Backscatter-assisted Hybrid Relaying Strategy for Wireless Powered IoT Communications

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***Abstract*—In this work, we consider multiple energy harvesting relays to assist information transmission from a hybrid access point (HAP) to a distant receiver. The multi-antenna HAP also beamforms RF power to the relays by using a power-splitting protocol. We aim to maximize the throughput by jointly optimizing the HAP's beamforming strategy as well as individual relays' energy harvesting and collaborative beamforming strategies. With dense user devices, the throughput maximization takes account of the direct links from the HAP to the receiver as they are short and contribute considerably to the overall throughput. Moreover, we introduce the concept of *hybrid relaying communications* which allows the energy harvesting relays to switch between two radio modes. In particular, the relays can operate either in RF communications or backscatter communications, depending on their channel conditions and energy status. This results in a non-convex and combinatorial throughput maximization problem. With the fixed relay mode, we can find a feasible lower performance bound via convex approximation, which further motivates our algorithm design to update the relay mode in an iterative manner. Simulation results verify that the proposed hybrid relaying strategy can achieve significant performance improvement compared to the conventional relaying strategy with all relays operating in the RF communications mode.**

***Index Terms*—Energy harvesting, wireless powered network, hybrid relaying, wireless backscatter.**

I. Introduction

Recently, wireless power transfer has been proposed as a cost-effective way to sustain wireless communications for billions of user devices [1], constituting the future Internet of Things (IoT). With densely deployed IoT devices, we can employ multiple energy harvesting relays to assist information transmission between the transceivers by leveraging signal and energy cooperation at individual relays [2]. Via cooperative transmissions, we can achieve improved link quality, extended coverage, higher spectral and energy efficiency [3]. However, the high power consumption in the relays' RF communications usually prevents them from cooperative transmissions, especially for those relays with insufficient power supply.

Compared to RF communications, wireless backscatter is a new promising communications technology featured with extremely low power consumption for data communications [4]. The backscatter radios transmit information in the passive mode by reflecting the incident RF signals. The change of signal reflections can be captured by the receiver via an energy detector [5]. The passive radio relies on the RF signals and its operation can also enhance the active radio's information transmission. The conventional relay communications have been extended to study passive relay communications [6], which can be more energy- and spectrum-efficient due to the extremely low power consumption. The authors in [7] and [8] showed that the backscatter signals can be exploited as a form of multi-path diversity to enhance active RF communications. In our previous works [9] and [10], we proposed the *passive relaying scheme* that uses the backscatter radios as wireless relays to assist information transmission between active radios. By optimizing the passive relays' reflection coefficients, the multi-path effect can be controlled to enhance signal reception [11]. The *passive relaying game* has been proposed in [12] as a concave game to model the competition and conflict in relay communications with multiple passive radios.

However, most of the existing works considered a simple passive relaying model in which one or more backscatter radios are employed to assist the active RF communications. In this paper, we propose a novel *hybrid relaying communications* model in which both passive and active relays can be employed to assist active RF communications. To maximize the overall throughput, each relay leverages a dual-mode radio that can switch between the active and passive modes independently [6], depending on its channel conditions and energy status. The relays' mode selection actually incurs the tradeoff between channel quality and multi-path diversity. As the conventional relay models focus on either the active or passive relays, the relay strategies are not applicable to this case. Hence, it calls for a novel algorithm design for relay optimization in the hybrid relaying communications.

In this paper, we focus on a two-hop hybrid relaying model. In the first hop, the multi-antenna source node beamforms information to the relays and the receiver. The passive relays instantly backscatter the RF signals to enhance signal reception at the active relays and the receiver. In the second hop, the active relays amplify and forward the received signals

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to the receiver, with the enhanced channels by the passive relays. We aim to maximize the throughput performance by jointly optimizing the source beamforming strategy, the relays' energy harvesting and mode selection strategies. It is clear that the throughput maximization problem is combinatorial and difficult to solve optimally. To overcome this difficulty, we propose a two-step solution to optimize the relay strategy. With a fixed relay mode, we firstly find a feasible lower bound on the throughput performance via convex approximation. Then, we evaluate individual relays' energy status or potential performance gain, which motivates the algorithm design to update the relay mode in an iterative manner. Simulation results verify that the proposed hybrid relaying strategy can significantly improve the throughput performance compared to the conventional relay strategy with all active relays. The performance improvement becomes higher as the passive radios set a greater magnitude to the reflection coefficients by antenna design or load modulation.

II. System model

We consider a multi-antenna hybrid access point (HAP) and a group of single-antenna user devices. The data transmission from the HAP to the receiver is assisted by a set of relays following the amplify-and-forward (AF) protocol. The set of relays is denoted by $\mathcal{N} = \{1, 2, \ldots, N\}$. The HAP has a constant power supply, while the relays are wirelessly powered by RF signals emitted from the HAP. Via signal beamforming, the HAP can control the rates of information and power transfer to the relays following the power-splitting (PS) protocol [13]. Our goal is to maximize throughput from the HAP to the receiver by optimizing the HAP's signal beamforming and the relaying strategies. Let $\mathbf{f}_0 \in \mathbb{C}^K$ and $\mathbf{f}_n \in \mathbb{C}^K$ denote the complex channels from the HAP to the receiver and from the HAP to the n-th relay, respectively. Let $\mathbf{g} \triangleq [g_1, g_2, \ldots, g_N]^T \in \mathbb{C}^N$ denote the channel from the relays to the receiver. All channels are block fading.

A. Two-Hop Relay Protocol with Direct Links

The relay-assisted information transmission follows a two-hop half-duplex protocol. As shown in Fig. 1, the information transmission is divided into two phases, i.e., the relay receiving and forwarding phases, corresponding to the information transmission in two hops. Due to a short distance between transceivers in a dense D2D network, the direct links between the HAP and the receiver can exist in both hops and contribute significantly to the overall throughput. Let $(\mathbf{w}_1, \mathbf{w}_2)$ denote the HAP's signal beamforming strategies in two phases.

In the first hop, the multi-antenna HAP beamforms the information signal with a fixed transmit power p_t and the beamforming vector $\mathbf{w}_1$. As shown in Fig. 1(a), the beamforming information can be received by both the relays and the receiver directly. Hence, the beamforming design has to balance the transmission performance to the relays and to the receiver. A higher rate in direct transmission potentially degrades the signal quality at the relays and reduces the data rate of relays' transmission. The HAP's beamforming in the first hop is also used for wireless power transfer in the PS protocol, as shown in Fig. 2. Each relay can set a different PS ratio to match the HAP's beamforming strategy and their energy demands. In the second hop, the relays amplify and forward the received signals to the receiver. Meanwhile, the HAP also beamforms the same information symbol directly to the receiver with a new beamforming vector $\mathbf{w}_2$. Hence, the received signal at the receiver is a mixture of the signals forwarded by the relays and the direct beamforming by the HAP. By maximal ratio combining (MRC) at the receiver, e.g., [14], the received signals in both hops can be combined together to enhance the reliability in transmission.

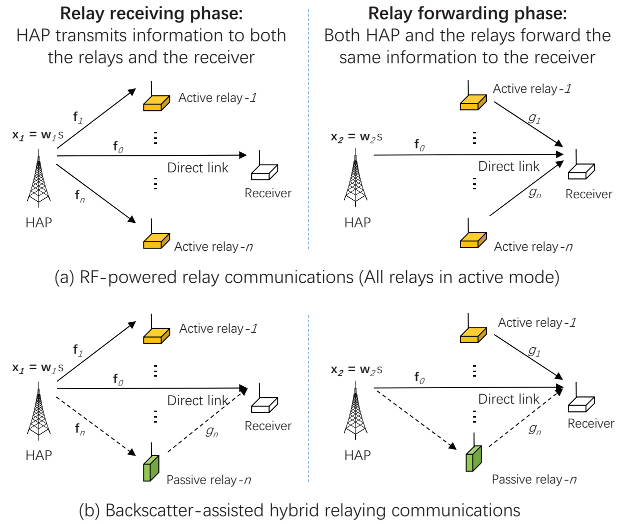

Fig. 1: Hybrid relaying communications with direct links.

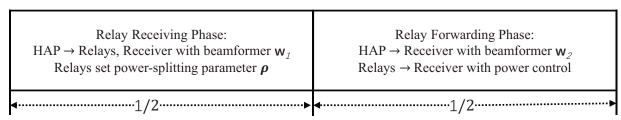

Fig. 2: Wireless power transfer to the relays by the PS protocol.

B. Hybrid Relaying via Dual-Mode Radios

We assume that each relay has a dual-mode radio structure that can switch between the passive and active modes, similar to that in [6] and [10]. In the passive mode, the relay sets a proper load impedance to backscatter a part of the incident RF signals, while the other part is harvested as energy by the antenna. The backscattered signal can be exploited to enhance the signal transmission to the receiver [8]. As shown in Fig. 1(b), when the HAP beamforms the information signal to the relays, the relay-n can turn to the passive mode and backscatter the RF signals from the HAP directly to the receiver. By adapting the antenna's complex reflection coefficient, the passive relay can equivalently enhance the direct channel from the HAP to the receiver, as well as the channels from the other active relays to the receiver. Hence, the relay's mode switching introduces the performance tradeoff between the channel quality and multi-path diversity. Let $b_n \in \{0, 1\}$ be the binary variable indicating the radio mode of relay-n. Then the set of relays will be split into two subsets, i.e., $\mathcal{N}_a \triangleq \{n \in \mathcal{N} : b_n = 0\}$ and

$\mathcal{N}_b \triangleq \mathcal{N} \setminus \mathcal{N}_a$, denoting the set of active and passive relays, respectively. Let $\hat{\mathbf{f}}_0$ and $\hat{\mathbf{f}}_k$ for $k \in \mathcal{N}_a$ denote the enhanced channels from the HAP to the receiver and to the active relays, respectively. Due to the passive relays' backscattering, the enhanced channels can be represented as follows:

$$\hat{\mathbf{f}}_0 = \mathbf{f}_0 + \sum_{n\in\mathcal{N}_b} g_n \Gamma_n \mathbf{f}_n = \mathbf{f}_0 + \sum_{n\in\mathcal{N}} b_n g_n \Gamma_n \mathbf{f}_n, \tag{1}$$

$$\hat{\mathbf{f}}_k = \mathbf{f}_k + \sum_{n\in\mathcal{N}_b} z_{n,k} \Gamma_n \mathbf{f}_n = \mathbf{f}_k + \sum_{n\in\mathcal{N}} b_n z_{n,k} \Gamma_n \mathbf{f}_n, \tag{2}$$

where $z_{n,k}$ denotes the complex channel from the passive relay-n to the active relay-k, and Γ_n denotes the complex reflection coefficient of the passive relay-n. Thus, the enhancement to the channels $\hat{\mathbf{f}}_0$ and $\hat{\mathbf{f}}_k$ depends on not only the binary indicator $b_n \in \{0,1\}$, but also the complex reflection coefficient Γ_n of each passive relay in set $\mathcal{N}_b$.

III. Throughput Maximization via Hybrid Relaying Communications

To maximize the overall throughput performance, we aim to optimize the HAP's beamforming strategies $(\mathbf{w}_1, \mathbf{w}_2)$ in two hops, as well as the radio mode and PS ratio of each relay. It is clear that the optimization of the binary relay mode is complicated due to the combinatorial structure. In the following, we propose to solve the performance maximization problem in two steps. Firstly, assuming fixed relay modes, we evaluate the enhanced channels and formulate the throughput maximization problem with only active relays, similar to that in [15]. Secondly, with the fixed beamforming strategy, we evaluate individual relays' energy status or potential performance gain. This further motivates our algorithm design to update the relay mode in an iterative manner.

A. Throughput Maximization with Fixed Relay Mode

Given a fixed set $\mathcal{N}_b$ of passive relays and the reflection coefficients Γ_n, the enhanced channels for active RF communications are given as in (1) and (2). Then, we can formulate the throughput maximization problem with the active relays alone. Let $s \in \mathbb{C}$ denote the complex information symbol with unit power, delivered from the HAP to the receiver. The HAP's beamforming can be represented as $\mathbf{x}_s = \sqrt{p_t}\mathbf{w}_1 s$. Assuming normalized noise power, the SNR at the receiver in the first hop is given by $\gamma_1 = p_t|\hat{\mathbf{f}}_0^H \mathbf{w}_1|^2$, where $\hat{\mathbf{f}}_0^H$ is the Hermitian transpose of channel $\mathbf{f}_0$. Given the transmit signal $\mathbf{x}_s$, the signal at the relay-n is $m_n = \hat{\mathbf{f}}_n^H \mathbf{x}_s$, where $\hat{\mathbf{f}}_n$ denotes the enhanced channel from the HAP to the relay-n.

The HAP can adjust the information and power transfer to different relays by controlling the beamforming vector $\mathbf{w}_1$. Each active relay $n \in \mathcal{N}_a$ in the PS protocol can choose a different PS ratio ρ_n to balance its power supply and demand. Hence, the power budget constraint of the relay-n is given by $p_n \leq \eta\rho_n p_t|\hat{\mathbf{f}}_n^H \mathbf{w}_1|^2$, where η denotes the energy harvesting efficiency. The other part $1-\rho_n$ is sent to the signal detector and thus the received signal at the relay-n is given by

$$r_n = \sqrt{(1-\rho_n)p_t}\hat{\mathbf{f}}_n^H \mathbf{w}_1 s + \sigma_n = y_n s + \sigma_n,$$

where $y_n \triangleq \sqrt{(1-\rho_n)p_t}\hat{\mathbf{f}}_n^H \mathbf{w}_1$ and σ_n is the complex Gaussian noise with zero mean and normalized unit variance.

In the second hop, the active relays amplify and forward the information to the receiver. We define the power amplifying coefficient of each relay-n as $x_n \triangleq \left(\frac{p_n}{1+|y_n|^2}\right)^{1/2}$. Meanwhile, the HAP can transmit the same information directly to the receiver by using a new beamforming strategy $\mathbf{w}_2$. Hence, the received signal r_d at the receiver is a mixture of the HAP's direct beamforming and the relays' joint transmissions, i.e.,

$$r_d = \sum_{n=1}^{N} x_n \hat{g}_n y_n s + \sum_{n=1}^{N} x_n \hat{g}_n \sigma_n + \sqrt{p_t}\hat{\mathbf{f}}_0^H \mathbf{w}_2 s + v_d,$$

where the first two terms correspond to the amplified signals by the relays. The third term represents the direct beamforming from the HAP. The channel $\hat{g}_n$ is also an enhanced version of g_n, due to the passive relays' backscattering. Till this point, we can formulate the SNR in the second hop as follows:

$$\gamma_2 = \frac{\left|\sum_{n\in\mathcal{N}} x_n y_n \hat{g}_n + \sqrt{p_t}\hat{\mathbf{f}}_0^H \mathbf{w}_2\right|^2}{1 + \sum_{n\in\mathcal{N}} |x_n \hat{g}_n|^2}. \tag{3}$$

When direct links are present in both hops, the overall SNR is given by $\gamma = \gamma_1 + \gamma_2$ by using MRC at the receiver [15].

With the fixed relay mode, our target is to maximize γ by optimizing the HAP's beamforming strategies $(\mathbf{w}_1, \mathbf{w}_2)$ in two hops and the relays' PS ratios $\boldsymbol{\rho}$, subject to the relays' power budget constraints:

$$\max_{\boldsymbol{\rho}, \mathbf{w}_1, \mathbf{w}_2} \quad \gamma_1 + \gamma_2 \tag{4a}$$

$$s.t. \quad p_n \leq \eta\rho_n p_t |\hat{\mathbf{f}}_n^H \mathbf{w}_1|^2, \quad \forall\, n \in \mathcal{N}_a, \tag{4b}$$

$$\rho_n \in (0,1), \quad \forall\, n \in \mathcal{N}_a \tag{4c}$$

$$||\mathbf{w}_1|| \leq 1 \text{ and } ||\mathbf{w}_2|| \leq 1. \tag{4d}$$

However, the throughput maximization (4) is still challenging due to the non-convex coupling between different active relays in the objective (4a). The HAP's beamforming strategy $\mathbf{w}_1$ is also coupled with the relays' PS ratio $\boldsymbol{\rho}$ in a non-convex form via the power budget constraint (4b).

B. Lower Bound via Convex Reformulation

In the sequel, we provide a feasible lower bound on (4), which is achievable by designing the beamforming and relay strategies. To proceed, we can view the HAP as a virtual relay node, i.e., denoted as relay-0. By setting $\rho_0 = 0$ and $y_0 \triangleq \sqrt{p_t}\mathbf{f}_0^H \mathbf{w}_2$, we can rewrite the SNR in (3) as $\gamma_2 = \frac{(\mathbf{x}\circ\hat{\mathbf{g}})^H (\mathbf{y}\mathbf{y}^H)(\mathbf{x}\circ\hat{\mathbf{g}})}{(\mathbf{x}\circ\hat{\mathbf{g}})^H (\mathbf{x}\circ\hat{\mathbf{g}})}$, where $\mathbf{x}$ and $\hat{\mathbf{g}}$ are $(N+1)\times 1$ vectors with $x_0\hat{g}_0 = 1$. The symbol $\circ$ denotes the element-wise product between two vectors. Define $\mathbf{z} = \mathbf{x}\circ\hat{\mathbf{g}}$, and then $\gamma_2 = \mathbf{z}^H(\mathbf{y}\mathbf{y}^H)\mathbf{z}/||\mathbf{z}||^2$. By Reyleigh quotient [15], we have

$$\gamma_2 \leq p_t|\hat{\mathbf{f}}_0^H \mathbf{w}_2|^2 + p_t \sum_{n\in\mathcal{N}_a} (1-\rho_n)|\hat{\mathbf{f}}_n^H \mathbf{w}_1|^2. \tag{5}$$

The equality holds when $\mathbf{z} = c\mathbf{y}$ for some scalar c, and thus we have the following equality constraints:

$$p_t c^2 |\hat{\mathbf{f}}_0^H \mathbf{w}_2|^2 = 1, \tag{6a}$$

$$p_t c^2 |\hat{\mathbf{f}}_n^H \mathbf{w}_1|^2 = \frac{p_n |\hat{g}_n|^2/(1-\rho_n)}{1+(1-\rho_n)p_t|\hat{\mathbf{f}}_n^H \mathbf{w}_1|^2}, \quad \forall\, n \in \mathcal{N}_a. \tag{6b}$$

A feasible lower bound of the throughput performance can be found by maximizing $\gamma_1+\gamma_2$, subject to the constraints in (6). It is clear that we can obtain the scalar variable c from (6a) and then substitute it into (6b) to simplify the problem. Let $s_{n,1} \triangleq (1-\rho_n)|\hat{\mathbf{f}}_n^H \mathbf{w}_1|^2$ and then we have the following result.

Proposition 1: *A feasible lower bound on* (4) *can be found by the convex reformulation as follows:*

$$\max_{\bar{\mathbf{W}}_1, \mathbf{W}_1 \succeq \mathbf{0}} \quad p_t||\hat{\mathbf{f}}_0||^2 + p_t|\hat{\mathbf{f}}_0^H \mathbf{w}_1|^2 + p_t \sum_{n\in\mathcal{N}_a} s_{n,1} \tag{7a}$$

$$s.t. \quad \begin{bmatrix} \kappa_n\theta_n - (1+\theta_n)s_{n,1} & \sqrt{p_t}s_{n,1} \\ \sqrt{p_t}s_{n,1} & 1 \end{bmatrix} \succeq 0, \ \forall n \in \mathcal{N}_a \tag{7b}$$

$$\kappa_n \le \hat{\mathbf{f}}_n^H \mathbf{W}_1 \hat{\mathbf{f}}_n, \quad \forall n \in \mathcal{N}_a \tag{7c}$$

$$s_{n,1} = \hat{\mathbf{f}}_n^H \mathbf{W}_1 \mathbf{f}_n - \hat{\mathbf{f}}_n^H \bar{\mathbf{W}}_1 \hat{\mathbf{f}}_n, \quad \forall n \in \mathcal{N}_a, \tag{7d}$$

where $\theta_n \triangleq \eta p_t |\hat{g}_n|^2 ||\hat{\mathbf{f}}_0||^2$ *is a constant. At optimum, the PS ratio of relay-*n *is given by* $\rho_n = \frac{\hat{\mathbf{f}}_n^H \bar{\mathbf{W}}_1 \hat{\mathbf{f}}_n}{\hat{\mathbf{f}}_n^H \mathbf{W}_1 \hat{\mathbf{f}}_n}$ *for* $n \in \mathcal{N}_a$.

The proof of Proposition 1 follows a similar idea as that in [15]. With the fixed relay mode, the channel information $\hat{\mathbf{f}}_0$ and $\hat{\mathbf{f}}_n$ can be estimated by a training process. The objective function in (7a) then becomes linear and the constraints (7b)-(7d) define a set of linear matrix inequalities[1]. Hence, the resulting problem can be efficiently solved by semi-definite programming. Once we find the optimal matrix solution $\mathbf{W}_1$, we can retrieve the HAP's beamforming vector $\mathbf{w}_1$ by eigen-decomposition or Gaussian randomization method [15].

C. Iterative Update of Hybrid Relaying Strategy

In this part, we devise heuristic algorithms to update the hybrid relaying strategy based on the problem structure. In each iteration, we switch the operating mode of one relay node for simplicity. The basic idea of the iterative algorithm is to start from the special case with all active relays and then update the relay mode one by one depending on the relay's potential performance gain. Once we update the set of passive relays, we solve problem (4) one more time to update the HAP's beamforming strategy and the active relays' PS ratios. Such an iterative process continues until no further improvement can be achieved by changing the relay mode.

1) Evaluation of Performance Gain: The most straightforward idea is to search for the passive relay that can produce the maximum performance gain. Hence, the evaluation of performance gain becomes the critical part for the iterative algorithm design. To this end, we turn to problem (7) and study its solution structure. It is clear that (7c) will hold with equality at optimum and we can prove the following property.

[1]The constraint (7d) can be rewritten into two linear matrix inequalities.

Proposition 2: *At optimum, the solution to* (7) *is given by* $s_{n,1} = (\bar{\rho}_n\theta_n - 1)/p_t$ *, and the objective* γ *in* (7a) *is given by*

$$\gamma = p_t||\hat{\mathbf{f}}_0||^2 + p_t|\hat{\mathbf{f}}_0^H \mathbf{w}_1|^2 + \sum_{n\in\mathcal{N}_a} \left(\eta\bar{\rho}_n p_t |\hat{g}_n|^2 ||\hat{\mathbf{f}}_0||^2 - 1 \right), \tag{8}$$

where $\bar{\rho}_n \triangleq \frac{\rho_n}{1-\rho_n}$.

Proof: The proof of Proposition 2 can be simplified by rewriting the matrix inequality in (7b) as $(\kappa_n - s_{n,1})\theta_n \ge s_{n,1}(1+p_t s_{n,1})$, which is equivalent to

$$\bar{\rho}_n\theta_n \ge 1 + p_t s_{n,1}, \tag{9}$$

when the equality holds in (7c). Now we need to show that (9) holds with the equality at optimum. This can be proved by a contradiction. Assuming that (9) holds with strict inequality at optimum, we can always improve $s_{n,1}$ by decreasing individual's PS ratio ρ_n, as we have $s_{n,1} = (1-\rho_n)|\hat{\mathbf{f}}_n^H \mathbf{w}_1|^2$ by definition. Meanwhile, we note that $\bar{\rho}_n\theta_n$ in the LHS of (9) is an increasing function in ρ_n. This implies that we can improve $s_{n,1}$ and correspondingly the objective in (7a) by properly increasing ρ_n while still maintaining the feasibility of (9). This brings a contradiction. Hence, we can conclude that (9) holds with the equality at optimum. As such, we have $s_{n,1} = (\bar{\rho}_n\theta_n - 1)/p_t$ and simply rewrite (7a) into (8). ■

Proposition 2 implies that the performance gain of a passive relay can be evaluated by (8). With the fixed strategy $(\mathbf{w}_1, \boldsymbol{\rho})$, we can check the performance gain of each relay when it is switched to the passive mode. Thus, after iterating over all passive relays, we can switch the relay with the maximum performance gain to the passive mode. The complete solution procedure is listed in Algorithm 1. In line 6 of Algorithm 1, the optimization of the passive relay's complex reflection coefficient Γ_n is critical for the channel enhancement in (1) and (2). To maximize the relay performance, the passive relays can simply set the modulus of Γ_n to its maximum, however the complex phase of Γ_n is more difficult to optimize due to its couplings cross different relays. The independence of different channels makes it difficult to enhance all relay channels simultaneously. A straightforward approach is to quantize its feasible region into a finite set and then devise the one-dimension search algorithm for the optimal phase that maximizes the relay performance. Alternatively, as an approximation, we can simply align the phase of Γ_n to the direct channel $\hat{\mathbf{f}}_0$, as the signal beamforming on the direct channel can be much stronger than that over the relay channels.

2) Energy-based Hybrid Relaying Strategy: Note that the performance evaluation of γ_n for relay-n in (8) requires the channel information of all active relays in set $\mathcal{N}_a$. Thus, the γ-based hybrid relaying strategy in Algorithm 1 is still challenging for practical implementation due to the requirement for information exchange. As such, we also design a simply heuristic algorithm, namely, the energy-based hybrid relaying strategy, by the intuition that the backscatter radios can be more energy efficient than the active radios. With low energy supply, the active relay prefers to operate in the passive mode. With a fixed set of passive relays, the throughput maximization

Algorithm 1 γ-based Hybrid Relaying Strategy

Initialize $(\mathbf{w}_1, \rho_n)$ by solving (7) with all active relays
Update the SNR performance γ^t
while $\gamma^t > \gamma^{t-1}$
    Evaluate each relay's performance gain by (8)
    Choose the passive relay with maximum gain
    Optimize the relays'complex reflection coefficient
    Update the set of passive relays: $\mathcal{N}_b \leftarrow \mathcal{N}_b \cup \{n_p\}$
    Update enhanced channels by (1) and (2)
    Update $(\mathbf{w}_1, \rho_n)$ and evaluate γ^t by (7)
end while

can be formulated as the convex optimization problem in (4). After we determine the beamforming and relaying strategies, we can sort the active relays by the RF power harvested from the HAP, i.e., $p_n = \eta\rho_n p_t|\hat{\mathbf{f}}_n^H \mathbf{w}_1|^2$. Then, the heuristic algorithm will switch the active relay with the minimum RF power to the passive mode. We receive this update of relay mode if it indeed improves the throughput performance.

Alternatively, we can order the active relays by the RF power at the antenna multiplied by the channel gain $|\hat{g}_n|^2$ in the second hop, i.e., $q_n \triangleq p_t|\hat{g}_n|^2|\hat{\mathbf{f}}_n^H \mathbf{w}_1|^2$, which can be viewed as a characterization of the transmission performance in the passive mode. A higher value q_n implies that the relay can have better transmission performance as it turns into the passive mode. Hence, we can switch the active relay with the maximum q_n to the passive mode. In practice, both the energy budget p_n and the backscatter performance q_n can be considered jointly for the relay mode selection.

IV. Numerical Results

In the simulation, we consider 3 antennas at the HAP and $N = 3$ energy harvesting relays to verify the feasibility of the proposed algorithms. The distance in meters between the HAP and the receiver is $d_0 = 4$. The relays are randomly distributed in a circular region between the HAP and the receiver. The noise power density is -90 dBm and the bandwidth is 100 kHz. In each simulation run, we generate a set of 100 random locations for the relays and evaluate the average throughput performance at the receiver. The HAP's transmit power p_t in milliwatts ranges from 10 to 100. Unless otherwise stated, the energy harvesting efficiency is set by $\eta = 0.5$. The complex modulus of the reflection coefficients is set by $\Gamma = 0.5$. The complex phase can be properly turned according to the direct channel $\mathbf{f}_0$ from the HAP to the receiver. The path loss is modeled by the log-distance propagation model $L = L_0 + 10\alpha \log_{10}(d)$, where $\alpha = 2$ and $L_0 = 30$ dB. The phase of complex channel is randomly generated. The equivalent antenna gain at the transceiver is set to 15 dB. We assume that all channels are fixed and known via a training process at the beginning of each data transmission.

A. Throughput Comparison in Different Relaying Schemes

Figure 3 shows the throughput performance with multiple energy harvesting relays in the PS protocols. The solid lines correspond to the cases with all active relays. The dotted lines correspond to the throughput performance with the γ-based and the energy-based hybrid relaying strategies, denoted as γ-based HRS and energy-based HRS in Fig. 3, respectively. The common observation is that the throughputs in all strategies initially increase and then stabilize when the HAP further increases its transmit power p_t. When power supply becomes sufficient, the channel conditions become the throughput bottleneck that limits its further improvement. The throughput performances with and without direct links are both shown in Fig. 3. We can observe that the throughput obtained from the direct beamforming also contributes significantly to the overall performance, and thus it cannot be ignored in practice.

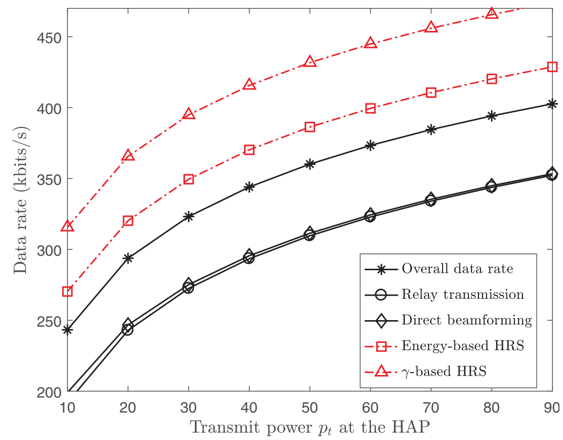

Fig. 3: Throughput comparison in different transmission schemes.

From the dotted lines in Fig. 3, we observe that both the γ-based and energy-based schemes significantly outperform the conventional relaying protocol with all active radios. The γ-based HRS is even better than the energy-based HRS. However, this improvement comes with the cost of higher computational complexity and communication overhead for information exchange. In general, both γ-based and energy-based schemes try to find the active relay with the worst channel conditions or energy status, and switch it to the passive mode with higher energy efficiency. Though a proof of optimality or performance guarantee is not available, our numerical results demonstrate that the proposed hybrid relaying strategies perform practically good and outperform the conventional relay strategies with all active radios.

B. Throughput Dynamics with Different Parameters

In this part, we focus on the throughput performance of the energy-based HRS due to its simplicity for implementation. As both the energy-based and γ-based HRS share the same design principle, we believe that the conclusions drawn for the energy-based HRS are also applicable to the γ-based HRS. In Fig. 4, we show the throughput dynamics of the energy-based HRS with different parameters, including the magnitude of the complex reflection coefficients and the number N of relays. We set $\Gamma = 0.5$ and $N = 3$ for the baseline case, in which we apply the energy-based HRS to determine the beamforming and the relaying strategies. Comparing to the baseline, we observe a clear drop in the throughput performance of the

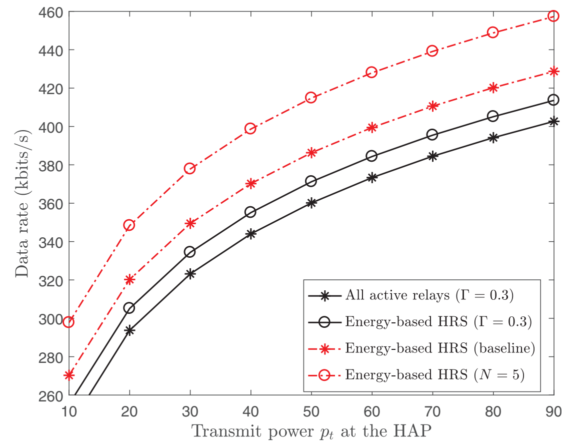

Fig. 4: Throughput comparison with different parameters

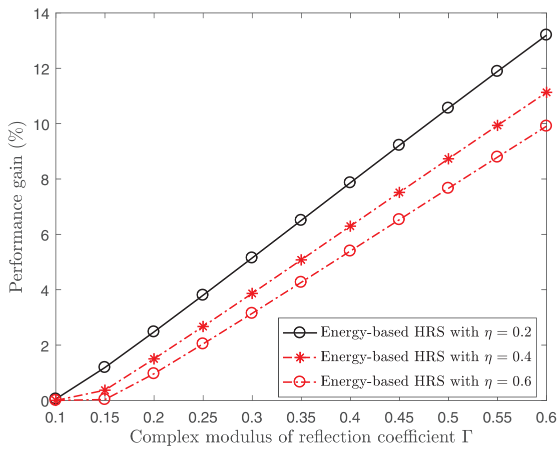

Fig. 5: The performance gain with different values for Γ and η.

energy-based HRS when we set a smaller value $\Gamma = 0.3$. This is reasonable and can be understood by the suppressed transmission capability in backscatter communications. A smaller reflection coefficient may be caused by the imperfection in load modulation or channel estimation. We further increase the number of relays to $N = 5$ and observe that the throughput performance can be significantly improved. With more relays, it is highly probable that some relays with worse transmission capability become the bottleneck. The energy-based HRS can significantly improve the performance by witching these relays to the passive mode.

The complex modulus of reflection coefficients has a great impact on the passive relays' transmission capability. Similarly, the efficiency η for energy harvesting is important for the energy harvesting active relays. In Fig. 5, we demonstrate the tradeoff between passive and active relays by showing the performance gain with different values for Γ and η, which is defined as the relative increase of throughput obtained by the energy-based HRS compared to the conventional protocol with all active relays. For any fixed η, we observe an increasing performance gain as we gradually increase the value of Γ. A similar observation has been made in Fig. 4. Moreover, we observe that the performance gain becomes more significant as the value η decreases, which implies the active relays are less efficient in energy harvesting.

V. Conclusions

In this paper, we have presented the formulations and algorithms to the throughput maximization problem involving both active and passive relays. We aim to jointly design the beamforming strategy at the source node, the energy harvesting and mode selection strategies at the relays. Though the throughput maximization is non-convex, with the fixed radio mode, we can find a feasible lower bound on throughput performance via convex approximation, which further motivates our algorithm design to update the hybrid relaying strategy. Simulation results have verified that the new design, taking account of both the direct links and hybrid relay communications, achieves much better performance gain compared to the conventional relaying protocol with all active relays. In our future work, we may consider using deep reinforcement learning based approaches to optimize the hybrid relaying strategy in a more complicated network environment.

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