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Relay Selection Strategies for SWIPT-Enabled Cooperative Wireless Systems

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***Abstract*—In this paper, we study a problem of relay selection in a two-hop relaying network where the destination is equipped with Simultaneous Wireless Information and Power Transmission (SWIPT) capabilities. In contrast to conventional cooperative networks, the destination node is considered to be capable of simultaneously decoding information and harvesting energy from both the source and the relay transmissions. In this context, we formulate two optimization problems for both *time switching (TS)* and *power splitting (PS)* based SWIPT schemes. The first problem is the maximization of the overall user data rate while ensuring a minimum harvested power. The second problem focuses on the maximization of the overall harvested power at the user under the constraint on the minimum achievable rate. Assuming an amplify-and-forward (AF) relay protocol, closed-form solutions are obtained for the selection of an optimal relay, relay amplification coefficient and the optimal time or power splitting factor. The performance of the proposed relay selection strategies with the aforementioned objectives is evaluated and compared with the case of random relay selection. Furthermore, the Rate-Energy (R-E) tradeoff performance of the scenario with both the direct and indirect relay-assisted links is compared to the case where only a relay-assisted link is available. Our simulation results demonstrate the significant benefits of combining direct and indirect links in SWIPT-enabled cooperative networks in terms of the R-E tradeoff.**

I. Introduction

The next generation of wireless applications like wearable devices, smart-phones or connected cars, has posed significant challenges in terms of capacity and performance demands. This is particularly challenging for the devices placed at a large distance from the transmitter, which usually suffer from uncertainity in the channel conditions and other physical phenomenon. On the other hand, the number of wireless devices is continuously and rapidly increasing, and it could reach to more than 50 billion connected devices by the end of year 2020 [1]. In this context, cooperative relaying has emerged as a promising technique to improve coverage and overall throughput [2], [3].

As the node density increases, various devices can act as relays to forward traffic from the transmit source to the far distant node and vice-versa. Within the network of relays, each relay may employ different kinds of cooperative strategies [4]. Two widely adopted cooperative strategies in the wireless relay networks are *regenerative* (e.g., decode-and-forward (DF) [5]), and *non-regenerative* (e.g., amplify-and-forward (AF) [6]). Due to the independence of choosing modulation schemes at the source terminal and its easy implementation, a non-regenerative relaying strategy stands out as a promising alternative [7], [8], and is hence considered in this paper.

In addition to improving availability and traffic capacity, another key objective of future wireless networks is to maximize power efficiency. Performing information reception and Radio Frequency (RF) energy harvesting simultaneously from the same RF input signal has gathered considerable attention over the last few years [9]. This approach is referred in the literature as Simultaneous Wireless Information and Power Transfer (SWIPT) [10], [11]. Using SWIPT, the receiver can act as an information decoder as well as an energy receiver by either considering time-switching (TS) or power splitting (PS) technologies.

Extending the range of communication systems may cause hindrance in establishing SWIPT due to limitations and constraints like the size and cost of devices, and power decay over the wireless medium. In this context, relaying plays an important role in achieving SWIPT. In order to enhance the rate-energy (R-E) trade-off [12], the relays can provide additional advantage for improving the SWIPT performance [13]. More specifically, optimal relay selection is one of the means to benefit from multiple relays to support SWIPT [14].

In this paper, we investigate the relay selection problem in cooperative wireless systems when the final receiver is equipped with SWIPT capabilities. The relay selection problem without power constraints has been investigated in [15], [16], and in [17], [18] considering power harvesting at the relay nodes, but without considering the demanded harvested power at the receiver. Unlike the aforementioned works, in this paper, we consider optimal relay selection for SWIPT along with the computation of the optimal relay amplification coefficient and optimal splitting factor considering power harvesting constraints at the receiver. This paper extends the authors' previous work [19], where only a two-hop relay link was considered. Herein, we consider the direct

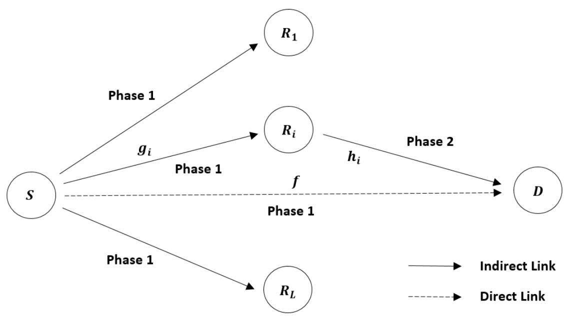


Fig. 1: System model for the proposed architecture.

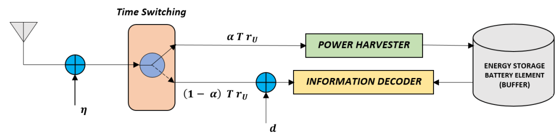


Fig. 2: Receiver architecture based on TS Scheme

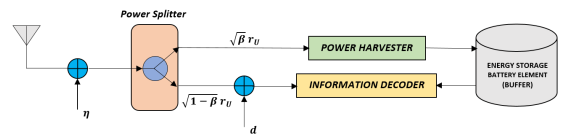


Fig. 3: Receiver architecture based on PS Scheme

link between the source and the destination on top of the relay-assisted link in the problem formulation, which we show that cannot be neglected unless its channel is severely affected by fading.

To overcome the well-known R-E trade-off, we formulate two optimization problems for both TS and PS SWIPT schemes. While the first one maximizes the transmission rate subject to a harvested power constraint, the second one maximizes the harvested power subject to throughput requirements. We provide closed-form solutions to both problems, and subsequently we evaluate their performance via simulation results.

The remainder of this paper is organized as follows. Section II presents a description of the system model. Section III focuses on the overall user rate maximization under user harvested power constraints while Section IV addresses the maximization of the total harvested power under user rate constraints. Section V presents the simulation results. Finally, Section VI concludes the paper.

II. System Model

We consider a cooperative wireless network with a single source, L non-regenerative relays, and a single destination. The source communicates to the destination via two communication links. In particular, besides the conventional direct link, we assume the availability of a relay-assisted link which assists the direct link to deliver the desired signal, as depicted in Fig. 1. The destination is assumed to be able to perform both information decoding and power harvesting simultaneously according to either a TS or PS SWIPT architecture, which are illustrated in Fig. 2 and Fig. 3, respectively.

The overall transfer of data and power takes place in two phases. In the first phase, the source broadcasts its information to the relays and the destination, while in the second phase the selected relay amplifies and forwards the signal to the destination. It should be noted that we consider indirect link communication only via the selected relay, and not through all the relays. In the following subsections, we provide the signal models for the two communication phases.

A. Signal Model for the First Phase

In the first phase, the source transmits a symbol $s \in \mathbb{C}$, which is received by the destination and all the relays. Without loss of generality, we assume $\mathbb{E}\{|s|^2\} = 1$.

The signal received at the destination via the direct link can be written as

$$r_U^{(1)} = \sqrt{P_T} f s + \eta, \tag{1}$$

where P_T is the total transmit power at the source, f denotes the channel gain between the source and the destination over the direct link, and η is the additive white Gaussian noise (AWGN) at the destination which is an independent and identically distributed (i.i.d.) complex Gaussian random variable with zero mean and variance σ_η^2.

On the other hand, the signal received by the ith relay, denoted by r_i, can be written as

$$r_i = \sqrt{P_T} g_i s + n_i, \tag{2}$$

where g_i denotes the channel gain between the source and the ith relay, and n_i is the AWGN at the ith relay which is an i.i.d. complex Gaussian random variable with zero mean and variance $\sigma_{n_i}^2$.

At the receiver, two different schemes, namely TS or PS may be adopted to enable SWIPT. For the TS scheme, we define a time switching ratio, α, where $0 \le \alpha \le 1$. In particular, for the first fraction of time period, all the received signal power is used for harvesting energy, whereas during the remaining time, information decoding from the received signal takes place. If the receiver implements a PS scheme, an optimal fraction of the received signal is provided to the information decoder and the remaining part is provided to the energy harvester. In this case, the PS ratio is denoted by β, where $0 \le \beta \le 1$.

The effective Signal-to-Noise Ratio (SNR) measured at the destination for the direct link considering the TS and PS schemes, respectively, is given by

$$\gamma_{TS}^{(1)} = \frac{P_T |f|^2}{\sigma_\eta^2 + \sigma_d^2}, \tag{3}$$

$$\gamma_{PS}^{(1)} = \frac{(1-\beta)P_T|f|^2}{(1-\beta)\sigma_\eta^2 + \sigma_d^2}, \quad (4)$$

where $d \in \mathbb{CN}(0,\ \sigma_d^2)$ is the the noise introduced by the baseband processing circuit, as illustrated in Fig. 2 and Fig. 3.

The power harvested by the destination using the direct link corresponding to the TS and PS schemes, respectively, is given by

$$P_{TS}^{(1)} = \zeta\alpha(P_T|f|^2 + \sigma_\eta^2), \quad (5)$$

$$P_{PS}^{(1)} = \zeta\beta(P_T|f|^2 + \sigma_\eta^2), \quad (6)$$

where ζ is the power conversion efficiency of the receiver [20], which is assumed to be known. For the sake of simplicity, we assume a normalized transmission time for each hop so that the terms energy and power can be used interchangeably.

B. Signal Model for the Second Phase

In the second phase, the selected relay re-transmits the signal after scaling it by a complex amplification coefficient w_i, $i = 1, \ldots, L$. The signal received at the destination from the indirect link, when the ith relay is selected, can be written as

$$r_{U}^{(2)} = w_i h_i r_i + \eta, \quad (7)$$

where h_i denotes the channel gain between the ith relay and the destination. In order to ensure feasibility of the system, we impose an upper bound on the total relay power defined by

$$0 < |w_i|^2 \leq \widetilde{P}_R, \quad (8)$$

where $\widetilde{P}_R = \frac{P_{Max} - P_T}{P_T|g_i|^2 + \sigma_{n_i}^2}$ is the maximum overall available power at the relay, and the transmitter-relay system is bounded by an overall power of P_{Max}, such that $P_{Max} > \max(P_T, \widetilde{P}_R)$.

The effective SNR measured at the destination during the second phase considering the TS and PS schemes is respectively given by

$$\gamma_{TS}^{(2)} = \frac{|w_i|^2|h_i|^2|g_i|^2 P_T}{|w_i|^2|h_i|^2\sigma_{n_i}^2 + \sigma_\eta^2 + \sigma_d^2}, \quad (9)$$

$$\gamma_{PS}^{(2)} = \frac{(1-\beta)|w_i|^2|h_i|^2|g_i|^2 P_T}{(1-\beta)(|w_i|^2|h_i|^2\sigma_{n_i}^2 + \sigma_\eta^2) + \sigma_d^2}. \quad (10)$$

The power harvested by the destination using the indirect link corresponding to the TS and PS schemes, respectively, is given by

$$P_{TS}^{(2)} = \zeta\alpha\big(|w_i|^2|h_i|^2(P_T|g_i|^2 + \sigma_{n_i}^2) + \sigma_\eta^2\big), \quad (11)$$

$$P_{PS}^{(2)} = \zeta\beta\big(|w_i|^2|h_i|^2(P_T|g_i|^2 + \sigma_{n_i}^2) + \sigma_\eta^2\big). \quad (12)$$

C. Overall Rate and Harvested Power

Let R_U and P_U denote the overall rate and the overall harvested power at the destination, respectively, after two communication phases considering both the direct and indirect links.

Assuming that the destination combines the direct link with indirect link using the Maximum Ratio Combining (MRC) technique [21], the overall SNR for TS and PS schemes, respectively, is given by

$$\hat{\gamma}_{TS} = \gamma_{TS}^{(1)} + \gamma_{TS}^{(2)}, \quad (13)$$

$$\hat{\gamma}_{PS} = \gamma_{PS}^{(1)} + \gamma_{PS}^{(2)}. \quad (14)$$

As a consequence, the overall user rates for TS and PS schemes are respectively given by

$$R_U = \begin{cases} R_{TS} = \frac{1}{2}(1-\alpha)\log_2\left(1+\hat{\gamma}_{TS}\right) \\ R_{PS} = \frac{1}{2}\log_2\left(1+\hat{\gamma}_{PS}\right), \end{cases} \quad (15)$$

where the pre-log fractor $\frac{1}{2}$ accounts for the two time slots required for the relaying process. The overall power harvested at the receiver can be expressed as

$$P_U = \begin{cases} P_{TS} = P_{TS}^{(1)} + P_{TS}^{(2)} \\ P_{PS} = P_{PS}^{(1)} + P_{PS}^{(2)}, \end{cases} \quad (16)$$

corresponding to the TS and PS schemes, respectively.

III. Maximization of User Rate subject to Harvested Power Constraint

We first consider the relay selection problem that maximizes the effective source-destination rate, while ensuring that the harvested power at the destination node is above a given threshold and that the total transmit power at the source does not exceed a given limit. Mathematically, we can represent the overall optimization problem as

$$(P1): \max_{i\in\mathcal{I},\theta,\{w_i\}} \quad R_U \quad (17)$$

$$\text{subject to}: \quad P_U \geq \kappa, \quad (18)$$

$$0 < |w_i|^2 \leq P_R, \quad (19)$$

$$0 \leq \theta \leq 1, \quad (20)$$

where i is the relay index, $\mathcal{I} = \{1, 2, \cdots, L\}$ is the set of relay indices, P_R is the upper limit on the relay power such that $P_R \leq \widetilde{P}_R$, and κ is the minimum harvested power demanded by the destination. We use θ to interchangeably refer to the TS or PS splitting factor α or β, respectively.

The problem $(P1)$ is difficult to solve, since it is a non-linear mixed-integer optimization problem for both TS and PS schemes. So, we recast $(P1)$ into a pair of coupled optimization problems for performing outer optimization involving relay selection, and inner optimization involving computations of the corresponding TS and PS splitting factors, and the optimal amplification coefficients of each relay. In the following subsections, we address the optimal solutions to the inner and outer optimizations, respectively.

A. Optimization of Amplification Coefficients and SWIPT Splitting Factor

In this section, we address the inner optimization problem of $(P1)$ involving the computations of optimal relay amplification coefficients and the SWIPT splitting factor (θ), according to the type of scheme chosen. This sub-problem $(P2)$ can be formulated as

$$(P2) : \max_{\theta, w_i} \quad R_U \tag{21}$$
$$\text{subject to :} \quad P_U \geq \kappa, \tag{22}$$
$$0 < |w_i|^2 \leq P_R, \tag{23}$$
$$0 \leq \theta \leq 1. \tag{24}$$

Computation of optimal solution for this problem involves joint computation of $\{\theta\}$ and $\{w_i\}$. The Lagrange dual method can be applied to solve this problem with reduced complexity. Consider a domain χ defined as the set of θ and $\{|w_i|^2\}$, $i = 1, 2, \cdots, L$, satisfying (23) and (24). The Lagrangian of $(P2)$ is given by

$$\mathcal{L}(\theta, w_i; \boldsymbol{\lambda}) = R_U + \lambda_1(P_U - \kappa) + \lambda_2(P_R - |w_i|^2) + \lambda_3(1 - \theta), \tag{25}$$

with $\boldsymbol{\lambda} = (\lambda_1, \lambda_2, \lambda_3) \geq 0$ being the vector of the dual variables associated with the harvested power, relay amplification coefficient, and the splitting factor, respectively. Then, the Lagrange dual function of $(P2)$ can be expressed as

$$\mathcal{L}_{\mathcal{D}}(\boldsymbol{\lambda}) = \max_{\{\theta, w_i\} \in \chi} \mathcal{L}(\theta, w_i; \boldsymbol{\lambda}). \tag{26}$$

Since $\mathcal{L}_{\mathcal{D}}(\boldsymbol{\lambda})$ is always a convex function [22], gradient or sub-gradient based methods can be used for minimizing $\mathcal{L}_{\mathcal{D}}(\boldsymbol{\lambda})$ with guaranteed convergence [23]. Thus, we obtain the following optimal solutions that maximize the Lagrangian in (25)

$$|w_i|^2 = P_R, \tag{27}$$
$$\theta = \frac{\kappa(\zeta)^{-1}}{P_T|f|^2 + P_R|h_i|^2(P_T|g_i|^2 + \sigma_{n_i}^2) + 2\sigma_\eta^2}. \tag{28}$$

B. Optimal Relay Selection

In this section, we consider optimal selection of a relay to address the solution of outer optimization of $(P1)$. Based on the above developments, we find the best relay which provides maximum throughput for both TS and PS schemes corresponding to (17). The index of the selected relay can be expressed as $j^\star = \text{argmax}_{j \in \{1,2,\cdots,L\}} R_j^\star$, where $R_j^\star$ is the rate achieved by the jth relay with optimal amplification coefficient.

IV. Maximization of Harvested Power subject to Rate Constraint

In this section, the problem of relay selection that maximizes the overall harvested power at the destination node is considered while ensuring that the user rate is above a given threshold. The latter can be formulated as follows

$$(P3) : \max_{i \in \mathcal{I}, \theta, w_i} \quad P_U \tag{29}$$
$$\text{subject to :} \quad R_U \geq \delta, \tag{30}$$
$$0 < |w_i|^2 \leq P_R, \tag{31}$$
$$0 \leq \theta \leq 1, \tag{32}$$

where i is the relay index, and δ is the lower bound on the overall rate. Since this problem is not tractable in its present form, we propose to recast $(P3)$ into two separate optimization problems by performing the outer and inner optimizations respectively, as in the previous case. The sub-problem involving outer optimization addresses the computation of the index of optimally selected relay, while the other sub-problem with inner optimization addresses the computations of the amplification coefficient of each relay, and the SWIPT splitting factor.

A. Optimization of Amplification Coefficients and SWIPT Splitting Factor

In this section, we consider the inner optimization problem of $(P3)$. We determine the optimal amplifying coefficients of the relay nodes, and the TS ratio (α) or PS ratio (β) according to the type of scheme chosen, for maximizing the total power harvested at the destination node under constraints on the minimum achievable rate, and limitation on the relay power. Mathematically, the sub-problem (P4) can be formulated as follows

$$(P4) : \max_{\theta, w_i} \quad P_U \tag{33}$$
$$\text{subject to :} \quad R_U \geq \delta, \tag{34}$$
$$0 < |w_i|^2 \leq P_R, \tag{35}$$
$$0 \leq \theta \leq 1. \tag{36}$$

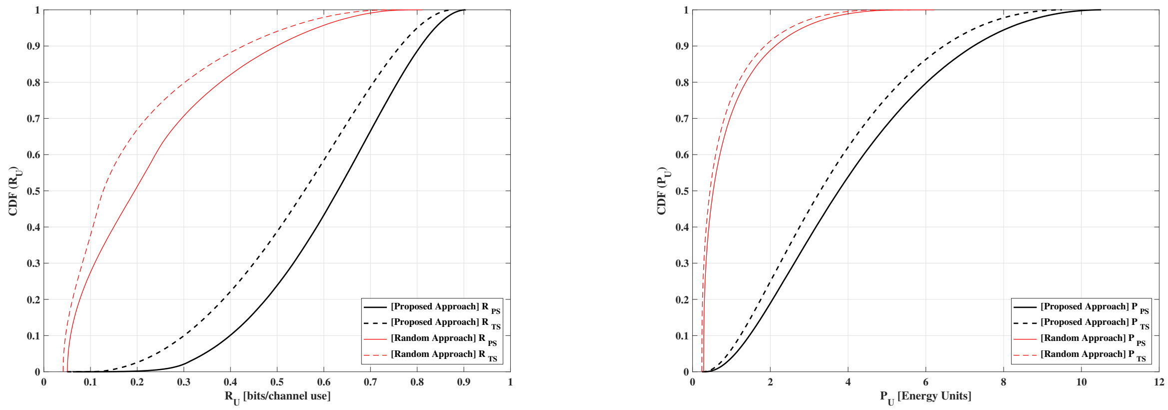
The solution to this problem can be found by using a similar approach as followed in previous section. Consider a domain $\mathcal{Y}$ defined as the feasible set of the optimization parameters of $(P4)$. Consequently, the Lagrangian of $(P4)$ can be expressed as

$$\mathcal{L}(\theta, w_i; \boldsymbol{\mu}) = P_U + \mu_1(R_U - \delta) + \mu_2(P_R - |w_i|^2) + \mu_3(1 - \theta), \tag{37}$$

with $\boldsymbol{\mu} = (\mu_1, \mu_2, \mu_3) \geq 0$ being the vector of the dual variables associated with the user rate, relay amplification coefficient, and the splitting factor, respectively. Then, the Lagrange dual function of $(P4)$ can be expressed as

$$\mathcal{L}_{\mathcal{D}}(\boldsymbol{\mu}) = \max_{\{\theta, w_i\} \in \mathcal{Y}} \mathcal{L}(\theta, w_i; \boldsymbol{\mu}). \tag{38}$$

As mentioned earlier, $\mathcal{L}_{\mathcal{D}}(\boldsymbol{\mu})$ is always a convex function [22] and the gradient or sub-gradient based methods can be used for minimizing $\mathcal{L}_{\mathcal{D}}(\boldsymbol{\mu})$ with guaranteed convergence [23]. Hence, after further analysis,



(a) (b)

Fig. 4: CDF plots assuming P_T = P_R = 5 dBW, $\sigma_{n_i}^2$ = σ_d^2 = 0 dBW, σ_η^2 = -7 dBW and $|f| = 0.3$ for: (a) CDF of R_U with $\kappa = 0.5$ energy units, and (b) CDF of P_U with $\delta = 0.1$ bits per channel use.

we obtain the following optimal solutions that maximize the Lagrangian in (37)

$$|w_i|^2 = P_R, \tag{39}$$

$$\alpha = 1 - \frac{2\delta}{\log_2(1+\hat{\gamma}_{TS})}, \tag{40}$$

$$\beta = 1 - \frac{-\mathcal{B} + \sqrt{\mathcal{B}^2 - 4\mathcal{AC}}}{2\mathcal{A}}, \tag{41}$$

where $\mathcal{A} = P_T|f|^2(|w_i|^2|h_i|^2\sigma_{n_i}^2 + \sigma_\eta^2) + |w_i|^2|h_i|^2P_T\sigma_\eta^2 - (2^{2\delta} - 1)(|w_i|^2|h_i|^2\sigma_{n_i}^2 + \sigma_\eta^2)\sigma_\eta^2$, $\mathcal{B} = P_T|f|^2\sigma_d^2 + |w_i|^2|h_i|^2|g_i|^2P_T\sigma_d^2 - (2^{2\delta}-1)\big(\sigma_\eta^2\sigma_d^2 + (|w_i|^2|h_i|^2\sigma_{n_i}^2 + \sigma_\eta^2)\sigma_d^2\big)$, and $\mathcal{C} = -(2^{2\delta} - 1)\sigma_d^4$. The solutions for α and β found in (40) and (41) are respectively obtained by letting equality hold for (34).

B. Optimal Relay Selection

From the methods proposed above, optimal amplification coefficients for all the relays can be computed easily. We propose to find the best relay which provides maximized harvested power corresponding to (29) for both the TS and PS schemes. In this context, the index of the optimally selected relay can be expressed as $j^\star = \mathrm{argmax}_{j\in\{1,2,\cdots,L\}} P_j^\star$, where $P_j^\star$ is the power harvested by the destination node considering jth relay with the corresponding optimal amplification coefficient.

V. Simulation Results

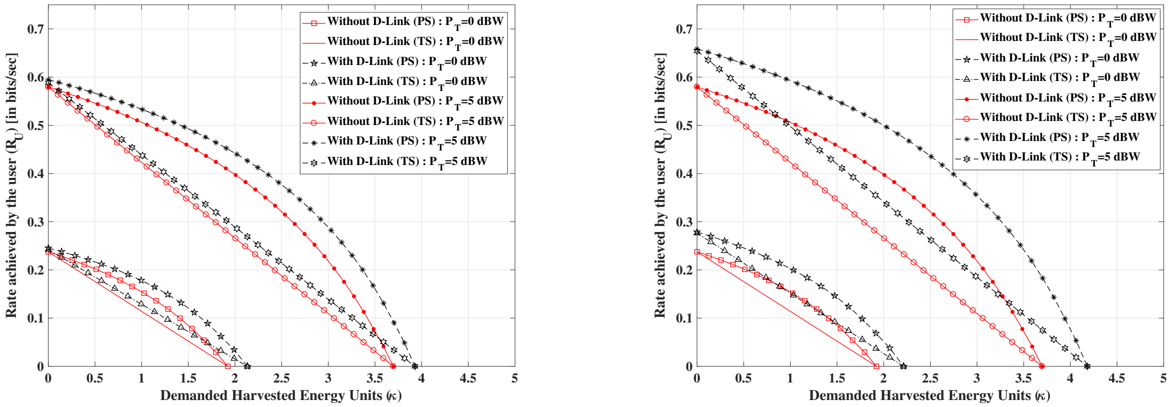
In this section, the performance of the proposed solutions is evaluated. The simulation results presented in this section assume an overall bandwidth of $B = 1$ MHz with $L = 6$ relay nodes and $\zeta = 1$. The channel coefficients are assumed to be i.i.d. and follow Rayleigh distribution.

Fig. 4(a) and Fig. 4(b) compare the proposed approach with a random approach for rate and power maximization respectively, considering both the direct and indirect links. In the random approach, the relay and its amplification factor are chosen randomly within the set of feasible solutions. The SWIPT splitting factor for the random approach is computed according to the constraints (18) and (30). The results depicted in Fig. 4(a) and Fig. 4(b) consider P_T = P_R = 5 dBW, $\sigma_{n_i}^2$ = σ_d^2 = 0 dBW, σ_η^2 = -7 dBW, and $|f| = 0.3$, for 1,000,000 Monte Carlo random channels and relay selection realizations. Both Fig. 4(a) and Fig. 4(b) show that the proposed method outperforms the random scheme with PS technology performing better than the TS technology for the SWIPT based cooperative communication as in [12].

Next, we compare the proposed scheme with the one proposed in [19], which considers the relay link only. This comparison is carried out for different values of P_T considering P_R = 0 dBW, $\sigma_{n_i}^2$ = σ_d^2 = 0 dBW, σ_η^2 = -7 dBW, and for two different values of $|f| = \{0.1, 0.3\}$.

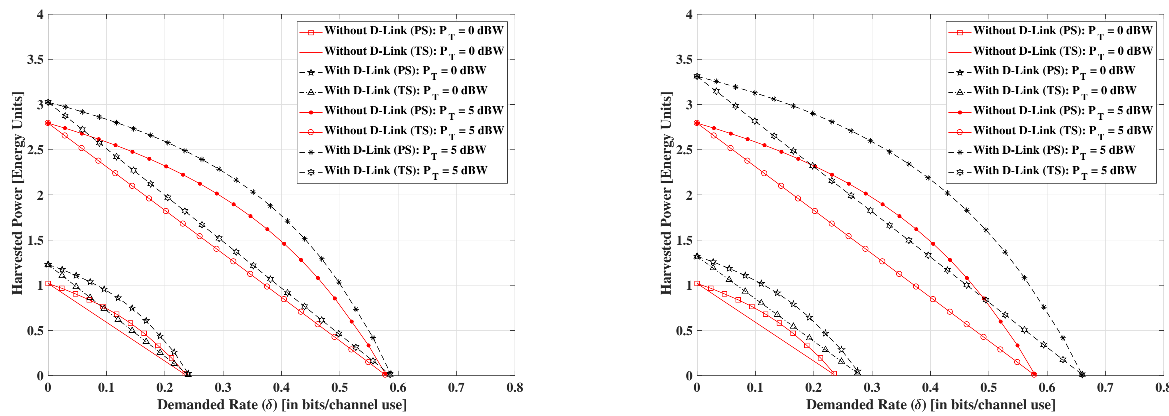
Fig. 5 depicts the variation in the user rate (R_U) over the indicated values of the harvested power (κ) demanded by the destination, as formulated in problem ($P1$). It is found that the proposed results perform considerably better when both direct and indirect links are considered, even when the direct link is significantly affected by fading. Interestingly, it is observed that there is an appreciable gain in terms of the R-E trade-off when the two communication links are considered.

Fig. 6 illustrates the decrease in the value of harvested power (P_U) when the demanded user rate (δ) increases, following the problem ($P3$). The results confirm the benefits of considering the combination of both relay-assisted and direct links. As expected, there is a significant gain in harvested power with the increasing values of P_T. However, it is observed that the maximum demanded rate decreases with the increasing values of



(a) (b)

Fig. 5: User rate (R_U) versus the demanded harvested power (κ) for different values of P_T considering P_R = 0 dBW, $\sigma_{n_i}^2 = \sigma_d^2$ = 0 dBW, σ_η^2 = -7 dBW, and (a) $|f| = 0.1$, and (b) $|f| = 0.3$.



(a) (b)

Fig. 6: Harvested power (P_U) versus the demanded rate (δ) for different values of P_T considering P_R = 0 dBW, $\sigma_{n_i}^2 = \sigma_d^2$ = 0 dBW, σ_η^2 = -7 dBW, and (a) $|f| = 0.1$ and (b) $|f| = 0.3$.

P_T, thereby facilitating the system to harvest more power and satisfying the requirements of the desired optimization problem.

VI. Conclusions

In this paper, a cooperative network of half duplex AF relays has been studied with SWIPT considering both the direct link between the source and the destination, and the relay-assisted indirect link. We performed optimal computations of the TS and PS factors, relay amplifying coefficients, and subsequently proposed optimal methods for the relay selection. An optimization problem to maximize the overall data rate has been solved in order to choose the best relay, without compromising the end-user quality of service (QoS). Similarly, the maximization of the harvested power has been addressed. With the help of numerical simulations, we demonstrated the potential of the proposed relay selection strategies over the random relay selection approach, and also we showed the benefits of combining both direct and relay-assisted links for SWIPT cooperative networks.

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