SCHOOL OF ELECTRICAL ENGINEERING
AND TELECOMMUNICATIONS

Resource Allocation for SWIPT-enabled Secure Communication Systems

by

Kaichen Feng

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Abstract

With the continuous upgrading of communication network technology, users' demand for lower latency and higher capacity network services is also rapidly expanding. In contrast, mobile network has also become a part of people's life, which affects people's life all the time. However, the energy consumption of mobile devices limits the working time and working range of mobile devices. To solve this problem, a new network called SWIPT has been developed that uses wireless signals to combine energy and information signals. The purpose of this paper is to review and introduce the existing SWIPT technology, propose my own system model and guarantee the quality of service of the users in the model. In this paper, we will discuss the maximum system channel capacity of a SWIPT system with the guarantee of security. The total power of the system and the eavesdropper's offensive and defensive equipment are also taken into account. Based on this model, a beamforming algorithm is proposed, in which SCA algorithm and SDP relaxation algorithm are used in convex optimization algorithm. Finally, the feasibility of the algorithm is proved by the simulation results.
Key Word---simultaneous wireless information and power transfer, channel capacity, beamforming design, SCA, SDP relaxation, KKT condition.

Abbreviations

1G	First Generation Communication System
2G	Second Generation Communication System
3G	Third Generation Communication System
4G	Fourth Generation Communication System
5G	Fifth Generation Communication System
BS	Base Station
SWIPT	Simultaneous Wireless Information and Power Transferring
IoT	Internet of Things
WPT	Wireless Power Transfer
EM	Electromagnetic
MISO	Multiple-Input Single-Output system
RF	Radio Frequency
WPCN	Wireless Power Communication Network
WPBC	Wireless Powered Backscatter Communication
SINR	Signal to Interference plus Noise Ratio
MIMO	Multiple-Input Multiple-Output system
TS	Time Switching
PS	Power Splitting
IoT	Internet of Things

Contents

Chapter 1 Introduction

With the rapidly developing of mobile wireless communication system, the wireless mobile devices become normal equipment for people all over the world. Up to 2021, the number of mobile internet subscribers is 4.2 billion people globally, which is the 59% of the global population. In future, the proportion will raise steadily [1].

However, because almost all wireless mobile devices are designed to be portable, the battery is small and cannot store much energy. It holds back the future application of the wireless communication system. To solving this problem, introducing a feasible energy-saving approach is raised recently that "harvesting" energy from surrounding environment. There have been some resources from the environment could be used to save energy, such as solar, wind and ocean. Considering that almost all normal mobile services work in an environment which is full of radio signal, "harvesting" energy from the electromagnetic radio frequency (RF) is a viable solution [2]. What's more, Simultaneous Wireless Information and Power Transfer (SWIPT) network system is designed to spread the information signal and energy signal at the same time [3]. Therefore, SWIPT network and RF-based harvest energy technology help to build a network whose users not only have constant source of energy but also the ability to self-collect energy from the base station (BS) [4] and the problems happened during the process of this system arrive in quick succession.

This thesis will focus on the security of the SWIPT system and provide a solution to keep a high bit rate at desired receivers during the noise jamming.

Chapter 2 Background

2.1 Development of the Telecommunication Network

The first phone was invented at 1980s. Since then, the use of wireless technology attracts the sight of the whole world. At first, it is an expensive technology just for basic voice services and the coverage is limited (1G).[5] From 2G, the network is improved that the network began to use digital signal to support users' service. What's more, users could send text by 2G [6]. During the 3G, the smartphone was invented, with the help of 3G network, people enjoy the telecommunication with more service [7]. After that, 4G supports music, online game and video application in mobile phone which means it has higher speed and wider bandwidth [8]. Today, the 5G is invented. This technology offers greater capacity, higher speed and better service [9]. Over all, there are huge changes in the speed and time to download. It means the wireless network could solve more problems and support more service [10].

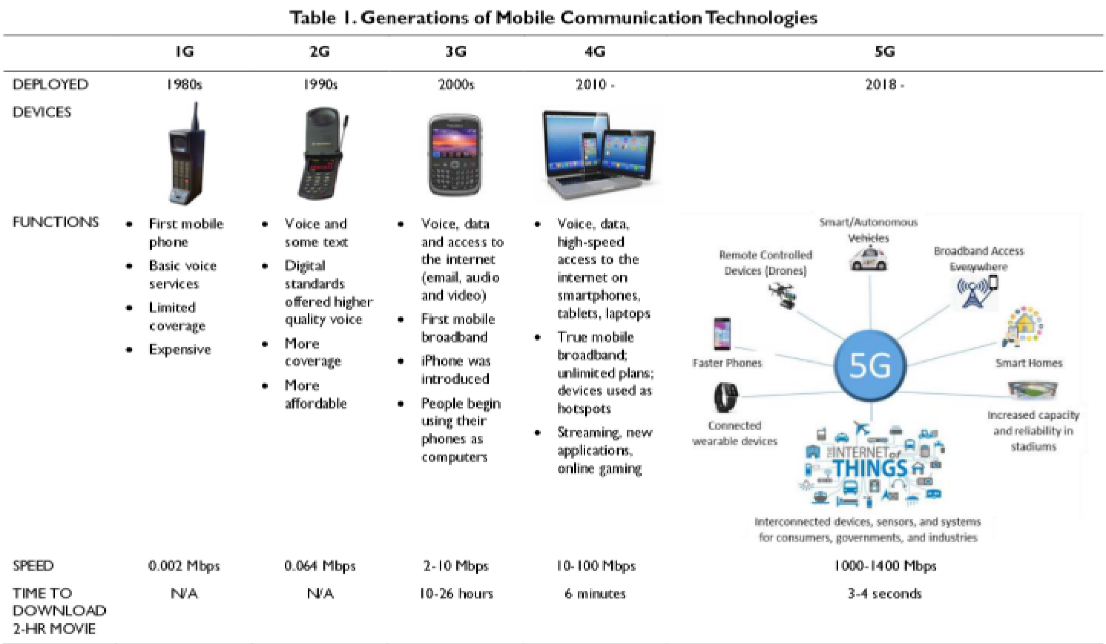

Table 1. Generations of Mobile Communication Technologies

	1G	2G	3G	4G	5G
DEPLOYED	1980s	1990s	2000s	2010 -	2018 -
DEVICES					
FUNCTIONS	• First mobile phone • Basic voice services • Limited coverage • Expensive	• Voice and some text • Digital standards offered higher quality voice • More coverage • More affordable	• Voice, data and access to the internet (email, audio and video) • First mobile broadband • iPhone was introduced • People begin using their phones as computers	• Voice, data, high-speed access to the internet on smartphones, tablets, laptops • True mobile broadband; unlimited plans; devices used as hotspots • Streaming, new applications, online gaming	
SPEED	0.002 Mbps	0.064 Mbps	2-10 Mbps	10-100 Mbps	1000-1400 Mbps
TIME TO DOWNLOAD 2-HR MOVIE	N/A	N/A	10-26 hours	6 minutes	3-4 seconds

Fig.1 Generations of Mobile Communication Technologies[11]

Therefore, the number of users of wireless mobile network raises rapidly at the same time. A report published by GSMA gives the raising trend of the global connection. It is obvious that in 2025 the 5G network will connect 2 billion people together, and to fill the need of users, we also propose the desideratum of 5G network. Of course, there are some challenges 5G need to solve. Such as data rate and network capacity expansion with energy, scalability and flexibility and so on [1].

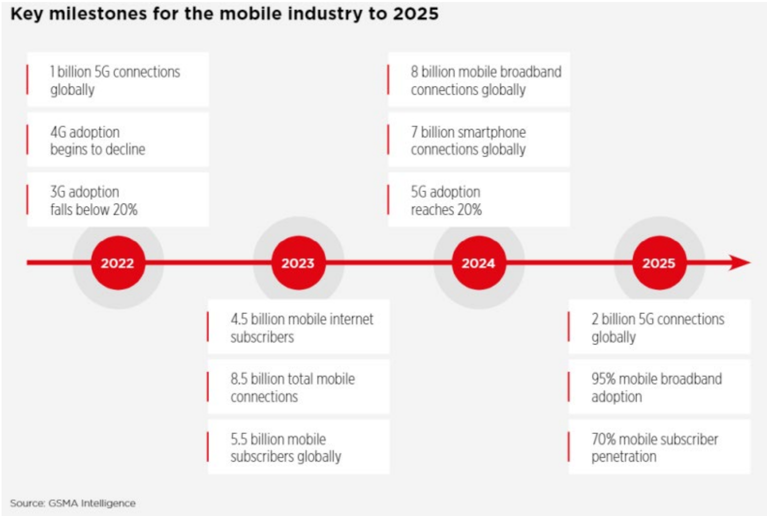

Fig.2 Key milestones for the mobile industry to 2025

2.2 Energy Problem

As I mentioned before, With the upgrade of the wireless communication system, the use of mobile phones has become widespread. On the one hand, people use mobile phones to add convenience to their life, but mobile phones also become an obstacle to restrict people's convenient life. According to a report published at 2016, there are 90% people will feel anxious when their smartphone battery drops to 20 percent or below [12]. It shows that it can influence not only the using of wireless device but also the user experience. For example, a case of the report tells us if a person is ready to go to the gym for exercise, but he will give up and stay at home when he finds his battery drops. Therefore, it is obviously important for the improving of wireless telecommunication network.

2.3 An Introduction of WPT

At 1900s, Nikola Tesla proposed the technique named wireless power transfer (WPT). He even performed experiments and filed the patens named Wardenclyffe Tower to be a pilot plant for the "World Wireless System". However, this ambitious project was interrupt because of concerns about the physical damage caused by strong electromagnetic (EM) waves at that time [11]. Recently, WPT attract engineers again as it is the key technology to improve the performance of IoT systems. For IoT system, there are numerous equipment and sensor need to charge which cause that introducing charging cables through the whole application scenario [13]. The WPT system is proposed to solve this problem by wireless charging [39].

For the system structure of SWIPT system, there are three types: RF-based WPT [14], Inductive coupling [15] and magnetic resonant coupling [16]. The latter two technologies are not universally applicable to wireless networks. Coupling requires the use of near-field electromagnetic waves to charge, which makes it much less mobile (charging within a few meters) [17]. At the same time, electromagnetic fields and energy-harvesting circuits must also be aligned, which reduces the diversity of wireless systems, because it means that charging can only be done using equipment from the same manufacturer, making it extremely difficult to bring in equipment from other manufacturers [18]. Comparing to them, RF-based WPT is a technology relay on the far-field properties of EM waves[43]. It can charge devices within hundreds of meters and through various EM wave sources, such as WIFI, base stations, etc. And RF signal can not only realize the transmission of energy, but also retain its information transmission characteristics, and the resource utilization of the system has been improved [19]. And the health problems caused by strong electromagnetic waves, which worried people 100 years ago, can be solved because the government can set the power of radio frequency so that it does not affect people's health [20].

2.4 Receiver Structures of SWIPT

As I mentioned before, the WPT is a technology transfer information and energy at the same time. There are three types of WPT: SWIPT, WPCNs and WPBC [22]. The WPCNs and WPBC are more stringent on the environment and will greatly increase the complexity of the receiving device, so they are not suitable for the popularization of all wireless devices [40][48]. Therefore, the SWIPT is attractive among them.

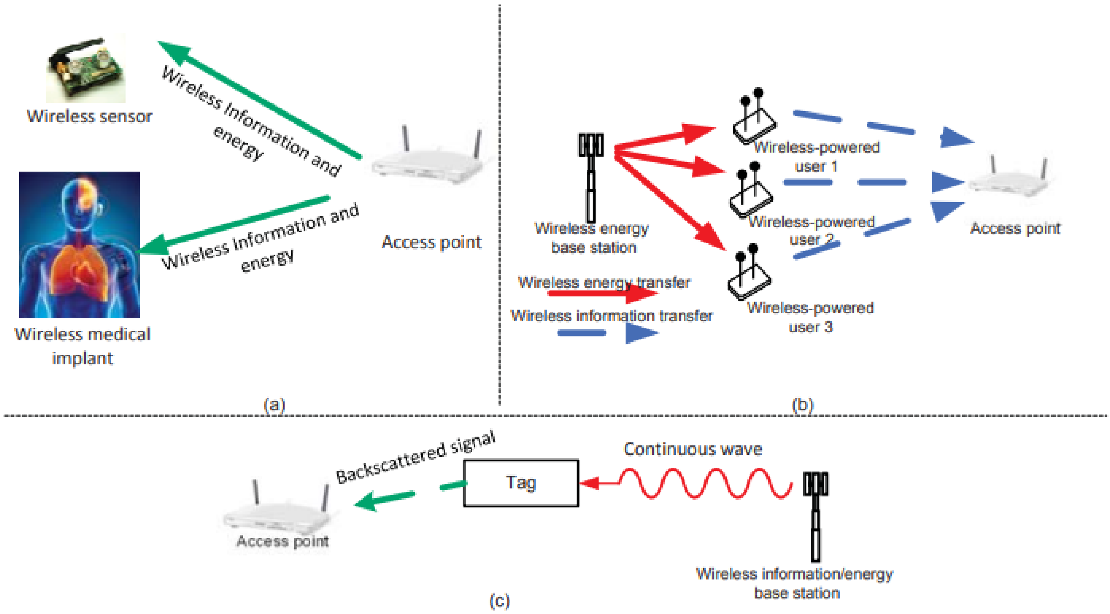

Fig.3 Basic Structure of SWIPT(a), WPCNs(b) and WPBC(c).

In SWIPT wireless network system, the information signal and energy are separately transferred at the same time[44]. The reason why the information signal is unable to use for save energy is that the process of energy harvesting could change the phase of the signal. It will cause the received information signal is hard to decoded. Correspondingly, the receiving antenna processes information and energy signals separately, and I will describe the two most typical receiving structures [22].

1.TS receiver structure keeps switching working mode between information signal mode and energy mode. It just has a function during a time slot, energy harvesting or information decoding. The advantage of this structure is the hardware implementation is relatively simple, but it also needs high-accuracy synchronization and information/energy scheduling.[41]

2.Power Splitting (PS) Receiver: PS receiver structure decodes the energy signal and information signal simultaneously. The whole signal will be divided into two streams by judging the power level by a PS unit. Then the energy signal and information signal will be decoded by energy harvester and information receiver severally. Furthermore, there is an optimization to control the balance between harvesting energy and decoding information. This kind of receiver antenna is suitable for wireless network as it could receive the information signal all the time although the structure is complex.[42]

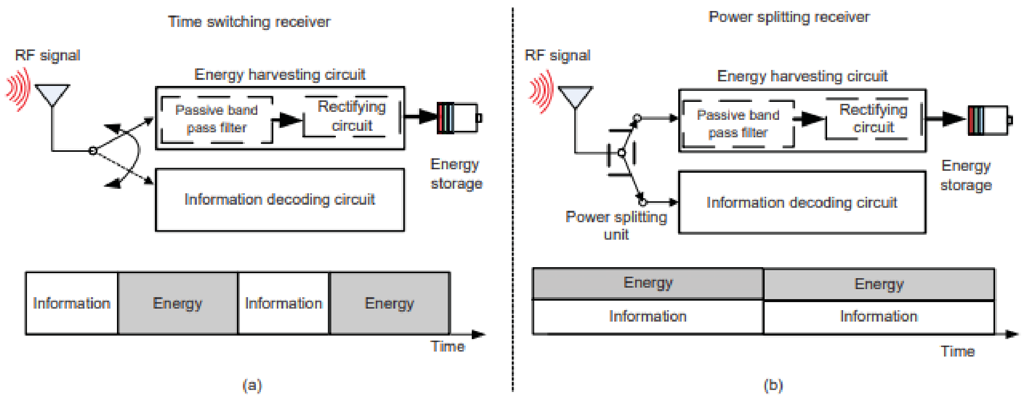

Fig.4 Basic Structure of TS(a) receiver and PS(b) receiver

2.5 Challenges in SWIPT

While SWIPT offers real benefits for energy capture, there are still some significant challenges in integrating SWIPT technology into wireless communication systems. In [23], a basic view of the tradeoff between WET and WIT when considering channel fading and frequency selection is given. In [24-27], the authors give a rate-energy tradeoff region for multiple input multiple-output (MIMO) systems. Despite numerous previous studies, the efficiency of wireless power transmission remains low. It is worth noting that the path loss of the channel attenuates the wireless signal significantly, which results in the end user harvesting only a small fraction of the total power [38]. As a result, other technologies are being combined with SWIPT systems to improve power transmission efficiency. Multiple antennas are the most common technology used for this purpose [29]. In particular, by increasing the spatial freedom of multiple antennas, the system will obtain more wireless energy, which can be transmitted to the desired receiver more accurately and specifically, improving the efficiency of energy transmission [37]. In addition, existing network protocols, resource allocation algorithms and receiver structures are designed for traditional communication systems [28], and are optimized for pure data communication services. Due to the nature of beamforming, the relevant technologies are not sufficient to meet the standard requirements for practical SWIPT implementation [30]. Besides, the other hand of challenge is security problem that I will mention later.

2.6 Security in SWIPT

As I mentioned before, the information signal and energy signal will spread by the BSs simultaneously. It causes that the energy signal will have bad impact on Signal to Interference plus Noise Ratio (SINR) of the system [31]. The transmitter needs to devote higher energy to produce information signal to keep the suitable SINR for users. It increases the possibility of eavesdropping. There are two ways to solving security problem, application layer security and physical layer security[45]. The application layer security achieved by changing the encryption method in application layer (Layer 7 of the OSI model). The physical layer describes the situation of signal in the channel of the wireless system[46]. Obtain physical layer security is to increase the confidentiality of the information signal by exploiting the physical properties of the channel [32]. In contrast, the condition of A is harsh. It can be realized on the premise that the encryption key of the communication system will not be leaked in other ways, but it is impossible to guarantee this in real life. Therefore, the physical layer security is thought of the considerable method to protect the information signal from being decoding by eavesdroppers [33]. There also are many works have been devoted into this field. Both the systems of [34]-[36] add artificial noise as the energy signal to achieve the dual function of charging and protecting. The author of [34] study a source allocation algorithm to guarantee a secure wireless communication system equipped with power splitting receivers. In [35], a resource allocation algorithm is proposed to build a multiple-input single-output (MISO) secure telecommunication system which has lower transmit power with reliable secrecy capacity. Besides, it shows that by using physical layer security is able to provide a reliable secret wireless communication network with guarantied quality of service (QoS) in [36]. In the system models of [33]-[36], the author set the eavesdropper as a "thief" without aggressivity. However, the eavesdropper is not only an equipment for decoding the encrypted information signal sometimes. It is completely possible that the eavesdropper has partner BS to spread noise to attack the wireless communication.

Keeping the data rate of the wireless communication system under the attack from the other BS is a problem. In following part of this report, I will build my system model and provide a solution to keep the data rate of the users of the SWIPT wireless system.

Chapter 3 Thesis Model

3.1 Notations

During the later model, the matrices will be represented by boldface letter, the vector will be represented by lower case font.

Notation	Description
$\boldsymbol{A}^{\boldsymbol{H}}$	Hermitian transpose of matrix
$Tr(\boldsymbol{A})$	Rank of matrix
$\boldsymbol{A} \succcurlyeq \boldsymbol{0}$	A is a positive semidefinite matrix
$\mathbb{C}^{N\times 1}$	The set of all N × 1 matrices with complex entries
$\mathrm{A} \in \mathbb{C}^{N_T\times 1}$	$\mathrm{Null}(\mathbf{A}) \triangleq \{\mathrm{y} \in \mathbb{C}^{N\times 1}: \mathrm{Ay} = 0, \lvert\lvert \mathrm{y} \rvert\rvert = 1\}$

Table.1 The Concept of Notations

3.2 System Descriptions

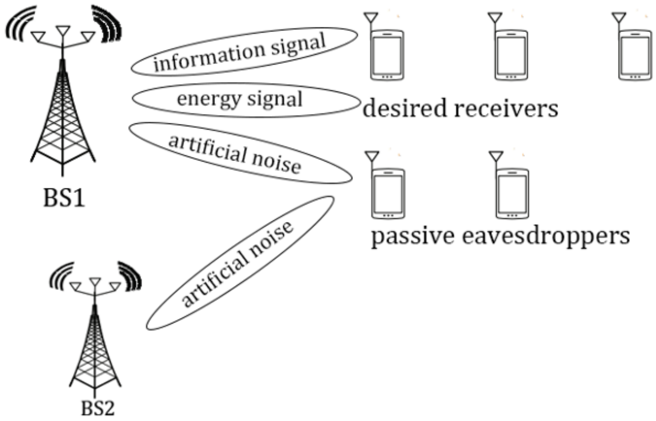

Fig.5 Basic Structure of System Model

I consider a SWIPT wireless telecommunication system for multiuser downlink communication. This network consists of two types receivers and two base stations.

The first kind of receiver is named desired receiver. The second kind of receiver is passive eavesdropper. The information base station (BS_1) is a transmitter with $N_T > 1$ antennas who can spread information signal, energy signal and artificial noise. It serves M passive eavesdroppers and K desired users. The attack base station (BS_2) equipped with $N_B > 1$ antennas who spreads artificial noise. For the desired receiver, it is a signal antenna equipment which equipped with the power splitting receiver structure. The other kind of receiver, passive eavesdropper, is also a receiver with same single structure. The desired receivers are the user of the wireless network, they can receive the information and energy signal to decode them. As for the passive eavesdroppers, they are roaming receivers from the other system who aim to research an energy additional resource at RF. However, they are ostensibly surreptitiously connected to the network to gain power, but in essence they may decode information signals to steal users' communications. Furthermore, they have a partner (attacking base station) to cause noise interference to the communication system. As the passive eavesdropper knows that there is a noise jamming, they will conduct the corresponding interference-free processing to obtain the correct information when receiving the information signal. However, the desired users can't judge if the system suffer the noise jamming. As a result, the artificial noise from the attack base station should be taken into the consider to give desired receiver a security wireless system.

3.3 Signal Model

In order to simplify the model and preserve its physical meaning, the channels are set as frequency flat fading channels and the system is a TDD system. What's more, the transmitters could obtain perfect CSI for all receivers [47].

In each time slot, all desired receivers will receive K different information signal. I set the vector $\boldsymbol{w_k} \in \mathbb{C}^{N_T \times 1}$ to denote the beamforming vector of the BS_1. At the same time, BS_1 itself has the function of transmitting artificial noise to disturb the decoding of potential eavesdroppers to ensure the security of the signal. Therefore, $\mathbf{x} \in \mathbb{C}^{N_T \times 1}$ which is the BS_1's transmitted signal vector is represent by the combination of the information signals and artificial noise which is given by

$$\mathbf{x} = \sum_{\mathrm{k}=1}^{K} \boldsymbol{w_k} s_k + \boldsymbol{v_1} \tag{1}$$

where $\boldsymbol{v_1} \in \mathbb{C}^{N_T \times 1}$is artificial noise from BS_2 and $v_1 \sim \mathcal{CN}(\mathbf{0}, \boldsymbol{V_1})$.It means that the artificial noise is modelled as zero mean and covariance matrix $\boldsymbol{V_1}$ is the positive semidefinite Hermitian matrix. $s_k \in \mathbb{C}$ means the symbols of the signals for the desired receiver k.

As there are K desired receivers, the received signal is given by

$$\boldsymbol{y_k} = \boldsymbol{h_k^H} \mathbf{x} + n_R + \boldsymbol{g_k^H} \boldsymbol{v_2} \tag{2}$$

where $\boldsymbol{h_k} \in \mathbb{C}^{N_T \times 1}$ is the channel vector between the BS_1 and the k-th desired receiver. The $\boldsymbol{g_k} \in \mathbb{C}^{N_T \times 1}$ is the channel vector between the BS_2 and the k-th desired receiver. The $n_R \sim \mathcal{CN}(0, \sigma_s^2)$ means the Gaussian noise of the receiver. $\boldsymbol{v_2} \in \mathbb{C}^{N_B \times 1}$is artificial noise from BS_2 and $v_2 \sim \mathcal{CN}(\mathbf{0}, \boldsymbol{V_2})$.It means that the artificial noise is modelled as zero mean and covariance matrix $\boldsymbol{V_2}$ is the positive semidefinite Hermitian matrix.
The receive signal at m-th passive eavesdropper is given as

$$\boldsymbol{y_m} = \boldsymbol{r_m^H} \mathbf{x} + n_R + \boldsymbol{q_m^H} \boldsymbol{v_2} \tag{3}$$

where $\boldsymbol{r_m} \in \mathbb{C}^{N_T \times 1}$ denotes the channel vector between the BS_1 and the m-th passive receiver. The $\boldsymbol{q_m} \in \mathbb{C}^{N_T \times 1}$ is the channel vector between the BS_2 and the m-th passive receiver. What's more, there is a structure to split the received signal at the RF, the structure is show as the figure 6.

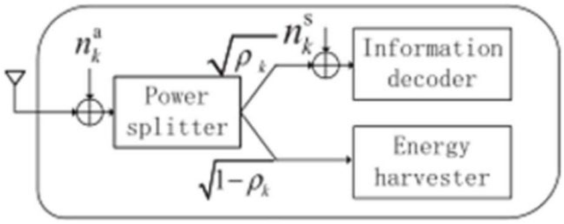

Fig.6 Structure of the Receiver

As I mentioned before, it will control the balance of the energy signal and information signal. As a result, the formulation which shows the information signal of k-th receiver structure is given by

$$\boldsymbol{y}_{\boldsymbol{k}}^{\boldsymbol{ID}} = \sqrt{\rho_k}\left(\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\mathbf{x} + n_R\right) + n_k^s \tag{4}$$

The $n_R \sim \mathcal{CN}(0, \sigma_I^2)$ means the Gaussian noise of the receiver.

3.4 Channel Capacity & Energy Harvesting

In this SWIPT wireless system, the Qos of receiver is extremely. I will give the SINR equations and Energy Harvesting equations of different receivers.

For k-th desired receiver, the SINR could be given as

$$\Gamma_k = \frac{\rho_k\left|\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{w}_{\boldsymbol{k}}\right|^2}{\rho_k\left(\sum_{j\neq k}^{K}\left|\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{w}_{\boldsymbol{j}}\right|^2 + \mathrm{Tr}(\boldsymbol{h}_{\boldsymbol{k}}\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{V}_{\boldsymbol{1}}) + \mathrm{Tr}(\boldsymbol{g}_k\boldsymbol{g}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{V}_{\boldsymbol{2}}) + \sigma_s^2\right) + \sigma_I^2} \tag{5}$$

The energy harvesting equation is

$$\mathrm{E_k} = \eta(1-\rho_\mathrm{k})\left(\sum_{j=1}^{K}\left|\boldsymbol{h_k^H w_j}\right|^2 + \mathrm{Tr}\left(\boldsymbol{h_k h_k^H V_1}\right) + \mathrm{Tr}\left(\boldsymbol{g_k g_k^H V_2}\right) + \sigma_\mathrm{s}^2\right) \quad (6)$$

Where $0 \le \eta \le 1$ means the efficiency of switching the RF energy into electrical energy at receivers. I assume this parameter as a constant.

For m-th passive eavesdropper, the SINR could be given as

$$\Gamma_\mathrm{m} = \frac{\rho_\mathrm{m}|\boldsymbol{r_m^H w_m}|^2}{\rho_\mathrm{m}\left(\sum_{j\neq k}^{K}\left|\boldsymbol{r_m^H w_j}\right|^2 + \mathrm{Tr}(\boldsymbol{r_m r_m^H V_1}) + \mathrm{Tr}(\boldsymbol{q_m q_m^H V_2}) + \sigma_\mathrm{s}^2\right) + \sigma_\mathrm{I}^2} \quad (7)$$

The energy harvesting equation is

$$\mathrm{E_m} = \eta(1-\rho_\mathrm{m})\left(\sum_{j=1}^{M}\left|\boldsymbol{r_m^H w_j}\right|^2 + \mathrm{Tr}(\boldsymbol{r_m r_m^H V_1}) + \mathrm{Tr}(\boldsymbol{q_m q_m^H V_2}) + \sigma_\mathrm{s}^2\right) \quad (8)$$

Chapter 4 Problem Formulation

As my aim of this project is to maximize the data rate of the desired receivers, the capacity of k-th desired receiver is given as

$$\mathrm{C_k} = \log_2(1 + \Gamma_k) \tag{9}$$

As a result, my problem formulation is given as

$$\max_{w_k,\rho_k} \sum_{k=1}^{K} C_k$$

$$= log_2\left(1 + \frac{\rho_k\left|\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{w}_{\boldsymbol{k}}\right|^2}{\rho_k\left(\sum_{j\neq k}^{K}\left|\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{w}_{\boldsymbol{j}}\right|^2 + \mathrm{Tr}(\boldsymbol{h}_{\boldsymbol{k}}\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{V}_{\boldsymbol{1}}) + \mathrm{Tr}(\boldsymbol{g}_{\boldsymbol{k}}\boldsymbol{g}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{V}_{\boldsymbol{2}}) + \sigma_s^2\right) + \sigma_I^2}\right) \tag{10}$$

s.t.C1: $\frac{\rho_k\left|\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{w}_{\boldsymbol{k}}\right|^2}{\rho_k\left(\sum_{j\neq k}^{K}\left|\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{w}_{\boldsymbol{j}}\right|^2 + \mathrm{Tr}(\boldsymbol{h}_{\boldsymbol{k}}\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{V}_1) + \mathrm{Tr}(\boldsymbol{g}_{\boldsymbol{k}}\boldsymbol{g}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{V}_2) + \sigma_s^2\right) + \sigma_I^2} > \Gamma_{\mathrm{req,k}}, \forall \mathrm{k},$

C2: $\sum_{k=1}^{K} ||\boldsymbol{w}_{\boldsymbol{k}}||^2 \leq \mathrm{P_{MAX}}$

C3:

$$\eta\left(\sum_{j=1}^{K}\left|\boldsymbol{r}_{\boldsymbol{m}}^{\boldsymbol{H}}\boldsymbol{w}_{\boldsymbol{j}}\right|^2 + \mathrm{Tr}(\boldsymbol{r}_{\boldsymbol{m}}\boldsymbol{r}_{\boldsymbol{m}}^{\boldsymbol{H}}\boldsymbol{V}_{\boldsymbol{1}}) + \mathrm{Tr}(\boldsymbol{q}_{\boldsymbol{m}}\boldsymbol{q}_{\boldsymbol{m}}^{\boldsymbol{H}}\boldsymbol{V}_{\boldsymbol{2}}) + \sigma_s^2\right) \leq \mathrm{P_{m,min}}, \forall \mathrm{m}$$

C4: $\boldsymbol{V}_{\boldsymbol{n}} \succcurlyeq \boldsymbol{0}$

C5: $0 \leq \rho_k \leq 1, \forall k$

C6: $0 < \eta < 1$

Constraint C1 means the SINR of the received signal at the desired receiver must be higher than a threshold, $\Gamma_{\mathrm{req,k}} > 0$. Constraint C2 means that the transmitted power of the base station should be under a proper limitation, $\mathrm{P_{MAX}} > 0$. Constraint C3 indicates that the energy of the whole signal must be less than the minimum requirements of the passive eavesdroppers, $\mathrm{P_{m,min}} > 0$. Constraint C4 ensures that the covariance matrix of artificial noise vector is one positive semidefinite Hermitian matrix. Constraint C5 indicates the physical constraints of the RF power splitter. I set that the power splitter structure is a passive device and won't consume any power in the process of splitting the received signal. Constraint C6 defines the conversion efficiency of the receiver structure is between 0 and 1.

Chapter 5 Problem Optimization

Convex optimization, or convex minimization, is a subfield of mathematical optimization, which deals with the minimization of convex functions defined in convex sets. In a sense, convex optimization is simpler than general mathematical optimization problems, for example, in convex optimization, the local optimal value must be the global optimal value.

The standard optimization problem can be expressed mathematically as follow:

$$\min_{x} f_0(x) \tag{11}$$

$$s.t. (x) \leq 0, i = 1, \ldots\ldots. m$$

$$g_j(x) = 0, j = 1, \ldots\ldots. n$$

$$f_0, \ldots\ldots, f_i \text{ is convex, and } g_j \text{ is affine}$$

However, it is obvious that for most system model, the problems equalization is un-convex which means they cannot be written into this format. My aim in this chapter is to transfer my model problem become convex problem.

5.1 SDP

The SDP relaxation method is an effective method to eliminate the unnecessary non-convexity in the formulation.[56] From the problem formulation, it is easy to find that there are non-convexity constraints C1, C2 and C3, the rest constraints are convex. Therefore, I use semi-definite programming (SDP) relaxation to convert non-convexity element into convex function. Then, we can replace the obvious constraints:

C1:

$$\frac{\rho_k\left|\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{w}_{\boldsymbol{k}}\right|^2}{\rho_k\left(\sum_{j\neq k}^{K}\left|\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{w}_{\boldsymbol{j}}\right|^2+\mathrm{Tr}(\boldsymbol{h}_{\boldsymbol{k}}\boldsymbol{h}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{V}_{\boldsymbol{1}})+\mathrm{Tr}(\boldsymbol{g}_{\boldsymbol{k}}\boldsymbol{g}_{\boldsymbol{k}}^{\boldsymbol{H}}\boldsymbol{V}_{\boldsymbol{2}})+\sigma_s^2\right)+\sigma_I^2}>\Gamma_{\mathrm{req,k}},\forall \mathrm{k},$$

$$\Rightarrow\frac{\mathrm{Tr}(\boldsymbol{H}_{\boldsymbol{k}}\boldsymbol{W}_{\boldsymbol{k}})}{\sum_{j\neq k}^{K}\mathrm{Tr}\left(\boldsymbol{H}_{\boldsymbol{k}}\boldsymbol{W}_{\boldsymbol{j}}\right)+\mathrm{Tr}(\boldsymbol{H}_{\boldsymbol{k}}\boldsymbol{V}_{\boldsymbol{1}})+\mathrm{Tr}(\boldsymbol{G}_{\boldsymbol{k}}\boldsymbol{V}_{\boldsymbol{2}})+\sigma_s^2+\frac{\sigma_I^2}{\rho_k}}>\Gamma_{\mathrm{req,k}},\forall \mathrm{k},\tag{12}$$

C2:

$$\sum_{k=1}^{K}\left|\left|\boldsymbol{w}_{\boldsymbol{k}}\right|\right|^2\leq \mathrm{P_{MAX}}\ \Rightarrow\ \sum_{k=1}^{K}\mathrm{Tr}(\boldsymbol{W}_{\boldsymbol{k}})\leq \mathrm{P_{MAX}}\tag{13}$$

C3:

$$\eta\left(\sum_{j=1}^{K}\left|\boldsymbol{r}_{\boldsymbol{m}}^{\boldsymbol{H}}\boldsymbol{w}_{\boldsymbol{j}}\right|^2+\mathrm{Tr}(\boldsymbol{r}_{\boldsymbol{m}}\boldsymbol{r}_{\boldsymbol{m}}^{\boldsymbol{H}}\boldsymbol{V}_{\boldsymbol{1}})+\mathrm{Tr}(\boldsymbol{q}_{\boldsymbol{m}}\boldsymbol{q}_{\boldsymbol{m}}^{\boldsymbol{H}}\boldsymbol{V}_{\boldsymbol{2}})+\sigma_s^2\right)\leq \mathrm{P_{m,min}},\forall \mathrm{m}$$

$$\Rightarrow\ \eta\left(\sum_{j=1}^{K}\mathrm{Tr}\left(\boldsymbol{R}_{\boldsymbol{m}}\mathbf{W}_{\mathrm{j}}\right)+\mathrm{Tr}(\boldsymbol{R}_{\boldsymbol{m}}\boldsymbol{V}_{\boldsymbol{1}})+\mathrm{Tr}(\boldsymbol{Q}_{\boldsymbol{m}}\boldsymbol{V}_{\boldsymbol{2}})+\sigma_s^2\right)\leq \mathrm{P_{min}},\forall \mathrm{m}\tag{14}$$

Additionally, the formulation (12) and (13) need a new constraint: $\mathrm{Rank}(W_k)\leq 1,\forall k$

Finally, the problem formulation is expressed as follow:

$$\underset{w_k,\rho_k}{\mathrm{maxmize}}\sum_{k=1}^{K}C_k=log_2(1+\Gamma_k)$$

$$=log_2\left(1+\frac{\mathrm{Tr}(\boldsymbol{H}_{\boldsymbol{k}}\boldsymbol{W}_{\boldsymbol{k}})}{\sum_{j\neq k}^{K}\mathrm{Tr}\left(\boldsymbol{H}_{\boldsymbol{k}}\boldsymbol{W}_{\boldsymbol{j}}\right)+\mathrm{Tr}(\boldsymbol{H}_{\boldsymbol{k}}\boldsymbol{V}_{\boldsymbol{1}})+\mathrm{Tr}(\boldsymbol{G}_{\boldsymbol{k}}\boldsymbol{V}_{\boldsymbol{2}})+\sigma_s^2+\frac{\sigma_I^2}{\rho_k}}\right)\tag{15}$$

s.t.C1: $\frac{\mathrm{Tr}(\boldsymbol{H}_{\boldsymbol{k}}\boldsymbol{W}_{\boldsymbol{k}})}{\sum_{j\neq k}^{K}\mathrm{Tr}\left(\boldsymbol{H}_{\boldsymbol{k}}\boldsymbol{W}_{\boldsymbol{j}}\right)+\mathrm{Tr}(\boldsymbol{H}_{\boldsymbol{k}}\boldsymbol{V}_{\boldsymbol{1}})+\mathrm{Tr}(\boldsymbol{G}_{\boldsymbol{k}}\boldsymbol{V}_{\boldsymbol{2}})+\sigma_s^2+\frac{\sigma_I^2}{\rho_k}}>\Gamma_{\mathrm{req,k}},\forall \mathrm{k},$

C2: $\sum_{k=1}^{K}\mathrm{Tr}(\boldsymbol{W}_{\boldsymbol{k}})\leq \mathrm{P_{MAX}}$

C3:

$$\eta\left(\sum_{j=1}^{K}\mathrm{Tr}\left(\boldsymbol{R}_{\boldsymbol{m}}\mathbf{W}_{\mathrm{j}}\right)+\mathrm{Tr}(\boldsymbol{R}_{\boldsymbol{m}}\boldsymbol{V}_{\boldsymbol{1}})+\mathrm{Tr}(\boldsymbol{Q}_{\boldsymbol{m}}\boldsymbol{V}_{\boldsymbol{2}})+\sigma_s^2\right)\leq \mathrm{P_{min}},\forall \mathrm{m}$$

C4: $\boldsymbol{V}_{\boldsymbol{n}}\succcurlyeq\mathbf{0}$

$\mathrm{C5}: 0 \leq \rho_k \leq 1, \forall k$

$\mathrm{C6}: 0 < \eta < 1$

$\mathrm{C7}: \mathrm{Rank}(W_k) \leq 1, \forall k$

From (14), it is obvious that the formulation is a log function, I need to change it into an easier format which is convenient to calculate.

Set

$$\tau_k = \mathrm{Tr}(\boldsymbol{H_k W_k}) \tag{16}$$

$$\beta_k = \sum_{j \neq k}^{K} \mathrm{Tr}\left(\boldsymbol{H_k W_j}\right) + \mathrm{Tr}(\boldsymbol{H_k V_1}) + \mathrm{Tr}(\boldsymbol{G_k V_2}) + \sigma_s^2 + \frac{\sigma_I^2}{\rho_k} \tag{17}$$

Then

$$C_k = log_2\left(1 + \frac{\tau_k}{\beta_k}\right) = \sum_{k=1}^{K} log_2\left(\frac{\beta_k + \tau_k}{\beta_k}\right) = \sum_{k=1}^{K} log_2(\beta_k + \tau_k) - log_2(\beta_k) \tag{18}$$

The formulation change into:

$$\underset{\beta_k, \tau_k}{\mathrm{maxmize}} \sum_{k=1}^{K} C_k = log_2(1 + \Gamma_k) = \sum_{k=1}^{K} log_2(\beta_k + \tau_k) - log_2(\beta_k) \tag{19}$$

$\mathrm{s.t.C1}: \frac{\tau_k}{\beta_k} \geq \Gamma_{\mathrm{req}} \Rightarrow 0 \geq \beta_k \Gamma_{\mathrm{req}} - \tau_k$

$\mathrm{C2}: \sum_{k=1}^{K} \mathrm{Tr}(\boldsymbol{W_k}) \leq \mathrm{P_{MAX}} \Rightarrow 0 \geq \sum_{k=1}^{K} \mathrm{Tr}(\boldsymbol{W_k}) - P_{MAX}$

$\mathrm{C3}: \eta\left(\sum_{j=1}^{K} \mathrm{Tr}\left(\boldsymbol{R_m}\mathbf{W_j}\right) + \mathrm{Tr}(\boldsymbol{R_m V_1}) + \mathrm{Tr}(\boldsymbol{Q_m V_2}) + \sigma_s^2\right) \leq \mathrm{P_{min}}, \forall \mathrm{m}$

$$\Downarrow$$

$$0 \geq \eta\left(\sum_{j=1}^{K} \mathrm{Tr}\left(\boldsymbol{R_m}\mathbf{W_j}\right) + \mathrm{Tr}(\boldsymbol{R_m V_1}) + \mathrm{Tr}(\boldsymbol{Q_m V_2}) + \sigma_s^2\right) - \mathrm{P_{min}}, \forall \mathrm{m}$$

$\mathrm{C4}: \boldsymbol{V_n} \succcurlyeq \mathbf{0}, \boldsymbol{W_k} \succcurlyeq \mathbf{0}$

$\mathrm{C5}: 0 \leq \rho_k \leq 1, \forall k$

$\mathrm{C6}: 0 < \eta < 1$

$\mathrm{C7}: \tau_k \leq \mathrm{Tr}(\boldsymbol{H_k W_k}) \Rightarrow 0 \geq \tau_k - \mathrm{Tr}(\boldsymbol{H_k W_k})$

$\mathrm{C8}: \beta_k \geq \sum_{j \neq k}^{K} \mathrm{Tr}\left(\boldsymbol{H_k W_j}\right) + \mathrm{Tr}(\boldsymbol{H_k V_1}) + \mathrm{Tr}(\boldsymbol{G_k V_2}) + \sigma_s^2 + \frac{\sigma_I^2}{\rho_k}$

$$\Downarrow$$

$$0 \geq \sum_{j \neq k}^{K} \mathrm{Tr}(\boldsymbol{H_k W_j}) + \mathrm{Tr}(\boldsymbol{H_k V_1}) + \mathrm{Tr}(\boldsymbol{G_k V_2}) + \sigma_s^2 + \frac{\sigma_I^2}{\rho_k} - \beta_k$$

C9: $\mathrm{Rank}(W_k) \leq 1, \forall k$

However, after these two steps, the problem formulation which is still a nonconvex. Then I adopt the SCA method [49] on it.

5.2 SCA

1. At the beginning, I establish an upper bound:

$$\log_2(\beta_k) \leq R^{(t)} \tag{20}$$

2. Calculate First-order Taylor Expansion [3]:

$$f'(x) = \frac{1}{\beta_k \ln(2)} \tag{21}$$

3. Calculate Second-order Taylor Expansion:

$$f''(x) = -\frac{1}{\beta_k^2 \ln(2)} < 0 \tag{22}$$

4. Form the theorem of Taylor's expansion I have known that:

   If

$$f''(x) \leq 0, f(x) \leq f(x_0) + f'(x_0) + f'(x_0)(x - x_0) \tag{23}$$

The equality holds when x is equal to x_0.

So,

$$\log_2(\beta_k) \leq \log_2\left(\beta_k^{(t)}\right) + \frac{1}{\beta_k^{(t)} \ln(2)}\left(\beta_k - \beta_k^{(t)}\right) = R^{(t)} \tag{24}$$

The equality holds when β_k is equal to $\beta_k^{(t)}$. $R^{(t)}$ is the Taylor series of $\log_2(\beta_k)$ in the t-th iteration.$\beta_k^{(t)}$ is the value of the β_k after the t-th iteration in the SCA-based algorithm [51-54]. Finally, the formulation could be written as:

$$\underset{\beta_k,\tau_k}{\text{maxmize}} \sum_{k=1}^{K} C_k = log_2(1+\Gamma_k) = \sum_{k=1}^{K} log_2(\beta_k+\tau_k) - R^{(t)} \quad (25)$$

s.t.C1: $0 \geq \beta_k \Gamma_{\text{req}} - \tau_k, \forall k$

C2: $0 \geq \sum_{k=1}^{K} \text{Tr}(\boldsymbol{W_k}) - P_{MAX}, \forall k$

C3: $0 \geq \eta\left(\sum_{j=1}^{K} \text{Tr}\left(\boldsymbol{R_m}\mathbf{W_j}\right) + \text{Tr}(\boldsymbol{R_m V_1}) + \text{Tr}(\boldsymbol{Q_m V_2}) + \sigma_s^2\right) - \text{P}_{\min}, \forall m$

C4: $\boldsymbol{V_n} \succcurlyeq \boldsymbol{0}, \boldsymbol{W_k} \succcurlyeq \boldsymbol{0}$

C5: $0 \leq \rho_k \leq 1, \forall k$

C6: $0 < \eta < 1$

C7: $\text{Rank}(W_k) \leq 1, \forall k$

C8: $0 \geq \tau_k - \text{Tr}(\boldsymbol{H_k W_k}), \forall k$

C9:$0 \geq \sum_{j\neq k}^{K} \text{Tr}\left(\boldsymbol{H_k W_j}\right) + \text{Tr}(\boldsymbol{H_k V_1}) + \text{Tr}(\boldsymbol{G_k V_2}) + \sigma_s^2 + \frac{\sigma_I^2}{\rho_k} - \beta_k, \forall k$

C10: $\log_2(\beta_k + \tau_k) - R^{(t)} \geq C_{min} \Rightarrow 0 \geq C_{min} + R^{(t)} - \log_2(\beta_k + \tau_k), \forall k$

Where C7 is imposed to guarantee that $W = w_k w_k^H$ holds after optimization. Now,if I can remove C7 by proofing KKT condition, this problem will change into a convex problem completely[55]. After that, I can begin to write MATLB program to simulation.

5.3 KKT Condition

Firstly, the Lagrangian function can by derived as follos

Lagrangian Function:

$$L(\boldsymbol{W},\lambda_1,\lambda_2,\lambda_3,\lambda_4,\lambda_5,\lambda_6) = \sum_{k=1}^{K} log_2(\beta_k+\tau_k) - R^{(t)}$$
$$+\lambda_1\left[C_{min} + R^{(t)} - \log_2(\beta_k+\tau_k)\right]$$
$$+\lambda_2\left[\sum_{k=1}^{K}\mathrm{Tr}(\boldsymbol{W_k}) - P_{MAX}\right]$$
$$+\lambda_3\left[\eta\left(\sum_{j=1}^{K}\mathrm{Tr}\left(\boldsymbol{R_m}\mathbf{W}_\mathrm{j}\right) + \mathrm{Tr}(\boldsymbol{R_m}\boldsymbol{V_1}) + \mathrm{Tr}(\boldsymbol{Q_m}\boldsymbol{V_2}) + \sigma_\mathrm{s}^2\right) - \mathrm{P}_{\min}\right]$$
$$+\lambda_4[\tau_k - \mathrm{Tr}(\boldsymbol{H_k}\boldsymbol{W_k})]$$
$$+\lambda_5\left[\sum_{j\neq k}^{K}\mathrm{Tr}\left(\boldsymbol{H_k}\boldsymbol{W_j}\right) + \mathrm{Tr}(\boldsymbol{H_k}\boldsymbol{V_1}) + \mathrm{Tr}(\boldsymbol{G_k}\boldsymbol{V_2}) + \sigma_\mathrm{s}^2 + \sigma_\mathrm{I}^2 - \frac{\beta_k}{\rho_\mathrm{k}}\right]$$
$$+\lambda_6\left[\beta_k\Gamma_{\mathrm{req}} - \tau_k\right] - Tr(\boldsymbol{YW}) \tag{26}$$

Where $\boldsymbol{Y} \succcurlyeq \boldsymbol{0}; \lambda_1,\lambda_2,\lambda_3,\lambda_4,\lambda_5,\lambda_6 > 0$ are dual variables corresponding to the constraint conditionsC10, C2, C3, C8, C9, C1.

Formulation after Lagrange:

$$\underset{\boldsymbol{Y},\lambda_1,\lambda_2,\lambda_3,\lambda_4,\lambda_5,\lambda_6}{\text{maxmize}} \ \inf_{\boldsymbol{W}} L \tag{27}$$

$$\frac{\partial L}{\partial \boldsymbol{W}} = \lambda_2\boldsymbol{I} + \lambda_3\eta\overline{r}_m\overline{r}_m^H - \lambda_4\overline{h}_k\overline{h}_k^H + \lambda_5\overline{h}_k\overline{h}_k^H - \boldsymbol{Y} \tag{28}$$

$$\boldsymbol{Y} = \lambda_2\boldsymbol{I} + \lambda_3\eta\overline{r}_m\overline{r}_m^H - \lambda_4\overline{h}_k\overline{h}_k^H + \lambda_5\overline{h}_k\overline{h}_k^H \tag{29}$$

$$\boldsymbol{Y} = \boldsymbol{A} - \boldsymbol{H} \tag{30}$$

$$\boldsymbol{A} = \lambda_2\boldsymbol{I}, \boldsymbol{H} = -\lambda_3\eta\overline{r}_m\overline{r}_m^H + \lambda_4\overline{h}_k\overline{h}_k^H - \lambda_5\overline{h}_k\overline{h}_k^H \tag{31}$$

Assuming A is a positive semi-definite matrix. Let $V = v^H v$ and multiplying the equation [57][58]:

$$\boldsymbol{Tr}(\boldsymbol{YV}) = \boldsymbol{Tr}(\boldsymbol{AV}) - \boldsymbol{Tr}(\boldsymbol{HV}) = -\boldsymbol{Tr}(\boldsymbol{HV}) \tag{32}$$

Since $Tr(\boldsymbol{HV})$ is large than zero, $Tr(\boldsymbol{YV})$ is greater than or equal to zero. Then matrix A should be a positive definite matrix with full-rank($A > 0$), Rank($\boldsymbol{A}$) $= N_t$.

Since $Rank(\boldsymbol{A}) \leq Rank(\boldsymbol{A} + \boldsymbol{B}) + Rank(-\boldsymbol{B})$[8]

Then

$Rank(\boldsymbol{Y}) = Rank(-\boldsymbol{Y}) = Rank(-\boldsymbol{A} + \boldsymbol{H}) \geq Rank(-\boldsymbol{A}) - Rank(\boldsymbol{H}) \geq N_t - 1$(33)

Accordingly, the columns of $\boldsymbol{W}$ are members of the null space of $\boldsymbol{Y}$, then I can conclude $Rank(\boldsymbol{W}) \leq 1$.

Chapter 6 Simulation Results

Simulation Parameters	
Noise Power	-110dBm
Carrier Frequency	2.1GHz
P_{min}	0 dBm
Cell Radius	150 meters
Number of Eavesdropper	1
Distance from BS_1	30 meters

Table.2 The Simulation Parameters

In this chapter, I analyze the simulation results which is system performance. The number of users is changed as a variable. The number of Eavesdropper is 1. The detailed simulation parameters can be found in Table 2. I assume that all desired users require the same minimum SINR, i.e., $\Gamma_{\mathrm{req,k}} = \Gamma_{\mathrm{req}}, \forall k \in \{1, \ldots, K\}$ for all results.

In Figure 7, I study the average achievable rate versus maximum transmit power of base station, for the different numbers of transmit antennas. It can be observed that the average achievable rate increases with the rising of maximum transmit power of base station. Indeed, to keep the security, the transmit power is limited as the signal may be used to collect energy for supporting the eavesdropper. On the other hand, a significant performance gain can be achieved as the number of the antennas increases from 4 to 8. The reason is that the increasing of number of transmit antennas could improve the degrees of freedom for resource allocation, which enables more reliable information signal for desired users. When the number raise from 8 to 12, the gain is lesser.

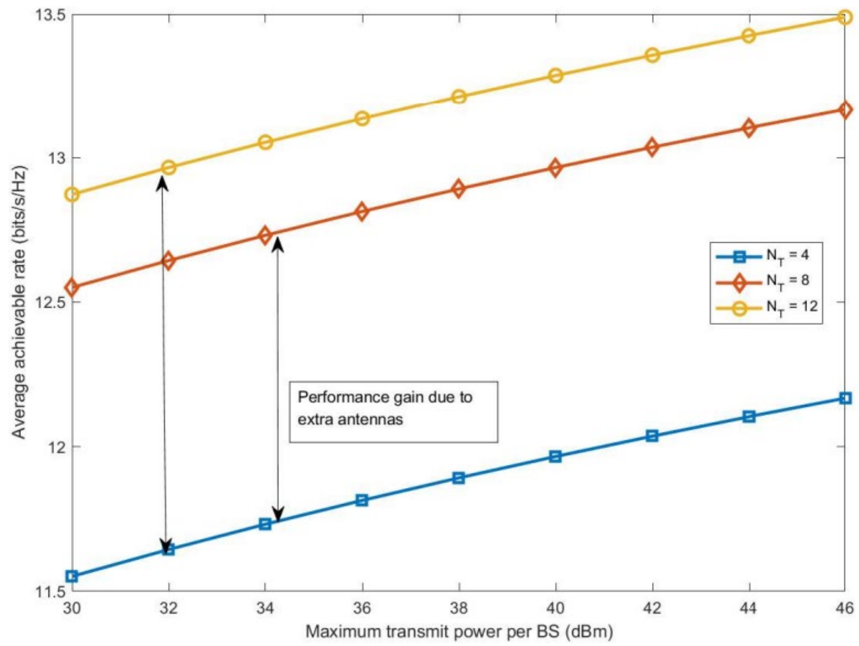

Fig.7 Average Achievable Rate vs Maximum Transmit Power per BS

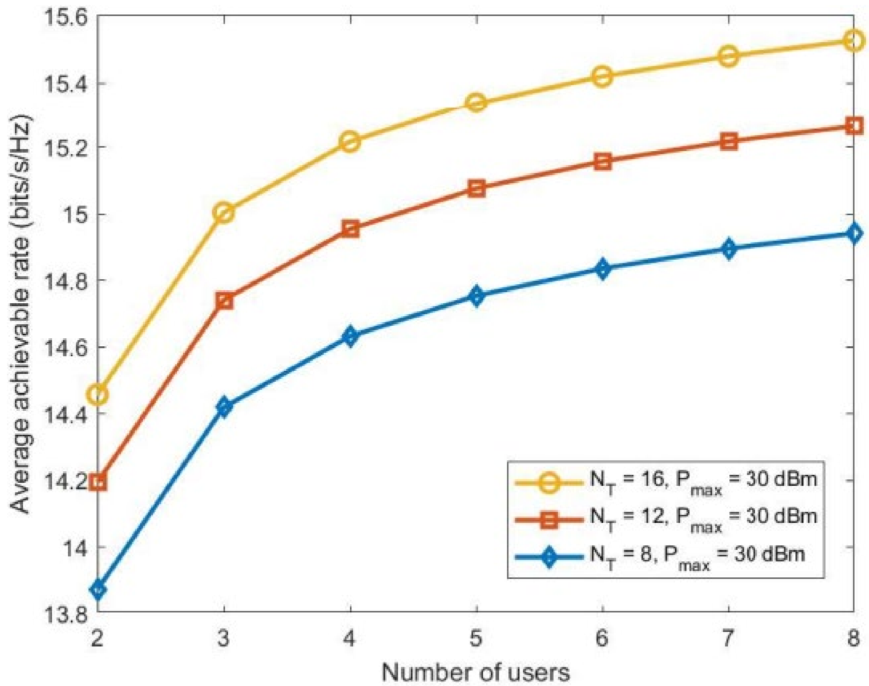

Fig.8 Average Achievable Rate vs Number of Users

Figure 8 illustrates the average achievable rate versus number of users above the different numbers of transmit antennas. It is obvious that the rate is steadily rising when the number of users increase. It is because that when the number of users increases, the users of system could receiver more information signal and encode it. Besides, the growth rate decreases as the number of users increases. Additionally, the added antennas also improve the average achievable rate gradually. The gains are almost the same when the antenna is increased from 8 to 12 and from 12 to 16, which is about 0.3bits/s/Hz.

Chapter 7 Conclusion and Future Work

7.1 Conclusion

This paper designs a MISO communication system based on SWIPT technology. Due to the presence of potential eavesdroppers and the presence of base stations used for attack signals, the security and reliability of communication systems are challenged. In this paper, a beam integration algorithm is designed to achieve the optimal solution of the communication system, in which convex optimization methods are used, such as SCA algorithm, SDP algorithm and KKT conditional proof. The final simulation results and analysis show that the beam integration algorithm designed and optimized in this paper can improve the corresponding performance of the system and maximize the channel capacity on the premise of ensuring security.

7.2 Future Work

In the design of the model, I set that there was only one eavesdropper and the distance between the eavesdropper and the base station was always at a fixed value. In fact, this was an idealized model, and I did not take into account the influence of external environment on the communication system. In future work, I will consider eavesdroppers in multiple locations to further improve the practicability of my algorithm. Besides, various emerging technologies, e.g., intelligent reflecting surfaces []-[]

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