Enhancing Energy Harvesting Efficiency for IRS-Aided TS-SWIPT Network with Practical Phase Shifts

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Abstract. Recently, intelligent reflecting surface (IRS) emerges as a promising technique to improve the spectral and energy efficiency in communication with low cost and low energy consumption. In this work, we investigate the simultaneous wireless information and power transfer (SWIPT) network with time-switching (TS) receivers where the base station (BS) sends both information and energy signals to the users with the aid of IRS. The phase shifts at the IRS elements are appropriately adjusted to enhance the transmission performance in terms of energy and information efficiency. The energy harvesting efficiency, i.e., the ratio of the sum harvested energy at the users and the transmission power at the BS is maximized while the required information rate at the users is guaranteed, the transmission power is limited, and the practical phase shifts are constrained. The iterative algorithm with the non-convex approximations is proposed to achieve the information beamformers, energy covariance matrix, and TS ratios. Lastly, the numerical simulations present the convergence and effectiveness of the proposed approach.

Keywords: Simultaneous wireless information and power transfer (SWIPT) · intelligent reflecting surface (IRS) · time-switching (TS) · energy harvesting efficiency · discrete phase shifts

1 Introduction

The emergence of the Internet of Things (IoT) and machine-type communication (MTC) in the fifth-generation (5G) networks has shifted the current wireless communications towards connecting machines and things, leading to the next phase of IoT of the sixth-generation (6G) networks, referred to as the Internet of Everything (IoE) [1]. In particular, IoE is anticipated to impose an unprecedented density of connections, e.g.

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at least 10^7 devices/km^2, characterized by limited power storage capabilities [2]. Such a massive number of battery-powered IoT devices pose a challenge as these devices require frequent charging or battery replacement, which can be both difficult and costly, especially for certain applications like body sensors. While well-known energy harvesting technologies, such as solar and wind energy, have been introduced to potentially achieve self-sustainability for those power-constrained IoT devices, these approaches, however, are susceptible to environmental fluctuations. In response, simultaneous wireless information and power transfer (SWIPT), which is based on radio frequency (RF), emerges as a potential energy harvesting alternative [3].

Based on the allocation tasks between information decoding and energy harvesting, SWIPT receivers can be classified into three primary types: time-switching (TS), power splitting (PS), and antenna switching (AS) [4]. Among those, the PS receiver amplifies the receiver's complexity while multiple antennas are necessitated at the AS receiver. On the other hand, the TS-based SWIPT design has been recognized as a relevant candidate for low-power IoT devices, particularly those expected to feature single-antenna configurations [5]. Regarding the TS schemes, the work [6] jointly optimized the TS factors and transmit covariance matrices within a two-user SWIPT Multiple-Input Single-Output (MISO) system, aiming to improve the achievable rate region. In [7], the Energy Efficiency (EE) maximization problem for a TS-based Non-Orthogonal Multiple Access (NOMA) has been investigated by considering the joint design of TS factors and power allocation.

Recently, the Intelligent Reflecting Surface (IRS), also referred to as Reconfigurable Intelligent Surface (RIS), has emerged as a prominent technology for re-shaping the wireless channel propagation environment and for improving the system performance [8]. Comprising numerous reflective elements, each programmable to alter its phase, IRS enables the coherent superposition of reflected signals at the receiver. This enhances the power of desired signals, while facilitating the coherent cancellation of interference signals. Notably, the reflective elements in IRS are passive, solely reflecting signals without amplification, resulting in a solution with low hardware and energy costs. Moreover, IRS can be designed with a thin profile, making it easily deployable on walls and glass surfaces. Thereby, the deployment of IRS does not require a restructuring of the existing network architecture.

Due to the significant potential of SWIPT and IRS in the EE enhancement, numerous efforts have been devoted to exploring the combination of these two technologies, to name a few. In the very first work [9], the authors investigated an IRS-aided SWIPT system, aiming to maximize the weighted sum power of EH receivers. Other related studies have investigated various benefits of the IRS-based SWIPT systems, addressing challenges of, e.g., EE maximization [10], weighted sum rate maximization [11], transmit power minimization [12], or sum harvested power maximization [13].

This work aims to enhance the energy harvesting efficiency, i.e., the ratio of the sum harvested energy at the users and the transmission power at the BS, for TS-SWIPT network by exploiting the configurable phase-shifts reflecting elements of IRS. This target guarantees the proficiency of energy usage while providing the information services. Moreover, the phase shifts are discrete values via practical IRS circuits. The EH efficiency maximization problem is formulated to obtain the BS beamformers, energy covariance matrix, TS factors, and discrete IRS phase shifts. In the scope of this study with fixed discrete phase shifts, the combination of mathematical transformation and successive convex approximation (SCA) method is proposed to solve the highly non-convex optimization problem. Finally, the numerical experiments show the convergence and performance of the proposed iterative algorithm.

The remaining of this study is organized as follows. The system description and problem formulation is presented in Sect. 2. The solution method of EH efficiency maximization is shown in Sect. 3. Lastly, the numerical simulations are performed in Sect. 4, proceeded by the closure in Sect. 5.

2 System Model and Problem Formulation

2.1 System Description

The considered SWIPT network includes one base station, one IRS, and multiple time-switching users as presented in Fig. 1. The BS is equipped with M antennas for transmission and the users are equipped with one antenna and time-switching structure. The IRS has N components which are configured to support the SWIPT incident RF signals for enhancing the power and information transfer. We denote the links from the BS and IRS to the l-th receiver is $\{\mathbf{f}_{d,l}, \mathbf{f}_{r,l}\}$, $\forall l = 1, 2, \cdots, L$ where $\mathbf{f}_{d,l} \in \mathbb{C}^{M\times 1}$, $\mathbf{f}_{r,l} \in \mathbb{C}^{N\times 1}$. In addition, the BS-IRS link is indicated as $\mathbf{G} \in \mathbb{C}^{N\times M}$. The IRS is configured with the phase-shift matrix $\mathbf{\Phi} = \text{diag}\left(e^{j\varphi_1}, e^{j\varphi_2}, \cdots, e^{j\varphi_N}\right)$ where j represents the imaginary unit. Furthermore, $\varphi_n \in [0, 2\pi)$, $\forall n = 1, 2, \cdots, N$, denotes the adjusted phases at the n-th IRS component. The signal transferred by the BS which is expressed as $\mathbf{x}_B = \sum_{l=1}^{L} \mathbf{b}_l s_l + \mathbf{v}$, where the precoding beamformer $\mathbf{b}_l \in \mathbb{C}^{M\times 1}$, is constructed for transmitting the information symbol s_l to the l-th TS users. Moreover, $\mathbf{v}$ is a power transferring vector which is a Gaussian pseudo-random sequence and utilized to harvest power with $\mathbf{v} \sim \mathcal{CN}(0, \mathbf{V})$ and a covariance matrix $\mathbf{V} \succeq 0$. We consider that the information symbols are the unit power, then the sum power consumed by the BS is computed as $\text{P}_B = \sum_{l=1}^{L} ||\mathbf{b}_l||^2 + \text{Tr}(\mathbf{V})$. As a result, the returned signal by intelligent

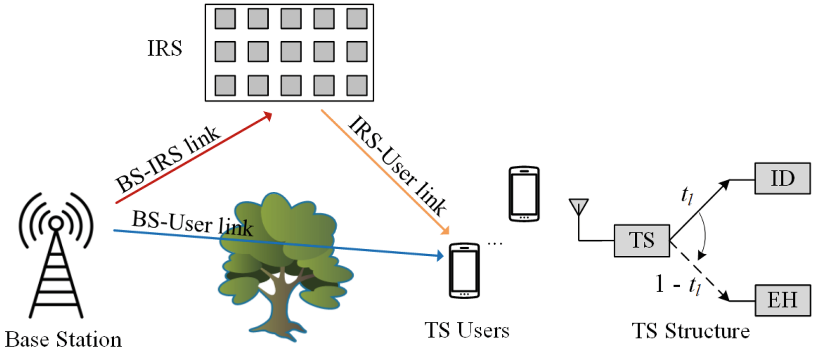

Fig. 1. The considered IRS-aided TS-SWIPT network

surface is expressed as $\mathbf{x}_{IRS} = \mathbf{\Phi G}\left(\sum_{l=1}^{L} \mathbf{b}_l s_l + \mathbf{v}\right)$ and the received signal at the l-th TS user is given by

$$r_l = \left(\mathbf{f}_{r,l}^H \mathbf{\Phi G} + \mathbf{f}_{d,l}^H\right)\left(\sum_{l=1}^{L} \mathbf{b}_l s_l + \mathbf{v}\right) + n_l, \forall l \tag{1}$$

when $n_l \sim \mathcal{CN}\left(0, \sigma_l^2\right)$ is the RF-to-baseband processing AWGN noise at the l-th receiver.

With the TS structure, the users are able to change the mode operations of the ID and the EH for receiving energy and information. Without loss of generality, the time of each operation is unit, then the time intervals of the l-th user for the ID and EH are expressed as t_l and $(1 - t_l)$, respectively. Therefore, the harvested power from the received signal at l-th user is calculated by:

$$\Lambda_l = (1 - t_l)\left(\sum_{k=1}^{L} \left|\left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi G}\right)\mathbf{b}_k\right|^2 + \mathrm{Tr}\left(\left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi G}\right)\left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi G}\right)^H \mathbf{V}\right)\right) \tag{2}$$

Moreover, the information rate is derived from the signal to interference plus noise ratio (SINR) as:

$$\Theta_l = t_l \log_2\left(1 + \frac{\left|\left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi G}\right)\mathbf{b}_l\right|^2}{\sum_{k=1,k\neq l}^{L} \left|\left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi G}\right)\mathbf{b}_k\right|^2 + \mathrm{Tr}\left(\mathbf{F}_l \mathbf{V}\right) + \sigma_l^2}\right) \tag{3}$$

2.2 Energy Harvesting Efficiency Design Problem

The transmission power at the base station is expressed as $\mathrm{P}_B = \sum_{l=1}^{L} ||\mathbf{b}_l||^2 + \mathrm{Tr}\left(\mathbf{V}\right)$. The total energy harvesting amount of all users under the linear circuit model is given by

$$\sum_{l=1}^{L} \Lambda_l = \sum_{l=1}^{L} \left[(1 - t_l)\left(\sum_{k=1}^{L} \left|\left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi G}\right)\mathbf{b}_k\right|^2 + \mathrm{Tr}\left(\mathbf{F}_l \mathbf{V}\right)\right)\right] \tag{4}$$

with $\mathbf{F}_l = \left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi G}\right)\left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi G}\right)^H$. Then, the energy harvesting efficiency maximization problem is formulated as:

$$(\mathbf{P1}) : \underset{\{\mathbf{b}_l, \mathbf{V}, t_l, \varphi_n\}}{\text{maximize}} \ \frac{\sum_{l=1}^{L} \left[(1 - t_l)\left(\sum_{k=1}^{L} \left|\left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi G}\right)\mathbf{b}_k\right|^2 + \mathrm{Tr}\left(\mathbf{F}_l \mathbf{V}\right)\right)\right]}{\sum_{l=1}^{L} ||\mathbf{b}_l||^2 + \mathrm{Tr}\left(\mathbf{V}\right)} \tag{5}$$

$$\text{subject to} : t_l \log_2\left(1 + \frac{\left|\left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi G}\right)\mathbf{b}_l\right|^2}{\sum_{k=1,k\neq l}^{L} \left|\left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi G}\right)\mathbf{b}_k\right|^2 + \mathrm{Tr}\left(\mathbf{F}_l \mathbf{V}\right) + \sigma_l^2}\right) \geq \gamma_l, \forall l \tag{6}$$

$$\sum_{l=1}^{L} ||\mathbf{b}_l||^2 + \mathrm{Tr}\left(\mathbf{V}\right) \leq P_{T,\max} \tag{7}$$

$$1 \geq t_l \geq 0, \ \forall l, \mathbf{V} \succeq 0, \left|\mathbf{\Phi}_{n,n}\right| = 1, \ \forall n. \tag{8}$$

The aim in (5) is to maximize the energy harvesting efficiency for the IRS-aided TS-SWIPT system. Constraint (6) provides the quality of services target with the minimum required information rate, γ_l, to the l-th user. Constraint (7) expresses the transmission power limited by the maximum value, $P_{T,\max}$. Constraint (8) indicates the TS factor limitation, energy covariance matrix, and phase-shifts matrix requirements. Problem (P1) is highly non-convex due to the non-convex functions of objective and constraints. Therefore, we transform the problem into the tractable form with SCA method and then solve by CVX solver [14].

3 Proposed Algorithm for Energy Harvesting Efficiency Design

3.1 Practical Discrete Phase Shifts $\{\varphi_n\}$

In practical circuit of IRS elements, the phase-shift angles $\{\varphi_n\}$ are only limited in finite values in the range of $[0, 2\pi)$. In particular, D represents the bit number for uniformly space in $[0, 2\pi)$. Then, all the values of phase shifts belong to the set of discrete values $\left\{0, \frac{2\pi}{2^D}, \cdots, \frac{2\pi\times(2^D-1)}{2^D}\right\}$. In this study, we perform several random values of the phase shifts, and then optimize the BS beamformer, the energy covariance matrix, and the TS factors in the following subsection. The finding of optimal discrete phase shifts will be investigated for future extension.

3.2 Finding $\{\mathbf{b}_l, \mathbf{V}, t_l\}$ with Fixed $\{\varphi_n\}$

We observe that the objective function in (5) is in a complicated form and challenging to solve. Thus, we derive some optimization problem transformations to simplify the non-convex problem. Firstly, the auxiliary set of variables $\{x_l, y\}$ are introduced and the objective function is converted as:

$$\underset{\{\mathbf{b}_l,\mathbf{V},t_l,x_l,y\}}{\text{maximize}} \ \frac{\sum_{l=1}^{L} x_l^2}{y} \tag{9}$$

$$\text{subject to}: \ (1-t_l)\left(\sum_{k=1}^{L}\left|\left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi}\mathbf{G}\right)\mathbf{b}_k\right|^2 + \operatorname{Tr}(\mathbf{F}_l\mathbf{V})\right) \geq x_l^2, \forall l \tag{10}$$

$$\sum_{l=1}^{L} \|\mathbf{b}_l\|^2 + \operatorname{Tr}(\mathbf{V}) \leq y, \forall l \tag{11}$$

$$x_l \geq 0, y \geq 0, \forall l. \tag{12}$$

Secondly, the information rate constraints are simplified by introducing the auxiliary variables $\{u_l, z_l\}$ and transformed as:

$$\frac{\left|\left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi}\mathbf{G}\right)\mathbf{b}_l\right|^2}{\sum_{k=1,k\neq l}^{L}\left|\left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi}\mathbf{G}\right)\mathbf{b}_k\right|^2 + \operatorname{Tr}(\mathbf{F}_l\mathbf{V}) + \sigma_l^2} \geq \exp\left(\ln 2 \cdot \frac{\gamma_l}{t_l}\right) - 1. \tag{13}$$

Then, that is equivalent to:

$$\left|\left(\mathbf{f}_{d,l}^{H}+\mathbf{f}_{r,l}^{H}\mathbf{\Phi}\mathbf{G}\right)\mathbf{b}_{l}\right|^{2}\geq\exp\left(z_{l}\right)\left(\exp\left(\ln 2\cdot\gamma_{l}u_{l}\right)-1\right),\tag{14}$$

$$\exp\left(z_{l}\right)\geq\sum_{k=1,k\neq l}^{L}\left|\left(\mathbf{f}_{d,l}^{H}+\mathbf{f}_{r,l}^{H}\mathbf{\Phi}\mathbf{G}\right)\mathbf{b}_{k}\right|^{2}+\mathrm{Tr}\left(\mathbf{F}_{l}\mathbf{V}\right)+\sigma_{l}^{2},\tag{15}$$

$$u_{l}\geq\frac{1}{t_{l}},u_{l}\geq 0.\tag{16}$$

We reformulate the energy harvesting efficiency maximization problem as follows:

$$(\mathbf{P2}):\underset{\{\mathbf{b}_{l},\mathbf{V},t_{l},x_{l},y,z_{l},u\}}{\text{minimize}}\quad-\sum_{l=1}^{L}\frac{x_{l}^{2}}{y}\tag{17}$$

$$\text{subject to}:0\geq\frac{x_{l}^{2}}{(1-t_{l})}-\sum_{k=1}^{L}\left|\left(\mathbf{f}_{d,l}^{H}+\mathbf{f}_{r,l}^{H}\mathbf{\Phi}\mathbf{G}\right)\mathbf{b}_{k}\right|^{2}-\mathrm{Tr}\left(\mathbf{F}_{l}\mathbf{V}\right),\forall l,\tag{18}$$

$$0\geq\sum_{l=1}^{L}||\mathbf{b}_{l}||^{2}+\mathrm{Tr}\left(\mathbf{V}\right)-y,\tag{19}$$

$$0\geq e^{z_{l}+\ln 2\cdot\gamma_{l}u_{l}}-e^{z_{l}}-\left|\left(\mathbf{f}_{d,l}^{H}+\mathbf{f}_{r,l}^{H}\mathbf{\Phi}\mathbf{G}\right)\mathbf{b}_{l}\right|^{2},\forall l,\tag{20}$$

$$0\geq\sum_{k=1,k\neq l}^{L}\left|\left(\mathbf{f}_{d,l}^{H}+\mathbf{f}_{r,l}^{H}\mathbf{\Phi}\mathbf{G}\right)\mathbf{b}_{k}\right|^{2}+\mathrm{Tr}\left(\mathbf{F}_{l}\mathbf{V}\right)+\sigma_{l}^{2}-e^{z_{l}},\forall l,\tag{21}$$

$$0\geq\frac{1}{t_{l}}-u_{l},\forall l,\tag{22}$$

$$x_{l}\geq 0,y\geq 0,u_{l}\geq 0,1\geq t_{l}\geq 0,\forall l,\tag{23}$$

$$0\geq\sum_{l=1}^{L}||\mathbf{b}_{l}||^{2}+\mathrm{Tr}\left(\mathbf{V}\right)-P_{T,\max},\tag{24}$$

$$\mathbf{V}\succeq 0.\tag{25}$$

Obviously, the objective function and constraints (18), (20) and (21) are non-convex. To overcome these challenges, we exploit the Taylor expansion for the objective function around a fixed point $\left\{x_{l}^{(i)},y^{(i)}\right\}$ as follows:

$$\frac{x_{l}^{2}}{y}\geq\frac{x_{l}^{(i)2}}{y^{(i)}}+\left[\frac{2\,x_{l}^{(i)}}{y^{(i)}}\left(x_{l}-x_{l}^{(i)}\right)-\frac{x_{l}^{(i)2}}{y^{(i)2}}\left(y-y^{(i)}\right)\right]=\frac{2\,x_{l}^{(i)}}{y^{(i)}}x_{l}-\frac{x_{l}^{(i)2}}{y^{(i)2}}y.\tag{26}$$

Similarly, for fixed $z_{l}^{(i)}$, we obtain the underestimation as

$$e^{z_{l}}\geq e^{z_{l}^{(i)}}+e^{z_{l}^{(i)}}\left(z_{l}-z_{l}^{(i)}\right)\tag{27}$$

$$\left|\left(\mathbf{f}_{d,l}^{H}+\mathbf{f}_{r,l}^{H}\mathbf{\Phi}\mathbf{G}\right)\mathbf{b}_{k}\right|^{2}=\mathbf{b}_{k}^{H}\mathbf{f}_{l}\mathbf{f}_{l}^{H}\mathbf{b}_{k}\geq 2Re\left\{\mathbf{b}_{k}^{(i)H}\mathbf{f}_{l}\mathbf{f}_{l}^{H}\mathbf{b}_{k}\right\}-\mathbf{b}_{k}^{(i)H}\mathbf{f}_{l}\mathbf{f}_{l}^{H}\mathbf{b}_{k}^{(i)},\forall k,l\tag{28}$$

with $\mathbf{f}_l^H = \mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi} \mathbf{G}$. We introduce the slack variables $\{c_{1,l}, c_2, c_{3,l}, c_{4,l}, c_{5,l}, c_6\}$ to achieve the feasible initial points for SCA algorithm and then the subproblem is expressed as follows.

$$\textbf{(P3)}: \underset{\left\{\begin{matrix} \mathbf{b}_l, \mathbf{V}, t_l, x_l, y, z_l, u, \\ c_{1,l}, c_2, c_{3,l}, c_{4,l}, c_{5,l}, c_6 \end{matrix}\right\}}{\text{minimize}} \quad -\sum_{l=1}^{L}\left(\frac{2\,x_l^{(i)}}{y^{(i)}} x_l - \frac{x_l^{(i)2}}{y^{(i)2}} y\right) + \lambda\left(\sum_{l=1}^{L}\left(c_{1,l} + c_{3,l} + c_{4,l} + c_{5,l}\right) + c_2 + c_6\right), \tag{29}$$

$$\text{s.t.}: 0 \geq \frac{x_l^2}{(1-t_l)} - \mathrm{Tr}\left(\mathbf{F}_l \mathbf{V}\right) - \sum_{k=1}^{L}\left(2Re\left\{\mathbf{b}_k^{(i)H} \mathbf{f}_l \mathbf{f}_l^H \mathbf{b}_k\right\} - \mathbf{b}_k^{(i)H} \mathbf{f}_l \mathbf{f}_l^H \mathbf{b}_k^{(i)}\right) - c_{1,l}, \forall l, \tag{30}$$

$$0 \geq \sum_{l=1}^{L} \|\mathbf{b}_l\|^2 + \mathrm{Tr}\left(\mathbf{V}\right) - y - c_2, \tag{31}$$

$$0 \geq e^{z_l + \ln 2 \cdot \gamma_l u_l} - \left(e^{z_l^{(i)}} + e^{z_l^{(i)}}\left(z_l - z_l^{(i)}\right)\right) - \left(2Re\left\{\mathbf{b}_l^{(i)H} \mathbf{f}_l \mathbf{f}_l^H \mathbf{b}_l\right\} - \mathbf{b}_l^{(i)H} \mathbf{f}_l \mathbf{f}_l^H \mathbf{b}_l^{(i)}\right) - c_{3,l}, \forall l, \tag{32}$$

$$0 \geq \sum_{k=1, k \neq l}^{L} \left|\left(\mathbf{f}_{d,l}^H + \mathbf{f}_{r,l}^H \mathbf{\Phi} \mathbf{G}\right) \mathbf{b}_k\right|^2 + \mathrm{Tr}\left(\mathbf{F}_l \mathbf{V}\right) + \sigma_l^2 - \left(e^{z_l^{(i)}} + e^{z_l^{(i)}}\left(z_l - z_l^{(i)}\right)\right) - c_{4,l}, \forall l, \tag{33}$$

$$0 \geq \frac{1}{t_l} - u_l - c_{5,l}, \forall l, \tag{34}$$

$$0 \geq \sum_{l=1}^{L} \|\mathbf{b}_l\|^2 + \mathrm{Tr}\left(\mathbf{V}\right) - P_{T,\max} - c_6, \tag{35}$$

$$\mathbf{V} \succeq 0, x_l \geq 0, y \geq 0, u_l \geq 0, 1 \geq t_l \geq 0, \forall l, \tag{36}$$

$$c_{1,l} \geq 0, c_2 \geq 0, c_{3,l} \geq 0, c_{4,l} \geq 0, c_{5,l} \geq 0, c_6 \geq 0, \forall l. \tag{37}$$

We start the initial point as:

$$\mathbf{b}_l^{(0)} = \frac{P_{T,\max}}{L \times M}[1, ..., 1]^T, \text{then } \left\|\mathbf{b}_l^{(0)}\right\|^2 = \frac{P_{T,\max}}{L}, \forall l. \tag{38}$$

Therefore, $\sum_{l=1}^{L}\left\|\mathbf{b}_l^{(0)}\right\|^2 = P_{T,\max}$, and $z_l^{(0)} = 0$, $x_l^{(0)} = 1$, $y^{(0)} = 1$. Finally, the proposed iterative algorithm is described in Algorithm 1.

4 Experiment Evaluations

The numerical simulations are performed to demonstrate the effectiveness of the proposed algorithm. The network diagram setting is as follows. The coordinates of the BS and the IRS are (0, 0) and (3, 2.5) with meter units. Moreover, L receivers with time-switching structure are uniformly located around a circle where the centered point is at (5, 0) and the radius is 0.5 m. The large-scale attenuation for every links is represented as $PL = 10^{-3}d^{-\alpha}$, where α is the attenuation exponent. The α component for the BS-IRS, IRS-User, and BS-User links are assigned by $\alpha_{\mathrm{BI}} = \alpha_{\mathrm{IU}} = 2.2$, $\alpha_{\mathrm{BU}} = 3.6$, respectively [15]. The Rician model is applied for small-scale fading in every channel where the Rician coefficient is given by 3 dB. Furthermore, the additive noise power at the receivers is $\sigma_l^2 = -60\,\mathrm{dBm}, \forall l$. The number of quantization bits is $D = 1$, and discrete phase shifts are assigned randomly. We first evaluate the convergence of the proposed approach for a random realization of all links and discrete phase shifts at the IRS.

Algorithm 1 The proposed iterative algorithm for obtaining the BS beamformers, energy covariance matrix, and TS ratios.

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Initialization: Start a feasible initial point of the problem (P2) as (38). Convergent accuracies $\zeta_1$ and $\zeta_2$. Set initial index $i = 0$.
repeat
    Solve the problem (P3) to obtain the optimal solution $\left\{\mathbf{b}_l^\dagger, \mathbf{V}^\dagger, t_l^\dagger, x_l^\dagger, y^\dagger, z_l^\dagger, u^\dagger, c_{1,l}^\dagger, c_2^\dagger, c_{3,l}^\dagger, c_{4,l}^\dagger, c_{5,l}^\dagger, c_6^\dagger\right\}$ with a fixed point $\left\{\mathbf{b}_l^{(i)}, t_l^{(i)}, x_l^{(i)}, y^{(i)}, z_l^{(i)}\right\}$.
    Assign $\mathbf{b}_l^{(i+1)} = \mathbf{b}_l^\dagger$, $t_l^{(i+1)} = t_l^\dagger$, $x_l^{(i+1)} = x_l^\dagger$, $y^{(i+1)} = y^\dagger$, $z_l^{(i+1)} = z_l^\dagger$.
    Set $i = i + 1$.
    $a = \sum_{l=1}^{L}\left(c_{1,l}^\dagger + c_{3,l}^\dagger + c_{4,l}^\dagger + c_{5,l}^\dagger\right) + c_2^\dagger + c_6^\dagger$
    $b = \left|\left(\sum_{l=1}^{L}\frac{x_l^{(i)2}}{y^{(i)}} - \sum_{l=1}^{L}\frac{x_l^{(i-1)2}}{y^{(i-1)}}\right)/\sum_{l=1}^{L}\frac{x_l^{(i-1)2}}{y^{(i-1)}}\right|$
until $a \le \zeta_1$ and $b \le \zeta_2$.
Outputs: Obtained solution $\left\{\mathbf{b}_l^{(i)}, \mathbf{V}^{(i)}\right\}, t_l^{(i)}, x_l^{(i)}, y^{(i)}, z_l^{(i)}$, and energy harvesting efficiency $\frac{\sum_{l=1}^{L}\left[\left(1-t_l^{(i)}\right)\left(\sum_{k=1}^{L}\left\|\left(\mathbf{f}_{d,l}^H+\mathbf{f}_{r,l}^H\mathbf{\Phi}\mathbf{G}\right)\mathbf{b}_k^{(i)}\right\|^2+\mathrm{Tr}(\mathbf{F}_l\mathbf{V})\right)\right]}{\sum_{l=1}^{L}\left\|\mathbf{b}_l^{(i)}\right\|^2+\mathrm{Tr}(\mathbf{V})}$.
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As shown in Fig. 2, the objective value of problem (P3) decreases and converges quickly in some tens of iterations under different minimum information rate requirements, γ_l. Since the objective value includes the relaxing variables $\{c_{1,l}, c_2, c_{3,l}, c_{4,l}, c_{5,l}, c_6\}$ which are used to obtain a feasible initial point for the SCA iteration, the optimal value of (P3) is large in several points in the beginning. Then, it decreases to approximately zero when the problem is feasible.

In Fig. 3, we observe the change of EH efficiency value according to the iteration in Fig. 2. Some beginning values of EH efficiency are large due to the assigned initial values of BS beamformers. Note that the information rate and power limitation constraints are not satisfied until the sum of the relaxing variables goes to approximated zero. In addition, the EH efficiency value converges around 40 iterations with the considered parameters.

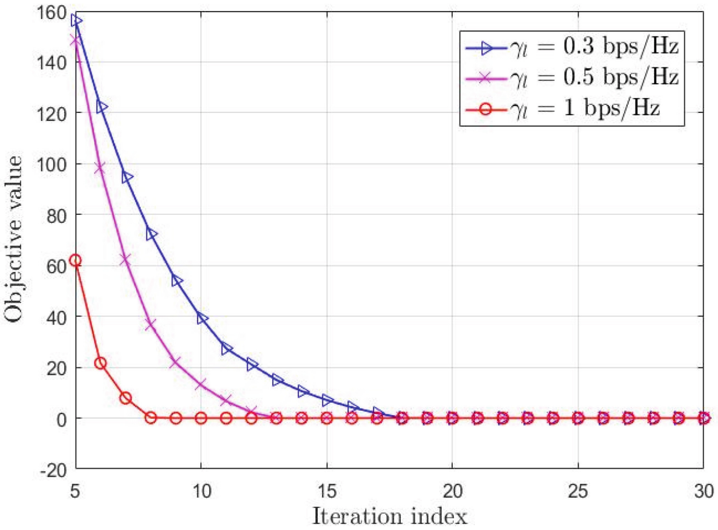

Fig. 2. The convergence of objective value (29) with a random realization of the channels and the phase shifts in Algorithm 1.

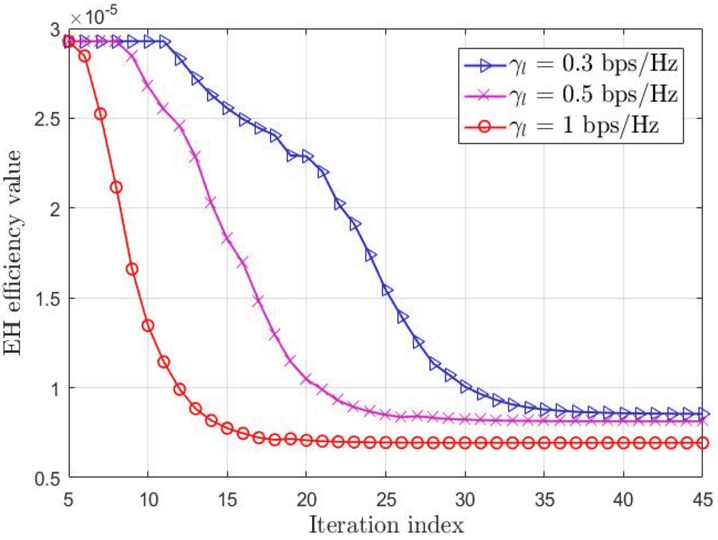

Fig. 3. The behavior of EH efficiency according to the convergence in Fig. 2.

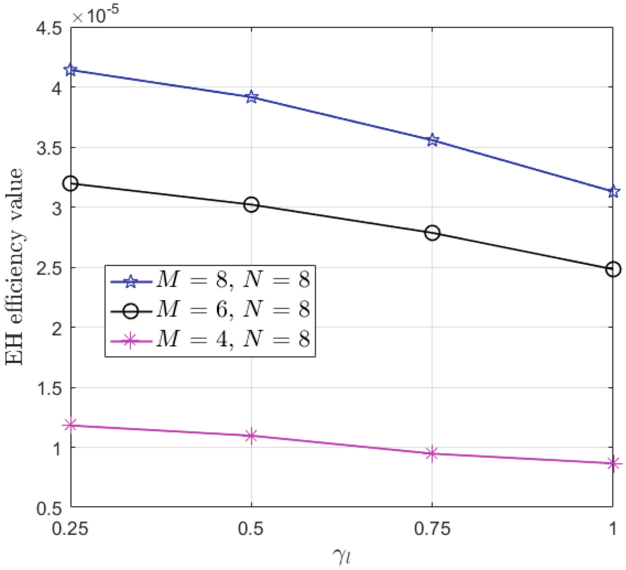

Fig. 4. The value of energy harvesting efficiency according to the minimum required information rate.

Figure 4 presents the EH efficiency value according to the minimum required information rate with $P_{T,\max} = 35$ dBW and some values of BS antenna number, M and IRS element number, N. It can be observed that the EH efficiency decreases when the minimum information rate increases. Moreover, the EH efficiency is higher with more BS antenna numbers. The reason is that the TS users harvest less energy when the required information rate rises and the BS has more extra degree of freedom variables to transmit data and energy with more antennas.

5 Conclusion

In this study, the energy harvesting efficiency maximization is investigated in the IRS-aided multiuser SWIPT system where the users exploit the TS structure and the IRS has discrete phase shifts. For a random value of discrete phase shifts, the highly non-convex problem is transformed and solved by the SCA method to achieve the optimal transceiver parameters. The numerical results express the convergence of the iterative algorithm and the EH efficiency values via the required information rate. A research on the optimal discrete values of reflecting phase shifts will be performed in the future extension.

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