Achieving Energy Diversity with Multiple Energy Harvesting Relays

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***Abstract*—Energy harvesting (EH) has recently emerged as a promising technology for next-generation green wireless networks, as it can power communication nodes with renewable energy. However, it is challenging to provide satisfactory performance in such systems, due to the sporadic energy arrival and the low harvesting rate. In this paper, we propose a novel cooperation strategy for EH networks with the help of multiple EH relays, each of a steady but low harvesting rate. Different relays will take turns to assist the source-destination transmission, and thus *energy diversity* can be achieved. To provide steady communications, we formulate the design problem as to maximize the minimum utility during the considered transmission duration, which, however, is NP-hard. We propose a general framework to develop efficient suboptimal algorithms, which consists of 1) a sufficient condition for the feasibility of the optimization problem and 2) an efficient bisection algorithm to find a suboptimal solution. Simulation results will show that the proposed cooperation strategy can provide significant power gains over the direct link transmission, and the proposed suboptimal algorithm can provide near-optimal performance. Compared to the best-effort cooperation that only optimizes the current transmission block, the proposed strategy can achieve the same performance with much fewer relays.**

***Index Terms*—Energy harvesting, power assignment, relay selection, cooperative communications.**

I. INTRODUCTION

Energy harvesting (EH) technology has recently emerged as a promising approach to provide renewable energy sources to power wireless networks, and thus realize green communications. The EH node can obtain energy from the environment [1], including solar energy, thermoelectric energy, vibration energy, RF energy, etc. EH technology can not only enable miscellaneous applications such as smart cities and machine-to-machine (M2M) communications [2], but also achieve the perpetual lifetime, as it can exempt the manual battery replacement [3]. However, it is difficult to provide satisfactory communication performance with EH transceivers, due to the fact that the harvested energy is typically in a small amount and also time-varying.

Cooperative communication has been demonstrated as an effective technique to improve the performance of wireless networks [4], and its potential in EH networks has been recently investigated. The authors in [5–9] investigated the single-relay two-hop EH network, and revealed that the communication protocols need to be redesigned for EH communication systems. With EH constraints, it turns out that the cooperation design with multiple EH relays is very challenging. In [10], a simple relay selection scheme based only on the average EH rate of each relay was analyzed, where the coupling among different relays was observed. Joint power allocation and relay selection was considered in [11] with either non-causal or causal channel and energy side information, but the complexity of the proposed algorithms is relatively high. Adopting fixed transmit power, an efficient but suboptimal relay selection method based on the so-called *relative throughput gain* was proposed in [12]. However, all the relay selection methods in [10–12] require channel side information of each relay in each transmission block, which is challenging to obtain, especially given the low EH rates of the EH relays. Meanwhile, previous works on EH networks focused on the cumulative performance over a certain time period, while the performance during a particular time slot may not satisfy the application requirement. Thus, EH communication systems with such design approaches cannot support applications with a strict QoS requirement [13].

In this work, we will investigate a cooperative EH network with multiple EH relays, and we intend to achieve energy diversity by allowing relays to take turns to forward the source information. To be practical, the proposed cooperation strategy will be of low complexity and will only depend on statistical channel information. In contrast, the previously proposed transmission strategies for EH networks are not quite practical, such as the offline approach that requires all the side information [6, 9] or the online algorithm with a high computational complexity [14].

The main contributions of this paper are three-folds: 1) We propose an effective yet low-complexity cooperation strategy, which consists of three components, namely *relay preselection*, *power assignment*, and *relay selection*. The preprocessing, i.e., relay preselection and power assignment, will greatly simplify the relay selection operation in each transmission block. 2) To optimize the proposed cooperation strategy, we will formulate a joint power assignment and relay selection problem, with maximizing the minimum utility among all the transmission blocks as the objective, while relay preselection is implicitly considered. This problem is found to be NP-hard, and we will propose a general framework to develop efficient suboptimal algorithms. 3) We shall demonstrate that the proposed cooperation strategy can provide significant power gains over the direct link transmission via simulations. We will also show that the proposed strategy outperforms the best-effort strategy that only optimizes the current transmission block. Moreover, the proposed suboptimal algorithms provide performance close to the corresponding upper bound.

Notation: Matrices are denoted by bold-face upper-case letters. Sets are denoted by calligraphic upper-case letters such as $\mathcal{A}$, and $|\mathcal{A}|$ represents the cardinality of $\mathcal{A}$. $x \leftarrow y$ represents assigning the value of y to x. For two sets $\mathcal{A}$ and $\mathcal{B}$, $\mathcal{A}-\mathcal{B}$ is the relative complement of $\mathcal{A}$ with respect to $\mathcal{B}$. $\mathbf{1}_{\varphi}$ denotes the indicator function. $\varphi_1 \Leftrightarrow \varphi_2$ means that φ_1 is sufficient and necessary for φ_2.

II. SYSTEM MODEL AND ENERGY MODEL

In this section, we will introduce the system model and the energy model considered in this paper.

A. System Model

We consider a network with one source-destination (S-D) pair, assisted by K relays. Both the source and relays are EH nodes. The set of relays is denoted as $\mathcal{K} = \{1, 2, ..., K\}$. All the relays are half-duplex and apply the amplify-and-forward (AF) relaying protocol, while the extension to other relaying protocols is straightforward. There is a peak transmit power constraint for each relay, denoted as $P_{k,\max}^{\mathrm{tr}}$ for the k-th relay. In particular, we assume that each EH relay has a low EH rate, e.g., around or below 1mW, but such nodes are cheap and there are plenty of them in the network.

All the channels are assumed to be experiencing block fading, with the coherence time denoted as T^{c}, corresponding to one transmission block. To be practical, we assume that the source does not have instantaneous channel state information, as the EH relays may not have enough energy for channel training/feedback. In the first half of each transmission block, the source will send the information signal to the selected relay, while in the second half, the selected relay will forward the information to the destination. The operation will be based on the statistical channel information and the EH rate of each node. We consider the system design within a given transmission duration of length T, which contains $N = \frac{T}{T^{\mathrm{c}}}$ transmission blocks, and normally N is much larger than K. Denote the set of all the transmission block indices in T as $\mathcal{N} = \{1, 2, ..., N\}$.

B. Energy Model

An important factor that determines the performance of an EH communication node is the *EH profile*, which models the cumulative harvested energy up to time t. As the EH rate usually does not vary frequently, we will consider a piecewise constant model for the EH profile, i.e., each EH node has a steady but low EH rate. The change of the EH rate is in the time unit of an EH interval T^{E}, which is assumed to be much larger than the channel coherence time. A similar EH model is adopted in [12, 14], and it can be used for such energy sources as solar energy. For simplicity, we will focus on one EH interval, i.e., $T = T^{\mathrm{E}}$. For the case where $T > T^{\mathrm{E}}$, the results can be generalized with updated EH rates at the beginning of each EH interval. For the k-th EH relay, denote the EH profile as $E_{k,\Sigma}^{\mathrm{EH}}(t)$, the initial energy in the battery as $E_k^{\mathrm{init}} = E_{k,\Sigma}^{\mathrm{EH}}(0)$, and the constant EH rate as P_k^{EH}.

The utilization of the harvested energy is constrained by the EH profile, which yields the *energy causality constraint* [8]. The energy causality means that the energy consumed thus far cannot exceed the total harvested energy. We only consider the energy consumption for information transmission, while ignore other types of energy consumption. Denote the instantaneous transmit power as $P(t)$, and then the energy causality constraint can be expressed as

$$\int_0^t P(\tau)\, d\tau \le E_{k,\Sigma}^{\mathrm{EH}}(t). \tag{1}$$

This constraint will bring major design challenges for the EH networks. In particular, with multiple EH relays, it will cause a coupling effect when determining the transmit powers of different relays and selecting different relays.

For each EH relay, we assume that the battery capacity is large enough, while the more general case is left to future work. Moreover, we assume that the initial energy in the battery for the k-th relay can support its maximum transmit power, i.e., $E_k^{\mathrm{init}} = P_{k,\max}^{\mathrm{tr}} T^{\mathrm{c}}/2$. This is mainly to guarantee the performance during the first few transmission blocks.

III. PROPOSED COOPERATION STRATEGY AND PROBLEM FORMULATION

In this section, we will propose a new cooperation strategy to overcome the low EH rates of relays. Based on the available energy, different relays will take turns to assist the S-D transmission in different transmission blocks. A joint power assignment and relay selection method will be proposed to balance the energy consumption of different relays.

A. Proposed Cooperation Strategy

The main components of the proposed cooperation strategy include relay preselection, power assignment, and relay selection, which are jointly determined, and are described as follows.

1) Relay Preselection: With different positions and EH rates, different relays will provide different performances while assisting the S-D communication. *Relay preselection* is a preprocess that will assign a particular subset of relays to the S-D pair, in order to simplify the relay selection operation and also assist the system design. It is performed at the beginning of each EH interval, and is fixed for the whole interval. The subset of relays assigned to the S-D pair is called the *candidate relay subset*, denoted as $\mathcal{S}$, while the subset of unassigned relays is denoted as $\mathcal{K} - \mathcal{S}$.

2) Power Assignment: To simplify the operation, within one EH interval, each relay will adopt constant power transmission, i.e., it will use the same transmit power whenever it is selected to forward information. *Power assignment* is to determine the transmit power for each relay. For a given relay, a low transmit power cannot provide a good performance, while a too high transmit power will exhaust its energy too soon, which implies that other candidate relays will be selected more often. Thus, there is coupling when assigning transmit powers for the relays in the candidate subset, and power assignment needs to be carefully decided. We denote the transmit power matrix as $\mathbf{P} = [P_k^{\mathrm{tr}}]$, where P_k^{tr} is the transmit power of the k-th relay. Similar to relay preselection, power assignment is also performed at the beginning of the EH interval.

3) Relay Selection: For the proposed cooperation strategy, once relay preselection and power assignment are finished at the beginning of the EH interval, relay selection will be performed in each transmission block, which will be based on each relay's available energy. A relay is called *active* if its available energy, denoted as $E_{k,\Sigma}(t)$, is enough to support its transmit power, i.e.,

$$E_{k,\Sigma}(t) \geq P_k^{\mathrm{tr}} T^{\mathrm{c}}/2. \tag{2}$$

At the beginning of each transmission block, one relay with enough energy, i.e., an active relay, will be selected from the candidate relay subset to assist the S-D communication. Denote the relay selection matrix as $\mathrm{Z} = [z_{k,n}]$ with

$$z_{k,n} = \begin{cases} 1 & k-\text{th relay is selected in } n\text{-th block} \\ 0 & \text{otherwise} \end{cases}.$$

Note that $\sum_{k=1}^{K} z_{k,n} \leq 1$, $n \in \mathcal{N}$, as at most one relay can be selected for each transmission block.

Remark 1. With the proposed cooperation strategy, different relays will take turns to assist the S-D communication, and each of them will have time to accumulate enough energy for transmission. This strategy bears a similar motivation as diversity in wireless communications [15]. With diversity, multiple copies of the same information will be sent through links with independent fading, so it is very unlikely that all the links will be weak, i.e., there will always be some link with a high channel gain, and thus the so-called *diversity gain* is achieved; while for our proposed cooperation strategy, the hope is that we can always find an EH relay with enough energy to help the S-D communication, and the achieved performance gain can be regarded as the *energy diversity gain*.

B. Utility Function

The system performance is measured by a general utility function [16], which is a monotonically increasing function of the allocated resource. It is denoted as $U^{(n)}$ in the n-th transmission block, with $n \in \mathcal{N}$. If the k-th relay is selected, the achieved utility is denoted as $U_k(P_k^{\mathrm{tr}})$ with transmit power P_k^{tr}. Then based on the relay selection matrix Z, we have

$$U^{(n)} = \sum_{k=1}^{K} z_{k,n} U_k\left(P_k^{\mathrm{tr}}\right). \tag{3}$$

In practice, many applications have a strict QoS requirement, e.g., real-time applications with strict delay constraints, such as fire detection and health care, which poses challenges for the steadiness and reliability of communication systems. In this paper, to achieve steady and reliable communications, the minimum utility within the transmission duration T is adopted as the design objective, which is given as

$$U^{(\mathcal{N})} = \min_{n \in \mathcal{N}} \sum_{k=1}^{K} z_{k,n} U_k\left(P_k^{\mathrm{tr}}\right). \tag{4}$$

With this objective function, $\sum_{k=1}^{K} z_{k,n} = 1$ shall hold for all $n \in \mathcal{N}$, i.e., one relay will be selected in each transmission block; otherwise, the utility will be zero.

C. Problem Formulation

Based on the above discussion, we can formulate the design problem in the following form

(OP1)

$$\begin{aligned} &\max_{\mathbf{P},\mathbf{Z}} U^{(\mathcal{N})} \\ &\text{s.t.} \sum_{n=1}^{l} z_{k,n} P_k^{\mathrm{tr}} \frac{1}{2} T^{\mathrm{c}} \leq E_k^{\mathrm{init}} + \left(l - \frac{1}{2}\right) P_k^{\mathrm{EH}} T^{\mathrm{c}}, \\ &\qquad \forall l \in \mathcal{N},\ k \in \mathcal{K}, && (5) \\ &\qquad P_k^{\mathrm{tr}} \leq P_{k,\max}^{\mathrm{tr}},\ \forall k \in \mathcal{K}, && (6) \\ &\qquad \sum_{k=1}^{K} z_{k,n} = 1,\ \forall n \in \mathcal{N}, && (7) \\ &\qquad z_{k,n} \in \{0,1\},\ k \in \mathcal{K},\ n \in \mathcal{N}, && (8) \end{aligned}$$

where (5) is based on the energy causality constraint (1), (6) is the peak power constraint for each relay, and (7) regulates that for each transmission block, one relay is selected to assist the S-D transmission. Note that relay preselection is implicitly contained in $\mathbf{Z}$, and later it will be shown that explicitly considering relay preselection will assist solving the design problem.

Problem **OP1** is a utility maximization problem involving joint power assignment and relay selection, i.e., we need to jointly design $\mathbf{P}$ and $\mathbf{Z}$. It is a highly complicated problem, as it belongs to the mixed-integer nonlinear programming (MINLP) problem [17], which is known to be NP-hard. Moreover, a particular difficulty is the coupling effect among the operations for different relays. Therefore, instead of solving **OP1** directly, we will provide an efficient suboptimal algorithm. The epigraph form of **OP1** is as follows

$$\textbf{(OP2)} \quad \begin{aligned} &\max_{\mathbf{P},\mathbf{Z},\eta} \ \eta \\ &\text{s.t.} \ U^{(\mathcal{N})} \geq \eta, \\ &\qquad \text{Constraints (5)} \sim \text{(8)}. \end{aligned}$$

In the following sections, we will first investigate the feasibility problem of **OP2**, which will then help develop efficient algorithms for the original problem.

IV. UTILITY MAXIMIZATION

We will first solve the feasibility problem with a given utility, based on which a bisection algorithm will be proposed to solve the utility maximization problem.

A. Solving the Feasibility Problem

With a single EH interval, the feasibility problem of **OP2** with a given η is

(FP1)

$$\begin{aligned} &\text{find} \quad \mathbf{P}, \mathbf{Z} \\ &\text{s.t.} \quad U^{(\mathcal{N})} \geq \eta, &(9)\\ &\sum_{j=1}^{l} z_{k,n} P_k^{\text{tr}} \frac{1}{2} T^{\text{c}} \leq E_k^{\text{init}} + \left(l - \frac{1}{2}\right) P_k^{\text{EH}} T^{\text{c}}, \\ &\forall l \in \mathcal{N},\ k \in \mathcal{K}, &(10)\\ &\text{Constraints (6)} \sim \text{(8)}. &(11) \end{aligned}$$

In the following, we will first reformulate this problem to a simpler form, which is still NP-hard, but can help derive a sufficient condition for the feasibility of **FP1**.

1) Problem Reformulation: We will take relay preselection into consideration, which will help fix $\mathbf{P}$ and remove constraint (9).

With a given utility η, for the k-th relay, if $U_k\left(P_{k,\max}^{\text{tr}}\right) < \eta$, then this relay should not be selected even once, i.e., $z_{k,n} = 0$, $\forall n \in \mathcal{N}$. Otherwise, it will be selected at least once within the transmission duration T, i.e., $\sum_{n=1}^{N} z_{k,n} \geq 1$, given $T \gg T^{\text{c}}$. Therefore, the temporary[1] relay preselection result with a given η is determined as

$$\mathcal{S}_\eta = \left\{ k \in \mathcal{K} \left| U_k\left(P_{k,\max}^{\text{tr}}\right) \geq \eta \right.\right\}. \tag{12}$$

For $k \in \mathcal{S}_\eta$, the minimum transmit power of the k-th relay that can meet the utility requirement η can be determined as $U_k^{-1}(\eta)$, where $U_k^{-1}(\cdot)$ is the inverse function of $U_k(\cdot)$. For a given η, this minimum transmit power only depends on the relay position. We denote $\hat{\mathbf{P}}_\eta = \left[\hat{P}_k(\eta)\right]$ where

$$\hat{P}_k(\eta) = \begin{cases} U_k^{-1}(\eta) & k \in \mathcal{S}_\eta \\ 0 & k \in \mathcal{K} - \mathcal{S}_\eta \end{cases}. \tag{13}$$

Then we have the following property that can simplify the feasibility checking of **FP1**:

Lemma 1. ***FP1*** *is feasible* $\Leftrightarrow$ ***FP1*** *with* $\mathbf{P} = \hat{\mathbf{P}}_\eta$ *is feasible.*

Proof: The proof is omitted due to space limitation. ■

With Lemma 1, we can replace the power vector $\mathbf{P}$ in **FP1** by $\hat{\mathbf{P}}_\eta$. Therefore, when checking the feasibility of **FP1**, we do not need to check the full domain of the power vector $\mathbf{P}$, but can only check a single vector $\hat{\mathbf{P}}_\eta$, which largely reduces the complexity.

Given $\mathcal{S}_\eta$, if constraint (7) is satisfied, i.e., there exists at least one active relay in each transmission block, we can simplify the utility function (4) as follows: $U^{(\mathcal{N})} = \min\limits_{n\in\mathcal{N}} U^{(n)} = \min\limits_{k\in\mathcal{S}_\eta} U_k$. Thus the minimization over time is replaced with minimization over candidate relays. Moreover, after substituting $\mathbf{P}$ with $\hat{\mathbf{P}}_\eta$, once (7) is satisfied, constraint (9) will also be satisfied, as $\min\limits_{k\in\mathcal{S}_\eta} U_k\left(\hat{P}_k(\eta)\right) \geq \eta$ based on (13). Thus (9) can be removed from **FP1**.

Based on the above discussion, we have fixed $\mathbf{P}$ and removed constraint (9), and thus obtain the following equivalent problem for **FP1**

(FP2)

$$\begin{aligned} &\text{find} \quad \mathbf{Z} \\ &\text{s.t.} \quad \sum_{n=1}^{l} \frac{1}{2} \hat{P}_k(\eta) T^{\text{c}} z_{k,n} \leq E_k^{\text{init}} + \left(l - \frac{1}{2}\right) P_k^{\text{EH}} T^{\text{c}}, \\ &\forall l \in \mathcal{N},\ k \in \mathcal{S}_\eta, &(14)\\ &\sum_{k\in\mathcal{S}_\eta} z_{k,n} = 1,\ \forall n \in \mathcal{N}, &(15)\\ &z_{k,n} \in \{0,1\},\ \forall k \in \mathcal{S}_\eta,\ n \in \mathcal{N}. &(16) \end{aligned}$$

Compared to **FP1**, the dimension of **FP2** is reduced as $\mathbf{P}$ is fixed, and constraint (9) is removed. It can be verified that **FP2** is the feasibility problem of the multi-resource generalized assignment problem (MRGAP) [18], which is NP-hard. A particular difficulty is the large size of $\mathbf{Z}$. Therefore, although the problem has been significantly simplified, it is still difficult to deal with. In the following, by exploiting the relationship of the EH rates and transmit powers of all the candidate relays, we will derive a sufficient condition for the feasibility of **FP2**, which is easy to check and can be used to provide a suboptimal algorithm for the utility maximization problem **OP2**.

2) Sufficient Condition for Feasibility: We have the following result, which provides a simple sufficient condition to check the feasibility of **FP2**.

Lemma 2. *The following is a sufficient condition for the feasibility of* ***FP2:***

$$\sum_{k\in\mathcal{S}_\eta} \frac{2P_k^{\text{EH}}}{\hat{P}_k(\eta)} \geq 1. \tag{17}$$

Proof: The proof is omitted due to space limitation. ■

Once condition (17) is satisfied, there exist active relays for each transmission block. In this way, different relays will take turns to assist the S-D communication, and the difficulty caused by the low EH rate at a single relay can be overcome. Moreover, based on Lemma 2, as the effect of the relay selection matrix $\mathbf{Z}$, which is of a large size, has been removed, condition (17) only depends on $\hat{\mathbf{P}}_\eta$, and thus it is easy to check.

B. Solving the Original Optimization Problem

In this subsection, we will propose an efficient bisection algorithm to solve the joint power assignment and relay selection problem for the single-pair case.

Based on Lemma 2, the following problem can provide a suboptimal solution for **OP2**

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[1] This relay preselection result $\mathcal{S}_\eta$ is only a "temporary" result, as it is for a given utility η, while it will be in general different from the final result.

Algorithm 1: Suboptimal power assignment and relay selection for **OP2**.

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Initialization:
    Pick an arbitrary $k \in \mathcal{K}$, set $\eta^{\mathrm{U}} \leftarrow U_k\left(P_{k,\max}^{\mathrm{tr}}\right)$, $\eta^{\mathrm{L}} \leftarrow U_k\left(P_k^{\mathrm{EH}}\right)$.
While $\eta^{\mathrm{U}} - \eta^{\mathrm{L}} > \epsilon$
    $\eta^{\mathrm{M}} \leftarrow \frac{1}{2}\left(\eta^{\mathrm{U}} + \eta^{\mathrm{L}}\right)$.
    Obtain $\mathcal{S}_\eta$ and $\hat{\mathbf{P}}_\eta$ by (12) and (13), respectively.
    If $\hat{\mathbf{P}}_\eta$ satisfies condition (17)
        $\eta^{\mathrm{L}} \leftarrow \eta^{\mathrm{M}}$.
    Else
        $\eta^{\mathrm{U}} \leftarrow \eta^{\mathrm{M}}$.
    End if
End while
Result:
    $\eta^{\mathrm{L}}$ is the final utility, $\mathcal{S}_\eta$ is the relay preselection result, and $\hat{\mathbf{P}}_\eta$ is the transmit power vector.
    For each transmission block, the source randomly selects an active relay (according to eq. (2)) within $\mathcal{S}_\eta$.
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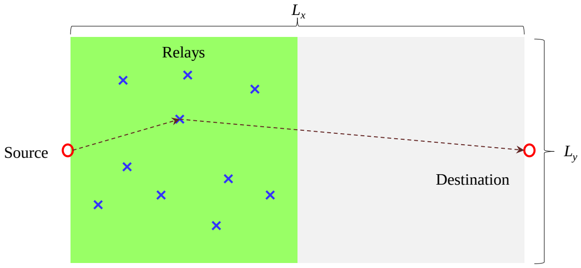

Figure 1. A rectangular area with 1 S-D pair and 10 relays.

$$\textbf{(OP3)} \quad \max_{\hat{\mathbf{P}}_\eta, \eta} \quad \eta \qquad \text{s.t.} \quad \sum_{k \in \mathcal{S}_\eta} \frac{2P_k^{\mathrm{EH}}}{\hat{P}_k(\eta)} \geq 1.$$

More specifically, if **OP3** is feasible, then **OP2** is feasible; the optimal value of **OP3** provides a lower bound to **OP2**. It can be checked that if **OP3** is feasible for a given η, then it must be feasible for any $\eta' < \eta$; on the other hand, if it is infeasible for a given η, then it must be infeasible for any $\eta' > \eta$. Thus we can use a bisection method to find an optimal solution of **OP3**, which provides a suboptimal solution for **OP2**. The proposed algorithm is shown as Algorithm 1, where ϵ represents the required accuracy.

In Algorithm 1, during each loop of the bisection, with a given utility η, we determine a temporary relay preselection result $\mathcal{S}_\eta$ and a temporary power assignment vector $\hat{\mathbf{P}}_\eta$, and then check the feasibility of $\hat{\mathbf{P}}_\eta$. If it is feasible, we increase the utility η; otherwise, we reduce it. The largest feasible η is the suboptimal value of **OP2**. Note that the proposed cooperation strategy with joint power assignment and relay selection has a low computational complexity, and also a low requirement on the side information. Moreover, as will be shown in the simulation, the performance of Algorithm 1 is close to optimal. On the other hand, this approach is very general, since the development only requires the utility function be monotonically increasing.

V. SIMULATION RESULTS

In this section, we will provide simulation results to demonstrate the performance of the proposed cooperation strategy.

As shown in Fig. 1, in the simulation, we consider a rectangular area with length L_x and width L_y. The source and destination are located in the center of the two opposite sides. With a low transmit power of each EH source, relays should be deployed close to the source rather than the destination [19], and thus we assume that all the relays are uniformly distributed inside the left half of the rectangle. Denote the reference distance for path loss as $d_0 = 10$m, and the free-space path loss at d_0 for a carrier frequency 2.4GHz is calculated as 60dB based on $[\lambda/(4\pi d)]^2$, where λ is the wavelength. We set $L_x = 2d_0$, $L_y = d_0$. We consider band-limited Rayleigh fading channels, with bandwidth $B = 1$MHz and noise power spectral density $N_0 = 10^{-16}$W/Hz, while the transmission block length T^{c} is 1ms. To characterize such steady energy source as solar power [14], we set the EH interval as $T^{\mathrm{E}} = 10^5 T^{\mathrm{c}}$, i.e., it is much larger compared to the channel coherence time. In the simulation, we adopt the successful transmission probability $\mathbb{P}^{\mathrm{s}} = 1 - \mathbb{P}^{\mathrm{o}}$ as the utility function, where $\mathbb{P}^{\mathrm{o}}$ is the outage probability, and will be used to demonstrate the performance in all the simulations. The outage probability with a single AF relay can be calculated based on eq. (3.65) in [4]. The SNR threshold is set as $\gamma = 3$.

For each realization, the EH rate of each relay is drawn randomly within $[\bar{P}^{\mathrm{EH}}(1-\alpha), \bar{P}^{\mathrm{EH}}(1+\alpha)]$, where $\bar{P}^{\mathrm{EH}}$ is the average EH rate, and $0 < \alpha < 1$; while the transmit power of each source is uniformly distributed within $\left[\bar{P}_{\mathrm{s}}^{\mathrm{tr}}(1-\alpha), \bar{P}_{\mathrm{s}}^{\mathrm{tr}}(1+\alpha)\right]$, which reflects its EH rate. In simulation, the default value of α is 0.5, while the maximum transmit power for each relay and the average source transmit power are set as $P_{k,\max}^{\mathrm{tr}} = 1$W and $\bar{P}_{\mathrm{s}}^{\mathrm{tr}} = 10$mW, respectively.

To demonstrate the advantage of the proposed approach, we will compare it with a *best-effort policy*, which will always select the relay that can provide the best performance within each transmission block. Such policy does not take EH constraints into consideration. We will also compare with a performance upper bound, which, different from Algorithm 1, will solve the linear programming (LP) relaxation of **FP2** rather than use the sufficient condition (17).

The outage probabilities versus the relay number for different policies are plotted in Fig. 2. As a reference, the outage probability of the direct link transmission without the assistance of any relay is calculated as 0.2134. Fig. 3 plots the average power gain over the single-hop transmission provided by different policies, which is the additional power required to

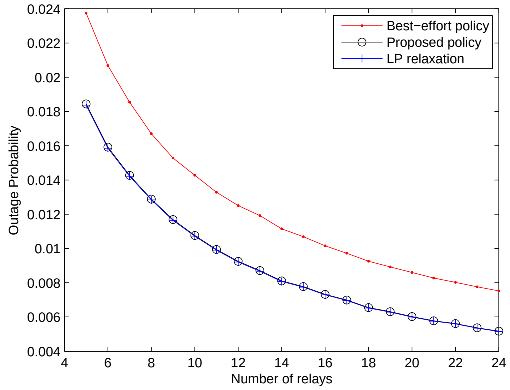

Figure 2. Outage probability versus the relay number with the average EH rate as 1mW.

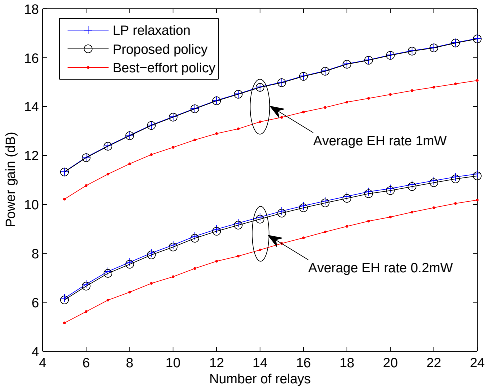

Figure 3. Average power gain versus the relay number with two average EH rates as 1mW and 0.2mW, respectively.

achieve the same performance by the direct link transmission.

We have the following observations from the simulation results:

- As shown in Fig. 2, the outage probability of the proposed policy decreases with the relay number, and it is much smaller than that provided by the direct link transmission, which is 0.2134. Moreover, the performance gain of adding additional relays diminishes when the relay number becomes large, i.e., there is no need to deploy too many relays. The performance of the proposed algorithm is close to that of the performance upper bound, which reveals the effectiveness of the proposed methodology.
- The proposed policy outperforms the best-effort policy, which only considers the current transmission block. For example, to have the outage probability less than 0.01, the proposed policy requires more than 11 relays, while the best-effort policy needs more than 16 relays.
- From Fig. 3, a significant power gain can be achieved by the proposed policy, which increases with the EH rate and the relay number. Similar to Fig. 2, it also shows that to achieve the same performance gain the proposed policy requires much fewer relays than the best-effort policy.

VI. CONCLUSIONS AND FUTURE WORKS

In this work, we proposed a cooperation strategy for EH networks, which exploits energy diversity via multiple EH relays. The proposed strategy is of a low complexity and only depends on the statistical channel side information. Simulation results demonstrated that such simple cooperation strategy can overcome the low EH rate at each single node, and provide significant power gain to improve the source-destination communication. For the future work, it would be interesting to extend the current study to more general EH profiles.

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