SCHOOL OF ELECTRICAL ENGINEERING

AND TELECOMMUNICATIONS

# Beamforming Design for Secure SWIPT Relaying Communication Systems

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Submitted: August 15, 2019

# Abstract

This article studies the beamforming design for SWIPT system. Aiming at the physical layer security communication problem of the eavesdroppers in the downlink MIMO system, a beamforming design scheme based on artificial noise is proposed. Firstly, the system model of the scheme is given, and the problem of optimizing the minimum total transform power, satisfying the security of communication at the same time, along with the receiver energy collection threshold and the information leakage control index constraint. The system works in the decode and forward scheme relay network and also adopt power splitting technology to improve the performance. For simulation part, different factors are texted to analyse the effects caused by them.

# Table of contents


**1.** Introduction ..... 4

**2.** Literature review ..... 6

**3.** System Model ..... 9

**3.1.** Motivation ..... 9

**3.2.** Overview for the Model ..... 10

**3.3.** Transmitted Signal at the source ..... 11

**3.4.** Received Signal at the Relay ..... 12

**4.** Problem Formulation ..... 13

**5.** Optimization solution ..... 14

**6.** Results and Analysis ..... 16

**6.1.** Minimum required SINR ..... 17

**6.2.** Number of users ..... 17

**7.** Conclusion ..... 18

Reference ..... 19

# 1. Introduction

The wireless communication system has undergone a qualitative leap after decades of technological innovation and evolution, but at the same time it will face enormous challenges. On the one hand, with the rise of mobile Internet and multimedia technologies and the widespread use of intelligent mobile terminals, people are eager to obtain richer data and multimedia services anytime and anywhere through wireless networks, and the demand of information transfer is increasing dramatically while the energy consumption of the terminal and the receiving end is simultaneously increased. On the other hand, in recent years, with the continuous breakthrough and development of wireless communication technology, it can be applied in many harsh or special environments. Sensors in these networks cannot be connected to the power supply system by wire due to environmental conditions. Therefore, they usually choose batteries as power with a capacity limitation. Once the battery is outage, it needs to be extended to extend the life of the device. If it is unable to provide continuous power supply for these energy-limited devices, the communication quality and service life of the network will be limited by the limited battery capacity. Therefore, whether an effective means can be found to provide a continuous and stable power supply for energy-limited devices becomes the key to prolonging the network survival time and improving communication quality.

In response to the above challenges, the industry and academia have done a lot of research to reduce equipment energy consumption and extend network survival time. The research direction is mainly divided into two categories. The first category is energy conservation optimization to save energy. Specifically, by using some technical methods improving the network energy efficiency, such as relay technology, cooperative communication technology, network coding technology, to reduce energy consumption [1], etc. The other is to use the advantage of energy around through energy harvesting technology to supply nodes in the communication net. recently, a new energy harvesting technique has been proposed that collects energy from radio frequency signals in the surrounding environment and stores it for subsequent wireless communication transmission [5]. Because there are a lot of radio frequency signals in the natural environment around space, these signals carry energy while carrying information. If the energy in these signals can be collected and utilized, the life time of some energy-limited devices in the network will be greatly extended. At the same time, it can also reduce the energy consumption of the communication network. Therefore, this technology for collecting energy from radio frequency signals has attracted widespread attention and research in scholars in just a few years, and is also called as simultaneous wireless information and power transfer.

Apart from problems mentioned above, secure communication is also a permanent topic in the field of communications. Traditional secure communication is based on cryptography, and its security is based on computational complexity and is usually implemented above the network layer [6]. However, with the rapid increase of computing resources available to humans, traditional computational complexity-based secure communication methods face enormous challenges [7]. The physical layer security method proposed in recent years is based on information theory. It is theoretically proved that when the information transmission rate is lower than the security capacity, the complete security of information transmission can be realized, which quickly becomes a research hotspot in the field of secure communication [8]. Physical layer security was established by Shannon's use of information theory in 1949 to define the concept of absolute security and Wyner's research on the volumetric area of the eavesdropping channel with doubts [2;4]. From the perspective of information theory, Wyner proves that as long as the primary channel has the advantage of channel transmission quality relative to the eavesdropping channel, it can realize the independent transmission of the traditional key technology to ensure the secure transmission of information. Different from the traditional encryption algorithm, physical layer security is an information security transmission mechanism without complicated mathematical calculation process and simple and unbreakable. The biggest feature of physical layer security is that no matter how strong the eavesdropper's computing power is, it is impossible for an eavesdropper to crack any useful information of the user [12]. Therefore, the physical layer security will provide a stable and reliable security mechanism for the wireless communication system on the bottom layer, which is very suitable for use in industries with high security requirements. Since the physical layer security method has these advantages, with the introduction of this method, many scholars have devoted themselves to the research of physical layer security theory and methods, and the related technologies have been greatly developed, such as the eavesdropping channel security capacity calculation method [3; 10; 11] , multi-antenna physical layer security technology [12; 13], synchronization and channel detection technology [1; 14; 15], secure coding and decoding methods [16-18], cooperative relay physical layer security technology [19; 20].

## 2. Literature review

In all research directions, the calculation and enhancement method of safety capacity has always been a hot issue in the research of physical layer security. Multi-antenna array (MIMO) technology, as a major breakthrough in wireless communication, has achieved good results not only in improving the communication rate of wireless communication systems, but also the channel capacity and spatial diversity gain of the wireless communication system are greatly improved [21-24]. In [25], the author provides a review of various SWIPT system models, for example, SWIPT in broadcasting channels, SWIPT in relaying systems and SWIPT in interference networks. The key technologies of physical layer security mainly include the following: signal processing technology [26], including precoding technology, beamforming technology, interference technology, cooperative communication technology, channel estimation technology, modulation technology, etc.; channel coding technology [27-30]; physical layer key agreement technology [31], etc. Among them, there are many research results in signal processing, generally using the random fading to improve the reception performance gap between legitimate receivers and eavesdroppers. In order to obtain a positive secrecy rate, the quality of the licensed channel is required to be better than that of the eavesdropping channel. However, with the development of multi-antenna technology, techniques such as beamforming [32;33] and artificial interference [34;35;36] can overcome the limitation of channel conditions, this means that a positive privacy rate can be obtained even if the quality of the licensed channel is worse than the eavesdropping channel. In a wireless communication network, a general form of cooperative communication [37] is that a plurality of wireless nodes equipped with a single antenna share each other's antennas to form a virtual multiple-input multiple-output transmission system to obtain gains in signal transmission quality, system capacity, and the like [38-40]. Relay signal forwarding technology is the basic technology of communication cooperation. In the application of physical layer security, in addition to forwarding signals, the cooperative node may generate interference signals to interfere with the reception of the eavesdropping node. Therefore, the use of cooperative nodes or destination nodes as auxiliary nodes to introduce artificial noise [41] to interfere with the reception of eavesdropping nodes, and to enhance the security performance of eavesdropping channels is called cooperative interference. Beamforming and cooperative interference can effectively improve the performance of the physical layer [36-40]. Literature [10] studies the two-hop network of the eavesdropper and proposes a cooperative mechanism of noise forwarding, that is, the artificial noise generated by the relay node completely independent of the information is transmitted together with the forwarded signal. Reference [42] also derives the upper limit of the safe transmission rate that the system can achieve. Reference [43] studies a secure transmission scheme in a model including a source node with single antenna, multiple single-antenna relays, a destination, and an eavesdropping node. In this scheme, one relay node is selected for cooperative interference, and the remaining relay nodes use cooperative beamforming technology to amplify the signal of the forwarding source node, through redesigning the beamforming vector, relay forwarding, the energy of source transmission, and cooperative interference is reasonably allocated to obtain a maximized privacy rate. Literature [44] studies the physical layer security of multi-user point-to-point amplifying and forwarding relay networks. The system contains users with security requirements, users without security requirements, and multi-antenna eavesdropping nodes. In order to prevent the eavesdropping node from stealing the secret information, the transmission signals of the plurality of power-restricted relay nodes are beamformed. Under the condition of the total power of the user and the minimum SNR at each user, the transmission power of the source end and the beamforming vector transmitted by relay are optimized jointly with the goal of maximizing the security rate. Literature [45] research shows the transmission performance of a two-hop MIMO system in which multiple channels interfere with each other when a destination node receives information. To achieve the maximum SNR and reduce the loss of long-distance transmission of wireless energy, the information and energy transmitted hop by hop are transmitted by beamforming technology. The relay has two strategies of time switching and power splitting to collect energy and use the collected energy for forwarding signals. The closed-form expressions of system outage probability and ergodic capacity are given in [45] and simulated. Compared with the physical layer security technology in the conventional network model, there are more factors to consider in the energy harvesting communication model. For example, when information and energy are transmitted simultaneously, it is necessary to consider how to select the power distribution ratio of energy and information in information and energy. When the recipients are different, it is also necessary to ensure that the information is not leaked to the energy receiver. For energy collectors, the artificial noise commonly used in physical layer secure can also be the energy source. So how to further utilize artificial noise on the basis of anti-eavesdropping is the focused problem. Some papers have examined the physical layer security issues in energy harvesting systems. Literature [46] studied that when information and energy are transmitted simultaneously in a three-node wireless eavesdropping channel, the transmitter injects artificial noise into the secret signal, and the protected secret message is not obtained by the energy receiver. Literature [46] jointly optimizes the energy distribution of the signal transmitting the secret information and the artificial noise under the constraint of the maximum transmittable energy of the transmitter and the energy collected by the energy receiver, which improves the confidentiality rate and reduces the probability of safe interruption. Reference [47] gives a scheme for redesigning the beamforming vector and power splitting factor at source to maximize the amount of energy transmission in the case where the channel state information is incomplete and the energy receiver is considered as a potential eavesdropper. Reference [48] studies physical layer security solution in the system model consisting of a single antenna source node, a destination node, an eavesdropping node, and a multi-antenna relay that the legal node does not know the CSI of the eavesdropper, and only knows the distance from the eavesdropper. In the model, the relay has no fixed energy supply, and extracts energy from the signals sent by the receiving source and the destination. Literature [49] analyses and studies the transmission strategy of energy and information at three relay nodes and the corresponding secure transmission performance: time-switched relay, ideal receive relay, power split relay, time splitting factor and the power splitting factor are optimized. Reference [50] studies the energy harvesting scheme for MISO secret channels with incomplete channel state information. The system includes a transmitter with multi-antennas, energy receivers with multiple multi-antenna and a single-antenna IR. The energy receiver is considered as a potential eavesdropper, and the transmitter interferes with the artificial noise embedded in the information signal. The information receiver uses the power splitter to simultaneously decode information and collect energy. Under the limitation of the minimum source transmit power, the artificial noise covariance and beamforming vector are optimized jointly in order to maximize the confidentiality rate at information receiver. Reference [51] studies a system including a single-antenna base station, a destination node, and a relay with multi-antennas. The relay selects part of the antenna to collect energy from the RF signal, and minimizes the source transmit power and the power consumption of antenna circuit under the constraint of the quality of serve. For reducing the challenge of the optimization scheme, the lower complexity sub-optimal divided into two cases is proposed and compared with the global optimal algorithm to prove that the performance difference between the performance and the global optimal algorithm is small.

# 3. System Model

## 3.1. Motivation

Cooperative relaying is able to effectively improve signal transmission performance in conventional wireless communicate system, because on the one hand it is equivalent to extending the transfer range, on the other hand it also provides a better gain. For this reason, cooperative relaying has the potential to improve the QoS in SWIPT system, figure 3.1 is the system model [52]. However, as shown in the figure, the information leakage may occur for that the information transfer in the cooperative relaying system needs two time slots to be finished, therefore, if no action is taken, the eavesdroppers can also receive the information signal, and due to the possibility that eavesdroppers are much closer to the base station compared with the IR, the quality of signal is much better than that received by information receiver, and the transmission is not secure enough.

To solve this problem, one of the methods is the introduce of multiple relays cooperation, by using part of the relays for information transfer while the rest of them transfer energy signal or artificial noise to the power receivers considered as potential eavesdroppers [53]. This is one of the possible solutions and many researches have be done already [54], and from the results it can be found that, the more relays included, the more secure the information transmission. But it could result in another problem: Larger systems mean more investment. In hence, in this article, the author wants to do research on the design of secure relay beamforming with a single relay with massive antennas. Artificial noise is the method to against the eavesdroppers and the relay works in decode-and-forward scheme. The relay based on the decoding and forwarding protocol detects the received transmitter signal and decodes the useful information and sends it to the destination. Unlike the amplifying and forwarding relay, the decoding and forwarding relay performs a decision when receiving the transmitting end signal, thereby avoiding amplification of noise and interference.

For energy harvesting, the hybrid receivers [41;55] is adopted to split the received radio frequency signal into two-part energy streams, one of which is sent to the ER and the other to the IR, the power splitting radio denoted as $\eta$.

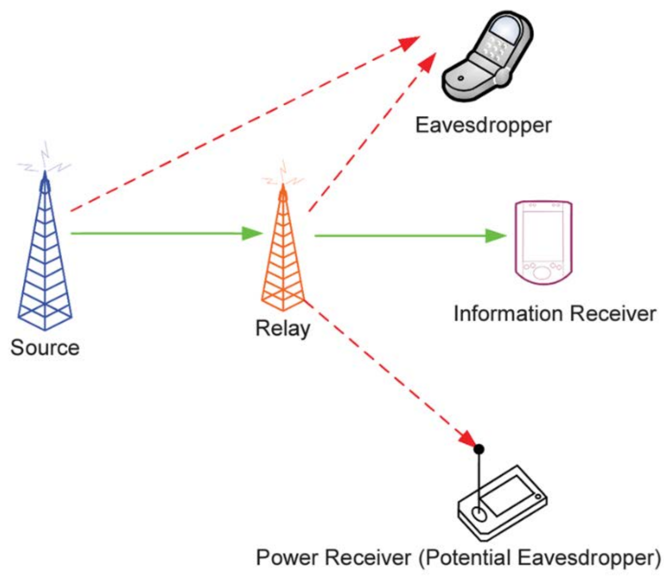


Figure 3.1. a SWIPT system model in relaying networks [41]

## 3.2. Overview for the Model

For the system considered in this report, it is as shown in figure 3.2. Its components are similar to the structure of the previous figure, except for the transmission process between different time periods. The multiantenna relay network includes one source, one relay, one information receiver (IR), one power receiver (PR) and one eavesdropper (EA). The relay is equipped with $\mathrm{N}_R$ antennas. The source is equipped with $\mathrm{N}_T$ single antennas. And the rest of the them are all have single antenna. It is assumed that, there is no direct link between each node and the relay has no energy source. It is also assumed that the channel state information of the information receiver is already known. For SWIPT, there are, time splitting and power splitting, two types of receiver designs. For TS model, to obtain the energy harvesting time slots, new frame structures are needed. For PS model, PS design does not need to be changed in traditional communication system except receiving circuit [56,57,58,60], which is widely used in MISO and MIMO. Therefore, the PS model is chosen in this paper and the TS model would be for future work. For the eavesdropper, it can achieve a better data because it can steel from both the basis station and the relay [59]. Considering the worst-case scenario for secure transmission, which assumes that the eavesdropper is located near the sender and within the reference distance of the path calculated for the model [61]. To improve the secure rate, this paper divided the time slot into three parts, $\tau_1, \tau_2, \tau_3$. In $\tau_1$, the source transmits power to the relay and transmit both power and information in $\tau_2$; In $\tau_3$, the relay works to transmit information to information receiver, and power to other, including power receiver and eavesdropper, for the reason that artificial noise can also work as power signal [62,63,64,65].

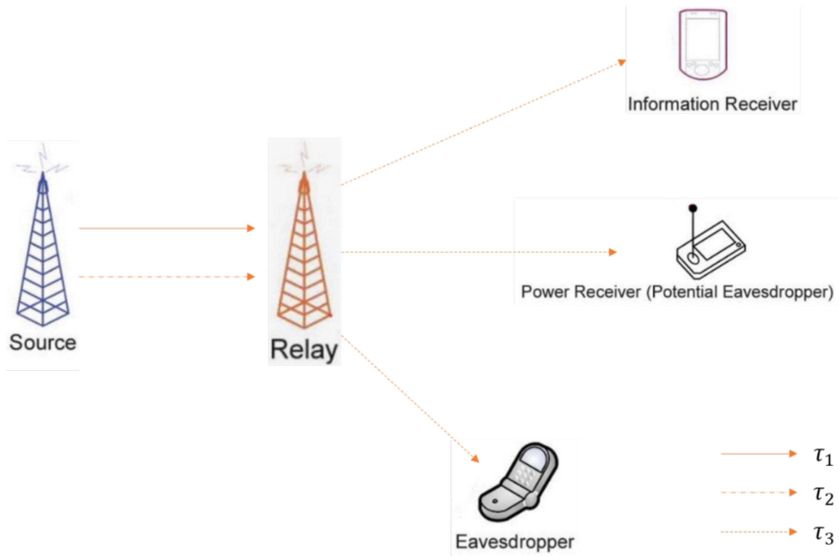


Figure 3.2. System model

## 3.3. Transmitted Signal at the source

In this paper, the source would first transfer an energy signal to relay before it transfers the real signal in order to provide the energy for the relay to create artificial noise during the second time slot. In that case, the security of transmission would increase, and the energy signal could be represented as $\boldsymbol{w}_1$, $\mathbf{w}_1 \in \mathbb{C}^{N_R * 1}$.

The signal at the source aims to minimize the transmitting power and ensure the communication security. The transmitted signal at the source can be represented as $\mathbf{w}_2$:

$$\mathbf{w}_2 = \mathbf{w}_3 s + \boldsymbol{w}_E + \boldsymbol{z}$$

(1)

Where $\mathbf{w}_3 \in \mathbb{C}^{\mathrm{N}_R * 1}$ is the information signal's beamforming vector, and s donates the information signal. The $\mathbf{w}_E \in \mathbb{C}^{\mathrm{N}_R * 1}$ represents the pseudo-random energy signal and $\mathbf{w}_E \sim \mathcal{CN}$ (0, $\boldsymbol{W}_E$). The $\boldsymbol{z} \in \mathbb{C}^{\mathrm{N}_R * 1}$ is a complex Gaussian random vector transmitted by the source to EA act as the AN, and $\boldsymbol{z} \sim \mathcal{CN}$ (0, $\boldsymbol{Z}$).

### 3.4. Received Signal at the Relay

In the first phase, the source sends a signal vector to the relay on all subcarriers, because the signal carries both information and energy, so the relay can collect energy from the received signal [66]. In the second phase, it decodes the information sent by the source and sends the reencoded signal using all the energy collected in the previous phase [67,68,69]. It is assumed that RF signals received by relay are only affected by AWGN in the frequency band and are not affected by AWGN after being sent to PS receiver [70-75].

For more detail, the signal received by the relay is firstly processed by the receiving filter, and then divided into two streams. Part $\eta$ is sent to the information receiver for information decoding, and part 1-$\eta$ is sent to the energy receiver for energy collection [76,77]. The collected energy is then distributed to the relay forwarding matrix [78,79,80].

Based on the transmitted signal, the received signal at the relay can be represented as:

$$\boldsymbol{y}_R = \boldsymbol{h}^H \mathbf{w}_2 + \boldsymbol{z}$$

(2)

Where $\mathbf{w}_2 \in \mathbb{C}^{\mathrm{N}_R * 1}$ is transmitted signal vector. $\boldsymbol{h}^H \in \mathbb{C}^{1 * \mathrm{N}_R}$ is the channel vector between the source and the relay. $\boldsymbol{z} \sim \mathcal{N}$ (0, $\boldsymbol{\sigma}_{ant}^2$) is the thermal noise at the receiver antennas and it is AWGN.

At the same time, the eavesdropper can also receive the information and it can be represented as:

$$\boldsymbol{y}_E = \boldsymbol{L}^H \mathbf{w} \quad + \boldsymbol{z} \tag{3}$$

Where $\mathbf{w} \in \mathbb{C}^{\mathrm{N}_R * 1}$ is transmitted signal vector. $\boldsymbol{l}^H \in \mathbb{C}^{1*\mathrm{N}_R}$ is the channel vector between the source and the eavesdropper. $\boldsymbol{z} \sim \mathcal{N}$ $(0, \boldsymbol{\sigma}_{\boldsymbol{ant}}^{\mathbf{2}})$ is the thermal noise at the receiver antennas and it is AWGN.

In hence, the SINR at relay is given by

$$SINR_E = \frac{Tr(\boldsymbol{l}\boldsymbol{l}^H \boldsymbol{W})}{\boldsymbol{Z}^2 + Tr(\boldsymbol{l}\boldsymbol{l}^H \boldsymbol{Z})} \tag{4}$$

In the final phase, the relay first decodes the signals sent by the base station, and then forwards the recoded signals to information receiver through subchannels [81,82]. The received signal at the information receiver can be represented as:

$$\boldsymbol{y}_I = \boldsymbol{f}^H \mathbf{w}_3 + \boldsymbol{z} \tag{5}$$

Where $\mathbf{w}_3 \in \mathbb{C}^{1*\mathrm{N}_R}$ is transmitted signal vector. $\boldsymbol{f}^H \in \mathbb{C}^{1*\mathrm{N}_R}$ is the channel vector between the relay and the information receiver. $\boldsymbol{z} \sim \mathcal{N}$ $(0, \boldsymbol{\sigma}_{\boldsymbol{ant}}^{\mathbf{2}})$ is the thermal noise at the receiver antennas and it is AWGN.

And the SINR can be represented as:

$$SINR_R = \frac{Tr(\boldsymbol{f}\boldsymbol{f}^H \boldsymbol{W}_3)}{\boldsymbol{Z}^2 + Tr(\boldsymbol{f}\boldsymbol{f}^H \boldsymbol{Z})} \tag{6}$$

## 4. Problem Formulation

This paper focus on minimizing the energy consumption and guarantee the security rate at the same time. An optimal solution should be found based on the formulations listed ahead. The energy consumption is described as the total energy during the transition between the source and the relay. Since the whole transmission process happening during the time $\boldsymbol{T}_{max}$, so the sum of the three time slots must less than the maximum value; For the third time slot, the information receiver would get the information from the relay, and the energy consumption must less the harvested energy at the relay. Apart from this, since the system needs qualified wireless communication, the received signal power of the required information decoder should meet the minimum requirement of SINR. And the SINR for both eavesdropper and receiver must less than the max available value for transmission security. In addition, the energy harvested at the relay should satisfied that it is large enough to encourage energy transmission [83].

Thus, the resource allocation formulations are shown as:

$$\min_{\tau_1,\tau_2,\tau_3,\boldsymbol{w}_1,\boldsymbol{w}_2,Z} \tau_1 * Tr(\boldsymbol{w}_1) + \tau_2 * Tr(\boldsymbol{w}_2)$$

$$C_1:\ \tau_1 + \tau_2 + \tau_3 \ \le\ T_{max};$$

$$C_2: \frac{|\boldsymbol{f^H w}_3|^2}{\boldsymbol{Z}^2 + Tr(\boldsymbol{f}\boldsymbol{f}^H\boldsymbol{Z})} \ge SINR_{req};$$

$$C_3: \frac{Tr(\boldsymbol{w}_1 H)}{\boldsymbol{Z}^2} \ge SINR_{req};$$

$$C_4: \tau_3 * [Tr(\boldsymbol{w}_3) + Tr(\boldsymbol{Z})] \le\ \tau_1 * \eta * Tr(\boldsymbol{w}_1 H);$$

$$C_5: \eta * [|\boldsymbol{s^H w}|^2 + Tr(\boldsymbol{Z}\boldsymbol{g}\boldsymbol{g}^H)] \ge P_{min};$$

$$C_6: \frac{|\boldsymbol{l^H w}|^2}{\boldsymbol{Z}^2 + Tr(\boldsymbol{l}\boldsymbol{l}^H\boldsymbol{Z})} \le SINR_{tot};$$

$$C_7: \boldsymbol{W}_1 \ge 0, \boldsymbol{W}_2 \ge 0, \boldsymbol{Z} \ge 0 \tag{7}$$

## 5. Optimization solution

The original formulation can be considered as a non-convex problem and what we need is minimum the transmit power. In hence, we need to transform this non-convex problem. By using SDP relaxation, we can change this problem into a convex problem [84,85].

After using SDP, we can rewrite the formulations as:

$$\min_{\tau_1,\tau_2,\tau_3,\boldsymbol{w}_1,\boldsymbol{w}_2,Z} \tau_1 * Tr(\boldsymbol{w}_1) + \tau_2 * Tr(\boldsymbol{w}_2)$$

$$C_1:\ \tau_1 + \tau_2 + \tau_3 \ \le\ T_{max};$$

$$C_2: \mu_{req} *[\boldsymbol{Z}^2 + Tr(\boldsymbol{f}\boldsymbol{f}^H\boldsymbol{Z})] - Tr(\boldsymbol{f}\boldsymbol{f}^H\boldsymbol{W}_3) \le 0;$$

$$C_3: \mu_{req} * \boldsymbol{Z}^2 - Tr(\boldsymbol{w}_1 H)\ \le 0;$$

$$C_4: \tau_3 * [Tr(\boldsymbol{w}_3) + Tr(\boldsymbol{Z})] - \tau_1 * \eta * Tr(\boldsymbol{w}_1 H) \le 0;$$

$$C_5: P_{min} - \eta * [Tr(\boldsymbol{s}\boldsymbol{s}^H\boldsymbol{W}) + Tr(\boldsymbol{Z}\boldsymbol{g}\boldsymbol{g}^H)] \le 0;$$

$$C_6: Tr(\boldsymbol{l}\boldsymbol{l}^H\boldsymbol{W}) - \mu_{tot} * \boldsymbol{Z}^2 + Tr(\boldsymbol{l}\boldsymbol{l}^H\boldsymbol{Z}) \le 0;$$

$$C_7: -\boldsymbol{W}_1 \le 0, -\boldsymbol{W}_2 \le 0, -\boldsymbol{Z} \le 0;$$

$$C_8: \text{Rank } (\boldsymbol{W}_i)=1,\ \forall\ \text{i} = 1,2,... \qquad (8)$$

However, there is still part of the formulations is non-convex, the $C_8$.

If we do not consider the $C_8$, the problem is a convex problem and then we can use some maths tools to analysis and simulate [86,87,88]. But in order to verify the SDP relaxation's correctness, the dual problem must be taken into consideration. To solve this problem, we have to use the KKT SDP relaxation conditions to optimize this problem [89 90].

Since we have already rewritten the formulations, we can find the Lagrange of the problem [91]:

L=$\tau_1 * Tr(\boldsymbol{w}_1) + \tau_2 * Tr(\boldsymbol{w}_2)$

$+\lambda_1\{\ \mu_{req} *[\boldsymbol{Z}^2 + Tr(\boldsymbol{f}\boldsymbol{f}^H\boldsymbol{Z})] - Tr(\boldsymbol{f}\boldsymbol{f}^H\boldsymbol{W}_3)\}$

$+\lambda_2\{\ \mu_{req} * \boldsymbol{Z}^2 - Tr(\boldsymbol{w}_1 H)\}$

$+\lambda_3\{\ \tau_3 * [Tr(\boldsymbol{w}_3) + Tr(\boldsymbol{Z})] - \tau_1 * \eta * Tr(\boldsymbol{w}_1 H)\}$

$+\lambda_4\{\ P_{min} - \eta * [Tr(\boldsymbol{s}\boldsymbol{s}^H\boldsymbol{W}) + Tr(\boldsymbol{Z}\boldsymbol{g}\boldsymbol{g}^H)]\}$

$+\ \lambda_5\ \{\ \ Tr(\boldsymbol{l}\boldsymbol{l}^H\boldsymbol{W}) - \mu_{tot} * \boldsymbol{Z}^2 + Tr(\boldsymbol{l}\boldsymbol{l}^H\boldsymbol{Z})\}\ -\ Tr(\boldsymbol{Y}\boldsymbol{W}_2)\ -\ Tr(\boldsymbol{Z}\boldsymbol{W}_1) -\ Tr(\boldsymbol{U}\boldsymbol{W}_3)$ (9)

Where Y is the dual variable matrices of $C_8$, $\lambda_1$, $\lambda_2$, $\lambda_3$, $\lambda_4$, $\lambda_5$ are the scalar dual variables of $C_2$~$C_7$.

Thus, we can transfer the optimization problem into a dual problem [92]:

$$\min_{\tau_1,\tau_2,\tau_3,\boldsymbol{w}_1,\boldsymbol{w}_2,Z} L(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \boldsymbol{w}_1, \boldsymbol{w}_2, , \boldsymbol{w}_3, \boldsymbol{Y}, \boldsymbol{Z}, \boldsymbol{U})$$

$$C_9: \frac{\partial \boldsymbol{L}}{\partial \boldsymbol{W}_2} = (\tau_2 + \lambda_3 * \tau_3 - \mathbf{Y}) * \mathrm{I} - \lambda_1 * \mathbf{F} = \mathbf{0};$$

$$C_{10}: \boldsymbol{Y}\boldsymbol{W}_2 = 0 \tag{10}$$

The dual formulation (10) equals to the optimization problem (8). And for the rank, we can proof that:

$$(\tau_2 + \lambda_3 * \tau_3 - \mathbf{Y}) * \mathrm{I} - \lambda_1 * \mathbf{F} = 0 \tag{11}$$

$$\mathbf{Y} = (\tau_2 + \lambda_3 * \tau_3) * \mathbf{I} - \lambda_1 * \mathbf{F} \tag{12}$$

According to the formulation: Rank (A-B) ≥ Rank (A) – Rank(B) [93,94],

$$\begin{aligned} \text{Rank } (\mathbf{Y}) &= \text{Rank } ((\tau_2 + \lambda_3 * \tau_3) * \mathbf{I} - \lambda_1 * \mathbf{F}) \\ &\geq \text{Rank } ((\tau_2 + \lambda_3 * \tau_3) * \mathbf{I}) - \text{Rank } (\lambda_1 * \mathbf{F}) \\ &= \text{Rank } (\mathbf{I}) - \text{Rank}(\mathbf{F}) \\ &= N_T - 1 \end{aligned} \tag{13}$$

Since $\boldsymbol{Y}\boldsymbol{W}_2$=0, and $\boldsymbol{W}_2$ is positive, it is obvious that

$$\text{Rank } (\boldsymbol{W}_2) = 1 \tag{14}$$

Now, we transformed the optimization problem into a convex problem, and we can use maths tools for simulation [94,95].

## 6. Results and Analysis

The simulation results for this system would be discussed in this part. We choose MATLAB for simulation and the logic is as mentioned above. Some parameters for simulation are in table 1:

Table 1 – simulation parameters

| | |
|---|---|
| Carrier central frequency | 915MHz |
| Bandwidth | 200kHz |

| | |
|---|---|
| Number of transmitter antenna | 3/6/9 |
| Transmit antenna gain | 18dBi |
| Energy conversion efficiency | 0.5 |

## 6.1. Minimum required SINR

Figure 5.1 shows the relationship between the average total transmit power and the minimum required SINR.

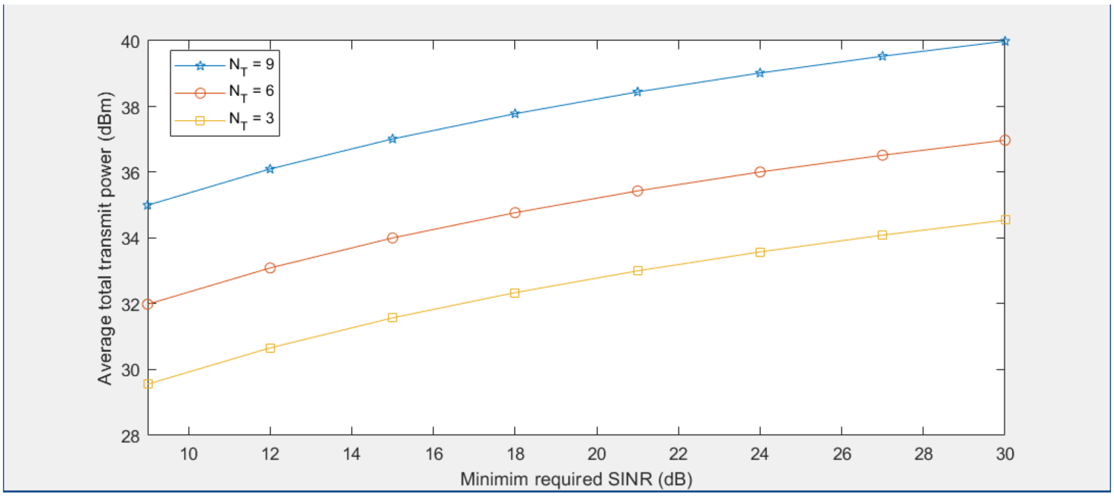


Figure 5.1 minimum required SINR

According to this figure, we can find that the average total transmit power increasing while the minimum required SINR increasing. This is because the change to the minimum required SINR would cause the change at the vectors for the signal transmitting, and we can find that it is a positive relation ship between them. Apart from this, the number of the transmit antennas also have a significant effect on the average total transmit power. With the decrease of the number of transmit antennas, the average transmit power will decrease. We can find that the more transmit antennas we use, the higher energy needed, but the lower the required SINR is.

## 6.2. Number of users

The figure 5.2 shows the relationship between the average total transmit power and the number of users.

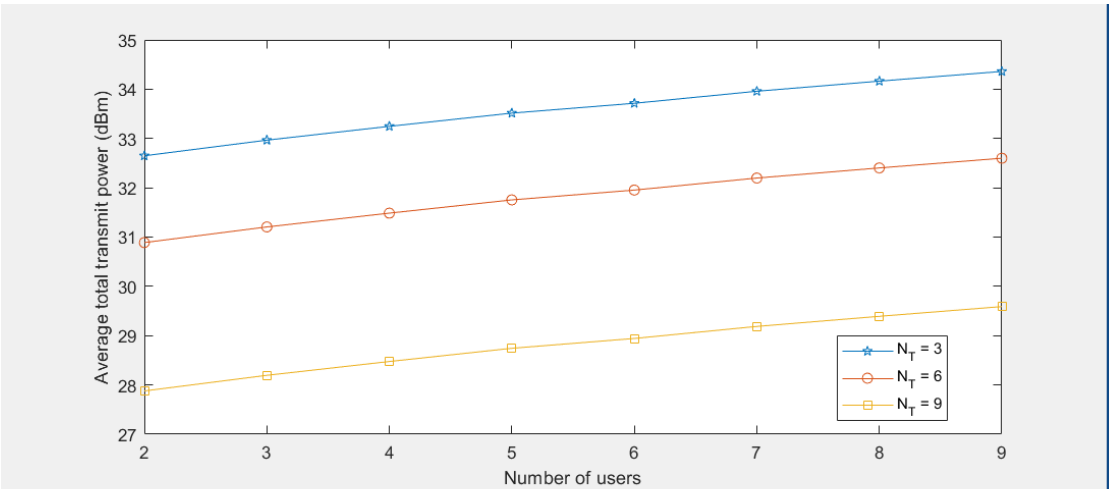


Figure 5.2 Number of users

According to this figure, we can find that with the increase in the number of users, the average total transmit power will decrease. But for the system with same users, with the increase in the number of the transmit antennas, the average total transmit power will decrease. It means that we can save the power by servicing more users, or we can use more antennas for a practical area since the number of the users is known.

## 7. Conclusion

In this paper, a DF SWIPT network is designed and simulated. The power consumption beamforming is analysed and the minimum transmit power is calculated. The source-relay network is a MIMO system and the relay- receiver network is a MISO system. The simulation is based on the formulations according to the system. And the key point is transforming the optimization problem into a convex function. Although we have some other ways even if the optimization problem is non-convex, it requires a lot of time to find the best solution.

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