A Multi-Relay Selection Scheme for Time Splitting Energy Harvesting Two-Way Relaying Systems

Hakim Ghazzai[1], Ahmad Alsharoa[2], Ahmed E. Kamal[2], and Abdullah Kadri[1]
[1]Qatar Mobility Innovations Center, Doha, Qatar,
Email: {hakimg, abdullahk}@qmic.com
[2]Iowa State University (ISU), Ames, Iowa, United States,
Email: {alsharoa, kamal}@iastate.edu

***Abstract*—In this paper, a multiple relay selection scheme for Energy Harvesting (EH)-based two-way relaying is investigated. All the relays are considered as EH nodes that harvest energy from renewable and radio frequency sources, then use it to forward the information to the sources. The time-switching protocol (TS), in which the receiver switches between transmitted information and harvested energy, is adopted in the relay side. The goal is to find the optimal TS ratios associated with the selected relays that maximize a rate-based utility function over multiple coherent time slots. Two metrics reflecting the degrees of fairness in the optimization are investigated. A joint-optimization solution based on binary particle swarm optimization is proposed to solve the problem. Numerical results illustrate the behavior of the TWR network according to the considered utility functions, the generated amount renewable energy, in addition to other system parameters.**

***Index Terms*—Energy harvesting, multiple relay selection, time splitting, two-way relaying.**

I. INTRODUCTION

The energy saving is one of the critical research problems that has been discussed in green communication over the last few years [1]. Replenishing a new battery or recharging it using traditional wired charging method is not feasible always (e.g., sensors located on mountains or in forests).

Energy Harvesting (EH) has been considered as one of the most effective solution to protract the lifetime and sustainability of wireless networks [2]. Many promising practical applications that use EH nodes have been discussed recently, such as, emerging ultra-dense small cell deployments, point-to-point sensor networks, far-field microwave power transfer, and dense wireless networks [3]. EH has different types and models. A well-known type is the traditional EH technique based on Renewable Energy (RE) sources, such as solar, wind, thermoelectric, or vibration, that are employed to overcome the battery challenge problems [4]. Recently, EH based on Radio Frequency (RF) has been considered as a promising harvesting technology since it is widely available in the ambient atmosphere in all hours, days, and nights [5].

Two EH protocols are proposed in literature: Time Switching-based (TS) protocol and Power Splitting-based (PS) protocol [6]. In the former, the receiver switches over time between EH and information processing, while in the latter, a portion of the received signal is used for EH and the remaining for the information processing. Three energy harvesting and transmission schemes are proposed in the literature; Harvest-and-Use (HU), Harvest-Use-and-Store (HUS), and Harvest-Store-and-Use (HSU) [7]. In HU, the node uses the harvested energy without storing it for the future. In HUS, the harvested energy is immediately used, then the remaining energy is stored for future use. Finally, in HSU, the harvested energy is partially/totally stored before its use in the future.

Two-Way Relaying (TWR) has lately attracted a lot of attention due to its capacity in reducing the total energy of the network and achieving higher data rate [8]. In conventional TWR, exchanging different messages between two sources takes place into two phases only instead of four phases in the traditional One-Way Relaying (OWR). In the first phase, which is known as the Multiple Access (MA) phase, the sources simultaneously transmit their signals to the relay. Subsequently, in the second phase, which is known as the Broadcasting (BC) phase, the relays broadcast the signal to the sources. Finally, the sources apply a self-interference cancellation operation to extract the desired data [9]. In this framework, we are interested in a HSU TWR Amplify-and-Forward (AF) relaying scheme where the relay amplifies the received signal before broadcasting it to the destination. AF allows faster transmission without processing delay compared to other relaying schemes.

Several studies have discussed the RF EH technique with OWR [10]. The work in [11] proposed AF delay-limited and delay-tolerant transmission modes and analyzed the outage probability and the ergodic capacity for each mode. The work presented in [12] proposed continuous time and discrete time EH based on TS protocol. Single relay selection using RE EH OWR is discussed in [13]. However, few works discussed the EH with TWR. The work in [14] focused on deriving the RF TS throughput using AF relay without optimization the total EH throughput for TWR system, while the authors of [15] focused on RE EH assuming that all the nodes harvest energy from RE sources where the power allocation of all the nodes for different relaying strategies are derived.

In this paper, the TS protocol for generic TWR scheme using AF and combining RF and RE harvesting techniques is investigated. A multiple relay selection scheme that maximizes the achievable sum-rate is proposed for this TWR system which have not been discussed so far. We firstly derive the throughput expression for multiple relays TWR-AF for EH-TS protocol. Afterwards, we formulate an optimization problem that maximizes the throughput of EH TWR while taking into account the relay power consumption and the relay storage constraints. Due to the non-convexity of the problem, we perform a joint-optimization technique in order to determine

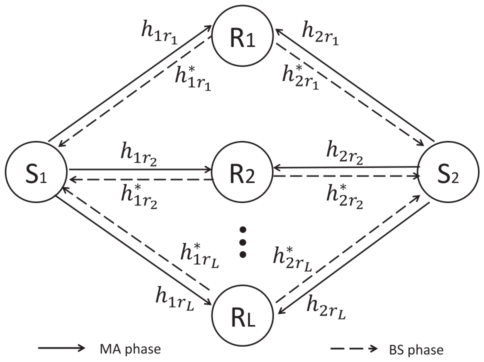

Fig. 1: System model of two-way relaying.

the time needed for energy harvesting per relays and the combination of active relays that are responsible in data transfer. A meta-heuristic approach based on Binary Particle Swarm Optimization (BPSO) algorithm is applied to find the AF relays selected for data transmission [16].

II. System Model

We consider a half-duplex TWR system where two battery-powered sources, denoted by S_1 and S_2, exchange information through the help of multiple self-powered EH relays, denoted by $R_l, l = 1, .., L$ as shown in Fig. 1. We assume that each node is equipped with a single antenna and that S_1 and S_2 are not within the communication range of each other. In the MA phase, both S_1 and S_2 transmit 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 BC phase, a set of relays are selected to broadcast the signal to the sources with a harvested power denoted by P_r (without loss of generality, it is assumed that all the selected relays have the same transmit power P_r).

The communication channel is assumed to be a block fading channel with a coherence time T_c sec. We consider a finite transmission period denoted by T sec divided into B blocks such that $T = B \times T_c$. Let T_c be the total time block or epoch length to exchange messages between S_1 and S_2 and let $h_{1r_l,b}$ and $h_{2r_l,b}$ be the channel gains during the b^{th} block between S_1 and R_l and between S_2 and R_l, respectively, where $b = 1, \cdots, B$. The reverse channel gain between R_l and S_1 and between R_l and S_2 are denoted by $h^*_{1r_l,b}$ and $h^*_{2r_l,b}$, respectively, where $(.)^*$ denotes the conjugate operator. Without loss of generality, all channel gains are assumed to be constant during the two transmission phases of TWR. Also, all noise variances are assumed to be equal to N_0 and the transmitted signals power during each block b $\mathbb{E}\left[|x_{1,b}|^2\right] = \mathbb{E}\left[|x_{2,b}|^2\right] = 1$, where $\mathbb{E}\left[\cdot\right]$ denotes the expectation operator.

A. Time Splitting Protocol

During each T_c, in MA phase, the received signal at the l^{th} relay is given by

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

where $n_{r,b}$ is the additive Gaussian noise at the l^{th} relay during block b. In TS protocol, only the selected relays spend a portion of T_c for EH and the remaining time for information transmission whereas the other relays spend the whole T_c for EH. Let α_b, $(0 < \alpha_b < 1)$, be the TS ratio during the b^{th} block. We assume that all selected relays have the same α_b for each block b due to synchronization reason (i.e., transmission and reception hold during the same duration for all transmitting relays and terminals $(1 - \alpha_b)T_c/2$) as shown in Fig. 2. This figure illustrates the TS protocol for TWR during the whole block B. Particularly, during $\alpha_b T_c$, the selected relays can harvest energy, while the remaining time $(1 - \alpha_b)T_c$ is used for communications. During the first $(1-\alpha_b)T_c/2$, information is transmitted from S_1 and S_2 to the selected relays (i.e., MA phase), while, during the second $(1 - \alpha_b)T_c/2$, the received signals are broadcast from the selected relays to S_1 and S_2 (i.e., the BC phase).

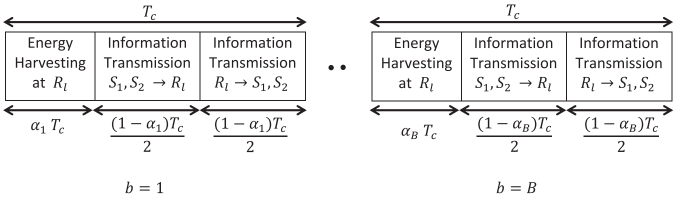

Fig. 2: Block diagram of the TS protocol during B blocks for one selected relay.

Note that the non-selected relays remain silent and harvest energy during the whole T_c including the RF signal coming from the selected relays in the second information processing slot. Later, it will be shown that the choice of the TS ratio affects the achievable sum-rate. In fact, increasing α_b allows the relays to harvest more energy in b^{th} block that will be employed in forwarding the received signals to the destination. However, this will reduce the allocated time to perform the whole transmission and vice versa. Therefore, an optimal choice of α_b is required in order to enhance the sum-rate.

B. Energy Harvesting Model

In this paper, two EH models are combined, i.e., the RE and RF models, for a HSU scheme. Super-capacitor is preferred for storage due to its high power density, good recycle ability and near perfectly [5]. We model the RE stochastic energy arrival rate as a random variable Φ Watt defined by a probability density 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. A binary variable, denoted by $\epsilon_{l,b}$, is introduced to indicate the status of each relay where $\epsilon_{l,b} = 1$ if the relay is selected to AF the signals, and $\epsilon_{l,b} = 0$, otherwise. By respecting the half-duplex constraint (i.e., each node can not harvest and transmit simultaneously), the total harvested energy of the l^{th} relay during block b for selected and non-selected relay, denoted by $E^h_{l,b}$, is given in (2), where η^{RF} and η^{RE} are the energy conversion efficiency coefficient of the RF and RE where $0 \leq \eta^{\text{RF}}, \eta^{\text{RE}} \leq 1$, $\varphi_{l,b}$ represents the instantaneous amount of RE produced during block b at relay l, and $\mathcal{J}_b$ is the set of selected relays during block b. Hence, the stored energy at the end of b block at relay l, denoted by $E^s_{l,b}$, is given as follows

$$E^s_{l,b} = E^s_{l,b-1} + E^h_{l,b} - \epsilon_{l,b} E^c_{l,b}, \tag{3}$$

$$E^h_{l,b} = \epsilon_{l,b}\Bigg(\underbrace{\left[\eta^{\text{RF}}\left(P_1|h_{1r_l,b}|^2 + P_2|h_{2r_l,b}|^2\right)\right]\alpha_b T_c}_{\text{RF EH from sources}} + \underbrace{\left[\eta^{\text{RE}}\varphi_{l,b}\right]\alpha_b T_c}_{\text{RE EH}}\Bigg) + (1-\epsilon_{l,b})\Bigg(\underbrace{\left[\eta^{\text{RF}}\left(P_1|h_{1r_l,b}|^2 + P_2|h_{2r_l,b}|^2\right)\right]\left(\frac{(1+\alpha_b)\,T_c}{2}\right)}_{\text{RF EH from sources}}$$

$$+ \underbrace{\eta^{\text{RF}}\sum_{j\in\mathcal{J}_b}\left[P_r|h_{r_l r_j,b}|^2\right]\left(\frac{(1-\alpha_b)\,T_c}{2}\right)}_{\text{RF EH from selected relays}} + \underbrace{\left[\eta^{\text{RE}}\varphi_{l,b}\right]T_c}_{\text{RE EH}}\Bigg). \tag{2}$$

where $E^c_{l,b}$ corresponds to the consumed energy during block b due to information processing and is equal to $\frac{P_r(1-\alpha_b)T_c}{2}$. Notice that the current stored energy depends on both the current harvested energy at block b and the previously stored energy during previous blocks. Therefore, the optimization of α_b and the active relays has to be performed in a one single shot every B blocks due to this energy dependency.

C. Sum-rate Expression for AF-TWR

We assume non-causal channel state which means that we know the current and future channels through prediction [13]. During the BC phase, the selected relays amplify the received signal $y_{r_l,b}$ by multiplying it by the relay amplification gain denoted by $w_{l,b}$ with fixed power P_r. 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, respectively, as

$$\begin{aligned} y_{1,b} &= \sum_{l=1}^{L}\epsilon_{l,b}h^*_{2r_l,b}w_{l,b}(\underbrace{h_{1r_l,b}\sqrt{P_1}x_{1,b}}_{\text{Self Interference}} \\ &\quad + h_{2r_l,b}\sqrt{P_2}x_{2,b} + n_{r_l,b}) + n_{1,b}, \\ y_{2,b} &= \sum_{l=1}^{L}\epsilon_{l,b}h^*_{2r_l,b}w_{l,b}(h_{1r_l,b}\sqrt{P_1}x_{1,b} + \\ &\underbrace{h_{2r_l,b}\sqrt{P_2}x_{2,b}}_{\text{Self Interference}} + n_{r_l,b}) + n_{2,b}, \end{aligned} \tag{4}$$

where $n_{1,b}$ and $n_{2,b}$ are the additive Gaussian noise at S_1 and S_2 during block b, respectively. The amplification gain at the relay r_l can be expressed as [17]

$$w_{l,b} = \sqrt{\frac{P_r}{P_1|h_{1r_l,b}|^2 + P_2|h_{2r_l,b}|^2 + N_0}}. \tag{5}$$

Since the channels are known perfectly at S_q, $q = \{1,2\}$, S_q can remove the self interference. Note that in the case when imperfect channel estimation is considered, self interference can still be applied, however, it will introduce an error related to the channel estimation that can be included in the noise. The investigation of the impact of the imperfect channel estimation on the system performance is left for a future extension of this work. Therefore, Signal-to-Noise Ratios (SNRs) at S_q, $q \in \{1,2\}$, in the b^{th} block is, respectively, given as follows

$$\gamma_{q,b}(\epsilon_{l,b}) = \frac{P_{\bar{q}}\left(\sum\limits_{l=1}^{L}\epsilon_{l,b}|w_{l,b}h_{qr_l,b}h_{\bar{q}r_l,b}|\right)^2}{N_0\left(1 + \sum\limits_{l=1}^{L}\epsilon_{l,b}|w_{l,b}h_{qr_l,b}|^2\right)}, \tag{6}$$

where $\bar{q} = 1$, if $q = 2$ and vice versa. Hence, the TWR sum-rate during a block b can be expressed

$$R_b(\alpha_b, \epsilon_{l,b}) = \frac{(1-\alpha_b)T_c}{2}\sum_{q=1}^{2}\log_2(1 + \gamma_{q,b}(\epsilon_{l,b})). \tag{7}$$

III. PROBLEM FORMULATION AND SOLUTION

The objective of this section is to formulate and solve an optimization problem that maximizes a sum-rate-based utility function while satisfying the energy consumption and energy stored constraints.

A. Optimization Problem

The optimization problem for TS protocol-based EH TWR system using AF is given as

$$\underset{\boldsymbol{\alpha},\boldsymbol{\epsilon}\geq 0}{\text{maximize}} \quad U\left(R_b\left(\alpha_b, \epsilon_{l,b}\right)\right), \tag{8}$$

subject to:

$$\epsilon_{l,b}E^c_{l,b} \leq E^s_{l,b-1} + E^h_{l,b},\ \forall l = 1,..,L, \forall b = 1,..,B, \tag{9}$$

$$E^s_{l,b-1} + E^h_{l,b} \leq \bar{E}^s,\ \forall l = 1,..,L, \forall b = 1,..,B, \tag{10}$$

$$0 \leq \alpha_b \leq 1,\ \forall b = 1,..,B, \tag{11}$$

$$\epsilon_{l,b} \in \{0,1\},\ \forall l = 1,..,L, \forall b = 1,..,B, \tag{12}$$

where $\boldsymbol{\alpha} = [\alpha_1,..,\alpha_B]_{L\times 1}$ is a vector containing the switching ratios during each block b and $\boldsymbol{\epsilon} = [\epsilon_{l,b}]_{L\times B}$ is a matrix containing the status of each relay at each block b. Constraint (9) ensures that the consumed energy during block b for any transmitting relay is always less than the stored energy. It means that the energy consumption during the first $(1-\alpha_b)T_c/2$ has to be less than the energy stored at the end of $\alpha_b T_c$ as indicates equation (2). Constraint (10) indicates that the energy stored at a relay can not exceed the capacity of its super-capacitor at any time. Finally, constraint (11) indicates the TS ratio limits.

B. Utility Selection

Two different utility metrics will be employed in the optimization problem (8)-(12).

Sum Utility: The utility of this metric is equivalent to the sum-rate of the network for all blocks: $U(R_b(\alpha_b, \epsilon_{l,b})) = \sum_{b=1}^{B} R_b(\alpha_b, \epsilon_{l,b})$ [18]. It promotes time blocks with favorable channel and energy conditions by allocating to them most of the resources, whereas time blocks suffering from poor channel conditions will be deprived from data transfer as they will have very low data rates.

Max-min Utility: Due to the unfairness of Sum utility, the need for more fair utility metrics arises. Max-min utilities are a family of utility functions attempting to maximize the minimum data rate in the network $U(R_b(\alpha_b, \epsilon_{l,b})) = \underset{b}{\min} R_b(\alpha_b, \epsilon_{l,b})$ [19]. By increasing the priority of time blocks having poorer channel conditions, Max-min utilities lead to more fairness in the system. In order to simplify the problem for this approach, we define a new decision variable $R_{\min} = \underset{b}{\min} R_b(\alpha_b, \epsilon_{l,b})$. Therefore, the optimization problem becomes

$$\underset{\boldsymbol{\alpha},\boldsymbol{\epsilon},R_{\min}\geq 0}{\text{maximize}} \quad R_{\min}, \tag{13}$$

subject to:

$$R_{\min} \leq R_b(\alpha_b, \epsilon_{l,b}), \forall b = 1, ..., B, \tag{14}$$

$$(9), (10), (11), \text{and } (12).$$

Note that Sum utility might lead to cases where there is no data transfer during certain time blocks. This is because the system might prefer to harvest the maximum of energy during these blocks and then use it in the next blocks in order to maximize the total rate. Max-min utility can be employed to avoid this unfairness among time blocks. If the user requires a certain minimum rate at each block b, Max-min utility impels the system to guarantee a non-negative rate at each block.

C. Proposed Solution

The formulated optimization problem is a non-convex problem and its optimal solution remains unsolved. For this reason, we propose to solve it using a joint optimization technique. First, we determine the optimal values of $\boldsymbol{\alpha}$ by assuming known and fixed relay selection matrix $\boldsymbol{\epsilon}$. By doing this, the formulated optimization problem is converted to a linear convex one and the optimal value of $\boldsymbol{\alpha}$ can be determined. Then, a BPSO is employed to jointly optimize the TS ratios and the selected relays.

The BPSO idea was introduced in 1997 [16] and it is inspired by swarm intelligence, social behavior, and food searching by a flock birds and a school of fish. Due to the following advantages of BPSO compared with the other heuristic approaches, we apply it for solving this problem: (i) simple search process and easy to implement by manipulating few numerical parameters (e.g., such as the number of particles and acceleration factors for BPSO) (ii) it requires low computational cost attained from small number of agents; and (iii) it provides a good convergence speed [20].

For fixed $\boldsymbol{\epsilon}$, the optimization problem becomes a linear programming problem with B and $B+1$ unknowns for Sum and Max-min utilities, respectively [21] and its solution can be easily determined using the Matlab toolbox CVX [22]. In order to optimize the matrix $\boldsymbol{\epsilon}$ of size $L \times B$, an exhaustive search can be employed to find the optimal selected relays combination. However, this will require a high computational complexity mainly for large-scale problems (i.e., about 2^{LB} tests). Therefore, lower complexity heuristic approaches such as BPSO can be exploited to reach suboptimal solutions. The BPSO starts by generating T particles $\boldsymbol{\epsilon}^{(t)}$, $n = 1 \cdots T$ of size $L \times B$ to form an initial population $\mathcal{S}$. Then, it computes the utility achieved by all particles by solving the optimization problem using CVX (either for Sum or Max-min utility) and finds the particle that provides the global optimal utility for this iteration, denoted by $\boldsymbol{\epsilon}^{\max}$. In addition, for each particle t, it maintains a record of the position of its previous best performance, denoted by $\boldsymbol{\epsilon}^{(\text{t,local})}$. Then, at each iteration i, BPSO computes a velocity term $V_{l,b}^{(t)}$ as follows:

$$V_{l,b}^{(t)}(i) = \Omega V_{l,b}^{(t)}(i-1) + \psi_1(i)\left(\epsilon_{l,b}^{(\text{t,local})}(i) - \epsilon_{l,b}^{(t)}(i)\right) + \psi_2(i)\left(\epsilon_{l,b}^{\max}(i) - \epsilon_{l,b}^{(t)}(i)\right) \tag{15}$$

where Ω is the inertia weight and ψ_1 and ψ_2 are two random positive numbers ($\psi_1, \psi_2 \in [0, 2]$) generated for each iteration i [16]. Then, it updates each element i of a particle $\boldsymbol{\epsilon}^{(t)}$ as follows:

$$\epsilon_{l,b}^{(t)}(i+1) = \begin{cases} 1 \text{ if } r_{\text{rand}} < \Phi\left(V_{l,b}^{(t)}(i)\right), \\ 0 \text{ otherwise.} \end{cases} \tag{16}$$

where r_{rand} is a pseudo-random number selected from a uniform distribution in $[0, 1]$ and Ψ is a sigmoid function for transforming the velocity to probabilities and is given as:

$$\Psi(x) = \frac{1}{1 + e^{-x}}. \tag{17}$$

This process is repeated until reaching convergence either by attaining the maximum number of iterations or by stopping the algorithm when the achievable utility remains constant after a several number of iterations. Details of the algorithm are given in Algorithm 1.

Algorithm 1 BPSO for TS-based EH TWR using AF

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Generate an initial population $\mathcal{S}$ composed of $T$ random particles $\boldsymbol{\epsilon}^{(t)},\ t = 1 \cdots T$.
while Not converged do
    for $t = 1 \cdots T$ do
        Find $\boldsymbol{\alpha}^{(t)}$ by solving optimization problem (8)-(11) for particle $t$ using CVX.
        Compute the corresponding utility $U^{(t)}(i)$.
    end for
    Find $(t_m, i_m) = \arg\max_{l,i} U^{(t)}(i)$ (i.e., $t_m$ and $i_m$ indicate the index and the position of the particle that results in the highest utility). Then, set $U_{\max} = U^{(t_m)}(i_m)$ and $\boldsymbol{\epsilon}^{\max} = \boldsymbol{\epsilon}^{(t_m)}(i_m)$.
    Find $i_t = \arg\max_{i} U^{(t)}(i)$ for each particle $t$ (i.e., $i_t$ indicates the position of the particle $t$ that results in the highest local utility). Then, set $U_{(\text{t,local})} = U^{(t)}(i_t)$ and $\boldsymbol{\epsilon}^{(\text{l,local})} = \boldsymbol{\epsilon}^{(t)}(i_t)$.
    Adjust the velocities and positions of all particles using equation (16).
    $i = i + 1$.
end while
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IV. SIMULATION RESULTS

In this section, numerical results are presented to demonstrate the performance of the investigated TS protocol with multiple EH relays in TWR systems. The transmission between S_1 and S_2 is generated periodically with time length $T_c = 1$ for $B = 10$ 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 noise variance and the conversion ratios are set to $N_0 = 0.001$ and $\eta^{\text{RF}} = \eta^{\text{RE}} = 0.9$, respectively. In the sequel, we assume that $P_1 = P_2 = P_s$. The renewable energy at each relay is assumed to be generated following a Gamma distribution

Table I: Behavior of the relay selection scheme with optimized TS ratios versus the used utility metrics

	Sum Utility	Max-min Utility
$\boldsymbol{\alpha}$	[0.6, 0.5, 0.24, 0.9, 0.73, 0.1, 0.03, 0, 0.03, 0]	[0.42, 0.5, 0.48, 0.44, 0.61, 0.39, 0.46, 0.31, 0.39, 0.65]
$\boldsymbol{\epsilon}$	$\begin{bmatrix} 0\,1\,0\,1\,1\,1\,1\,0\,1\,1 \\ 1\,0\,0\,0\,1\,1\,0\,1\,1\,1 \\ 1\,0\,1\,1\,1\,0\,0\,1\,1\,0 \end{bmatrix}$	$\begin{bmatrix} 0\,1\,0\,0\,1\,0\,0\,1\,1\,0 \\ 0\,0\,0\,1\,1\,1\,1\,1\,0\,1 \\ 1\,0\,1\,1\,0\,0\,1\,1\,1\,0 \end{bmatrix}$
$\boldsymbol{R}$	[1.61, 2.19, 2.01, 0.22, 0.93, 3.75, 3, 77, 4.2, 4.36, 5.04]	[2.16, 2.19, 1.37, 1.37, 1.52, 2.21, 2.1, 2.86, 2.22, 1.62]
$\sum_{b=1}^{B} R_b$	28.2	19.65

with shape parameter $k = 0.5$ and scale parameter $\theta = 1$ and the total stored energy cannot exceed $\bar{E}^s = 1$ Joules. A Monte Carlo simulation is performed to determine the average performance of the investigated TWR system with the two considered utility metrics using the BPSO-based solution proposed in Section III-C. The BPSO is executed with the following parameters: $T = 12$ and $\Omega \in [0, 1]$ is a linear decreasing function of the BPSO iterations expressed as follows: $\Omega = 0.9 - \frac{t(0.9-0.2)}{\mathcal{I}}$, where $\mathcal{I}$ is the maximum number of iterations.

In Table I, we study the behavior of the TWR system equipped with $L = 3$ relays for a given channel realization and fixed relay power $P_r = 20$ dBm. P_s is set to be equal to 20 dBm. The objective is to study in details the advantages and disadvantages of each utility function and the differences in the decision variables for both utilities. It can be noticed that the use of the Max-min metric can help in avoiding low rates achieved in certain blocks with the Sum utility such as the rates in blocks 4 and 5: $R_4 = 0.22$ bps/Hz and $R_5 = 0.93$ bps/Hz. Thanks to the fairness level obtained with Max-min utility, these rates are enhanced since the objective is to maximize the minimum rate. Nevertheless, the Sum utility allows the system to achieve higher sum-rates as it is not focusing on the rate per each block. A deeper look at the optimized decision variables, i.e., TS ratios and active relays, shows the reaction of the system depending on the channel conditions per each block. Notice that, with the Sum utility, the strategy is to simultaneously harvest the maximum amount of energy while keeping active the relays even if this leads to low rates in certain blocks. In other words, the system keeps active the relays to transmit data during $1-\alpha_b$ but sets $\alpha_b \rightarrow 1$ for blocks with bad conditions ($b = 4, 5$). This is performed in order to use the harvested energy in next time slots to achieve higher rates ($b = 9, 10$). Indeed, we can see that in the rest of the blocks $b = 6, \cdots, 10$, the energy harvested is extremely low for the active relays (as $\alpha_b \rightarrow 0$). This lack of harvested energy is sometimes compensated by turning off higher number of relays ($b = 7$) depending on the system needs. A final remark concerns the Max-min metric. We notice that the achieved rates in each block are almost close to each other, this is due to the optimized values of α_b which are around 0.5 ($[0.31, 0.65]$).

In Fig. 3 and Fig. 4, we plot the achieved sum-rate for both utility functions while varying the value of the relays transmit power P_r, for different terminals power levels $P_s = 10, 20$ dBm, and different number of relays $L = \{3, 6\}$, respectively. It is shown that while increasing P_r, the sum-rate increases up to a certain value of P_r (this value depends on the parameters L and P_s). Then, it starts to decrease. This decrease is explained by the fact that by having high value of P_r, the selected relays at block b need to spend more time for harvesting (i.e., higher α_b's) in order to transmit with this value of P_r. As a result, the time for information processing is reduced, hence, the sum-rate is reduced. Therefore, optimizing the value of P_r in addition to $\boldsymbol{\alpha}$ and $\boldsymbol{\epsilon}$ represents an interesting extension of this work (see [23] for more details). On the other hand, as expected, it is noticed that the Sum utility achieves better sum-rate than the Max-min utility in all cases and increasing L enhances the system performance as additional relays provide more flexibility to the system to decide whether to turn off a relay or to transmit according to the channel conditions. Higher values of P_s also improve the total sum-rate for two reasons (i) they enhance the system's SNRs (see equation (6)) and (ii) allow the system to allocate more time for the data transfer since higher values of P_s lead to reduced values of α_b (see equation (2)).

Finally, in Fig. 5(a), we investigate the effect of the harvested renewable energy on the system performance by varying the parameter k for different values of storage capacity

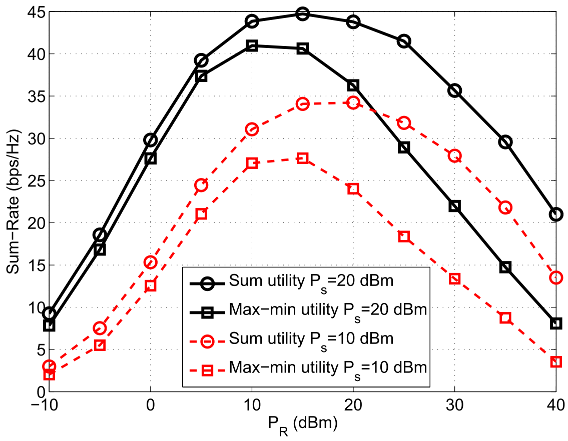


Fig. 3: Achieved sum-rate using Sum and Max-min utilities versus the relay power P_r for $L = 3$.

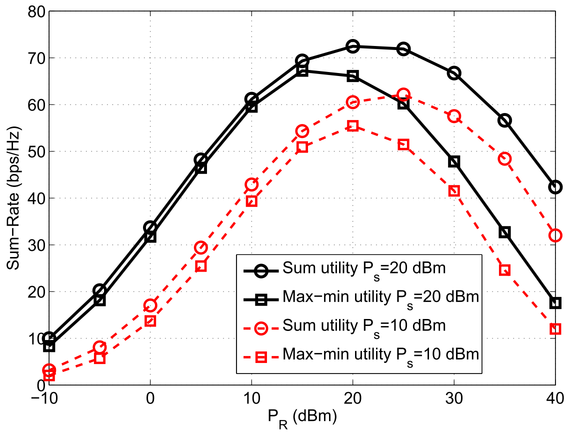
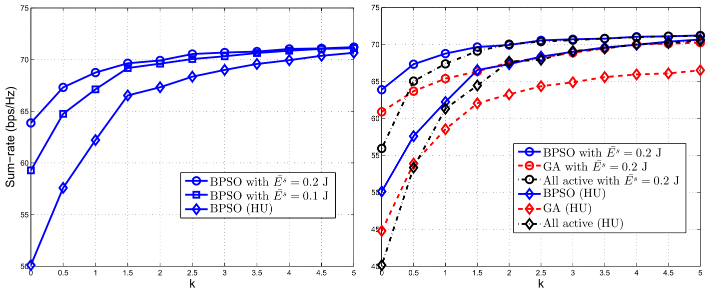


Fig. 4: Achieved sum-rate using Sum and Max-min utilities versus the relay power P_r for $L = 6$.



(a) (b)

Fig. 5: Achieved sum-rate using Sum utility using the BPSO and GA algorithms versus the renewable energy parameter k for $L = 4$ and different values of $\bar{E}^s$ (a) Effect of storing capacity (b) Comparison with GA and all active scenario.

(i.e., $\bar{E}^s = 0, 0.1, 0.2$ J), $L = 4$, and $P_s = 20$ dBm and using the Sum utility. Note that, when $\bar{E}^s = 0$, we are considering the harvest-and-use (HU) scenario and, when $k = 0$, the system is only powered by RF. As expected, the sum-rate is enhanced as $\bar{E}^s$ and renewable energy becomes more available. However, we notice that, for $\bar{E}^s > 0$, the storing capacity has an impact on the system performance up to a certain value of $k \approx 1.5$. We deduce that the energy harvested during α_b is enough to achieve the maximum sum-rate as it is remaining almost constant for high values of k. So, it is useless to store additional harvested energy as the achieved sum-rate with $\bar{E}^s = \{0.1, 0.2\}$ J are almost equal. Compared to the HU scenario, we notice that the HSU presents a certain gain in terms of achievable sum-rate mainly for RF-based schemes where the gain is around 16%. In Fig. 5(b), we also compare the performance achieved by BPSO to those achieved by the Genetic Algorithm (GA) and the all active schemes where all the relays are kept active. The results show that BPSO significantly outperforms both schemes. However, the performance of BPSO and all active scenario coincide for high values of k. This means that, starting from this value, the optimal solution is to keep all the relays active since the harvested energy before transmission during α_b is sufficient. Hence, there is no need to turn off the relays to harvest energy in next blocks.

V. CONCLUSION

In this paper, we proposed a multiple relay selection scheme for TS protocol-based energy harvesting two-relaying system. The relays harvest energy from renewable and radio frequency sources. We formulated an optimization problem aiming to maximize rate-based utility functions over multiple time blocks. Two utility functions are employed according to the need of the user: the Sum utility and the Max-min utility. After solving the problem using a joint-optimization approach, we investigated, via numerical results, the behavior of the proposed scheme versus various system parameters.

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