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Joint power splitting and power allocation for two-way OFDM relay networks with SWIPT

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A B S T R A C T

This paper studies power-splitting relaying (PSR) in an orthogonal-frequency-division-multiplexing (OFDM) amplify-and-forward (AF) two-way relay network (TWRN) which implements simultaneous wireless information and power transfer (SWIPT), with the goal of maximizing information exchanging rates of two terminals in the network. To achieve this, we investigate the joint optimization of power-splitting (PS) ratio of the relay and power allocation over subcarriers. The formulated optimization problem not only bears a non-convex energy-harvesting constraint of the relay but also tightly couples the PS ratio and power allocation variables in the non-convex objective function. To tackle this challenging problem, we show that it can be transformed into a problem which fits well in the d.c.(difference of two convex functions) programming framework by two different approaches, and thus can be effectively solved by two constrained concave-convex procedure based algorithms, respectively. Simulation results show that the performance of the PSR-based OFDM AF TWRN employing our proposed schemes is not only better than that of the existing time-switching based relaying OFDM AF TWRN, but also superior over that of the PSR-based OFDM AF TWRN employing the simple scheme with fixed PS ratio.

1. Introduction

Simultaneous wireless information and power transfer (SWIPT) uses radio frequency (RF) to deliver information as well as energy to energy-constrained nodes [1–3]. By employing SWIPT in a wireless relay network, an energy-constrained relay node can harvest energy and receive information from a source node's RF signals, and then retransmit the information to a destination node by using the harvested energy. For the wireless relay networks with SWIPT, the studies can be classified into two categories based on a linear or non-linear model employed for the energy-harvesting (EH) receiver at the relay. In general, non-linear EH model is more practical than linear EH model [4,5]. Nevertheless, linear EH model facilitates the analysis and can provide insight into the performance of the involved networks, especially for complicated wireless networks, and thus has drawn much attention of researchers in recent years. For the wireless relay networks employed with linear EH receivers at the relay, Nasir et al. [6] proposed time-switching based relaying (TSR) or power-splitting based relaying (PSR) protocols. A relay node operating with the TSR protocol usually takes two successive fractions of time to harvest energy and receive information, respectively, while a relay node operating with the PSR protocol normally harvests energy and receives information simultaneously by splitting the received power into two portions. Therefore, the PSR protocol is more efficient than the TSR protocol, and the simulation results in [6] showed that the PSR relay node helps to achieve higher rate than the TSR relay node does. Hereafter, quite a few studies have been carried out to investigate TSR or PSR in various scenarios, e.g. multi-pair relay networks [7,8], multiple-input multiple-output (MIMO) relay networks [9,10], multi-relay networks [11,12], two-way relay networks [13,14] and secure relaying communications [15,16]. However, these studies mainly focus on narrowband channels.

In order to achieve large transmission capacity, broadband channels are employed in future and emerging wireless communication networks [17,18]. This motivates more recent studies on SWIPT to investigate broadband relay networks with orthogonal-frequency-division multiplexing (OFDM) modulations [19–22]. While these studies focus on one-way relaying, a two-way relay network has wide application scenarios and is able to utilize RF spectrum more efficiently because its two terminals may simultaneously exchange their information by using the same relay channel. In [23], we studied a TSR-based OFDM AF two-way relay network (TWRN) to improve transmission rates by jointly optimizing time-switching (TS) ratio of the relay and the power allocation (PA) over subcarriers. Unlike this pervious work, in this paper, we study a PSR-based OFDM AF two-way relay network as the PSR

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protocol may have better performance than the TSR protocol [6].

More specifically, for the PSR-based OFDM AF TWRN, we jointly optimize power-splitting (PS) ratio of the relay and PA over subcarriers. Our objective is to improve the information exchanging rates of two terminals. In the formulated optimization problem, there are not only a non-convex EH constraint but also a highly non-convex objective rate function. Our contributions to solve the non-convex optimization problem are listed as follows.

- Different from the joint TS and PA optimization algorithm for TSR-based OFDM AF TWRNs [23], the joint PS and PA optimization algorithm faces the challenge that PS ratio and PA variables tightly couple with each other in the objective rate function, which results in that its structure is more complicated than that for TSR-based OFDM AF TWRNs in [23] so that we can not transform the optimization problem into the fractional programming framework which has been employed in [23].
- We propose to solve the joint PS and PA optimization problem by reformulating it as a tractable d.c. (difference of two convex functions) programming problem, which can be effectively solved by a constrained concave-convex procedure (CCCP) based algorithm. To achieve this, we firstly simplify the structure of the objective rate function by introducing new auxiliary equalities, and then tackle the auxiliary equalities by two approaches. In first approach, we transform the auxiliary equalities into a matrix equality constraint; and then by equivalently expressing the matrix equality as a convex inequality constraint and a reverse convex inequality constraint. In the second approach, we directly rewrite the auxiliary equalities into two groups of reverse inequalities, which can be expressed in d.c. forms. For both approaches, we obtain a penalty function which can be transformed into a d.c. programming problem, respectively.
- By solving the optimization problem, we propose two efficient algorithms which can jointly optimize PS and PA, respectively. By simulations, we find that the rate achieved by our proposed joint PS and PA optimization algorithms is higher than that of the existing TSR-based OFDM AF TWRN, while the rate achieved by only optimization of PA with fixed PS ratio is lower that of the existing TSR-based OFDM AF TWRN.

Notations: Boldface lowercase and upper letters denote vectors and matrices, respectively. $\mathbf{X}^T$ and $\mathrm{tr}(\mathbf{X})$ denote the transpose and trace of the matrix $\mathbf{X}$, respectively. $\mathrm{vec}\{\mathbf{X}\}$ denotes the vectorization of $\mathbf{X}$. $\mathbf{X} \succeq \mathbf{0}$ indicates that matrix $\mathbf{X}$ is positive semidefinite. Denote $\langle \mathbf{x}, \mathbf{y} \rangle = \mathbf{x}^T\mathbf{y}$ for $\mathbf{x} = [x_1, x_2, ..., x_N]^T \in \mathbb{R}^N$ and $\mathbf{y} = [y_1, y_2, ..., y_N]^T \in \mathbb{R}^N$.

2. System model and problem formulation

The system model of the investigated PSR-based OFDM AF TWRN in this paper is depicted in Fig. 1. As illustrated in Fig. 1(a), two terminals $\mathscr{T}_A$ and $\mathscr{T}_B$ cannot communicate directly due to obstacles and thus exchange their information by a relay node $\mathscr{R}$ [6,7,9,11,14,15,16,19]. It is assumed that $\mathscr{R}$ is an energy-constrained node equipped with PS receiver and thus can harvest energy from ambient RF signals. By using the harvested energy, $\mathscr{R}$ amplifies and forwards the received signals to destinations. It is assumed that the circuitry energy consumption of the transceiver at the relay is neglected, since the energy used for relaying is much larger than that for circuitry energy consumption [6].

The communications are time-frame basis, and the length of each time frame is T_f. Two equal time slots constitute one time frame. In the first time slot, $\mathscr{T}_\mathrm{A}$ and $\mathscr{T}_\mathrm{B}$ simultaneously sends their signals s_n^A and s_n^B to $\mathscr{R}$ over subcarrier n with OFDM modulation, where the number of subcarriers is N and $\mathbb{E}\{|s_n^\mathrm{A}|^2\} = \mathbb{E}\{|s_n^\mathrm{B}|^2\} = 1$, $n \in \{1, 2, ..., N\}$. As in [24], we assume that the channels are reciprocal and use $h_1(n)$ and $h_2(n)$ to denote the channel responses of the two hop links over subcarrier n respectively, which do not vary in the duration of one time frame and vary independently between different time frames. Let p_n^A and p_n^B denote the transmit power of $\mathscr{T}_A$ and $\mathscr{T}_B$ over subcarrier n, respectively. Then, in the first time slot, the received signal over subcarrier n at $\mathscr{R}$ can be expressed as

$$y_{\mathscr{R}}(n) = h_1(n)\sqrt{p_n^\mathrm{A}}s_n^\mathrm{A} + h_2(n)\sqrt{p_n^\mathrm{B}}s_n^\mathrm{B} + n_{\mathscr{R},b},$$

where $n_{\mathscr{R},b} \sim \mathscr{CN}(0, \sigma_b^2)$ is the baseband additive white Gaussian noise (AWGN) over each subcarrier at $\mathscr{R}$. As the PS receiver equipped at $\mathscr{R}$, $\mathscr{R}$ splits the energy of the received signal into two streams. This is illustrated in Fig. 1(b), where the upper stream with PS ratio $1-\rho$ is for EH and the lower stream with PS ratio ρ is for information processing. Then, the amount of harvested energy at relay is [2]

$$E = \frac{1}{2}T_f\eta(1-\rho)\sum_{n=1}^{N}(p_n^\mathrm{A}|h_1(n)|^2 + p_n^\mathrm{B}|h_2(n)|^2), \tag{1}$$

where η denotes EH efficiency factor. And the signal for information processing can be expressed as

$$y_{\mathscr{R}}^\mathrm{I}(n) = \sqrt{\rho}(h_1(n)\sqrt{p_n^\mathrm{A}}s_n^\mathrm{A} + h_2(n)\sqrt{p_n^\mathrm{B}}s_n^\mathrm{B} + n_{\mathscr{R},b}) + n_{\mathscr{R},c},$$

where $n_{\mathscr{R},c} \sim \mathscr{CN}(0, \sigma_c^2)$ is the noise introduced by information processing circuit while performing RF band to baseband signal conversion [6]. Denote the total power of the baseband AWGN and the circuit AWGN as σ_R^2, then $\sigma_b^2 + \sigma_c^2 = \sigma_\mathrm{R}^2$.

In the second time slot, by using the harvested energy, $\mathscr{R}$ amplifies and broadcasts the information signals to $\mathscr{T}_A$ and $\mathscr{T}_B$. Let p_n^R denote the transmit power at $\mathscr{R}$ over subcarrier n. Moreover, define

$$\pi(n) = \sqrt{p_n^\mathrm{R}/(\rho(p_n^\mathrm{A}|h_1(n)|^2 + p_n^\mathrm{B}|h_2(n)|^2 + \sigma_b^2) + \sigma_c^2)}.$$

Then, the received signals at $\mathscr{T}_A$ and $\mathscr{T}_B$ over subcarrier n can be written as

$$y_\mathrm{A}(n) = \pi(n)h_1(n)(\sqrt{\rho}(h_1(n)\sqrt{p_n^\mathrm{A}}s_n^\mathrm{A} + h_2(n)\sqrt{p_n^\mathrm{B}}s_n^\mathrm{B} + n_{\mathscr{R},b}) + n_{\mathscr{R},c}) + n_\mathrm{A} \tag{2}$$

and

$$y_\mathrm{B}(n) = \pi(n)h_2(n)(\sqrt{\rho}(h_1(n)\sqrt{p_n^\mathrm{A}}s_n^\mathrm{A} + h_2(n)\sqrt{p_n^\mathrm{B}}s_n^\mathrm{B} + n_{\mathscr{R},b}) + n_{\mathscr{R},c}) + n_\mathrm{B}, \tag{3}$$

where $n_\mathrm{A} \sim \mathscr{CN}(0, \sigma_\mathrm{A}^2)$ and $n_\mathrm{B} \sim \mathscr{CN}(0, \sigma_\mathrm{B}^2)$ are the AWGN over each subcarrier at $\mathscr{T}_A$ and $\mathscr{T}_B$, respectively. Without loss of generality, let $\sigma_\mathrm{A}^2 = \sigma_\mathrm{B}^2 = \sigma_\mathrm{R}^2 = \sigma^2$. Moreover, in this paper, it is assumed that $\mathscr{T}_A$, $\mathscr{T}_B$ and $\mathscr{R}$ have the knowledge of $h_1(n)$ and $h_2(n)$ for $n \in \{1, 2, ..., N\}$. Then, $\mathscr{T}_A$ and $\mathscr{T}_B$ can suppress the self-interferences in the received signals. After the self-interference terms have been subtracted, (2) and (3) can be written as

$$y_\mathrm{A}(n) = \pi(n)h_1(n)(\sqrt{\rho}(h_2(n)\sqrt{p_n^\mathrm{B}}s_n^\mathrm{B} + n_{\mathscr{R},b}) + n_{\mathscr{R},c}) + n_\mathrm{A}$$

and

$$y_\mathrm{B}(n) = \pi(n)h_2(n)(\sqrt{\rho}(h_1(n)\sqrt{p_n^\mathrm{A}}s_n^\mathrm{A} + n_{\mathscr{R},b}) + n_{\mathscr{R},c}) + n_\mathrm{B}.$$

Thus, the signal-to-noise ratios (SNRs) over subcarrier n at $\mathscr{T}_A$ and $\mathscr{T}_B$ can be expressed as

$$\Upsilon_n^A(\rho, \mathbf{p}_n) = \frac{\rho p_n^\mathrm{B}|h_2(n)|^2 p_n^\mathrm{R}|h_1(n)|^2}{(\rho(p_n^\mathrm{A}|h_1(n)|^2 + p_n^\mathrm{B}|h_2(n)|^2 + \sigma_c^2) + \sigma_b^2)\sigma^2 + p_n^\mathrm{R}|h_1(n)|^2(\rho\sigma_b^2 + \sigma_c^2)} \tag{4}$$

and

$$\Upsilon_n^B(\rho, \mathbf{p}_n) = \frac{\rho p_n^\mathrm{A}|h_1(n)|^2 p_n^\mathrm{R}|h_2(n)|^2}{(\rho(p_n^\mathrm{A}|h_1(n)|^2 + p_n^\mathrm{B}|h_2(n)|^2 + \sigma_c^2) + \sigma_b^2)\sigma^2 + p_n^\mathrm{R}|h_2(n)|^2(\rho\sigma_b^2 + \sigma_c^2)}, \tag{5}$$