SCHOOL OF ELECTRICAL ENGINEERING
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Energy-Efficient Resource Allocation for Multiple Relays Assisted SWIPT Systems

by

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Abstract

The number of wireless communication devices, such as the mobile phones, wireless sensors, e-health system, and smart home applications, is growing rapidly in these days, but the conventional power charging process, which through batteries or wired circuits, becomes the limitation of these devices. In addition, the popularity of wireless devices is supposed to lead to the energy shortage. So as to meet the increasing requirements of telecommunication and achieve green communication, simultaneous wireless information and power transfer (SWIPT) emerges. SWIPT shows its advantages in multiple situations, such as harsh environment and medical system. SWIPT is based on the radio frequency (RF) signals to collect energy while transmitting information. It is the integration of Wireless power transfer (WPT) and Wireless information transfer (WIT), and not only achieves the high-efficient communication but also takes advantage of the energy value.

There are four kinds of receiver structure of SWIPT: Time splitting (TS) receiver, Power splitting (PS) receiver and Antenna splitting (AS) receiver. In the project, power splitting receiver will be used in the relay part. In the thesis project, relays will be added between the transmitter and receiver, leading to improvement of the energy efficiency. In the system model, DF relays only collecting energy from the source will be used. The purpose of the project is to improve the energy efficiency of SWIPT system with multiple relays.

Key Words: SWIPT, relay system, power splitting, energy efficiency

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1 Introduction

Because of the rapid development of information and communication technologies, such as mobile Internet, Internet of Things (IoT), and 5G networks, and the increasing demand for information services, the number of the information carriers which is responsible for information collection and transmission, such as sensors and mobile devices, or other functions, are growing [1]. According to the survey, wireless devices that are connected to the internet simultaneously in the world are expected to exceed 5 billion in 2020 [2]. However, the communication nodes in these networks are typically powered by batteries with limited capacity or inconvenient wires, which has become a bottleneck in the development of network applications [3]. In addition, the popularity of wireless devices will also cause the escalation of energy demands, so saving energy becomes a significant part of telecommunication in the future [4].

In the old days, the natural environment can provide people with multiple methods to collect energy, such as solar energy, wind energy, and thermoelectric effects [5]. These natural energy sources are susceptible to location and weather impact. Wireless Power Transfer (WPT) emerged to satisfy such social needs, which can eliminate the limitations of natural resources [6]. WPT can be mainly divided into two parts: one is Non-radiative coupling-based charging and Radiative radio frequency-based charging [7]. The non-radiative coupling-based charging depends on two methods: inductive coupling and magnetic resonant coupling. Inductive coupling is easy to implement, but its charging range is only about 20cm, so it can only be used in the near-field charging [8]. The magnetic resonant coupling has high energy efficiency while powering, but the limitation of it is charging distance so it cannot be adapted in the far-field charging. If the transmission distance is about 1meter, the power transmission efficiency of magnetic resonant coupling can reach approximately 90% [9]. The radiative radio frequency-based charging utilizes microwave or Radio Frequency (RF) to provide radiant energy, which can be used in the far-field charging.

Simultaneous Wireless Information and Power Transfer (SWIPT) is the integration of WPT and Wireless information transfer (WIT), which takes good advantage of RF energy and helps to achieve Green Communication [10]. It has an important prospect in communication technology and transmission technology [11]. Based on the existing wireless power transfer technology, the aim of SWIPT is to realize the simultaneous transmission of information and power. Efficient energy communication will be realized while energy transmission and collection are completed through certain technical methods.

SWIPT is a kind of Radio Frequency (RF) based Wireless Power Transfer. RF can transfer energy and information simultaneously [12]. With 1Watt transmit power and less than 1GHz carrier frequency, RF-based WPT can transmit energy from microwatts and milliwatts in the distance of 10 meters [13]. What is more, SWIPT based on RF, are suitable for the far-field communication due to the properties of electromagnetic (EM). In addition, RF is used widely currently, so the source of the power is available easily [14].

SWIPT not only has all the characteristics of a battery-powered wireless communication network for mobile devices but also has the basic characteristics of information and energy simultaneous transportation. There are some significant advantages of SWIPT.

- Introduction a longer network lifetime: SWIPT technology is supposed to be widely adopted for information exchange and energy transmission between Radio Frequency Identification (RFID), IoT and various mobile terminals [15]. While realizing high-speed information exchange, the transmission energy in the process is expected to be collected and power the terminal devices, which can help to eliminate the limitation and inconvenience of the power method with battery. Therefore, SWIPT can help to increase the lifespan of the network operation.
- Better service quality and customer experience: Traditional wireless communication terminals are energy-constrained, and the energy limitation not only reduces the service quality of the network but also significantly affects the user experience. For SWIPT, because the information is received, the energy is harvested at the same time, thus greatly improving the quality of the network service and the quality of the user experience [16]. In the field of e-health, for implantable auxiliary electronic devices, the traditional power supply method uses either a wire to penetrate the skin to connect the implant device with an external power source, or implanted battery put into the human body to supply power to the device, which causes great pain and inconvenience to the patient and also brings threatens to the patients

lives because of unreliability and unsustainability [17]. SWIPT technology can power the devices in vitro with non-contact methods and realize data interaction between in-vivo devices and external terminals at the same time, which is able to complete control of electronic devices located in the body, and collect and monitor medical data simultaneously, so that patients can get rid of the constraints of traditional wires and batteries, leading to improvement of the quality of life and ensure life safety [18]-[19].

- A wider range of applications: Due to the characteristics of the non-contact transmission of energy and information, SWIPT technology is able to control and power equipment in harsh working environments, such as space, ocean, forest, desert, canyon, mine, and earthquake-stricken areas, and address the problem of artificially construction of lines and battery replacement constantly in these complex situations. It can not only provide non-contact power supply to the equipment remotely but also avoid the insecure factors caused by the aging of the line. SWIPT is also expected to realize the remote control and information interaction of the equipment, which greatly improves the adaptability of the equipment to the extreme working environment [20].
- Have a more promising application prospect: Due to the shackles of the previous wires, wireless terminal devices have become universal [21]. SWIPT are expected to be applied in daily life, such as multi-functional human wristbands, smart phones, and smart furniture terminals. Wireless charging and remote control with SWIPT are supposed to make "smart, green" life a reality.

However, the exponential growth of connected devices in wireless communication networks poses an unprecedented challenge to network energy supply [22]. The target of the data rate setting for future 5G networks is about 1000 times higher than the current system. Obviously, according to Shannon's theorem, increasing the transmission power cannot satisfy the requirements. Therefore, researchers began to shift from focusing on network capacity to network energy efficiency. Currently, energy efficiency has become a new research direction in academia and industry, and researchers began to pay attention to the energy efficiency optimization [23]. The development of energy-efficient green communications, reducing the energy consumption of network operations, saving maintenance costs, and reducing emissions of environmental pollution make SWIPT's energy efficiency an important and urgent research topic.

In the article, relays will be adapted in the SWIPT system and in the transmitter side, there will be multiple output antennas. Relays in the circuit are supposed to collect energy from the source and then forward the information to the destination, which is able to increase energy efficiency and extend the range of transmission [24]-[25]. Compared with the single input and single output (SISO), multiple antennas in the source assist to improve information capacity [26].

In this article. Chapter 2 will introduce the previous work and some fundamental concepts related to the project. In the Chapter 3, the system model will be illustrated and explained with corresponding equations. After that, the problem to be solved is supposed to be listed in the Chapter 4 and he optimal solution will be given in the Chapter 5. In addition, the simulation results will be presented and explained in the Chapter 6. Conclusions are supposed to be drawn up in the Chapter 7. Finally, Chapter 8 and Chapter 9 are the appendix to prove the theorem used in the sector of optimal solutions.

2 Background

2.1 *Research Status*

In the 1890s, Nikola Tesla was the first people who developed the concept of Wireless Power Transmission (WPT). He used the earth and the atmospheric ionosphere as conductors to realize wireless transmission. However, due to the poor technical conditions, the experiment failed [27]. After that, Goubau and Schweing estimated that free-space beam waveguide could achieve almost 100% transmission efficiency and this theory had been validated on a reflected beam waveguide system [28]. After that, the cooperation, Raytheon, headed by William C.Brown, began to research on the technology and the experiment that use a 2.45GHz microwave to drive a helicopter was completed in 1964 [29]. In the 1980s, the Canadian Communications Research Center proposed to construct a relay platform for applications such as broadcasting, television, and communications and proposed to use wireless transmission methods to provide this platform with power [30]. By the 1990s, wireless energy transmission technology has been welcomed in small and medium power applications.

In 2001, G.Pignolet from the French National Scientific Research used microwave wireless transmission to power a 200W bulb which was located 40m away. In 2003, a 10 kW experimental microwave power transmission device was established and carried out an end-to-end wireless power transfer to provide a village in a remote distance with electricity in the frequency of 2.45GHz [31]. In November 2006, Kurs successfully used the "electromagnetic resonance principle" to achieve wireless energy transfer between two coils 2.13 m apart and illuminate a 60 W bulb, in 2006, which achieved the efficiency increased more than 1 million times than the ordinary non-resonant magnetic induction [32]. A company in America, called Lockheed Martin, reported in 2012 that, they developed a laser-based wireless charging system that could power the unmanned reconnaissance aircraft, which enabled the aircraft to fly for 48 hours constantly [32].

After that, because people have not satisfied with information transmission with radio waves only but hope that while transmitting information, it is also possible to fully utilize the transmission power to transmit energy in order to charge the device. Under this demand, SWIPT technology based on the simultaneous transmission of energy and information has received high attention from researchers.

Varshney first proposed and analyzed the problem of information and energy transmission from the perspective of information theory for SISO, and theoretically defined Capacity-Energy function, and illustrated the connection of channel capacity and energy transmission efficiency for Additive white Gaussian noise (AWGN) channel [33]. In [34], the researchers studied the problem of wireless information and energy transmission with coupled inductor circuit, realized the optimal power allocation by using water-filling power allocation algorithm and proposed the optimal equilibrium solution regarding information transmission rate and energy conversion.

Researchers also pay attention to the transmitters and receivers for the SWIPT system. Optimization of point-to-point data transmission in a fading channel for a transmitter with energy harvesting was proposed in [35] to realize the highest transmission rate and minimum transmission time. In [36], Liu and his partners illustrated the joint optimization problem of transmission energy control, information and energy transmission switching, and receiver mode switching. Zhou proposed a dynamic power splitting (DPS) receiver structure, in which can harvest energy and decode information respectively by splitting power [37].

Cooperative relay technology not only reduces the transmit power of nodes, reduces energy consumption, but also improves channel quality and gains cooperative diversity gain. Therefore, these years, the cooperative relay is also welcomed by the researchers. Nasir and Zhou studied the throughput, relay probability and ergodic capacity of the TS and PS methods in the half-duplex relay mode, and analyzed the effects of the different parameters of the two transmissions on the relay [38]. They also studied the issue of wireless cooperative network amplification (AF) with SWIPT relay. In [39]-[40], SWIPT with the power-splitting receiver in full-duplex mode was researched. The author found that while relaying, the source transmitted energy and information to relay simultaneously, which enhanced the transmission power of relay, and the self-interference in duplex mode could also be collected by the receive antenna as an energy source. In [41], The non-convex optimization problem of SWIPT in half-duplex and full-duplex modes with time splitting receiver is studied and a closed-form approximation result is obtained. It can be found that full-duplex mode can transmit information more effectively. Yuan Liu and Xiaodong Wang maximized the data rate from the source in the field of SWIPT based on PS and TS modes with OFDM cooperative relay system [42].

From the previous illustration, it can be found that SWIPT research is still in its infancy, and the design and optimization studies of SWIPT can mainly focus on energy harvesting modes, energy efficiency, total energy capture, and channel capacity. Therefore, the project thesis will analyze the energy efficiency of the SWIPT system with multiple relays.

2.2 *Receiver Structure*

In the conventional transmission system, the information reception and RF energy capture have different power sensitivities. However, in the SWIPT, due to the fact that the RF signal can both transmit information and carry energy, in theory, energy capture and information transmission can be realized by sharing of the same RF input antenna.

However, in practice, energy harvesting can be easily affected by information decoding. Therefore, the receiving node must split the signal for information decoding and energy capturing respectively [43]. The SWIPT technology is mainly based on the following three methods: time splitting receiver, power splitting receiver and antenna splitting receiver [44].

2.2.1 Time Splitting (TS)

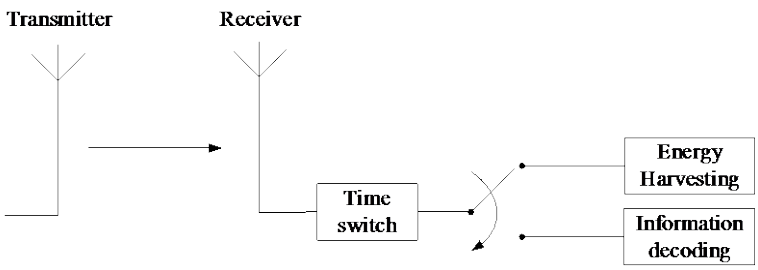

FIGURE 1. Time Splitting Receiver Structure [45].

The TS receiver splits the signal by two time slots: one kind of time slots for energy collection, and one for information decoding [46]. The TS receiver switching between the two-time slots almost successively（FIGURE 1）. Compared with Power splitting(PS) the hardware implementation of the time slot switcher is easier, and the information decoder and energy harvester can operate with different power sensitivities.

2.2.2 Power Splitting (PS)

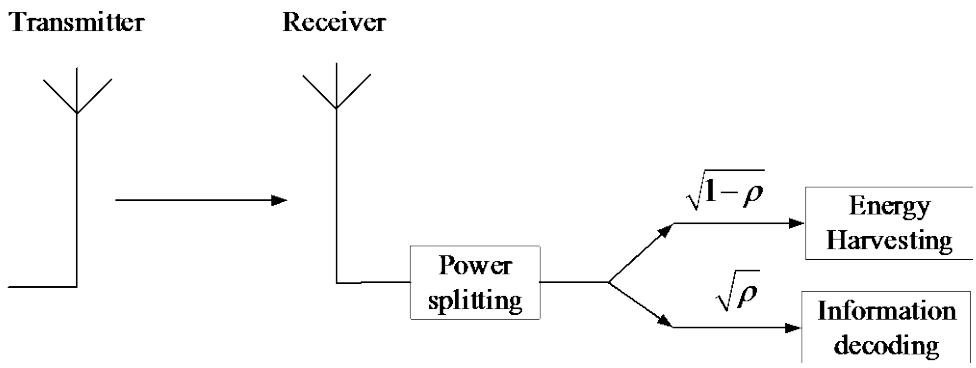

FIGURE 2. Power Splitting Receiver Structure [45].

For the PS receiver (FIGURE 2), the received RF signal is divided energy collection and information decoding by two streams with different power levels [47]-[49]. The PS method is used for simultaneous transmission of information and energy, so it makes SWIPT possible. At the receiving end, a power splitter needs to be designed to divide the power of each subcarrier by a fixed ratio (ρ). A certain proportion ($\sqrt{\rho}$) of the power is split to decode received information, and the remaining proportion ($\sqrt{1-\rho}$) is distributed to collect energy. In this method, each subcarrier has the same power splitting factor (ρ), and how to optimize the power splitting factor is the research focus.

2.2.3 Antenna Splitting (AS)

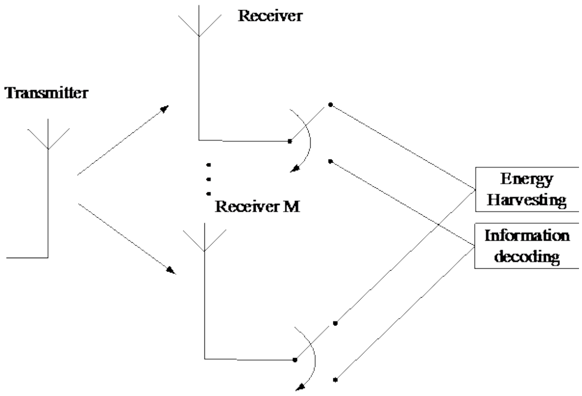

FIGURE 3. Antenna Splitting Receiver Structure [45].

The model of AS receiver is FIGURE 3. In the AS system, some of the antennas are used to decode information, and the other antennas received the signals for energy collection [50]. This method requires the design of a time slot switcher in each receive antenna, which is easier to implement than the PS method. However, the choice of antenna assignment requires solving the entire optimization problem in each communication frame, so it has some complexity as well.

2.3 *Relay Technology*

In 1979, Cover and Ganmal analyzed the network capacity of a three-point system with relay, assuming that all the nodes work on the same frequency, and found the information theory characteristic of such system. This is the basic idea of the cooperative relay, which lays a theoretical foundation for wireless network cooperative relay [51].

In the cooperative relay network, the relays play a significant role in the system, located between the source nodes and the destinations, assisting source to transfer information, which leads to spatial diversity [52]. The relays processing the signals in the source node is an important step in the cooperative relay network [53]. There are multiple cooperative relay protocols for different information processing schemes. For the fixed relay, there are two basic ways: one is Decode-and-Forward (DF), the other is Amplify-and-Forward (AF) [54]-[55].

2.3.1 Amplify-and-Forward (AF)

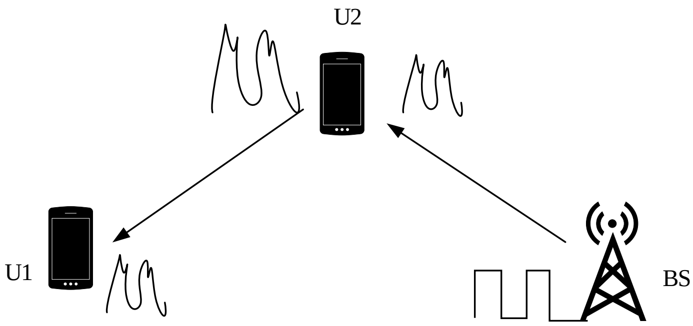

FIGURE 4. Diagram of Amplify-and-Forward Relay.

The principle diagram of AF can be illustrated following FIGURE 4. The base station (BS) can be assumed to be the source. U_1 is the transmission destination. U_2 is the relay node. BS sends signals to U_1 and U_2. After U_2 gets signals from BS , U_2 only linearizes the signal without any demodulation and decoding and then sends it to U_1. The function of the relay node, U_2, is only to amplify the signals and then forward the signals. In this signal processing, since U_2 received both signal and noise from the BS, the signal and noise will be simultaneously amplified by U_2 [61]. Although this forwarding method is simple in concept and often used to analyze the principle of cooperative relay communication channel, but, in practical applications, due to the limited size of the device, the relay node needs to sample, amplify and retransmit the analog signal, which is difficult to realize

2.3.2 Decode-and-Forward (DF)

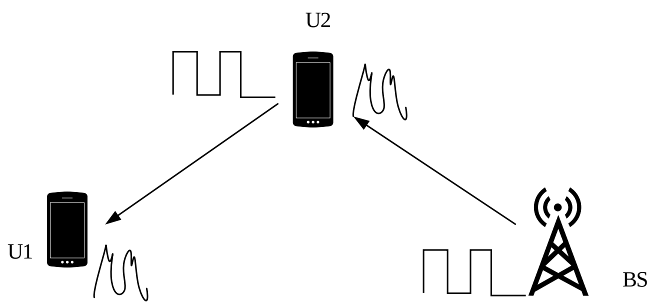

FIGURE 5. Diagram of Decode-and-Forward Relay.

FIGURE 5. illustrates the function of DF. The base station (BS) can be the source. U_1 is the transmission destination. U_2 is the relay node. BS sends signals to U_1 and U_2. In the DF

mode, U_2 first decodes the received information from BS, and then forwards it to U_1. In contrast to AF, the relay node, U_2 of the DF mode does not amplify the Gaussian white noise, but eliminates it. If U_2 can decode the signal correctly, then the communication destination node, U_1, will combine the signals of the two channels (one from the relay, the other from BS directly) and restore the original signal , leading to improvement of system performance. In contrast, if U_2 cannot decode the signal correctly, the wrong signal will be sent to the receiver, resulting in worse result compared with the situation without relays [57]. In order to avoid such situation happening, the relay node can adapt some check technology, such as Cyclic Redundancy Check, in order to check the received data for verification.

2.4 *Convex Optimization theory*

The convex optimization theory will be applied to the resource allocation in this project to get the ideal solution. The convex optimization theory has gradually become an important optimization calculation tool. It can be expressed as follow:

$$\min_x f_0(x) \tag{2-1}$$

subject to :

$$f_i(x) \leq 0, i = 0,1, \dots, m. \tag{2-2}$$

$$h_j(x) = 0, j = 0,1, \dots, p. \tag{2-3}$$

In theory, a standard convex problem can use the convex optimization solution when the object function and the constrains satisfy the above conditions, which means the convex optimization theory is mainly for the standard convex problem [58]. However, the contribution of the convex optimization theory can not be limited as this. For the non-convex problems, they can be transformed into convex problems with the convex optimization theory and be solved in a simpler process.

2.4.1 Lagrange Duality Law

When the problem is not the convex problem, it can be transformed into the convex problem from the former illustration, so determining an optimization problem whether is a convex optimization problem is the key to solve the problem [59]. The Lagrange duality law is an outstanding method.

Based on the original expression of optimization problem, from equation (2-1) to (2-3). For $x \in R^n$, q^* can be assumpted as the optimization solutions for the problem. In addition, the λ is the dual variable for the inequality constraint and ν is the dual variable for the equality constraint, where $\lambda, \nu \in R$. The Lagrange function is:

$$\mathcal{L}(x, \lambda, \nu) = f_0(x) + \sum_{i=1}^{m} \lambda_i\, f_i(x) + \sum_{j=1}^{n} \nu_j\, h_j(x) \quad (2\text{-}4)$$

For the equation (1-4), the dual function can be used and then:

$$g(\lambda, \nu) = \min \quad \mathcal{L}(x, \lambda, \nu) \quad (2\text{-}5)$$

At last the original problem can be transformed to:

$$\max_{\lambda,\nu} g(\lambda, \nu) \quad (2\text{-}6)$$

With constraints: $$\lambda \geq 0, \nu \in R^n \quad (2\text{-}7)$$

After all, the equation (2-6) and (2-7) show that the objective function and the constraint conditions is the linear function about dual variables, so regardless whether the original problem is whether convex or not, the transformed problem is a convex problem.

2.4.2 KKT Conditions

Karush-Kuhn-Tucker Condition is a significant for the optimization problem, especially for the problem whose objective function and constraints can be differentiated [60]. There are four conditions for KKT Condition:

(1) The essential condition: $\mathrm{f_i(x) \leq 0, i = 0,1, \dots, m \quad h_j(x) = 0, j = 0,1, \dots, p}$

(2) The dual condition: $\lambda \geq 0$

(3) $\lambda_i\, f_i(x) = 0, i = 1,2 \dots, m$

(4) Lagrange multiplier partial differential condition:

$$\nabla\mathcal{L}(x, \lambda, \nu) = \nabla f_0(x) + \sum_{i=1}^{m} \lambda_i\, \nabla f_i(x) + \sum_{j=1}^{n} \nu_j \nabla\, h_j(x) = 0$$

Therefore, although the original problem is non-convex problem with duality, the necessary condition for the optimal solution satisfies the KKT conditions. What is more, if the original problem is convex problem, the KKT conditions are the necessary and sufficient condition for the optimization outcome.

3 System Model

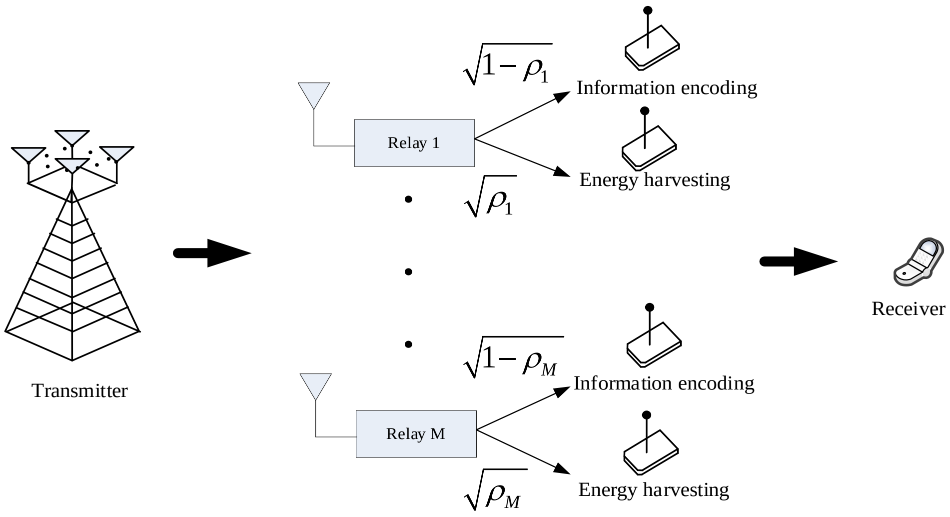

FIGURE 6. System Model.

The system model can be illustrated in FIGURE 6. In the project, a downlink SWIPT system will be considered. We focus on the SWIPT system that contains a transmitter (TX) with multiple (N) antennas, multiple relays (R_i), and a destination receiver (D). The relays are DF half-duplex relays, equipped with single antenna. Without direct link, the reliable communication from the transmitter to the receiver must is via one of the relays. In addition, there is no additional power supply for relays, so relays are supposed to capture energy from the transmitter and then forward the signal, which can be called EH relays. What is more, relays operate in power splitting mode with different power splitting factors (ρ_i).

In order to avoid interference, in the project time division multiple access (TDMA) is adapted. The communication from the transmitter to the destination can be divided into two phases: the first phase is from the transmitter to one of the relays, and the second duration is from the relay to the receiver. We assume that the total transmission time is 1 that can be split equally by the two consequently phases.

In the first phase whose duration is $\frac{1}{2}$, the signal from the transmitter to the destination can be expressed by $\boldsymbol{x}$,

$$\boldsymbol{x} = \boldsymbol{\omega} s \qquad \boldsymbol{x} \in \mathbb{C}^{N_i \times 1} \tag{3-1}$$

with $E[|s|^2] = 1$, where. $\boldsymbol{\omega}$ is precoding vector and s is information symbol.

Then, the signals arrived at the ith relay can be given by:

$$y_i^{Relay} = \boldsymbol{h_{1i}}^H \boldsymbol{x} + n_{ai} \tag{3-2}$$

$\boldsymbol{h_{1i}}$ is the channel coefficient from source to the ith relay. n_{ai} represents the additive white Gaussian noise (AWGN) at the ith relay where $n_{ai} \sim \mathrm{N}(0, {\delta_{ai}}^2)$. In the ith relay, PS splitter coefficient is ρ_i, that splits $\sqrt{1-\rho_i}$ of the total received energy to energy harvest and $\sqrt{\rho_i}$ to information forward, so the power for energy collection in the ith relay is :

$$\begin{aligned} E_i^{Relay} &= \mathcal{E}\left[\left|y_i^{RelayEH}\right|^2\right] = \mathcal{E}\left[\left|\boldsymbol{h_{1i}}^H \boldsymbol{x}\right|^2\right](1-\rho_i) \\ &= \mathcal{E}\left[\left|\boldsymbol{h_{1i}}^H \boldsymbol{\omega} s\right|^2\right](1-\rho_i) \\ &= \left|\boldsymbol{h_{1i}}^H \boldsymbol{\omega}\right|^2 (1-\rho_i) \end{aligned} \tag{3-3}$$

The signal forwarded by the ith relay is:

$$y_i^{RelayID} = \sqrt{\rho_i}\, y_i^{Relay} \tag{3-4}$$

In the second time slot, in the receiver side, because the relay is the DF relay, the signal transferred to the receiver is $\boldsymbol{x}$. Therefore, the signal received can be presented:

$$y^r = \boldsymbol{h_{2i}}^H \boldsymbol{x} + n_r \tag{3-5}$$

where $\boldsymbol{h_{2i}}$ is the channel coefficient from the ith relay to the receiver and n_r is AWGN in the receiver, $n_r \sim \mathrm{N}(0, {\delta_r}^2)$.

3.1 *Relay Selection*

There are M relays in the system. In the process of telecommunication, there will be only one relay will be used, so relay selection is a significant process in the project. We assume the relay factor for ith relay is s_i where $i \in M$, and

$$s_i \in \{0,1\}. \tag{3-6}$$

$$\textstyle\sum_{i=1}^{M} s_i = 1 \tag{3-7}$$

3.2 *Energy Efficiency*

The relays in the system model are all DF relays. Therefore, the signal to interference plus noise ratio (SINR) of system from transmitter to receiver can be illustrated by:

$$SNR_i^{End-to-end} = \min_{i \in M}\{SNR_{1i}, SNR_{2i}\} \quad (3\text{-}8)$$

In the first phase, the SNR is:

$$SNR_{1i} = \frac{\rho_i \left|\boldsymbol{h_{1i}}^H \boldsymbol{\omega}\right|^2}{{\delta_{ai}}^2} \quad (3\text{-}9)$$

For the second phase, the SNR is:

$$SNR_{2i} = \frac{\left|\boldsymbol{h_{2i}}^H\right|^2 P_i}{{\delta_r}^2} \quad (3\text{-}10)$$

P_i is the power transferred from the ith relay to the destination.

The data rate can be expressed by equation (2-11).

$$R_i^{End-to-End} = \log_2\left(1 + SNR_i^{End-to-end}\right) \quad (3\text{-}11)$$

The energy efficiency can be expressed:

$$EE = \frac{\sum_{i=1}^{M} s_i \log_2\left(1+SNR_i^{End-to-end}\right)}{P_C + \|\boldsymbol{\omega}\|^2 - E_i^{Relay}} \quad (3\text{-}12)$$

where P_C is the power of the circuit.

4 Problem Formulation

The purpose of the project is to maximize the energy efficiency of the system under the circumstances of secure communication. As the result, the resource allocation design can be formulated as following:

Resource Allocation Design

$$\max_{\boldsymbol{\omega}} \quad EE = \frac{\sum_{i=1}^{M} s_i \log_2\left(1+SNR_i^{End-to-end}\right)}{P_C + \left\|\boldsymbol{\omega}\right\|^2 - E_i^{Relay}} \text{ for } \forall i \in [1, M] \quad (4\text{-}1)$$

$$\text{C1: } \|\boldsymbol{\omega}\|^2 \le P_{max}$$

$$\text{C2: } P_i \le (1-\rho_i)\left|\boldsymbol{h_{1i}^H}\boldsymbol{\omega}\right|^2$$

$$\text{C3: } \sum_{i=1}^{M} s_i = 1$$

$$\text{C4: } s_i \in \{0,1\}$$

The first constrain means that the transmitter power is supposed to be less or equal to the maximum transmitting power (P_{max}) offered by the transmitter in order to guarantee the safety of people's health [61]. In the constrain 2, the relay transmitting power for the i-th relay P_i ought to be not larger than the relay receiving power. The C3 and C4 are to guarantee only one relay will be used at a time.

5 Optimal Solution

The problem formulation listed in (3-1)is non-convex function. Therefore, the Lagrange duality law may be required to obtain the optimal solution for the problem.

Firstly, we transfer SNR_{1i}, SNR_{2i} and E_i^{Relay}

$$\mathrm{SNR_{1i}} = \frac{\rho_i \left|h_{1i}{}^H \omega\right|^2}{\delta_{ai}{}^2} = \frac{\rho_i (h_{1i} h_{1i}{}^H \omega \omega^H)}{\delta_{ai}{}^2} = \frac{\rho_i \mathrm{Tr}(h_{1i} h_{1i}{}^H \boldsymbol{W}_i)}{\delta_{ai}{}^2} \tag{5-1}$$

In (5-1), $W = \omega\omega^H$ is a matrix. Also, we can use the same method for SNR_{2i} and E_i^{Relay}.

$$SNR_{2i} = \frac{\rho_i Tr(\boldsymbol{h_{2i}} \boldsymbol{h_{2i}}{}^H)}{\delta_r{}^2} \tag{5-2}$$

$$E_i^{Relay} = (1-\rho_i) Tr\left(\boldsymbol{h_{1i}} \boldsymbol{h_{1i}^H} \boldsymbol{W_i}\right) \tag{5-3}$$

In addition, it is the same process for $\|\boldsymbol{\omega}\|^2$, so $\|\boldsymbol{\omega}\|^2 = Tr(\boldsymbol{W})$

In order to reduce the complexity, we use:

$$\tau = \mathrm{SNR_i}^{\mathrm{End-to-end}} = \min_{i \in [1,M]} \left\{ \frac{\rho_i |h_{1i}^H W_i|^2}{\sigma_{ai}^2}, \frac{P_i |h_{2i}^H|^2}{\sigma_r^2} \right\} = \min_{i \in [1,M]} \left\{ \frac{\rho_i Tr(\boldsymbol{h_{1i}} \boldsymbol{h_{1i}}{}^H \boldsymbol{W}_i)}{\delta_{ai}{}^2}, \frac{\rho_i Tr(\boldsymbol{h_{2i}} \boldsymbol{h_{2i}}{}^H)}{\delta_r{}^2} \right\}$$

However, the calculation complexity increase with the number of transmitting antennas, so with the combination of the C3 and C4 in (3-1), assumption $s_k = 1$ will be taken into consideration for efficient calculation.

We can notice that the objective function in (3-1) is by the division of two equations, so we can consider the fractional program. For simplification, we are able to define $\mathcal{F}$ as a collection of all variables. We can get: $\{\boldsymbol{W}_k, P_k, \tau\} \in \mathcal{F}$. And we use q^* to present the optimal energy efficiency. So the objective function can be written as :

$$q^* = \frac{\log_2(1+\tau^*)}{P_C + \mathrm{Tr}(\boldsymbol{W_k}^*) - (1-\rho_k) Tr\left(\boldsymbol{h_{1k}} \boldsymbol{h_{1k}^H} \boldsymbol{W_k}^*\right)} = \max_{\boldsymbol{W}_k, P_k, \tau \in H^{N_i}} \frac{\log_2(1+\tau)}{P_C + \boldsymbol{W_k} - (1-\rho_k) Tr\left(\boldsymbol{h_{1k}} \boldsymbol{h_{1k}^H} \boldsymbol{W}_k\right)} \tag{5-4}$$

After that, we can import the Theorem to continue.

Theorem 1: *When* $\{\boldsymbol{W}_k, P_k, \tau\} \in \mathcal{F}$, *the optimal energy efficiency* q^* *can be obtained if and only if:*

$$\max_{\boldsymbol{W}_k, P_k, \tau \in H^{N_i}} \ log_2(1+\tau) - q^*\left(P_C + Tr(\boldsymbol{W_k}) - (1-\rho_k)Tr\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)\right)$$

$$= log_2(1+\tau^*) - q^*\left(P_C + Tr(\boldsymbol{W_k}^*) - (1-\rho_k)Tr\left(\boldsymbol{h_{1k}h_{1k}^H W_k}^*\right)\right) = 0$$

(5-5)

when $log_2(1+\tau) \geq 0$ *and* $P_C + Tr(\boldsymbol{W_k}) - (1-\rho_k)Tr\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right) > 0.$

According to the Theorem 1, we can conclude that when the objective function is fractional structure, we can rewrite the objective function in another way, so the problem formulation can be transformed as below:

Problem Transformation:

$$\max_{\boldsymbol{W}_k, P_k, \tau \in H^{N_i}} EE = \log_2(1+\tau) - q\left(P_C + \mathrm{Tr}(\boldsymbol{W_k}) - (1-\rho_k)\mathrm{Tr}\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)\right)$$

(5-6)

C1: $\mathrm{Tr}(\boldsymbol{W_k}) \leq P_{max}$

C2: $P_k \leq (1-\rho_k)\mathrm{Tr}\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)$

C3: $\tau \geq \frac{\rho_k \mathrm{Tr}\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)}{\sigma_{ak}^2}$

C4: $\tau \geq \frac{P_k \left|\boldsymbol{h_{2k}^H}\right|^2}{\sigma_r^2}$

C5: $\boldsymbol{W_k} \geq \boldsymbol{0}$

After transformation, the equation of energy efficiency is a convex function, and Lagrange duality law and KKT conditions will be applied to solve the problem for the optimal solution.

5.1 *Dual Problem Formulation and Solution*

In this sector, dual solution will be used to solve the problem. The Lagrangian function for the problem (5-6) can be given by (5-7):

$$\mathcal{L} = \log_2(1+\tau) - q\left(P_C + \mathrm{Tr}(\boldsymbol{\omega_k}) - (1-\rho_k)\mathrm{Tr}\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)\right) - \mu\left(\mathrm{Tr}(\boldsymbol{W_k}) - P_{max}\right) -$$

$$\kappa\left(P_k - (1-\rho_k)\mathrm{Tr}\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)\right) - \alpha\left(\tau - \frac{\rho_k \mathrm{Tr}\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)}{\sigma_{ak}^2}\right) - \beta\left(\tau - \frac{P_k\left|\boldsymbol{h_{2k}^H}\right|^2}{\sigma_r^2}\right) + Tr(\boldsymbol{W_k M_{c5}}) \quad (5\text{-}7)$$

In (5-7), $\boldsymbol{M_{c5}} \succcurlyeq \boldsymbol{0}$ is a Lagrange multiplier matrix in respect to the constrain 5. In addition, $\mu \geq \boldsymbol{0},\ \kappa \geq \boldsymbol{0},\ \alpha \geq \boldsymbol{0},\ \beta \geq \boldsymbol{0}$ are Lagrange multipliers corresponding to the C1 to

C4 respectively. μ is related to the total power constrain. κ is the constrain of the transmission power of the relay. α , β are related to the τ, which is the SNR in the whole circuit. The dual problem is transformed to:

$$\min_{\substack{\boldsymbol{M_{c5}},\mu,\\ \kappa,\alpha,\beta}} \max_{\boldsymbol{W}_k,P_k,\tau\in H^{N_i}} \mathcal{L} \tag{5-8}$$

Due to the fact that $\mathcal{L}$ is a convex function, the KKT conditions will be the necessary and sufficient conditions fot the optimal solution to the problem for $\boldsymbol{W}_k{}^*, P_k{}^*, \tau^*$.

$$\mu^*(\operatorname{Tr}(\boldsymbol{W_k}{}^*) - P_{max}) = 0 \tag{5-9}$$

$$\kappa^*\left(P_k{}^* - (1-\rho_k)\operatorname{Tr}\left(\boldsymbol{h_{1k}}\boldsymbol{h_{1k}^H}\boldsymbol{W_k}{}^*\right)\right) = 0 \tag{5-10}$$

$$\alpha^*\left(\tau^* - \frac{\rho_k\operatorname{Tr}\left(\boldsymbol{h_{1k}}\boldsymbol{h_{1k}^H}\boldsymbol{W_k}{}^*\right)}{\sigma_{ak}^2}\right) = 0 \tag{5-11}$$

$$\beta^*\left(\tau^* - \frac{P_k{}^*\left|\boldsymbol{h_{2k}^H}\right|^2}{\sigma_r^2}\right) = 0 \tag{5-12}$$

$$\boldsymbol{W_k}{}^*\boldsymbol{M_{c5}}{}^* = 0 \tag{5-13}$$

Here μ^*, κ^*, α^*, β^* are the optimal lagrange multipliers and $\boldsymbol{M_{c5}}{}^*$ is the optimal Lagrange multiplier matrix.

Theorem 2:*if* $P_{max} > 0$ *and the problem formulation (4-1) has the optimal solution, the rank of optimal beamforming matrix* $\boldsymbol{W_k}$ *ought to be one. i.e.* $Rank(\boldsymbol{W_k}{}^*) = 1$

Proof: Please refer to Appendix A

The theorem 2 illustrates that the beamforming matric $\boldsymbol{W_k}{}^*$ is a rank-one matrix which is the solution to the problem (4-1), and this kind of beamforming can help to maximize the energy efficiency of the system.

6 Simulation Results

In this section, simulations will be provided to evaluate the performance of the project. In the model system, although there are multiple DF half-duplex relays, we will select one with optimal energy efficiency to transmit, and in the receiver side, the power splitting design is applied. The table 1 listed the simulation parameters for the project [62].

TABLE I

SIMULATION PARAMETERS

Carrier center frequency	915 M

Bandwidth	200 *kHz*
Single antenna power consumption	$P_{ant} = 1\ W$
Static circuit power consumption	$P_c = 150\ W$
Power amplifier efficiency	$\xi = 0.2$
Transmit antenna gain	18 *dBi*
Noise power	${\delta_{ai}}^2 = {\delta_r}^2 = -95\ dBm$
Transmitter-to-relays fading distribution	Rician with Rician factor of 6 *dB*
Relay-to-receiver fading distribution	Rayleigh
Energy conversion efficiency	$\eta = 0.5$

The transmitter is with multiple antennas, so in the simulation, we assume that the transmitter is equipped with $N_t = 3{,}6{,}9$, 3 situations respectively.

Figure 7 depicts the average achievable rate efficiency verse the maximum transmit power allowance P_{max} in the power station with different number of transmitter antennas in the transmitter side. By comparing the x-axis and y-axis, it can be observed from figure 7 that with the increase number of the transmitter antennas N_t, the energy efficiency increase as well. According to analyzation, this is because that with more transmitting antennas, the required power consumption decreases for each antenna to maintain the desired SNR, so it assists to achieve energy efficiency. What is more, from the figure 7, it can be conclude that the average achievable rate efficiency performs increase monotonically until the power in the transmission side P_{max} is approximate equal to 31 *dBm*, and after that the curve shows a stable trend. In other words, when the transmitting power reach the threshold, the energy efficiency will not rise with the increase of the power, which means that the energy efficiency has arrived at its optimal situation.

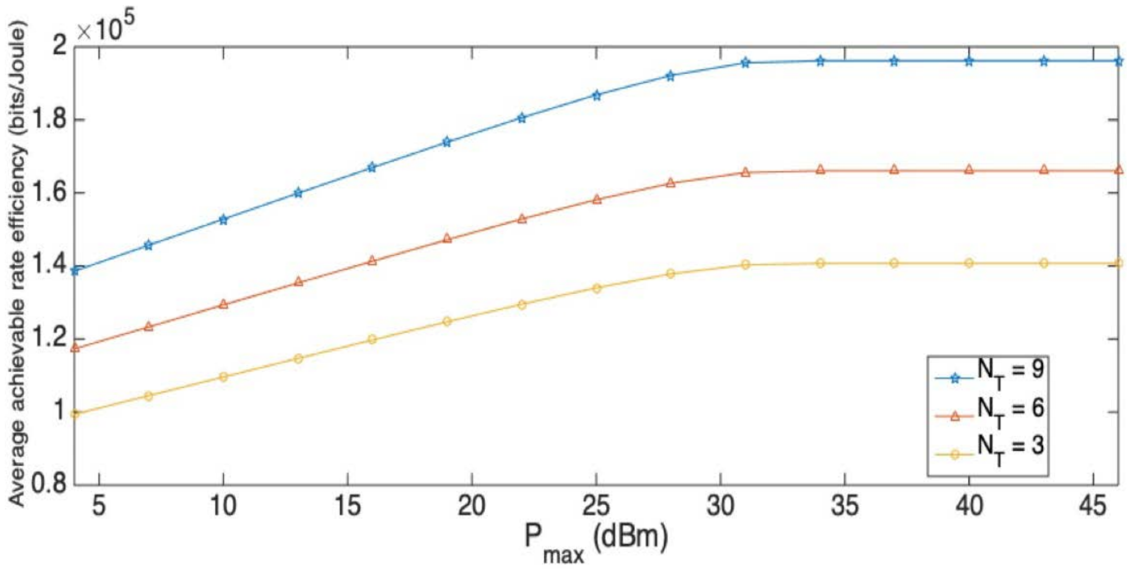

FIGURE 7. Average achievable rate efficiency (bits/joule) verse the maximum transmit power P_{max} in the power station (dBm).

Figure 8 illustrates the average achievable rate efficiency verse the number of iterations with different transmission antennas N_t. It describes the energy efficiency and iteration times and the convergence speed of iterative algorithms for the power splitting mode in the receiver side. In the low iteration times (1 or 2), the different number of transmission antennas have little effect on the energy efficiency. As the number of iterations increases, the number of transmission antennas has obvious effect on energy efficiency. It is obvious that when the iteration times is from 3 to 5, the energy efficiency increases rapidly and when the number of iteration reaches 5, the energy efficiency becomes stable, which means it reaches the convergence state after 5 iterations. On the other hand, more transmission antennas lead to higher convergence speed.

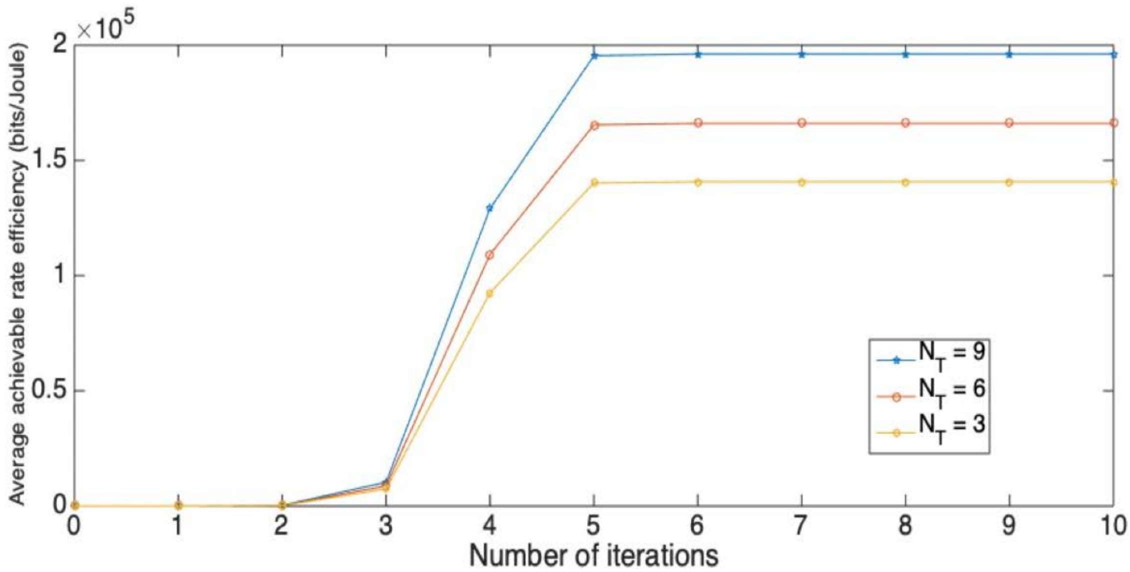

FIGURE 8. Average achievable rate efficiency (bits/joule) verse the number of iterations.

7 Conclusions

In this paper, we studied the energy efficiency resource allocation for SWIPT systems with multiple relays. In particular, we considered a system with multiple antennas in transmitter side, multiple relays serving and a single-antenna receiver. In order to improve the energy efficiency in the system, we select only one relay to assist to transmit. In addition, we designed a resource allocation algorithm to maximize the energy efficiency of the SWIPT system. Although the resource allocation algorithms are non-convex optimization problem, by applying the Lagrangian dual law and KKT conditions, the problem is solved optimally in the paper. Finally, from the numerical results, the proposed resource allocation can help improving the energy efficiency with increase of transmitting antennas.

8 Appendix- Proof of Theorem 1

Following the similar approach in [63]-[64], we can prove the theorem 1. In the former sector, we have defined $\{\boldsymbol{W}_k, P_k, \tau\} \in \mathcal{F}$ as a collection of optimal variables and used q^* to present the optimal energy efficiency, so the original problem formulation can be expressed as :

$$q^* = \frac{\log_2(1+\tau^*)}{P_C + \mathrm{Tr}(\boldsymbol{W}_k{}^*) - (1-\rho_k)Tr\left(\boldsymbol{h}_{1k}\boldsymbol{h}_{1k}^H\boldsymbol{W}_k{}^*\right)} \geq \frac{\log_2(1+\tau)}{P_C + \mathrm{Tr}(\boldsymbol{W}_k) - (1-\rho_k)Tr\left(\boldsymbol{h}_{1k}\boldsymbol{h}_{1k}^H\boldsymbol{W}_k\right)} \quad \forall\{\boldsymbol{W}_k, P_k, \tau\} \in \mathcal{F}$$

(8-1)

then, from (8-1), we can get (8-2) and (8-3):

$$\log_2(1+\tau) - q^*\left(P_C + \mathrm{Tr}(\boldsymbol{W_k}) - (1-\rho_k)Tr\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)\right) \leq 0 \tag{8-2}$$

$$\log_2(1+\tau^*) - q^*\left(P_C + \mathrm{Tr}(\boldsymbol{W_k}^*) - (1-\rho_k)Tr\left(\boldsymbol{h_{1k}h_{1k}^H W_k}^*\right)\right) = 0 \tag{8-3}$$

From the previous work, we can find that:

$$\max_{\boldsymbol{W}_k, P_k, \tau} \log_2(1+\tau) - q^*\left(P_C + \mathrm{Tr}(\boldsymbol{W_k}) - (1-\rho_k)Tr\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)\right) = 0 \tag{8-4}$$

On the other hand, we prove the converse theorem of Theorem 1. From equation (8-2) and (8-3), with the information that $\boldsymbol{W}_k{}^*, P_k, \tau$ we can find:

$$\log_2(1+\tau) - q^*\left(P_C + \mathrm{Tr}(\boldsymbol{W_k}) - (1-\rho_k)Tr\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)\right) \leq$$

$$\log_2(1+\tau) - q^*\left(P_C + \mathrm{Tr}(\boldsymbol{W_k}) - (1-\rho_k)Tr\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)\right) = 0 \tag{8-4}$$

From (8-4), the inequality can imply that:

$$q^* = \frac{\log_2(1+\tau^*)}{P_C + \mathrm{Tr}(\boldsymbol{W_k}^*) - (1-\rho_k)Tr\left(\boldsymbol{h_{1k}h_{1k}^H W_k}^*\right)}$$

$$q^* \geq \frac{\log_2(1+\tau)}{P_C + \mathrm{Tr}(\boldsymbol{W_k}) - (1-\rho_k)Tr\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)} \qquad \forall\{\boldsymbol{W}_k, P_k, \tau\} \in \mathcal{F} \tag{8-5}$$

From equation (8-5), we can conclude that, the optimal resource allocation $\boldsymbol{W}_k{}^*$, $P_k{}^*, \tau^*$ for the energy efficiency are the optimal solutions for the equivalent function. In conclusion, the optimazation lets the inequivalent original function be equal to 0, and when getting equivalent of the function, the solutions is the optimal resources allocation.

9 Appendix- Proof of Theorem 2

In this section, in order to proof the theorem 2, the steps in the [65]-[66] is extremely helpful. The objective of theorem 1 is to describe the structure of matrix $\boldsymbol{W_k}^*$, we will adapted the KKD condition in this part. According to the equation (5-9)-(5-13), it can be found that $\boldsymbol{M_{c5}}^*$ is the Lagrangian multiplier matrix, which is also the null space for the columns of $\omega_k{}^*$. Therefore, in order to get the structure of the beamforming matrix, studying the rank and the null space of $\boldsymbol{M_{c5}}^*$ is essential.

According to the KKT conditions, we can get that:

$$\frac{\nabla\mathcal{L}}{\nabla \boldsymbol{W_k}} = -q\left(\frac{\nabla \mathrm{Tr}(\boldsymbol{W_k})}{\nabla \boldsymbol{W_k}} - (1-\rho_k)\frac{\nabla \mathrm{Tr}\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)}{\nabla \boldsymbol{W_k}}\right) - \mu\ \frac{\nabla \mathrm{Tr}(\boldsymbol{W_k})}{\nabla \boldsymbol{W_k}} + \kappa\frac{\nabla(1-\rho_k)\mathrm{Tr}\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)}{\nabla \boldsymbol{W_k}} - \alpha\frac{\nabla\frac{\rho_k \mathrm{Tr}\left(\boldsymbol{h_{1k}h_{1k}^H W_k}\right)}{\sigma_{ak}^2}}{\nabla \boldsymbol{W_k}} + \frac{\nabla Tr(\boldsymbol{W_k M_{c5}})}{\nabla \boldsymbol{W_k}} = 0 \quad (9\text{-}1)$$

From (9-1), the $\boldsymbol{M_{c5}}^*$ can be expressed by (8-2).

$$\boldsymbol{M_{c5}}^* = (q+\mu^*)\boldsymbol{I_N} - \left(q(1-\rho_k) + \kappa^*(1-\rho_k) + \alpha^*\frac{\rho_k}{\sigma_{ak}^2}\right)\boldsymbol{h_{1k}h_{1k}^H} \quad (9\text{-}2)$$

To make the equation simple, let $\left(\mathrm{q}(1-\rho_k) + \kappa^*(1-\rho_k) + \alpha^*\frac{\rho_k}{\sigma_{ak}^2}\right)\boldsymbol{h_{1k}h_{1k}^H} = \Gamma$, so the equation (9-2) can be rewritten to (9-3).

$$\mathrm{M_{c5}}^* = (\mathrm{q}+\mu^*)\mathrm{I_N} - \Gamma \quad (9\text{-}3)$$

It is obvious that the Γ is a hermitian matrix. And $\boldsymbol{M_{c5}}^*$ is positive semi-definite, we should hold that:

$$q+\mu^* \geq \lambda_\Gamma^{max} \geq 0 \quad (9\text{-}4)$$

In equation (9-4) $\lambda_\Gamma^{\max}$is the real-valued maximum eigenvalue of Γ. From (9-4), we can find that to proof that $\mu^* > 0$ and $q > 0$ is important. From the constrain 1 (5-9), if $\mu^* > 0$, the constrain $\mathrm{Tr}(\boldsymbol{W_k}^*) - P_{max} = 0$, so we should make $\mu^* > 0$. The same process for q, we can get that $q > 0$, so $q+\mu^* > 0$. According to the KKT conditions of $\boldsymbol{W_k}^*$, if $q+\mu^* > \lambda_\Gamma^{max}$, the matrix $\mathrm{M_{c5}}^*$ must be the full rank and positive definite, which may lead to $\boldsymbol{W_k}^* = 0$. However the beamforming matrix $\boldsymbol{W_k}^*$should not be zero, if we want to transmit successfully. In addition, due to $q+\mu^* > 0$ and $P_{max} > 0$, in order to get the optimal solution, $q+\mu^*$ has to be equal to λ_Γ^{max}, i.e., $q+\mu^* = \lambda_\Gamma^{max}$.

Now let assume $\mathrm{u}_{\Gamma,\max}$ is the unit-norm eigenvector of Γ associated with eigenvalue $\lambda_\Gamma^{\max}$. In order to get the dual solution, we can use vector $\boldsymbol{u}_{\Gamma,\max}$ to span the matrix $\boldsymbol{M_{c5}}^*$. The beamforming matrix $\boldsymbol{W_k}^*$can be written as:

$$\boldsymbol{W_k}^* = \delta\boldsymbol{u}_{\Gamma,\max}\boldsymbol{u}_{\Gamma,\max}{}^{\boldsymbol{H}} \quad (9\text{-}5)$$

Due to that $\mathrm{q}+\mu^* > 0$ and $\mathrm{P_{max}} > 0$, we can conclude that $\delta = \mathrm{P_{max}}$ and $\mathrm{Tr}(\mathbf{W_k}^*) = \mathrm{P_{max}}$ holds at the optimal solution.so:

$$\mathrm{Rank}(\mathbf{W_k}^*) = 1$$

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