Optimal Relay Selection Strategy for Joint Data and Energy Transfer in Wireless Systems

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***Abstract*—We study a problem of relay selection in a two-hop amplify-and-forward (AF) enabled relaying network for facilitating simultaneous Wireless Transmission of Information and Energy (Wi-TIE) to a destination able to perform both information processing and energy harvesting concurrently. Considering the *time switching (TS)* and *power splitting (PS)* based Wi-TIE schemes, we formulate an optimization problem to maximize the overall user data rate while ensuring a minimum harvested power. In this context, we obtain suitable closed form solution and demonstrate through simulation results the Rate-Energy (R-E) trade-off in two different scenarios: *(i)* with only the relay assisted link, and *(ii)* with the direct link together with the relay assisted link.**

I. Introduction

Simultaneous Wireless Transmission of Information and Energy (Wi-TIE) is central to major emerging technologies and has gathered considerable attention over the last few years. Incorporation of relay networks in wireless systems enables expansion of the network coverage area and provides diversity gains [1].

By focusing on amplify-and-forward (AF) strategies, in this work, we consider optimal relay selection for Wi-TIE along with the computation of the optimal relay amplification coefficient and optimal splitting factor considering power harvesting constraints at the receiver. To overcome the well-known R-E trade-off [2], we formulate an optimization problem for both TS and PS Wi-TIE schemes to maximize the transmission rate subject to a harvested power constraint. Subsequently, we solve the problem by providing closed-form solutions.

The remainder of this work 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. Section IV presents the simulation results. Finally, Section V concludes the work.

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 such that the overall transfer of data and power takes place in two phases, 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 Wi-TIE architecture. For the TS scheme, we define a time switching ratio, α, where $0 \leq \alpha \leq 1$ whereas the power splitting ratio is denoted by β, where $0 \leq \beta \leq 1$.

In the first phase, the source transmits a symbol $s \in \mathbb{C}$, which is received by all the relays and, in the case where the

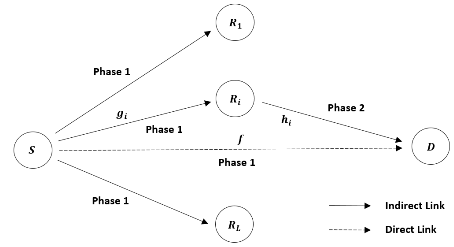

Fig. 1: System model for the proposed architecture.

direct link is considered, by the destination. Without loss of generality, we assume $\mathbb{E}\{|s|^2\} = 1$.

The signals received by the ith relay, and by the destination via the direct link can be respectively written as,

$$r_i = \sqrt{P_T} g_i s + n_i, \text{ and } r_U^{(1)} = \sqrt{P_T} f s + \eta, \quad (1)$$

where g_i denotes the channel gain between the source and the ith relay, $n_i \in \mathbb{CN}(0, \sigma_{n_i}^2)$ is the additive white Gaussian noise (AWGN) at the ith relay which is an i.i.d. complex Gaussian random variable (CGRV), 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 $\eta \in \mathbb{CN}(0, \sigma_\eta^2)$ is the AWGN at the destination which is an i.i.d. CGRV.

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

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

where $d \in \mathbb{CN}(0,\ \sigma_d^2)$ is the the noise introduced by the baseband processing circuit. The power harvested by the destination using the direct link corresponding to the TS and PS schemes, respectively, are

$$P_{TS}^{(1)} = \zeta\alpha(P_T|f|^2 + \sigma_\eta^2), \text{ and } P_{PS}^{(1)} = \zeta\beta(P_T|f|^2 + \sigma_\eta^2), \quad (3)$$

where ζ is the power conversion efficiency of the receiver [2], 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.

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, is given by

$$r_U^{(2)} = w_i h_i r_i + \eta, \text{ with } 0 < |w_i|^2 \leq \widetilde{P}_R, \quad (4)$$

where h_i denotes the channel gain between the ith relay and the destination, $\widetilde{P}_R = \frac{P_{Max} - P_T}{P_T|g_i|^2 + \sigma_{n_i}^2}$ is the maximum overall available power at the relay, and the transmitter-relay system has an overall power of $P_{Max} > \max(P_T, \widetilde{P}_R)$.

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Without the Direct Link	With the Direct Link
$\lvert w_i\rvert^2 = P_R$, and $\theta = \frac{\kappa(\zeta)^{-1}}{P_R\lvert h_i\rvert^2(P_T\lvert g_i\rvert^2+\sigma_{n_i}^2)+\sigma_\eta^2}$	$\lvert w_i\rvert^2 = P_R$, and $\theta = \frac{\kappa(\zeta)^{-1}}{P_T\lvert f\rvert^2+P_R\lvert h_i\rvert^2(P_T\lvert g_i\rvert^2+\sigma_{n_i}^2)+2\sigma_\eta^2}$

The effective SNR measured at the destination during the second phase for the TS and PS schemes are given by

$$\gamma_{TS}^{(2)} = \frac{|w_i|^2|h_i|^2|g_i|^2 P_T}{|w_i|^2|h_i|^2\sigma_{n_i}^2 + \sigma_\eta^2 + \sigma_d^2}, \quad (5)$$

$$\gamma_{PS}^{(2)} = \frac{(1-\beta)|w_i|^2|h_i|^2|g_i|^2 P_T}{(1-\beta)(|w_i|^2|h_i|^2\sigma_{n_i}^2 + \sigma_\eta^2) + \sigma_d^2}. \quad (6)$$

The power harvested by the destination using the indirect link for the TS and PS schemes, respectively, are given by

$$P_{TS}^{(2)} = \zeta\alpha\big(|w_i|^2|h_i|^2(P_T|g_i|^2 + \sigma_{n_i}^2) + \sigma_\eta^2\big), \quad (7)$$

$$P_{PS}^{(2)} = \zeta\beta\big(|w_i|^2|h_i|^2(P_T|g_i|^2 + \sigma_{n_i}^2) + \sigma_\eta^2\big). \quad (8)$$

Let R_U and P_U denote the overall rate and the overall harvested power at the destination, respectively, after two communication phases. Assuming that the destination combines the direct link with indirect link using the Maximum Ratio Combining (MRC) technique, the overall SNR for TS and PS schemes, respectively, are given by

$$\hat{\gamma}_{TS} = \gamma_{TS}^{(1)} + \gamma_{TS}^{(2)}, \text{ and } \hat{\gamma}_{PS} = \gamma_{PS}^{(1)} + \gamma_{PS}^{(2)}. \quad (9)$$

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

$$R_U = \begin{cases} R_{TS} = \frac{1}{2}(1-\alpha)\log_2\left(1 + \hat{\gamma}_{TS}\right) \\ R_{PS} = \frac{1}{2}\log_2\left(1 + \hat{\gamma}_{PS}\right), \end{cases} \quad (10)$$

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

$$P_U = \begin{cases} P_{TS} = P_{TS}^{(1)} + P_{TS}^{(2)} \\ P_{PS} = P_{PS}^{(1)} + P_{PS}^{(2)}, \end{cases} \quad (11)$$

corresponding to the TS and PS schemes, respectively.

III. User Rate Maximization for Relay Selection

We consider the relay selection problem that maximizes the effective source-destination rate, while ensuring a minimum harvested power at the destination node. Mathematically, we can represent the overall optimization problem as

$$(P1): \max_{i\in\mathcal{I},\theta,\{w_i\}} \quad R_U \quad (12)$$

$$\text{subject to}: \quad P_U \geq \kappa, \quad (13)$$

$$0 < |w_i|^2 \leq P_R, \quad (14)$$

$$0 \leq \theta \leq 1, \quad (15)$$

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. We use the Lagrange dual method to find the optimal solutions for the inner optimization, as illustrated at the top of this page. The solution of outer optimization yields the index of the selected relay, which 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. Proofs are omitted due to the space limitation.

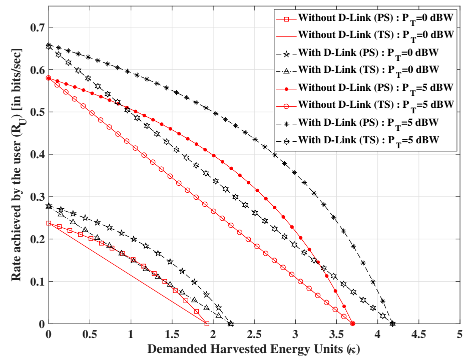

Fig. 2: User rate (R_U) versus the demanded harvested power (κ) for different values of P_T considering P_R = 0 dBW, $\sigma_{n_i}^2 = \sigma_d^2$ = 0 dBW, σ_η^2 = -7 dBW, and $|f| = 0.3$.

IV. Simulation Results

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. 2 depicts the variation in the user rate (R_U) over the indicated values of the harvested power (κ) demanded by the destination for the mentioned parameter values. 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.

V. Conclusions

In this work, a cooperative network of half duplex AF relays has been studied with Wi-TIE considering both the direct link between the source and the destination, and the relay-assisted indirect link. An optimization problem to maximize the overall data rate has been solved in order to choose the best relay. With the help of numerical simulations, we showed the benefits of combining both direct and relay-assisted links for Wi-TIE cooperative networks.

References

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