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Efficient Beamforming Design for SWIPT Systems

by

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Abstract

This report firstly presents the demand and development of wireless communication technology. It describes the state-of-the art situation in the Wireless Power Transmission (WPT) and Wireless Information Transfer (WIT) in the field of study. Then, this report analyses the relative content in wireless powered communication (WPC) systems, multiple antennas, and beamforming. These techniques can enhance the efficiency of SWIPT. Finally, this report presents three types of SWIPT systems. In particular, one type of the four systems is carried on specific research. We aim to design a beamforming scheme which maximize the total system harvested power while satisfying the minim requirement of the information receiver signal-to-interference plus noise.

Abbreviations

SWIPT	Simultaneous Wireless Information and Power Transfer
RFID	Radio Frequency Identification
IoT	Internet of Things
RF	Radio Frequency
WIT	Wireless Information Transfer
WPT	Wireless Power Transmission
AWGN	Additive White Gaussian Noise
MIMO	Multiple Input Multiple Output
OFDM	Orthogonal Frequency Division Multiplexing
WPCNs	Wireless Powered Cellular Networks
HAP	Hybrid Access Point
BP	Power Beacons
AP	Access Point

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1. Introduction

With the rapid development of society, multiple platforms integration has gradually become the important trend of technological innovation and industrial progress of flow dynamics. However, energy and the radio spectrum have become a scarce resource. Therefore, it is urgent to integrate communications technology and energy technology on the existing research results. The innovation of technology will not only satisfy people's demand for highly efficient and reliable information interaction, but also the shortage of energy and frequency spectrum can be effectively handled. Simultaneous Wireless Information and Power Transfer, namely SWIPT, is developed under this background of the social demand. It is a promising and emerging direction which combines communication technology and transmission energy technology. The purpose is to achieve the parallel transmission of information and energy. On the basis of the existing wireless power supply technology, through some kind of technical methods, SWIPT needs to complete energy transmission and collection at the same time. This will be an efficient and reliable communication mode. Because it can make full use of the limited transmission power. So it has important practical significance and technical challenges.

2. Background

Based on the characteristics of parallel transmission, SWIPT technology is expected to be widely used in radio frequency identification (RFID), Internet of things (IoT), information exchange and energy transmission between mobile terminals. It is expected that SWIPT can provide high speed information exchange to energy limited communication device. At the same time, it will extract energy from the received signal and transmit power to a variety of feeder terminal equipment. It means that energy limited receivers can harvest the energy from the receiver RF-signal. In this way, this new technology can replace the inconvenience of traditional battery. It can reduce the size and cost of terminal equipment and greatly extend the standby time. It is especially suitable for the large-scale terminal nodes.

Based on the characteristics of far-field information transmission, the SWIPT technology is expected to achieve to supply power and control the equipment in unpleasant work environment. In space, sea, forest, desert, canyon, mine, earthquake and other complex environments, it is difficult to artificially set up power lines and regularly replace batteries. The SWIPT can provide wireless power supply and avoid the unsafe factors by aging line. It means that the SWIPT can remote control device and achieve information interaction. It can greatly improve the equipment ability to adapt to extreme working conditions.

Based on the characteristics of stable and reliable, SWIPT have broad application prospects in biomedical field. With the continuous development of technology, artificial

organs and medical auxiliary electronic equipment becomes the hot spots of research such as pacemakers and cochlear. These devices can reach tens of watts and even just a few million watts. For this type of implantable auxiliary electronic equipment, traditional way will penetrate skin with wires between implants and external power supply, or implanted battery into body. It means that RF-based energy harvesting target only for sensor type applications such as small power consumptions. These actions all can bring great pain and inconvenience to the patient. It is also difficult to solve the problem of the reliability and continuity. These will threat the safety of patients. Using SWIPT technology, not only can achieve non-contact power supply in vitro, but also can achieve data interaction between the body of equipment and terminal in vitro. In this way, SWIPT can complete the control of the electronic devices in the body as well as the medical data acquisition and monitoring. Patients can get rid of the bondage of traditional wires and battery to ensure the safety of life.

Moreover, SWIPT also has a wide application in our daily life such as mobile phone, household appliances and other wireless charging with remote control, etc. It is expected to make all kinds of household appliances and portable devices to achieve the true sense of smart. By getting rid of the traditional wire, monitoring. It makes possible to "smart" home.

3. Literature Review

The following content is a series of literature review which is related to this research. Firstly, I study the development of SWIPT technology. In particular, we provide a brief history on the development of SWIPT technology. Then we will discuss various types to techniques which can be adopted to improve the efficiency of SWIPT.

3.1 The Development of SWIPT Technology

Since 1831 Faraday discovered electromagnetic induction phenomenon, physical wire is the main carrier of electricity transmission, but the traditional methods cannot meet the requirements of modern need. People ask for convenience and safety. Besides, with the improvement of environmental protection consciousness, the battery caused serious damage in the water and soil. These problems all contributes to the exploration and thinking of new method.

In early 1900s, Nikola Tesla first came up with the idea of wireless transmitting energy. He tried to use the earth itself and the atmosphere layer as conductor to achieve wireless transmission. But it is limited by technical conditions at that time. The experiment had failed to achieve the goal [1]. In the late 1950s, Goubau and Schweing theoretically calculate the free space beam guided wave transmission efficiency can reach almost 100%, and verified it on the reflected beam guided wave system [2]. Followed by these, Raytheon company, William c. Brown [3] and others as leaders,

began to research this technology. And in 1964, they finished driving helicopters experiment with 2.45 GHz microwave. In 1968, Peter Glaser imagined the construction of solar power stations in satellite; therefore, solve the energy crisis [4]. In the late 1980s, the Canadian communication research center established service platform for radio, television, communications and other application, and used wireless method supply energy to the platform [1]. Until the 1990s, the wireless transmitting energy technology received widespread attention in close distance application, small and medium-sized power.

In May 2001, the international conference about wireless power transmission technology had meeting in Reunion Island. France scientists G. Pignolet used microwave wireless transmission power to light a 200W bulb beyond 40m away. In 2003, the island set up a 10 kW experimental microwave transmission device, and transmitted point-to-point wireless-power to the bottom of the Grand Canyon villages with a 2.45 GHz frequency [5]. In November 2006, in the United States at the Massachusetts Institute of Technology (MIT), Marin Soljacic and his team used "magnetic resonance principle" successfully achieved the wireless energy transmission between two coils, which the spacing distance was 2.13m. They also lighted a 60W bulb, which 1 million times efficient than ordinary non-resonant induction [6].

It is clear to see that WIT certainly becomes popular in the future. The study of WPT also will have a great breakthrough. However, people are not satisfying with simply transmitting information by radio waves. People not only require transmitting information, but also hope making the full use of the precious power to transmit energy.

In this kind of demand, it is particularly important to research the information and energy transmission SWIPT system architecture, information modulation mode, energy relay way and small power efficient rectifying antenna, etc.

Vanershy first puts forward and analyses the problem of information transmission and power transmission at the one time [7]. He defines the capacity energy function and give the trade-off between channel capacity and power transfer efficiency, which aims for binary discrete channel and limited range of additive AWGN channel. Pulkit Grover and Anant Sahai gives the near-field energy transmission circuit which based on coupling inductance model. They also analysed the wireless transmission problem between information and energy, which based on noise coupling inductance in the circuit [8]. Liang Liu, Rui Zhang and Kee - Chaing Chua considered the influence under a time varying narrowband flat fading channel. They researched the point to point wireless links problem in narrowband flat fading channel [9]. Omur Ozel and Jing Yang studied one energy collection transmitter which can optimize the point to point data transmission in fading channel [10]. Xun Zhou, Rui Zhang and Chin Keong Ho solved the problem that hardware cannot simultaneously doing information demodulation and energy collection. They put forward concept of Dynamic Power Splitting [11].The above content provides different point-to-point single antenna transmission system [7-11]. The below content are considered in the literature [12-14], which mainly focus on the same time information and energy transmission problems in MIMO system.

Rui Zhang and Chin Keong Ho [12] considers the SWIPT problem in a 3-node MIMO wireless radio system. The MIMO wireless broadcasting system is fixed by the

AP and distributed user terminal. They separately design the information transmission rate and power transfer efficiency for a single user and multi-user. Finally, they design the optimal transmission strategy and derive the rate-energy region. Batu K. Chalise [13] used more energy receiver antenna to enlarge the performance of the relay system. In this system, the source and relay nodes both are Orthogonal Space-Time Block Code (OSTBC). The optimal joint design obtained a trade-off between transmission rate and energy, which source relayed under different conditions. Ali Mohammad Fouladgar and Osvaldo Someone considers SWIPT in multiuser system [14]. They point out the best way of time division multiplexing.

In addition, [15] studied SWIPT resource allocation algorithms in multiuser OFDMA system. Convex optimization problem is solved by the combination of the non-linear fractional programming and Lagrangian dual decomposition. They designed a new iterative algorithm to obtain the maximum energy efficiency system. That design reveals the potential benefits of system capacity in the multi-user. [16] studied hybrid network. In the uplink of cellular network, we can charge mobile device through random setting energy beacon.

3.2 WPCN System

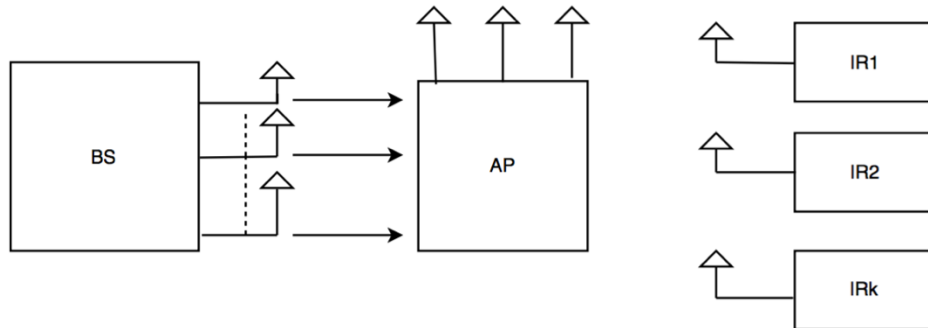


Figure.1 WPCNs system.

Energy collection of wireless cellular network has become an emerging industry. It is by cutting the last wires to implement the 5G cellular networks [17-28]. Mobile devices can connect and get energy anytime and anywhere. It has great attraction to the customer, which is why the wireless energy of cellular network caused the development of new industry.

Recent research main considers harvesting-energy from the ambient energy, such as kinetic energy ,solar energy, wind energy, heat, etc. Therefore, the choice of energy source mainly depends on the efficiency in different time, location and weather. Nevertheless, this is the key point to ensure that users can receive sufficient energy at any time. On the premise of this, researchers are studying a hybrid access point (HAP) in wireless powered cellular networks (WPCNs). It can guarantee the information and energy transmission at user mobile device. Consequently, new challenges and experiments of WPCNs has become a global topic. The relative research areas include prototyping receiver architectures [29, 30], which optimizie time allocation for wireless

energy and information transfer and consider single antenna or multi antenna HAPs [31, 32], wireless energy transfer in heterogeneous small-cell networks [22], relay assisted cooperative protocol designs [33, 34], etc. In addition, some other professional technology are also under study, such as mobile charging vehicles [35] and dedicated power beacons (PBs) [36].

A graphical illustration of the emerging WPCNs is shown in Fig. 1. The base station (BS) transmit the energy and information to access point (AP). The AP processes energy and information. And then it efficiently transmits to the mobile device.

3.3 Multi-Antenna Techniques and Beamforming for SWIPT systems

Wireless energy transmission has become a hotspot in the field of wireless research. It can use the simple way to effectively extend the lifetime of energy-limited network. Especially in extreme circumstances, wireless energy transmission has a lots of advantages [37-45]. And it can reduce the requirement for power cords and chargers. Radio frequency signals are adequate resources for energy harvesting [46-50]. In recent, energy harvesting can achieve microwatts to million-watts of power over a range of several meters for a transmit power of 1 W and a carrier frequency of less than 1 GHz [51]. The radio frequency (RF) signal has attracted considerable attention for wireless power transfer. The supporter presents two reasons [52][53]. First of all, this is a controllable method. Because its flexibility can increase transmission energy to

improve the quality of the receiver. In addition, information and energy can simultaneously transmit through the RF signal. Therefore, this technology does not require an external power for communication.

Compared with the traditional wireless communication, the SWIPT has the similarities and differences. The similarities are that both system suffer from path loss and channel fading, which result in performance loss. Especially in relatively short distance, EH is more sensitive than information decoding [54]. As above reasons, it is necessary to solve the fading effects. And it will also enhance the efficiency and increase the distance of energy transmission. Compared with traditional wireless information transfer, the multiple antenna technique is an effective method to improve the performance in fading channels.

Multiple antenna techniques can used with the transmit signal to channel states through spatial beamforming. In this way, channel fading can be reduced and the performance can be improved. It is similar that multiple antenna technique can be combined with radio frequency signal in power receiver. Thus, the energy transfer efficiency is improved. Therefore, it is reasonable to make full use of multiple antenna technique for improving the WIPT performance. Besides, wireless information and power transfer (WIPT) has two important performance indicators. The first one is spectral efficiency for information transmission. Another one is energy efficiency for energy transfer. But these two indicators are contradictory. Because information and energy all ask for the same radio frequency signal and energy resources. However, it is fortunate that multiple antenna techniques can get an optimal trade-off between energy

efficiencies and spectral, when the spatial beams for information and energy transmission is appropriate [55]. Besides, it is important that multi antenna techniques could simultaneously support information and power transfer because of its multiple streams. Thus, the performance is greatly improved.

In specific, the transmitter needs full or partial channel state information (CSI). The information and power both are transferred adaptively to the channel conditions, which is based on the CSI. It means that a transmitter chooses the optimal transmit index such as transmit beam and transmit power. Besides, accessing users can maximize the efficiencies over fading channels. As the [56] assumption shows, full CSI is available at the transmitter when a good multiple user WIPT system is designed appropriately. Nevertheless, it is important to obtain instantaneous CSI at the transmitter. Because the channel is a multi-dimensional time varying random matrix. In general, there are two CSI acquisition methods in multiple antenna systems because of different duplex modes [57].

Compared with the CSI in FDD systems, CSI in TDD systems may reduce the use of resources, but it will result in performance loss. Because transceiver hardware is impaired. To handle this, robust beam-forming for WIPT was proposed in [58]. It will ensure high efficiencies even with imperfect CSI. Not only these, CSI could also be implemented to build transmit beams. Nevertheless, the beamforming, which is established on estimated CSI, will experience a significant performance degradation. Therefore, adaptive multiple antenna transfers techniques, which use CSI feedback, are effective ways to improve the performance for WIPT over fading channels.

To be specific, multiple antenna should be carefully designed for SWIPT system. Because there are a lots of new challenges and Quality of Service requirements on efficient WPT. The basic trade-off should be respectively considered in frequency selective fading and flat fading for SWIPT system. Moreover, EH and information decoding should be simultaneously performed on the same received signal. As for solutions, there are three types of receivers. They are power-splitting, separated and time-switching [59, 60]. To be specific, the power splitting receiver separates the received power into two power streams, which both two streams have a certain power splitting ratio to facilitate simultaneous energy-harvesting and information decoding in the same receiver [61–68]. Rate energy tradeoff regions is respectively studied in two receiver and point-to-point systems [59,60]. Furthermore, [61] investigated the power allocation algorithm design in ergodic fading channels, which is used for a point-to-point single user SWIPT system with a power splitting receiver. [62] considered the power consumption in electronic circuitries and radio frequency transmission and proposed different power allocation algorithms. These demonstrated that power splitting receivers can enhance the energy efficiency of a communication system. Moreover, the characteristic of broadcast channels and the high signal power is relative with SWIPT system. Therefore, communication security of SWIPT raises concerns. According to these problems, beamforming design for multi-antenna SWIPT system is related with physical layer security which was investigated in [24,28-30]. Using multi-objective framework [17] to deal with the conflict of system design goal which is provided for communications security. At the same time, it can guarantee the QoS in

energy-harvesting receiver. Beamforming design was studied in maximizing the secrecy rate [30]. [25,28-30] used artificial noise generation and multiple antennas for confirming the secure SWIPT. To be specific, the artificial noise is regarded as interference. It not only can degrade the channel quality of potential eavesdroppers, but also can serve as an energy source for expediting energy harvesting at the receivers.

4. System Model

There are three types of SWIPT. Diagrams are shown in Figure.2-4. These three types all can achieve the goal of SWIPT. The first type in Figure.2 shows that BS can transmit both energy and information to different receivers. When anyone of IR1-IRk has the request of information transmission. The BS will only transmit the information to the request receiver rather than transmitting energy to ER1-ERk. As long as there is no request on IR1- IRk, ER1-ERk will be charged energy in design. This paper will mainly discuss this type of SWIPT in the following parts. The second type is shown in Figure.3. The BS station can simultaneously transmit the information and energy to the same receiver. The receiver will transmit the received information and energy to different internal terminals, namely information decoding (ID) and energy harvesting (EH). The information decoding (ID) terminal has the direct proportion of δ chance to select information from receiver. The energy harvesting (EH) terminal has the direct proportion of $1 - \delta$ chance to select energy from receiver. In this way, the type 2 achieve the objective of SWIPT. The last type of SWIPT is time-switching which is shown in Figure.4. The information receive and energy receive will be switched in time. Each time block can be set as required. Therefore, the third type also can achieve the SWIPT goal. All these types of SWIPT can achieve the purpose, but there all have the disadvantages. For example, the BS multi-antennas have the frequency interference between each other. And the interference still exists in the internal receivers. These problems all will be solved in future study.

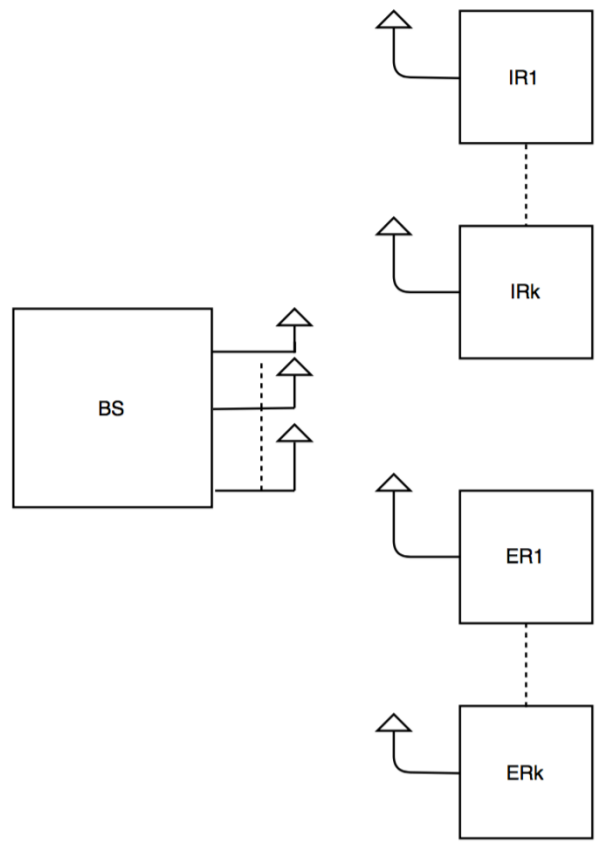


Figure.2 Type 1 of SWIPT

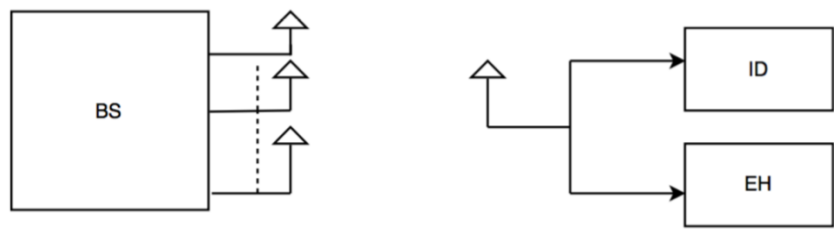


figure.3 Type 2 of SWIPT.

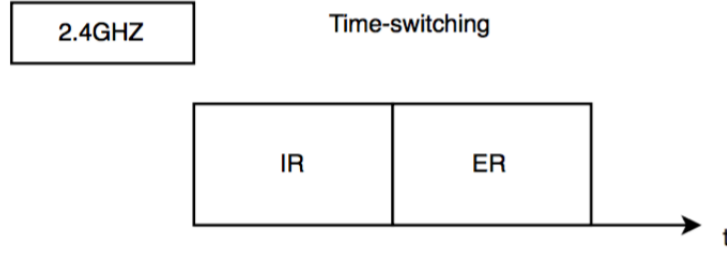


Figure.4 Type 3 of SWIPT.

As this paper mainly focus on figure.2 type 1 of SWIPT, there are a series of basic formulations for this system model. The equations (4.1-3) show the basic system signal. The received signal at ER_j is shown in equation (4.4-5). Furthermore, the harvest power at ER_j is shown in equations (4.6-7). Total Power T_x efficiency is shown in equation (4.8). Total transmit power is shown in (4.9).

$$y_{IR_k} = \vec{h}_k^H \vec{x} + n_k \quad (4-1)$$

$$h_k = \mathbb{C}^{N_i \times 1} \quad (4-2)$$

$$\vec{x} = \sum_{k=1}^K \vec{\omega}_k s_k \quad (4-3)$$

s_k means the information bear of IR_k

$\vec{\omega}_k$ means the beamforming vector of IR_k

Received signal at ER_j :

$$y_{ER_j} = \vec{g}_j^H \vec{x} + n_j, \forall j \in \{1, \dots, j\} \quad (4-4)$$

Harvest Power at ER_j :

$$P_{ER_j} = \eta_j \mathcal{E}\{\sum_{k=1}^K |g_j^H \vec{\omega}_k|^2\} = \eta_j \sum_{k=1}^K g_j^H \vec{\omega}_k \vec{\omega}_k^H g_j \quad (4-6)$$

$$0 \leq \eta_j \leq 1 \quad (4-7)$$

Total Power T_x Efficiency:

$$\frac{p_{EH}^{\text{Total}}}{p_{\text{total}}^{\text{Tx}}} = \mu_{\text{Eff}} \quad (4-8)$$

Total transmit power:

$$P_{\text{total}}^{\text{Tx}} = \sum_{k=1}^k \overline{\omega_k^H \omega_k} \quad (4-9)$$

5. Problem Formulation

To achieve maximize the efficiency of SWIPT, we need to lower down the SINR and maximize the received power. The equation (5-1) shows the the received SINR at IR_k .

The received SINR at IR_k :

$$SINR_k = \frac{|\bar{h}_k^H \bar{\omega}_k|}{\sum_{i \neq k} |\bar{h}_k^H \bar{\omega}_i| + \sigma_k^2} \quad (5-1)$$

From the equation (5-1), we need to maximize $\bar{\omega}_k$ and achieve the μ_{Eff} . As for solving these problem, we need to achieve the subject C1 and C2. Therefore, we can acquire the lower SINR and maximize the efficiency of SWIPT.

As shown in equation format, there are the subject to:

$$C1: SINR_k \geq reg_k, \quad \forall k \in \{1, \dots, k\} \quad (5-2)$$

The above reg_k is constant.

$$C2: \sum_{k=1}^k \|\bar{\omega}_k^H\|^2 \leq P_{max} \quad (5-$$

3)

From the above content (5.2-5.3), it can be specific to the following question:

Non-convex optimization problem

Objective function

C1 \Leftrightarrow Non-convex

Maximize $\max_{\vec{\omega}} \sum_j^J P_{ER_j}$

St. C1: $\text{SINR}_k \geq \text{reg}_k$

C2: $\sum_{k=1}^k \|\vec{\omega}_k^H\|^2 \leq P_{\max}$

6. Problem Solution

The considered problem is a non-convex optimization problem. Before we tackle the problem, we first provide a brief instruction of local optimum and global optimum in non-convex optimization problem. However, we should firstly know some useful mathematics theories to tackle the problem.

6.1 Mathematics Theories

A local optimum is a selection from a given domain which provides either the highest value or lowest value of a function specific function within a neighboring set of solutions, as shown in Figure.5.

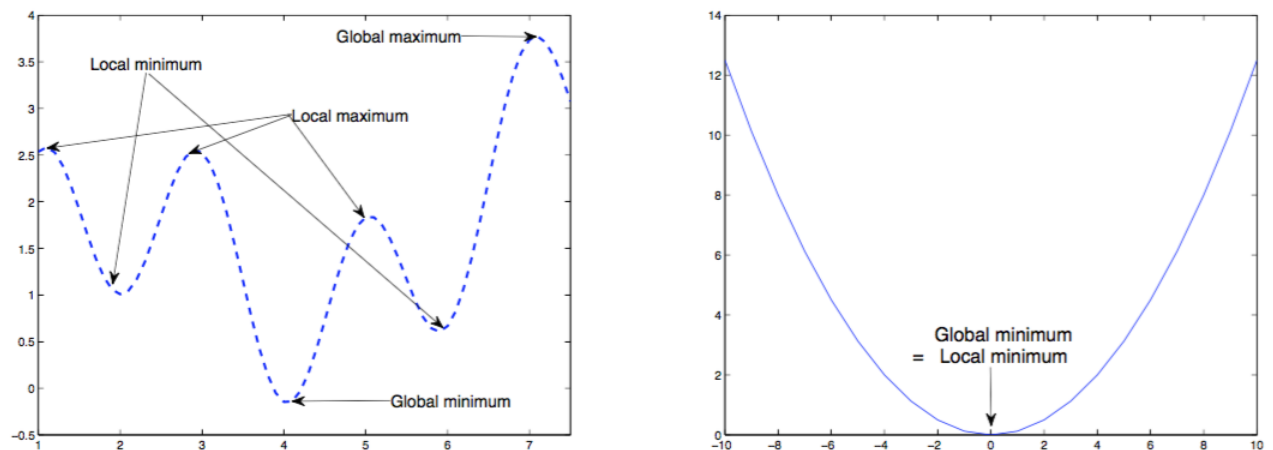


Figure.5 Local Optimal versus Global Optimal

The approach used above is to find an optimal solution by determining the objective contour having the smallest objective value that intersects the feasible region. As shown in figure.6.

Only suitable for small problems and is not practical for problems having more than two variables.

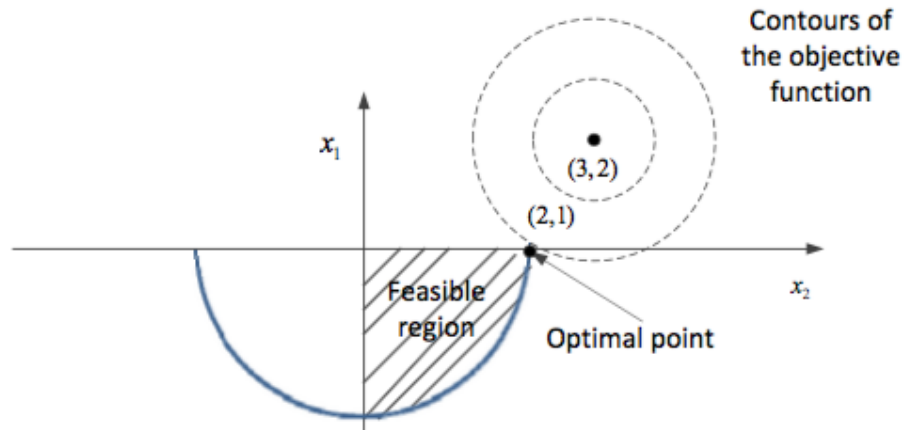


figure.6 Convex Optimization Problem

Besides the above, it is also necessary to know the mathematics theory of KKT conditions. It will also be used in the problem solution.

Now we define the P^* as equation (6-16).

$$P^* = \min_x f_0(x) \quad (6-1)$$

As shown in equation format, there are some new subject to:

$$f_i(x) \leq 0, \forall i \in \{1, \dots, L\} \quad (6-$$

2)

$$h_j(x) = 0, \forall j \in \{1, \dots, J\} \quad (6-$$

3)

$$L = f_0(x) + \sum_{i=1}^L \lambda_i f_i(x) + \sum_{j=1}^J h_j(x) \beta_j \quad (6-4)$$

As we want to solve the problem, we need use some knowledge in Dual Function, Weak Duality and Karush–Kuhn–Tucker (KKT) conditions. Now we show them as follow:

From Dual Function, now we can define the $\inf_{x \in \mathcal{D}} L$ into d^* . And we can get the dual problem in equation (6-5).

$$d^* = \max_{\lambda_i, \beta_j \geq 0} \inf_{x \in \mathcal{D}} L \quad (6-5)$$

From the theory of Weak Duality, we can solve the dual problem.

If (x_1, x_2, \dots, x_n)

is a feasible solution for the primal minimization linear program and (y_1, y_2, \dots, y_m)

is a feasible solution for the dual maximization linear program, then the weak duality

theorem can be stated as $\sum_{i=1}^m b_i y_i \leq \sum_{j=1}^n c_j x_j$, where c_j and b_i are the coefficients of the respective objective functions. Now we can know the equation (6-6).

$$d^* \leq P^* \quad (6-$$

6)

If the convexity problem is strong duality, we can obtain the equation (6-7).

$$d^* = P^*$$

(6-7)

As for KKT conditions, we first need know its necessary conditions. Suppose that the objective function $f: \mathbb{R}^n \rightarrow \mathbb{R}$ and the constraint functions $g_i: \mathbb{R}^n \rightarrow \mathbb{R}$ and $h_j: \mathbb{R}^n \rightarrow \mathbb{R}$ are continuously differentiable at a point x^* . If x^* is a local optimum and the optimization problem satisfies some regularity conditions (see below), then there exist constants $\mu_i (i = 1, \dots, m)$ and $\lambda_j (j = 1, \dots, \ell)$, called KKT. The following parts are necessary four conditions:

Stationarity

For maximizing $f(x)$:

$$\nabla f(x^*) = \sum_{i=1}^m \mu_i \nabla g_i(x^*) + \sum_{j=1}^{\ell} \lambda_j \nabla h_j(x^*) \quad (6-8)$$

For minimizing $f(x)$:

$$-\nabla f(x^*) = \sum_{i=1}^m \mu_i \nabla g_i(x^*) + \sum_{j=1}^{\ell} \lambda_j \nabla h_j(x^*) \quad (6-9)$$

(2) Primal feasibility

$$g_i(x^*) \leq 0, \text{ for } i = 1, \dots, m. \quad (6-10)$$

$$h_j(x^*) = 0, \text{ for } j = 1, \dots, \ell. \quad (6-11)$$

(3) Dual feasibility

$$\mu_i \geq 0, \text{ for } i = 1, \dots, m. \quad (6-12)$$

(4) Complementary slackness

$$\mu_i g_i(x^*) = 0, \text{ for } i = 1, \dots, m. \quad (6-13)$$

In the particular case $m = 0$, i.e., when there are no inequality constraints, the KKT conditions turn into the Lagrange conditions, and the KKT multipliers are called Lagrange multipliers. If some of the functions are non-differentiable, sub differential versions of Karush–Kuhn–Tucker (KKT) conditions are available.

6.2 Mathematical Proof

To achieve maximize the efficiency of SWIPT, we need to lower down the SINR and maximize the received power. The equation (6-14) shows the the received power at energy receiver.

The received power at ER_j :

$$\max_{\vec{\omega}} \sum_j P_{ER_j} \quad (6-14)$$

As shown in equation format, there are the subject to:

$$C1: \text{SINR}_k = \frac{|\vec{h}_k^H \vec{\omega}_k|^2}{\sum_{i \neq k} |\vec{h}_k^H \vec{\omega}_i| + \sigma_k^2} \geq \text{reg}_k, \quad (6-15)$$

$$C2: \sum_{k=1}^k \|\vec{\omega}_k^H\|^2 \leq P_{\max} \quad (6-16)$$

From the above content (6.41-6.16), it can be specific to the following objective function. As we know this formulation is non-convex:

$$\sum_j \sum_{k=1}^k |g_j^H \vec{\omega}_k|^2 \quad (6-$$

17)

As shown in equation format, there are the subject to:

$$C1: |\vec{h}_k \vec{\omega}_k|^2 \geq \text{reg}_k (\sum_{i \neq k} |\vec{h}_k^H \vec{\omega}_i| + \sigma_k^2), \quad \forall k \quad (6-$$

18)

From the C1 formulation, $\sum_{i \neq k} |\vec{h}_k^H \vec{\omega}_i| + \sigma_k^2$ and $|\vec{h}_k \vec{\omega}_k|$ both are convex parts.

$$C2: \sum_{k=1}^k \|\vec{\omega}_k^H\|^2 \leq P_{\max} \quad (6-19)$$

From the theory of Semidefinite Relaxation, we can transform those above problems into the following part. The objective function is shown as equation (6.20-6.21).

$$\sum_j \sum_k g_j^H \omega_k \omega_k^H g_j = \sum_j \sum_k \text{Tr}(g_j^H \omega_k \omega_k^H g_j) \quad (6-$$

20)

$$\sum_j \sum_k \text{Tr}(g_j^H \omega_k \omega_k^H g_j) = \sum_j \sum_k \text{Tr}(\vec{\omega}_k \vec{\omega}_k^H g_j g_j^H)$$

(6-21)

Now we define the ω_k in equation (6-22):

$$\omega_k = \vec{\omega}_k \vec{\omega}_k^H \quad (6-22)$$

From the equation (6.14-6.22), we can transform those into the equivalent problem.

It can be shown in following parts. Now we transform the objective problem into the equation (6-23).

$$\max_{\omega_k} \sum_j \sum_k \text{Tr}(\omega_k g_j g_j^H) \quad (6-$$

23)

As shown in equation format, there are the subject to:

$$C1: \text{Tr}(\omega_k H_k H_k^H) \geq \text{reg}_k(\sum_{j \neq k} \text{Tr}(\omega_j H_k H_k^H) + \delta_k^2) \quad (6-24)$$

$$C2: \sum_k \text{Tr}(\omega_k) \leq P_{\max} \quad (6-25)$$

$$C3: \text{Rank}(\omega_k) \leq 1, \forall k \quad (6-$$

26)

The only non-convexity of the problem is due to constraint C3.

Now we define the two possible situations as bellow:

If $\text{Rank}(\omega_k) = r$, we can obtain the equation(6-27).

$$\omega_k = \sum_{t=1}^r \alpha_t \phi_t \phi_t^H \quad (6-27)$$

If $\text{Rank}(\omega_k) = 1$, we can obtain the equation(6-28).

$$\omega_k = \alpha_1 \phi_1 \phi_1^H \quad (6-28)$$

From the above equations (6.1-6.28) and knowledge in Dual Function, Weak Duality and Karush–Kuhn–Tucker (KKT) conditions. Now we can solve the problem in the following steps:

Step1: SDP Relaxation (Remove the rank one constraint)

Step2: Primal

$$\min_{W_k \in \mathbb{H}^{N_T}} - \sum_j \sum_k \text{Tr}(W_k g_j g_j^H) \quad (6-29)$$

As shown in equation format, there are some new subject to:

$$\text{C1: } \text{Tr}(W_k H_k) \geq \Omega_{\text{req}_k} (\sum_{j \neq k} \text{Tr}(\omega_j H_k H_k^H) + \delta_k^2), \quad \forall k \quad (6-30)$$

$$\text{C2: } \sum_k \text{Tr}(W_k) \leq P_{\text{max}}, \quad \forall k \quad (6-31)$$

$$\text{C3: } W_k \geq 0, \quad \forall k \quad (6-32)$$

The equation (6-32) means positive semidefinite. And all of these subjective (6.30-6.32) are convex problems. Therefore, we can solve them.

Step 3: Now we get the L in equation (6-33).

$$L = - \sum_j \sum_k \text{Tr}(W_k g_j g_j^H) + \sum_{k=1}^K \lambda_k \{ \Omega_{\text{req}_k} [\sum_{j \neq k} \text{Tr}(\omega_j H_k H_k^H) + \delta_k^2] - \text{Tr}(W_k H_k) \} + \beta [\sum_k \text{Tr}(W_k) - P_{\text{max}}] - \sum_k \text{Tr}(Y_k W_k), \quad \forall k \quad (6-33)$$

As we also know the Dual problem is following:

$$\max_{\lambda_k, \beta, Y_k \geq 0} \inf_{\omega_k} L \quad (6-34)$$

From the above KKT conditions, now we can get the following:

$$\frac{\partial L}{\partial \omega_k} = - \sum_{j=1}^J g_j g_j^H - \lambda_k H_k + \sum_{j \neq k} \Omega_{\text{req}_k} H_j \lambda_j + \beta I - Y_k = 0 \quad (6-35)$$

$$Y_k = \beta I + \sum_{j \neq k} \Omega_{\text{req}_k} H_j \lambda_j - \sum_{j=1}^J g_j g_j^H - \lambda_k H_k \quad (6-36)$$

Now if we have the condition as following:

$$\text{Rank}(Y_k) = N_T - 1 \quad (6-$$

37)

$$\text{and we can get } W_k Y_k = 0 \quad (6-38)$$

From equations(6.34-6.38),we can get the Rank (ω_k) .

Now we define M:

$$M = \mu I - \sum \sum U_g M U_g^H \quad (6-39)$$

As we know these:

$$\sum \sum U_g M U_g^H \geq 0 \quad (6-40)$$

$$Y = \beta I - \sum \beta \lambda - \lambda \quad (6-$$

41)

$$\text{Where } B = \sum \beta \lambda - \lambda \geq 0 \quad (6-42)$$

Now we assume B is positive semi-definite where $Y W = 0$ and $\beta > 0$. As we use KKT condition, we can get the following:

$$\beta [\sum_k \text{Tr}(W_k) - P_{\max}] = 0 \quad (6-43)$$

It is the complementary slackness condition. First, constraint C2 is active

$$\Rightarrow \beta > 0$$

From the KKT condition, we know $Y \geq 0$. Therefore, we can get the following:

$$\beta \geq \lambda_B^{\max} \geq 0 \quad (6-44)$$

$$\Rightarrow \text{maximum eigenvector of B}$$

Now we assume two possible cases of β .

$$\text{Case 1: } \beta \geq \lambda_B^{\max}$$

$$\Rightarrow Y_k > 0$$

$$\Upsilon_k W_k = 0$$

Because $\text{reg}_k > 0$ in C1, $W_k \neq 0$. Therefore, $\beta > \lambda_B^{\max}$ is not possible.

Case 2: $\beta = \lambda_B^{\max}$

$$W_k = \alpha u_{Y_m} u_{\text{reg}^B}^H \quad (6-45)$$

Therefore, $\text{Rank}(W_k) \leq 1$. And we prove the Following:

$$B = \sum^{\text{rank}(B)} \alpha u_{B_{\max}} u_{B_{\max}}^H \quad (6-46)$$

Therefore, we can have the convex situation for SWIPT. And we can maximize the efficiency of SWIPT, lower down the SINR and maximize the received power.

7. Simulation

Figure 7. shows the trade-off of different systems. We have the same numbers of information transmit antennas, N_T and different numbers of energy receive antennas, ER. We can find that their minimum data per information receiver will obtain the almost same extreme. For example, when we have same N_T equal to 6, the number of energy receiver is 6 and 3 respectively. Their extreme is almost the same. For another example, when we have same N_T equal to 8, the number of energy receiver is 6 and 3

respectively. Their extreme is also almost the same. Besides these, we also can find that we we have the same N_T . We can obtain the more energy when the number of ER receiver is more. However, we can obtain more energy and information when we have the same ER receiver but their N_T is more. For example, when we have same energy receiver, the N_T is 6 and 8 respectively. The space of under-line means that the information and energy will be obtained.

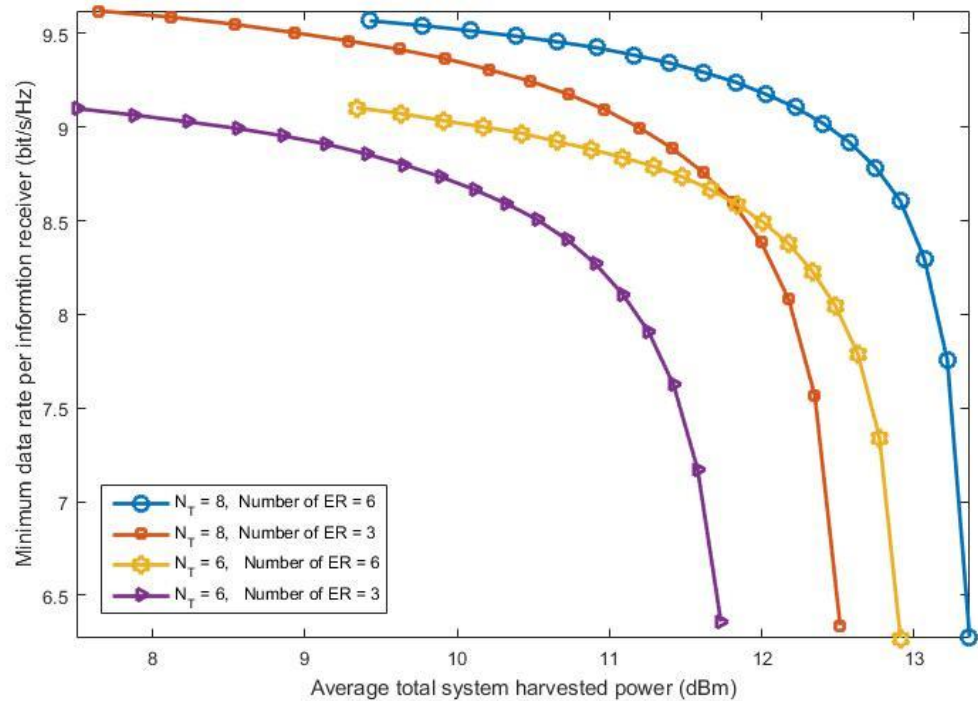


Figure 7. trade-off between the minimum information rate and total system harvested power

Figure.8 shows harvested power vs number. When we have more N_T , the average total harvested power is more. However, the gain is constantly reducing when the N_T constantly increasing. For example, the gain between $N_T = 8$ and $N_T = 10$ smaller than $N_T = 6$ and $N_T = 8$. When the N_T constantly increasing to certain value, the harvested power will no more increase. It will reach their extreme value.

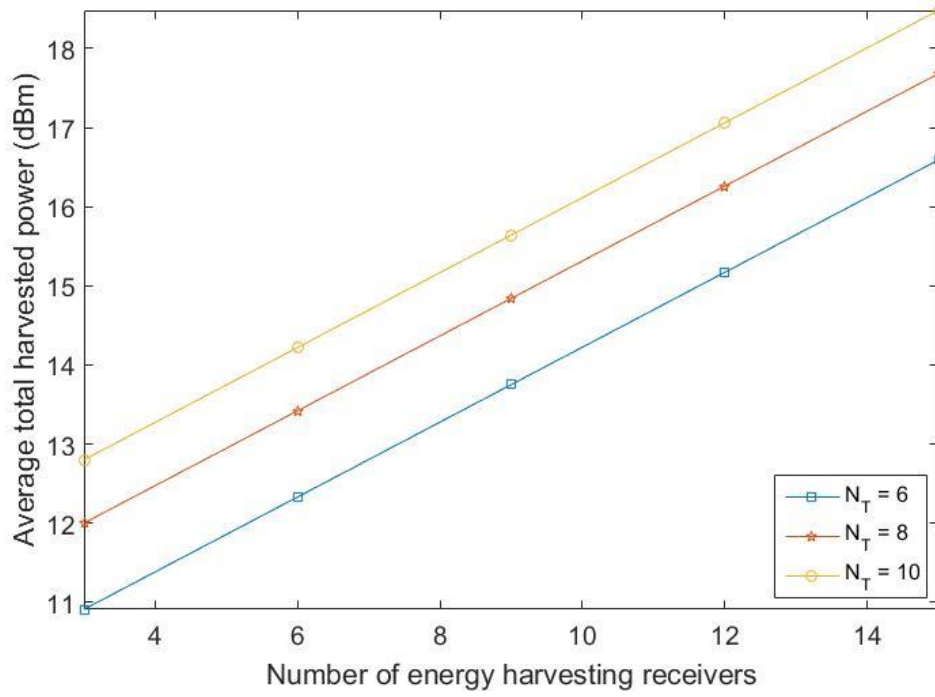


Figure8. Average harvested power vs number of energy harvesting receivers.

8. Conclusion

Wireless power and information transmission technology will bring great convenience to people daily life and it will lead to the industrial innovation. It will have a wide application prospect. For consumers, the significance of wireless charging is not only bringing the convenience of charging, but it also facilitates the wireless development of charging technology for mobile phones, tablets and other small power equipment. Even the expansion of large equipment such as electric cars. More surprise is worth looking forward to this technology.

From this semester study, I learn the relative basic information about the SWIPT and deeply study the WPCNs and the multi-antennas and beamforming for SWIPT. Finally, I design the system model and choose the final research target. With the help of my supervisor, I understand some difficult formulations. In particular, wireless information and energy transmission, which is combined with multiple antenna systems network, can effectively reduce the energy consumption and improve system performance effectively. So it can meet the needs of communication service development. For the future, we can improve the conversion efficiency so as to achieve or close to the conversion efficiency of microwave wireless energy transmission system.

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