Relay Selection for Energy Harvesting Cooperative Communication Systems

Yaming Luo, Jun Zhang, and Khaled B. Letaief, *Fellow, IEEE*
ECE Department, Hong Kong University of Science and Technology
Email: {luoymhk, eejzhang, eekhaled}@ust.hk

***Abstract*—Energy harvesting (EH) has recently emerged as a promising technique for green communications, as it can power communication systems with renewable energy. In this paper, we investigate how to adopt cooperative relay selection to improve the short-term performance of EH communication systems. The main focus is on how to efficiently utilize the available side information (SI), including channel side information (CSI) and energy side information (ESI). We formulate relay selection problems with either non-causal or causal SI, with an emphasis on the more practical causal case. For this causal SI case, we propose a low-complexity relay selection strategy based on the relative throughput, that is, in each block, the relay with enough energy and with the highest instantaneous throughput compared with the average throughput is selected. This relay selection rule captures the key characteristic of EH systems, namely, each relay should have some chance to be selected so that the harvested energy can be efficiently utilized, and it should be selected only if its throughput is near its own peak. Simulation results will show that the proposed relay selection method provides significant throughput gain over the conventional one which is only based on the current side information.**

***Index Terms*—Energy harvesting, cooperative communication, relay selection, non-causal/causal side information.**

I. Introduction

Energy harvesting (EH) has recently emerged as a promising candidate to realize green communications, and it has attracted lots of attention from both academia and industry. The EH device can harvest energy from the environment [1], including solar energy, vibration energy, thermoelectric energy, RF energy, etc. Thus, there is no need to manually replace the battery and perpetual lifetime is possible for wireless networks. However, as the harvested energy is typically in a small amount and also random, how to guarantee satisfactory short-term performance is challenging, i.e., how to sustain the required QoS.

What is critical in designing EH communication systems is the efficient utilization of different side information (SI), including channel side information (CSI) and energy side information (ESI). With the block Markov EH model, the authors in [2] studied the throughput maximization problem over the fading AWGN channel and derived the optimal power allocation polices for causal and non-causal CSI/ESI, respectively. The transmission completion time minimization problem with non-causal ESI was considered in [3]. In [4], an outage minimization problem was solved without CSI at the transmitter and with either non-causal or causal ESI; while CSI training optimization in EH systems with non-causal ESI was investigated in [5].

Cooperative communication has been demonstrated as an important technique to improve the performance of wireless networks, and its potential in EH networks has been recently investigated. However, efficient cooperative protocols need to be redesigned for EH systems. In particular, besides taking CSI into consideration as in conventional non-EH systems, ESI should also be considered, which complicates the relay selection. For example, even if a particular EH relay always has a better channel than other relays, always selecting this relay may not be a good strategy as its harvested energy will be exhausted very soon. It is not clear how different types of side information will affect the relay selection strategy. Currently for two-hop EH systems, the authors in [6], [7], [8] and [9] investigated the power allocation and scheduling for the single relay case. In [10], the SER performance of EH systems with a simple relay selection scheme was analyzed, where the selection is based on the current available energy and the current CSI. Although this kind of relay selection scheme performs well in the ergodic scenario, the short-term performance may not be good as the available ESI/CSI is not fully utilized.

In this paper, we will investigate optimal relay selection in EH cooperative communication systems, with different assumptions on the availability of CSI and ESI. With non-causal ESI/CSI, we show that relay selection can be formulated as a convex assignment problem, and can be solved by a branch-and-bound algorithm, which serves as a performance upper bound but may not be implementable in practice. With causal CSI and non-causal/causal ESI, we formulate relay selection as a dynamic programming problem, and propose a very simple and efficient solution. In each block, for each relay, we define a relative throughput gain, which is the difference between the instantaneous throughput and the average throughput. The proposed relay selection rule is to select the one with enough harvested energy and with the best relative throughput gain. Such a relay selection rule reflects the unique characteristics of EH systems: Each relay needs to be selected in the whole transmission period so that all the harvested energy can be utilized, while it should be selected only when its throughput is close to its own peak, which can be measured by the relative throughput gain. Moreover, this relay selection rule is of

This work is supported in part by the Hong Kong Research Grant Council under Grant No. 610212.

low complexity and with low feedback overhead. Simulation results shall demonstrate the improvement of the proposed relay selection rule compared with the conventional one that is only based on the current side information.

The organization of this paper is as follows. In Section II, we introduce the energy harvesting model and discuss the differences of the relay selection in EH systems with that in conventional non-EH systems. In Section III, the relay selection problem with non-causal CSI/ESI is handled; while in Section IV, the causal CSI case is investigated and a simple relay selection rule is proposed. Simulation results are given in Section V. Finally, Section VI summarizes our work.

II. System Model

As shown in Fig. 1, we consider a communication system with M EH relays, denoted as R_i, $i = 1, 2, \ldots, M$, and one source and one destination, both of which are non-EH nodes. All the relays are half-duplex and apply the amplify-and-forward protocol. The source-destination channel is assumed to be too weak to support direct transmission. The channel is block fading, with the coherence time denoted as T^{C}, corresponding to a transmission block in this paper. We consider a finite transmission period of $T = NT^{\mathrm{C}}$, as shown in Fig. 2. For the i-th relay, the channel gain for the source-relay (S-R)/relay-destination (R-D) channel in the j-th block is denoted as $h^{\mathrm{s}}_{i,j}/h^{\mathrm{d}}_{i,j}$. The relays cooperate in a two-phase mode during each channel block, and each phase occupies half of the block length, i.e., $T^{\mathrm{C}}/2$. Specifically, in the first half, the source broadcasts to all the relays with transmit power P^{s}, while in the second half, one relay is selected to forward the source information. For simplicity, all the relays, once selected, are assumed to transmit at a constant power, P^{tr}, and the transmission is in the unit of one packet, which consumes an energy of $P^{\mathrm{tr}}T^{\mathrm{C}}/2$. One relay is called *active* if it has enough energy to transmit a packet. The end-to-end SNR is denoted by $\Lambda_{i,j} = \frac{\gamma^{\mathrm{s}}_{i,j}\gamma^{\mathrm{d}}_{i,j}}{\gamma^{\mathrm{s}}_{i,j}+\gamma^{\mathrm{d}}_{i,j}+1}$, where $\gamma^{\mathrm{s}}_{i,j} = \left|h^{\mathrm{s}}_{i,j}\right|^2 \frac{P^{\mathrm{s}}T^{\mathrm{C}}/2}{N_0}$, $\gamma^{\mathrm{d}}_{i,j} = \left|h^{\mathrm{d}}_{i,j}\right|^2 \frac{P^{\mathrm{tr}}T^{\mathrm{C}}/2}{N_0}$. The respective end-to-end throughput is $R_{i,j} = \log_2\left(1 + \Lambda_{i,j}\right)$. For reference, we list the main notations defined in this paper in Table I.

A. Energy Model

An important factor that determines the performance of an EH system is the *EH profile*, denoted as $E^{\mathrm{EH}}_{i,\Sigma}(t)$ for the i-th relay, which models the cumulative harvested energy up to time t. As the fluctuation of the energy harvesting rate (which is also called EH power in this paper) usually does not vary too much, we shall treat it as a piece-wise constant function with time. The change of the EH power is in the time unit of an EH interval T^{E}, similar to [4], with $P^{\mathrm{EH}}_{i,j}$ denoting the EH power of the i-th relay in the j-th EH interval. Practically, the EH interval is much larger than the channel coherence time. Therefore, we assume that there are N^{C} channel blocks in one EH interval, and in total $N^{\mathrm{E}} = N/N^{\mathrm{C}}$ EH intervals inside the transmission period T, i.e., $T = N^{\mathrm{E}}T^{\mathrm{E}}$, as shown in Fig. 2.

The utilization of the harvested energy is constrained by the EH profile, which yields the energy causality constraint

Table I
Main Notations

Symbols	Definition
T	Total transmission period
T^{E}	Energy harvesting interval
T^{C}	Channel coherence time (block length)
M	Number of relays
N	Number of channel blocks in T
N^{E}	Number of EH intervals in T
N^{C}	Number of channel blocks in T^{E}
P^{s}	Source transmit power
P^{tr}	Relay transmit power
$P^{\mathrm{EH}}_{i,j}$	EH power (i-th relay, j-th block)
$\Lambda_{i,j}$	End-to-end SNR (i-th relay, j-th block)
$\bar{R}$	Average end-to-end throughput in T

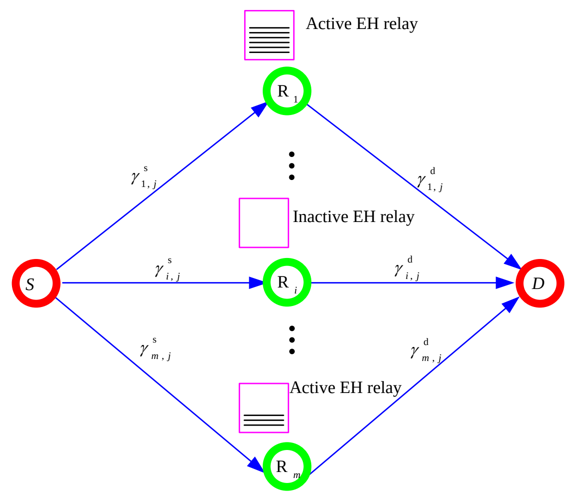

Figure 1. The system model.

[11]. The energy causality means that the energy consumed thus far cannot exceed the total harvested energy. Denote the instantaneous transmit power as $P(t)$, then the energy causality constraint can be expressed as

$$\int_0^t P(\tau)\, d\tau \le E^{\mathrm{EH}}_{i,\Sigma}(t)\,. \qquad (1)$$

Besides the EH profile, the capacity and initial energy of the battery for the EH node is also important for the EH link performance. In this paper, we assume that the battery capacity is large enough and the initial energy is zero; while the more general case with a finite battery capacity and nonzero initial energy will be handled in future work.

B. Relay Selection

In each channel block, at most one relay is selected among all the active relays. The overall objective is to maximize the average end-to-end throughput over T. We want to emphasize two points. First, there exists some time instant when there is no active relay, i.e., no relay has harvested enough energy.

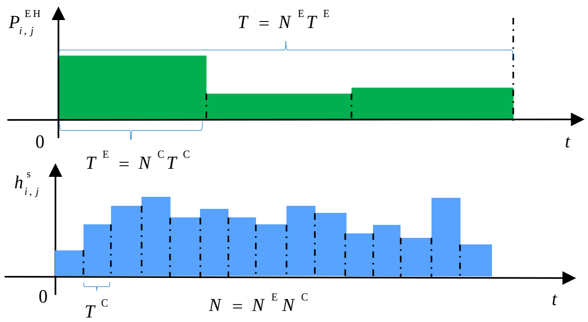

Figure 2. Illustration of the ESI and the CSI versus time. The time units of the total transmission period T, EH interval T^{E} and channel block T^{C} are shown.

Second and in contrast to precious works, for the relay selection in each block, we should take into consideration not only the throughput of this block, but also the average throughput of the whole transmission period, to obtain a better overall performance. These special properties make it difficult to directly apply relay selection strategies developed for conventional power constrained communication systems.

The relay transmit power can be determined according to the basic fact that in the whole transmission period, a balance should be achieved between the total harvested energy and the total consumed energy from all the relays. Therefore, the value is set as $P^{\mathrm{tr}} = 2\left(\sum P_{i,\mathrm{ave}}^{\mathrm{EH}}\right)$, where the factor 2 is obtained because each relay can only transmit in half of each block, while the energy harvesting procedure is performed all the time. The same assumption is also adopted in [10].

To demonstrate the result of relay selection, we define the following relay selection matrix $\mathrm{X} = [x_{i,j}]_{M\times N}$

$$x_{i,j} = \begin{cases} 1, & \text{relay } \mathrm{R}_i \text{ is selected for the } j\text{th block,} \\ 0, & \text{otherwise.} \end{cases}$$

Particularly and for simplicity, we denote the case when no relay is selected for the j-th block as $x_{0,j} = 1$.

III. Relay Selection with Non-causal CSI/ESI

For different types of devices or different application scenarios, both CSI and ESI may be either causal or non-causal. Here causal ESI means that we only know the harvesting rate in the current EH interval, while the non-causal ESI means that we also know the future EH power, e.g., through prediction. Similarly, causal CSI means that we have knowledge of the instantaneous CSI in the current block, while non-causal CSI means that the channel states in all the blocks within the transmission period T are known. With different assumptions on ESI/CSI, different problems can be formulated. Since in practice, the channel will change much faster than the EH power, we will assume that ESI will in general be easier to predict than CSI, and ignore the case with non-causal CSI but causal ESI. In this section, we will deal with the relay selection with non-causal ESI/CSI. Although the solution of this case may not be applicable, it can serve as a performance upper bound for the causal cases.

A. Problem Formulation

Since the information of both the current CSI/ESI and the future CSI/ESI is known in advance, the optimal relay selection can be formulated as follows

Problem 1:

$$\max_{x_{i,j}} \quad \bar{R} = \frac{1}{N}\sum_{i=1}^{M}\sum_{j=1}^{N} R_{i,j}x_{i,j} \tag{2}$$

$$\text{s.t.} \quad \frac{1}{2}P^{\mathrm{tr}}T^{\mathrm{C}}\sum_{j=1}^{l} x_{i,j} \le E_{i,\Sigma}^{\mathrm{EH}}\left(lT^{\mathrm{C}}\right), \forall l \in J, i \in I, \tag{3}$$

$$\sum_{i=1}^{M} x_{i,j} \le 1, \forall j \in J, \tag{4}$$

$$x_{i,j} \in \{0,1\}, J = \{1,...,N\}, I = \{1,...,M\}. \tag{5}$$

Not that Constraint (3) is the energy causality constraint, while Constraint (4) means that for each channel block, at most one relay can be selected.

B. Relay Selection Strategy

Problem 1 is closely related to the assignment problem (AP). In particular, it belongs to a convex assignment problem (CAP) [12]. By removing all the constraints in (3) except for $l = N$, this problem can be reduced to the generalized assignment problem (GAP). Since GAP is NP-hard, Problem 1 is also NP-hard [12]. In [13], a branch-and-bound algorithm was proposed to find the optimal solution for GAP, which can be modified to solve our problem. Since this is not our emphasis, we will not provide the details of the algorithm. It is also important to emphasize that the branch-and-bound algorithm has a worst-case exponential time complexity.

IV. Relay Selection with Causal CSI

In this section, relay selection with causal CSI and causal/non-causal ESI will be investigated. This case is more practical, and the relay selection problem can be formulated as a dynamic programming (DP) problem. We will not solve it directly, due to the dimensionality of dynamic programming. Instead, we will propose a practical relay selection method.

A. Problem Formulation with Non-causal ESI

Since only the current CSI is available, we can evaluate the average future throughput at the k-th block as follows

$$\begin{aligned} \bar{R}(k) &= \mathrm{E}\left[\frac{1}{N-k+1}\sum_{i=1}^{M}\sum_{j=k}^{N} R_{i,j}x_{i,j}\,|x_{i,k}\right] \\ &= \frac{\sum_{i=1}^{M} R_{i,k}x_{i,k} + \mathrm{E}_{\substack{\gamma_{i,j}^{\mathrm{s}},\gamma_{i,j}^{\mathrm{d}} \\ \forall i,j}}\left[\sum_{i=1}^{M}\sum_{j=k+1}^{N} R_{i,j}x_{i,j}\,|x_{i,k}\right]}{N-k+1}, \end{aligned} \tag{6}$$

where $\mathrm{E}\left[\cdot\,|x_{i,k}\right]$ means that the expectation is conditioned on a given relay selection result for the k-th block. Therefore the optimal relay selection problem, denoted as Problem 2, can be obtained by dynamic programming with (6) as the objective function, with only some trivial modifications in the constraints on Problem 1.

Remark 1. This dynamic programming formulation not only takes into consideration the instantaneous throughput, but also the average throughput of the future blocks. This represents a sharp difference from the conventional relay selection strategies, which only consider the current state information and may sacrifice the future performance. This is similar to the power allocation problem in EH systems. The conventional power allocation rule that always optimizes the current throughput, i.e., always exhausting the available energy, will degrade the overall performance with an EH transmitter. On the other hand, power allocation based on the EH profile of the whole transmission period can achieve a much better performance, as the directional water-filling (DWF) algorithm proposed in [14].

Remark 2. When all relays have exactly the same statistical CSI, then Eqn. (6) is reduced to the conventional relay selection, which is only based on the instantaneous throughput, as the future average is the same for each relay. However, this special case rarely occurs in practice.

B. Relay Selection Strategy with Non-causal ESI

Without loss of generality, we assume that the relay selection based on dynamic programming is currently being executed during the k-th block. In this subsection, our derivation includes two steps. First we will derive the expression for the average throughput, i.e., the objective function, based on which we will then propose a low-complexity relay selection rule.

1) Average Throughput Expression: For an arbitrary j-th ($k \le j \le N$) block, given all the respective selection results $x_{i,j}$ and CSI, the throughput is expressed as

$$\sum_{i=1}^{M} R_{i,j} x_{i,j} = \sum_{i=1}^{M} \log_2\left(1+\Lambda_{i,j}\right) x_{i,j}.$$

As all the random variables are inside $\Lambda_{i,j}$, the expectation in Eqn. (6) can be taken only over each $\Lambda_{i,j}$. The PDF and CDF for $\Lambda_{i,j}$ is provided in (13) and (14) of [15], respectively. For any $j \ge k+1$, denote the average throughput if the i-th relay is selected as $\bar{R}_{i,j}$, then we can verify that it is independent of j, which is then rewritten as $\bar{R}_i$. Further denote the average throughput if no relay is selected (i.e., $x_{0,j}=1$) as $\bar{R}_{0,j} = \bar{R}_0 = 0$, then the average throughput of the j-th block is

$$\bar{R}_{\text{ave},j} = \sum_{i=0}^{M} \bar{R}_i \text{Prob}\left(x_{i,j}=1 \left| \{x_{i,k}\}, k<j \right.\right), \quad (7)$$

and therefore the objective function in Eqn. (6) is

$$\begin{aligned} \bar{R}(k) &= \frac{1}{N-k+1}\left(\sum_{i=1}^{M} R_{i,k}x_{i,k} + \sum_{j=k+1}^{N} \bar{R}_{\text{ave},j}\right) \quad (8) \\ &= \frac{1}{N-k+1}\left(\sum_{i=1}^{M} R_{i,k}x_{i,k} + \sum_{i=0}^{M} \bar{R}_i r_i\right) \quad (9) \end{aligned}$$

where $r_i = \sum_{j=k+1}^{N} \text{Prob}\left(x_{i,j}=1 \left| \{x_{i,k}\}\right.\right)$, indicating the average number of times the i-th relay is selected among all blocks after the k-th block.

Since the exact values for all $\text{Prob}\left(x_{i,j}=1 \left| \{x_{i,k}\}\right.\right)$ are difficult to obtain and possess the curse of dimensionality (need to take expectation over $\left\{\gamma_{i,j}^{\text{s}}\right\}, \left\{\gamma_{i,j}^{\text{d}}\right\}$ as in Eqn. (6), which is about $2NM$-dim), we will propose to use an approximation instead. We assume there will always be available relays during each channel block. Thus $\text{Prob}\left(x_{0,j}=1 \left| \{x_{i,k}\}\right.\right)=0$, and we shall denote this assumption as (*). Unless otherwise mentioned, all of the following results and derivations are based on (*). If this assumption can be guaranteed by the given system parameters, our approximation solution becomes the exact optimal solution. It is possible to achieve this by adjusting the initial energy of each relay, and a full investigation is left to our future work.

We can further verify that all the harvested energy equals the total consumed energy. Since we know the future ESI, we can calculate the proportion that the i-th relay is selected based on the EH profiles of all relays given as

$$r_i = \left\lfloor \frac{2E_{i,\Sigma}^{\text{EH}}(T)}{P^{\text{tr}}T^{\text{C}}} \right\rfloor - \sum_{i=1}^{M}\sum_{j=1}^{k} x_{i,j}.$$

Thus we have obtained a new expression for Eqn. (6).

2) New Relay Selection Rule: Based on the overall throughput expression of Eqn. (9), we are now ready to investigate how to pick the best relay among the active ones. Without loss of generality, we will compare two active relays i_1 and i_2. To distinguish parameters with different selected relays, a subscript of $\cdot_{|i_1}$(or $\cdot_{|i_2}$) is added to the parameter, e.g., the average throughput is $\bar{R}_{|i_1}$ if we select the relay i_1.

Based on Assumption (*), and the value of relay transmit power P^{tr}, it can be verified that the proportion of a certain relay being selected among the whole transmission period is fixed. Then, it can be shown that $r_{i_2|i_1} - r_{i_2|i_2} = 1$ and $r_{i_2|i_1} - r_{i_1|i_1} = 1$. Therefore, from (9) we have,

$$\begin{aligned} \bar{R}_{|i_1} &= R_{i_1,k} - \bar{R}_{i_1} + C \quad (10) \\ \bar{R}_{|i_2} &= R_{i_2,k} - \bar{R}_{i_2} + C \quad (11) \end{aligned}$$

where C is the same constant for i_1 and i_2, since $r_{i|i_2} = r_{i|i_1}$ for all the i such that $i \ne i_1, i \ne i_2$.

We define the difference between the instantaneous throughput and the average throughput as the *relative throughput gain*, denoted as $\triangle R_{i,k} = R_{i,k} - \bar{R}_i$ for the i-th relay in the k-th block. Then, based on Eqns. (10)-(11), we can obtain the following relay selection rule.

Relative throughput gain based relay selection:

For the k-th block, under Condition (*), the optimal relay is determined as

$$K_k = \underset{i}{\text{argmax}} \left\{ \triangle R_{i,k} \left| \text{Constraints. (3)} - \text{(5)} \right. \right\}. \quad (12)$$

This relay selection rule implies that, in the k-th block, among all active relays, the one with the best relative throughput gain will be selected. This actually well reflects the characteristics of the EH system. In EH systems, each relay needs to be proportionally selected, so that all the harvested energy in the network can be utilized. Meanwhile, as the harvested energy is cumulative, each relay cannot be continuously selected. As indicated by (12), each relay should be selected only when its current throughput is high relative to the average throughput, i.e., close to its own peak.

Remark 3. This relay selection rule is of a very low complexity for either computation or feedback, despite that it takes into consideration the statistical information of future CSI, as well as the estimated throughput for the future blocks. First, it reduces the variables that need to be taken expectation over from the large size of $2NM$-dim for each step in Eqn. (6), to only one dimension, $\Lambda_{i,j}$, for each relay only once. Second, this relay selection rule induces a very low feedback overhead. Particularly, each relay only needs to feed back to the source when it becomes active, and it only needs to inform the source about its own value of the relative throughput gain.

C. Relay Selection Strategy with Causal ESI

With causal ESI, the only non-trivial difference with the previous case of the non-causal ESI is that the expectation in Eqn. (6) needs to be operated also with respect to the future EH power, i.e., the $\mathrm{E}_{\gamma^{\mathrm{s}}_{i,j},\gamma^{\mathrm{d}}_{i,j}}[\cdot]$ becomes $\mathrm{E}_{\gamma^{\mathrm{s}}_{i,j},\gamma^{\mathrm{d}}_{i,j},P^{\mathrm{EH}}_{i,j}}[\cdot]$.

For this case, all r^k can only be determined statistically as $r_i = \left\lfloor \frac{P^{\mathrm{EH}}_{i,\mathrm{ave}}}{P^{\mathrm{tr}}/2} N \right\rfloor - \sum_{i=1}^{M} \sum_{j=1}^{k} x_{i,j}$. But we can verify that under Condition (*), Eqns. (10)-(11) still hold, and the proposed relative throughput gain based relay selection rule is still valid. In other words, the solution for the causal ESI is the same as that with non-causal ESI. A brief explanation for this is that all the new information that the non-causal ESI can provide is already contained in Condition (*). Once we can guarantee Condition (*), the optimal relay selection whether with causal ESI or non-causal ESI is indeed the same. Since the solutions of these two cases are the same, we will not differentiate these two cases in the simulation part.

V. Simulation Results

In this section, we will demonstrate the performance of the proposed relay selection rule. We use the conventional relay selection method that always maximizes the instantaneous throughput as the performance baseline, and the solution with the non-causal ESI/CSI as an upper bound.

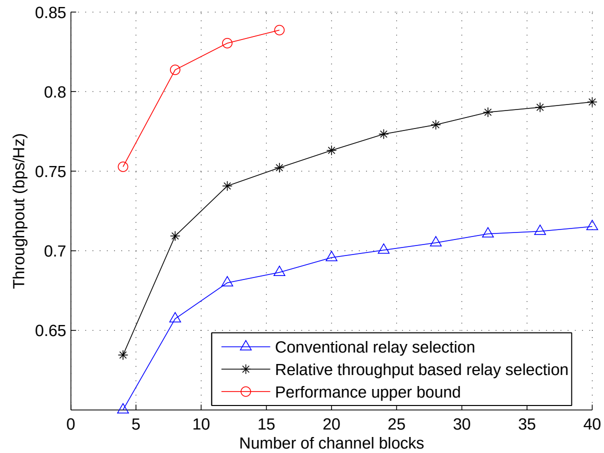

Figure 3. Throughput versus the number of channel blocks, for the relative throughput gain based relay selection and the conventional relay selection, compared with the upper bound obtained with non-causal ESI/CSI.

We consider the number of relays as $M = 4$. All S-R and R-D channels are band-limited additive white Gaussian noise channels, with bandwidth W = 1MHz and noise power spectral density $N_0 = 10^{-19}$W/Hz. $T^{\mathrm{C}} = 100$ms. The path losses for both S-R and R-D channels of R_1 are 100dB. To illustrate the influence of different relay channel gains, we set the variances of the S-R and R-D channels of $\mathrm{R}_2 \sim \mathrm{R}_4$, normalized by those of R_1, as 2, 3, 4, respectively. Both the source and relay transmit powers are 1mW. For simplicity, for the EH profile, we set $P^{\mathrm{EH}}_{i,j}$ to be of three possible values with different probabilities:

$$P^{\mathrm{EH}}_{i,j} = \begin{cases} P^{\mathrm{EH}}_{i,\mathrm{ave}}(1+\varepsilon), & p, \\ P^{\mathrm{EH}}_{i,\mathrm{ave}}, & 1-2p, \\ P^{\mathrm{EH}}_{i,\mathrm{ave}}(1-\varepsilon), & p. \end{cases}$$

In the simulation, we set $p = 0.4$, $\varepsilon = 0.9$, and $P^{\mathrm{EH}}_{i,\mathrm{ave}} = \frac{P^{\mathrm{tr}}}{2M}$.

The achievable rates versus the number of channel blocks N^{C} with the number of EH intervals $N^{\mathrm{E}} = 4$ are shown in Fig. 3, while the achievable rates versus N^{E} with $N^{\mathrm{C}} = 4$ are shown in Fig. 4[1]. We see that there is a large throughput gap between our proposed relay selection method and the conventional method. This is because the conventional method is only based on the maximization of performance in the current channel block, irrespective of the overall performance of the whole transmission period T. On the other hand, our relay selection rule (12), although very simple, takes the special property of the EH system into consideration, and can make a better use of the available side information to optimize the overall performance in T. For example, assume that one of the relays is with a larger average channel magnitude (either the S-R or R-D channel); but in a certain block, it is experiencing a channel gain realization which is not good enough for itself (i.e., based on the CDF of its CSI), while still

[1]The number of simulated points for the performance upper bound is relatively small, due to the high complexity of the branch-and-bound algorithm.

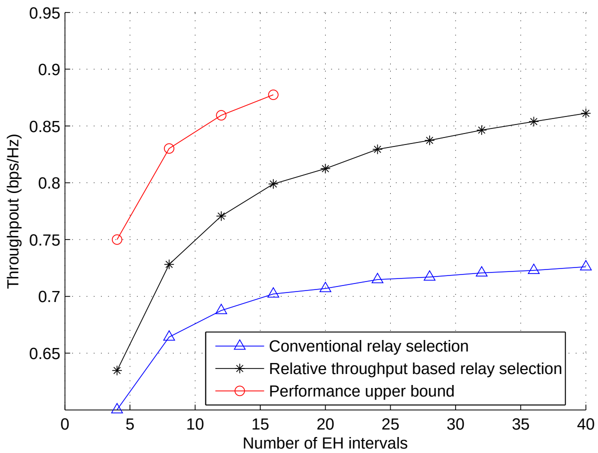

Figure 4. Throughput versus the number of EH intervals, for the relative throughput gain based relay selection and the conventional relay selection, compared with the upper bound obtained with non-causal ESI/CSI.

a little better than other relays. Then a good strategy would be to save this relay's limited energy for a real good channel in future and to select another relay for this block, which can be reflected in the relative throughput gain based relay selection. However, the conventional relay selection will always select this relay and waste this relay's energy in all such cases.

The performance upper bound with non-causal information can provide further throughput gain, but such information may not be available and the complexity of the optimal solution prohibits its practical implementation.

VI. Conclusions

The communication protocol design for EH systems differs significantly from that of conventional non-EH systems. In this paper, we considered EH cooperative communication systems. We showed that conventional relay selection method does not work well for EH systems. We proposed a new relay selection rule based on the relative throughput gain of each active relay, which makes better use of the available side information and improves the performance of the EH cooperative communication system. This relay selection method is of a low feedback overhead, and is therefore very practical.

References

[1] J. Paradiso and T. Starner, "Energy scavenging for mobile and wireless electronics," *IEEE Pervasive Comput.*, vol. 4, no. 1, pp. 18–27, Jan.-Mar. 2005.

[2] C. K. Ho and R. Zhang, "Optimal energy allocation for wireless communications with energy harvesting constraints," *IEEE Trans. Signal Process.*, vol. 60, pp. 4808–4818, Sep. 2012.

[3] J. Yang and S. Ulukus, "Optimal packet scheduling in an energy harvesting communication system," *IEEE Trans. Commun.*, vol. 60, no. 1, pp. 220–230, Jan. 2012.

[4] C. Huang, R. Zhang, and S. Cui, "Optimal power allocation for outage minimization in fading channels with energy harvesting constraints," available online at arXiv:1212.0075.

[5] Y. Luo, J. Zhang, and K. B. Letaief, "Training optimization for energy harvesting communication systems," in *Proc. IEEE Globecom*, Anaheim, CA, Dec. 2012.

[6] D. Gunduz and B. Devillers, "Two-hop communication with energy harvesting," in *Proc. 4th International Workshop on Computational Advances in Multi-Sensor Adaptive Processing (CAMSAP)*, San Juan, PR, Dec. 2011.

[7] O. Orhan and E. Erkip, "Optimal transmission policies for energy harvesting two-hop networks," in *Proc. 2012 Conf. Inform. Sciences and Systems*, Princeton, NJ, Mar. 2012.

[8] ——, "Energy harvesting two-hop networks: Optimal policies for the multi-energy arrival case," in *35th IEEE Sarnoff Symposium (SARNOFF)*, Newark, NJ, May 2012, pp. 1–6.

[9] Y. Luo, J. Zhang, and K. B. Letaief, "Optimal scheduling and power allocation for two-hop energy harvesting communication systems," *IEEE Trans. Wireless Comm.*, to appear, available at arXiv:1212.5394.

[10] B. Medepally and N. B. Mehta, "Voluntary energy harvesting relays and selection in cooperative wireless networks," *IEEE Trans. Wireless Commun.*, vol. 9, pp. 3543–3553, Nov. 2010.

[11] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, "Power management in energy harvesting sensor networks," *ACM Trans. Embed. Comput. Syst.*, vol. 6, no. 4, pp. 1–38, Sept. 2007.

[12] D. Romero Morales and H. Romeijn, *The generalized assignment problem and extensions, in Handbook of Combinatorial Optimization, Supplement Volume B*, D. Du and P. e. Pardalos, Eds. Kluwer Academic Publishers, Dordrecht, The Netherlands, 2005.

[13] G. T. Ross and R. M. Soland, "A branch and bound algorithm for the generalized assignment problem," *Math. Progr.*, vol. 8, pp. 91–103, 1975.

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

[15] S. S. Soliman and N. C. Beaulieu, "Exact analysis of dual-hop AF maximum end-to-end SNR relay selection," *IEEE Trans. Commun.*, vol. 60, no. 8, pp. 2135–2145, Aug. 2012.