SCHOOL OF ELECTRICAL ENGINEERING
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Energy-Efficient Design for Secure SWIPT Multiple-Relay Systems

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Abstract

With the development of telecommunication technology, wireless communication ability had become considerably mature in recent decades. At the same time, although the requirement of long-distance communication can be achieved due to the massive equipping of relays, the power consumption had been a problem that collects the attention of people. In addition, the location of relay stations usually is unmovable and inflexible as a result of the fixed energy supplies. Therefore, it is necessary to research a relay system based on joint information and power transmitting system with a designed transmitting protocol which could provide the long-distance service and minimum energy efficiency simultaneously. It also guarantees the security of user information in the physical layer. Aiming at this problem, this report generally introduces some previous work about two aspects, the relay system and SWIPT (Simultaneous Information and Power Transmitting) system. Hence, this paper would also introduce some relative techniques and protocols as well as their pros and cons. This report would put forward a cooperation relay model which achieves joint information and power transmitting, as the potential solution which could perform the best energy efficiency in AWGN context.

Keywords: Cooperative communication, Relay network, SWIPT, Physical layer security.

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I. Introduction

With the increasing requirement of the information and communicating service from a large group of consumers of wireless devices, the information and communication technology developed rapidly. The energy consumption of wireless devices and wireless forward nodes would be a considerable number in the foreseeable future. Simultaneously, the energy scarcity and limited carbon budget would be a bottleneck of the development of wireless communication technology. Thus, energy conservation and energy efficiency had been a hotspot of this researching aspect.

For a relay network, the energy resource is a critical problem to be resolved. Traditionally, the energy supply of a relay station always depends on the solid media such as copper cable or a fixed large-capacity-battery. It is stable enough as long as the system is established. However, it actually restricts the site selection and operating contexts such as space, ocean, forest, desert, canyon, mine, and earthquake-stricken areas, while the complexity of electricity grid built and battery recharging. As a result of this, the SWIPT system is much suitable to be employed to solve this problem.

This paper would introduce a relay system which deployed SWIPT technology in relay side. There are multiple antennas used in energy and information source (base-station). The relay stations would harvest energy from the wireless signal and forward the information signal to the destination and operated in a maximum energy efficiency condition. With the help of relays, the communicating distance could be incredibly increased. At the same time, multiple relays would provide physical secrecy.

1.1 Background

The history researching of the relay network and cooperative system could be traced back to 1971 when the article of E. C. Van der Meulen which named ‘Three terminal communication channels’ was published [1]. Immediately, the similar work had been done by T. Cover and A. El Gamal after 8 years [2]. Generally, a simple relay network is composed of three-part, which are a source, relay station, and receiver [4]-[7].

After that, cooperative wireless communication [3] became a popular aspect that plenty of research had been done in this field in recent decades. In this report, the cooperative wireless communication we researched is mainly relative to the cellular wireless network, especially about the base station. The total capacity can be increased sharply in the cellular network with the equipping of cooperative communication. Besides, not only the reliability of the network but also the wireless courage of the cellular could be improved considerably. In this way, both the uplink and downlink communication could be benefited. The cooperative wireless node could be a base station, or a fixed relay station or even a movable relay station. the data of source and CSI information might be known by the cooperative node and the cooperation action could be implemented in lower layers in the ISO 7-layer model or higher-level layer sometimes. To ameliorate the performance of the traditional cellular network, there was a mass of various methods to achieve a cooperative system, which really a promotion at the research outcomes. However, many gaps are still not solved in this aspect. In this paper, we are tending to provide further research about this aspect and trying to figure some problems out.

A new theory related to the relay-assisted system [4]-[10] which gathers a large number of distributed stations as a relay to cooperating with each other to deliver information. Generally, although there is a barrier or bad quality channel between destination and source, the signal transmitted by source would also be received by the relay station. Later on, the relay station might retransmit the same signal to the destination again. Thus, the receiver could decode the combination of the signal which is more accurate.

For the low-energy-consumption devices, wireless energy harvesting could be regarded as a replacement method of the conventional charging technology. In this way, these devices could be charged by harvesting energy from the power source in the wireless context. Briefly, this method is a kind of power transmitting technique that acquiring electromagnetic energy in wireless space. Thus, no matter the energy is aiming to transport or the surrounding electromagnetic noise energy, could be harvested by the receiver. With equipping of SWIPT [21]-[30] [90]-[92], exchanging and line-recharging of battery could be rejected. As a result of this, the more flexible and sustainable wireless communication could be achieved. However, with the processing of simultaneous wireless information and power transmitting, the increase of signal power would also provide a convenience to the eavesdropper. Because of the openness of the wireless broadcast, there would be some unexpected receiver who could also catch the message which could cause potential information divulging.

On the other hand, it sharply helps to deal with other problem, the security of wireless communication could be an implementation with wireless power transmitting by providing a security technique in the physical layer. The conventional coding technology, which usually means energy-consumption and highly computing difficulty, has its natural weakness compared with physical layer security. In addition, the encryption based on software always could be encoded eventually. Thus, physical layer security based on the fading of the wireless channel, adding jamming could be regarded as a better replacement of traditional security preventing methods. Hence, the energy signal could be used as a jamming signal to interfere with the eavesdropper, since it is a power source of other energy harvesting devices. So that, the physical layer security technique could well-integrated with SWIPT system.

1.2 Arrangement of Thesis

The main content of this proposal is described below:

In this section, it has been provided a brief description of the background of this project. It also introduces the problem that this project tending to deal with.

The second section explaining the problem detailly. The project definition would be introduced minutely

For the third chapter, it contains a serious of previous research and techniques, as well as their merit and demerit.

In the fourth section, there would be a description of the preliminary work in this semester. In this section, a potential solution would be provided.

The fifth section provides an experimental researching plan for next semester with a reasonable scheme. Then, analysis and evaluate the availability of this experiment.

The last part would provide a conclusion of the whole project.

II. Project Definition

2.1 Problem Statement

The problem is to establish a downlink cooperative relay system which could achieve joint information and power transmitting. In the second hop, to prevent the eavesdropping between relay and information destination, there would be a physical layer protecting measure in this hop. Under the situation that normal operation of the whole system is guaranteed, the energy efficiency should be maximized by transmitting protocol and time scheduling [78]-[87].

2.2 Motivation

To provide long-distance communication and high quality of service for the selected terminal, there is a requirement to design a relay system to solve this problem. At the same time, SWIPT system also helps to avoid the limitation that relay station is usually inflexible and unsustainable since its energy requirement makes unmovable. Moreover, after the establishment of communication, people start to focus on privacy and information security area.

This prompted me to design a joint information and power transmitting relay system which provides physical layer security [87]-[88].

On the other hand, with the mature of fifth-generation wireless communication, there is a large number of new technologies such as NOMA and cognize radio could be equipped to realize data rate and spectral efficiency increasing, the sustainable communication theory had also been a part of central research. Thus, there is a need to calculate a scheme to implement the maximum energy efficiency.

Personally, the wireless power transmitting technology attracts me hugely. As a part of the 5G technology revolution, it would be an amazing technique and I believe that it would change the lifestyle of human beings in one day there is a great breakthrough. The SWIPT system could liberate wireless devices form the traditional charging limitation and liberate people from where the line power exists. Thus, I think it is necessary to combine the SWIPT system with the relay system.

III. Relative Theory and Technology

3.1 Cooperative Relay Networks

3.1.1 Cooperative Communication

According to the cooperative communication system established based on Van der Meulen's relaying theory and some other contribution. It is shown in figure 3-1. In this system, the information source would communicate with the destination terminal and whatever communicate directly or by retransmitting form a relay station is available. In further research, there is a huge requirement to increase the capacity and decrease the outage probability while the data rate is constant [6]-[10]. Thus, a new cooperative protocol was raised. Following this protocol, the base station, which aims to transmit information to the destination node, would broadcast its information to the nearby base station at first. Then, the base station related to the previous stage would retransmit the message to the destination again [10]-[16]. This scheme would achieve a higher diversity degree due to the parallel channels between base stations and destination. However, due to the relays could usually be another source in some other scheme, in which the other signal it would transmit for other destination, all the nodes are receiving the noise signal during the cooperative processing.

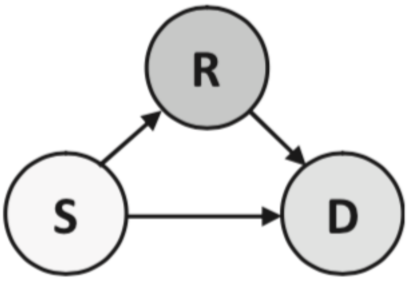

Figure 3-1 Cooperation communication system (relay channel model).

3.1.2 Relay Channel

With the introduce of cooperation communication system, the principle of relay channel had also been promoted. As the model is shown in figure 3-1, there is a communication hope between source and destination. Firstly, the information could be sent to the destination node directly from the source. Simultaneously, the relay station could also help to forward this information to the destination which is called relay-assisted transmission. In addition, the relay could send attachment into the original signal if necessary. While the link between source and destination and there is an obvious better between relay and destination, the additional path could improve the quality of service sharply [17]-[20]. Although full-duplex could not be deployed in the realistic system now and half-duplex mode is hard to provide multiplexing, the capacity increment is considerable.

3.1.3 Relay Protocol

(1) Protocol I

For the first protocol (figure 3-2), source broadcast signal to both relay and destination (solid line) in the first stage. In the next stage, relay retransmits the signal to the destination (dashed line) [48]-[50].

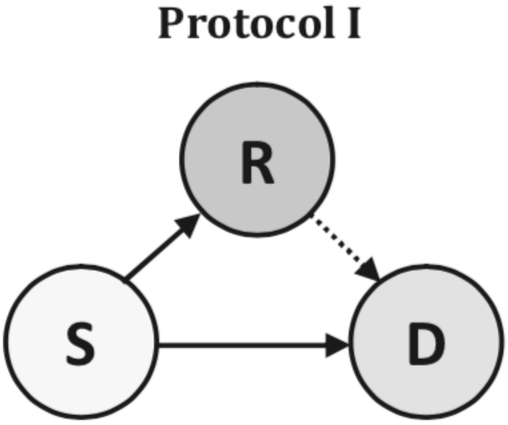

Figure 3-2 protocol I.

(2) Protocol II

In the first stage, the signal transmitted by the source only received by the relay (solid line). The destination receives nothing this time.

In the second stage, source and relay transmitting signal to destination simultaneously (dashed line). In this stage, there would be a multiple access channel between these three terminals [51][52].

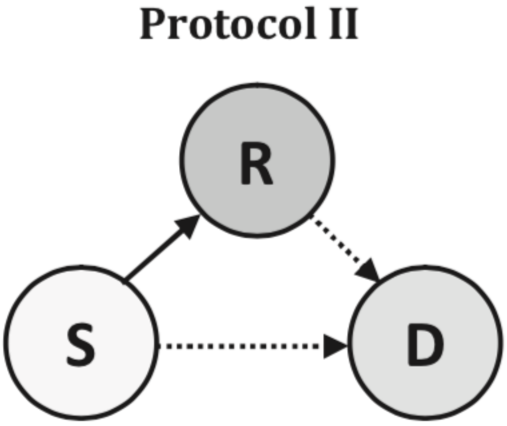

Figure 3-3 Protocol II.

(3) Protocol III

This protocol could be regarded as an assembly of the previous two protocols. It is shown in figure 3-4 below.

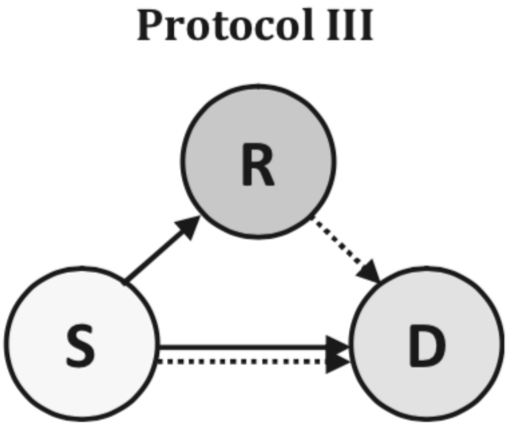

Figure 3-3 Protocol III.

In the first stage, processing as protocol I, source broadcast signal to both the relay and destination (solid line).

In the relay stage, processing as protocol II, source and relay transmitting the signal to destination simultaneously (dashed line). In this stage, the relay station has no idea of the signal sent by the source [53][54].

This protocol provides a higher spectral efficiency compared with the protocol I.

3.1.4 Strategies of Relay-assisted Transmission

To manage the transmitting rate, decoding mode and resource scheduling of relay-assisted transmission should be considered carefully. Here are some commonly used strategies used in relay-assisted systems.

(1) Amplify-and-forward (AF)

AF is the strategy that could be most easy to achieve at a relay. Without any decode processing and just after a simply amplifying, the signal could be forward to the destination directly in relay station. Thus, it is also be named non-regenerative relaying mode [55]-[60]. However, the noise received by the relay is also amplified and forwarded with the information signal together simultaneously.

(2) Decode-and-forward (DF)

Opposite with AF strategy, the DF is a regenerative relaying strategy. In this method, there is a higher requirement of the receiver’s fabrication. The relay station should recover the signal received from the source and forward it after re-coding it in this scheme. At the same time, the re-transmitted signal could be repetition coded (using the same coding algorithm as source) or unconstrained coded (using a different coding algorithm with source) [61]-[65].

(3) Compress-and forward (CF)

For the compress-and-forward scheme, relay compresses the received signal and forward it to the destination. This could be a better strategy than DF, although the complexity of the system grows considerably [66]-[70].

3.2 SWIPT

3.2.1 Wireless Power Receiver Model

Basically, the diagram of the receiver with an energy harvesting function could be generally presented as figure 3-4. The power collected by the antenna could be stored to generate the CPU of the system and as a power supply of the transceiver antennas [31]-[47].

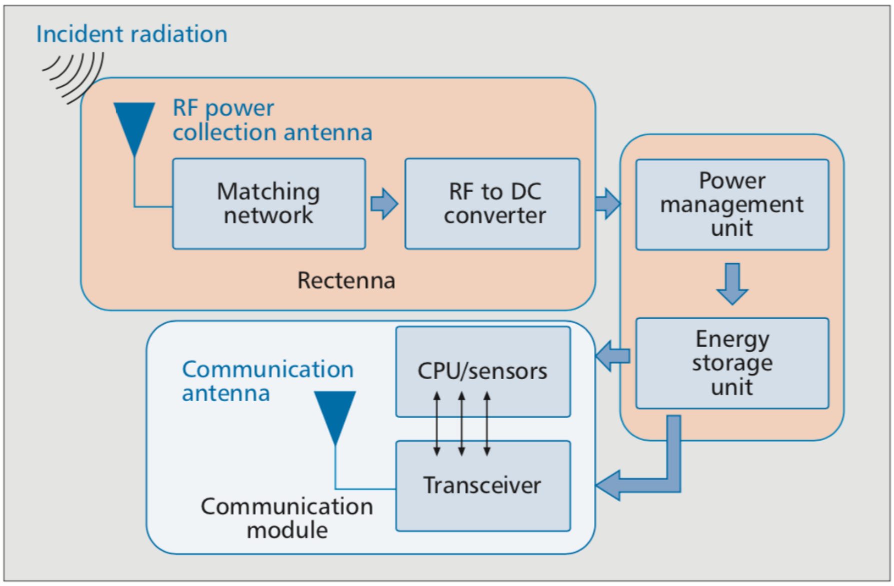

Figure 3-4 Diagram of receiver with an energy harvesting function [3].

3.2.2 Technologies of SWIPT

(1) Time switching

In this scheme, energy harvesting and signal decoding are processed in different time duration (figure 3-5). The action of the receiver is switching between energy harvesting and signal decoding. In this way, there is only one mode could be done in one time slot [31]-[37]. Although time switching is simple to implement in hardware design, there is a high requirement of the time synchronization and managing.

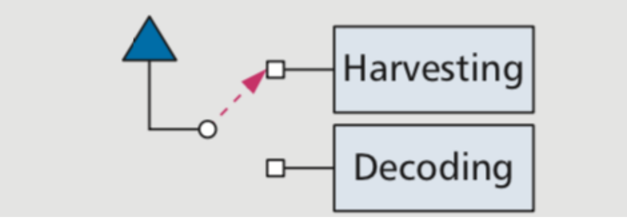

Figure 3-5 Time switching [3].

(2) Power splitting

By separating the received signal power to two streams which have different power levels. Then, a part of power is collected as energy harvesting and the other part is used to decoding the received signal directly [38]-[42]. The energy harvested could be used in further operations. Power splitting technology introduces a new factor □ which is used to divide the received signal as two streams. Compared with previous technology, this scheme presents more complexity that the power is separated into two parts to do energy harvesting and decoding at one time slot. The situation that requires less delay would be corresponding to power splitting technology.

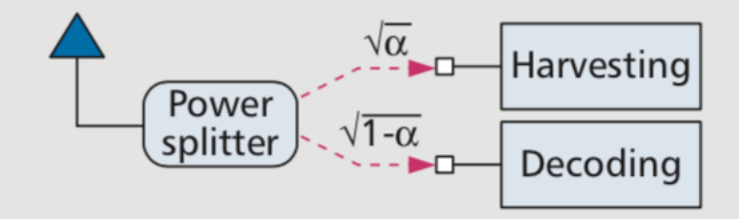

Figure 3-6 Power splitting [3].

(3) Antenna switching

Conventionally, antenna arrays (figure 2-7) are used to achieve diversity gain and multiple access in wireless systems. In antenna switching technology, the receiver antennas are separated into two groups. One group antenna is used in energy harvesting, while the other group is used to decoding. Similar to the power splitting technology, the antenna switching also needs to figure out an optimisation problem which related to the number of antennas used for each function [43]-[45].

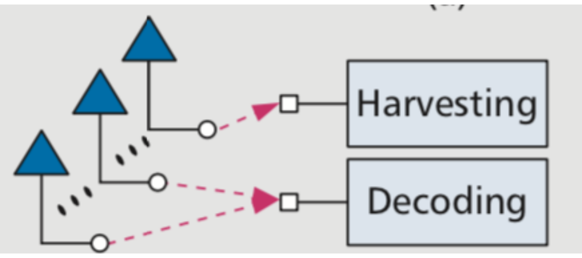

Figure 3-7 Antenna switching [3].

(4) Spatial switching

Based on the property of MIMO system, the spatial switching could be implemented which takes advantages of the degree of freedom. In theory, we can generate parallel eigenchannels with the MIMO channels [46][47]. This could be done through singular value decomposition. Generally, this scheme comes with a complex optimization problem.

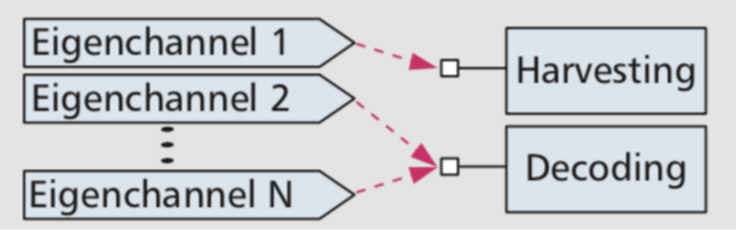

Figure 3-7 Spatial switching [3].

3.3 Artificial Noise

In theory, when we interfere an eavesdropper by adding jamming on it, quality of service of the real information receiver could be impacted less or more. If it is possible to jamming the eavesdropper and cancelling the noise influence on the receiver, the security performance would be grown sharply [71]-[75] [87]-[88]. Thus, the artificial noise could be introduced into the SWIPT system. In SWIPT system, the power transmitting signal could be used as a jamming signal directly and the other jammers could harvest energy from power transmitting signals. At the same time, as artificial noise, it could be easily cancelled in the receiver side by offering successive interference canceler (SIC).

IV. System Model

Here is a general assumption of a joint information and power transmitting relay network which is provided in figure 4-1.

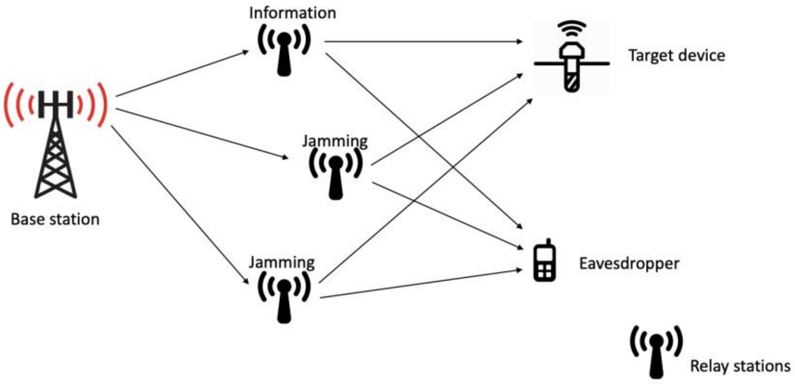

Figure 4-1 Joint information and power transmitting relay network.

The network includes 4 main components, one base station with multiple antennas, i relay stations with one antenna, a destination and an eavesdropper (both are one antenna receiver).

One thing has to be mention is that the relay strategy and power harvesting technology used in relay stations are decoding-and-forward and time switching respectively.

In space aspect, as a two hops relay system, each hop could be analysed separately. One hop is between the base station and relay station. The second hop located between the relay stations and the destination.

In time aspect, there are three time-stages. In stage τ1, the base station broadcast a power single to charging all the relay stations. In stage τ2, the base station transmits information to the k_{th} relay station and the destination. The other $j \neq k_{th}$ ($j \in i$) relay station broadcast jamming to their surrounding area. In the last stage τ_3, k_{th} relay station transmits information to destination, The other $i \neq k_{th}$ relay station broadcast jamming to their surrounding area. After received two same signals from source and the k_{th} relay station in τ_2 and τ_3 respectively, the destination and eavesdropper are deploying selective combining technique to improving the accuracy of signal decoding. Obviously, stages τ_1 happens in the first hop, τ_2 happens in both of two hops and τ_3 only happens in the second hop.

In stage τ_1, base station transmits power signal to relay stations. The schematic diagram is shown in figure 4-2.

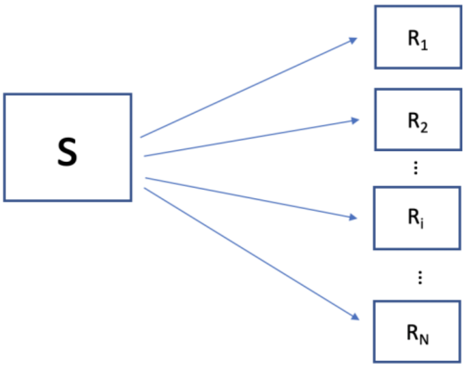

Figure 4-2 Power allocation in τ_1.

The expression function of this professing is:

$$y_R^i = \vec{h}_i^H \vec{q} + \sigma_i \qquad i \forall \,(1,2,3 \ldots N) \tag{4-1}$$

where $y_R^i, \vec{h}_i^H, \sigma_i$ are the received signal, channel coefficient matrix and AWGN noise of i_{th} relay station respectively. And $\vec{q}$ is power matrix transmitted by source base station.

In stage τ_2, base station transmits information signal to k_{th} relay station and destination. The rest $j \neq k$ $(j \in i)$ relay stations broadcast jamming signal to the surrounding area to mask information signal to the eavesdropper. The schematic diagram is shown in figure 4-3. The blue solid line and red dashed line in figure 4-3 are information signal and jamming signal respectively.

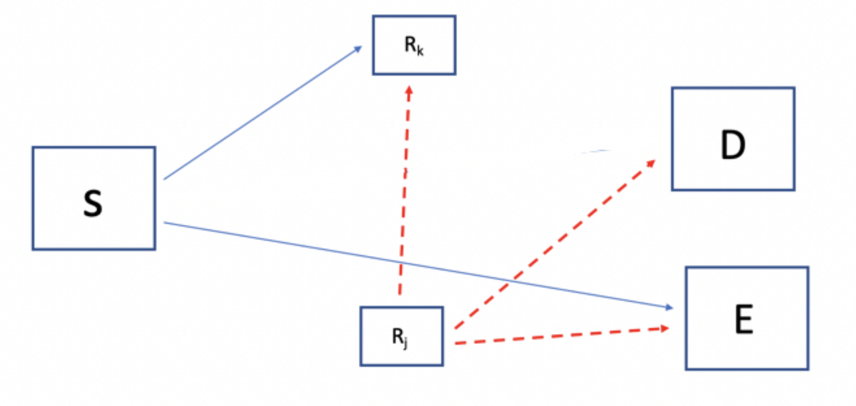

Figure 4-3 Signal transmitting in τ_2.

In this stage, the signal received by the k_{th} relay station is expressed as:

$$y_{\tau 2}^{R_K} = \vec{h}_{k,\tau 2}^H \vec{w} \vec{s} + n_{k,\tau 2} + \sum_{j \neq k} g_j^{k,\tau 2} \sqrt{P_j^R} \quad k, j \in i, \quad i \forall \,(1,2,3 \ldots N) \tag{4-2}$$

where $y_{\tau 2}^{R_K}$ and $n_{k,\tau 2}$ are signal and AWGN noise received in k_{th} relay station. $\vec{h}_{k,\tau 2}^H$ is channel coefficient of the wireless channel between source and this relay station. $\sum_{j \neq k} g_j^{k,\tau 2} \sqrt{P_j^R}$ is the jamming signal received by the k_{th} relay station, where $g_j^{k,\tau 2}$ and P_j^R are channel coefficient of j_{th} jamming relays to the k_{th} relay station and jamming signal power sent from j_{th} relay station.

The signal to interference and noise ratio (SINR) in the k_{th} relay station is presented in equation (4-3) could be calculated according to equation (4-2).

$$SINR_{k,\tau 2} = \frac{Tr(\vec{h}_{k,\tau 2}^{H}\vec{w}\vec{w}^{H}\vec{h}_{k,\tau 2})}{|n_{k,\tau 2}|^{2}} \tag{4-3}$$

The interference from the jamming signal had been cancelled by offering successive interference canceler.

The relay stations are tending to expend the transmitting distance and it is defiantly that the target receiver could acquire nothing from the base station. However, to prevent information security, jamming relay stations start to broadcast jamming to defend the eavesdropper.

The signal received by eavesdropper could be expressed as:

$$y_{\tau 2}^{E} = \vec{h}_{E,\tau 2}^{H}\vec{w}\vec{s} + n_{E,\tau 2} + \sum_{j \neq k} g_{j}^{E,\tau 2}\sqrt{P_{j}^{R}} \quad k,j \in i, \quad i \,\forall\, (\,1,2,3\,\ldots N) \tag{4-6}$$

where $y_{\tau 2}^{E}$ and $n_{E,\tau 2}$ are signal and AWGN noise received in eavesdropper. $\vec{h}_{E,\tau 2}^{H}$ is the channel coefficient of the wireless channel between source and eavesdropper. $\sum_{j \neq k} g_{j}^{E,\tau 2}\sqrt{P_{j}^{R}}$ is the jamming signal received by the eavesdropper, where $g_{j}^{E,\tau 2}$ and P_{j}^{R} are channel coefficient of j_{th} jamming relays to the eavesdropper and jamming signal power sent from j_{th} relay station.

The SINR in eavesdropper presented in equation (4-7) could be calculated according to equation (4-6).

$$SINR_{E,\tau 2} = \frac{Tr(\vec{h}_{E,\tau 2}^{H}\vec{w}\vec{w}^{H}\vec{h}_{E,\tau 2})}{|n_{E,\tau 2}|^{2} + \sum_{j \neq k}|g_{j}^{E,\tau 2}|^{2} P_{j}^{R}} \tag{4-7}$$

During stage τ_3, the k_{th} relay station continues forwarding the information signal which produced by decoding and re-coding based on the signal transmitted from source in stage τ_2. Simultaneously, the rest relay stations would transmit a jamming signal as they did in stage τ_2. The schematic diagram is shown in figure 4-4. The blue solid line and red dashed line in figure 4-4 are information signal and jamming signal respectively.

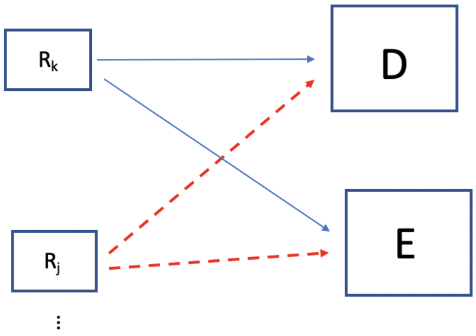

Figure 4-4 Signal transmission in τ_3.

In this stage, the signal received by destination is expressed as:

$$y_{\tau 3}^{D} = g_k^{D,\tau 3}\vec{R}\sqrt{P_k^R} + \sigma_d + \sum\nolimits_{j\neq k} g_j^{D,\tau 3}\sqrt{P_j^R} \quad k,j \in i, \quad i \;\forall\; (1,2,3 \ldots N) \tag{4-4}$$

where $y_{\tau 3}^{D}$ and σ_d are received signal and AWGN noise in destination respectively. $\vec{R}$ is transmitted signal re-coded by the $\mathrm{k_{th}}$ relay station. $g_k^{D,\tau 3}$ is the channel coefficient of the channel between the $\mathrm{k_{th}}$ relay and destination. P_k^R is the signal power transmitted by this relay station. $\sum_{j\neq k} g_j^{D,\tau 3}\sqrt{P_j^R}$ is the jamming signal received by the destination, where $g_j^{D,\tau 3}$ and P_j^R are channel coefficient of $\mathrm{j_{th}}$ jamming relays to destination and jamming signal power sent from $\mathrm{j_{th}}$ relay station.

The SINR in destination node is:

$$SINR_{D,\tau 3} = \frac{\left|g_k^{D,\tau 3}\right|^2 P_k^R}{{\sigma_d}^2} \tag{4-5}$$

The signal received by eavesdropper is expressed as:

$$y_{\tau 3}^{E} = g_k^{E,\tau 3}\vec{R}\sqrt{P_k^R} + \sigma_e + \sum\nolimits_{j\neq k} g_j^{E,\tau 3}\sqrt{P_j^R} \quad k,j \in i, \quad i \;\forall\; (1,2,3 \ldots N) \tag{4-6}$$

where $y_{\tau 3}^{E}$ and σ_d are received signal and AWGN noise in eavesdropper respectively. $\vec{R}$ is transmitted signal re-coded by the $\mathrm{k_{th}}$ relay station. $g_k^{E,\tau 3}$ is the channel coefficient of the channel between the $\mathrm{k_{th}}$ relay and the eavesdropper. P_k^R is the signal power transmitted by this relay station. $\sum_{j\neq k} g_j^{E,\tau3}\sqrt{P_j^R}$ is the jamming signal received by eavesdropper, where $g_j^{E,\tau3}$ and P_j^R are channel coefficient of j_{th} jamming relays to eavesdropper and jamming signal power sent from j_{th} relay station.

The SINR in eavesdropper node is:

$$SINR_{E,\tau3} = \frac{\left|g_k^{E,\tau3}\right|^2 P_k^R}{\sigma_e{}^2 + \sum_{j\neq k}\left|g_j^{E,\tau3}\right|^2 P_j^R} \qquad (4\text{-}7)$$

Thus, the channel capacity of the channel between source and the k_{th} relay station in $\tau2$ could be wrote as:

$$C_{\tau2,S\to k} = \log_2(1 + SINR_{k,\tau2}) \qquad (4\text{-}8)$$

The channel capacity of the channel between the k_{th} relay station and destination in $\tau3$ could be represented as:

$$C_{\tau3,k\to D} = \log_2(1 + SINR_{D,\tau3}) \qquad (4\text{-}9)$$

Obviously, there are two paths that the destination could receive the signal sent by the source. First one is the signal directly transmitted by the source in stage $\tau2$. The other one is the signal DF by relay station. The channel capacity of first path is C_1=$C_{\tau2,S\to D}$ and the second channel capacity could be expressed as a cascade channel which channel capacity is C2=min{$C_{\tau2,S\to k}, C_{\tau3,k\to D}$}. In practice, destination prefers to choose the signal to decode which with better channel state information (CSI) and this could be regard as a random selection.

Thus, the total channel capacity of the whole system could be expressed as:

$$C = \log_2\left(1 + \min\left\{SINR_{k,\tau2}, SINR_{D,\tau3}\right\}\right) \qquad (4\text{-}10)$$

The total energy consumption of this system is:

$$E = \tau 1\left[Tr(\vec{q}\vec{q}^H) - \sum_{i=1}^{N} Tr\left(\vec{h}_i^H \vec{q}\vec{q}^H \vec{h}_i\right)\right] + \tau 2\left[Tr(\vec{w}\vec{w}^H) - Tr\left(\vec{h}_k^H \vec{w}\vec{w}^H \vec{h}_k\right)\right]$$

$$+\tau 2 \sum_{j \neq k, j \in i} P_j^R + \tau 3\left(P_k^R + \sum_{j \neq k, j \in i} P_j^R\right) + P_C \tag{4-11}$$

Where Pc is power consumed by hardware. A

V. Problem Formulation

The energy efficiency is defined as ration of spectral efficiency (data rate) and total energy consumption and it is represented in equation (5-1).

$$\max_{\vec{w},\vec{q}} \mu_{EE} = \max_{\vec{w},\vec{q}} \frac{C}{E} = \max_{\vec{w},\vec{q}} \frac{log_2(1 + min\{SINR_{k,\tau 2}, SINR_{D,\tau 3}\})}{E}$$

Subjected to:

$$C_1: SINR_{k,\tau 2} \geq 2^{\frac{R_k}{\tau 2}} - 1$$

$$C_2: SINR_{D,\tau n} \geq 2^{\frac{R_D}{\tau n}} - 1 \quad n \in 2{,}3$$

$$C_3: SINR_{E,\tau m} \leq 2^{\frac{R_E}{\tau m}} - 1 \quad m \in 2{,}3$$

$$C_4: Tr(\vec{q}\vec{q}^H) \leq P_{max}^{S,\tau 1}$$

$$C_5: Tr(\vec{w}\vec{w}^H) \leq P_{max}^{S,\tau 2}$$

$$C_6: \tau 3 \cdot P_k^R \leq Tr\left(\tau 1 \cdot \vec{h}_k^H \vec{q}\vec{q}^H \vec{h}_k\right)$$

$$C_7: (\tau 2 + \tau 3) \cdot P_j^R \leq \tau 1 \cdot Tr\left(\vec{h}_j^H \vec{q}\vec{q}^H \vec{h}_j\right)$$

$$C_8: \tau 1 + \tau 2 + \tau 3 \leq T_\tau$$

$$C_9\colon \tau i \le T_\tau \quad i \in 1,2,3 \tag{5-1}$$

Where R_k, R_D, R_E are the data rate which is able to communicate for the k_{th} relay station, destination and eavesdropper respectively. $P_{max}^{S,\tau 1}$ and $P_{max}^{S,\tau 2}$ are power constrains of source in $\tau 1$ and $\tau 2$. $T\tau$ is the total time duration of once downlink communication.

The main objective of this design is to find the maximum value of μ_{EE} by adjusting the time duration of each stage and the transmitted signal power and find a balance between these factors.

VI. Optimal Solution

6.1 Convex formula transformation

As the problem formulation (5-1) is a non-convex function obviously, it is necessary to transfer it to the Lagrange duality function to acquire the optimal solution of this problem.

Before that, the original $SINR_{k,\tau 2}$ (Equation 4-3) and E (Equation 4-11) should be transferred as below:

$$SINR_{k,\tau 2} = \frac{Tr(\vec{h}_{k,\tau 2}^{H}\vec{w}\vec{w}^{H}\vec{h}_{k,\tau 2})}{\left|n_{k,\tau 2}\right|^{2}} = \frac{Tr(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_{k})}{\left|n_{k,\tau 2}\right|^{2}} \qquad (6\text{-}1)$$

$$E = \tau 1\left[Tr(\vec{q}\vec{q}^{H}) - \sum_{i=1}^{N} Tr\left(\vec{h}_{i}^{H}\vec{q}\vec{q}^{H}\vec{h}_{i}\right)\right] + \tau 2\left[Tr(\vec{w}\vec{w}^{H}) - Tr\left(\vec{h}_{k}^{H}\vec{w}\vec{w}^{H}\vec{h}_{k}\right)\right]$$

$$+\tau 2\sum_{j\neq k,j\in i} P_{j}^{R} + \tau 3\left(P_{k}^{R} + \sum_{j\neq k,j\in i} P_{j}^{R}\right) + P_{C}$$

$$= \tau 1\left[Tr(\boldsymbol{Q}) - \sum_{i=1}^{N} Tr(\boldsymbol{H}_{i}\boldsymbol{Q})\right] + \tau 2\left[Tr(\boldsymbol{W}_{k}) - Tr\left(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_{k}\right)\right]$$

$$+\tau 2\sum_{j\neq k,j\in i} P_{j}^{R} + \tau 3\left(P_{k}^{R} + \sum_{j\neq k,j\in i} P_{j}^{R}\right) + P_{C}$$

(6-2)

Where $\boldsymbol{W} = \vec{w}\vec{w}^{H}$, $\boldsymbol{H}_{k,\tau 2} = \vec{h}_{k}^{H}\vec{h}_{k}$, $\boldsymbol{Q} = \vec{q}\vec{q}^{H}$ and $\boldsymbol{H}_{i} = \vec{h}_{i}^{H}\vec{h}_{i}$.

We define that:

$$x = SINR_{End\ to\ End} = min\left\{SINR_{k,\tau 2}, SINR_{D,\tau 3}\right\}$$

$$= min\left\{\frac{Tr(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_{k})}{\left|n_{k,\tau 2}\right|^{2}}, \frac{\left|g_{k}^{D,\tau 3}\right|^{2} P_{k}^{R}}{{\sigma_{d}}^{2}}\right\}$$

(6-3)

Thus, the problem formulation could be represented as:

$$\underset{\vec{w},\vec{q}}{max}\,\mu_{EE} = \underset{\vec{w},\vec{q}}{max}\frac{C}{E} = \underset{\vec{w},\vec{q}}{max}\frac{log_{2}(1+x)}{E}$$

$$= \underset{\boldsymbol{W},\boldsymbol{Q}}{max}\frac{log_{2}(1+x)}{\tau 1\left[Tr(\boldsymbol{Q}) - \sum_{i=1}^{N} Tr(\boldsymbol{H}_{i}\boldsymbol{Q})\right] + \tau 2\left[Tr(\boldsymbol{W}_{k}) - Tr\left(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_{k}\right)\right] + \tau 2\sum_{j\neq k,j\in i} P_{j}^{R} + \tau 3\left(P_{k}^{R} + \sum_{j\neq k,j\in i} P_{j}^{R}\right) + P_{C}}$$

(6-4)

For simplification, we are able to define $\mathcal{F}$ as a collection of all variables. We can get: $\{\boldsymbol{W}_k, \boldsymbol{Q}, x, P_k^R, P_j^R\} \in \mathcal{F}$. And we use ρ^* to present the optimal energy efficiency [78]-[87]. So that the objective function can be written as:

$$\rho^* = \frac{log_2(1+x^*)}{E^*}$$

$$= \frac{log_2(1+x^*)}{\tau1[Tr(\boldsymbol{Q}^*)-\sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q}^*)]+\tau2\left[Tr(\boldsymbol{W}_k{}^*)-Tr\left(\boldsymbol{H}_{k,\tau2}\boldsymbol{W}_k{}^*\right)\right]+\tau2\sum_{j\neq k,j\in i} P_j^{R^*}+\tau3\left(P_k^{R^*}+\sum_{j\neq k,j\in i} P_j^{R^*}\right)+P_C}$$

$$= \max_{\mathcal{F}} \frac{log_2(1+x)}{\tau1[Tr(\boldsymbol{Q})-\sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q})]+\tau2[Tr(\boldsymbol{W}_k)-Tr\left(\boldsymbol{H}_{k,\tau2}\boldsymbol{W}_k\right)]+\tau2\sum_{j\neq k,j\in i} P_j^R+\tau3\left(P_k^R+\sum_{j\neq k,j\in i} P_j^R\right)+P_C}$$

(6-5)

After this process, we define a new theorem to promote the problem simplifying.

Theorem 1: *When* $\{\boldsymbol{W}_k, \boldsymbol{Q}, x, P_k^R, P_j^R\} \in \mathcal{F}$, *the optimal energy efficiency* [78]-[87] ρ^**can be obtained if and only if:*

$$max_{\mathcal{F}} \;\; log_2(1+x) - \rho^*\left[\tau1[Tr(\boldsymbol{Q}) - \sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q})] + \tau2\left[Tr(\boldsymbol{W}_k) - Tr\left(\boldsymbol{H}_{k,\tau2}\boldsymbol{W}_k\right)\right] + \tau2\sum_{j\neq k,j\in i} P_j^R + \tau3\left(P_k^R + \sum_{j\neq k,j\in i} P_j^R\right) + P_C\right]$$

$$=$$

$$log_2(1+x^*) - \rho^*\left[\tau1[Tr(\boldsymbol{Q}^*) - \sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q}^*)] + \tau2\left[Tr(\boldsymbol{W}_k{}^*) - Tr\left(\boldsymbol{H}_{k,\tau2}\boldsymbol{W}_k{}^*\right)\right] + \tau2\sum_{j\neq k,j\in i} P_j^{R^*} + \tau3\left(P_k^{R^*} + \sum_{j\neq k,j\in i} P_j^{R^*}\right) + P_C\right]$$

$$= 0$$

(6-6)

when

$$log_2(1+\tau) \geq 0,$$

and

$$\tau1[Tr(\boldsymbol{Q}^*) - \sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q}^*)] + \tau2\left[Tr(\boldsymbol{W}_k{}^*) - Tr\left(\boldsymbol{H}_{k,\tau2}\boldsymbol{W}_k{}^*\right)\right] + \tau2\sum_{j\neq k,j\in i} P_j^{R^*} + \tau3\left(P_k^{R^*} + \sum_{j\neq k,j\in i} P_j^{R^*}\right) + P_C > 0.$$

The proof of theorem 1 is provided in the appendix.

According to 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:

$$max_{\mathcal{F}} \;\; log_2(1+x) - \rho^{*}\left[\tau 1[Tr(\boldsymbol{Q}) - \textstyle\sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q})] + \tau 2\left[Tr(\boldsymbol{W}_k) - Tr\left(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_k\right)\right] + \right.$$

$$\left. \tau 2 \textstyle\sum_{j\neq k, j\in i} P_j^R + \tau 3\left(P_k^R + \textstyle\sum_{j\neq k, j\in i} P_j^R\right) + P_C\right]$$

$$C1: Tr(\boldsymbol{Q}) \leq \; P_{max,t1}$$

$$C2: Tr(\boldsymbol{W}_k) \leq \; P_{max,t2}$$

$$C3: x \; \geq \; \frac{Tr(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_k)}{\left|n_{k,\tau 2}\right|^2}$$

$$C4: x \; \geq \; \frac{\left|g_k^{D,\tau 3}\right|^2 P_k^R}{{\sigma_d}^2}$$

$$C5: \frac{Tr\left(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_k\right)}{\left|n_{k,\tau 2}\right|^2} \geq 2^{\frac{R_k}{\tau n}} - 1$$

$$C6: \frac{\left|g_k^{D,\tau 3}\right|^2 P_k^R}{{\sigma_d}^2} \geq 2^{\frac{R_D}{\tau n}} - 1$$

$$C7: \frac{\left|g_k^{E,\tau 3}\right|^2 P_k^R}{{\sigma_e}^2 + \sum_{j\neq k}\left|g_j^{E,\tau 3}\right|^2 P_j^R} \leq 2^{\frac{R_E}{\tau 3}} - 1$$

$$C8: \frac{Tr\left(\boldsymbol{H}_{E,\tau 2}\boldsymbol{W}_k\right)}{\left|n_{E,\tau 2}\right|^2 + \sum_{j\neq k}\left|g_j^{E,\tau 2}\right|^2 P_j^R} \leq 2^{\frac{R_E}{\tau 2}} - 1$$

$$C9: \tau 3 \cdot P_k^R \leq \; \tau 1 \cdot Tr(\boldsymbol{H}_k\boldsymbol{Q})$$

$$C10: (\tau 2 + \tau 3)P_j^R \leq \tau 1 \cdot Tr\left(\boldsymbol{H}_j\boldsymbol{Q}\right)$$

$$C11: \boldsymbol{W}_k \geq 0$$

$$C12: \boldsymbol{W}_k \geq 0$$

(6-7)

After the operation before, the problem formulation had been transferred as a convex optimization problem.

6.2 Convex optimization

Generating the Lagrange dual function of problem formula (6-7) as below:

$$\begin{aligned}\mathcal{L} = {} & log_2(1+x) - \rho\big[\tau 1[Tr(\boldsymbol{Q}) - \textstyle\sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q})] + \tau 2\big[Tr(\boldsymbol{W}_k) - Tr\big(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_k\big)\big] + \\ & \tau 2 \textstyle\sum_{j\neq k, j\in i} P_j^R + \tau 3\big(P_k^R + \textstyle\sum_{j\neq k, j\in i} P_j^R\big) + P_C\big] - \lambda_1\big[Tr(\boldsymbol{Q}) - P_{max,t1}\big] - \\ & \lambda_2\big[Tr(\boldsymbol{W}_k) - P_{max,t2}\big] + \lambda_3\left[x - \frac{Tr\big(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_k\big)}{|n_{k,\tau 2}|^2}\right] + \lambda_4\left[x - \frac{\left|g_k^{D,\tau 3}\right|^2 P_k^R}{\sigma_d{}^2}\right] + \\ & \lambda_5\left[\frac{Tr\big(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_k\big)}{|n_{k,\tau 2}|^2} - \left(2^{\frac{R_k}{\tau n}} - 1\right)\right] + \lambda_6\left[\frac{\left|g_k^{D,\tau 3}\right|^2 P_k^R}{\sigma_d{}^2} - \left(2^{\frac{R_D}{\tau n}} - 1\right)\right] - \lambda_7\left[\frac{\left|g_k^{E,\tau 3}\right|^2 P_k^R}{\sigma_e{}^2 + \sum_{j\neq k}\left|g_j^{E,\tau 3}\right|^2 P_j^R} - \right. \\ & \left.\left(2^{\frac{R_E}{\tau 3}} - 1\right)\right] - \lambda_8\left[\frac{Tr\big(\boldsymbol{H}_{E,\tau 2}\boldsymbol{W}_k\big)}{|n_{E,\tau 2}|^2 + \sum_{j\neq k}\left|g_j^{E,\tau 2}\right|^2 P_j^R} - \left(2^{\frac{R_E}{\tau 2}} - 1\right)\right] - \lambda_9[\tau 3 \cdot P_k^R - \tau 1 \cdot \\ & Tr(\boldsymbol{H}_k\boldsymbol{Q})] + \lambda_0\big[(\tau 2 + \tau 3)P_j^R - \tau 1 \cdot Tr\big(\boldsymbol{H}_j\boldsymbol{Q}\big)\big] + \boldsymbol{W}_k \cdot \boldsymbol{M}_W + \boldsymbol{Q} \cdot \boldsymbol{M}_Q\end{aligned}$$

(6-8)

Where $\boldsymbol{M_M} \succcurlyeq \mathbf{0}, \boldsymbol{M}_Q \succcurlyeq \mathbf{0}$ are Lagrange multiplier matrixes in respect to the constrain 11 and 12 respectively. In addition, $\lambda_i \geq \mathbf{0}$, $i \in [0,9]$ are Lagrange multipliers corresponding to the C1 to C4 respectively. The dual problem is transformed to:

$$\min_{\substack{\boldsymbol{M_M}, \boldsymbol{M}_Q, \lambda_i \\ i\in[0,9]}} \max_{\mathcal{F}} \mathcal{L}$$

(6-9)

Due to the fact that $\mathcal{L}$ is a convex function, the KKT conditions will be the necessary and sufficient conditions for the optimal solution to the problem.

$$\lambda_1\left[Tr(\boldsymbol{Q}^*) - P_{max,t1}\right] = 0$$

$$\lambda_2\left[Tr({\boldsymbol{W}_k}^*) - P_{max,t2}\right] = 0$$

$$\lambda_3\left[x - \frac{Tr\left(\boldsymbol{H}_{k,\tau2}{\boldsymbol{W}_k}^*\right)}{\left|n_{k,\tau2}\right|^2}\right] = 0$$

$$\lambda_4\left[x - \frac{\left|g_k^{D,\tau3}\right|^2 P_k^{R*}}{{\sigma_d}^2}\right] = 0$$

$$\lambda_5\left[\frac{Tr\left(\boldsymbol{H}_{k,\tau2}{\boldsymbol{W}_k}^*\right)}{\left|n_{k,\tau2}\right|^2} - \left(2^{\frac{R_k}{\tau n}} - 1\right)\right] = 0$$

$$\lambda_6\left[\frac{\left|g_k^{D,\tau3}\right|^2 P_k^{R*}}{{\sigma_d}^2} - \left(2^{\frac{R_D}{\tau n}} - 1\right)\right] = 0$$

$$\lambda_7\left[\frac{\left|g_k^{E,\tau3}\right|^2 P_k^{R*}}{{\sigma_e}^2 + \sum_{j\neq k}\left|g_j^{E,\tau3}\right|^2 P_j^{R*}} - \left(2^{\frac{R_E}{\tau 3}} - 1\right)\right] = 0$$

$$\lambda_8\left[\frac{Tr\left(\boldsymbol{H}_{E,\tau2}{\boldsymbol{W}_k}^*\right)}{\left|n_{E,\tau2}\right|^2 + \sum_{j\neq k}\left|g_j^{E,\tau2}\right|^2 P_j^{R*}} - \left(2^{\frac{R_E}{\tau 2}} - 1\right)\right] = 0$$

$$\lambda_9\left[\tau3 \cdot P_k^{R^*} - \tau1 \cdot Tr(\boldsymbol{H}_k\boldsymbol{Q}^*)\right] = 0$$

$$\lambda_0\left[(\tau2 + \tau3)P_j^{R^*} - \tau1 \cdot Tr\left(\boldsymbol{H}_j\boldsymbol{Q}^*\right)\right] = 0$$

$${\boldsymbol{W}_k}^* \cdot {\boldsymbol{M}_W}^* = 0$$

$$\boldsymbol{Q}^* \cdot {\boldsymbol{M}_Q}^* = 0$$

(6-10)

Here $\lambda_i \geq \boldsymbol{0}$, $i \in [0,9]$ are the optimal Lagrange multipliers and ${\boldsymbol{M}_Q}^*, {\boldsymbol{M}_W}^*$ are the optimal Lagrange multiplier matrixes.

Theorem 2: *If* $P_{max,t2} > 0$ *and the problem formulation (5-1) has the optimal solution, the rank of optimal beamforming matrix* $\boldsymbol{W_k}$ *ought to be one. i.e.* $Rank(\boldsymbol{W_k}^*) = 1.$ *If* $P_{max,t1} > 0$ *and the problem formulation (5-1) has the optimal solution, the rank of optimal beamforming matrix* $\boldsymbol{Q}$ *ought to be one. i.e.* $Rank(\boldsymbol{Q}^*) = 1.$

Which means the optimal beamformer $q^*$and w^*can be obtained by performing eigenvalue decomposition of $\boldsymbol{W_k}^*$, $\boldsymbol{Q}^*$ and selecting the principal eigenvector as the beamformer.

VII. Simulation results

To provide an assessment of the performance of this design, it is necessary to process a project simulation. For this project, we randomly select one of the N relay stations as the data relay station, and the rests are used for security. The simulation parameters are given in table-1.

Table-1 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	$\eta = 0.5$

Figure 7-1 represents the relationship between average achievable energy efficiency, maximum transmit power and number of antennas used in the base station. It is obvious that the number of antennas contributes much to the performance of the system. Generally, the more antennas, the higher energy efficiency which means better performance. In addition, for each scenario with 3,6,9 antennas, the variation of the trend between average achievable energy efficiency and maximum transmit power are similar. They all approximately achieve the optimal energy efficiency at the same x-axle point when the maximum transmits power achieves 14 dBm. Before that, the achievable energy efficiency keeps raising with the increasing of maximum transmit power. The number of antennas also impact the increasing rate of average energy efficiency.

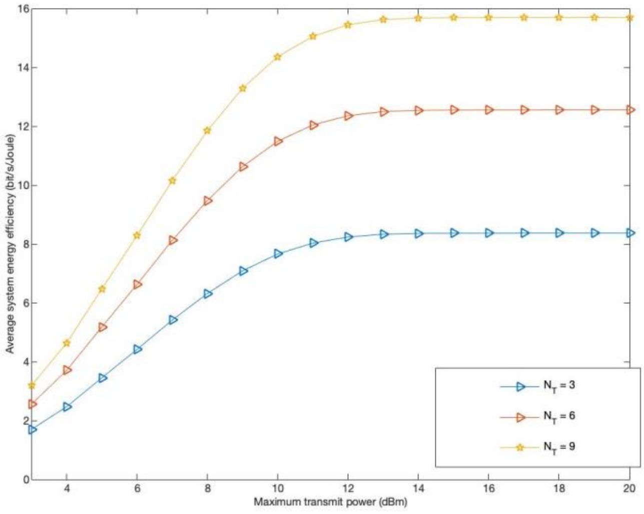

Figure 7-1 Average achievable energy efficiency verse the maximum transmit power with 3,6,9 antennas in base station.

The relationship of average achievable rate efficiency and the number of iterations in different maximum transmit power while the 9 antennas are employed in base station is shown in Figure 7-2.

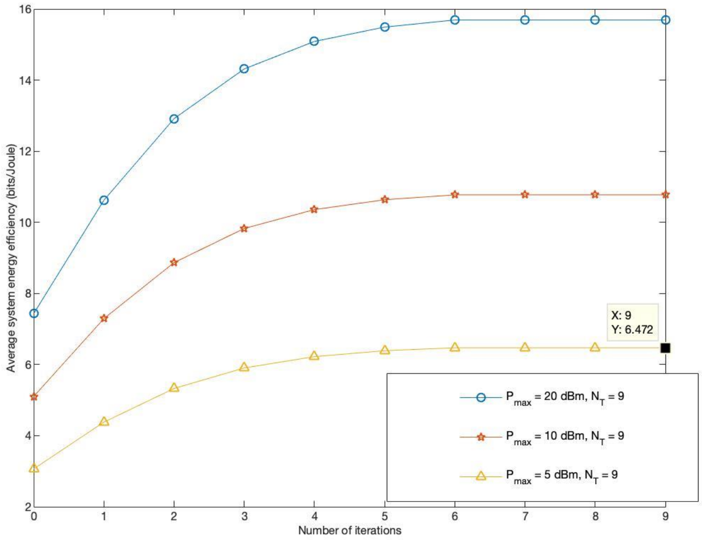

Figure 7-2 Average achievable rate efficiency verse the number of iterations.

The number of iterations generally describes the convergence rate of the iterative algorithms which is used to resolve the problem of this project. With the increase in the number of iterations, the difference between various maximum transmits power is to keep growing while the number of iterations is slower. This phenomenon continuous until the iteration times grows to about 6 times. The energy efficiency and the difference between energy efficiencies with different maximum power become stable which represents that it reaches the convergence state in 6 iterations. The most import thing it shows is that the larger power allocated could provide a better convergence performance.

VIII. Conclusion

This paper researches an optimal problem related to the energy efficiency of a SWIPT relay system. The whole system is divided into 3 parts, which are a base station with multiple antennas, N relay stations with one antenna and receivers (target receiver and eavesdropper). One of the relay stations are chosen as data transmitting node and the rests are used to deploy jamming signal to provide physical layer security. Simultaneously, a decent resource allocation algorithm which is tending to maximize the energy efficiency for this system was established. As a non-convex optimization problem, the optimal algorithm is resolved with the help of the LaGrange dual law and KKT conditions in the last chapter. After a series of the simulation process, the simulation results indicate that the number of antennas employed in the base station impacts the average energy efficiency considerably. In conclusion, this paper represents a practical SWIPT relay system with optimal energy efficiency which also provided a physical layer security function to prevent signal security in far-end.

Appendix

Proof of theorem 1

According to the Dinkelbach method [74][93], the theorem 1 could be proven easily. As shown before,

we have defined that $\mathcal{F}$ as a collection of all variables. Thus, $\{\boldsymbol{W}_k, \boldsymbol{Q}, x, P_k^R, P_j^R\} \in \mathcal{F}$, and we use ρ^* to present the optimal energy efficiency. Therefore, the original objective function could be wrote as:

$$\rho^* = \frac{log_2(1 + x^*)}{E^*}$$

$$= \frac{log_2(1+x^*)}{\tau 1\left[Tr(\boldsymbol{Q}^*) - \sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q}^*)\right] + \tau 2\left[Tr({\boldsymbol{W}_k}^*) - Tr\left(\boldsymbol{H}_{k,\tau 2}{\boldsymbol{W}_k}^*\right)\right] + \tau 2\sum_{j\neq k, j\in i} P_j^{R^*} + \tau 3\left(P_k^{R^*} + \sum_{j\neq k, j\in i} P_j^{R^*}\right) + P_C}$$

$$\geq \max_{\mathcal{F}} \frac{log_2(1+x)}{\tau 1\left[Tr(\boldsymbol{Q}) - \sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q})\right] + \tau 2\left[Tr(\boldsymbol{W}_k) - Tr\left(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_k\right)\right] + \tau 2\sum_{j\neq k, j\in i} P_j^{R} + \tau 3\left(P_k^{R} + \sum_{j\neq k, j\in i} P_j^{R}\right) + P_C}$$

(9-1)

Then, equation (9-2) and (9-3) could be obtained from (9-1):

$$log_2(1 + x^*) - \rho^*\left[\tau 1[Tr(\boldsymbol{Q}^*) - \sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q}^*)] + \tau 2\left[Tr({\boldsymbol{W}_k}^*) - Tr\left(\boldsymbol{H}_{k,\tau 2}{\boldsymbol{W}_k}^*\right)\right] + \tau 2\sum_{j\neq k, j\in i} P_j^{R^*} + \tau 3\left(P_k^{R^*} + \sum_{j\neq k, j\in i} P_j^{R^*}\right) + P_C\right] = 0$$

(9-2)

$$log_2(1 + x) - \rho^*\left[\tau 1[Tr(\boldsymbol{Q}) - \sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q})] + \tau 2\left[Tr(\boldsymbol{W}_k) - Tr\left(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_k\right)\right] + \tau 2\sum_{j\neq k, j\in i} P_j^{R} + \tau 3\left(P_k^{R} + \sum_{j\neq k, j\in i} P_j^{R}\right) + P_C\right] \leq 0$$

(9-3)

Thus, it is obvious that:

$$\max_{\mathcal{F}}\ log_2(1 + x) - \rho^*\left[\tau 1[Tr(\boldsymbol{Q}) - \sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q})] + \tau 2\left[Tr(\boldsymbol{W}_k) - Tr\left(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_k\right)\right] + \tau 2\sum_{j\neq k, j\in i} P_j^{R} + \tau 3\left(P_k^{R} + \sum_{j\neq k, j\in i} P_j^{R}\right) + P_C\right] = 0$$

(9-4)

Simultaneously, with the combining with equation (9-3), the relationship of these two equations could be represented as equation (9-5).

$$log_2(1+x)-\rho^*\left[\tau 1[Tr(\boldsymbol{Q})-\sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q})]+\tau 2\left[Tr(\boldsymbol{W}_k)-Tr\left(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_k\right)\right]+\right.$$
$$\left.\tau 2\sum_{j\neq k,j\in i} P_j^R+\tau 3\left(P_k^R+\sum_{j\neq k,j\in i} P_j^R\right)+P_C\right]\leq$$
$$log_2(1+x^*)-\rho^*\left[\tau 1[Tr(\boldsymbol{Q}^*)-\sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q}^*)]+\tau 2\left[Tr({\boldsymbol{W}_k}^*)-Tr\left(\boldsymbol{H}_{k,\tau 2}{\boldsymbol{W}_k}^*\right)\right]+\right.$$
$$\left.\tau 2\sum_{j\neq k,j\in i} P_j^{R^*}+\tau 3\left(P_k^{R^*}+\sum_{j\neq k,j\in i} P_j^{R^*}\right)+P_C\right]=0$$

(9-5)

It could be transfer as:

$$\rho^*=\frac{log_2(1+x^*)}{\tau 1\left[Tr(\boldsymbol{Q}^*)-\sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q}^*)\right]+\tau 2\left[Tr({\boldsymbol{W}_k}^*)-Tr\left(\boldsymbol{H}_{k,\tau 2}{\boldsymbol{W}_k}^*\right)\right]+\tau 2\sum_{j\neq k,j\in i} P_j^{R^*}+\tau 3\left(P_k^{R^*}+\sum_{j\neq k,j\in i} P_j^{R^*}\right)+P_C}$$

$$\rho^*\geq\frac{log_2(1+x)}{\tau 1\left[Tr(\boldsymbol{Q})-\sum_{i=1}^{N} Tr(\boldsymbol{H}_i\boldsymbol{Q})\right]+\tau 2\left[Tr(\boldsymbol{W}_k)-Tr\left(\boldsymbol{H}_{k,\tau 2}\boldsymbol{W}_k\right)\right]+\tau 2\sum_{j\neq k,j\in i} P_j^R+\tau 3\left(P_k^R+\sum_{j\neq k,j\in i} P_j^R\right)+P_C}$$

(9-6)

According to this equation s, we find that, the solution of the optimal energy efficiency could be defined by optimal resource schedule $\{{\boldsymbol{W}_k}^*,\boldsymbol{Q}^*,x^*,P_k^{R^*},P_j^{R^*}\}\in\mathcal{F}^*$. Thus, this optimization makes the original equation equals to 0, which the optimal resource allocation could be achieved [89].

Proof of theorem 2

As the equation (6-8) is a convex function with respect to the optimization variables. As a result of this, the KKT conditions could be employed to figure this problem[94][95]. In addition, the concertation of the KKT condition is with ${\boldsymbol{W}_k}^*$ and $\boldsymbol{Q}^*$**.**

(1) Proof of $rank({\boldsymbol{W}_k}^*) = 1$

KKT conditions that are need for peove:

$$ {\boldsymbol{W}_k}^* \cdot {\boldsymbol{M}_W}^* = 0 \tag{9-7} $$

$$ {\boldsymbol{M}_W}^* \succcurlyeq 0 \tag{8} $$

After the derivation that the partial derivative of equation (6-8) with respect to $\boldsymbol{W}_k$ and set it equals to 0, we could get the formula of ${\boldsymbol{M}_W}^*$ which is given by equation (9-9).

$$ \begin{aligned} {\boldsymbol{M}_W}^* &= (\rho^* \cdot \tau 2 + {\lambda_2}^*) I_N - \left[\rho^* \cdot \tau 2 - \frac{{\lambda_3}^*}{\left|n_{k,\tau 2}\right|^2} + \frac{{\lambda_5}^*}{\left|n_{k,\tau 2}\right|^2}\right] H_{k,\tau 2} + \frac{{\lambda_8}^*}{{\sigma_e}^2 + \sum_{j \neq k} \left|g_j^{E,\tau 3}\right|^2 P_j^R} \cdot H_{E,\tau 2} \\ &= \boldsymbol{A} - \left[\rho^* \cdot \tau 2 - \frac{{\lambda_3}^*}{\left|n_{k,\tau 2}\right|^2} + \frac{{\lambda_5}^*}{\left|n_{k,\tau 2}\right|^2}\right] H_{k,\tau 2} \end{aligned} \tag{9-9} $$

where $\boldsymbol{A} = (\rho^* \cdot \tau 2 + {\lambda_2}^*) I_N + \frac{{\lambda_8}^*}{{\sigma_e}^2 + \sum_{j \neq k} \left|g_j^{E,\tau 3}\right|^2 P_j^R} \cdot H_{E,\tau 2}$ and ${\boldsymbol{M}_W}^*\ and\ {\lambda_2}^*, {\lambda_3}^*, {\lambda_5}^*, {\lambda_8}^* \geq 0$ are optimal Lagrange multipliers for equation (6-8) and . Equation (9-8) is complementary slackness condition and is satisfied when the columns of ${\boldsymbol{W}_k}^*$ lay in the null space of ${\boldsymbol{M}_W}^*$. Thus, while $rank({\boldsymbol{M}_W}^*) = N_t - 1$ and ${\boldsymbol{W}_k}^* \neq 0$, it could be proved that $rank({\boldsymbol{W}_k}^*) = 1$. Therefore, the eigenvalue decomposition of ${\boldsymbol{W}_k}^*$ could be directly used to find the optimal w^*.

The original problem currently translates to a problem which is to prove that $\boldsymbol{A}$ is a full-rank matrix with its $rank(\boldsymbol{A}) = N_t$.

Suppose $\boldsymbol{A}$ is a rank deficient matrix with at least one zero eigenvalue and we denote the associated eigenvector as u. Without loss of generality, we create a matrix $\boldsymbol{U} = uu^H$ from the eigenvector. By multiplying both sides of equation (9-9) with $\boldsymbol{U}$ and applying the trace operator, we obtain that:

$$Tr(\boldsymbol{M}_W{}^*\boldsymbol{U}) = Tr(\boldsymbol{AU}) - \left[\rho^* \cdot \tau 2 - \frac{\lambda_3{}^*}{\left|n_{k,\tau 2}\right|^2} + \frac{\lambda_5{}^*}{\left|n_{k,\tau 2}\right|^2}\right] Tr(H_{k,\tau 2}\boldsymbol{U})$$

$$= -\left[\rho^* \cdot \tau 2 - \frac{\lambda_3{}^*}{\left|n_{k,\tau 2}\right|^2} + \frac{\lambda_5{}^*}{\left|n_{k,\tau 2}\right|^2}\right] Tr(H_{k,\tau 2}\boldsymbol{U})$$

(9-10)

Where $\boldsymbol{u}$ is generated from the null space of $\boldsymbol{A}$ and $Tr(\boldsymbol{AU}) = \mathrm{Tr}(u\boldsymbol{A}u^H) = 0$.

We defined that $\rho^*, \lambda_3{}^*, \lambda_5{}^* \geq 0$ and assume that $\rho^* \cdot \tau 2 - \frac{\lambda_3{}^*}{\left|n_{k,\tau 2}\right|^2} + \frac{\lambda_5{}^*}{\left|n_{k,\tau 2}\right|^2}$. Then, it could be proved that $Tr(H_{k,\tau 2}\boldsymbol{U}) \geq 0$. We note that $h_{E,\tau 2}$ belongs to the subspace of $\boldsymbol{A}$ because $\frac{\lambda_8{}^*}{\sigma_e{}^2 + \sum_{j \neq k}\left|g_j^{E,\tau 3}\right|^2 P_j^R} \geq 0$, and $h_{E,\tau 2}$ and $h_{k,\tau 2}$ are independent. So that, the probability that $h_{E,\tau 2}$ and $h_{k,\tau 2}$ share the same null space is equal to 0 since $Tr(H_{k,\tau 2}\boldsymbol{U}) \neq 0$. As a consequence, for the right side of equation (9-10), $H_{k,\tau 2}$ should be a positive semidefinite matrix, which means $Tr\left(H_{k,\tau 2}\boldsymbol{U}\right) > 0$ and $-\left[\rho^* \cdot \tau 2 - \frac{\lambda_3{}^*}{\left|n_{k,\tau 2}\right|^2} + \frac{\lambda_5{}^*}{\left|n_{k,\tau 2}\right|^2}\right] Tr\left(H_{k,\tau 2}\boldsymbol{U}\right) < 0$.

Simultaneously, for the left side of equation (9-10), while $\boldsymbol{M}_W{}^*$ is a positive semidefinite matrix and $Tr(\boldsymbol{M}_W{}^*\boldsymbol{U}) \geq 0$ which is different with the right side of this equation, matrix $\boldsymbol{A}$ could be derived as a full-rank matrix with its rank equals to N_t.

After that, according to equation (9-9), we can derive that:

$$rank(\boldsymbol{M}_W{}^*) + rank\left(\left[\rho^* \cdot \tau 2 - \frac{\lambda_3{}^*}{\left|n_{k,\tau 2}\right|^2} + \frac{\lambda_5{}^*}{\left|n_{k,\tau 2}\right|^2}\right] H_{k,\tau 2}\right)$$

$$\geq rank\left(\boldsymbol{M}_W{}^* + \left[\rho^* \cdot \tau 2 - \frac{\lambda_3{}^*}{\left|n_{k,\tau 2}\right|^2} + \frac{\lambda_5{}^*}{\left|n_{k,\tau 2}\right|^2}\right] H_{k,\tau 2}\right)$$

$$= rank(\boldsymbol{A}) = N_t \Rightarrow rank(\boldsymbol{M}_W{}^*) \geq N_t - 1$$

(9-11)

Finally, it is obvious that $\boldsymbol{W}_k{}^* \neq 0$, which conduct that $rank(\boldsymbol{W}_k{}^*) = 1$.

(2) Proof of $rank(\boldsymbol{Q}^*) = 1$

Similar to the previous proof of $rank(\boldsymbol{W}_k{}^*) = 1$, we find the KKT condition satisfies that:

$$\boldsymbol{Q}^* \cdot \boldsymbol{M}_Q{}^* = \boldsymbol{0} \tag{9-11}$$

$$\boldsymbol{M}_Q{}^* \succcurlyeq \boldsymbol{0} \tag{9-12}$$

The

$$\boldsymbol{M}_Q{}^* = (\rho^* \cdot \tau1 + \lambda_1{}^*)I_N + \rho^* \cdot \tau2 \cdot \sum_{i=1}^{N} H_i - \lambda_9{}^* \cdot \tau1 \cdot H_k + \lambda_0{}^* \cdot \tau1 \cdot H_j \tag{9-13}$$

After the derivation that the partial derivative of equation (6-8) with respect to $\boldsymbol{W}_Q$ and set it equals to 0, we could get the formula of $\boldsymbol{M}_Q{}^*$ which is given by equation (9-9).

With the same calculation proves of section (1), we can also prove that $rank(\boldsymbol{Q}^*) = 1$.

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