THE UNIVERSITY OF
NEW SOUTH WALES

School of Electrical Engineering and Telecommunications

BEAMFORMING DESIGN FOR SIMULTANEOUS WIRELESS INFORMATION AND POWER TRANSFER

by

Duojiao Chen

Thesis submitted as a requirement for the degree

Master of Science Engineering (Telecommunication)

Date of submission: 13-June-2018

Abstract

This thesis focuses on the beamforming design for wireless information and power transfer system. The system adopted in this paper is multiuser Multi-input and Multi-output antennas (MIMO) with separated receivers and simultaneous wireless information and power transfer (SWIPT) under the circumstances that eavesdroppers are trying to wiretap the transmitted information. The proposed problem is to maximize the energy transfer efficient for idle receivers while maintaining the security of wireless communication between transmitter and desired receiver. It takes into consideration of the maximum power can be supplied by power grid, minimum data rate for recovering transmitted signal and minimum power required for energy harvesting circuit. We exploit the physical layer security with power constraints and signal design to ensure the secrecy in signal transmission. In particular, the energy signal and artificial noise generated at transmitter and embedded in transmitted signal are utilized for protecting signal which contains information needed to be decode. However, the formulated optimization problem is a non-convex equation which is hard to solve in general. In this thesis, we have proposed a series of transformations and obtain the optimum solution. Numerical simulation results show the relationship for average energy transfer efficiency versus maximum required total transmit power and minimum required SINR between transmitter and idle energy receivers respectively. Moreover, the results reveal a dual use of energy signal and artificial noise injected into information signal which can improve energy harvesting efficiency and ensure security of wireless communication simultaneously. The system can also provide a remarkable performance gain with extra transmit antennas equipped at base station.

Acknowledgement

I would like to express my greatest gratitude to my supervisor Derrick Wing Kwan Ng, who gave me the opportunity to do this topic and supported me throughout the project. It’s been really helpful with his aspiring guidance, invaluably constructive criticism and friendly advice through the learning process of master thesis.

Table of Contents

1 Introduction

The increasing interest of next generation network based on Internet-of-Things (IoT) has led to rapid growth in number of wireless communication devices recent years. There are 20.35 billion smart devices (e.g., smart phones and sensors) connect together into IoT network in 2017 [1]. This kind of networks are supposed to guarantee a communication with high data rate and secrecy while maintain acceptable quality of service (QoS), and need sufficiently high energy consumption in order to meet those requirements. As a result, various technologies have been proposed such as channel coding, MIMO and multipath routing. In particular, multi-input multi-output (MIMO) introduces spatial degrees of freedom into the resource allocation security as a solid solution to reduce energy consumption while maintaining the system performance. Furthermore, multiuser MIMO technology where several single-antenna receivers are served by one base station equipped with multiple antennas, can be considered as alternative way of achieve the latent gains and improves the efficiency of energy utilization.

Majority of devices in IoT networks are sensors which are typically powered by battery with limited energy leading constrained network life time. The development of battery energy storage technology is unable to keep pace with the significant growth of energy demand, cf. [2] - [4]. Although replacement of batteries can extend their lifetime effectively, it will cause high cost and sometime impossible (e.g. medical implant). The energy harvesting circuit could collect power from natural resources such as solar, hydro energy, and background radio-frequency (RF) signals. It is a promising way for providing a more stable wireless communication system. However, renewable sources are labile for the limitation caused by unpredictable climate and change of position. Besides, it may not be applicable for some circumstances (i.e., indoor environment), while collecting energy from RF signals is controllable. Simultaneous wireless information and power transfer (SWIPT) exploits different aspects of RF signals, which are signal transmission and power transfer.

Recently, there is an increasing interest about wireless power transfer (WPT) in power related academic and industry society. However, the concept of this topic was proposed by Nikola Tesla in early 20th century, cf. [5]. The project he conducted of building power station for wireless charging is not successful and that power station was only used for experiment. In the late 20th century, there is a re-emerged need of WPT technology due to various reasons. For instance, the popularization of mobile devices (i.e., personal computers, smart phones) and rapid growth of hybrid electric vehicles, cf. [6]. Nowadays RF signals are widely employed in wireless communication system. In 2008, Varshney proposed the concept of simultaneous wireless information and power transfer (SWIPT) in [7] and first conducted a study of rate-energy trade off. This technology becomes appealing in both academia and industry since it exploits the dual use of RF signals which are information delivering and power transferring.

Green communication design has gained extensive attention in recent years [7] - [12]. The challenges of current SWIPT network have been studied in [15]. It mainly focuses on presenting the security of wireless transmission in different networks and interference management. A power distribution algorithm for frequency selective fading channel to achieve optimal data rate and total harvested power for given transmit power was proposed in [10]. Nevertheless, the assumption made in [7] and [10] indicates that the receivers can reuse the same transmitted signal for gaining energy and decode information. Unfortunately, this is impossible because of hardware limitation for now. Two types of EH receiver (separated receiver and integrated receiver) were proposed in [11] - [16]. Integrated receiver with power splitting splits the received signal into two parts (it can be static ratio or dynamic ratio), one part of signal is used for energy harvesting and the other one is used for information decoding. Integrated receiver is equal to separated receiver under certain circumstances, for instance, time switching receiver and antenna switching receiver with same static splitting ratio. The simulation results of rate-energy trade-off for different receivers under various channel state showed in [17] and [18]. The authors of [11] conducted a study of rate-energy region of different type of energy harvesting circuits for system has two users, while the results of numerical simulation show that separated receivers have better performance in low energy region. Moreover, the integrated receivers have high energy transformation efficiency in high energy region. A different resource allocation algorithm for integrated power splitting receiver was proposed in [19] for optimizing power transfer efficiency. The power consumption during the process of information decoding and energy transfer has been considered. The circuit constituted by different electrical component will have impact on the overall harvested energy. However, the hardware circuit of energy harvester is not the primary consideration of this paper. The impact caused by different circuits are considered to be ignored and we only concern about the structure of EH receivers. Yet, there is a power consumption of digital circuit which cannot be overlooked when designing power allocation and it regards as an important role in [20] and [21]. In [22], the authors provide a new system model which transmits information signal with energy signal for improving the energy transferred in system. There is a positive correlation between the transmitted power and the harvested energy. However, increasing the transmit power may also increase the potential of successful eavesdropping and risk of information leakage in [23] - [27]. Hence, a rising concern about secrecy transmission in SWIPT system need to be considered.

Providing information security in signal transmission is elementary in wireless communication systems. The most common way for improving information secrecy is encryption which requires a private key. The maximum secrecy data rate for desired information receiver can be achievable was studied in [28] and [29]. The definition of secrecy data rate is the data rate that complete reliable for transmitter to send signal without bearing the risk of information leakage. The concept of perfect security can be obtained by using the physical layer method that restricts the received signal power or signal-to-noise ratio (SNR) at eavesdropper was provided in [30]. In [31], the authors assumed all the potential eavesdroppers are in the near field of transmitting area to further constrains the requirement for achieving security. There are two major approaches listed in [32] for data protection in physical layer, power constraint and signal design. Unlike the method been used in application layer (i.e., cipher), the methodology in physical layer focuses on constraints exploits in the fundamental of wireless communication, cf. [33]. Utilizing artificial noise generated by multiple antennas and inject into null space of channel between transmitter and eavesdroppers can degrade the effectively reduce the probability of information leakage as the results showed in [34] - [42]. The key for decoding energy signal is assumed to be known at legitimate receivers, thus can improve the system security and harvest energy at the same time. Furthermore, the dual utilization of energy signal and artificial noise is fully exploits in [43]. Changing the power allocation algorithm could be used for solving different optimization problem.

In fact, beamforming technology can provide secrecy in wireless communication that concentrate the transmit power of information into certain direction where the desired receiver is in by using multiple antennas to generate the beamforming vector. Not only it can boost the security during transmission, also helpful for various maximization objectives, cf. [44] - [54]. The authors in [55] proposed a transmit signal with information beam focuses on desired information decoder and artificial noise focuses on other energy harvester. However, the accuracy of beamforming vector relies heavily on channel state information at transmitter (CSIT). The beamforming technology relies on CSI obtained through channel estimation, cf. [56]. At the first stage of each time slot, all legitimate receivers need send signal which contains handshaking information to base station for reporting their status. The information indicates the location of desired information decoder and the received signal could be used to estimate the channel at transmitter. The pilot sequence embedded in the handshaking signal can be used for channel estimation between transmitter and legitimate receivers. The CSI can be further update and perfection through sending back acknowledgement (ACK) packages to transmitter through transmission. However, the CSIT cannot always be perfect for instances outdated CSIT between transmitter and idle receivers and estimation error. Although the computation complexity will be significant reduced if the CSIT assumed to be perfect. The channel between transmitter and idle receivers may not be updated since last transmission, thus, the CSI at base station may not be perfect. Besides, the CSIT for eavesdroppers is nearly impossible to achieve in reality since eavs are passive receivers which means they do not communicate with transmitter. Authors in [43] and [55] study the optimal design of certain circumstance that partial CSIT for receivers except desired receiver. The deterministic model proposed in [57] and [58] determines a presentation of CSIT uncertainty between transmitter and receiver. Nevertheless, there are several reasons that may cause imperfect CSIT for channel between transmitter and desired information decoder [59]. For example, Estimation error, limited feedback and delayed CSIT. The performance of secrecy communication system with outdated CSIT feedback and transmit antenna selection (TAS) is addressed in [60]. The proposed algorithms in [61] indicate the solution for optimize system performance under the constraint of QoS through precoding. In this paper, we focus on multi-user MIMO optimization problem for maximizing energy transfer efficient. Beamforming not only can improve the secrecy of the information transmitted, but also can help to neglect the effect of fading and multi-path of power transfer under long-distance circumstance in [62] and [63].

2 System Model

The system in this report is assumed to be multiuser MIMO that multiple antennas equipped at transmitter serves several single antenna receivers with Time Division Duplex (TDD) as example shown in Fig. 1. The system has i+1 legitimate receivers in two types. One is desired information decoder and the other is idle receiver which is potential eavesdroppers. Only one desired receiver at each time slot with i idle receivers and k passive eavesdroppers. The primary task for idle receivers are harvest energy from ambient RF signals as many as possible that the energy will transfer into power stored in battery. Meanwhile the active information decoder supposed to make sure the error probability for information decoding is able to meet the system requirement. The eavesdroppers are passively receiving signal from transmitter. To tighten security requirement of transmission, the desired information receiver will place farther than both idle energy receivers and eavesdroppers.

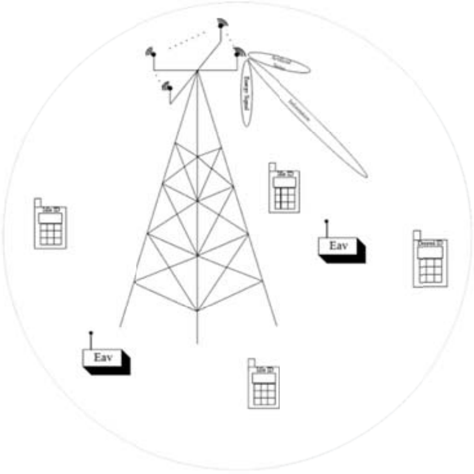

Figure 1 – System model for I+1 = 4 legitimate receivers and J = 2 eavesdroppers wireless communication network.

2.1 Transmitted Signal

The signal generated at base station is designed to ensure the security of wireless communication and to increase the harvested energy at idle receivers. Artificial noise and energy signals transmitted with the beamformed information signal simultaneously can achieve the effect that the channels between base station and eavesdroppers worse and serve as a reliable energy source for power transfer. The transmit signal vector ***s*** is:

$$\boldsymbol{s} = \underbrace{\boldsymbol{w}x}_{information\,signal} + \underbrace{\boldsymbol{w}_E}_{energy\,signal} + \underbrace{\boldsymbol{n}_A}_{artificial\,noise} \tag{1}$$

where $x \in \mathbb{C}$ and $\boldsymbol{w} \in \mathbb{C}^{N_T \times 1}$ is the signal generated at base station carrying information to be transmit and the beamforming vector for corresponding legitimate receiver while N_T represents the total number of antennas equipped at BS. The information signal is assumed to be independent sequence with $\mathcal{E}\{|x|^2\} = 1$. $\boldsymbol{w}_E \in \mathbb{C}^{N_T \times 1}$ is Gaussian pseudo-random vector generated at transmitter as energy signal with

$$\boldsymbol{w}_E \sim \mathcal{CN}(\boldsymbol{0}, \boldsymbol{W}_E), \tag{2}$$

where $\boldsymbol{W}_E \in \mathbb{H}^{N_T}$ and $\boldsymbol{W}_E \succeq 0$ represent the covariance matrix of energy signal. The energy signal is used for providing energy source for receivers other than desired information decoder. While $\boldsymbol{n}_A \in \mathbb{C}^{N_T \times 1}$ is the artificial noise signal vector for providing secrecy in communication and is assumed to be complex Gaussian random vector that

$$\boldsymbol{n}_A \sim \mathcal{CN}(\boldsymbol{0}, \boldsymbol{N}_A), \tag{3}$$

where $\boldsymbol{N}_A \in \mathbb{H}^{N_T}$ and $\boldsymbol{N}_A \succeq \boldsymbol{0}$ represent the covariance matrix of artificial noise. In this system, the generated artificial noise is completely random which means it is unknown to both desired information receivers and idle energy receivers.

Assumption 1: The energy signal $\boldsymbol{w}_E$ is assumed to be Gaussian pseudo-random vector which can be decoded at legitimate receiver as it is a pre-defined sequence. The key is assumed to be unknown at passive eavesdroppers. Transmitter need to change the key used for decipher constantly to prevent being obtained by eavs and cause information leakage.

2.2 Separated Receiver with Time Switching

Several types of EH receiver are available for SWIPT system. According to the experimental results showed in [9] - [12], different hardware may have significant difference when considering rate-energy trade-off under same circumstance. However, the hardware circuit is not the main consideration for this report. Thus, there is no specific energy harvesting circuit indicated in this report. Specifically, the EH receiver been adopted is separated receiver with time switching in dynamic ratio. The structure of the receiver is shown in Fig. 2. The receiver contains separated circuit for information decoding and energy harvesting. The legitimate receivers switch to information decoding only when they are allocated as desired information decoder. The receiver switch to different circuit based on the information embedded in handshake signal which indicates whether it is the desired receiver. However, for passive eavesdropper, in order to increase the probability of success in wiretap the receiver is assumed to always switch to information decoding status. In spite of that, we need to exploit physical layer security with power constraints due to non-negligible probability that legitimate receivers are potential eavesdroppers.

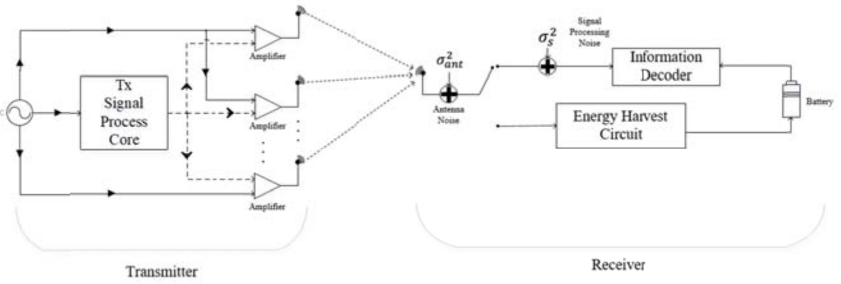

Figure 2 – Block diagram of separated energy harvesting receiver with time switching.

2.3 Downlink Received Signal

Based on the channel model and transmitted signal we proposed, the received signals at downlink for desired information decoder, i -th idle receivers, j -th eavesdroppers are given.

$$y_1 = \boldsymbol{h}^H \boldsymbol{s} + n_{ID} \tag{8}$$

$$y_{2,i} = \boldsymbol{g}_i^H \boldsymbol{s} + n_{ID,i}, \forall i \in \{1, \dots, I\} \tag{9}$$

$$y_{3,j} = \boldsymbol{l}_j^H \boldsymbol{s} + n_{eav,j}, \forall j \in \{1, \dots, J\} \tag{10}$$

where $\boldsymbol{s} \in \mathbb{C}^{N_T \times 1}$ represent the vector of transmitted signal. $\boldsymbol{h}^H \in \mathbb{C}^{1 \times N_T}$, $\boldsymbol{g}_i^H \in \mathbb{C}^{1 \times N_T}$ and $l_j^H \in \mathbb{C}^{1 \times N_T}$ denotes the channel vector between transmitter and desired information receiver, idle energy receiver i , $i \in \{1, \dots, I\}$ and eavesdropper j , $j \in \{1, \dots, J\}$, respectively. $n_{ID} \sim \mathcal{N}(0, \sigma_{ant}^2)$, $n_{ID,i} \sim \mathcal{N}(0, \sigma_{ant}^2)$ and $n_{eav,j} \sim \mathcal{N}(0, \sigma_{ant}^2)$ are additive white Gaussian noises (AWGN) which denote the thermal noise through transmission and antenna noise generated at the receivers' antenna.

2.4 Linear Energy Harvesting Model

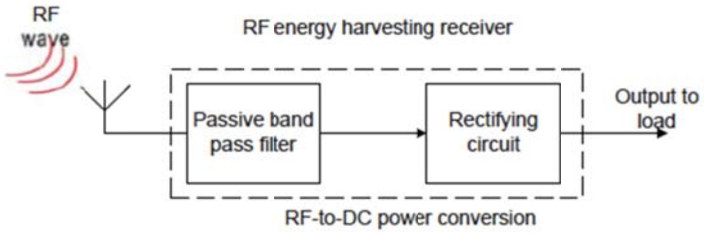

Figure 3 – Block diagram of energy harvesting circuit [64]

Figure 3 shows the block diagram of energy harvesting circuit mentioned in figure 2 which can convert received RF signal into electricity. The received signal first passes the passive bandpass filter to maximize the power transfer, cf. [65]. Then the rectifying circuit will transfer the filtered signal into DC power. The total power received at i-th idle receiver is:

$$P_{idle,i} = Tr(\boldsymbol{G_i W}) + Tr(\boldsymbol{G_i W_E}) + Tr(\boldsymbol{G_i N_A}) \tag{11}$$

where $\boldsymbol{G_i} = g_i g_i^H, \forall i \in \{1, \dots, I\}$. In this paper, we are considering linear energy harvesting model which means the collected transferred energy increased with the growth of total received energy. Which means the harvested energy is linear proportional to total received power with efficiency η. Hence, total harvested power at i-th idle receiver can be presented as:

$$\mathrm{P}_{idle,i}^{linear} = \eta P_{idle,i} \tag{12}$$

where η is defined as circuit energy harvesting efficiency of the harvesting circuit.

2.5 System Capacity and Secrecy Rate

The vector of energy signal $\boldsymbol{w_E}$ we designed is assumed to be Gaussian pseudo-random sequence that means the interference between adjacent receivers caused by energy signal could be cancelled at legitimate receivers. However, the artificial noise vector $\boldsymbol{n_A}$ is complex Gaussian random sequence thus the interference cannot be cancelled at all receivers, cf. [66]. The channel capacity (bit/s/Hz) between base station and desired information decoder is [67]

$$SINR_{ID} = \frac{\boldsymbol{w}^H \boldsymbol{H w}}{\sigma_{ant}^2 + Tr(\boldsymbol{H N}_A) + \sigma_s^2} \tag{13}$$

$$C_{ID} = log_2(1 + SINR_{ID}), \tag{14}$$

where $SINR_{ID}$ is the signal-to-interference-plus-noise ratio (SINR) between transmitter and desired information receiver and C_{ID} is the corresponding channel capacity which cancelled the interference caused by energy signal with $\boldsymbol{H} = \boldsymbol{hh}^H$. σ_s^2 is the noise generated at desired receiver when decoding the received signal. The channel capacity between transmitter and i-th idle receiver can be represented as

$$SINR_{ID,i} = \frac{\boldsymbol{w}^H \boldsymbol{G_i w}}{\sigma_{ant}^2 + Tr(\boldsymbol{G}_i \boldsymbol{N}_A) + \sigma_s^2} \tag{15}$$

$$C_{ID,i} = log_2(1 + SINR_{ID,i}), \tag{16}$$

where $SINR_{ID,i}$ and $C_{ID,i}$ denote the SINR when the potential eavesdropper choose to decode the received signal rather than harvest energy and channel capacity at corresponding i-th idle receiver, respectively with $\boldsymbol{G_i} = \boldsymbol{g_i}\boldsymbol{g}_i^H, \forall i \in \{1, \dots, I\}$. The location and CSI for passive eavesdroppers is unknown for transmitter. The capacity between transmitter and j-th eavesdropper in this case can be written as

$$SINR_{eav,j} = \frac{\boldsymbol{w}^H \boldsymbol{L_j w}}{\sigma_{ant}^2 + Tr(\boldsymbol{L}_j \boldsymbol{W}_E) + Tr(\boldsymbol{H}\boldsymbol{N}_A) + \sigma_s^2} \tag{17}$$

$$C_{eav,j} = log_2(1 + SINR_{eav,j}), \tag{18}$$

where $\boldsymbol{L_j} = \boldsymbol{l}_j \boldsymbol{l}_j^H, \forall j \in \{1, \dots, J\}$. The physical meaning of equation (17) is that j-th passive eavesdropper cannot cancel the interference caused by both energy signal and artificial noise, thus reveals the dual use of these signals.

The secrecy channel capacity is defined as even when the potential eavesdroppers or passive eavesdroppers with best channel cannot have enough power to decode the information signal. The maximum security transmission capacity can be written as

$$C_{sec} = \left[C_{ID} - max\left\{\max_{i \in \{1,\dots,I\}} C_{ID,i}, \max_{j \in \{1,\dots,J\}} C_{eav,j}\right\}\right]^+ \tag{19}$$

The utilization of artificial noise vector n_A, energy signal vector w_E can provide security for wireless communication system in different objectives. More specifically, the artificial noise vectors are able to disturb the channel for idle receivers and passive eaves, while energy signal vectors are only influence the channel between transmitter and passive eavesdroppers. Both signals are reliable source for energy harvesting.

3 Problem Formulation

The CSIR is assumed to be perfect and there is no uncertainty of channel information at transmitter. We intended to find the optimal solution of resource allocation to maximize the energy transfer efficiency. The energy transfer efficiency is defined as total energy harvested by energy receivers over total transmit power. There are several constraints to ensure system performance while maintaining security of wireless communication. In theory, the total harvested energy will increase with increment of total transmit power. However, resource allocation differs with different situation. For instance, if information decoder requires high SINR for decoding, transmitter will allocate more power to beamform information vector to ensure overall system meets the requirement thus less power could be radiated to energy harvester. The transmit power contains 3 parts which are power of information signal, energy signal and artificial noise, and summation of these 3 parts should be less or equal to required maximum transmit power. Moreover, the received signal power at desired information decoder should satisfies minimum requirement of SINR since the system requires qualified wireless communication. Meanwhile, SINR for idle receivers and eavesdroppers should be less or equal to maximum tolerable value to ensure secure transmission. The design of this constraint means that power of information vector received in both idle receivers and eavesdroppers should not enable the energy harvesters to successfully decode transmitted information. In addition, energy harvested at energy receiver should be large enough to trigger energy transfer circuit and linear energy transfer model is adopted.

Thus, optimum resource allocation algorithm for maximizing the energy transfer efficiency with transmit signal variables $\{\boldsymbol{W}^{*}, \boldsymbol{W_E}, \boldsymbol{N_A}\}$ can be achieved by solving following equations:

$$\max_{\boldsymbol{W},\boldsymbol{W_E},\boldsymbol{N_A}} \frac{\sum_i [Tr(\boldsymbol{G_i W}) + Tr(\boldsymbol{G_i W_E}) + Tr(\boldsymbol{G_i N_A})]}{Tr(\boldsymbol{W}) + Tr(\boldsymbol{W_E}) + Tr(\boldsymbol{N_A})}$$

Subject to:

$$C_1: Tr(\boldsymbol{W}) + Tr(\boldsymbol{W_E}) + Tr(\boldsymbol{N_A}) \leq P_{max},$$

$$C_2: \frac{Tr(\boldsymbol{HW})}{\sigma_{ant}^2 + Tr(\boldsymbol{HN_A}) + \sigma_s^2} \geq SINR_{req},$$

$$C_3: \frac{Tr(\boldsymbol{G_i W})}{\sigma_{ant}^2 + Tr(\boldsymbol{G_i N_A}) + \sigma_s^2} \leq SINR_{tol}, \forall i \in \{1, \dots, I\},$$

$$C_4: \frac{Tr(\boldsymbol{L_j W})}{\sigma_{ant}^2 + Tr(\boldsymbol{L_j W_E}) + Tr(\boldsymbol{L_j N_A}) + \sigma_s^2} \leq SINR_{tol}, \forall j \in \{1, \dots, J\},$$

$$C_5: \eta[Tr(\boldsymbol{G_i W}) + Tr(\boldsymbol{G_i W_E}) + Tr(\boldsymbol{G_i N_A})] \geq P_{min}, \forall i \in \{1, \dots, I\},$$

$$C_6: \boldsymbol{W} \succeq \boldsymbol{0}, \boldsymbol{W_E} \succeq \boldsymbol{0}, \boldsymbol{N_A} \succeq \boldsymbol{0}\ . \qquad (20)$$

The value of P_{max} in C_1 indicates the maximum radiation power at transmitter which limited by the hardware of circuit. P_{max} is a constant value for the sum of transmit power. The constant $SINR_{req}$ in C_2 is the minimum required SINR for desired receiver to decode the received signal. While $SINR_{tol,i}$ in C_3 and $SINR_{tol}$ in C_4 represent the maximum SINR acceptable between transmitter and i -th idle receivers and j -th eavesdroppers, respectively. In this paper, the idle receivers and eavesdroppers are considered as energy harvester and randomly distributed near transmitter, hence the maximum tolerable SINR for both idle receivers and eavesdroppers are same. The energy harvest receiver used in this paper is separated receiver with dynamic time switching. which means if the receiver is assigned to decode information, all the power of received signal is assigned to information decoding circuit. Similarly, the eavesdroppers are more switch to information decoding circuit to improve the probability of successfully wiretap. The passive eavesdroppers are assumed not be able to decode the energy signal while potential eavesdroppers which are legitimate receivers are able to cancel the interference caused by it. Therefore, the constraints C_3 and C_4 set the upper limitation of achievable SINR for passive eavesdroppers and potential eavesdroppers which exploits the physical layer security using power constraint. The maximum tolerance SINR listed in C_3 and C_4 should be less than the minimum required SINR in C_1 , $SINR_{req} \gg SINR_{tol,i} > 0, \forall i \in \{1, \dots, I\}$ and $SINR_{req} \gg SINR_{tol} >$

$0, \forall j \in \{1, \dots, J\}$, in order to provide security in wireless information transmission. Accordingly, the secrecy rate for desired receiver is bounded by C_1, C_3 and C_4 together with the definition of secrecy rate mentioned in section 3.4, $C_{sec} = log_2(1 + SINR_{req}) - log_2(1 + \max_i\{SINR_{tol}, SINR_{tol,i}\})$. The number of passive eavesdroppers and their location is unknown at transmitter, although the number of overall eaves J is set to be maximum tolerable value which transmitter can ensure the security in signal transmission. Furthermore, maximize the secrecy rate is not the primary task for this paper. The variable η and $P_{min,i}$ in C_5 indicates efficiency of energy harvesting for receiver and the minimum harvested energy for trigger the power harvesting circuit, respectively. C_6 and $\boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A} \in \mathbb{H}^{N_T}$ set the constraint of matrices $\boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A}$ to be positive semi-definite Hermitian matrices.

4 Solution for Optimization Problem

4.1 Transformation of Optimization Function

The maximization objective is in fractional form which may increase the computational complexity in vector calculation. First of all, we define P as a set of possible solutions of the proposed problem in (20) with constraints C_1 to C_6. Then, assume $\{\boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A}\} \in$ P and we denote q^* as the optimum energy transfer efficiency for the designed system and it could be presented as

$$q^* = \max_{\boldsymbol{W},\boldsymbol{W_E},\boldsymbol{N_A}} \frac{\sum_i [Tr(\boldsymbol{G_i W}) + Tr(\boldsymbol{G_i W_E}) + Tr(\boldsymbol{G_i N_A})]}{Tr(\boldsymbol{W}) + Tr(\boldsymbol{W_E}) + Tr(\boldsymbol{N_A})}. \tag{21}$$

For notation simplicity, $\sum_i [Tr(\boldsymbol{G_i W}) + Tr(\boldsymbol{G_i W_E}) + Tr(\boldsymbol{G_i N_A})]$ is defined as total received power for i-th idle receiver $P_{rec}(\boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A})$ and $[Tr(\boldsymbol{W}) + Tr(\boldsymbol{W_E}) + Tr(\boldsymbol{N_A})]$ is defined as total transmit power $P_{tot}(\boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A})$. Now we could give the transformation of objective function into the form in theorem 1. Furthermore, nonlinear fractional programming [68] could be used to solve the proposed optimization problem in (20).

Theorem 1: The energy transfer efficiency can be achieved the maximum value q^* if and only if

$$\max_{\boldsymbol{W},\boldsymbol{W_E},\boldsymbol{N_A}} P_{rec}(\boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A}) - q^* P_{tot}(\boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A})$$

$$= P_{rec}(\boldsymbol{W}^*, \boldsymbol{W}_{\boldsymbol{E}}^*, \boldsymbol{N}_{\boldsymbol{A}}^*) - q^* P_{tot}(\boldsymbol{W}^*, \boldsymbol{W}_{\boldsymbol{E}}^*, \boldsymbol{N}_{\boldsymbol{A}}^*) = 0 \tag{22}$$

for $P_{rec}(\boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A}) > 0$ and $P_{tot}(\boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A}) > 0$.

Proof: The proof of Theorem 1 could use the approach proposed in [69] and [70].

The subtractive form equation (22) in Theorem 1 is equivalent to the fractional form of optimization equation in (20). Which means the optimum resource allocation algorithm for achieving maximum energy transfer efficiency in both equation is the same. In particular, for an optimization problem written in fractional equation, e.g. $\frac{P_{rec}(\boldsymbol{W},\boldsymbol{W_E},\boldsymbol{N_A})}{P_{tot}(\boldsymbol{W},\boldsymbol{W_E},\boldsymbol{N_A})}$, it will have an equivalent solution that could be obtained by the problem formulated in subtractive form, e.g. $P_{rec}(\boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A}) - q^* P_{tot}(\boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A})$ for same

$$\max_{\boldsymbol{W},\boldsymbol{W_E},\boldsymbol{N_A}} P_{rec}(\boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A}) - q P_{tot}(\boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A})$$

$$\text{Subject to: } C_1 - C_8. \tag{23}$$

resource allocation algorithm. Thus, the proposed optimization formulation can be presented as the following form:

Hence, the proposed problem is still find optimal resource allocation for achieving maximum energy transfer efficiency but transferred into another form.

4.2 Semidefinite Programming Relaxation

The optimization problem formulated in (23) contains non-convex constraintC_2, thus it could be sorted as a non-convex quadratically constrained quadratic program (QCQP), cf. [71] – [72]. In particular, the non-convexity of the proposed problem is mainly caused by constraint C_2 on the beamforming vector $\mathbf{w}$ for information carrying signal. However, there is no general standard method to solve an optimization problem in non-convex form since the set of feasible solution is continuous which means it contains infinitely solutions. It is impossible to run all possible solutions in extreme case for achieving optimal resource allocation algorithm. In order to obtain the optimum solution more efficiently, we first eliminate non-convexity of the problem related to constraint C_2 by transform the optimization problem formulation in (23) into semi-definite programming (SDP) problem. Then, the method of semi-definite programming relaxation (SDR) [73], [74] could be used to derive the optimum resource allocation policy and maximum energy harvesting efficiency for the transformed problem.

We define $\boldsymbol{W} = \boldsymbol{w}\boldsymbol{w}^{\boldsymbol{H}}$ to facilitate SDP relaxation, and problem (23) is represented as

$$\boxed{\begin{aligned} &\max_{\boldsymbol{W},\boldsymbol{W_E},\boldsymbol{N_A}} P_{rec}(\boldsymbol{W},\boldsymbol{W_E},\boldsymbol{N_A}) - qP_{tot}(\boldsymbol{W},\boldsymbol{W_E},\boldsymbol{N_A}) \\ &\text{Subject to: } C_1 - C_8. \\ &C_9: Rank(\boldsymbol{W}) = 1. \qquad (24) \end{aligned}}$$

where $\boldsymbol{W} \succeq 0$, $\boldsymbol{W} \in \mathbb{H}^{N_t}$, and Rank($\mathbf{W}$)=1 in problem (24) are applied to guarantee that $\boldsymbol{W} = \boldsymbol{w}\boldsymbol{w}^{\boldsymbol{H}}$. Problem (24) is equivalent to problem (23) which means formula (24) is the necessary and sufficient condition of (23). The optimization problem will become a convex SDP by relaxing the constraintC_9, for instance, remove it from the constraints.

Then the optimal resource allocation algorithm can be derived by numerical solvers, for example SeDuMi [75] - [76].

4.3 Optimality Conditions for SDP Relaxation

The fundamental theory of optimization problem reveals that if the rank of derived solution $\mathbf{W}$ for the SDR problem is 1, then it can also achieve the optimal energy efficiency for the original problem in (24). The proposed problem (24) with SDP relaxation satisfies the sufficient condition of problem (24) without relaxation. Thus we need to prove the tightness of SDP relaxation will not affect convexity of the optimization problem. The tightness of SDP relaxation will be demonstrated by examine the dual problem and Kaursh-Kuhn-Tucker (KKT) conditions for the relaxed problem in (24), cf. [77]. The Lagrange multiplier should be larger than 0 if the constraint inequation is less than 0. Then, we transfer all constraints into form that is convenient to derive Lagrangian function. Indeed, summation of signals is larger than zero in transformation of constraints. In order to transfer the proposed formulation into SDP relaxed form, we first need to derive KKT conditions. It is necessary condition for achieving solution of optimal nonlinear problem and detail of KKT conditions is illustrated in appendix. To obtain the Lagrangian function, we first need to transfer the problem constraints. For example, C_1 could be transferred to $[Tr(\boldsymbol{W}) + Tr(\boldsymbol{W_E}) + Tr(\boldsymbol{N_A}) - P_{max}]$. Hence, he Lagrangian function of (24) is shown as

$$
\begin{aligned}
&\mathcal{L}(\lambda, \alpha, \beta, \gamma, \xi, Y, Z, U, \boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A}) \\
&= \sum_i [Tr(\boldsymbol{G_i W}) + Tr(\boldsymbol{G_i W_E}) + Tr(\boldsymbol{G_i N_A})] - q[Tr(\boldsymbol{W}) + Tr(\boldsymbol{W_E}) + Tr(\boldsymbol{N_A})] \\
&+\lambda[Tr(\boldsymbol{W}) + Tr(\boldsymbol{W_E}) + Tr(\boldsymbol{N_A}) - P_{max}] \\
&+\alpha\left[SINR_{req}(\sigma_{ant}^2 + Tr(\boldsymbol{HN_A}) + \sigma_s^2) - Tr(\boldsymbol{HW})\right] \\
&+\sum_i \beta_i [Tr(\boldsymbol{G_i W}) - SINR_{tol}(\sigma_{ant}^2 + Tr(\boldsymbol{G_i N_A}) + \sigma_s^2)] \\
&+\sum_j \gamma_j [Tr\left(\boldsymbol{L_j W}\right) - SINR_{tol}\,(\sigma_{ant}^2 + Tr\left(\boldsymbol{L_j N_A}\right) + Tr(\boldsymbol{L_j W_E}) + \sigma_s^2)] \\
&+\sum_i \xi_i [P_{min} - \eta[Tr(\boldsymbol{G_i W}) + Tr(\boldsymbol{G_i W_E}) + Tr(\boldsymbol{G_i N_A})]] \\
&-Tr(\boldsymbol{YW}) - Tr(\boldsymbol{ZW_E}) - Tr(\boldsymbol{UN_A}) \qquad (25)
\end{aligned}
$$

where $\lambda \geq 0$ is the Lagrange multiplier for the maximum transmit power in C_1. $\alpha \geq 0$ is the Lagrange multiplier for the bottom line of required data rate for desired information receiver in C_2. β is a vector of Lagrange multiplier for highest tolerable SINR between transmitter and idle receivers in C_3 with $\beta_i \geq 0, \forall i \in \{1, \dots, I\}$. Similarly, γ represents the Lagrange multiplier vector of maximum tolerable SINR between transmitter and eavesdroppers in C_4 with $\gamma_j \geq 0, \forall j \in \{1, \dots, J\}$. ξ is the vector of Lagrange multiplier for minimum acceptable received power for energy harvesting circuit required in C_5 with $\xi_i \geq 0, \forall i \in \{1, \dots, I\}$. Matrices $\boldsymbol{Y}, \boldsymbol{Z}$ and $\boldsymbol{U} \succeq 0$ are the Lagrange multipliers of the semidefinite constraints for $\boldsymbol{W}, \boldsymbol{W_E}$ and $\boldsymbol{N_A}$ in C_6, respectively.

With Lagrangian function of problem (24), we could further transfer the optimal resource allocation problem into dual problem. Thus, the dual problem of the proposed problem is represented as

$$\boxed{\begin{aligned} & \min_{\boldsymbol{W},\boldsymbol{W_E},\boldsymbol{N_A}} \max_{\lambda,\alpha,\beta_i,\gamma_j,\xi_i} \mathcal{L}(\lambda, \alpha, \beta, \gamma, \xi, Y, Z, U, \boldsymbol{W}, \boldsymbol{W_E}, \boldsymbol{N_A}) \\ & \text{Subject to: } C_9\text{: } \frac{\partial L}{\partial \boldsymbol{W}} = \sum_i (1 + \beta_i - \eta\xi_i)\boldsymbol{G}_i + \sum_j \gamma_j \boldsymbol{L}_j + (\lambda - q)\boldsymbol{I} - \alpha\boldsymbol{H} - \boldsymbol{Y} = 0 \\ & \qquad C_{10}\text{: } \boldsymbol{YW} = 0 \qquad (26) \end{aligned}}$$

where C_9 means the first derivation of Lagrangian function about **W** equals to 0 in order to minimize $\mathcal{L}$ close to 0 and to achieves the lower bound. Nevertheless, C_{10} represents that the columns of **W** lies in the null space in Lagrange multiplier matrix **Y**. The dual problem (26) is equivalent to (24) with relaxation of constraint C_8. However, the stringent of relaxation of C_8 needs to be proved.

Proposition 1: Suppose the problem is feasible with $SINR_{req} > 0$ for problem (24) in relaxed version. Then, Rank(W)=1 when $\beta_i \geq \eta\xi_i \geq 0, \forall i \in \{1, \dots, I\}$.

Proof: The proof of proposition 1 is presented in first part of Appendix.

More directly, if the minimum power requirement of energy harvesting circuit in C_5 becomes less rigorous, i.e. $P_{min} \rightarrow 0 \Rightarrow \xi_i \rightarrow 0$, the probability of deriving rank-one matrix solution will be higher. Thus higher chance to achieve the global optimization power allocation algorithm.

5 Results and Analysis

The simulation results of system performance for maximizing energy harvesting efficiency will be discussed in this section. We use matlab with designed parameters to realize the system design with proposed optimal resource allocation for achieving maximum energy harvesting efficiency. Some important simulation parameters are summarized in Table 1:

Carrier Centre Frequency	$f_c = 915\ MHz$
Bandwidth	$B = 200\ kHz$
Transmit Antenna Gain	$G_t = 18\ dBi$
Number of Receive Antenna	$N_R = 2$
Noise Power	$\sigma_{s,T}^2 = 95\ dBm$
Energy Conversion Efficiency	$\eta = 0.5$

Table 1 – Simulation parameters

In this simulation, the desired information receiver is located at 100 meters away from the base station BS. Meanwhile, totally J idle energy receivers and eavesdroppers randomly distributed at a distance of 10 meters from the BS. Each energy harvesters are equipped with 2 receive antennas. The bandwidth of this system is $B = 200\ kHz$ with carrier center frequency assumed as $f_c = 915\ MHz$. The fading between transmitter and energy receivers is assumed to be small scale fading and the coefficients are generated by independently and identically Rician distribution with Rician factor 6 dB. However, the transmission between transmitter and desired information decoder is assumed to follow Rayleigh distribution. The total power of thermal noise and antenna noise is set to $\sigma_{s,T}^2 = 95\ dBm$. Furthermore, the power consumption for single antenna is $P_{ant} = 1\ W$ and minimum required power for energy harvesting circuit is $P_{min} = 1\ \mu W$ with energy conversion efficiency $\eta = 0.5$. The maximum tolerable SINR for idle energy receivers and eavesdroppers is assumed $SINR_{tol} = 0\ dB$ unless specified. Both pathloss fading and multipath fading are averaged in order to obtain the average total harvested power of energy receivers, and total transmit power.

Figure 4 depicts the average energy transfer efficiency versus total transmit power P_{max} for base station equipped with different amout of transmit antennas. Y-axis is the percentage of average efficiency which obtained by total harvested energy over total transmit power. It can be observed from the figure that the averaged energy transfer efficiency is monotonically increased with the increment of total transmit power. Moreover, the total transmit power consists of power of information signal, energy signal and artificial noise that can be seen in constraint C_1 in (20). Therefore, the power dissipated to energy signal and artificial noise will increase if system meets the minimum SINR requirement in C_2. It is clear in Figure 4 that the average efficiency is close to zero and barely change for P_{max} from 3 to 25 dBm. This is because most power is allocated to information signal to meet SINR requirement since the information decoder is 100 meters away from base station while the distance for energy receivers is only 10 meters. Thus only small amount of RF power is radiated to energy receivers. Although, the optimal power allocation scheme is being used, it achieves really low energy transfer efficiency. To operate this designed system in feasible manner, the total transmit power needs to be set larger than 30 dBm.

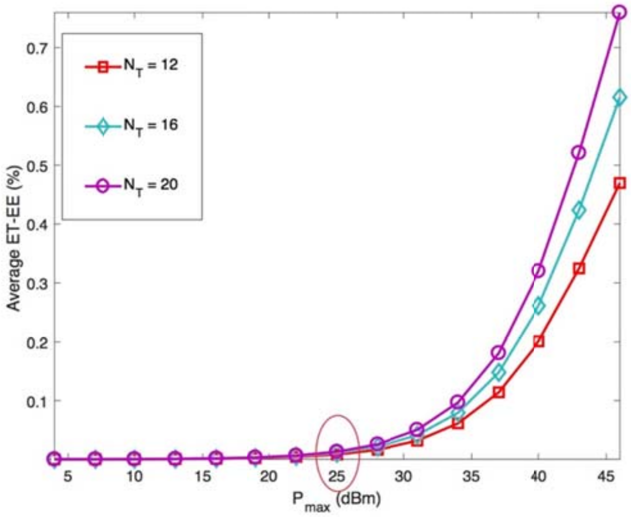

Figure 4 – Average energy transfer efficiency (%) versus total transmit power P_{max} (dBm) with different number of transmit antennas

In spite of that, average efficiency increases dramatically when P_{max} larger than 30 dBm. The reason is that when system meets the minimum SINR requirement, rest of transmit power could allocate to other RF signal which means energy receivers could harvest more power from environment. The increment of power of energy signal and artificial noise also helps to satisfy constraints C_3, C_4 and C_5 and to achieve higher energy transfer efficiency with optimal resource allocation scheme. Moreover, we could see an increasing performance gain for more transmit antennas with same total transmit power. More transmit antennas could provide more flexible resource allocation algorithm and generate more accurate beamforming vector which requires less power for information signal to combat fading in transmission channel.

The relationship between average energy transfer efficiency and minimum required SINR for desired information decoder $SINR_{req}$ for different number of transmit antennas is shown in Figure 5. As it could be observed from the figure, the efficiency decrease monotonically with increment of minimum required SINR between transmitter and desired information receiver. The higher the minimum requirement of SINR for desired receiver, it requires more accurate beamforming vector and more power allocated to information signal. Because system needs more power to ensure that received signal at information decoder is strong enough to combat fading and recover the transmitted signal with acceptable error. In fact, direction of beamformed information stream needs to managed towards the desired information receiver in order to satisfy larger value of required SINR which means more stringent decoding requirement. On the other hand, transmitter needs to allocate more power at information vector to meet SINR requirement and total transmit power is fixed. Thus, less RF power is radiated to energy receivers and a decrease in energy transfer efficiency.

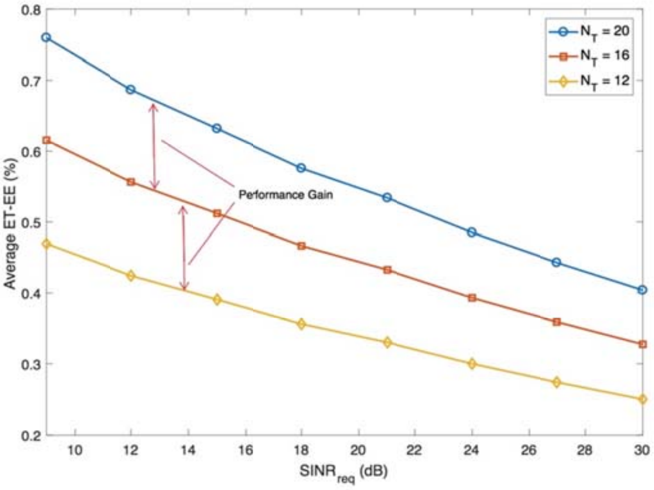

Figure 5 – Average energy transfer efficiency (%) versus minimum $SINR_{req}$ of the desired information receiver $SINR_{req}$ (dB) for different number of transmit antenna

Despite of that, the base station can provide resource allocation algorithm with more flexibility if extra transmit antennas are equipped at base station, since more transmit antennas could further provide spatial degrees of freedom. Particularly, base station could manage the beamforming vector to focus the stream of artificial noise and energy signal to energy receivers more accurately which improves efficiency. Therefore, there is a remarkable performance gain of average energy harvesting efficiency that can be achieved with more transmit antennas equipped at BS. However, greater number of transmit antennas means more cost when building such system in practice. Thus, trade-off between total cost and system performance needs to take into consideration.

6 Conclusion

In this paper, we presented a beamforming power allocation design that maximize efficiency of energy transfer for secure multiuser MIMO SWIPT communication system. The design of this optimal algorithm is based on traditional linear energy harvesting model and proposed a non-convexity optimal problem formulation for maximizing total harvested power of energy receivers while maintain an acceptable level of total transmit power. In particular, physical layer security with signal design is considered to build secure wireless transmission environment. The energy signal and artificial noise are injected into transmit signal to ensure security of communication. A series of transformation of proposed formulation was taken for SDP relaxation and convert the problem into convex form. Then, the numerical simulation results of problem in relaxed version showed the relationship between average energy transfer efficiency with total transmit power and minimum required SINR for information decoder respectively. It shows the growing trend of average efficiency with increment of total transmit power and inverse trend for increasing $SINR_{req}$. The results also reveal the duality of energy signal and artificial noise which can achieve secure communication and enlarge energy harvesting simultaneously.

Research for SWIPT based energy harvesting system needs to build a more precisely system model for better realizing realistic scenario. Hence, non-linear energy harvesting model should be considered for future work. Furthermore, we could propose some suboptimal method to solve the proposed problem since the process of achieving optimal solution is complex. In particular, the tradeoff between computational complexity and system performance should be discussed.

7 References

[1] Internet of Things (IoT) connected devices installed base worldwide from 2015 to 2025 (in billions). (2017). Retrieved from [https://www.statista.com/statistics/471264/iot- number-of-connected-devices-worldwide/](https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/)

[2] K. Pentikousis, "In search of energy-efficient mobile networking," IEEE Commun. Mag., vol. 48, Jan. 2010, pp. 95-103.

[3] D. W. K. Ng, L. Xiang, and R. Schober, "Multi-objective beamforming for secure communication in systems with wireless information and power transfer," in Proc. IEEE Int. Pers., Indoor Mobile Radio Commun. Symp., Sep 2013, pp. 7-12.

[4] T. Chen, Y. Yang, H. Zhang, H. Kim, and K. Horneman, "Network energy saving technologies for green wireless access networks," IEEE Wireless Commun., vol. 18, no. 5, pp. 30-38, Oct. 2011.

[5] N. Tesla, "Apparatus for Transmitting Electrical Energy," US patent number 1,119,732, issued in Dec. 1914.

[6] Kaneko, Y. and S. Abe, "Technology trends of wireless power transfer systems for electric vehicle and plug-in hybrid electric vehicle," 2013 IEEE 10th International Conference on Power Electronics and Drive Systems (PEDS), 1009–1014, 2013.

[7] L. R. Varshney, "Transporting Information and Energy Simultaneously," in Proc. IEEE Int. Symp. Inf. Theory, Jul. 2008, pp. 1612-1616.

[8] D. W. K. Ng, E. Lo, and R. Schober, "Energy-efficient Resource Allocation in Multiuser OFDM Systems with Wireless Information and Power Transfer," in Proc. 2013 IEEE Wireless Commun. And Networking Conf.

[9] D. W. K. Ng, E. Lo, and R. Schober, "Energy-efficient Power Allocation in OFDM Systems with Wireless Information and Power Transfer," in Proc. 2013 IEEE Intern. Commun. Conf., 2013.

[10] P. Grover and A. Sahai, "Shannon meets Tesla: Wireless Information and Power Transfer," in Proc. IEEE Int. Symp. Inf. Theory, Jun. 2010, pp. 2363-2367.

[11] X. Zhou, R. Zhang, and C. K. Ho, "Wireless Information and Power Transfer: Architecture Design and Rate-energy Tradeoff," in Proc. IEEE Global Telecommun. Conf., Dec. 2012, pp. 3982-3987.

[12] R. Zhang and C. K. Ho, “MIMO Broadcasting for Simultaneous Wireless Information and Power Transfer,” IEEE Trans. Wireless Commun., vol. 12, no. 5, May 2013, pp. 1989-2001.

[13] 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,” IEEE Commun. Mag., vol. 52, no. 11, pp. 104–110, Nov. 2014.

[14] Z. Ding, C. Zhong, D. W. K. Ng, M. Peng, H. A. Suraweera, R. Schober and H. V. Poor, “Application of smart antenna technologies in simultaneous wireless information and power transfer,” IEEE Commun. Mag., vol. 53, no. 4, pp. 86–93, Apr. 2015.

[15] Z. Xiang and M. Tao, “Robust Beamforming for Wireless Information and Power Transmission,” IEEE Wireless Commun. Lett., vol. 1, no. 4, pp. 372-375, Aug. 2012.

[16] H. Jabbar, Y. Song, and T. Jeong, “RF Energy Harvesting System and Circuits for Charging of mobile Devices,” IEEE Trans. Consum. Electron., vol. 56, no. 1, pp. 247-253, Feb. 2010.

[17] X. Chen, D. W. K. Ng, and H.-H. Chen, “Secrecy Wireless Information and Power Transfer: Challenges and Opportunities,” IEEE Commun, Mag., 2016.

[18] L. Liu, R. Zhang, and K.-C. Chua, “Wireless Information Transfer with Opportunistic Energy Harvesting,” IEEE Trans. Wireless Commun., vol. 3, Jan. 2013, pp. 345-362.

[19] D. W. K. Ng, E. S. Lo, and R. Schober, “Wireless Information and Power Transfer: Energy Efficiency Optimization in OFDMA Systems,” IEEE Trans. Wireless Commun., vol. 23, no. 23, Dec. 2013, pp. 6352-6370.

[20] C. Isheden, Z. Chong, E. Jorswieck, and G. Fettweis, “Framework for link-level energy efficiency optimization with informed transmitter,” IEEE Trans. Wireless Commun., vol. 11, Aug. 2012, pp. 2946-2057.

[21] G. Miao, N. Himayat, and G. Li, “Energy-efficient link adaptation in frequency-selection channels,” IEEE Trans. Commun., vol. 58, Feb. 2010, pp. 545-554.

[22] J. Xu, L. Liu, and R. Zhang, “Multiuser MISO Beamforming for Simultaneous Wireless Information and Power Transfer,” in Proc. IEEE Int. Conf. Acoust., Speech Signal Process., May 2013, pp. 4754-4758.

[23] M. Zhang, Y. Liu, and R. Zhang, “Artificial noise aided secrecy information and power transfer in OFDMA systems,” IEEE Trans. on Wireless Commun., vol. 15, no. 4, pp. 3085–3096, 2016.

[24] G. Zhang, X. Li, M. Cui, G. Li, and L. Yang, “Signal and artificial noise beamforming for secure simultaneous wireless information and power transfer multiple-input multiple-output relaying systems,” IET Commun., vol. 10, no. 7, pp. 796–804, Apr. 2016.

[25] T. A. Le, Q.-T. Vien, H. X. Nguyen, D. W. K. Ng, and R. Schober, "Robust Chance-Constrained Optimization for Power-Efficient and Secure SWIPT Systems," IEEE Trans. Green Commun. and Networking, no. 3, pp. 333-346, Sep. 2017.

[26] R. Liu and W. Trappe, Securing Wireless Communications at the physical Layer. New York, NY, USA: Springer-Verlag, 2009.

[27] M. Bloch and J. Barros, Physical-Layer Security: From Information Theory to Security Engineering, 1st ed. Cambridge, U.K.: Cambridge University, 2011.

[28] S. Goel and R. Negi, “Guaranteeing Secrecy using Artificial Noise,” IEEE Global Telecommun. Conf., Dec. 2012.

[29] D. W. K. Ng and S. Robert, “Resource Allocation for Secure Communication in Systems with Wireless Information and Power Transfer”, IEEE Globecom, 2013.

[30] A. D. Wyner, “The Wiretap Channel,” Bell Sytem Tech. J., vol. 54, 1975, pp. 1355-87.

[31] L. Liu, R. Zhang, and K. C. Chua, “Secrecy Wireless Information and Power Transfer with MISO Beamforming”, IEEE Globecom, 2013.

[32] Y. S. Shiu, H. C. Wu, S. C. H. Huang and H. H. Chen, “Physical Layer Security in Wireless Networks: A Tutorial,” in IEEE Wireless Commun., vol. 18, issue 2, Apr. 2011, pp. 1536-1284.

[33] A. D. Wyner, “The wire-tap Chanel,” Beel Syst. Tech. J., vol. 54, no. 8, pp. 1355-1387, Oct. 1975, Tech Rep.

[34] B. Li, Z. Fei, Z. Chu, Y. Zhang, “Secure Transmission for Heterogeneous Cellular Networks with Wireless Information and Power Transfer,” in IEEE Systems Journal, vol. pp, issue 99, June. 2017, pp. 1-12.

[35] S. Goel and R. Negi, “Guaranteeing Secrecy using Artificial Noise,” IEEE Trans. Wireless Commun., vol. 7, no. 6, pp. 2180-2189, Jun. 2008.

[36] D. W. K. Ng, E. S. Lo, and R. Schober, “Secure resource allocation and Scheduling for OFDMA decode-and-forward relay networks,” IEEE Trans. Wireless Commun., vol. 10, no. 10, pp. 3528-3540, Oct. 2011.

[37] W. –C. Liao, T.-H. Chang, W.-K. Ma, and C.-Y. Chi, “QoS-based transmit beamforming in the presence of eavesdroppers: An optimized artificial-noise-based-aided approach,” IEEE Trans. Signal Process., vol. 59, no. 3, pp. 1202- 1216, Mar. 2011.

[38] Q. Li, W.-K. Ma, and A.-C. So, “Safe Convex Approximation to Outage-Based MISO Secrecy Rate Optimization under Imperfect CSI and with Artificial Noise,” in Proc. ASILOMAR Conf. Comput. Commun. Signals, Syst. Comput., Nov. 2011, pp. 207-211.

[39] H.-M. Wang, C. Wang, D. W. K. Ng, M. H. Lee, and J. Xiao, “Artificial Noise Assisted Secure Transmission for Distributed Antenna Systems," IEEE Trans. Signal Processing, vol. 64, no. 15, pp. 4050-4064, Aug.1, 2016.

[40] X. Chen, D. W. K. Ng, W. Gerstacker, and H.-H. Chen, “A Survey on Multiple Antenna Techniques for Physical Layer Security," IEEE Communications Surveys and Tutorials, vol. 19, no. 2, pp. 1027-1053, Secondquarter 2017.

[41] T. H. Chang, Y. W. P. Hong, and C. Y. Chi, “Training Signal Design for Discriminatory Channel Estimation”, IEEE Globecom, 2009.

[42] D. W. K. Ng, L. Xiang, and R. Schober, “Multi-Objective Beamforming for Secure Communication in Systems with Wireless Information and Power Transfer”, in IEEE Int. Symp, 2013, ISSN. 2166-9570.

[43] D. W. K. Ng and R. Schober, “Robust Beamforming for Secure Communication in systems with Wireless Information and Power Transfer,” IEEE Trans. Wireless Commun., vol. 13, pp. 4599-4615, Aug. 2014.

[44] J. Xu, L. Liu, and R. Zhang, “Multiuser MISO Beamforming for Simultaneous Wireless information and Power Transfer”, in IEEE Trans. on Signal Process., vol. 62, No. 18, Sep. 2014, pp. 4798-4814.

[45] Z. Wang, D. W. K. Ng, V. W.S. Wong, and R. Schober, “Robust Beamforming Design in C-RAN with Sigmoidal Utility and Capacity-Limited Backhaul,” a IEEE Trans. Wireless Commun., vol. 16, no. 9, pp. 5583-5598, Sept. 2017.

[46] C. Wang, H.-M. Wang, D. W. K. Ng, X.-G. Xia, and C. Liu, “Joint Beamforming and Power Allocation for Secrecy in Peer-to-Peer Relay Networks,” accepted for publication, IEEE Trans. Wireless Commun., vol. 14, no. 6, pp. 3280-3293, Jun. 2015.

[47] D. W. K. Ng, S. Leng, and R. Schober, “Multiple-Antenna and Beamforming for SWIPT Systems,” book chapter in Wireless Powered Communication Networks: Architectures, Protocols, and Applications, Eds. E. Hossain, D. Niyato, D. I. Kim, and V. K. Bhargava, Cambridge University Press. ISBN: 9781107135697

[48] C. Guo, Y. Cui, D. W. K. Ng, and Z. Liu, “Power-Efficient Multi-Quality Multicast Beamforming based on SVC and Superposition Coding,” accepted for presentation, IEEE Globecom 2017, Singapore.

[49] E. Boshkovaka, X. Chen, L. Dai, D. W. K. Ng, and R. Schober, “Max-min Fair Beamforming for SWIPT Systems with Non-linear EH Model,” accepted for presentation, IEEE VTC Fall 2017, Toronto, Canada.

[50] Z. Wang, D. W. K. Ng, V. W.S. Wong, and R. Schober, “Transmit Beamforming for QoE Improvement in C-RAN with Mobile Virtual Network Operators,” in Proceedings of the IEEE International Conference on Communications (ICC) 2016, Kuala Lumpur, Malaysia, Jun. 2016.

[51] D. W. K. Ng, R. Schober, and H. Alnuweiri, “Power Efficient MISO Beamforming for Secure Layered Transmission,” in Proceedings of the IEEE Wireless Communications and Networking Conference (WCNC) 2014, Istanbul, Turkey, Apr. 2014.

[52] S. Leng, D. W. K. Ng, N. Zlatanov, and R. Schober, “Multi-Objective Beamforming for Energy-Efficient SWIPT Systems,” in Proceedings of the International Conference on Computing, Networking and Communications, USA, Feb. 2016.

[53] E. Boshkovska, D. W. K. Ng, L. Dai, and R. Schober, “Power-Efficient and Secure WPCNs with Hardware Impairments and Non-Linear EH Circuit," IEEE Trans. Commun., accepted for publication, Dec. 2017.

[54] E. Boshkovska, D. W. K. Ng, N. Zlatanov, and R. Schober, "Robust Resource Allocation for MIMO Wireless Powered Communication Networks Based on a Non-linear EH Model," IEEE Trans. Commun., vol. 65, no. 5, pp. 1984-1999,

May 2017.

[55] S. Gerbracht, C. Scheunert, and E. A. Jorswieck, “Secrecy Outage in MISO Systems with Partial Channel Information,” IEEE Trans. Inf. Forensics Security, vol. 7, no. 2, Apr. 2012, pp. 704-716.

[56] Li, Y.; Cimini, L.J., Jr.; Sollenberger, N.R.; “Robust channel estimation for OFDM systems with rapid dispersive fading channels,” Communications, IEEE Transactions on, vol. 46, issue. 7, Jul 1998

[57] G. Zheng, K. K. Wong, and T. S. Ng, “Robust Linear MIMO in the Downlink: A Worst-case Optimization with ellipsoidal Uncertainty Regions,” EURASIP J. Adv. Signal Process., vol. 2008, no. 1, p. 609 028, Jul. 2008.

[58] C. Shen, T.-H. Chang, K.-Y. Wang, Z. Qiu and C.-Y. Chi, “Distributed Robust Multicell Coordinated Beamforming with Imperfect CSI: An ADMM Approach,” IEEE Trans. Signal Process., vol. 60, no. 6, Jun. 2012, pp. 2988-3003.

[59] A. Hyadi, Z. Rezki, and M. S. Alouini, “An Overview of Physical Layer Security in Wireless Communication Systems with CSIT Uncertainty”, IEEE Trans., Sep. 2016, pp. 2169-3536.

[60] J. Hu, Y. Cai, and W. Yang, “A New Secure Transmission Scheme with Outdated Antenna Selection,” IEEE Trans. Forensics Security, vol. 10, no. 11, pp. 2435-2446.

[61] N. Vucic and H. Boche, “Robust QoS-Constrainted Optimization of Downlink multiuser MISO Systems,” IEEE Trans. Signal Process., vol. 57, Feb. 2009, pp. 714-725.

[62] X. Chen, X. Wang, and X. Chen, “Energy-Efficient Optimization for Wireless information and Power Transfer in Large-Scale MIMO Systems Employing Energy Beamforming,” IEEE Wireless Commun. Lett., vol. 2, Dec. 2013, pp. 1-4.

[63] X. Chen, Z. Zhang. H.-H. Chen, and H. Zhang, “Enhancing Wireless Information and Power Trans by Exploiting Multi-Antenna Techniques,” IEEE Commun. Mag., no. 4, Apr. 2015, pp 133-141.

[64] E. Boshkovska, N. Zlatanov, L. Dai, D. W. K. Ng, R. Schober, “Secure SWIPT Networks Based on a Non-linear Energy Harvesting Model”, *in IEEE WCNC Information Theory*, arXiv:1701.07871, Jan. 2017.

[65] R. Cid-Fuentes, H. Martinez, A. Poveda and E. Alarcon, "Electronically Tunable switch-Mode High-Efficiency Adaptive Band-pass Filters for Energy Harvesting Applications", 2012 IEEE International Symposium on Circuits and Systems, 2012.

[66] Q. Wang, H. Su, K. Ren, and K. Kim, “Fast and Scalable Secret Key Generation Exploiting Channel Phase Randomness in Wireless Networks,” in Proc. IEEE Int. Conf. Comput. Commun., Apr. 2011, pp. 1422-1430.

[67] D. Tse and P. Viswanath, Fundamentals of Wireless Communication, 1st ed. Cambridge, U.K.: Cambridge University, 2005.

[68] W. Dinkelbach, “On nonlinear fractional programming,” Management Science, vol. 13, pp. 492-498, Mar. 1967.

[69] M. Shenouda and T. Davidson, “Outage-based designs for multi-user transceivers,” in Proc. IEEE Int. Conf. Acoust., Speech Signal Process., Apr. 2009, pp. 2389-2392.

[70] K.-Y. Wang, A. M.-C. So, T.-H. Chang, W.-K. Ma, and C.-Y. Chi, Outage Constrained Robust Transmit Optimization for Multiuser MISO Downlinks: Tractable Approximations by Conic Optimization, 2011.

[71] D. W. K. Ng, E. Lo, and R. Schober, “Energy-efficient Resource Allocation in OFDMA Systems with Large Numbers of base station Antennas,” IEEE Trans. Wireless Commun., vol 11, pp. 3292-3304, sep. 2012.

[72] W. Dinkelbach, “On nonlinear fractional programming,” Management Science, vol. 13, pp. 492–498, Mar. 1967.

[73] M. Bengtsson and B. Ottersten, “Optimal Downlink Beamforming Using Semidefinite Optimization,” in Proc. Annu. Allerton Conf. Commun., Control Comput., Sep. 1999, pp. 987-996.

[74] Z.-Q. Luo, W.-K. Ma, A.-C. So, Y. Ye, and S. Zhang, “Semidefinite Relaxation of Quadratic Optimization Problems,” IEEE Signal Process. Mag., vol. 27, no. 3, pp. 20-34, May 2010.

[75] J. F. Strurm, “Using SeDuMi 1.02, A MATLAB Toolbox for Optimization over Symmetric Cones,” Optimiz. Methods and Software, vol. 11-12, pp. 625-653, Sep. 1999.

[76] K. C. Toh, M. J. Todd, and R. H. Tutuncu, “SDPT3 – A matlab Software Package for Semidefinite Programming, version 1.3,” Optim. Methods Softw., vol. 11, no. 1-4, pp. 545-581, Jan. 1999.

[77] S. Boyd and L. Vandenberghe, Convex Optimization. Cambridge University Press, 2004.

8 Appendix

- Proof of *Proposition 1*

In order to proof the tightness of SDP relaxation and Proposition 1, the Lagrangian function is given. The KKT conditions related to optimal solution $\boldsymbol{W}^*$ can be represented as:

$$\boldsymbol{Y}^* \succeq 0. \quad \lambda^*, \alpha^*, {\beta_i}^*, {\gamma_j}^*, {\xi_i}^* \geq 0.$$

$$\nabla_W \mathcal{L} = 0. \quad \boldsymbol{Y}^* \boldsymbol{W}^* = 0.$$

$$\boldsymbol{Y}^* = \boldsymbol{I}_{\boldsymbol{N}_t}(1+\lambda^*) - \boldsymbol{H}\alpha^* + \textstyle\sum_i \boldsymbol{G}_i({\beta_i}^* - \eta {\xi_i}^*) + \sum_j \boldsymbol{L}_j {\gamma_j}^*$$

$$= \boldsymbol{A} - \boldsymbol{H}\alpha^*,$$

$$where\ \boldsymbol{A} = \boldsymbol{I}_{\boldsymbol{N}_t}(1+\lambda^*) + \textstyle\sum_i \boldsymbol{G}_i({\beta_i}^* - \eta {\xi_i}^*) + \sum_j \boldsymbol{L}_j {\gamma_j}^* \tag{27}$$

The complementary slackness condition of SDP relaxation problem in (24) is $\boldsymbol{Y}^* \boldsymbol{W}^* = 0$. If the columns of $\boldsymbol{W}^*$ lies in the null space of $\boldsymbol{Y}^*$, this condition will be satisfied. Therefore, if $Rank(\boldsymbol{Y}^*) = N_t - 1$ and $Rank\ (\boldsymbol{W}^*) \neq 0$, then the optimal solution of beamforming vector $\boldsymbol{W}^*$ must be a rank-one matrix. Moreover, $\beta_i \geq \eta \xi_i \geq 0, \forall i \in \{1, \ldots, I\}$ must hold since $\boldsymbol{Y}^*$ is a positive semi-definite matrix defined in KKT conditions. In order to proof the rank of matrix $\boldsymbol{Y}^*$ is N_t-1, we first need to prove that **A** is a full rank matrix. Suppose that **A** is a rank deficient matrix, i.e., $Rank(\boldsymbol{A}) < N_t$, and there is at least one zero eigenvalue with the associated eigenvector. The eigenvector is denoted as u, where $\boldsymbol{U} = uu^H$. Multiplying **U** to both sides of the first KKT condition, we could get:

$$Tr(\boldsymbol{Y}^*\boldsymbol{U}) = Tr(\boldsymbol{AU}) - \alpha Tr(\boldsymbol{HU})$$

$$= -\alpha Tr(\boldsymbol{HU}) \geq 0, \tag{28}$$

where **U** is generated from the null space of A, thus Tr(**AU**)=0. However, the channel between transmitter and different receivers are statically independent. Thus the probability that $\boldsymbol{H}, \boldsymbol{G}_i, \boldsymbol{L}_j$ share the same null space is zero which means $Tr(\boldsymbol{HU}) > 0$. α is the Lagrange multiplier of C_2 and $\alpha > 0$. $-\alpha Tr(\boldsymbol{HU}) < 0$ contradicts the results obtained in theory and the assumption. Thus, **A** is a positive definite full rank matrix with $Rank(\boldsymbol{A}) = N_t$.

From the KKT conditions, we could get that:

$$Rank(\boldsymbol{Y}^*) + Rank(\boldsymbol{H}\alpha^*) \geq Rank(\boldsymbol{Y}^* + \boldsymbol{H}\alpha^*)$$

$$= Rank(\boldsymbol{A})$$

$$= N_t$$

$$Rank(\boldsymbol{H}\alpha^*) = 1$$

$$\Rightarrow Rank(\boldsymbol{Y}^*) \geq N_t - 1 \tag{29}$$

The optimal beamforming vector $\boldsymbol{W}^* \neq \boldsymbol{0}$ is required to satisfy the minimum SINR requirement in C_2 for information transmission between transmitter and desired receiver. Thus, $Rank(\boldsymbol{Y}^*) = N_t - 1$ and $Rank(\boldsymbol{W}^*) = 1$.