amounts of energy arriving (emitted) by each source at a given time slot. From the figure, we see that the transmitter stays at its initial position in the first time slot, i.e., $x_1^* = 2.5$. This is mainly because the initial position of the transmitter is inclined towards the first source, and the fact that the energy amount at the second source is higher than that of the first source in the first time slot. One more reason for this movement behavior is that the first source receives higher amounts of energy in later

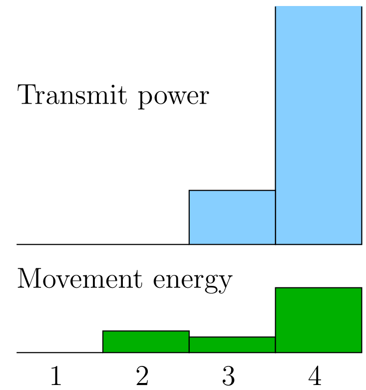

Fig. 3. Transmit power and movement energy consumptions.

slots. Therefore, we see that the transmitter moves towards the first source during slots 2 and 3 until it reaches the end of the line in slot 4. The optimal position is given by $\boldsymbol{x}^* = [2.5, 1.98, 1.58, 0]$, with powers $\boldsymbol{p}^* = [0, 0, 0.68, 101.44]$, and movement energy consumption of $[0, 0.25, 0.2, 0.67]$.

We plot the optimal transmit power and movement energy consumptions over the four time slots in Fig. 3. The height in blue and green represents the transmit power and the movement energy costs, respectively. We see that the transmitter neither moves nor transmits during the first time slot and saves all its harvested energy for later slots' movements and transmission. It starts spending some energy in movement during the second time slot while still not transmitting, and then finally during the third and fourth time slots it both moves and transmits to the receiver, achieving a throughput of 2.57.

Next, we show the effect of the movement energy cost per unit distance, ϵ_m, on the throughput. We shift the initial position to $x_0 = 3$ and use the same parameter values from the previous example except that we decrease ϵ_m to 0.01. The solution in this case is $x^* = [7, 7, 0, 0]$ with a throughput equal to 9.7. Due to the small movement energy cost, the transmitter in this case rides the energy peaks from the two sources, i.e., it harvests $E_i = \frac{1}{r^\alpha} \max\{E_{1i}, E_{2i}\}$, $\forall i$. The optimal location is shown by the green transmitter in Fig. 4. We then increase ϵ_m to 3 and re-solve. In this case, we get $x^* = [3.5, 3.5, 3.5, 3.5]$ with a throughput equal to 0.484. Due to the large movement energy cost, the transmitter does not move during the course of communication and uses all of its available energy only for transmission. The optimal location in this case is shown by the brown transmitter in Fig. 4.

VI. Conclusion

We considered mobility effects on energy harvesting nodes. Energy arrivals at a node depend on the node's relative position to energy emitting sources, and therefore movement is motivated by finding better energy harvesting locations. However, nodes incur a moving cost per unit distance travelled. We considered movement along a straight line, where two energy sources are located towards the opposite ends of the line. We characterized the optimal tradeoff between staying at the same spot so as to spend all available energy in transmission, and

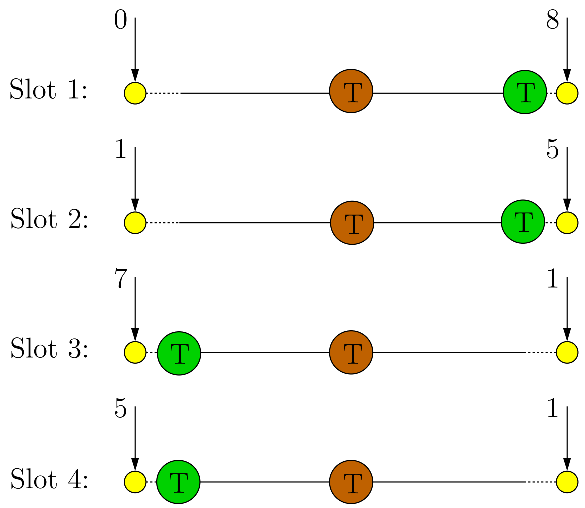

Fig. 4. Effect of moving cost on optimal location.

spending some energy to move to a potentially better energy location so as to achieve higher throughput. We first solved the case with a single energy arrival at each source, and then generalized that to the case of multiple energy arrivals.

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