Near Optimal Power Splitting Protocol for Energy Harvesting based Two Way Multiple Relay Systems

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Abstract—This paper proposes an optimized transmission scheme for Energy Harvesting (EH)-based two-way multiple-relay systems. All relays are considered as EH nodes that harvest energy from renewable and radio frequency (RF) sources, then use it to forward the information to the destinations. The power-splitting (PS) protocol, by which the EH node splits the input RF signal into two components for information transmission and energy harvesting, is adopted in the relay side. The objective is to optimize the PS ratios and the relays' transmit power levels in order to maximize the total sum-rate utility over multiple coherent time slots. An optimization approach based on geometric programming is proposed to solve the problem. Numerical results illustrate the behavior of the EH-based two-way multiple-relay system with respect to various parameters and compare the performance of the proposed approach with that of the dual problem-based approach.

Index Terms—Energy harvesting, power-splitting, two-way relaying.

I. INTRODUCTION

Two-way relaying (TWR) has lately attracted a great deal of interest due to its potential in achieving high throughput with low power consumption [1]. Unlike the typical One-way relaying (OWR) transmission approach, where four phases are needed to exchange different messages between two communicating terminals, TWR requires only two phases. In the first phase, the terminals transmit their signals simultaneously to relays which, in the second phase, broadcast the signal to the terminals using one of the relaying strategies, e.g., amplify-and-forward (AF) or decode-and-forward (DF). Finally, the terminals acting as receivers apply a self-interference cancellation operation to extract the desired data [2].

On the other hand, nowadays, there has been a considerable interest in energy harvesting (EH) technique as one of the most robust methods to perpetuate the lifetime and sustainability of wireless systems [3]. Many promising practical applications that can exploit this technique have been discussed recently,including emerging ultra-dense small cell deployments, point-to-point sensor networks, far-field microwave power transfer, and dense wireless networks [4].

One of the advantages of the EH technique is to power wireless devices located in remote or inaccessible areas, such as sensors placed in forests or mountains, where replenishing a new battery or recharging it using traditional wired techniques is not always possible. In addition, EH techniques, also known as energy scavenging techniques, enable networks' owners to behave green towards the environment [5] as the devices will be powered by non-polluting alternative sources such as solar, wind, thermoelectric, or vibration [6]. Recently, radio frequency (RF)-based EH, also known as wireless energy transfer, has been introduced as an effective harvesting technology where energy is collected from RF signals generated by other neighbor devices. Unlike other renewable energy (RE) sources, RF energy is widely available in the ambient atmosphere during all hours, days, and nights [3], [7].

Two protocols are proposed for RF-based EH [8]: 1) the time switching (TS) protocol, where the EH node switches over time between the energy harvester equipment and the information decoder, and 2) the power splitting (PS) protocol where a portion of the RF signal is used for EH and the remaining is used for information processing.

Most of the works existing in the literature investigated the RF-based EH for the traditional OWR technique [9], [10]. However, few studies dealt with RF-based EH with TWR and have mainly focused on the special case with one relay scheme. For instance, in [11], the authors studied the achievable throughput using a single RF-based EH relay using the TS protocol. The authors of [12] focused on RE-based EH scheme assuming that all nodes harvest energy only from RE sources. A power allocation solution for different relaying strategies is discussed.

In this framework, we investigate a hybrid RF/RE-based EH scheme using the PS protocol for two-way multiple-relay systems. With the AF scheme, the relays receive a superimposition of the terminals' signals and broadcast an amplified version of it to destinations. This allows a faster transmission without processing delay compared to other relaying strategies. The PS protocol is adopted in this paper as it outperforms the TS protocol mainly at high signal-to-noise ratio (SNR) regime as shown in [13]. We consider that relays are simultaneously powered through RF signals and RE sources. The objective of the framework is to maximize the total throughput of the EH TWR system over a certain number of time slots while respecting the power budget and the storage capacity constraints at each relay. This is performed by determining, for each relay, the fraction of signals to be harvested and the amplification gain to be allocated for the broadcast phase. Due to the non-convexity of the problem, we propose to employ a geometric programming (GP) technique allowing the achievement of a near-optimal solution to the problem [14].

The performance of the proposed approach is compared to that of the dual problem-based solution.

II. SYSTEM MODEL

We consider a half-duplex TWR system consisting of two terminals, denoted by S_1 and S_2, separated by a distance D. These two terminals aim to exchange information between each other through the help of multiple self-powered EH relays, denoted by $R_l, l = 1, .., L$, placed within the communication range of both terminals. The relays are placed within a circle centered in the middle of S_1 and S_2 with a radius equals to $\frac{D}{2}$ as shown in Fig. 3. We assume that S_1 and S_2 are not within the communication range of each other and each node is equipped with a single antenna. In the multiple access channel (MAC) phase, both S_1 and S_2 send their messages x_1 and x_2 simultaneously to R_l, $\forall l = 1, .., L$, with a power denoted by P_1 and P_2, respectively. In the broadcast channel (BC) phase, the relays amplify and broadcast the signal to the terminals.

A. Channel Models

We assume that the transmission will be performed in a finite period of time divided into B blocks of equal size, T_c, where T_c is the transmission time to exchange messages between S_1 and S_2.

We denote by $h_{1r_l,b}$ and $h_{2r_l,b}$ the channel gains during the bth block between S_1 and R_l and between S_2 and R_l, respectively, where $b \in [1, B]$. The channel gain between R_l and S_1 and between R_l and S_2 (i.e., reverse link channels) are denoted by $h_{1r_l,b}^*$ and $h_{2r_l,b}^*$, respectively, where $(.)^*$ is the conjugate operator. The communication channel between two nodes x and y of the TWR system at time block b is given by:

$$h_{uv,b} = \sqrt{d_{xy}^{-\alpha}} \tilde{h}_{xy,b}, \tag{1}$$

where d_{xy} is the Euclidean distance between the nodes x and y, α is a pathloss constant, and $\tilde{h}_{xy,b}$ is a fading coefficient with a coherence time T_c sec. Without loss of generality, all channel gains are assumed to be constant during the two transmission phases of TWR (i.e., one time block).

Although it is more important to investigate scenarios with causal channel state (i.e., the current and future channels are imperfectly known), in this study we consider a simpler scenario assuming non-causal channel state known through prediction [15]. The results obtained in this paper constitute an upper bound for realistic scenarios and they provide a good insight on the behavior of the system over the time. The analysis of imperfect channel state information scenarios are more elaborate and will be investigated in the future extension of this work. The transmitted signal power levels during each block b are given as $\mathbb{E}\left[|x_{1,b}|^2\right] = \mathbb{E}\left[|x_{2,b}|^2\right] = 1$, where $\mathbb{E}[\cdot]$ denotes the expectation operator.

B. Energy Harvesting Model

In this paper, two EH models are combined, i.e., the RE and RF models. We model the RE stochastic energy arrival rate as a random variable Φ Watt defined by a probability density
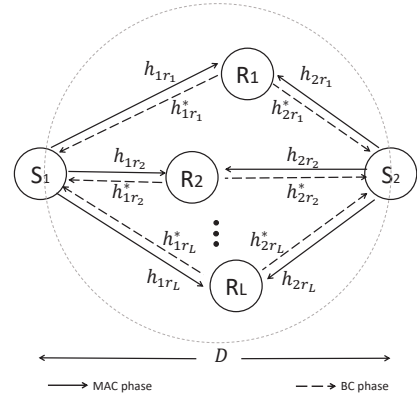

Fig. 1: System model of two-way relaying system.

function (pdf) $f(\varphi)$. For example, for photovoltaic energy, Φ can be interpreted as the received amount of energy per time unit with respect to the received luminous intensity in a particular direction per unit solid angle. By respecting the half-duplex RF EH constraint, each node cannot harvest from RF and transmit simultaneously. On the other hand, each relay can harvest from RE during the whole period T_c. Note that, the harvested energy is stored to be used in future time blocks.

In this paper, $\varphi_{r_l,b}$ represents the instantaneous amount of RE produced during block b at relay l. η^{RF} and η^{RE} denote the energy conversion efficiency coefficients of the RF and RE, respectively, where both η^{RF} and η^{RE} are in $[0, 1]$.

C. Relay Power Model

The total power consumption of a relay, denoted by $P_{r_l,b}^t$, can be computed as follows:

$$P_{r_l,b}^t = a_0 + \begin{cases} a_t P_{r_l,b}, & \text{for transmission,} \\ a_r, & \text{for reception,} \end{cases} \tag{2}$$

where a_0 is the offset of site power which is consumed independently of the transmit power and is due to signal processing, battery backup, and cooling. The coefficient a_t corresponds to the power consumption that scales with the radiated power due to amplifier and feeder losses, while a_r represents the consumed power due to the power reception. Finally, $P_{r_l,b}$ denotes the radiated power by relay r_l at a given time block b.

III. PROBLEM FORMULATION

In the MAC phase, the received signal at the lth relay during each T_c is given by:

$$y_{r_l,b} = \sqrt{P_1} h_{1r_l,b} x_{1,b} + \sqrt{P_2} h_{2r_l,b} x_{2,b} + n_{r_l,b}. \tag{3}$$

where $n_{r_l,b}$ is the sum of two noises: 1) the antenna additive Gaussian white noise (AWGN) at the lth relay during block b with variance $\mathcal{N}_r$ and, 2) the noise introduced by the signal processing circuit from passband to baseband and also assumed to be AWGN with zero mean and variance $\mathcal{N}_0$. In practice, the antenna noise has a negligible effect on the information signal and the average power of the received signal as well [16]. Hence, we ignore its impact in (3) (i.e., $\mathcal{N}_r \ll \mathcal{N}_0$).

In the PS protocol, before transforming the received signal from passband to baseband, the relay uses a part of it for
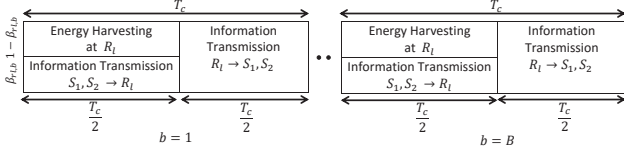
Fig. 2: The PS protocol during B blocks for one relay.

EH while uses the remaining part for information transmission. Let us assume that $\sqrt{1 - \beta_{r_l,b}}$ is the relay l PS ratio during the bth block, where $0 \leq \beta_{r_l,b} \leq 1$, such that $\sqrt{1 - \beta_{r_l,b}}(\sqrt{P_1}h_{1r_l,b}x_{1,b} + \sqrt{P_2}h_{2r_l,b}x_{2,b})$ corresponds to the part of RF signal that will be converted to a current, while the remaining part of the signal $\sqrt{\beta_{r_l,b}}(\sqrt{P_1}h_{1r_l,b}x_{1,b} + \sqrt{P_2}h_{2r_l,b}x_{2,b})$ is used for information processing as shown in Fig. 2. In this protocol, the transmission in each phase is performed during $T_c/2$.

The total harvested energy of the lth relay during block b, denoted by $E_{r_l,b}^h$, is given as follows:

$$
E_{r_l,b}^h = \left(\underbrace{(1 - \beta_{r_l,b}) \left[\eta^{\text{RF}} \left(P_1|h_{1r_l,b}|^2 + P_2|h_{2r_l,b}|^2 \right) \right] \frac{T_c}{2}}_{\text{EH from RF sources}} \right) + \underbrace{\left[\eta^{\text{RE}} \varphi_{r_l,b} \right] T_c}_{\text{EH from RE source}} . \tag{4}
$$

The stored energy at the end of block b at relay l, denoted by $E_{r_l,b}^s$, is given as follows:

$$
E_{r_l,b}^s = E_{r_l,b-1}^s + E_{r_l,b}^h - E_{r_l,b}^c - E_{le}, \tag{5}
$$

where $E_{r_l,b}^c$ corresponds to the consumed energy by relay l during block b due to information processing and is given as:

$$
E_{r_l,b}^c = a_0 T_c + \left[(a_r + a_t P_{r_l,b}) \frac{T_c}{2} \right], \tag{6}
$$

and E_{le} is the leakage energy within block b. Note that, initially, we assume that the battery of relay l may already have a certain amount of charge denoted by $B_{r_l,0}$ (i.e., $E_{r_l,0}^s = B_{r_l,0}$). During the BC phase, the relays amplify the received signal by multiplying it by the relay amplification gain denoted by $w_{r_l,b}$. Then, they broadcast it to S_1 and S_2. Hence, the received signals at S_1 and S_2 at block b are given as:

$$
y_{1,b} = \sum_{l=1}^{L} h_{1r_l,b}^* w_{r_l,b} (\sqrt{\beta_{r_l,b}} (\underbrace{h_{1r_l,b}\sqrt{P_1}x_{1,b}}_{\text{Self Interference}} + h_{2r_l,b}\sqrt{P_2}x_{2,b}) + n_{r_l,b}) + n_{1,b},
$$

$$
y_{2,b} = \sum_{l=1}^{L} h_{2r_l,b}^* w_{r_l,b} (\sqrt{\beta_{r_l,b}} (h_{1r_l,b}\sqrt{P_1}x_{1,b} + \underbrace{h_{2r_l,b}\sqrt{P_2}x_{2,b}}_{\text{Self Interference}}) + n_{r_l,b}) + n_{2,b}, \tag{7}
$$

where $n_{1,b}$ and $n_{2,b}$ are the AWGN noises with zero mean and variance $\mathcal{N}_0$ at the terminals S_1 and S_2, respectively. The

amplification gain at the relay l during b can be expressed as:

$$
\begin{aligned}
w_{r_l,b} &= \sqrt{\frac{P_{r_l,b}}{\beta_{r_l,b}(P_1|h_{1r_l,b}|^2 + P_2|h_{2r_l,b}|^2) + \mathcal{N}_0}}, \\
&\approx \sqrt{\frac{P_{r_l,b}}{\beta_{r_l,b}(P_1|h_{1r_l,b}|^2 + P_2|h_{2r_l,b}|^2)}}.
\end{aligned} \tag{8}
$$

In (8), we ignore the noise effect in the denominator [17]. Without loss of generality, this approximation simplifies the subsequent derivations without having a significant impact on the achieved results. Therefore, the TWR sum-rate during the block b can be expressed as $R_b = \frac{T_c}{2} \sum_{q=1}^{2} \log_2(1 + \gamma_{b,q})$ where the SNRs at the terminals S_q, $q \in \{1,2\}$ is given as follows:

$$
\gamma_{b,q} = \frac{P_{\bar{q}} \left(\sum_{l=1}^{L} w_{r_l,b} \sqrt{\beta_{r_l,b}} |h_{qr_l,b} h_{\bar{q}r_l,b}| \right)^2}{\mathcal{N}_0 \left(1 + \sum_{l=1}^{L} w_{r_l,b}^2 |h_{qr_l,b}|^2 \right)}, \tag{9}
$$

where $\bar{q} = 1$ if $q = 2$ and vice versa. Consequently, the optimization problem maximizing the TWR sum-rate, denoted by R, while satisfying the energy consumed and stored constraints for EH with PS protocol using AF strategy is given as:

$$
\underset{\boldsymbol{\beta}, \boldsymbol{P}_r \geq 0}{\text{maximize}} \quad R = \sum_{b=1}^{B} R_b \tag{10}
$$

subject to:

$$
E_{r_l,b}^c + E_{le} \leq E_{r_l,b-1}^s, \quad \forall l = 1,..,L, \forall b = 1,..,B, \tag{11}
$$

$$
E_{r_l,b-1}^s + E_{r_l,b}^h \leq \bar{E}^s, \quad \forall l = 1,..,L, \forall b = 1,..,B, \tag{12}
$$

$$
0 \leq P_{r_l,b} \leq \bar{P}_r, \quad \forall l = 1,..,L, \forall b = 1,..,B, \tag{13}
$$

$$
0 \leq \beta_{r_l,b} \leq 1, \quad \forall l = 1,..,L, \forall b = 1,..,B, \tag{14}
$$

where $\boldsymbol{\beta} = [\beta_{r_l,b}]_{L \times B}$, and $\boldsymbol{P}_r = [P_{r_l,b}]_{L \times B}$ are matrices containing the PS ratios, and the relay transmit power levels of each relay l at each block b, respectively. Constraint (11) ensures that the consumed energy during block b for any relay is always less than or equal to the stored energy at block $b-1$. Constraint (12) indicates that the energy stored at a relay cannot exceed the capacity of its super-capacitor at any time. Constraints (13) and (14) indicate the transmit power and PS ratio limits, respectively.

IV. GEOMETRIC PROGRAMMING METHOD

Due to the non-convexity of the optimization problem formulated in (10)-(14), we propose to optimize $\boldsymbol{\beta}$ and $\boldsymbol{P}_r$ using GP. We apply a successive convex approximation (SCA) approach to transform the non-convex problem into a sequence of relaxed convex subproblems [14], [18].

GP is a class of nonlinear and nonconvex optimization problems that can be efficiently solved after converting them to a nonlinear but convex problems [19]. The interior-point method can be applied to GP with a polynomial time complexity [19]. The standard form of GP is defined as the minimization of a posynomial function subject to inequality posynomial constraints and equality monomial constraints, where a monomial is defined as a function $f : \mathbf{R}_{++}^n \to \mathbf{R}$ where for each input

vector $\boldsymbol{\omega}$, we associate $f(\boldsymbol{\omega}) = \nu\omega_1^{c_1}\omega_2^{c_2}...\omega_n^{c_n}$, where ω_i are the elements of $\boldsymbol{\omega}$, ν is a non-negative multiplicative constant $\nu \geq 0$, and $c_i \in \mathbf{R}$, $i = 1,...,n$ are the exponential constants. A posynomial is a non-negative sum of monomials.

In general, GP in its standard form is a non-convex optimization problem because posynomials and monomials functions are not convex functions. However, with a logarithmic change of the variables, objective function, and constraint functions, the optimization problem can be turned into an equivalent convex form using the property that the logarithmic sum of exponential functions is a convex (see [19] for more details). From a relaxed GP, we propose an approximation to solve out the original non-convex problem. Therefore, for a given ϵ, we transform the objective function as follows:

$$\operatorname*{maximize}_{\boldsymbol{z} \geq 0} \sum_{b=1}^{B} R_b = \operatorname*{maximize}_{\boldsymbol{z} \geq 0} \frac{T_c}{2} \sum_{b=1}^{B} \sum_{q=1}^{2} \log_2(1 + \gamma_{b,q})$$

$$\equiv \operatorname*{minimize}_{\boldsymbol{z} \geq 0} \prod_{b=1}^{B} \prod_{q=1}^{2} \frac{1}{1 + \gamma_{b,q}}, \quad (15)$$

where $\boldsymbol{z} \triangleq [\boldsymbol{\beta}_r, \boldsymbol{P}_r]$. For notational convenience, let us define:

$$\delta_{r_l,b,q}^{(1)} \triangleq \frac{|h_{qr_l,b}|^2}{P_1|h_{1r_l,b}|^2 + P_2|h_{2r_l,b}|^2}, \quad (16)$$

$$\delta_{r_l,b,q}^{(2)} \triangleq \frac{|h_{qr_l,b}h_{\bar{q}r_l,b}|}{\sqrt{P_1|h_{1r_l,b}|^2 + P_2|h_{2r_l,b}|^2}}. \quad (17)$$

Hence, after simple manipulations, (15) can re-expressed as:

$$\operatorname*{minimize}_{z \geq 0} \prod_{b=1}^{B} \prod_{q=1}^{2} \frac{1}{1 + \gamma_{q,b}} \triangleq \operatorname*{minimize}_{z \geq 0} \prod_{b=1}^{B} \prod_{q=1}^{2} \frac{f_{r_l,b,q}(z)}{g_{r_l,b,q}(z)}, \quad (18)$$

where

$$f_{r_l,b,q}(z) = 1 + \sum_{l=1}^{L} \delta_{r_l,b,q}^{(1)} P_{r_l,b}\beta_{r_l,b}^{-1}, \quad (19)$$

$$g_{r_l,b,q}(z) = 1 + \sum_{l=1}^{L} \delta_{r_l,b,q}^{(1)} P_{r_l,b}\beta_{r_l,b}^{-1} + \frac{P_{\bar{q}}}{\mathcal{N}_0}\left(\sum_{l=1}^{L} \delta_{r_l,b,q}^{(2)}\sqrt{P_{r_l,b}}\right)^2. \quad (20)$$

It can be noticed from (18) that $f_{r_l,b,q}(z)$ and $g_{r_l,b,q}(z)$ are posynomials, however, their ratio is not necessary a posynomial. Therefore, in order to convert the objective function to a posynomial, we propose to apply the single condensation method to approximate the denominator posynomial $g_{r_l,b,q}(z)$ to a monomial function, denoted by $\tilde{g}_{r_l,b,q}(z)$, using the arithmetic-geometric mean inequality as a lower bound [14]. Given the value of z at the iteration $i-1$ of the SCA $z^{(i-1)}$, the posynomial $g_{r_l,b,q}$ that, by definition, has the form of $g_{r_l,b,q}(z) \triangleq \sum_{k=1}^{K} \mu_k(z)$, where $\mu_k(z)$ are monomials, can be approximated as:

$$g_{r_l,b,q}(z) \geq \tilde{g}_{r_l,b,q}(z) = \prod_{k=1}^{K} \left(\frac{\mu_k(z)}{\vartheta_k(z^{(i-1)})}\right)^{\vartheta_k(z^{(i-1)})}, \quad (21)$$

where $\vartheta_k(z^{(i-1)}) = \frac{\mu_k(z^{(i-1)})}{g(z^{(i-1)})}$. The upper limit of the product $K = (L+1)(L+2)/2$ corresponds to the total number of monomials in $g_{r_l,b,q}(z)$ given in (18). It can be seen that the objective function is now posynomial because posynomial over

monomial is posynomial and the product of posynomials is posynomial. Next, we apply the same approximations to the inequality constraints to obtain posynomials and fit into the GP standard form. Let us define the following:

$$\zeta_{r_l,b}^{(1)} \triangleq \left[\eta^{\text{RF}}\left(P_1|h_{1r_l,b}|^2 + P_2|h_{2r_l,b}|^2\right)\right]\frac{T_c}{2},$$

$$\zeta_{r_l,b}^{(2)} \triangleq \left[\eta^{\text{RF}}\left(P_1|h_{1r_l,b}|^2 + P_2|h_{2r_l,b}|^2\right)\right]\frac{T_c}{2} + \left[\eta^{\text{RE}}\varphi_{r_l,b}\right]T_c,$$

$$\theta_{r_l,b}^{(1)} \triangleq a_t\frac{T_c}{2}, \theta_{r_l,b}^{(2)} \triangleq a_0 T_c + \left[a_r\frac{T_c}{2}\right]. \quad (22)$$

Thus, $E_{r_l,b}^h$ and $E_{r_l,b}^c$ given in (4) and (6), can be, respectively, expressed as

$$E_{r_l,b}^h = -\zeta_{r_l,b}^{(1)}\beta_{r_l,b} + \zeta_{r_l,b}^{(2)}, \quad (23)$$

$$E_{r_l,b}^c = \theta_{r_l,b}^{(1)}P_{r_l,b} + \theta_{r_l,b}^{(2)}. \quad (24)$$

By expanding $E_{r_l,b-1}^s$, constraint (11) can be re-written as:

$$\frac{\sum_{t=1}^{b}(\theta_{r_l,t}^{(1)}P_{r_l,t} + \theta_{r_l,t}^{(2)} + E_{le} + \zeta_{r_l,t}^{(1)}\beta_{r_l,t})}{\sum_{t=1}^{b}\zeta_{r_l,t}^{(2)}} \leq 1, \quad \forall l, \forall b. \quad (25)$$

The equivalent constraint given in (25) is a posynomial since the denominator of (25) does not depend on neither $\beta_{r_l,b}$ nor $P_{r_l,b}$. Similarly, we can rewrite constraint (12) as follows:

$$\frac{\sum_{t=1}^{b}\zeta_{r_l,t}^{(2)}}{\bar{E}^s + \sum_{t=1}^{b-1}(\theta_{r_l,t}^{(1)}P_{r_l,t} + \theta_{r_l,t}^{(2)} + E_{le}) + \sum_{t=1}^{b}(\zeta_{r_l,t}^{(1)}\beta_{r_l,t})} \leq 1, \forall l, \forall b. \quad (26)$$

The equivalent constraint given in (26) is a posynomial over posynomial, which is not necessarily a posynomial. Therefore, we can use the approximation used in (21) to lower bound the denominator in (26). In this case, the upper limit of the product $K = 2b$ (i.e., total number of monomials in the denominator in (26)). We denote this approximation by $\tilde{v}_{r_l,b}(z)$. By considering the approximations of (26), we can formulate a GP approximated subproblem at the ith iteration of the SCA for the considered optimization problem given in (10)-(14) as follows:

$$\operatorname*{minimize}_{\boldsymbol{z} \geq 0} \quad \prod_{b=1}^{B} \prod_{q=1}^{2} \frac{f_{r_l,b,q}(z)}{\tilde{g}_{r_l,b,q}(z)} \quad (27)$$

subject to:

$$\frac{\sum_{t=1}^{b}(\theta_{r_l,t}^{(1)}P_{r_l,t} + \theta_{r_l,t}^{(2)} + E_{le} + \zeta_{r_l,t}^{(1)}\beta_{r_l,t})}{\sum_{t=1}^{b}\zeta_{r_l,t}^{(2)}} \leq 1, \quad \forall l, \forall b, \quad (28)$$

$$\frac{\sum_{t=1}^{b}\zeta_{r_l,t}^{(2)}}{\tilde{v}_{r_l,b}(z)} \leq 1, \quad \forall l, \forall b, \quad (29)$$

$$\frac{P_{r_l,b}}{\bar{P}_r} \leq 1, \quad \forall l = 1,..,L, \forall b = 1,..,B, \quad (30)$$

$$0 \leq \beta_{r_l,b} \leq 1, \quad \forall l = 1,..,L, \forall b = 1,..,B. \quad (31)$$

Hence, this optimization problem can be solved at each iteration of the SCA as given in Algorithm 1.

Algorithm 1 SCA Algorithm

1: i=1.
2: Select a feasible initial value of $\boldsymbol{z}^{(i)} = [\boldsymbol{\beta}_r^{(i)}, \boldsymbol{P}_r^{(i)}]$.
3: **repeat**
4:      i=i+1.
5:      Approximate the denominators of (18) and (26) using the arithmetic-geometric mean as indicated in (21) using $\boldsymbol{z}^{(i-1)}$.
6:      Solve the optimization problem (27)-(30) using the interior-point method to determine the new approximated solution $\boldsymbol{z}^{(i)} = [\boldsymbol{\beta}_r^{(i)}, \boldsymbol{P}_r^{(i)}]$.
7: **until** No improvement in the objective function.

In Algorithm 1, each GP in the iteration loop (line 3-7) tries to improve the accuracy of the approximations to a particular minimum in the original feasible region until no improvement can be made.

V. SIMULATION RESULTS

In this section, selected numerical results are provided to evaluate the performance of the PS protocol with multiple EH relays in TWR systems. S_1 and S_2 transmit their messages periodically every $T_c = 1$ ms for $L = 3$ relays and $B = 8$ time blocks. All the fading channel gains adopted in the framework are assumed to be independent and identically distributed (i.i.d) Rayleigh fading gains. The relays are randomly placed inside a circle centered in the middle of S_1 and S_2 with a distance $D = 50$ meters unless otherwise stated. The noise variance and the efficiency conversion ratios are set to be $N_0 = 10^{-8}$ W and $\eta^{\text{RF}} = \eta^{\text{RE}} = 0.9$, respectively. For simplicity, we assume that $P_1 = P_2 = P_s$. The relay power parameters are given as: $a_0 = 1.2$ W, $a_r = 1$ mW, and $a_t = 4$ mW [20]. At each relay, RE is assumed to be generated following a Gamma distribution with shape and scale parameters equal to 1 and 1.6, respectively. RE is generated such that the constant power consumption of the relays, i.e., namely a_0, is handled. In other words, the transmit power consumption is covered by the harvested RF energy in addition to the extra available RE. The total stored energy cannot exceed $\bar{E}^s = 5$ J and the battery leakage is set to be $E_{le} = 1$ mJ every b. A Monte Carlo simulation with 1000 iterations is performed to determine the average performance of the investigated TWR system.

In Table I, we study the behavior of the TWR system for a given channel realization with a relay power budget $\bar{P} = 20$ dBm and a source transmit power $P_s = 10$ dBm. In this table, we consider the total sum-rate as objective function and we compare its performance with that of a utility maximizing the minimum rate of all time blocks denoted by "max-min" utility. With the max-min utility, the problem is solved using the same approach employed in this paper, however, the corresponding derivations are omitted due to space limitation. The objective is to study in details the advantages and disadvantages of each utility function and the differences in the corresponding optimal power solution. It can be noticed that the use of max-min utility helps in avoiding low rates achieved in certain blocks with the sum utility such as the rates in blocks 1 and 2: $R_1 = 3.14$ bps/Hz and $R_4 = 2.06$ bps/Hz. However, this

Table I: Behavior of the relay selection scheme for $\bar{P}_r = 20$ dBm, and $P_s = 10$ dBm

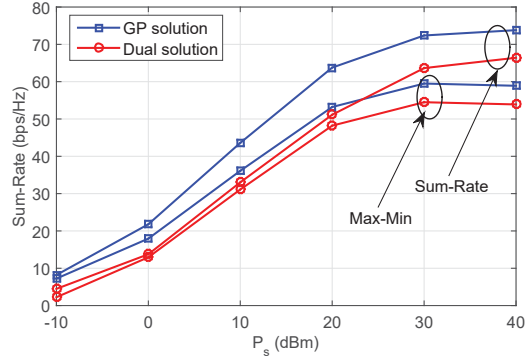|	Sum	Max-min
$\boldsymbol{R}$	[3.14, 5.08, 4.75, 2.06, 4.82, 9.51, 4.13, 9.04]	[4.15, 3.92, 3.91, 4.23, 4.51, 4.74, 4.43, 4.84]
$\sum_{b=1}^{B} R_b$	42.55	35.76

Fig. 3: A comparison between the proposed approach using GP and the dual problem-based solution. Achieved sum-rate versus the source power for $\bar{P}_r = 20$ dBm.

advantage is compensated by a lower total sum-rate over the blocks. With sum utility, the system prefers to harvest more RF energy in order to exploit it during next time slots to achieve higher rates. For instance, it achieves $R_6 = 9.51$ bps/Hz and $R_8 = 9.04$ bps/Hz with sum utility instead of $R_6 = 4.74$ bps/Hz and $R_8 = 4.84$ bps/Hz with the max-min one.

In Fig. 3, we compare between the performance of the two utility metrics by plotting the average sum-rate versus the terminals' power levels P_s for a TWR system transmitting messages for the same parameter used in Table I. The proposed approach is compared with the dual problem-based solution. Obviously, as P_s increases, the total sum-rate increases up to a certain value. In fact, increasing P_s allows relays to harvest more RF energy and, at the same time, contribute to the rate improvement. The average results in Fig 3 confirm those of Table I, the sum-rate utility reaches higher performance than that of the max-min one. On the other hand, we notice that an important gap has been achieved thanks to the use of the GP method instead of the dual method. Although GP is not optimal, it clearly achieves a near-optimal solution.

In Fig. 4, we investigate the impact of the relay power budget $\bar{P}_r$ on the achieved sum-rate using the proposed approach. Similar to Fig. 3, as $\bar{P}_r$ increases, the sum-rate increases up to a certain level where the TWR system becomes limited by the power budget at the sources. Furthermore, in Fig. 4, we compare the proposed approach with another suboptimal scenario where all $P_{r_l,b}$ are chosen to be fixed and constant ($P_{r_l,b} = \bar{P}_r$). This is performed to show the importance of the optimization of the relay transmit power levels simultaneously with the PS ratios and its impact on the reached sum-rate. We adopt the GP-based solution to optimize the PS ratios $\boldsymbol{\beta}_r$. For instance, for medium $\bar{P}_r$ regime, it is noticed that the simultaneous optimization of $\bar{P}_r$ and $\boldsymbol{\beta}_r$ outperforms the fixed $\boldsymbol{P}_r$ case by more than 4 bps/Hz when using sum-rate utility.
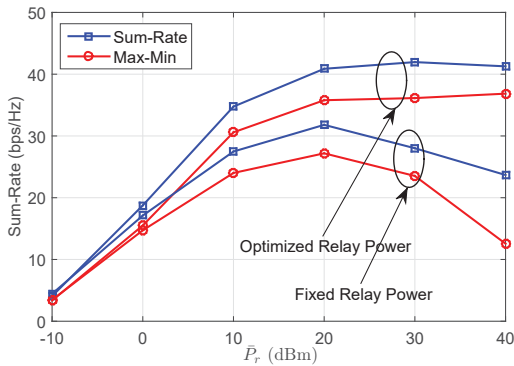
Fig. 4: A comparison between the proposed approach with relay power optimization and without relay power optimization (fixed power). Achieved sum-rate versus the relay power budget for $\bar{P}_s = 10$ dBm.
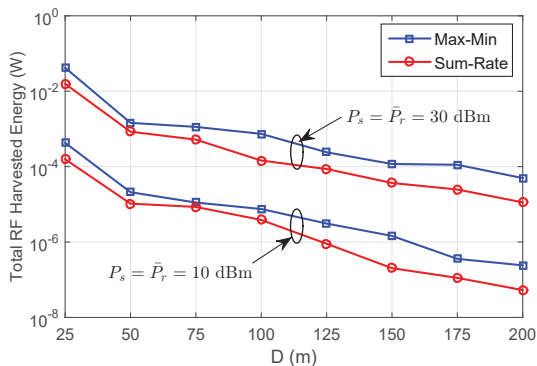

Fig. 5: Total RF harvested energy versus the distance D for different values of $\bar{P}_r = P_s$.

However, for high $\bar{P}_r$ regime, the sum-rate drops significantly with the fixed $\boldsymbol{P}_r$ case, while with the proposed approach, the achieved sum-rate remains constant. Indeed, for fixed $\boldsymbol{P}_r$, some of the relays are forced to transmit during the first blocks only in order to respect the storage constraint. This leads to non-optimized energy management and hence, the performance decreases.

Finally, we investigate the pathloss effect on the RF harvested energy by varying the distance D separating the sources from 25 to 200. As it is shown in Fig. 5, RF energy is no more available for power transmission as the harvested energy is almost zero. This confirms that RF energy harvesting can be applied only for short-range communications. Fig. 5 also shows that high levels of terminals' transmission power P_s helps in producing more RF energy.

VI. CONCLUSIONS

In this paper, we proposed an optimized a power splitting protocol-based energy harvesting scheme for two-way multiple-relays system. The relays simultaneously harvest energy from renewable energy sources and radio frequency signals. We formulated an optimization problem aiming at maximizing the total sum-rate over multiple time blocks. This is performed by jointly optimizing the relays' power levels and the PS ratios for each time block. Due to the non-convexity of the optimization problem, a geometric programming-based approach is developed. The proposed solution enables the

system to achieve near-optimal solutions with a significant gain compared to dual problem-based solution.

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