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A novel joint transmit beamforming and receive time switching strategy for MISO SWIPT system

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Abstract

In multi-antenna simultaneous wireless information and power transfer (SWIPT) system, beamforming strategy has been widely analyzed due to the increasing signal strength. It can not only increase the signal strength in the direction of the antenna array but also reduce the interference strength, which is a good option for SWIPT system to achieve directional transmission of information and energy. However, the traditional beamforming strategy only uses single beamforming vector, and it does not consider the differences between information and energy in SWIPT system. Actually, interference can also be collected as energy. Based on the traditional beamforming strategy, the resources in SWIPT system are not properly utilized. Therefore, this paper proposes a joint beamforming strategy in multi-input and single-output (MISO) SWIPT system. We extend the traditional single beamforming vector into two beamforming vectors to realize independent control of information and energy based on time switching (TS) receiving mode. In information receiving phase, information beamforming vector is used to carry specific user's information for information alignment. Since there is an orthogonal relationship between information beamforming vector and channel gain vector, we can achieve to eliminate interference and realize error-free information transmission. In energy receiving phase, energy beamforming vector is used to carry user's energy. Energy beamforming vector and channel gain vector do not require the orthogonality so that the interference can also be collected as energy. In this paper, we model it as a transmission power optimization (TPO) problem, which is a complex non-convex problem. We firstly transform it into a convex problem, and then, it can be solved using CVX toolbox. Simulation results show that the proposed strategy could increase the energy collection at the same transmission power and also decrease the transmission power at the same energy collection.

Keywords: MISO, SWIPT, Joint beamforming, Time switching, Convex optimization

1 Introduction

With the development of Internet of Things and communication, low-power sensors are becoming ubiquitous, which increasingly leads to convenient electric charging. In our daily life, a power line is the most popular way to transmit power for charging the battery [1]. But in some cases, there are obvious limitations for cable charging, such as sensors in the wall and furniture for a smart home or in the body for medical implantation [2, 3]. Thus, the wireless charging is a prominent solution to a wide range of applications. Wireless charging is a charging method in which the device and the charger do not have to be connected to each other by the cable but by the wireless medium as the carrier for energy transmission. It is a new idea for a terminal to obtain energy. In a traditional wireless communication system, the radio frequency (RF) signal plays a role of information transmitter; nevertheless, the RF signal could carry not only information but also energy [4–6]. Therefore a new wireless communication system that uses the RF signal to transmit information as well as energy has emerged, which was called simultaneous wireless information and power transfer (SWIPT) system proposed by Varshney in 2008 [7].

In a SWIPT system, there are two kinds of receivers, information receiver (IR) and energy receiver (ER) for information reception and energy collection, respectively.

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It outperforms the traditional communication system by wireless charging to prolong the system service lifetime. Based on a special hardware circuit design, ER has the ability to convert the received RF signal to energy and store it in the battery to charge IR for reception of the information [8, 9].

In SWIPT system, the transmission power is a key performance parameter. It provides an evaluation criterion on the resource consumption. However, due to the power dissipation in the free space and low efficiency of energy conversion, the energy collection efficiency is usually not high. Currently, scholars throughout the world have paid much attention to decrease the transmission power by focusing on the transmitter design, receiver design, and transmitter and receiver joint design [10]. Transmitter design involves beamforming, user selection, and power control [11–13]. Receiver design studies the RF signal receiving modes, such as power splitting (PS) mode and time switching (TS) mode [14, 15]. Based on the above studies, joint designs of transmitter and receiver with TS or PS scheme [16, 17] were proposed.

Especially, in the SWIPT studies, beamforming strategy has widely attracted attention because it well combines the antenna technology and digital signal processing technology for directional information transmission. In the traditional wireless communication system, beamforming strategy could increase the signal strength in the direction of the antenna array and suppress the interference between users. When beamforming strategy is introduced to the SWIPT system, it just makes use of the traditional beamforming vector to achieve the information and energy alignment for directional information and energy transmission. As a result, the transmission power could be reduced by the beamforming strategy. In order to achieve good transmission power performance, beamforming strategies based on different system models, receiving modes, and optimization goals were proposed and analyzed.

The research of beamforming in SWIPT system based on different system models includes multiple antenna technology, IR and ER position relation, and single-cell or multi-cell scenario. For multiple antenna technologies, multi-input and single-output (MISO) and multiple-input and multiple-output (MIMO) are usually the hot topics. When the number of the base station antenna is more than the number of users, interference could be suppressed by the beamforming strategy. In [18, 19], MISO technology was well studied in SWIPT system. In this case, user terminal has one antenna, which means the received signal could be directly allocated for IR and ER. And further, in [20, 21], MIMO technology was proposed in the SWIPT system. When the user terminal is equipped with multiple antennas, multiple signals were received, which should be firstly synthesized as one signal and then allocated it to IR and ER. According to different positions of IR and ER, the SWIPT receiver could be categorized into a co-channel receiver and non-co-channel receiver. Most of the literature available studied the co-channel receiver. Particularly, [22] studied the non-co-channel receiver, whose energy and information are actually not simultaneously transmitted. In addition, most of the SWIPT research studies are focusing on the single-cell scenario, such as in [18–21]. There is also a few of literature studied the multi-cell scenario [22].

The beamforming based on different receiving modes in SWIPT system is called joint optimization of transmitting beamforming and receiving modes, which is one of the most important topics in SWIPT research. TS and PS are the two most popular receiving modes. In [19–21], terminals adopted PS mode to receive information and energy at the same time. The received RF signal was divided into two parts, one part for the information reception and the other one for the energy collection. The optimal beamforming vector design was realized by adjusting the power splitting ratio. In [23–25], terminals adopted TS mode to receive information and energy simultaneously in a unit time. In this mode, a unit time was divided into two slots, which were information slot and energy slot. In the information slot, IR conducted information reception. In the energy slot, ER conducted energy collection. Finally, the optimal beamforming vector was designed by adjusting the time switching ratio.

The mathematical model for SWIPT system usually uses energy collection, system sum-rate, and transmission power as optimization goals, where the system sum-rate is usually measured by the signal-to-interference plus noise ratio (SINR). In [17, 26], their optimization goal was to maximize the collected energy under the constraints of IRs' SINR and the total transmission power from the base station. And in [27], the author considered the constraints of the non-linearity of energy harvesting circuits and the quality of service requirements for secure communication.The optimization goal of [18–21] was to minimize the total transmission power under the constraints of the SINR of IRs and the collected energy of ERs. Particularly, References [28, 29] considered the imperfect channel statement information (CSI). And Reference [30] considered separated IRs and ERs in cellular networks to prevent possible eavesdroppers of ERs to detect information aimed for IRs. The objective of [31] was to maximize the SINR of IRs with the constraints of the collected energy of ERs and the total transmission power. The optimization goal of [32] was to minimize the total transmission power under the restraints of the security information transmission rate and the collected energy of ERs. The optimization goal of [33] was to maximize the energy efficiency of the system, and the constraints were the SINR of IRs and the collected energy of ERs.

In summary, although the literature available showed that the beamforming strategy in the SWIPT system could improve the transmission power performance, the studies were limited to the system model, receiving mode, or optimization goal. The above research works only introduced the traditional beamforming strategy to dependently transmit information and energy by single beamforming vector but not take consideration of the differences between the SWIPT system and the traditional wireless communication system. In SWIPT system, there are two kinds of resources, information and energy, whereas only information in the traditional wireless communication system. Hence, the beamforming strategy for the traditional wireless communication system could not be directly implemented in the SWIPT system, due to the difference between information and energy.

In this paper, we compare with the following two common beamforming schemes, namely, conventional beamforming and zero-forcing beamforming. In zero-forcing beamforming design, there is a orthogonality between the beamforming vector of the corresponding user and the channel gain vector of the interference user, so that the interference between the users can be completely eliminated. But this design ignores the fact that the interference between users can serve as a source of energy. While in the conventional beamforming design, there is no orthogonality relation, but the existence of the interference has a negative impact on information reception. Therefore, we need to separate the information reception and energy reception. All in all, we hope that interference cancelation can be achieved in the receiving phase of information. And interference collection can be achieved during the energy reception phase.

Therefore, a novel joint beamforming strategy is proposed in this paper to achieve independent control of information and energy in SWIPT system, so as to attain the simultaneous transmission of information and energy. We extend the traditional beamforming vector into two independent beamforming vectors. For information reception, the orthogonal relation of information beamforming vector and channel gain vector is used to realize the directional information transmission. For energy collection, the interference is also collected as energy, because the non-orthogonal relation between energy beamforming vector and channel gain vector is considered. In this way, the energy collection is improved, so as to decrease the transmission power.

The rest of the paper is organized as follows. Section 2 describes the SWIPT system, which includes the joint beamforming strategy schematic, receiving mode. Then, we provide the optimization problem as a transmission power optimization (TPO) problem according to the above model. In Section 3, we present the method to solve the TPO problem. In Section 4, implementation and performance analysis is provided. Finally, the conclusion is drawn in the last section.

2 System model and TPO problem

2.1 System model

For discussion brevity, we consider a multi-input and single-output simultaneous wireless information and power transfer (MISO SWIPT) system which includes one base station with N_t transmitting antennas and M co-channel receiving terminals as shown in Fig. 1. The transmission channel is assumed to be quasi-static, and the channel statement information (CSI) is known by the BS. The base station transmits the RF signal in a unit time with two slots. One of the slots is for the information transmission as depicted in solid line, and the other slot is for the energy transmission as plotted in dotted line. In the

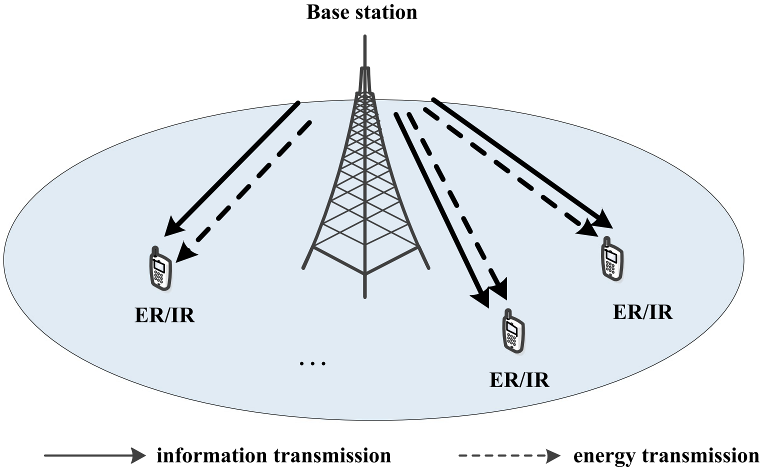

Fig. 1 MISO SWIPT system model

SWIPT system, the base station transmits the RF signals carrying information and energy to the terminal through the free space. After the signals transmitting through the quasi-static channel, IR and ER obtain the information and energy, respectively, in a receiving mode. IR decodes the signals into information to realize the reception information. ER converts the signal into energy for battery charging to swift the energy collection.

The receiving modes commonly used in SWIPT system are TS and PS. Since the TS receiving mode outperforms PS receiving mode in simple circuit design and high energy collection efficiency, we implement TS receiving mode in the SWIPT system shown in Fig. 2. We divide a unit time into two slots. In slot 1, information is transmitted by the information beamforming vector. In slot 2, energy is transmitted by the energy beamforming vector. Since the RF signal received by ER can not be directly stored in the battery as energy, there has to be an energy transformation [26]. First, the received signals are sent to the matching network for impedance matching. Then, the alternating current (AC) signal is converted to a direct current (DC) signal by a DC converter. Finally, the energy is stored in the battery, which could charge for IR.

Based on the TS receiving mode, we propose a novel transmitting beamforming design, namely joint beamforming strategy as shown in Fig. 3. It inherits the advantages of traditional beamforming strategy in which it increases the signal strength in the direction of the antenna array and reduce the strength of interference to improve the system sum-rate in the SWIPT system. We extend the single beamforming vector into two independent beamforming vectors as information beamforming vector and energy beamforming vector, which independently control the information and energy resources, respectively. When the base station sends information, the interference could be suppressed by the orthogonal relationship between information beamforming vector and channel gain vector. When the energy is transmitted, there is no orthogonal relationship between energy beamforming vector and channel gain vector, so that interference could be collected as energy.

In Figs. 2 and 3, we obtained the specific process of signal transmission in MISO SWIPT system based on the proposed joint beamforming strategy. In slot 1, the base station uses information beamforming vector to send information, and then, a narrow information beam to the target user is formed. At the same time, the IR in the terminal is ready for information reception, so that the information transmission is realized. In slot 2, the base station uses energy beamforming vector to send energy, and then, an energy beam to the target user is formed. Meanwhile, the ER in the terminal is ready for energy collection, so that the energy transmission is realized.

So far, in this subsection, we describe the MISO SWIPT system model in detail. In the next subsection, we will offer the optimization problem according to the system stated above. In order to better introduce our proposed strategy, Table 1 summarizes the major symbols used for the rest of this paper.

2.2 TPO problem description

In this subsection, a detailed optimization problem is formulated for the system introduced above. We aim to minimize the transmission power for achieving the optimal joint beamforming design with the constraints of minimum SINR of IRs and minimum collection energy of ERs. To sum up, we get the problem with inequality constraints as the following.

$$\begin{aligned} \min \quad & P_{\text{sum}} && \text{(1a)} \\ \text{s.t.} \quad & \psi_k \geq \gamma_k, && \text{(1b)} \\ & \theta_k \geq e_k, && \text{(1c)} \end{aligned}$$

where P_{sum} is the tansmission power of the base ststion; ψ_k represents the received SINR of the kth IR; γ_k stands for the received SINR threshold of the kth IR; θ_k is the energy collection of the kth ER; and e_k denotes the energy collection threshold of the kth ER. γ_k and e_k are both preset values in the system, presenting information and energy requirement, respectively. And they would be determined by the practical condition. In order to obtain the variables in (1), it is necessary to make mathematical models in the two slots respectively for the SWIPT MISO system.

In slot 1, the base station uses information beamforming vector to make a weighted sum of the user's information. Thus, the transmitting information of the antenna array can be represented as

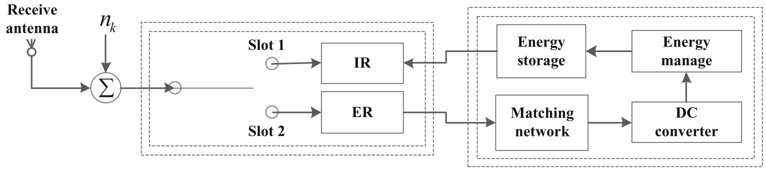

Fig. 2 TS receiving mode

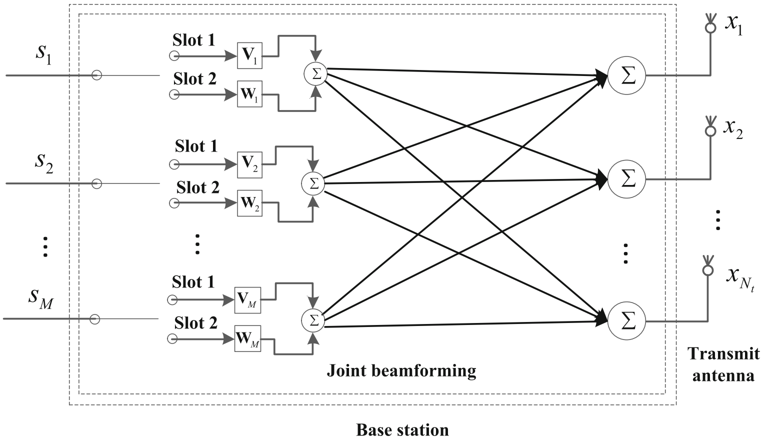

Fig. 3 Joint beamforming strategy schematic

$$\mathbf{x} = \sum_{k=1}^{M} \mathbf{v}_k s_k. \tag{2}$$

After the information passes through the quasi-static wireless channel, the information received by the kth user becomes

$$y_k = \mathbf{h}_k^H \sum_{i=1}^{M} \mathbf{v}_i s_i + n_k + \mathrm{z}_k, \forall k, \tag{3}$$

where $(.)^{\mathrm{H}}$ stands for the conjugate transpose of matrix.

Table 1 List of major symbols used in this papers

Symbol	Description
M	Number of users (co-channel receiving terminal)
N_t	Number of base station transmitting antenna
s_i	Information of the ith user, $s_i \sim CN(0,1)$
Slot 1	Information slot
Slot 2	Energy slot
$\mathbf{v}_i$	Information beamforming vector for the ith user, $\mathbf{v} \in \mathbb{C}^{N_t \times 1}$
$\mathbf{w}_i$	Energy beamforming vector for the ith user, $\mathbf{w} \in \mathbb{C}^{N_t \times 1}$
x_i	The information of antenna i
$\mathbf{h}_k$	Channel gain vector for the kth user, $\mathbf{h} \in \mathbb{C}^{N_t \times 1}$
W	Bandwidth
n_k	Antenna noise for the kth user, $n_k \sim CN\left(0, \sigma_k^2\right)$
z_k	Demodulation noise for the kth user, $z_k \sim CN\left(0, \delta_k^2\right)$
α	Time switching ratio, $0 \le \alpha \le 1$
ζ_k	Energy conversion efficiency
γ_k	Minimum SINR threshold of IR
e_k	Minimum energy collection threshold of ER
P	Maximum transmission power threshold of base station

In this paper, we assume a zero-forcing beamforming in the transmitter when receivers are receiving information. So, the orthogonal relation between the information beamforming vector and the channel gain vector is provided in (4).

$$\mathbf{h}_i^H \mathbf{v}_j = 0, \forall i \ne j. \tag{4}$$

In (4), we can obtain the information received by the kth user without interference given by

$$y_k = \mathbf{h}_k^H \mathbf{v}_k s_k + n_k + \mathrm{z}_k, \forall k. \tag{5}$$

Because the power of the finite signal is the square of the signal form, we can obtain the received signal power is $|\mathbf{h}_k^H \mathbf{v}_k|^2$, the noise power is σ_k^2, and the interference power is 0. Therefore, the SINR of the kth IR can be expressed as

$$\mathrm{SINR}_k = \frac{\left|\mathbf{h}_k^H \mathbf{v}_k\right|^2}{\sigma_k^2 + \delta_k^2}, \forall k. \tag{6}$$

Therefore, expression (1b) can be changed into

$$\frac{\left|\mathbf{h}_k^H \mathbf{v}_k\right|^2}{\sigma_k^2 + \delta_k^2} \ge \gamma_k, \forall k. \tag{7}$$

In slot 2, the base station uses energy beamforming vector to make a weighted sum of users' energy. The transmitting energy is given by

$$\mathbf{x} = \sum_{i=1}^{M} \mathbf{w}_i s_i. \tag{8}$$

After the energy passes through the quasi-static wireless channel, the energy signal received by the kth user becomes

$$y_k = \mathbf{h}_k^H \sum_{i=1}^{M} \mathbf{w}_i s_i + n_k, \forall k. \tag{9}$$

In this slot, we do not need to take consideration on the orthogonality between the energy beamforming vector and the channel gain vector so as to collect interference as energy. Thus, the collected energy by the kth user is

$$E_k = (1-\alpha)\zeta_k \left(\sum_{i=1}^{M} |\mathbf{h}_k^H \mathbf{w}_i|^2 + \sigma_k^2 \right), \forall k. \tag{10}$$

Therefore, expression (1c) can be rewritten as

$$(1-\alpha)\zeta_k \left(\sum_{i=1}^{M} |\mathbf{h}_k^H \mathbf{w}_i|^2 + \sigma_k^2 \right) \geq e_k, \forall k. \tag{11}$$

The total transmission power in the unit time can be represented as

$$P_{\text{sum}} = \alpha \sum_{k=1}^{M} |\mathbf{v}_k|^2 + (1-\alpha) \sum_{k=1}^{M} |\mathbf{w}_k|^2. \tag{12}$$

Hence, expression (1a) can be expressed as

$$\min \quad \alpha \sum_{k=1}^{M} |\mathbf{v}_k|^2 + (1-\alpha) \sum_{k=1}^{M} |\mathbf{w}_k|^2. \tag{13}$$

In summary, we can get the parameters of the SWIPT MISO system such as SINR, energy collection, and transmission power as shown in (6), (10), and (12), respectively. In order to eliminate the interference, the constraint of (4) should also be considered. Therefore, the problem can be formulated by combining the objective function and the constraints as provided as

$$\min_{\{\mathbf{v}_k, \mathbf{w}_k, \alpha\}} \quad \alpha \sum_{k=1}^{M} |\mathbf{v}_k|^2 + (1-\alpha) \sum_{k=1}^{M} |\mathbf{w}_k|^2 \tag{14a}$$

$$\text{s.t.} \frac{\left|\mathbf{h}_k^H \mathbf{v}_k\right|^2}{\sigma_k^2 + \delta_k^2} \geq \gamma_k, \forall k, \tag{14b}$$

$$(1-\alpha)\zeta_k \left(\sum_{i=1}^{M} |\mathbf{h}_k^H \mathbf{w}_i|^2 + \sigma_k^2 \right) \geq e_k, \forall k, \tag{14c}$$

$$\mathbf{H}_k^H \mathbf{v}_k = \mathbf{0}, \forall k, \tag{14d}$$

$$0 < \alpha < 1, \tag{14e}$$

where $\mathbf{H}_k^H \triangleq [\mathbf{h}_1 \cdots \mathbf{h}_{k-1} \mathbf{h}_{k+1} \cdots \mathbf{h}_M] \in \mathbb{C}^{N_t \times (M-1)}$. Expression (14) is the transmission power optimization problem, which is simplified as a TPO problem. In the next section, we will offer the solution to the TPO problem in detail.

3 Methodology

In MISO SWIPT system, when the number of the transmitting antenna at the base station is more than or equal to the number of users, zero-forcing beamforming strategy obviously has advantages to eliminate the interference. We introduce this strategy to our discussed system and set $N_t = M$.

Since the problem in (14) is a non-convex problem, it is difficult to solve the problem by using the existing mathematical tools. Therefore, we first simplify the problem. By observing the form of the problem in (14), we find that the constraints of the information beamforming vector $\mathbf{v}_k$ and the energy beamforming vector $\mathbf{w}_k$ are separated, namely, the value of information beamforming vector $\mathbf{v}_k$ is irrelevant with the value of energy beamforming vector $\mathbf{w}_k$ and time switching ratio α. In addition, the value of energy beamforming vector $\mathbf{w}_k$ and time switching ratio α is irrelevant with the value of information beamforming vector $\mathbf{v}_k$.

Therefore, the information beamforming vector $\mathbf{v}_k$ is independent of the energy beamforming vector $\mathbf{w}_k$ and the time switching ratio α. To sum up, the solution to the problem (14) can be carried out in two stages. In the first stage, the information beamforming vector $\mathbf{v}_k$ is solved independently. In the second stage, the energy beamforming vector $\mathbf{w}_k$ and the time switching ratio α are solved simultaneously.

In the first stage, we solve the information beamforming vector $\mathbf{v}_k$. The problem (14) is equivalent to

$$\min_{\{\mathbf{v}_k\}} \sum_{k=1}^{M} |\mathbf{v}_k|^2 \tag{15a}$$

$$\text{s.t.} \frac{\left|\mathbf{h}_k^H \mathbf{v}_k\right|^2}{\sigma_k^2 + \delta_k^2} \geq \gamma_k, \forall k, \tag{15b}$$

$$\mathbf{H}_k^H \mathbf{v}_k = \mathbf{0}, \forall k. \tag{15c}$$

Observing the above equation, we find that the information beamforming vectors of different users can be independently solved; thus, problem (15) can be transformed into

$$\min_{\mathbf{v}_k} |\mathbf{v}_k|^2 \tag{16a}$$

$$\text{s.t.} \frac{\left|\mathbf{h}_k^H \mathbf{v}_k\right|^2}{\sigma_k^2 + \delta_k^2} \geq \gamma_k, \ \forall k \tag{16b}$$

$$\mathbf{H}_k^H \mathbf{v}_k = \mathbf{0}, \ \forall k. \tag{16c}$$

Lemma 1 *When the information beamforming vector* $\mathbf{v}_k$ *gets the optimal value, the SINR constraint is tight.*

Proof We prove it using the rebuttal method. It is assumed that the SINR constraint is not tight when the information beamforming vector $\mathbf{v}_k$ gets the optimal value. Set the optimal value of the information beamforming vector $\mathbf{v}_k$ is $\bar{\mathbf{v}}_k^*$; then, there exists $\mathbf{v}_k = \theta \bar{\mathbf{v}}_k^*$ which makes the SINR constraint being tight. At this point, the new information beamforming vector $\mathbf{v}_k = \theta \bar{\mathbf{v}}_k^*$ causes the transmission power of the base station less than before. Therefore, it is inconsistent with the original hypothesis. □

According to the Lemma above, problem (16) can be changed into

$$\min_{\mathbf{v}_k} |\mathbf{v}_k|^2 \tag{17a}$$

$$\text{s.t.} \frac{\left|\mathbf{h}_k^H \mathbf{v}_k\right|^2}{\sigma_k^2 + \delta_k^2} = \gamma_k,\ \forall k \tag{17b}$$

$$\mathbf{H}_k^H \mathbf{v}_k = \mathbf{0},\ \forall k. \tag{17c}$$

By setting $\mathbf{v}_k = \sqrt{p_k}\bar{\mathbf{v}}_k$ and $\|\bar{\mathbf{v}}_k\|^2 = 1$, (17) becomes

$$\min_{\bar{\mathbf{v}}_k, p_k} \tag{18a}$$

$$\text{s.t.} p_k \left|\mathbf{h}_k^H \bar{\mathbf{v}}_k\right|^2 = \gamma_k \left(\sigma_k^2 + \delta_k^2\right),\ \forall k \tag{18b}$$

$$\mathbf{H}_k^H \bar{\mathbf{v}}_k = 0,\ \forall k \tag{18c}$$

$$\|\bar{\mathbf{v}}_k\| = 1,\ \forall k. \tag{18d}$$

In (18), the minimization of p_k is equivalent to the maximization of $\left|\mathbf{h}_k^H \bar{\mathbf{v}}_k\right|^2$; thus, we can have

$$\max_{\bar{\mathbf{v}}_k} \left|\mathbf{h}_k^H \bar{\mathbf{v}}_k\right|^2 \tag{19a}$$

$$\text{s.t.} \mathbf{H}_k^H \bar{\mathbf{v}}_k = \mathbf{0},\ \forall k \tag{19b}$$

$$\|\bar{\mathbf{v}}_k\| = 1\ ,\ \forall k. \tag{19c}$$

The solution of (19) is given by

$$\bar{\mathbf{v}}_k = \frac{\mathbf{U}_k \mathbf{U}_k^H \mathbf{h}_k}{\left\|\mathbf{U}_k \mathbf{U}_k^H \mathbf{h}_k\right\|}, \tag{20}$$

where $\mathbf{U}_k$ is the orthogonal basis of $\mathbf{H}_k^H$. By (20), we have

$$p_k = \frac{\gamma_k \left(\sigma_k^2 + \delta_k^2\right)}{\left\|\mathbf{U}_k \mathbf{U}_k^H \mathbf{h}_k\right\|^2}. \tag{21}$$

Therefore, the optimal value of the information beamforming vector $\mathbf{v}_k$ can be written as

$$\bar{\mathbf{v}}_k^* = \sqrt{\gamma_k \left(\sigma_k^2 + \delta_k^2\right)} \frac{\mathbf{U}_k \mathbf{U}_k^H \mathbf{h}_k}{\left\|\mathbf{U}_k \mathbf{U}_k^H \mathbf{h}_k\right\|^2}. \tag{22}$$

In the second stage, the time switching ratio α and the energy beamforming vector $\mathbf{w}_k$ are solved. The problem (14) can be equivalent to

$$\min_{\{\mathbf{w}_k\},\alpha} \alpha \sum_{k=1}^{M} \left|\bar{\mathbf{v}}_k^*\right|^2 + (1-\alpha) \sum_{k=1}^{M} |\mathbf{w}_k|^2 \tag{23a}$$

$$\text{s.t.}\ (1-\alpha)\,\zeta_k \left(\sum_{i=1}^{M} \left|\mathbf{h}_k^H \mathbf{w}_i\right|^2 + \sigma_k^2 \right) \geq e_k, \forall k, \tag{23b}$$

$$\alpha \in (0, 1)\,. \tag{23c}$$

Let us set $\mathbf{W}_k = \mathbf{w}_k \mathbf{w}_k^H$. Ignoring the rank-one constraint, we can have

$$\min_{\{\mathbf{W}_k,\alpha\}} \alpha \sum_{k=1}^{M} \left|\bar{\mathbf{v}}_k^*\right|^2 + (1-\alpha) \sum_{k=1}^{M} \mathbf{Tr}\left(\mathbf{W}_k\right) \tag{24a}$$

$$\text{s.t.} \sum_{i=1}^{M} \mathbf{h}_k^H \mathbf{W}_i \mathbf{h}_k \geq \frac{e_k}{(1-\alpha)\,\zeta_k} - \sigma_k^2, \forall k, \tag{24b}$$

$$\mathbf{W}_k \succ 0, \forall k, \tag{24c}$$

$$\alpha \in (0, 1)\,. \tag{24d}$$

In the problem (24), the left of the first constraint is a linear function, and the right is a convex function of the time switching ratio α, so the first constraint is a convex constraint. The second and third constraints are obviously convex constraints, so all constraints in the problem (24) are convex constraints.

Obviously, the objective function of the problem (24) is linear about $\mathbf{W}_k$, so the objective function is a convex function about $\mathbf{W}_k$. Let $\left\{\mathbf{W}_k^*\right\}$ denote the optimal solution to problem (23). If Rank $\left(\mathbf{W}_k^*\right) = 1, \forall k$, we can use the convex optimization toolbox to solve it. Then the optimal beamforming vector $\mathbf{w}_k^*$ could be obtained by the eigenvalue decomposition (EVD) of $\left\{\mathbf{W}_k^*\right\}$. Thus, we discuss the rank-one constraint in the following.

Lemma 2 *For problem (24), given* $e_k > 0, \forall k$, *we have* $\left\{\mathbf{W}_k^*\right\}$ *satisfies Rank*$\{\mathbf{W}_k^*\} = 1, \forall k$.

Proof The objective of problem (24) could be seen as linear relation of α and transmitting power in the energy receiving phase. On the other hand, (24b) is its harvest power constraints. So, this problem can be considered as a special case of the problem in [30]. □

Therefore, we firstly assume a known α and solve the problem (24) by the convex optimization toolbox. By the optimal result above, we can get the relationship between $\mathbf{W}_k^*$ and α. For this case, the objective function can be seen to contain the only variate α. According to the definition, time-switching factor has a range of $0 < \alpha < 1$, so then we can find the minimum (24a) by scanning the range. The algorithm for solving the problem is given in Algorithm 1.

Algorithm 1 Optimal Algorithm for Problem (24)

```
Step1: Given $\alpha$, solve (24) and obtain the optimal solutions $\{\mathbf{W}_k^*(\alpha)\}$;
Step2: Find $\alpha^*$ to make $\min_{\{\alpha\}} \alpha \sum_{k=1}^{M} \left|\bar{\mathbf{v}}_k^*\right|^2 + (1-\alpha) \sum_{k=1}^{M} \mathbf{Tr}\left(\mathbf{W}_k\right)$;
Step3: Obtain $\mathbf{w}_k^*$ by EVD of $\mathbf{W}_k^*$.
```

In summary, we have solved the optimal information beamforming vector, the optimal energy beamforming vector, and the optimal time switching ratio, by interior point algorithm, using existing software, e.g., CVX. And finally, we can use (12) to obtain the form of the transmission power of the base station. According to [34], it is known that the complexity for solving is $O\left(\sqrt{MN_t}\left(M^3N_t^2+M^2N_t^3\right)\right)$.

4 Implementation and performance analysis

4.1 Simulation parameters and simulation process

We assume that the base station of the MISO SWIPT system equipped N_t transmitting antennas, and the receiver has M users with one antenna each. In order to eliminate the interference, it is necessary to satisfy $N_t \geq M$. We set $N_t = M = 4$. For the sake of reducing the computational complexity, we assume that the parameters of each user are the same; the SINR threshold γ_k, the noise power σ_k^2, the energy conversion efficiency ζ_k, and the energy threshold ε_k are equal, that is, $\gamma_k = \gamma$, $\sigma_k^2 = \sigma^2$, $\zeta_k = \zeta$, and $\varepsilon_k = \varepsilon$. It is further assumed that the channel is modeled by the Rician fading [31], which is given by

$$\mathbf{h}_k = \sqrt{\frac{K_R}{1+K_R}}\mathbf{h}_k^{\mathrm{LOS}} + \sqrt{\frac{1}{1+K_R}}\mathbf{h}_k^{\mathrm{NLOS}}. \tag{25}$$

where $\mathbf{h}_k^{\mathrm{LOS}}$ is the LOS deterministic component and $\mathbf{h}_k^{\mathrm{NLOS}}$ is the Rayleigh fading component. And other details are described in [31].

The application of joint beamforming strategy in SWIPT system is studied in this paper. To verify the joint beamforming strategy has better performance than the traditional beamforming strategy, we need to simulate the energy collection of ER and the transmission power of base station in the SWIPT system. The parameters used in this simulation are provided in Table 2.

In the second part of this paper, the expressions of the various parameters are described in detail, for instance, the energy collection and the transmission power, which are given by (10) and (12), respectively. In the third part of the paper, TPO problem is solved in detail. With the above theoretical basis, we can carry on a simulation of this MISO SWIPT system.

Table 2 Simulation parameters

Parameter	Value
System bandwidth	Normalized bandwidth
Transmit power threshold	1 W
Antenna noise power	$\sigma^2 = -70$ dBm
Demodulation noise power	$\sigma^2 = -50$ dBm
SINR threshold	0∼40 dB
Energy conversion efficiency	$\zeta_k = 0.5$
Energy threshold	− 20∼ 5 dBm

4.2 Simulation result analysis

In this section, we present a detailed analysis of the proposed joint beamforming algorithm and two comparison algorithms; they are conventional beamforming and zero-forcing beamforming. Conventional beamforming means the beamforming vector is used to make a weighted user information, and there is no orthogonality relation with the channel gain vector. Zero-forcing beamforming refers to the orthogonality between the beamforming vector and the channel gain vector.

First, we verify the increasing function of the objective function about the time switching ratio as shown in Fig. 4. For arbitrary energy threshold and SINR threshold, the increasing function is established by taking $e = -20$ dBm and $\gamma = 20$ dB. The abscissa is the time switching ratio, and the ordinate is the transmission power of the base station.

As we can see in Fig. 4, the transmission power of the base station increases with the time switching ratio. This proves the correctness of the derivation process in Section 3. Thus, the minimum value of the objective function is obtained when $\alpha \rightarrow 0$. The time switching ratio $\alpha \rightarrow 0$ means that in each time unit, there are very small slots for information transmission and larger time slots for energy harvesting such as low-power implantable biomedical devices. In order to maintain its normal work, most of the time is in wireless charging. It only takes a very little time for information feedback from internal equipment.

Then, the relation between the transmission power of the base station and the SINR threshold of IR is studied when the energy threshold is fixed as shown in Fig. 5.

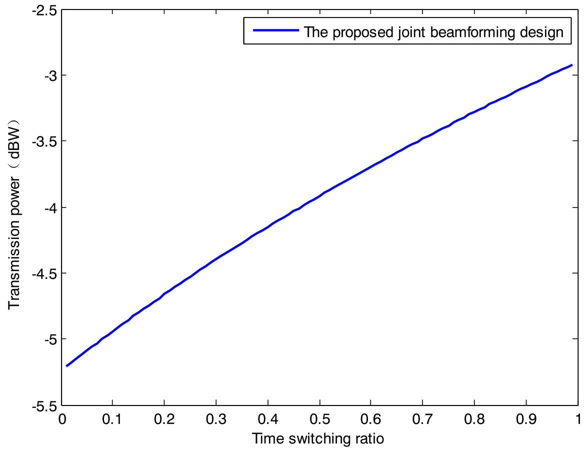

Fig. 4 The relation between transmission power and time switching ratio

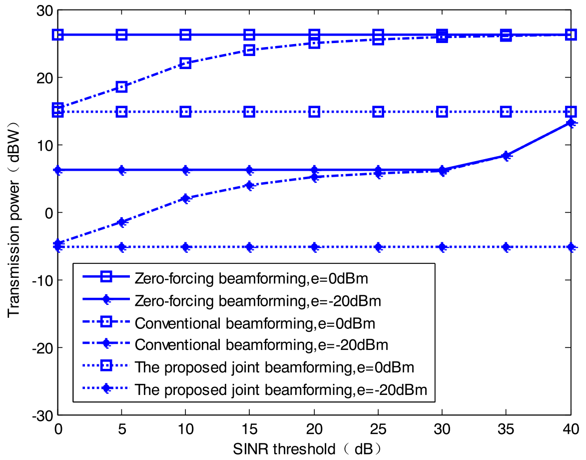

Fig. 5 The relation between transmission power and SINR threshold

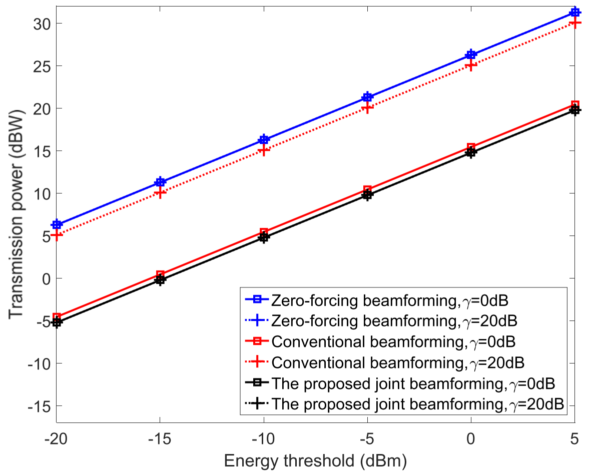

Fig. 6 The relation between transmission power and energy threshold

As can be seen in Fig. 5, the proposed joint beamforming design is superior to the conventional beamforming and zero-forcing beamforming. This is because the proposed method can eliminate the interference in the phase of information reception, so it is easy to satisfy the SINR threshold requirement of the IR. Moreover, the proposed method can collect the interference between users during the energy reception phase, so that to increase the energy collection, and thus more easily to meet the energy threshold requirements of the ER. Finally, the purpose of saving the transmission power of the base station is achieved. In addition, we find that the transmission power of the base station does not change with the SINR threshold under the condition that the energy threshold is fixed. This is because the base station's transmission power refers to the average power of the two slots, as shown in (12). Since the information slot ratio is very small, the average transmission power basically comes from the energy slot. However, energy consumption is irrelevant with the SINR threshold.

Next, we study the relation between the transmission power of the base station and the energy threshold of ER when the SINR threshold is fixed as shown in Fig. 6.

As we can see in Fig. 6, when the SINR threshold is fixed, the transmission power of the base station increases with increasing energy threshold. This is because, in order to meet higher energy requirements, the base station must send more power. We can also see that the transmission power of zero-forcing beamforming and the proposed joint beamforming with different γ are the same. It is because energy consumption is irrelevant with the SINR threshold. In addition, it can be seen in Fig. 6 that the proposed joint beamforming design is superior to the conventional beamforming and zero-forcing beamforming design. The reason is the same as mentioned above.

Then, we study the relation between the transmission power of the base station and the number of antennas at the base station when the SINR threshold of IR and the energy threshold of ER are fixed as shown in Fig. 7.

When the SINR threshold and the energy threshold are fixed as $e = -10$ dBm and $\gamma = 10$ dB, respectively, the transmission power of the base station decreases as the number of antennas increases as depicted in Fig. 7. This shows that the application of large-scale antenna array can save the transmission power of the base station. In addition, when the number of antennas is the same, the proposed joint beamforming design is better than the conventional beamforming and zero-forcing beamforming.

We also have another target in this paper which is to realize the independent control of information and energy, so as to collect excess interference between users as a source of energy and then improve the energy collection of ER. Therefore, we also study the relation between the energy collection and the energy threshold of the ER as illustrated in Fig. 8.

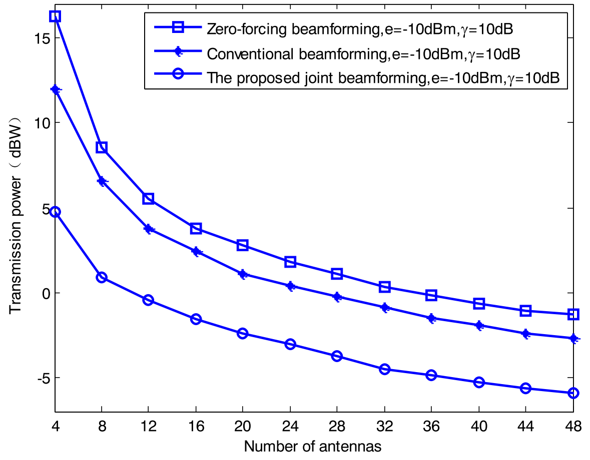

Fig. 7 The relation between transmission power and antenna number

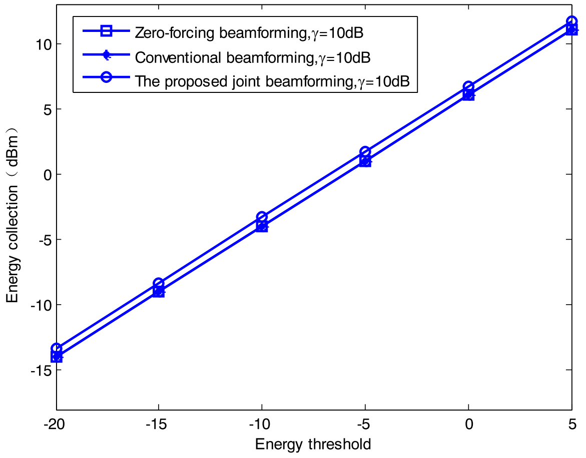

Fig. 8 The relation between energy collection and energy threshold

Figure 8 shows that with the same energy threshold, conventional beamforming has the same performance as zero-forcing beamforming. This is because, in the above two kinds of design, energy collection only means energy threshold. On the other hand, the joint beamforming design has a better performance than conventional beamforming and zero-forcing beamforming on account that beamforming design can independently transfer information and energy. It makes the optimization problem based on joint beamforming be not tight to energy constraint. Therefore, the proposed joint beamforming design has a better performance.

5 Conclusions

Traditional beamforming strategy uses the same beamforming vector to align information resources and energy resources, which does not consider the diversity of resources in the SWIPT system and the utilization of interference. This results in a waste of system resources. In this paper, a joint beamforming strategy based on SWIPT system has been proposed, which realizes the independent control of information resources and energy resources and reduces the mutual restraint between the two resources. As a result, the interference in the SWIPT system is effectively used. In order to eliminate the interference, we still use the zero-forcing beamforming strategy with the information beamforming vector, and we need not consider the energy beamforming vector too much. In this paper, we propose a TPO problem with complex constraints, which is a non-convex problem. Experimental results show that the joint beamforming strategy can achieve a better energy collection at the same transmission power of the base station and can also attain a less transmission power at the same energy collection.

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Authors' contributions

LM, YW, YX, SW, and TMB conceived the idea of the paper. YW designed and performed the experiments. LM and YX analyzed the data. YW wrote the paper. LM, YX, SW, and TMB revised the paper. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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