SCHOOL OF ELECTRICAL ENGINEERING AND TELECOMMUNICATIONS

Resource Allocation Design for Efficient SWIPT Systems

By

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Abstract

In this thesis, we study the resource allocation algorithm for simultaneous wireless information and power transfer (SWIPT) systems with multiuser. In particular, we focus on separated receivers which can harvest energy and decode information respectively. We consider the system performance using average system wireless energy transfer efficiency which takes into account the maximum transmission power at the transmitters and minimum required signal-to-interference-plus-noise ratio (SINR) at multiple receivers. The proposed resource allocation algorithm improves energy transfer efficiency and guaranteeing secure communication. In particular, we aim at maximizing the average system wireless energy transfer efficiency via jointly transmit transforming vectors, maximum transmission power, and minimum requirement SINR. The transform of non-convex optimization problem is achieved via semidefinite programming (SDP). The solution of transformed convex optimization problem is obtained using SDP relaxation. In addition, we proofed that our solution can achieve the global optimum of the original problem. Finally, the performance of the proposed system is illustrated by simulation results.

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Abbreviations

SWIPT Simultaneous wireless information and power transfer

SINR Signal-to-interference-plus-noise ratio

SDP Semidefinite programming

QoS Quality of Service

EH Energy harvesting technology

ID Information decoding

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1. Introduction

Background

The rapid development of wireless communications has significantly improved people’s quality of life. Equipment such as smartphones, electronic tablets and sensors, is widely used in various fields, for example, electronic medical care, fire prevention, automatic control, environmental monitoring [1]. Under the next telecommunications standard, the fifth-generation (5G) of wireless communication, it is estimated that at least l00 billion devices worldwide would be connected into network and approximately 7.6 billion mobile users in the worldwide enjoying an up to 10 Gb/s individual user experience [2], [3]. Meanwhile, there are great demands on the supplement of energy. However, there are tremendous problems in the current energy supply. On the one hand, the energy storage of batteries is limited and has expensive replacement costs or cannot be replaced in some special scenarios [1]. On the other hand, both green communications and the usage of energy-saving devices are the vital requirements for future 5G systems, which has caused an increasing awareness in the industries and academia [4]. Recently, it is expected that energy harvesting technology (EH) can be used as an available solution to achieve self-sustainable communication systems, which can satisfy the requirements of future wireless communications and maintain Quality of Service (QoS) [5]. By applying the EH technology, base stations capture and convert harvested energy to support their regular operation [6]. These energies come from nature such as wind energy and solar energy, etc. An alternative solution to overcome the shortages of EH problem is wireless power transform (WPT) technology [7]. WPT uses time-varying electric, magnetic, or electromagnetic fields rather than wires to transform electrical energy, which is useful for powering small but massive amount of wireless communication devices. This electrical equipment usually located in some special scenarios, where are inconvenient, dangerous or impossible for interconnecting conductors. From the above, wireless power transfer greatly reduces the cost of equipment maintenance.

1.1 Literature review

In the past two decades, research on WPT has had significant improvement. In near-field WPT, power is transmitted by a beam of electromagnetic radiation, such as a microwave or a laser beam [8], [9], [10]. The far-field WPT technique has become a hot topic recently. However, there are still many shortages impeding the development of near-field WPT, for example distance constraints, difficulty in maintaining field strength at a safe level, high initial cost, difficulty in tuning resonant inductors, and infeasibility of using high frequency and air ionization techniques in power supplies [11]. Long-distance communication network is a critical part of wireless communication. Besides, the traditional wireless communication system only focuses on signal-to-noise ratio (SNR), but ignore systems' transmission efficiency importance. As long as the SNR could satisfy the minimum requirements, the transmit signal could be decoded at the receiver. The aim of traditional wireless communication is reached. However, the energy transmission efficiency is also an important indicator in WPT. The low energy transmission efficiency also obstructs the development of WPT due to the associated path loss. This leads to an urgent improvement of far-field WPT.

An improved technology which have the ability to transfer information and transform power during this period was proposed [12].

SWIPT provide a promising solution to get rid of the wires for truly future mobile wireless communication [13], [14]. The authors in [15] provided the basic concept of SWIPT systems including hardware components of rectenna circuits and practical application in many field. It also explains the advantages of SWIPT technologies, when 5G networks set about allocating resource and making radio networks cooperative and cognitive. A fundamental tradeoff between the energy rate and information reliability for flat fading channel has been studied in [16]. The concept of capacity-energy function is provided and several experiments have been done for different channels, which points out that this expression is a non-increasing convex function [16]. In paper [17], the researchers also studied the balance between the energy harvesting rate and information processing reliability for frequency selective fading, where a perfect receiver has been assumed, namely the process of energy harvesting and information decoding performed at the same time for one received signal. Three types of receivers have been proposed to meet the requirement as much as possible, that is the power-splitting receiver, separated receiver, and time-switching receivers [17]. Moreover, the authors in [18] investigate the way of signal and energy conversion at the wireless link. In particular, it is assumed that only two endpoints in this link. The channel state is modeled as narrowband flat-fading. Also, the interference is added to this link. The optimal mode switching rules have been given in [18], which provide a possible solution for the high performance of future wireless communication systems. In addition , paper [19] came up with a power allocation algorithm at a point-to-point wireless link with an energy-splitting receiver, which offers precious experiment for optimal practical receiver design about SWIPT. The author in [20] based on power splitting hybrid receivers and studied two different resource allocation algorithm for receivers who are the power streams are continuous and have arbitrary power splitting ratios as well as receivers who are the power streams are discrete and have fixed power splitting ratios respectively. The result shows that this iterative resource allocation algorithm could reach relevant satisfactory results when there are few iterations. In previous studies, it is assumed that this model is linear. In particular, it is assumed that the power conversion efficiency is constant. However, the experiment shows that RF-EH circuits are nonlinear in practical systems [21]. To restore the real scene, the author in [21] come up with a EH model which no longer satisfy the ideal linear principle and combined with logistic function and real data. Also, multi-users resource allocation has been studied in [22]. The system performance shows a significant increase under the nonlinear energy harvesting model. paper [23] studies a novel iterative algorithm for the energy harvesting model, in which the model is assumed as a non-linear one. This algorithm has ability to this difficult question and get the relatively best result. This robust beamforming design shows the significant benefits in harvested energy. Moreover, the author in [24] studies resource allocation algorithm for energy-efficient SWIPT system and proposes that rank-constrained semidefinite program (SDP) can be used in the non-convex optimization problem. The proper trade-off solution improves system energy efficiency. Furthermore, as the increasing signal power for SWIPT, the safety in physical layer becomes attract people's attention. The authors in [25] design a resource allocation algorithm. This algorithm considers multiple-input-single-output (MISO) systems and multiusers. Also, the semidefinite programming (SDP) is adopt. The simulation results show that this algorithm well-performed in secure communication. Paper [26] also focus on MISO system and solve the anti-eavesdropping problem though obtaining the optimal beamforming result by the technique of semidefinite relaxation (SDR). Moreover, the authors also consider the actual situation with adding a fixed signal-to-interference-plus-noise ratio (SINR) is added. Paper [27] proposes a distributed beamforming design framework for the imperfect CSI, which has various cells cooperation and artificial noise. The local channel state information in this system can be obtained by each base station through considering robustness under different scenarios [27]. The simulation results show the minimum power can be guaranteed to satisfy the requirement of information decoding and energy harvesting for authorized users while unauthorized users cannot get information. For the same system model, the authors in [28] propose using multiple artificial redundant signals (MARSs) when transmitting signals. Only transmit power maintained at the threshold by combining the beamforming phase optimization with the covariance matrixes of MARSs. Thus, the requirement of transmission rate can get guarantee as well as the energy harvesting requirement, while SINR at Eves is lower than the threshold due to artificial noise. The result is satisfying for the non-robust design. Gaussian randomization procedure also provides an approximately optimal solution for the robust design. The paper [29] studied the secure method to achieve the power and time setting, aiming at maximizing safety and efficiency and proposed that using Lagrange dual problems to substitute non-convex SEE maximization problems. This approach can decrease the complexity though solving two SEE resource allocation algorithms [29].

1.2 Contributions

The traditional researches usually focus on several information decoding receivers and energy harvesting receivers. The general results could be given. However, the situation often became more complicated when the users number increasing. This article discusses the multi-users system model. Therefore, the simulation results would more reliable. Also, the result would provide some reference opinions for the future works.

1.3 Thesis Organization

In this article, we adopt the linear energy harvesting model for multiple users SWIPT systems. The purpose of this article is to obtain optimal the SWIPT system performance by maximizing the energy transmission efficiency. In particular, the SWIPT system harvests energy form a variety of energy source, which includes the non-renewable energy source and the renewable energy source. In our system, we adopt separated receiver structure. In particular, the receivers are divided in two part. The one is for harvest energy, and the other is used for decode information.

In the following, we focus on the concept of SWIPT and the system model. In Section 2, we introduce beaming, receiver structures, and resource allocation in SWIPT system respectively, which give readers the key points of this article. In Section 3, we show the provided system model and formulate the resource allocation design as an optimization problem. In Section 4, we provide the problem solution and the proof process is given. In section 5, we use Matlab to simulate and the results are shown.

2. SWIPT Systems

2.1 Multi-Antenna Techniques: Beamforming for SWIPT Systems

In Long-Term Evolution (LTE)，there are three main multiple antenna techniques, including diversity processing, spatial multiplexing, and beamforming. Diversity processing is a mature technology, which has been used in early mobile communication. Multiple antennas can be set at the transmitter, the receiver or both to increase the received signal power as well as reduce the amount of fading. Spatial multiplexing is a relatively new technology, compared with diversity processing. The transmitter use multiple antennas. Also, the receiver both adopt the multiple antennas technique. In this way the data rate could increase [30], [31]. When using beamforming in the base station (BS), the more antennas used, the larger cell coverage. Moreover, the performance of beamforming is better than diversity processing or spatial multiplexing when the antennas are close together, because of constructive interference and the high received signal power. This characteristic of beamforming makes it more suitable for multi-user SWIPT system [32].

In this article, we pay attention to the beamforming for SWIPT systems. The basic principle of beamforming is that the BS uses multiple antennas to adjust the energy distribution radiated in the channel. In particular, the angles can be decided by phase ramp coming from the information. Then, constructive interference can be achieved. It means that the amplitudes and phases can be set though adjust the antenna weights. In multi-antenna SWIPT system, all kinds of antenna weights can be used at different sub-carriers processing, then the synthetic antenna beams can be produced and send to different directions. As a result, the multi-user SWIPT system can be achieved by beamforming [33], [34].

There are a variety of hardware circuitries achieving the energy harvesting from the RF. An improvement voltage double circuit based on complementary metal–oxide–semiconductor (CMOS) has been proved to a significant increase in output energy compared with traditional circuits at 0 dBm input energy [35]. The actual receiver architecture, such as separated versus integrated information and energy receivers, can use dynamic power splitting (DPS) to achieve optimal receive [36]. Therefore, we ignore the type of energy harvesting circuit and only consider beamforming design.

Total harvested power at $\mathrm{ER_j}$:

$$\mathrm{P_{ER_j}} = \eta\varepsilon\left\{\left|\vec{\mathbf{g}}_{\mathbf{j}}^{\mathbf{H}}\vec{\mathbf{x}}\right|^2\right\} = \eta\sum_{k=1}^{K}\left|\vec{\mathbf{g}}_{\mathbf{j}}^{\mathbf{H}}\vec{\mathbf{w}}_{\mathbf{k}}\right|^2 \tag{1}$$

where $\vec{\mathbf{x}}$ is the received signal, $\vec{\boldsymbol{g}}_{\boldsymbol{j}}$ is the channel gain at channel j, η is power transmission efficiency.

Total harvested power in the system

$$\mathrm{P_{ER_j}^{total}} = \sum_{i=1}^{J}\sum_{k=1}^{K}\left|\vec{\mathbf{g}}_{\mathbf{j}}^{\mathbf{H}}\vec{\mathbf{w}}_{\mathbf{k}}\right|^2 \tag{2}$$

2.2 Four types of the basic receiver structure

In general, if received signal is going to information decoding, it cannot harvest energy again. Special receiver structures are needed and have been proposed in many papers to satisfy the requirement of the SWIPT system, such as separation receiver structure, time switching receiver, power splitting receiver, antenna switching receiver and spatial switching receiver. In this section, we outline four common receiver configurations, which has shown as follow [37]:

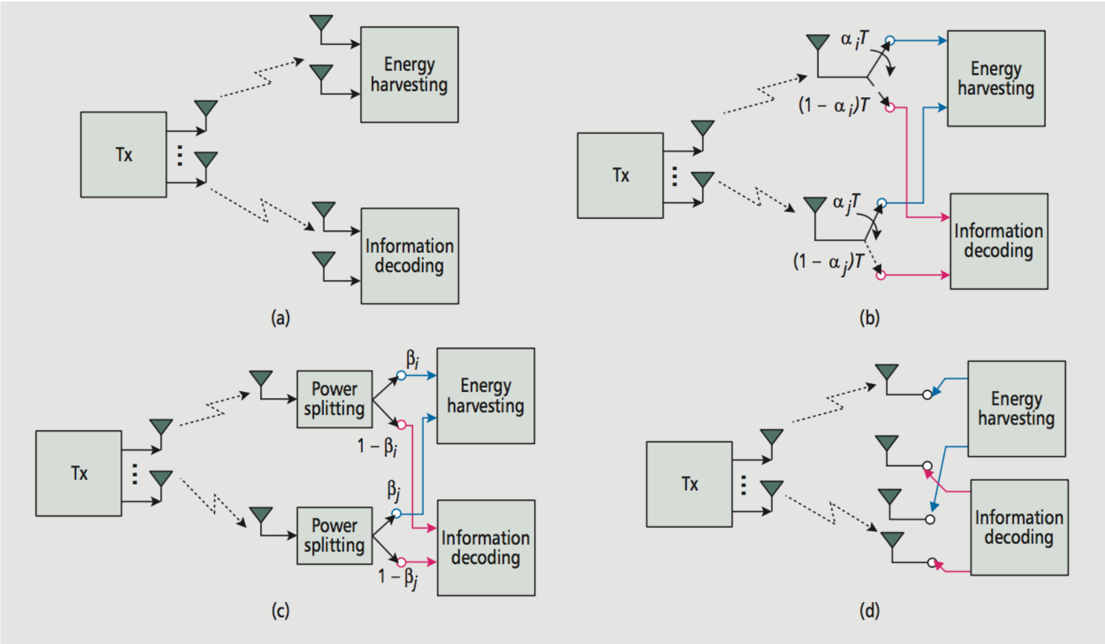


Fig. 2-1 Four types of receiver structure [37].

The separated receiver has shown in fig 2-1(a), is can be achieved by two separated receivers with separated antennas. Also, the common multiple antenna transmitters provide service for these receivers [38]. There is two information need to collect to achieve the trade-off between ID receiver and EH receiver, including channel state information (CSI) and the relative information collected by the receivers [35]. The separated receiver can achieve information and energy transmission without time delay, namely the process of information decoding and energy harvesting will work simultaneously during the information transmission period. The applications with strict transmission requirements or delays limits would prefer this structure. This technique is closer to the optimal problem standard of information theory. In this article, we also use this structure in SWIPT systems.

Fig 2-1(b) shows the time switching receiver. Except for information decoder and RF energy harvester, the time receiver also need to facilitate antennas' switch [38]. The function of the switch is achieving the convert between the signal decoder and the RF power harvester. The principle about switch is decided by the periodical time switching sequence. Particularly, the principle about switch can be adjusted based on the different requirement of different system [37]. Only a simple hardware implementation is required. However, it requires very precise time synchronization and information or power allocation scheme.

Figure 2-1(c) is power splitting receiver. At the antenna, the RF signals have two directions based on a certain energy separated ratio [39]. A direction is going to decode the information; the other goes to harvest power. In particular, the process of ID and EH are facilitated simultaneously [40]. To obtain the optimal energy, the suitable power splitting ratio is required.

Figure 2-1(d) shows the antenna receiver. The antennas can achieve dynamic switch between decoding and rectifying though making use of the form of array which located in the relay node and carried out the process of decoding and rectifying using the antenna elements, which results in low complexity. The strongest one is used for signal processing, and the other paths are located for rectifying [41]. The antenna receiver technology needs to give the best answer during the communication process, namely the way of optimal schedule and the arrangement of the information decoding and energy collection of the antenna elements.

2.3 Resource Allocation Algorithms

The resource allocation in the SWIPT system can achieve the improvement of network performance as well as the high utilization of network resources under the condition of satisfying the QoS requirement through flexible allocation and dynamic adjustment of resources available within the network. In this article, we discuss three resource allocations, include power allocation algorithm, relay selection algorithm and joint resource allocation algorithm.

A. Power Allocation Algorithm

Power allocation technology is used to distribute the total available power at the transmitter. The goal is to guarantee the transmission performance, which relates to power loss, communication link characteristics and service guarantee etc. Power allocation algorithm based on game-theoretic can coordinate the question of collaboration and competition during the power allocation. It can also design the cooperation and competition mechanism, which can motivate users to participate in network activities [42] [43].

In paper [44], a distributed precoding problem has been proposed, which can be used in SWIPT system based on decode-and forward MIMO relay networks. A non-cooperative game model is proposed based on the practical scenario. In particular, two rational game players are source and relay respectively. Also, the function of signal rate as well as the harvesting power is used to measure the network performance as the game award. Another power allocation algorithm is related to the signal to interference ratio (SINR). Paper [45] studies multi-link interference channel with SWIPT. The goal is to get the optimal threshold of SINR with the limitations of minimum energy harvesting and maximum transmit power. In this paper, the nonconvex problem is solved a centralized method. Furthermore, power allocation algorithm based on throughput optimization is also an alternative algorithm for SWIPT. Paper [46] combines the wireless network with classic cognitive wireless system. In this scenario, it is assumed that the classic cognitive users can harvest energy form nearby transmitters from a primary network. The cognitive users can occupy the channel and transmit information using the harvested energy when they far away from the primary network. The simulation result shows that the random geometric model can maximize the spatial throughput.

B. Relay Selection Algorithm

Relay communication plays a vital role in long-distance SWIPT to overcome Multipath effects, path loss, shadow fading etc. Relay selection algorithm is proposed to trade off the ID and EH. A relay selection algorithm based on outage probability optimization is proposed in [47]. Three relay selection mechanisms are used to trade off the throughput and outage probability according time, threshold or weight. Based on the algorithm in [47], the author in [48] studies how to make use of side information to improve the performance in SWIPT system, including energy side information and channel side information. The simulation result shows a significant improvement of throughput can be achieved using this algorithm.

C. Joint Resource Allocation Algorithm

To improve the total network performance, Multiple factors should be considered, namely achieving the joint resource allocation. In particular, the power allocation algorithm with the channel information or relay selection.

a) Joint channel information and power allocation algorithm

The paper [49] proposed the joint optimal power and subcarrier allocation strategy based on orthogonal frequency division multiplexing (OFDM). The goal is optimizing the weight information rate.

b) Power allocation algorithm combining with relay selection

The bisection search method can be used as a solution to the suboptimal scheme in a relay SWIPT system. At first, the power allocation in the source node and relay node processes using extensive search method, which assumes that the single relay participates in information transmission. The aim relay is chosen as the one which has the maximum instantaneous information rate based on the power allocation scheme. The objective to maximize is throughput [50].

3. System Model

3.1 System Model

A multi-user MIMO broadcast system for SWIPT has been built and the system model has been provided in Fig.3-1. As the system shown, the renewable energy source has been collected and storage in the battery. Only the battery power is insufficient, would the grid network be used as an optional solution of energy supplement. In the downlink of this system, it is assumed that there are K numbers information decoding receivers and J numbers energy harvesting receivers. It is assumed that the BS has N_T antennas and users are equipped with single antenna devices. The transmitter sends RF signals to the energy harvesting receivers only for harvesting energy, while the information receivers split RF signal to decode information [51] - [60].

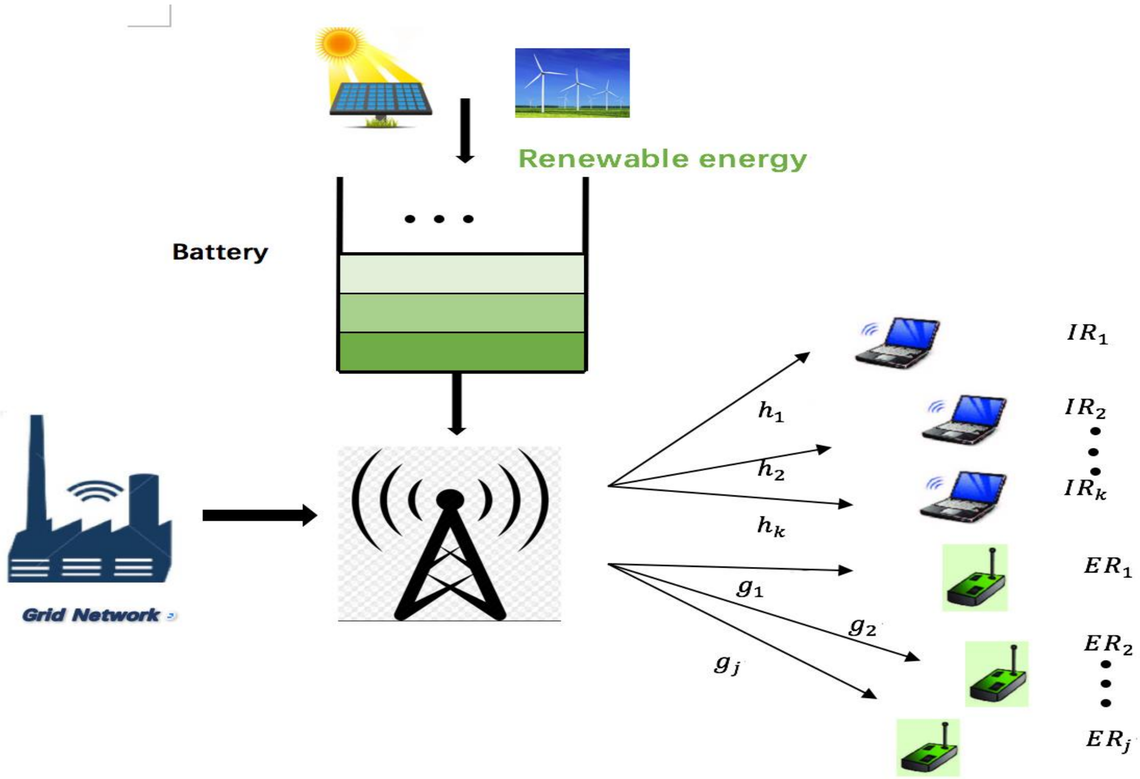


Fig 3-1. Multi-user MIMO system for SWIPT system model.

In a downlink SWIPT system, the received signal at the information decoding receiver k and energy harvesting receiver j are given by, respectively,

$$y_{IR_k} = \vec{\boldsymbol{h}}_{\boldsymbol{k}}^{\boldsymbol{H}} \vec{\boldsymbol{x}} + z_k \tag{3}$$

$$y_{ER_j} = \vec{\boldsymbol{g}}_{\boldsymbol{j}}^{\boldsymbol{H}} \vec{\boldsymbol{x}} + z_j \tag{4}$$

where $\vec{\boldsymbol{x}}$ represents the transmitted symbol vector. The channel vectors are represented by $\vec{\boldsymbol{h}}_{\boldsymbol{k}}^{\boldsymbol{H}}$ and $\vec{\boldsymbol{g}}_{\boldsymbol{j}}^{\boldsymbol{H}}$, where $\vec{\boldsymbol{h}}_{\boldsymbol{k}}^{\boldsymbol{H}}$ means the vector from the transmitter to the information receiver k and $\vec{\boldsymbol{g}}_{\boldsymbol{j}}^{\boldsymbol{H}}$ means the vector from the transmitter and the energy harvesting receiver g. It is assumed that both multipath fading and path loss in related channels are included by the variables$\vec{\boldsymbol{h}}_{\boldsymbol{k}}^{\boldsymbol{H}}$ and $\vec{\boldsymbol{g}}_{\boldsymbol{j}}^{\boldsymbol{H}}$. We also add the additive white Gaussian noises in receive antennas at IR_k and ER_g, which has $z_k \sim N(0, {\sigma_{ant}}_k^2)$ and $z_j \sim N(0, {\sigma_{ant}}_j^2)$.

3.2 Energy beamforming

Beamforming is used for directional signal transmission in sensor arrays, which is a signal processing technique. It can achieve spatial selectivity through emit signals at particular angles. In this system, random signals are chosen as the energy carrier, and transmitted symbol vector $\vec{x}$ shows as follow:

$$\vec{x} = \sum_{k=1}^{K} \vec{\boldsymbol{w}}_{\boldsymbol{k}} s_k \tag{5}$$

The $\vec{\boldsymbol{w}}_{\boldsymbol{k}}$ represents information beamforming vector, which is the pseudo-random transmit signal. $\mathrm{s_k}$ means the information bear of IR_k and is also the pseudo-random transmit signal and satisfies $\varepsilon\{|s_k|^2\} = I$.

3.3 Transmission efficiency

The performance metric of this system is transmission efficiency, namely maximizing the transmission efficiency as well as maintain the requirement of SINR.

The received signal r_k at information decoding receiver k is:

$$r_k = \vec{\boldsymbol{h}}_{\boldsymbol{k}}^{\boldsymbol{H}} \vec{\boldsymbol{w}}_{\boldsymbol{k}} s_k + \sum_{t \neq k} \vec{\boldsymbol{h}}_{\boldsymbol{k}}^{\boldsymbol{H}} \vec{\boldsymbol{w}}_{\boldsymbol{t}} s_t + n_k \tag{6}$$

where $\vec{\boldsymbol{h}}_{\boldsymbol{k}}^{\boldsymbol{H}} \vec{\boldsymbol{w}}_{\boldsymbol{k}} s_k$ is the desired part, while $\sum_{t \neq k} \vec{\boldsymbol{h}}_{\boldsymbol{k}}^{\boldsymbol{H}} \vec{\boldsymbol{w}}_{\boldsymbol{t}} s_t$ represents interference part, n_k is noise.

To maximize the transmission efficiency in this system, we need to satisfy the minim signal to interference ratio (SINR), then maximize the power we get from the transmitters.

The SINR in information decoding receiver k is:

$$SINR_k = \frac{|\vec{\boldsymbol{h}}_{\boldsymbol{k}}^{\boldsymbol{H}} \overrightarrow{\boldsymbol{w}_{\boldsymbol{k}}}|^2}{\sum_{t \neq k} |\vec{\boldsymbol{h}}_{\boldsymbol{k}}^{\boldsymbol{H}} \overrightarrow{\boldsymbol{w}_{\boldsymbol{t}}}|^2 + Z_k^2} \tag{7}$$

Total transmission power in the system

$$\mathrm{P_T} = \sum_{\mathrm{k=1}}^{\mathrm{K}} |\vec{\mathbf{w}}_{\mathbf{k}}|^2 \tag{8}$$

The power dissipation of the system as

$$\mathrm{TP(w, W_E)} = \mathbf{P_T} + \mathrm{P_c} \tag{9}$$

$$P_{ER_j}^{total} = \sum_{\mathrm{k=1}}^{\mathrm{K}} \left|\boldsymbol{g}_{\boldsymbol{j}}^{\boldsymbol{H}} \vec{\mathbf{w}}_{\mathbf{k}}\right|^2 \tag{10}$$

where $\mathbf{P_T}$ is amplifier power consumption. $\mathrm{N_T}$ stands for the number of antennas. $\mathrm{P_c}$ represents the fixed power consumption, which caused by the baseband signal processing.

Then, we can get the total transform efficiency:

$$\mu_{eff} = \frac{P_{ER_j}^{total}}{\mathrm{TP(w, W_E)}} \tag{11}$$

3.4 Problem Formulation

The target of this report is to maximize the efficiency of the given SWIPT system. In order to achieve this goal, the value of SINR should as low as possible under the constrain of requirement, which can be expressed as C1:

$$SINR_k \geq \mu_{requ} \ \forall k \in \{1 \ldots, k\} \tag{12}$$

where μ_{requ} is requirement of $SINR_k$.

On the other hand, the received power should be as large as possible under the constrain of the Maximum power P_{max}, which is a constant value. This can be expressed by C2:

$$\sum_{k=1}^{K} \|\vec{\boldsymbol{w}}_{\boldsymbol{k}}\|^2 \leq P_{max} \tag{13}$$

$$\text{maximise}_{\vec{w}_k} \quad \mu_{eff} = \max_{\vec{w}_k} \frac{\sum_{\mathrm{k=1}}^{\mathrm{K}} \left|\boldsymbol{g}_{\boldsymbol{j}}^{\boldsymbol{H}} \vec{\mathbf{w}}_{\mathbf{k}}\right|^2}{\sum_{\mathrm{k=1}}^{\mathrm{K}} |\vec{\mathbf{w}}_{\mathbf{k}}|^2 + \mathrm{P_c}} \tag{14}$$

$$\text{St.} \qquad \text{C1:} \ \sum_{k=1}^{K} |\vec{\boldsymbol{w}}_{\boldsymbol{k}}|^2 \leq P_{max},$$

$$\text{C2:} \ \frac{\left|\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}} \overrightarrow{\boldsymbol{w}_{\boldsymbol{k}}}\right|^2}{\sum_{t \neq k} \left|\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}} \overrightarrow{\boldsymbol{w}_{\boldsymbol{t}}}\right|^2 + Z_k^2} \geq \mu_{requ} \ \ \forall k \in \{1 \ldots, k\}.$$

4. Problem Solution

There are two challenges to solving this problem. The main difficulty is non-convex problem. The objective function and C2 are non-convex expressions, which are hard to obtain the optimal solution. In addition, the objective function with the form of fraction is difficult to solve. In this part, we introduce the SDP and fraction programming transforming non-convex function to convex function, respectively.

4.1 SDP Relaxation

According to (14), we can know that $\sum_{\mathrm{k}=1}^{\mathrm{K}}\left|\boldsymbol{g}_{\boldsymbol{j}}^{\boldsymbol{H}}\vec{\mathbf{w}}_{\mathrm{k}}\right|^2$ and $\left|\vec{\boldsymbol{h}}_{\boldsymbol{k}}^{\boldsymbol{H}}\overrightarrow{\boldsymbol{w}_{\boldsymbol{k}}}\right|^2$ are non-convex part. This problem might produce multiple local optimal solution. Semidefinite programming provides a feasible method to transform these non-convex expressions into the following part.

$$\sum_{\mathrm{k}=1}^{\mathrm{K}}\left|\boldsymbol{g}_{\boldsymbol{j}}^{\boldsymbol{H}}\vec{\mathbf{w}}_{\mathrm{k}}\right|^2 = \sum_{j=1}^{J}\sum_{k=1}^{K}\boldsymbol{g}_{\boldsymbol{j}}^{\boldsymbol{H}}\vec{\mathbf{w}}_{\mathrm{k}}\overrightarrow{\boldsymbol{w}_{\boldsymbol{k}}^{\boldsymbol{H}}}\,\boldsymbol{g}_{\boldsymbol{j}} = \sum_{j=1}^{J}\sum_{k=1}^{K}\boldsymbol{Tr}(\boldsymbol{g}_{\boldsymbol{j}}^{\boldsymbol{H}}\vec{\mathbf{w}}_{\mathrm{k}}\overrightarrow{\boldsymbol{w}_{\boldsymbol{k}}^{\boldsymbol{H}}}\,\boldsymbol{g}_{\boldsymbol{j}}) =$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K}Tr(\vec{\mathbf{w}}_{\mathrm{k}}\overrightarrow{\boldsymbol{w}_{\boldsymbol{k}}^{\boldsymbol{H}}}\,\boldsymbol{g}_{\boldsymbol{j}}\boldsymbol{g}_{\boldsymbol{j}}^{\boldsymbol{H}}) = \sum_{j=1}^{J}\sum_{k=1}^{K}Tr(W_k\,\boldsymbol{g}_{\boldsymbol{j}}\boldsymbol{g}_{\boldsymbol{j}}^{\boldsymbol{H}}) \qquad (15)$$

Set $W_k = \vec{\mathbf{w}}_{\mathrm{k}}\overrightarrow{\boldsymbol{w}_{\boldsymbol{k}}^{\boldsymbol{H}}}$.

$$\left|\vec{\boldsymbol{h}}_{\boldsymbol{k}}^{\boldsymbol{H}}\overrightarrow{\boldsymbol{w}_{\boldsymbol{k}}}\right|^2 = \boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\vec{\mathbf{w}}_{\mathrm{k}}\overrightarrow{\boldsymbol{w}_{\boldsymbol{k}}^{\boldsymbol{H}}}\boldsymbol{h}_{\boldsymbol{k}} = Tr\left(\vec{\mathbf{w}}_{\mathrm{k}}\overrightarrow{\boldsymbol{w}_{\boldsymbol{k}}^{\boldsymbol{H}}}\boldsymbol{h}_{\boldsymbol{k}}\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\right) = Tr(\boldsymbol{W}_{\boldsymbol{k}}\boldsymbol{h}_{\boldsymbol{k}}\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}) \qquad (16)$$

Similarly,

$$\sum_{k=1}^{K}\|\vec{\boldsymbol{w}}_{\boldsymbol{k}}\|^2 = \sum_{k=1}^{K}Tr\left(\vec{\mathbf{w}}_{\mathrm{k}}\overrightarrow{\boldsymbol{w}_{\boldsymbol{k}}^{\boldsymbol{H}}}\right) = \sum_{k=1}^{K}Tr(W_k) \qquad (17)$$

$$\sum_{t\neq k}\left|\overrightarrow{\boldsymbol{h}}_{\boldsymbol{k}}^{\boldsymbol{H}}\overrightarrow{\boldsymbol{w}_{\boldsymbol{t}}}\right|^{2}+Z_k^2=\sum_{t\neq k}\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\overrightarrow{\mathbf{w}}_{\mathrm{t}}\overrightarrow{\boldsymbol{w}_{\boldsymbol{t}}^{\boldsymbol{H}}}\boldsymbol{h}_{\boldsymbol{k}}+Z_k^2=\sum_{t\neq k}Tr(\boldsymbol{W}_{\boldsymbol{t}}\boldsymbol{h}_{\boldsymbol{k}}\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}})+Z_k^2$$

Therefore, the equivalent function can be expressed as follow:

maximize $\quad {}_{W_k}\dfrac{\sum_{j=1}^{J}\sum_{k=1}^{K}Tr(W_k\boldsymbol{g}_{\boldsymbol{j}}\boldsymbol{g}_{\boldsymbol{j}}^{\boldsymbol{H}})}{\sum_{k=1}^{K}Tr(W_k)+\mathrm{P_c}}$

(18)

St. C1: $\sum_{k=1}^{K}Tr(W_k)\leq P_{max}$,

C2: $\dfrac{Tr(W_k\boldsymbol{h}_{\boldsymbol{k}}\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}})}{\sum_{t\neq k}Tr(W_k\boldsymbol{h}_{\boldsymbol{k}}\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}})+Z_k^2}\geq\mu_{requ}\ \forall k\in\ \{1\ldots,k\}$,

C3: Rank(W_k)≤ 1 , $\forall k$.

After conversion of SDP, only C3 is non-convex expression. Theorem 2 reveals a feasible solution related to the tightness of the SDP relaxation [61] - [63].

Theorem 1. If channel H and G are independent and the transformed problem in (17) is possible, then the optimal information beamforming matrix W_k is rank one at the most situations. The proof process will be shown at the end of this part.

Therefore, the SDP relaxation is very efficient to solving this problem. In particular, constraint C3 is removed and yield:

$$\underset{\vec{w}_k}{\text{maximise}}\ \frac{\sum_{j=1}^{J}\sum_{k=1}^{K}Tr(W_k\boldsymbol{g}_{\boldsymbol{j}}\boldsymbol{g}_{\boldsymbol{j}}^{\boldsymbol{H}})}{\sum_{k=1}^{K}Tr(W_k)+\mathrm{P_c}} \qquad (19)$$

St. C1: $\sum_{k=1}^{K}Tr(W_k)\ -P_{max}\leq 0$, C2: $\mu_{requ}\left(\sum_{t\neq k} Tr\left(W_t \boldsymbol{h_k} \boldsymbol{h_k^H}\right) + Z_k^2\right) - \; Tr\left(W_k \boldsymbol{h_k} \boldsymbol{h_k^H}\right) \leq 0 \;\; \forall k \in \{1 \ldots, k\},$

C3: $W_k \geq 0 \;,\; \forall k$

4.2 Transformation of the objective function by fraction programming

We define q^* as the maximum transform efficiency for the given system. According to the (17), we can get:

$$q^* = \frac{\sum_{\mathrm{k=1}}^{\mathrm{K}} \left|\boldsymbol{g_j^H} \vec{\boldsymbol{w}}_{\boldsymbol{k}}^*\right|^2}{\sum_{\mathrm{k=1}}^{\mathrm{K}} \left|\vec{\boldsymbol{w}}_{\boldsymbol{k}}^*\right|^2 + \mathrm{P_c}} = \max_{\vec{w}_k} \mu_{eff} = \max_{\vec{w}_k} \frac{\sum_{\mathrm{k=1}}^{\mathrm{K}} \left|\boldsymbol{g_j^H} \vec{\mathbf{w}}_{\mathbf{k}}\right|^2}{\sum_{\mathrm{k=1}}^{\mathrm{K}} |\vec{\mathbf{w}}_{\mathbf{k}}|^2 + \mathrm{P_c}} \tag{20}$$

We use an important theorem of nonlinear fractional programming to get the optimal solution. According to [64] - [66], the information beamforming vector achieves the maximum energy efficiency q∗ if and only if

$$\max_{\vec{w_k}} \sum_{\mathrm{k=1}}^{\mathrm{K}} \left|\boldsymbol{g_j^H} \vec{\mathbf{w}}_{\mathbf{k}}\right|^2 - q^* \left(\sum_{\mathrm{k=1}}^{\mathrm{K}} |\vec{\mathbf{w}}_{\mathbf{k}}|^2 + \mathrm{P_c}\right)$$

$$= \sum_{\mathrm{k=1}}^{\mathrm{K}} \left|\boldsymbol{g_j^H} \overrightarrow{\boldsymbol{w}_{\boldsymbol{k}}^*}\right|^2 - q^* \left(\sum_{\mathrm{k=1}}^{\mathrm{K}} \left|\overrightarrow{\boldsymbol{w}_{\boldsymbol{k}}^*}\right|^2 + \mathrm{P_c}\right) = 0 \tag{21}$$

for $\sum_{\mathrm{k=1}}^{\mathrm{K}} \left|\boldsymbol{g_j^H} \vec{\mathbf{w}}_{\mathbf{k}}\right|^2 \geq 0$ and $\left(\sum_{\mathrm{k=1}}^{\mathrm{K}} |\vec{\mathbf{w}}_{\mathbf{k}}|^2 + \mathrm{P_c}\right) > 0.$

So far we can transform (17) to the following form:

$$\min_{\overrightarrow{w_k}} \;\; q^*\left(\sum_{k=1}^{K} Tr(W_k) + \mathrm{P_c}\right) - \sum_{j=1}^{J} \sum_{k=1}^{K} Tr\left(W_k \, \boldsymbol{g_j} \boldsymbol{g_j^H}\right) \tag{22}$$

St. C1: $\sum_{k=1}^{K} Tr(W_k) - P_{max} \leq 0$

C2: $\mu_{requ}\left(\sum_{t\neq k} Tr\left(W_t \boldsymbol{h_k} \boldsymbol{h_k^H}\right) + Z_k^2\right) - Tr\left(W_k \boldsymbol{h_k} \boldsymbol{h_k^H}\right) \leq 0 \;\; \forall k \in \{1 \ldots, k\}$

C3: $-W_k \leq 0 \,, \; \forall k$

By applying the Dinkelbach method to solve (22). We following a similar approach as in [56] for proving Dinkelbach method. The algorithm is shown as following:

TABLE I

ITERATIVE RESOURCE ALLOCATION ALGORITHM (Dinkelbach method) .

```
1. Initialization $L_{max}$ = the maximum number of iteration and $\Delta$ = the maximum tolerance
2. Set $q = 0$ and iteration index $i = 0$
3. Repeat {Iteration Process: Main Loop}
4. Solving the problem (15), then obtain each feasible information beamforming vector $\overrightarrow{\boldsymbol{w'_k}}$
   for the given $q$
5. If $\sum_{k=1}^{K}\left|\boldsymbol{g_j^H}\overrightarrow{\boldsymbol{w'_k}}\right|^2 - q\left(\sum_{k=1}^{K}\left|\overrightarrow{\boldsymbol{w'_k}}\right|^2 + P_c\right) < \Delta$ then
6. Convergence = True
7. Return $\overrightarrow{\boldsymbol{w_k^*}} = \overrightarrow{\boldsymbol{w'_k}}$ and $q^* = \frac{\sum_{k=1}^{K}\left|\boldsymbol{g_j^H}\overrightarrow{\boldsymbol{w}}_{\boldsymbol{k}}^*\right|^2}{\sum_{k=1}^{K}\left|\overrightarrow{\boldsymbol{w}}_{\boldsymbol{k}}^*\right|^2 + P_c}$
8. Else
9. Set $q' = \frac{\sum_{k=1}^{K}\left|\boldsymbol{g_j^H}\overrightarrow{\boldsymbol{w}}'_{\boldsymbol{k}}\right|^2}{\sum_{k=1}^{K}\left|\overrightarrow{\boldsymbol{w}}'_{\boldsymbol{k}}\right|^2 + P_c}$ and i = i + 1
```

```
    Convergence = false
    end if
until Convergence = true or i = $L_{max}$
```

4.3 Proof theorem 1

We use Karush–Kuhn–Tucker (KKT) conditions and dual function to verify the theorem1. Now, we introduce KKT conditions, generally.

For a given minimization problem:

$$\min_{x\in\mathbb{R}^n} f(x) \tag{23}$$

$$subject\ to\ h_i(x) \leq 0, i = 1, \dots m$$

$$l_j(x) = 0, j = 1, \dots r$$

Then, we can define the Lagrange function:

$$L(x,u,v) = f(x) + \sum_{i=1}^{m} u_i\, h_i(x) + \sum_{j=1}^{r} v_j\, l_j(x) \tag{24}$$

and Lagrange dual function can be shown as follow:

$$g(u,v) = \min_{x\in\mathbb{R}^n} L(x,u,v) \tag{25}$$

The subsequent dual problem is

$$\max_{u\in\mathbb{R}^m, v\in\mathbb{R}^r} g(u,v) = \max_{u\in\mathbb{R}^m, v\in\mathbb{R}^r} \min_{x\in\mathbb{R}^n} L(x,u,v) \tag{26}$$

The KKT conditions are:

- ✓ stationary: $0 \in \partial \mathrm{f(x)} + \sum_{i=1}^{m} u_i \, \partial h_i(x) + \sum_{j=1}^{r} v_j \, \partial l_j(x).$

- ✓ complementary slackness: $u_i h_i(x) = 0 \quad for\ all\ i$

- ✓ primal feasibility: $h_i(x) \le 0,\ l_j(x) = 0\ for\ all\ i, j$

- ✓ dual feasibility: $u_i \ge 0 \ \ for\ all\ i$

According to above, we can define the Lagrange function for (18):

$$L = q^*(\sum_{k=1}^{K} Tr(W_k) + \mathrm{P_c}) - \sum_{j=1}^{J} \sum_{k=1}^{K} Tr(W_k \, G_j) + \sum_{k=1}^{K} \lambda_k \{ \mu_{requ} (\sum_{t \neq k} Tr(W_t H_k) + Z_k^2) - Tr(W_k H_k)\} + \beta [\sum_{k=1}^{K} Tr(W_k) - P_{max}] - \sum_{k=1}^{K} Tr(Y_k W_k) \quad \forall k \in \{1 \ldots, k\} \tag{27}$$

Let $H_k = \boldsymbol{h_k h_k^H},\ G_j = \boldsymbol{g_j g_j^H}$.

Where $Y_k\ and\ \lambda_k$ are dual variables, β is dual constant. The constraints C3, C2 and C1 directly depends the value of $Y_k,\ \lambda_k$ and β. The dual problem of (19) can be expressed as follow:

$$\max_{Y_k, \lambda_k, \beta} \inf_{x \in \mathbb{R}^n} L \tag{28}$$

Deriving L, we can get:

$$\frac{\partial L}{\partial \omega_k} = q^* - \sum_{j=1}^{J} G_j + \sum_{t \neq k} \lambda_t \mu_{requ} H_t - \lambda_k H_k + \beta I - Y_k = 0 \tag{29}$$

$$Y_k = q^* + \beta I - \sum_{j=1}^{J} G_j + \sum_{t \neq k} \lambda_t \mu_{requ} H_t - \lambda_k H_k \tag{30}$$

We define $B = q^* + \beta I - \sum_{j=1}^{J} G_j + \sum_{t \neq k} \lambda_t \mu_{requ} H_t$.

According to KKT condition, we can get

$$Y_k \geq 0, \lambda_k \geq 0, \beta \geq 0 \tag{31}$$

$$Y_k W_k = 0 \tag{32}$$

$$\boldsymbol{Y_k} = \boldsymbol{B} - \boldsymbol{H_k} \tag{33}$$

The complementary slackness characteristic results in the equation (31). That means the columns of matrix $\mathrm{W_k}$ fall into the null-space spanned by $\boldsymbol{Y_k}$ for $\mathrm{W_k} \neq 0$. Therefore, if the beamforming matrix $\mathrm{W_k}$ is a rank one matrix or a zero matrix, we must have $\mathrm{Rank}(\boldsymbol{Y_k}) \geq N_T - 1$.

Let us analysis the function (33):

Firstly, we suppose B is a positive semi-definite matrix. Then, we must have at least one zero eigenvalues which has the associated eigenvector v. According to eigenvector, we define a matrix $\mathrm{V} = \mathbf{v}\mathbf{v}^{\mathbf{H}}$. Now, we multiple the matrix $\mathbf{H}$ and add trace operation on (30), we obtain:

$$\mathrm{Tr}(\boldsymbol{Y_k}\mathrm{V}) = -\mathrm{Tr}(\boldsymbol{H_k}\mathrm{V}) + \mathrm{Tr}(\boldsymbol{B}\mathrm{V}) = -\mathrm{Tr}(\boldsymbol{H_k}\mathrm{V}) \tag{34}$$

It is known that $\boldsymbol{H_k}$ and $\boldsymbol{G_j}$ are independent, so we can get $\mathrm{Tr}(\boldsymbol{H_k}\mathrm{V}) > 0$. Also, we already know $\mathrm{Tr}(\mathbf{Y_k}\mathrm{V}) \geq 0$, which leads to a contradiction. Therefore, us suppose is invalid. Hence, we indirectly prove that matrix $\boldsymbol{B}$ is a positive definite matrix, $\mathrm{Rank}(\boldsymbol{B}) = \mathrm{N_T}$.

The basic inequality rule for the matrix rank tell us that $\mathrm{Rank}(\boldsymbol{A} + \boldsymbol{B}) \geq \mathrm{Rank}(\boldsymbol{A}) - \mathrm{Rank}(\boldsymbol{B})$ under the same matrix dimension. Because $\mathrm{Rank}(\boldsymbol{A} + \boldsymbol{B}) + \mathrm{Rank}(-\boldsymbol{B}) \geq \mathrm{Rank}(\boldsymbol{A})$ and $\mathrm{Rank}(-\boldsymbol{B}) = -\mathrm{Rank}(\boldsymbol{B})$. Using this basic rule on function (25):

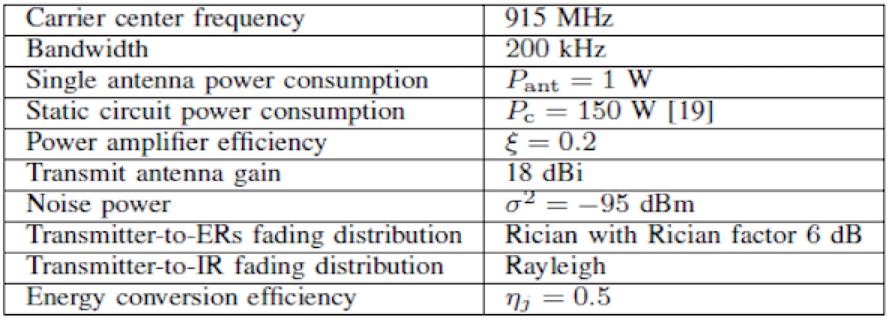
$$\mathrm{Rank}(\boldsymbol{Y_k}) = \mathrm{Rank}(-\boldsymbol{Y_k}) = \mathrm{Rank}(-\boldsymbol{B} + \boldsymbol{H_k}) \geq \mathrm{Rank}(-\boldsymbol{B}) - \mathrm{Rank}(\boldsymbol{H_k}) = \mathrm{N_T} - 1 \tag{35}$$

From now, we proof $\mathrm{Rank}(\mathrm{Y_k}) = \mathrm{N_T} - 1$, then $\mathrm{Rank}(\mathcal{W}_\mathrm{k}) \leq 1$ can be confirmed.

5. Simulation Results

In this section, we demonstrate the relationship between the average system wireless energy efficiency and SINR requirement and the maximum transmit power via simulation. The basic simulation parameters are listed in Table 1. Figure 5-1 shows that the average wireless energy transfer efficiency depends on the requirement SINR. The stricter SINR requirement, the lower average wireless energy transfer efficiency. This is caused by the constraint of transmit power. Moreover, the number of antenna also has an important impact on energy transfer efficiency. As the increasing of antennas, the average wireless energy transfer efficiency is increased under the same maximum transmit power. It is worth mentioning that energy transfer efficiency is more sensitive to the change in SINR in the case of a larger number of antennas.

TABLE I
SIMULATION PARAMETERS



Carrier center frequency	915 MHz
Bandwidth	200 kHz
Single antenna power consumption	$P_{\text{ant}} = 1$ W
Static circuit power consumption	$P_c = 150$ W [19]
Power amplifier efficiency	$\xi = 0.2$
Transmit antenna gain	18 dBi
Noise power	$\sigma^2 = -95$ dBm
Transmitter-to-ERs fading distribution	Rician with Rician factor 6 dB
Transmitter-to-IR fading distribution	Rayleigh
Energy conversion efficiency	$\eta_j = 0.5$

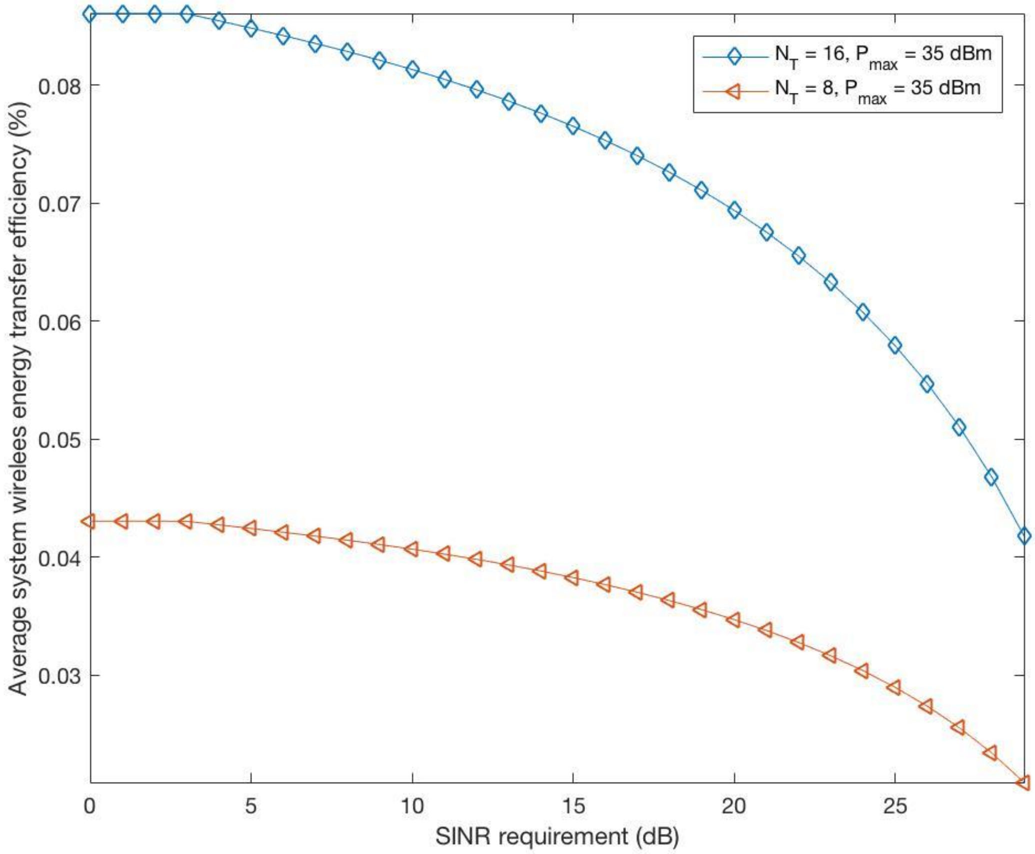


fig.5-1 Average system wireless energy efficiency (%) versus SINR (dB)

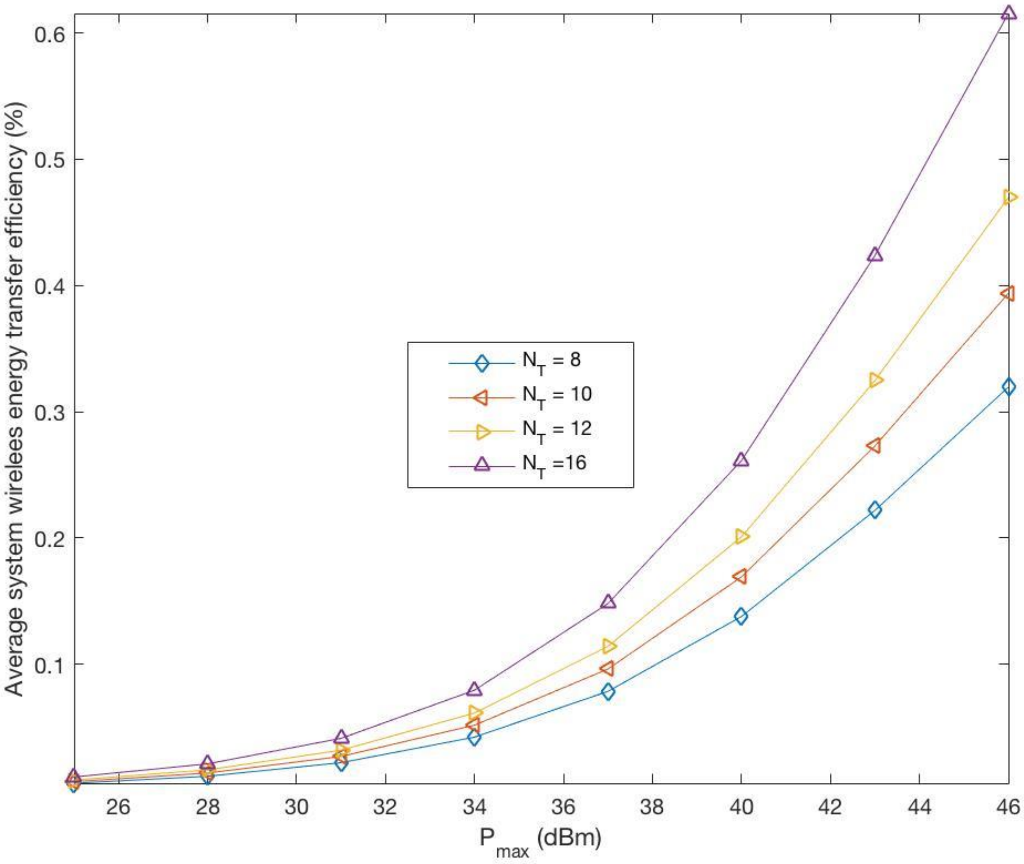


fig. 5-2 average system wireless energy transfer efficiency (%) versus maximum transmit power (dBm)

Figure 5-1 shows the trade-off between the average system wireless energy transfer efficiency and the maximum transmit power for the given SWIPT system model under proposed optimal beamforming scheme. By comparing the y-axis under the same x-axis for different transmit antenna numbers, it is obvious that with increasing number of transmitter antennas, the average system wireless energy transfer efficiency increases. This is because the multiple transmit antennas provide the extra spatial degrees of freedom, which improve the accuracy in beamforming. Furthermore, with the increasing of the maximum transmit power, the average system wireless energy transfer efficiency increases sharply under the same antenna number.

6. Conclusion

In conclusion, we address the performance of the given multi-user SWIPT system by the average system wireless energy transfer efficiency. Firstly, SDP and SDP relaxation is introduced to solve non-convex problem. Then, optimization problem is solved by using fraction programming and the property of duality. In addition, iterative resource allocation algorithm is given to get the optimal result. Finally, we present the simulation results to show the good performance of the given system via energy transfer efficiency.

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