SCHOOL OF ELECTRICAL ENGINEERING
AND TELECOMMUNICATIONS

Beamforming Design for 6G SWIPT Networks

by

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Abstract

With the expansion of mobile network consumers and the rapidly growing demands of better communication performance such as lower latency, massive date streaming, quality of service and so on, many telecommunication engineers are concentrated to update and deploy new communication generation system. However, to satisfy the higher performance requirement, the energy consumption problem has been the main bottleneck. Therefore, one new method named Simultaneous Wireless Information and Power Transferring has been in considerations and research. Its most obvious advantage is that it can transfer the information and power concurrently due to the property of radio frequency signals. In this thesis, we will discuss the optimal average secrecy rate of one SWIPT system assisted with power beacon and under passive eavesdropping. Meanwhile, some important constraints such as the total system energy consumption and the QoS of each desired user has been taken into consideration. We find out that the optimization problem is non convex and a beamforming algorithm is designed based on the non convex optimal transform and solution algorithm of applying SCA and SDP relaxation. Moreover, the simulation result can prove the algorithm is feasible.

Key Word---simultaneous wireless information and power transfer, secrecy rate, beamforming design, SCA, SDP relaxation.

Abbreviations

5G	Fifth Generation Communication System
QoS	Quality of Service
SWIPT	Simultaneous Wireless Information and Power Transferring
IoT	Internet of Things
B5G	Beyond 5G
MIMO	Multiple-Input Multiple-Output system
MISO	Multiple-Input Single-Output system
RF	Radio Frequency
ID	Information Decoding
EH	Energy Harvesting
RF-EH	Radio Frequency Energy Harvesting
CSI	Channel State Information
WPCN	Wireless Power Communication Network
ZFBF	Zero Forcing Beamforming Algorithm
CoMP	Coordinated Multipoint Network
TS	Time Switching
PS	Power Splitting
NOMA	Non Orthogonal Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
TDMA	Time Division Multiple Access
WPCN	Wireless Powered Communications Network
SCA	Successive Convex Approximation
SDP	Semidefinite Programming

Contents

1. Introduction

1.1 Brief Statement

With the rapid growth of wireless communication, it is obvious that the demand for higher data rate, QoS and security is increasing evidently. For example, 5G has become the main role for next wireless communication generation due to its higher capacity, higher security, lower latency and other features. The huge benefits of 5G communication network applying to the commercial field has drawn the attention from the researchers and engineers.

However, the surge in data traffic caused by the upgrading of wireless communication networks also exposed the shortcomings of the energy-constraint network device. Charged by batteries, these devices have a limited lifetime and power storage capacity. In order to prolong the lifetime of wireless devices, a huge amount of engineer trends to solve this problem by using natural renewable resources such as solar and wind [1]-[2]. Unfortunately, the method of obtaining energy from nature is not feasible in some situations where the ecological environment lacks stable power resource. Besides, some small wireless network device such as sensor or mobile phone cannot get the power supply from the nature.

Due to these limitations, one advanced method named SWIPT technique has been in considerations. This technology aims to implement information decoding and energy harvesting simultaneously based on the property of radio frequency signals. Though the initial idea was born in the early 20th century, here are many limitations and constraints to practical use. Recent research has focused on performance problems such as data rate and minimal transmitted power. This thesis aims to formulate one SWIPT system under the MISO downlink flat-fading channel and eavesdropping and optimize the secure data rate of the total desired users.

1.2 Thesis Arrangement

In order to figure out the optimization problem of data rate of total desired users under SWIPT security communication system, Thesis has four steps to finish. The main steps are outlined as followings:

1) Design one proper SWIPT downlink system with energy limitation, eavesdropping considerations, and energy harvesting requirement. This model is one proof for both physic and mathematical.
2) Transfer the system model into mathematical expression. To complete this aim, the element and propagation procession can be expressed into mathematical equations. Then the optimal problems and the practical constraints can be formulated into mathematical expression. Briefly introduce the relationship between them.
3) Find the non-convexity in the optimization problem, and use a feasible algorithm to solve it.
4) Simulate and optimize with MATLAB to verify the security of SWIPT system.

1.3 Chapter Outline

This Thesis will be divided into 6 parts. Chapter 2 aim to do a literature review which contains some basic concept of wireless communication networks, wireless power transferring methods and some technique for SWIPT. Chapter 3 provides the SWIPT downlink secure communication system model and its problem mathematical formulation. Chapter 4 will introduce the beamforming algorithm for the security rate of the system and the mathematical derivation process of the related feasibility in detail. Chapter 5 will simulate and analyze the results of MATLAB and Chapter 6 will give the conclusion of Thesis and a brief introduction to some future work.

2. Background

2.1 Communication System Evolution

From the birth of the first-generation communication system to now, people's requirements for communication quality and diversification of network functions have changed with each passing day. Under this objective phenomenon, the communication system is also constantly updated by the telecommunication engineers to meet the growing needs of a larger number of communication users, such as data transmission efficiency, security, mobility and privacy.

The first generation was invented in 1980s, which can just propagate analog signals for only voice communication with lower security. Based on 1G communication networks, 2G got the improvement to implement digital signals transmission, which guaranteeing higher security voice communication and message texting communication. The physical architecture of 1G and 2G communication systems is microcell cellular design, which has brought lots of problems such as lower data rate and higher interference at the edge of cells, information security and higher cost for deployment of base stations. Based on this motivation, 3G communication system was deployed into practical use in 1990s. Compare with 2G, the microcell design has weakened the interference between cells which gives the 3G communication networks ability to implement wireless mobile access and television. The most innovative progress brought by the development of 3G network is the combination of mobile communication network and Internet. However, it cannot gain much benefit from higher speed Internet which has limited the consumers that per cell can accommodate. To solve this problem, in the early 21th century, 4G has been invented to implement higher data rate communication which can be up to hundreds of megabits per seconds [3]. However, there are some limitations in 4G communication such as co-channel interference and limited connectivity.

In recent decades, the explosive growing demands of wireless service quality and increasing scale of network consumers has burdened 4G communication system. To fulfill these requirements, in 2018, 5G communication networks has been in deployment. Fig2.1 has shown the improvement between 5G and 4G systems. Compared with 4G communication, 5G can support massive devices such as mobile devices, small elements such as sensors, smart home devices and so on. Ubiquitous connectivity that 5G provides to users has improve device scalability and gives the concept of IoT possibility to practical use. Moreover, 5G communication can ensure massive data streaming based on its two-tier hetnet network system design and multiple antenna technique. Zero latency can expand the performance of mobile devices, including health detection function, real-time game, instantaneous interaction function and so on [3].

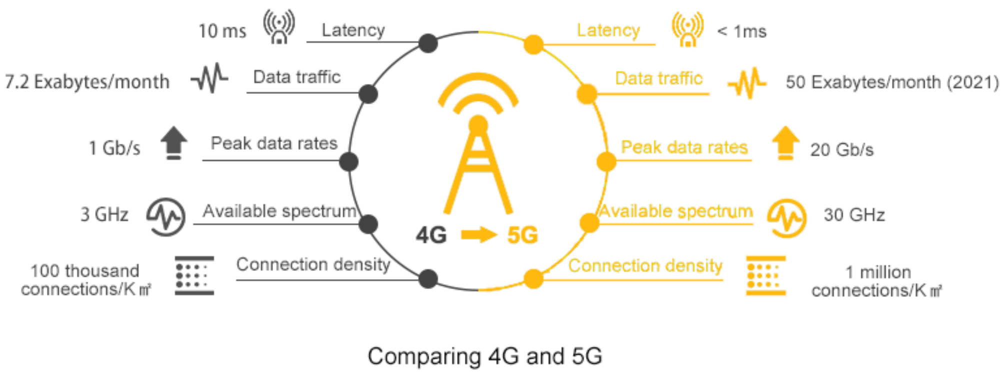

Fig2.1 Comparison between 4G and 5G [3]

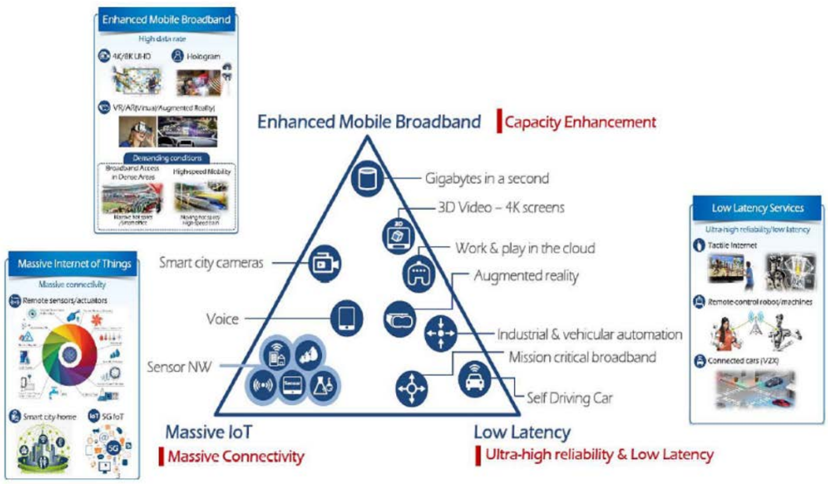

Fig2.2 Possible use of 5G [4]

In conclusion, the evolution of communication network system is not just the enhancement of previous existing system or progress of science and technology. It is the starting point of industry revolution into the new era. Fig2.2 shows that the possible use of 5G technology. With the support of 5G, Internet of things, smart city, real-time games and other aspects has bloomed in recent years. The huge commercial success that 5G brought cannot be ignored. Therefore, the concepts of Beyond 5G (B5G) and 6G communication networks are also gradually put forward and valued by the telecommunication engineers [3].

2.2 Energy-Harvesting Problem

In recent years, the explosively expansion of mobile network users has led to the increasing of data traffic. Fig2.3 shows the phenomenon of explosively increasing of the connectivity coverage. Higher requirement of QoS, lower latency, more efficient network performance and other evolution direction of wireless communication network has exacerbated the energy consumption in both transmitter sides and receiver sides. In this degree, energy consumption problem has been the main bottleneck of telecommunication industry revolution. It is crucial to find one proper and feasible energy harvesting scheme to supply the sufficient energy to the communication devices. Under these considerations, there are many existing research and investment on green energy harvesting [5]. However, there are still many limitations on these existing methods. For instance, multisuser MIMO technology can effectively lighten the energy supply problem since it can reduce the energy dissipation with multiple antennas at transmitter sides, but it is infeasible for energy harvesting to small elements such as sensors, laptors, and mobile devices. Renewable resource has been the main direction of energy harvesting research and this method surely can solve the energy consumption without losing environmental protection. However, renewable resource from nature sometimes is lack of reliability.

In conclusion, the existing methods or research direction can just lighten the burden of energy consumption of base stations or power beacons at transmitter sides. There is not one green and feasible way to supply energy to receiver sides when the ending users are mobile devices or small elements. In general, these devices are battery charging, and the energy consumption caused by the massive data traffic and lower latency requirement can be damaged to the lifetime of battery. Under such realistic conditions, frequent battery replacement may be required to maintain a high level of performance. However, the high cost and inconvenience for replacing these batteries can attract many troubles. Therefore, no matter from the perspective of information industry innovation or commercial cost, find a suitable environmentally friendly, efficient and high mobility technology or method to prolong the service life of battery powered equipment.

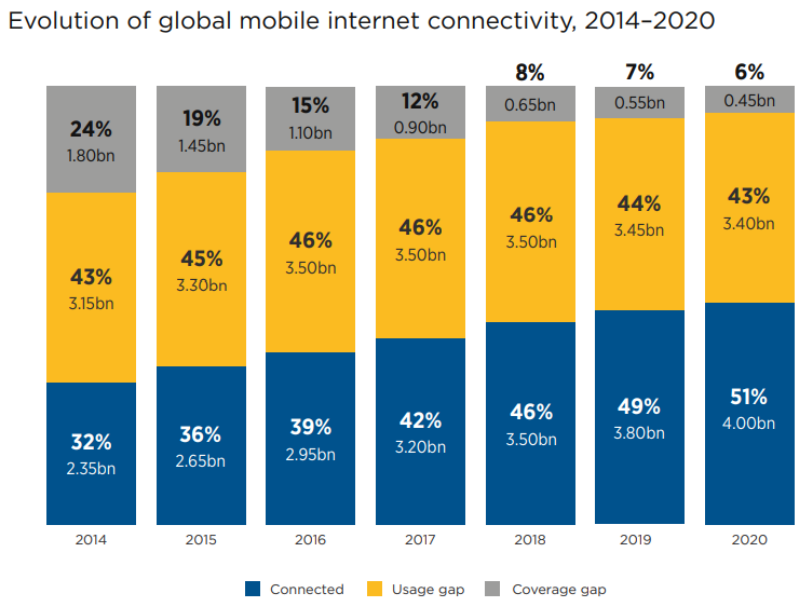

Fig2.3 Evolution of global mobile internet connectivity 2014-2020 [6]

2.3 Wireless Power Transferring

2.3.1 Radio Frequency Energy Harvesting Technology

Under these considerations, one feasible way is to draw the support from the RF-EH technology [5], [7]. This concept is initially based on the Nikola Tesla's work [7]. The transmitter sends the RF signals to the energy-constraint devices to compete energy-harvesting. The most obvious advantage comparing to the method scavenging energy from the nature is that RF-EH technology can charge the energy-constraint devices depends on the necessity of demands.

Since the concern about the possible hurting to human health, the early research or investment on wireless power transferring are aiming to implement short distance wireless energy transmission such as 10 meters under the indoor conditions. The weakness and limitations of these initial wireless power transferring techniques is that the limited range of service cannot provide mobility to the desired users. In order to increase the scalability of wireless charging technology, RF-EH technology aimed to solve the far-field energy harvesting problems. RF-EH technology can implement wireless energy charging and data transferring concurrently over long distances such as hundreds of meters. The biggest advantage of RF signals is that it can be the carrier of both information and energy simultaneously. Besides, RF energy signal is invisible and ubiquitous so it can be transmitted from random public transmitters such as Wi-Fi devices or cellular base station that won't be hurt to human health [8].

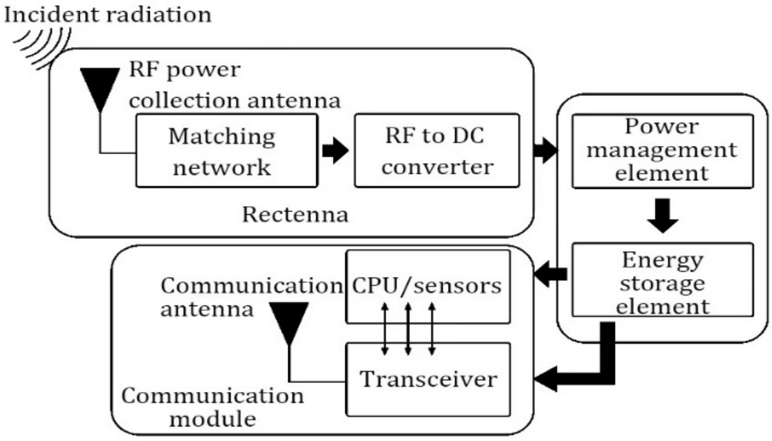

Fig2.4 Block diagram of RF-EH technology receiver [8]

The components of one typical wireless power receiver are always formed by a receiver antenna or antenna arrays, a matching network, a direct current converter, the element for power management and the element for power storage [9]. Moreover, the storage element often consists of a rechargeable battery to supply the energy consumption of the communication receiver. The schematic block diagram of this module can be shown in Fig2.4.

2.3.2 Simultaneous Wireless Information and Power Transferring

One advanced concept based on RF-EH technology, the simultaneous wireless information and power transferring, which can create a combination with power transferring and information communication has imposed many new ideas for telecommunication engineering in recent decades.

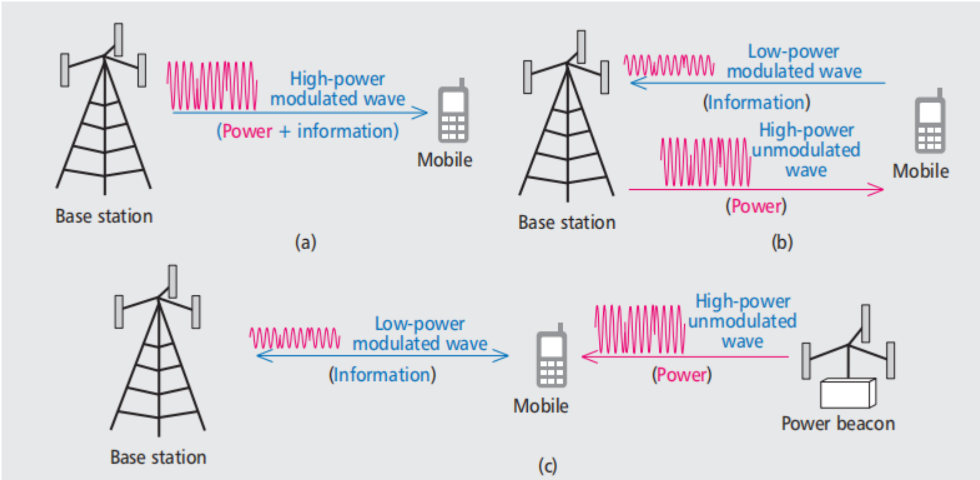

Fig2.5 Typical model of SWIPT technology [10]

Fig2.5 shows three typical model of SWIPT technology. (a) shows that one SWIPT base station can transmit RF signal in downlink to the ending users to implement power transferring and information transmission concurrently. (b) shows that one SWIPT base station can just be the energy charging device to supply mobility and power to the mobile devices. (c) shows that the power beacon can be assisting to wireless power transferring to lighten the burden of base stations.

2.4 Literature Review

There are many researching direction and optimal solutions on SWIPT technology. The author of [11] aimed to investigate the trade-off between capacity and energy over the frequency-selective channel based on single-input single-output communication systems. In [12], the author has investigated the maximal value of weighted sum rate of multiple users under the perfect or imperfect CSI. Also, the maximal value of weighted sum rate based on multiple-input single-output communication system has been investigated in [13]. In [14], the author aimed to find a resource allocation scheme to solve the max-min fairness in a downlink multiuser communication system under the secrecy rate constraint. The author in [15] aimed to investigate the max value of the network energy efficiency through the resource allocation and power control based on the WPCN. Besides, the authors in [15] set up the initial power of users. In [16], The author investigated the MISO-SWIPT proportional fairness problem base on the classical ZFBF algorithm. In [17], the author aimed to maximize the secrecy rate of information user based on MISO-SWIPT system, while under a two-tier hetnet constraint. In [18], the authors assume the conditions that the devices of WPT system can complete both energy harvesting and power storage. These new assumptions reveal a new optimal resource allocation on fairness problem. In [19], the author assumed the MIMO system and devote themselves to investigate the optimal solution of the trade-off between data rate and energy transfer for the two typical SWIPT receivers, which is in time switching mode or power splitting mode. In [20], the author aimed to optimize the minimum value of transmitting power under the constraint guaranteeing the date rate and energy efficiency higher than a threshold. In [21], the authors assumed a non-linear WPT model and aimed to use the power allocation algorithm to optimize the max value of the total harvested energy under the constraint ensuring the minimum required SINR for the information decoding. In [22], the authors applied the SWIPT to CoMP networks and investigated the optimal resource allocation aimed at ensuring both the minimum of total transmitting power and the maximum of capacity consumption per backhaul link. In [23], based on the consideration of downlink MISO-SWIPT system under eavesdropping, the author aimed to design a resource allocation scheme to minimize the total transmit power, which ensures the SINR of desired users higher than the required threshold and the SINR of the potential eavesdroppers less than the tolerable threshold. In [24-26], It focuses on the discussion of the practicability of SWIPT technology in terms of power and space based on rectangular circuit hardware, and discusses the resource allocation strategy in the context of cooperative networks. In [27], The author studies the resource allocation strategy that can be used in MC-NOMA systems. The model discussed in this paper is based on the full duplex base station serving several users. The key point of its strategic algorithm implementation is to solve the optimal solution (non convex problem) of system throughput. In [28-32], This paper studies the resource allocation algorithm for energy saving optimization of the system in the downlink network integrated with SWIPT and OFDMA. In the paper [28-29], the imperfect channel state information at the transmitter and the maximum tolerable channel outage probability are considered. In [33-35], based on the defects of CSI, the author designs an optimal beam integration algorithm which uses multiple receivers to realize charging and communication functions at the same time. After solving a chance optimization constraint problem, two robust reconstructions are proposed for the original problem. In [36], the author uses the NOMA communication scheme in the new millimeter wave communication system. In order to give full play to the greatest advantage of the NOMA scheme in improving the system energy efficiency, the author proposes two wave width control algorithms in this paper, and designs a filter that effectively reduces the power loss caused by the disappearance of the main lobe power. In [37], The author optimizes the weighted sum of the target user efficiency of WPCN through the joint resource allocation optimization algorithm of base stations. Based on the characteristics of joint transmission between distributed radio receivers and central processing units, in [38-40], the authors respectively equip them with renewable energy distributors to design resource allocation strategies that can promote mobile terminals to achieve information security and maximize green renewable energy in the entire antenna communication process. Based on the question whether the NOMA protocol can improve the spectral efficiency of the system and reduce energy consumption in the 5G communication system under WPCN, in [41], the author theoretically deduced. Through the discussion on the time allocation of WPCN systems based on TPMA and NOMA protocols, it was found that the NOMA protocol almost plays a negative role in the key performance of WPCN. In [42], this author proposes the weighted Tchebycheff most resource allocation algorithm of the multi-objective optimization framework, which enables the secondary receiver to obtain energy from the RF antenna wave in idle time, and makes the secondary system have the characteristics of SWIPT system. In [43], The author replaces the passive eavesdropper with the active eavesdropper who can destroy the channel to detect the security of the Massive MIMO system. In [44-45], The author also discussed the latest progress in laying the foundation for the envisaged dual-use network by establishing the signal theory and design of SWIPT and identifying the basic trade-off between wireless transmission information and power. In [46], in order to improve the practicability of SWIPT, the author establishes the SWIPT system in a reliable nonlinear energy collection model, and solves the maximization of SINR through convex optimization.

In this paper, I consider a promising application of SWIPT based on MISO systems. I formulate the maximation problem about secrecy rate for downlink multiuser MISO-SWIPT system under the constraint of power transfer, base station energy and eavesdroppers' SINR. Besides, the wireless power charging station is introduced to stabilize the energy transferring of the whole system. By exploiting the structure of this problem, we will derive the optimal beamforming solution. Applying the beamforming technology, the transmitted signal can be forced to the desired users.

2.5 Receiver Technique for SWIPT

It is not realistic to implement concurrent EH and ID perfectly without any loss. The procession of energy harvesting will destroy the information carried by RF signals. In order to realize practical SWIPT, the typical receiver is designed to sperate the received signals into two parts for energy harvesting and information decoding respectively [47-48]. Fig2.6 shows that the two typical receivers for SWIPT technique.

In time domain, TS mode is applied to realize the signal splitting which means the signals are entirely transmitted into two orthogonal time slots. In one time slot, the receiver can do either information decoding or energy harvesting. The receiver device must have the ability to switches between information decoding circuits and energy harvesting circuits [48]. The biggest advantage of time switching techniques is that it is easy and low-cost to implement under the consideration of hardware layer. However, to avoid the latency problem, the precise time synchronization and information or energy scheming is demanded for time switching technique.

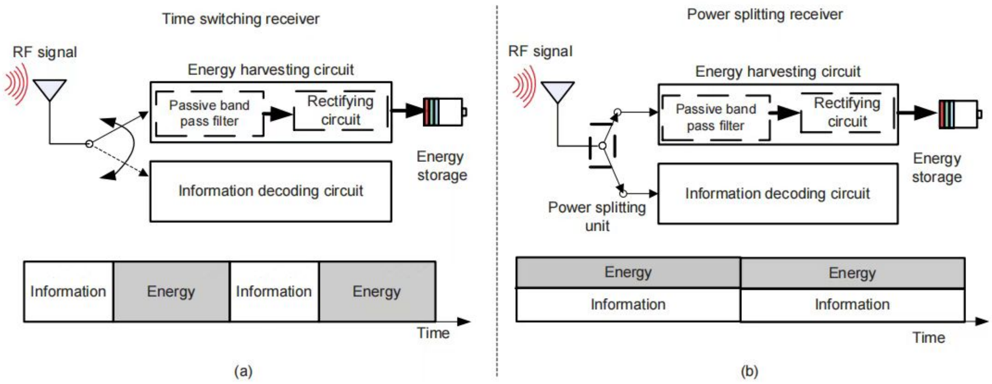

Fig2.6 Typical receivers for SWIPT

In power domain, PS mode is employed to realize practical SWIPT. The core of the PS receiver is the power splitting element. Typically, the functional principle of PS receiver is that the PS element can divide the received signal into two streams at the receiving antenna. One stream is relayed to the energy circuits based on RF-EH technology, and the other is converted to baseband for information decoding [49]. Though the delay constraint is not strict compared to TS receivers, the additional noise and circuit interference can also do damage to the information content. However, the PS receiver can realize energy harvesting and information decoding concurrently which ensure the feasibility of SWIPT.

2.6 Beamforming Design

Efficient beamforming design can concentrate microwave with high radiation power on desired customers, thus reducing interference and energy consumption. Beamforming technology with considerable performance can be realized through smart multi antenna technology [50]. To avoid the phenomenon of the multi-beam, each array elements are designed smaller intervals. In general, the intervals are smaller than a half wavelength to sharpen the beamforming.

With the extensive deployment of multiuser MIMO technology, rich scattering is one favorable factor to implement parallel data streaming to multiple data users without broadening bandwidth frequency domain [51]. However, one typical scatter can be damaged to the cluster beamforming then it is the main effect for beam free-space propagation, which can reduce the beam efficiency rapidly.

The definition of beam efficiency means the ratio between the received and formed transmitted beam [52]. The mathematical expression of beam efficiency is shown as follows:

$$\xi = 1 - e^{-\left(\frac{A_t A_r}{(\lambda d)^2}\right)} \quad (1)$$

Where A_t and A_r means the bore diameter of the antenna arrays at transmitter sides and receiver sides respectively. λ means the wavelength of beam and d means the transmission distance. Based on the observation of mathematical equation, to improve the beamforming efficiency, enlarging the apertures of the antenna arrays of both transmitter sides or receiver sides is one practical method in telecommunication industry.

3. System Model

3.1 Notations

In this thesis, bold upper case letters and lower case letters are used to represent matrices and vectors respectively. $\mathrm{Tr}(\mathbf{W})$, $\mathrm{Rank}(\mathbf{W})$, $\mathbf{W}^H$ are used to represent trace, rank, and Hermitian transpose. $\mathbf{W} \succ \mathbf{0}$ and $\mathbf{W} \succcurlyeq \mathbf{0}$ are used to introduce that $\mathbf{W}$ is a positive definite and a positive semi-definite matrix respectively. $\mathbf{I}_N$ means that it is a N × N identity matrix. $\mathbb{C}^{N\times M}$ means it use to establish a set f all N × M matrices with complex entries. The function $[\cdot]^+$ means taking non negative value.

3.2 Model Description

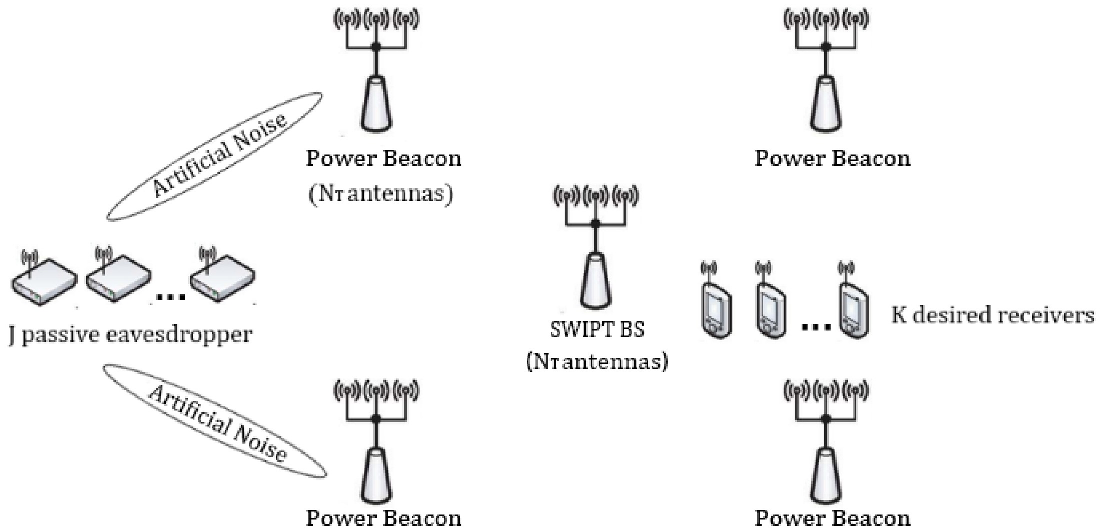

Fig3.1 System Model

In my thesis, I consider one multiuser MISO downlink with power beacons assisting SWIPT system [53]. Typically, One SWIPT base station equipped with $N_T > 1$ antennas can do information transmission and energy harvesting to K desired users concurrently. Desired receivers work as the PS receivers equipped with one single antenna [54]. Under the consideration of enhancing the security of the total system, J passive eavesdroppers equipped with one single antenna are assumed. To ensure the energy harvesting efficiency and lighten the energy consumption burden of SWIPT base station, the $N_B > 1$ power beacons equipped with $N_T > 1$ antennas are assisting to the power transferring to the desired users. Simultaneously, the power beacons also have the target to emit the artificial noise in order to prevent the eavesdropping procession of passive eavesdroppers

To simplify the complexity without losing generality, I assume that the total system is working in the free-space propagation with flat-fading channel. Besides, I assume that CSI is perfectly known at transmitter sides [55].

After these assumptions and descriptions, the transmitted signal vector from the SWIPT base station, $\boldsymbol{x_1} \in \mathbb{C}^{N_T \times 1}$, which can contain the K desired PS receivers signals can be expressed as:

$$\boldsymbol{x_1} = \sum_{k=1}^{K} \boldsymbol{w_k} s_k \tag{2}$$

$s_k \in \mathbb{C}$ means the symbols and $\boldsymbol{w_k} \in \mathbb{C}^{N_T x 1}$ means the beamforming vector of SWIPT base station. In like wise, the transmitter signal vector from the N_B power beacons, $\boldsymbol{x_2} \in \mathbb{C}^{N_T \times N_B \times 1}$, which contains the energy signals to desired K users and the artificial noise can be expressed as:

$$\boldsymbol{x_2} = \sum_{n=1}^{N_B} \sum_{k=1}^{K} \boldsymbol{p_{n,k}} e_{n,k} + \sum_{n=1}^{N_B} \boldsymbol{v_n} \tag{3}$$

$\boldsymbol{p_{n,k}} \in \mathbb{C}^{N_T \times N_B \times 1}$ means the beamforming vector of power transferring and $e_{n,k} \in \mathbb{C}$ means the symbols. Particularly, vector $\boldsymbol{v_n}$ means the artificial noise vector and $v_n \sim \mathcal{CN}(\boldsymbol{0}, \boldsymbol{V_n})$, which shows that the artificial noise is modelled as zero mean and covariance matrix $\boldsymbol{V_n}$ is the positive semidefinite Hermitian matrix.

After the propagation in flat-fading channel, the received signals at the desired user k can be expressed as follows:

$$\boldsymbol{y_k} = \boldsymbol{h_k^H} \boldsymbol{x_1} + \boldsymbol{r_{n,k}^H} \boldsymbol{x_2} + z_k \ \forall k \in \{1, \dots \dots, K\} \tag{4}$$

In this equation, the flat-fading downlink channel vector from the SWIPT base station to the desired user k is denoted by $h_k \in \mathbb{C}^{N_T}$ and the downlink channel vector from the power beacons and the desired user k is denoted by $r_{n,k} \in \mathbb{C}^{N_T \times N_B}$. $z_k \sim \mathcal{CN}(0, \delta_s^2)$ means the AWGN. In likewise, the received signals at the potential eavesdroppers after the flat-fading downlink channel are given by:

$$\boldsymbol{y_j} = \boldsymbol{g_j^H x_1} + \boldsymbol{q_{n,j}^H x_2} + \mathrm{z_{ev}}\ \forall \mathrm{j} \in \{1, \dots \dots, \mathrm{J}\} \tag{5}$$

In this equation, the flat-fading downlink channel vector from the SWIPT base station to the potential eavesdropper *j* is denoted by $gj \in \mathbb{C}^{N_T}$ and the downlink channel vector from the power beacons and the potential eavesdropper *j* is denoted by $q_{n,j} \in \mathbb{C}^{N_T \times N_B}$. $z_{ev} \sim \mathcal{CN}(0, \delta_o^2)$ means the AWGN.

3.3 System Performance

In the considered system, the signal to noise interference ratio (SINR) can be expressed as follows [56]:

$$SINR_k = \frac{\rho_k \left|\boldsymbol{h_k^H w_k}\right|^2}{\rho_k (\sum_{m \neq k}^{K} |\boldsymbol{h_m^H w_m}|^2 + \sum_{n=1}^{N_B} \sum_{i=1}^{K} \left|\boldsymbol{r_{n,i}^H p_{n,i}}\right|^2 + \sum_{n=1}^{N_B} Tr(\boldsymbol{R_{n,k} V_n}) + \delta_s^2} \tag{6}$$

Where and means power splitting ratio and the limitation is [0,1]. This equation shows that the desired user can be regarded as a PS receiver with a weight of for information decoding and for energy harvesting. On this basis, we can further list the mathematical expression of the realizable data rate of desired user k [56]:

$$C_k = log_2(1 + SINR_k) \tag{7}$$

Moreover, the received signal streaming to the EH circuit for energy harvesting in the desired k user can be obtained as:

$$E_k = \mu_k (1 - \rho_k) \sum_{m=1}^{K} \left|\boldsymbol{h_m^H w_m}\right|^2 + \left(\sum_{n=1}^{N_B} \sum_{i=1}^{K} \left|\boldsymbol{r_{n,i}^H p_{n,i}}\right|^2 + \sum_{n=1}^{N_B} Tr(\boldsymbol{R_{n,k} V_n}) + \delta_s^2 \right) \tag{8}$$

Where means the energy efficient of the desired k mobile user. After the description of the communication model of the desire k user, we then can find out the SINR and possible data rate that the potential passive eavesdropper j can obtain. To consider the worst case for security communication, we assume that the potential passive eavesdroppers can perfectly obtain the CSI and eliminate the possible interference caused by channels between desired K users. Under this assumption, we can express the SINR and possible achievable data rate of potential eavesdropper j mathematically:

$$SINR_j = \frac{\left|\boldsymbol{g_j^H w_j}\right|^2}{\sum_{n=1}^{N_B}\sum_{i=1}^{K}\left|\boldsymbol{r_{n,i}^H p_{n,i}}\right|^2 + \sum_{n=1}^{N_B}\mathrm{Tr}(\boldsymbol{Q_{n,j} V_n}) + \delta_o^2} \tag{9}$$

$$C_j = log_2\left(1 + SINR_j\right) \tag{10}$$

Where $Q_{n,j} = q_{n,j} q_{n,j}^H$. Thus, the realizable secrecy rate of the desired user k can be expressed as follows:

$$C_{sec_k} = [C_k - \max_{\forall j}\{C_j\}]^+ \tag{11}$$

3.4 Optimization Problem Formulation

The system objective is to maximize the secrecy rate of the total considered system under some performance limitation. The beamforming algorithm design can be formulated as an optimization problem which is given by:

$$\max_{w_k, p_{n,k}, \rho_k} \sum_{k=1}^{K} C_{sec_k}$$

s.t.

$$C1: \sum_{k=1}^{K} \|\boldsymbol{w_k}\|^2 \leq P1^{max}$$

$$C2: \sum_{n=1}^{N_B} Tr(\boldsymbol{v_n}) + \sum_{n=1}^{N_B}\sum_{k=1}^{K} \left\|\boldsymbol{p_{n,k}}\right\|^2 \leq P2^{max}$$

$$C3: \sum_{k=1}^{K} E_k \geq E_{th}$$

$$C4: SINR_k \geq SINR_{req} \quad \forall k$$

$$C5: SINR_j \leq SINR_{th} \quad \forall j$$

$$C6: V_n \succcurlyeq \boldsymbol{0} \tag{12}$$

Constraint C1 demonstrates that the transmitted power of the SWIPT base station must be under a proper limitation, $P1^{max} > 0$. In constraint C2, the upper bound $P2^{max} > 0$ indicates that the transmitted power of the assisting power beacons must be under a proper limitation. Constraint C3 indicates that the required total energy harvesting must be higher than a given threshold, $E_{th} > 0$, for ensuring the wireless power transferring performance. Constraint C4 means that the SINR of any desired k user should be higher than a given lower bound, $SINR_{req} > 0$, for guaranteeing the performance of wireless communication. Constraint C5 restricts the possible achievable SINR of potential eavesdroppers if any eavesdropper attempts to process information decoding. Constraint C6 combined with $\boldsymbol{V_n} \in \mathbb{H}^{N_T \times N_B}$ can guarantee that the covariance matrix of artificial noise vector is one positive semidefinite Hermitian matrix.

4. Optimization Solution

Due to the non-convexity of my objective function, C3 C4 and C5, the optimization problem of the SWIPT system in this thesis can be regarded as the non-convexity problem. Under this consideration, the method to transform the non-convexity is very crucial. In this thesis, we can use SCA and SDP relaxation to solve this difficulty [57-60].

The principle of SCA is to construct a more solvable approximate function as a bound of the original function to gradually approximate the original function, so as to find the global optimal solution of the original function. Generally, we need to build up the approximate function iteratively from x^k to x^{k+1}[61-63]. Moreover, we will use the Taylor Expansion to conduct the approximation function.

So, in the first step, I will do some simplification about the objective function for easy demonstration:

$$C_k = log_2\left(1 + \frac{A_k}{B_k}\right) = log_2(A_k + B_k) - log_2(B_k) \tag{13}$$

In this formulation, we can easily find that we need to set up one upper bound of $log_2 B_k$ to replace it, we can express that:

$$log_2 B_k \leq C^{(t)} \tag{14}$$

The exist of $C^{(t)}$ is easier to prove. We assume that $f(B_k) = log_2 B_k$. Based on the theorem of Taylor Expansion [64-66], we can observe that:

$$\frac{\partial log_2 B_k}{\partial B_k} = \frac{1}{B_k ln2} \tag{15}$$

$$\frac{\partial^2 log_2 B_k}{\partial B_k^2} = -\frac{1}{B^2 ln2} < 0 \tag{16}$$

So we can find the proper upper bound for $f(B_k)$:

$$log_2(B_k) \leq log_2\left(B_k^{(t)}\right) + \frac{1}{B_k^{(t)} ln2}\left(B_k - B_k^{(t)}\right) = C^{(t)} \tag{17}$$

The equality holds when $B_k = B_k^{(t)}$.

If we apply SDP method to the optimization problems [67], we find that:

$$\|w_k\|^2 = w_k^H w_k = W \tag{18}$$

W is the symmetric matrix and if we prove the inequation of C3, C4 and C5 is linear or convex function which is satisfied KKT conditions [68-70], we can use SDP method to convert the non-convexity of C3, C4 and C5.

In conclusion, to solve this non-convexity optimization problem, we firstly apply SCA method to the objective function and apply SDP to the non-convexity constraint of C3, C4 and C5.

Therefore, the original objective question can be expressed as:

$$\max_{A_k, B_k, \rho} \sum_{k=1}^{K} log_2(A_k + B_k) - C^{(t)}$$

s.t.

$$\text{C1:} \sum_{k=1}^{K} Tr(W_k) - P_1 \le 0$$

$$\text{C2:} \sum_{n=1}^{N_B} Tr(V_n) + \sum_{n=1}^{N_B} \sum_{i=1}^{K} Tr(P_{n,i}) - P_2 \le 0$$

$$\text{C3:} Tr(W_k H_k) - B_k \ge 0$$

$$\text{C4:} A_k \ge \sum_{m \ne k}^{K} Tr(W_m H_m) + \sum_{n=1}^{N_B} \sum_{i=1}^{k} Tr(P_{n,i} R_{n,i}) + \sum_{n=1}^{NB} Tr(V_n R_{n,k}) + \frac{\delta}{\rho}$$

$$\text{C5:} log_2(A_k + B_k) - C^{(t)} - R_{k,min} \ge 0$$

$$\text{C6:} \tau_k \left(\sum_{n=1}^{N_B} \sum_{i=1}^{K} \left| r_{n,i}^H p_{n,i} \right|^2 + \sum_{n=1}^{N_B} Tr(Q_{n,j} V_n) + \delta_2 \right) - \left| g_j^H w_j \right|^2 \ge 0$$

$$\text{C7:} W_k \ge 0, V_n \ge 0.$$

$$\text{C8:} Tr(W_k) \le 1$$

(19)

C8 is the constraint that can be removed if the SDP relaxation can be proved to be tight and the global optimized solution is feasible. In order to prove it, the KKT solution is applied to solve it.

$$L(W, \lambda_1, \lambda_2, \lambda_3, \dots\dots, \lambda_6) - \sum_{k=1}^{K} log_2(A_k + B_k) - C^{(t)} + (\lambda_1 \dots\dots \lambda_6) - Tr(YW) \tag{20}$$

Where $Y \ge 0 \ and\ \lambda_1 \dots\dots \lambda_6$ are the dual variables corresponding to the constraint conditions C9 and C1 to C6 of the optimization problem respectively. So we can redefine the Lagrangian Function:

$$\max_{Y,\lambda_1 \ldots\ldots \lambda_6} \frac{Inf\ L}{W} \tag{21}$$

Therefore, we can obtain the value of Y when the gradient of the Lagrange Function is zero:

$$\frac{\partial L}{\partial W} = 0 \tag{22}$$

$$Y = \lambda_1 I - \lambda_3 h_k h_k^H + \lambda_4 h_k h_k^H - \lambda_6 h_k h_k^H \tag{23}$$

Where $A = \lambda_1 I, and\ H = \lambda_3 h_k h_k^H - \lambda_4 h_k h_k^H + \lambda_6 h_k h_k^H$

As we got that:

$$Tr(YV) = Tr(AV) - Tr(HV) = -Tr(HV) \tag{24}$$

So:

$$Rank(Y) = -Rank(Y) = Rank(-A + H) \geq Rank(-A) - Rank(H) \geq N_t - 1 \quad (24)$$

Accordingly, the columns of W are the members of null space of Y:

$$Rank(W) \leq 1 \tag{25}$$

5. Optimization Result Analysis

In these chapter, the MATLAB simulation result and some analysis based on result will be introduced in details. In order to make the more clear and concise presentation of MATLAB simulation environment, Table 1 lists some key parameters about the system that the thesis mentioned above.

Noise Power	-110 dBm
Carrier Frequency	2.1 GHz
Minimum Power	0 dBm
Cell Radius	150 meters
SINR Requirement	10dB
Path Loss Model	TGN model [71]
Number of Power Beacon	1
Number of Base Station	1

Table1. Key Simulation Parameters

5.1 Average Secrecy Rate V.S. Number of eavesdroppers

What is shown on Fig5.1 has explained the relationship between the average secrecy rate and the number of eavesdroppers under the consideration that the number of desired receivers is 3 and the maximum transmit power is 46 dBm.

Obviously, from this figure we can get the analysis that the whole system average secrecy rate is inevitably declining with the number of eavesdroppers increasing. In addition, from the perspective of numerical value, it can be seen that the average secrecy rate of the overall system will decrease by 0.2-0.3bits/s/Hz for every passive eavesdropper added in the SWIPT system. This also shows that when the number of eavesdroppers increases, the security of the system will decline. Meanwhile, according to this figure, when the number of antennas in the base station increases, the overall average secrecy rate of the system is significantly improved. Especially from the numerical analysis, when the antenna is increased from 8 to 12, the average secrecy rate of the system is improved better than that when the antenna is increased from 12 to 16. This shows that an appropriate increase in the antenna can effectively improve the security of the SWIPT system under a certain maximum transmission energy.

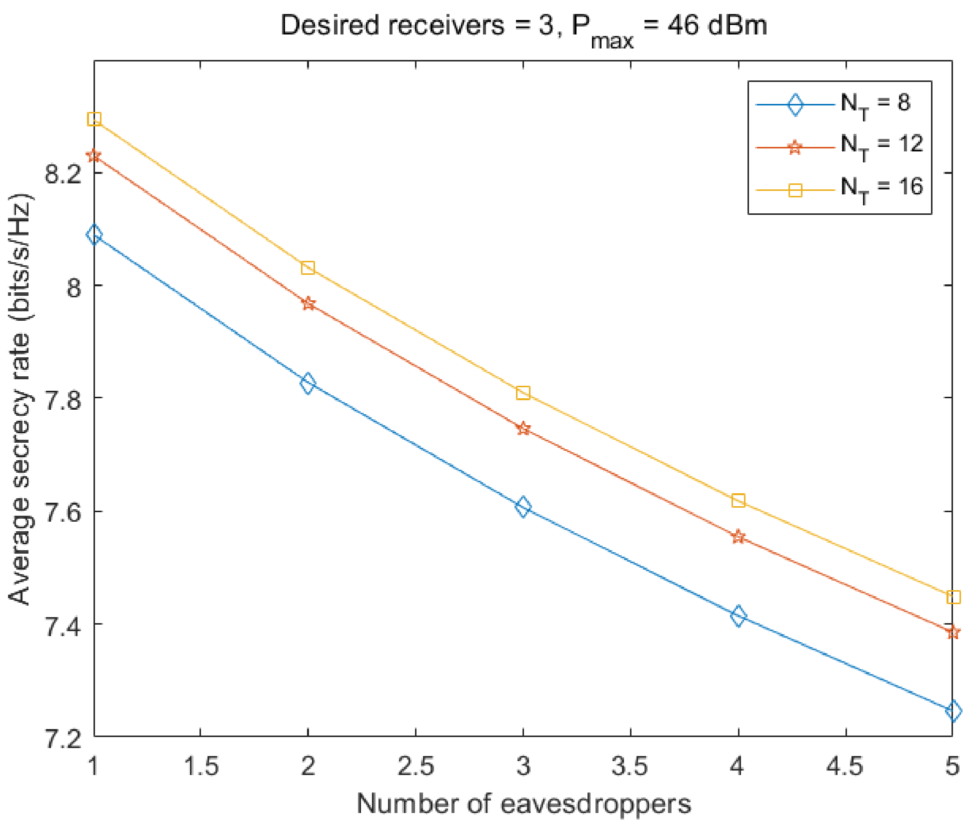

Fig5.1 Average secrecy rate v.s. number of eavesdropper

5.2 Average Secrecy Rate V.S. Maximum Power per BS

What is shown on Fig5.2 has explained the relationship between average secrecy rate and the maximum transmit power per BS under the consideration that the number of the passive eavesdropper is 1 and the number of the desired receiver is 3.

Obviously, from the figure we can get the analysis that the whole system average secrecy rate is increasing gradually with the maximum transmit power per BS increasing. More detailed numerical analysis shows that although the number of antennas at the transmitting end is different, when the maximum transmitting power of each base station increases from 30dBm to 46dBm, the average password rate of the overall system increases by 0.2-0.3bits/s/Hz. Meanwhile, When the maximum transmit power of each base station is the same, the increase of the number of antennas at the transmitter can significantly improve the average password rate of the overall system. From the numerical point of view, when the number of antennas increases from 4 to 8, the security improvement effect of the system is the most obvious.

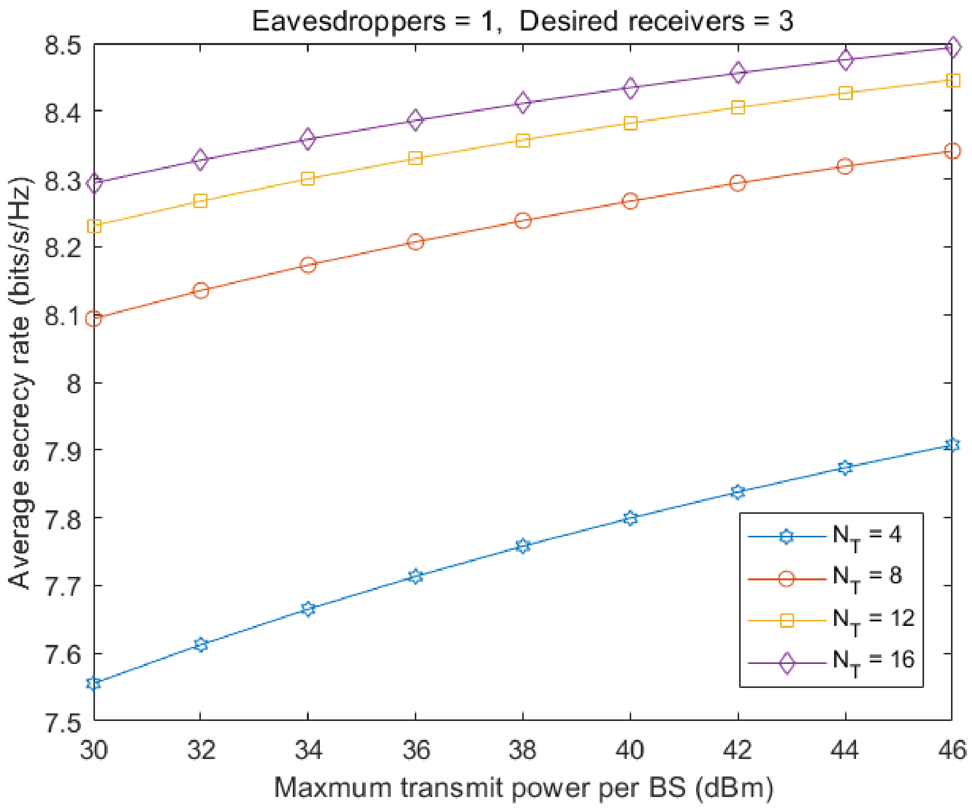

Fig5.2 Average Secrecy Rate v.s. Maximum Transmit Power per BS

6. Conclusion and Future Work

6.1 Conclusion

In the thesis, I designed a SWIPT system based on MISO. With the help of Power Beacon, the entire SWIPT has security problems due to the existence of passive eavesdroppers. The optimal solution of the average secrecy rate of the SWIPT system can be obtained through the beamforming algorithm designed in this paper. The architecture idea of the beamforming algorithm is based on the transformation and optimization of non convex problems. The result and analysis of simulation can introduce that the beamforming algorithm proposed by this thesis is proved to be feasible and the maximum average secrecy rate of different simulation parameters can be obtained.

6.2 Future Work

Although the model of SWIPT system proposed in this paper has some full practicability, its basic architecture is still to consider a fairly ideal communication environment. Based on these considerations, in the future research work, I am committed to further improving the practicability of the SWIPT system and discussing the security of more complex application scenarios. For instance, in the future, I will consider the situation that some information is missing at the transmitter of CSI, so as to design a set of SWIPT model for performance optimization analysis. In addition, with the continuous evolution of communication system, MISO communication architecture will be gradually replaced by MIMO communication architecture due to reliability and service performance. Therefore, I will do some optimization algorithm design of SWIPT system based on MIMO communication system in the future.

References

[1] I. Krikidis, S. Timotheou, S. Nikolaou, G. Zheng, D. W. K. Ng and R. Schober, "Simultaneous wireless information and power transfer in modern communication systems," in IEEE Communications Magazine, vol. 52, no. 11, pp. 104-110, Nov. 2014.

[2] Ozel, O. and Ulukus, S. (2012) “Achieving AWGN capacity under stochastic energy harvesting,” *IEEE Transactions on Information Theory*, 58(10), pp. 6471–6483.

[3] Prasad, R. (2014) “5G: 2020 and beyond,” *5G: 2020 and Beyond*, pp. 1–125.

[4] Milovanovic, D.A. and Bojkovic, Z.S. (2020) “An evolution of 5G Multimedia Communication,” *5G Multimedia Communication*, pp. 129–156.

[5] Pinuela, M., Mitcheson, P.D. and Lucyszyn, S. (2013) “Ambient RF energy harvesting in urban and semi-urban environments,” *IEEE Transactions on Microwave Theory and Techniques*, 61(7), pp. 2715–2726.

[6] Majumdar, A.K. (2019) “Potential applications for broadband global internet connectivity,” *Optical Wireless Communications for Broadband Global Internet Connectivity*, pp. 259–268.

[7] Nintanavongsa, P. et al. (2012) “Design optimization and implementation for RF Energy Harvesting Circuits,” *IEEE Journal on Emerging and Selected Topics in Circuits and Systems*, 2(1), pp. 24–33.

[8] Naderi, M.Y., Chowdhury, K.R. and Basagni, S. (2015) “Wireless sensor networks with RF Energy Harvesting: Energy Models and analysis,” 2*015 IEEE Wireless Communications and Networking Conference (WCNC)*.

[9] Tung, N. (2016) “Multi-band ambient RF Energy Harvesting Rectifier for autonomous wireless sensor networks,” *2016 IEEE Region 10 Conference (TENCON)*.

[10] Wu, Y. et al. (2016) “Low-complexity MIMO precoding with discrete signals and statistical CSI,” *2016 IEEE International Conference on Communications (ICC)*.

[11] Varshney, L.R. (2008) “Transporting information and energy simultaneously,” *2008 IEEE International Symposium on Information Theory*.

[12] Yang, Z. et al. (2022) “Energy-efficient wireless communications with distributed reconfigurable intelligent surfaces,” *IEEE Transactions on Wireless Communications*, 21(1), pp. 665–679.

[13] Xu, J., Liu, L. and Zhang, R. (2013) “Multiuser MISO beamforming for simultaneous wireless information and Power Transfer,” *2013 IEEE International Conference on Acoustics, Speech and Signal Processing.*

[14] Ng, D.W. and Schober, R. (2014) “Max-min fair wireless energy transfer for secure Multiuser Communication Systems,” *2014 IEEE Information Theory Workshop (ITW 2014)*.

[15] Wu, Q. et al. (2015) “Energy-efficient transmission for wireless powered Multiuser Communication Networks,” *2015 IEEE International Conference on Communications (ICC)*.

[16] Dong, Y. et al. (2017) “Proportional fairness-based beamforming and signal splitting for miso-SWIPT systems,” *IEEE Communications Letters, 21(5)*, pp. 1135–1138.

[17] Li, B., Fei, Z. and Chu, Z. (2017) “Optimal transmit beamforming for secure SWIPT in a two-tier HetNet,” *IEEE Communications Letters*, 21(11), pp. 2476–2479.

[18] Wu, Q. et al. (2019) “Generalized wireless-powered communications: When to activate wireless power transfer?,” *IEEE Transactions on Vehicular Technology,* 68(8), pp. 8243–8248.

[19] Xiang, L. et al. (2015) “Cross-layer optimization of fast video delivery in cache-enabled relaying networks,” *2015 IEEE Global Communications Conference (GLOBECOM)*.

[20] Shiyang Leng, Ng, D.W. and Schober, R. (2014) “Power efficient and secure multiuser communication systems with wireless information and Power Transfer,” *2014 IEEE International Conference on Communications Workshops (ICC)*.

[21] Boshkovska, E. et al. (2015) “Practical non-linear energy harvesting model and resource allocation for SWIPT Systems,” *IEEE Communications Letters*, 19(12), pp. 2082–2085.

[22] Ng, D.W. and Schober, R. (2014) “Resource allocation for Coordinated multipoint networks with wireless information and Power Transfer,” 2*014 IEEE Global Communications Conference.*

[23] Ng, D.W. and Schober, R. (2013) “Resource allocation for secure communication in systems with wireless information and Power Transfer,” 2*013 IEEE Globecom Workshops (GC Wkshps)*.

[24] Clerckx, B. et al. (2019) “Fundamentals of Wireless Information and Power Transfer: From RF Energy Harvester models to signal and system designs,” *IEEE Journal on Selected Areas in Communications*, 37(1), pp. 4–33.

[25] Chen, X. et al. (2017) “A survey on multiple-antenna techniques for Physical Layer Security,” *IEEE Communications Surveys & Tutorials*, 19(2), pp. 1027–1053.

[26] Zhang, J. et al. (2020) “Prospective multiple antenna technologies for beyond 5G,” *IEEE Journal on Selected Areas in Communications*, 38(8), pp. 1637–1660.

[27] Sun, Y. et al. (2017) “Optimal joint power and subcarrier allocation for full-duplex multicarrier Non-Orthogonal Multiple Access Systems,” *IEEETransactions on Communications*, 65(3), pp. 1077–1091.

[28] Ng, D.W. and Schober, R. (2012) “Energy-efficient resource allocation in OFDMA systems with large numbers of base station antennas,”*2012 IEEE International Conference on Communications (ICC).*

[29] Ng, D.W., Lo, E.S. and Schober, R. (2012) “Energy-efficient resource allocation in multi-cell OFDMA systems with limited backhaul capacity,” *2012 IEEE Wireless Communications and Networking Conference (WCNC)*.

[30] Ng, D.W., Lo, E.S. and Schober, R. (2013) “Energy-efficient resource allocation in OFDMA systems with hybrid energy harvesting base station,” *IEEE Transactions on Wireless Communications*, 12(7), pp. 3412–3427.

[31] Ng, D.W. and Schober, R. (2011) “Dynamic Resource Allocation in OFDMA systems with full-duplex and hybrid relaying,” *2011 IEEE International Conference on Communications (ICC)*.

[32] Ng, D.W. and Schober, R. (2010) “Resource allocation and scheduling in multi-cell OFDMA decode-and-forward relaying networks,” *2010 IEEE Global Telecommunications Conference GLOBECOM 2010*.

[33] Qi, Q. et al. (2019) “Robust beamforming design for SWIPT in cellular internet of things,” *2019 IEEE/CIC International Conference on Communications in China (ICCC)*.

[34] Qi, Q., Chen, X. and Ng, D.W. (2020) “Robust beamforming for NOMA-based cellular massive IOT with SWIPT,” *IEEE Transactions on Signal Processing*, 68, pp. 211–224.

[35] Boshkovska, E. et al. (2017) “Robust resource allocation for MIMO Wireless Powered Communication Networks based on a non-linear EH model,” *IEEE Transactions on Communications*, 65(5), pp. 1984–1999.

[36] Wei, Z., Ng, D.W. and Yuan, J. (2016) “Power-efficient resource allocation for MC-NOMA with statistical channel state information,” *2016 IEEE Global Communications Conference (GLOBECOM)*.

[37] Ng, D.W. and Schober, R. (2015) “Secure and green SWIPT in distributed antenna networks with limited backhaul capacity,” *IEEE Transactions on Wireless Communications*, 14(9), pp. 5082–5097.

[38] Ng, D.W., Leng, S. and Schober, R. (2016) “Multiple antennas and beamforming for SWIPT systems,” *Wireless-Powered Communication Networks*, pp. 170–216.

[39] Xu, D. et al. (2021) “Resource allocation for large IRS-assisted SWIPT systems with non-linear energy harvesting model,” *2021 IEEE Wireless Communications and Networking Conference (WCNC)*.

[40] Ng, D.W., Wu, K. and Leung, V.C.M. (2019) “Enhanced energy-efficient downlink resource allocation in green non-orthogonal Multiple Access Systems,” *Computer Communications*, 139, pp. 78–90.

[41] Ng, D.W. and Hanzo, L. (2022) "IRS-Aided Wireless powered MEC systems: TDMA or Noma for computation offloading?," *IEEE Transactions on Wireless Communications*, pp. 1–1.

[42] Wu, Q. et al. (2016) "User-centric energy efficiency maximization for wireless powered communications," *IEEE Transactions on Wireless Communications, 15(10)*, pp. 6898–6912.

[43] Wu, Y. et al. (2015) "Secure massive MIMO transmission in the presence of an active eavesdropper," *2015 IEEE International Conference on Communications (ICC)*.

[44] Ng., D.W. et al. (2022) "Beamforming optimization for active intelligent reflecting surface-aided SWIPT," *IEEE Transactions on Wireless Communications*, pp. 1–1.

[45] Morsi, R. et al. (2020) "Conditional capacity and transmit signal design for SWIPT systems with multiple nonlinear energy harvesting receivers," *IEEE Transactions on Communications, 68(1), pp. 582–601*.

[46] Boshkovska, E. et al. (2018) "Power-efficient and secure WPCNS with hardware impairments and non-linear EH Circuit," *IEEE Transactions on Communications*, 66(6), pp. 2642–2657.

[47] Ahmed, I. et al. (2013) "Power allocation for an energy harvesting transmitter with hybrid energy sources," *IEEE Transactions on Wireless Communications*, 12(12), pp. 6255–6267.

[48] Boshkovska, E. et al. (2017) "Secure SWIPT networks based on a non-linear energy harvesting model," *2017 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*.

[49] Ng, D.W., Schober, R. and Alnuweiri, H. (2014) "Secure layered transmission in multicast systems with wireless information and Power Transfer," *2014 IEEE International Conference on Communications (ICC)*.

[50] Sun, X. et al. (2018) "Joint beamforming and power allocation in downlink Noma Multiuser MIMO Networks," *IEEE Transactions on Wireless*

Communications, 17(8), pp. 5367－5381.

[51] Zhai, X. et al. (2021) “Hybrid beamforming for massive MIMO over-the-air computation,” *IEEE Transactions on Communications*, 69(4), pp. 2737–2751.

[52] Ng, D.W., Lin Xiang and Schober, R. (2013) “Multi-objective beamforming for secure communication in systems with wireless information and Power Transfer,” *2013 IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC)*.

[53] Kumar, V. et al. (2021) “On the secrecy rate under statistical QoS provisioning for RIS-assisted miso wiretap channel,” *2021 IEEE Global Communications Conference (GLOBECOM).*

[54] Zhang, J. et al. (2014) “Effective rate analysis of miso systems over α-μ fading channels,” *2015 IEEE Global Communications Conference (GLOBECOM)*.

[55] Sun, Y., Ng, D.W. and Schober, R. (2017) “Optimal Resource Allocation for multicarrier miso-noma systems,” *2017 IEEE International Conference on Communications (ICC)*.

[56] Ng, D.W. et al. (2016) “Robust layered transmission in secure miso multiuser unicast cognitive radio systems,” *IEEE Transactions on Vehicular Technology*, 65(10), pp. 8267–8282.

[57] Li, Q., Ma, W.-K. and So, A.M.-C. (2011) “Safe convex approximation to outage-based MISO secrecy rate optimization under imperfect CSI and with artificial noise,” *2011 Conference Record of the Forty Fifth Asilomar Conference on Signals, Systems and Computers (ASILOMAR)*.

[58] Wang, C. et al. (2015) “Joint beamforming and Power Allocation for secrecy in peer-to-peer relay networks,” *IEEE Transactions on Wireless Communications*, 14(6), pp. 3280–3293.

[59] Liang, X. et al. (2017) “Outage performance for cooperative noma transmission with an AF relay,” *IEEE Communications Letters*, *21(11)*, pp. 2428–2431.

[60] Ng, D.W., Lo, E.S. and Schober, R. (2013) “Energy-efficient power allocation in OFDM systems with wireless information and Power Transfer,” *2013 IEEE International Conference on Communications (ICC)*.

[61] Zhou, Y. et al. (2020) “Robust trajectory and transmit power optimization for secure UAV-enabled Cognitive Radio Networks,” *IEEE Transactions on Communications, 68(7)*, pp. 4022–4034.

[62] Sun, Y. et al. (2018) “Resource allocation for solar powered UAV Communication Systems,” *2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*.

[63] Liu, C. et al. (2021) “Location-aware predictive beamforming for UAV Communications: A deep learning approach,” *IEEE Wireless Communications Letters, 10(3)*, pp. 668–672.

[64] Xie, H. et al. (2021) “User grouping and reflective beamforming for IRS-AIDED URLLC,” *IEEE Wireless Communications Letters, 10(11)*, pp. 2533–2537.

[65] Yu, X. et al. (2021) “Smart and reconfigurable wireless communications: From IRS modeling to Algorithm Design,” *IEEE Wireless Communications*, 28(6), pp. 118–125.

[66] Fu, H., Feng, S. and Kwan Ng, D.W. (2021) “Resource Allocation Design for IRS-aided downlink mu-miso RSMA Systems,” *2021 IEEE International Conference on Communications Workshops (ICC Workshops)*.

[67] You, L. et al. (2021) “Reconfigurable intelligent surfaces-assisted multiuser MIMO uplink transmission with partial CSI,” *IEEE Transactions on Wireless Communications*, 20(9), pp. 5613–5627.

[68] Zhang, W. et al. (2021) “Cascaded Channel Estimation for IRS-assisted mmwave multi-antenna with quantized beamforming,” *IEEE Communications Letters, 25(2)*, pp. 593–597.

[69] Liu, C. et al. (2021) “Deep residual network empowered channel estimation for IRS-Assisted Multi-user Communication Systems,” *ICC 2021 - IEEE International Conference on Communications*.

[70] S. Hu, Z. Wei, Y. Cai, C. Liu, D. W. K. Ng and J. Yuan, "Robust and Secure Sum-Rate Maximization for Multiuser MISO Downlink Systems With Self-Sustainable IRS," in IEEE Transactions on Communications, vol. 69, no. 10, pp. 7032-7049, Oct. 2021.

[71] Habib, B., Zaharia, G. and El Zein, G. (2012) “Mimo Hardware Simulator: Digital Block Design for 802.11ac applications with TGN channel Model Test,” *2012 IEEE 75th Vehicular Technology Conference (VTC Spring)*.