Abstract

Cooperative cognitive radio networks (CCRN) has been proposed to increase the utilization rate of spectrum resources. But its implementation in practice is compromised because of the power constrained problem of secondary user (SU). For solving the problem, this paper introduces a wireless powered CCRN system, in which the secondary transmitter (ST) can harvest energy from both energy signal and information signal. And the ST can get paid by providing decode-and-forward (DF) services for PU, but it has to pay for the harvested energy. This paper aims to maximize the payoff of ST by jointly designing the beamforming vectors, power splitting ratio, power allocation factor and the selection of energy access points (EAP). Meanwhile, this paper also proposes an algorithm to reduce the operation complexity in the progress of selecting EAPs. And the proposed algorithm can achieve good performance, which can be proved by the simulation results.

Acknowledgment

First and foremost, I would like to thank my supervisor, Professor Arumugam Nallanathan, for his guidance, support and constant encouragement. He provided me many useful papers and guided me to have my own idea from existing technologies. And he keeps giving me help and encouragement when I am doing the project. I am lucky to meet my tutor.

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I would like to thank Dr. Xing Hong. She has a clever brain and she is proficient in wireless communication. Her experience and help throughout my thesis were invaluable.

I would like to thank my parents and grandparents, for their constant support and endless love.

I would like to thank my girlfriend, Yvonne, for her care and encouragement in my oversea study life.

Last but not least, I would like to thank all the friend than I met in U.K, for the wonderful time we spent together.

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Nomenclature

CR: Cognitive radio
CCRN: Cooperative cognitive radio network
PU: Primary user
SU: Secondary user
PT: Primary transmitter
ST: Secondary transmitter
PU: Primary receiver
SR: Secondary receiver
SWIPT: Wireless power and information transfer
WPCN: Wireless powered communication network
MIMO: Multiple-input-multiple-output
DF: Decode-and-forward
EAP: Energy access point
WET: Wireless energy transfer
WD: Wireless device
HAP: Hybrid access point
CSI: Channel state information
ER: Energy receiver
SNR: Signal-to-noise ratio
SSCR: Spectrum-sensing cognitive radio
SH: Spectrum hole
OCR: Overlay cognitive radio
UCR: Underlay cognitive radio
AF: Amplify-and-forward
SINR: Signal-to-interference-plus-noise ratio
R_{PR}: The rate requirement of primary receiver (bps/Hz)
R_{SR}: The rate requirement of secondary receiver (bps/Hz)
P_0: The power of energy access point (W)
P_P: The power of primary transmitter (W)
c_1: The reward parameter (dB)
c_2: The consumption parameter (dB)

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Chapter 1: Introduction

1.1. Motivation

With the development of mobile communication and wireless communication, the number of mobile users and traffic demand increase rapidly. The demand for wireless spectrum resources is also increasing. However, lots of spectrum resources are idle and wasted in time and frequency domain in different extent because of the existing fixed spectrum allocation mechanism. According to the data provided by the Federal Communications Commission [16], the average spectrum utilization rate is 5.2% in the frequency band from 3GHz to 30GHz. Even for the city which has the highest utilization rate, the figure is only 13.1%. This situation restricts the development of wireless communication.

Cognitive radio technique makes the unlicensed user can access the authorized frequency band in the case of ensuring the communication quality of primary user. And in Cooperative cognitive radio network (CCRN), some unlicensed secondary users can help relaying primary user's traffic to improve the diversity when they are allowed to access the frequency band. In return, unlicensed users which provide the relaying service can also access the frequency band and get paid. This results in a "win-win" situation and greatly increases the utilization rate of the spectrum resources. But the secondary transmitters are usually power constrained and it will limit the performance of the system.

Recent advances in wireless energy transfer technology make remotely charging possible. Besides, simultaneously wireless power and information transfer (SWIPT) technology and wireless powered communication network (WPCN) technology can further improve the efficiency of the system. With the help of these techniques, ST can harvest energy remotely, which solve the power constrained problem. So, we are planning to apply these wireless energy transfer technologies into the CCRN system to achieve both information-level and energy-level cooperation.

In addition, we assume that secondary transmitter can get paid by providing relaying service for primary user but it has to pay for the harvested energy. We plan to maximize the payoff of secondary transmitter by jointly designing the system parameters.

1.2. Aim & objectives

1. Design the system model that combines cooperative cognitive radio network with wireless powered communication network. In this system, the secondary transmitter can harvest energy remotely.
2. Jointly design the system parameters to maximize the payoff of the secondary transmitter.
3. Design an algorithm to achieve a balance between operation complexity and system performance.
4. Do simulation to prove the efficiency of the proposed algorithm, and analyze the simulation results.

1.3. Contribution

In this paper, we consider a CCRN system with a decode-and-forward (DF) relay, and the relay is powered by both primary transmitter and multi-antenna wireless energy access points (EAP). In order to improve the efficiency of both energy and information transfer, we also apply multiple-input-multiple-output (MIMO) and energy beamforming technology into the system. In this system, secondary users have the access to share the spectrum with primary users. In return, secondary user need to provide relaying service for primary user to increase the spatial diversity.

The main contribution of this paper can be summarized as follows:

1. Design the system model that combine s cooperative cognitive radio network with wireless powered communication network to solve the power constrained problem for secondary transmitter.
2. From the economic perspective of secondary user, this paper investigates a payoff maximization problem. The secondary user can get paid by providing relaying services for primary user, but it has to pay for the harvested energy from EAP.
3. Jointly design the energy beamforming vector, power splitting ratio, power allocation factor over two time slots and selections of EAPs to maximize the payoff of secondary user.
4. Introduce an algorithm to reduce the operation complexity during selecting the EAPs. And the algorithm can also achieve good performance, which can be proved by the simulation results.

1.4. Report structure

Chapter 2 provides the technique background of this project. It introduces the previous technologies and existing algorithm in the areas related to my project. And it analyzes the pros and cons of these technologies and then explains why we choose them in this project.

Chapter 3 describes the system model we have designed. It introduces the structure of the model and explains the communication progress in detail. And it uses the mathematical expression to represent the communication progress and the payoff optimization problem.

Chapter 4 explains how we simplify the original optimization problem and how we solve the problems step by step. It also introduces the proposed algorithm, which can greatly reduce the operation complexity.

Chapter 5 provides the simulation results of this project to prove the efficiency of the algorithms we proposed. It also gives the precise settings of the parameters and explanation for each simulation.

Chapter 6 provides a conclusion of this paper.

Chapter 2: Background & Literature Review

2.1. Wireless Powered Communication Part

2.1.1. Wireless Energy Transfer Techniques

In recent years, with the development of new media and mobile communication technology like YouTube, Instagram, 4G, 5G, the data volume of the wireless communication system increases exponentially. This results in large energy consumption. But mobile devices are often powered by batteries with limited capacity and sometimes it is inconvenient to replace or recharge the batteries, which limits the lifetime and the performance of wireless system.

Wireless energy transfer (WET) technique can be used to fixed this problem by supplying stable energy remotely. Base on different physical mechanism, WET technologies can be divided into three types [3]: electromagnetic radiation, magnetic resonant coupling and inductive coupling. Magnetic resonant coupling and inductive coupling both have high power density and high transfer efficiency but their performance drop rapidly with the increase of the distance. So, they are not suitable for mobile and remote charging. Instead, electromagnetic radiation (especially RF wave) doesn't has this limitation. Its far-field properties make it possible that receivers can harvest energy from the RF waves remotely. In addition, the traditional energy harvesting techniques that harvest energy from the natural environment (such as solar, wind, pyroelectric effect and other physical phenomena) can be easily affected by location and climate. Using RF signals can avoid this kind of influence. So, RF-enabled WET is widely used in low-power wireless systems like wireless sensor network.

2.1.2. Simultaneous Wireless Information and Power Transfer (SWIPT)

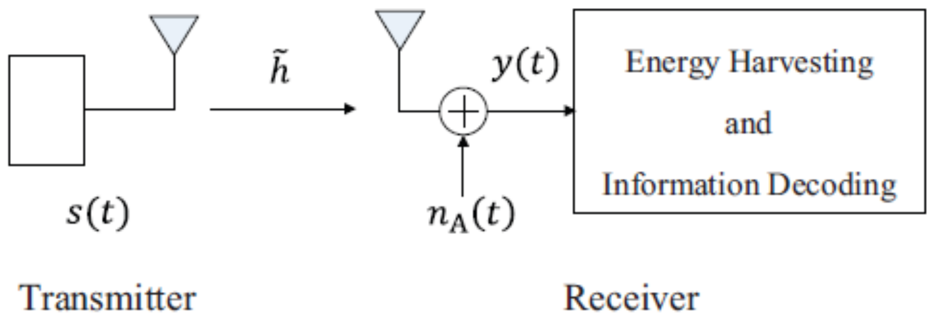

Figure 1. The structure of SWIPT system

Because RF signal can carry both information and energy, [1] and [2] introduce a new paradigm called simultaneous wireless information and power transfer (SWIPT) that combine wireless power transfer and information transmission. In SWIPT system, the transmitter sends wave to the receiver, which include both information and energy. And the receiver can harvest energy from the information carrying signals, which is more efficient in spectrum usage than transmitting information and energy in orthogonal time or frequency channels.

2.1.3. Structure of Practical Receiver

Base on different requirements, there are different kinds of receiver. [4] and [5] introduced the structures of different receiver and tested their performances.

Power splitting receiver and time switching receiver

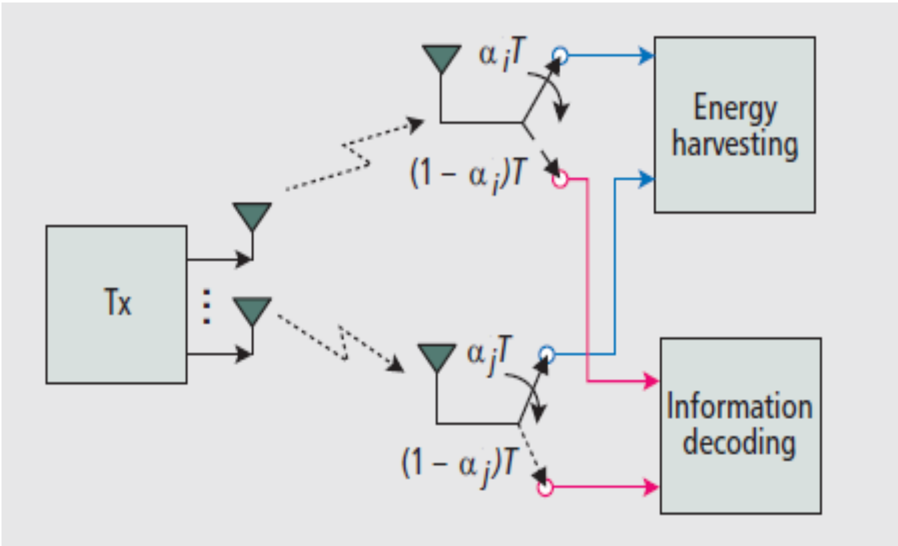

Figure 2. The structure of time switching receiver

As we can see in the figure.2, in the time switching receiver, there is a switcher in front of the energy harvester and the information decoder. Base on the time switching factor α and transmission duration T, it decides the time allocation for energy harvesting and information decoding. And we can adjust these parameters to meet different requirements. However, there is only one module can work at the same time. In practice, this feature will result in seamed communication, which is not suitable for some networks like cooperative cognitive radio network.

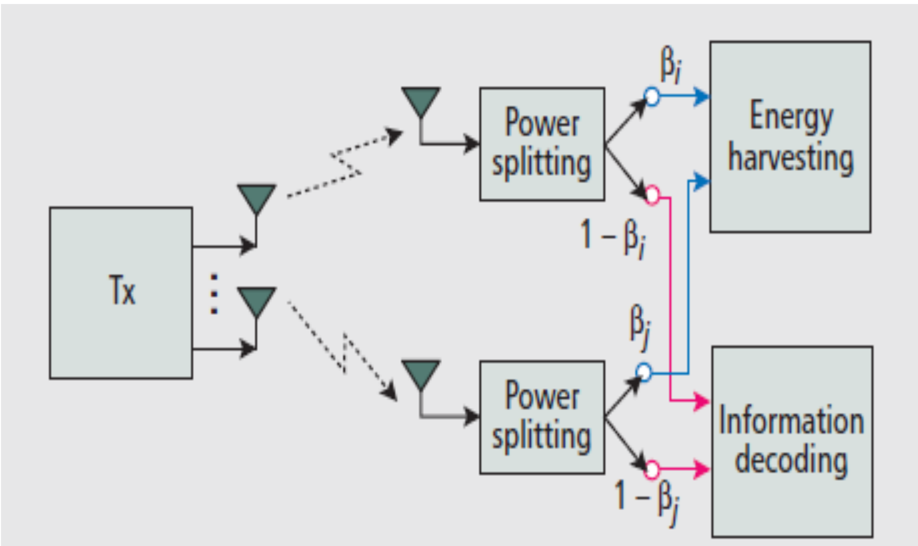

Figure 3. The structure of power splitting receiver

In the power splitting receiver, there is power splitting module in front of the energy harvester and the information decoder. β is the dynamic power splitting ratio. After RF signals are received by the antenna, power splitting module splits it into two power streams base on β (β part of the RF signals for energy harvesting and 1 − β part for information decoding). This kind of receiver has simple structure and it can do energy harvesting and information decoding simultaneously. So, power splitting receiver is widely used in practice and we also use it in this paper.

Separated receiver and integrated receiver

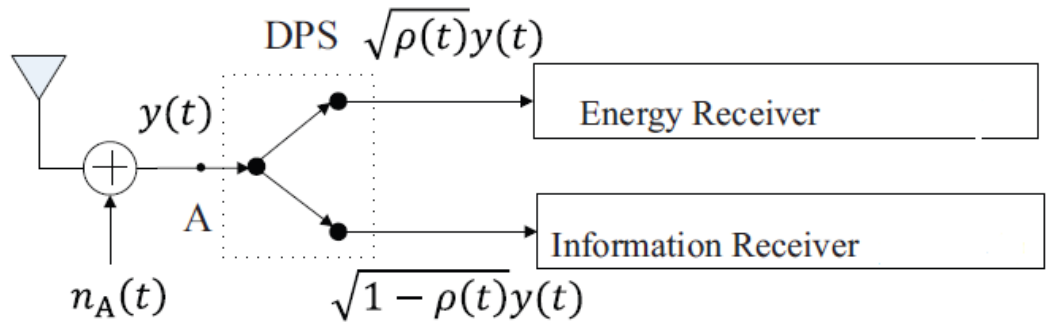

Figure 4. The structure of separated receiver

As we can see in the figure.4, there is a power splitter at point 'A'. The received signal y(t) is split into two signal streams in the RF band base on the dynamic power splitting ratio. Then the signal streams are sent to the energy receiver and information receiver for energy harvesting and information decoding, respectively.

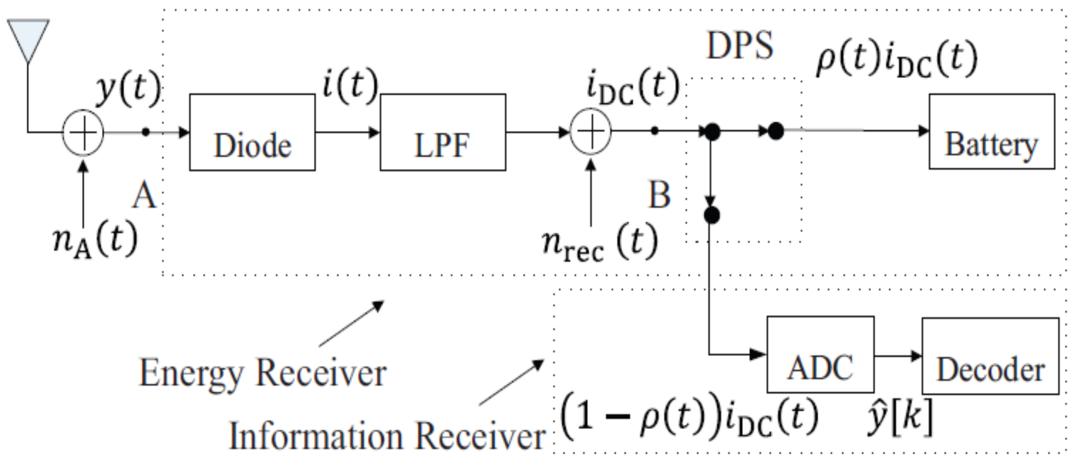

Figure 5. The structure of integrated receiver

As we can see in the figure.5, the RF signal are first converted into direct current by the diode and the low-pass filter. Then it comes to the power splitter. Part of the direct current is used for battery charging, and the rest part is used for information decoding. It can only do non-coherent detection because of direct current.

According to the results in [5], the integrated receiver saves more energy than the separated receiver. However, the separated receiver performs better than the integrated receiver when the data-rate is high. In addition, the structure of the separated receiver is simpler. So, we use the separated receiver in this paper.

2.1.4. Wireless Powered Communication Network

SWIPT can transfer information and energy simultaneously in the downlink. However, it will bring a heavy burden on the information transmitter when receiver require lots of energy. [6] introduce a new paradigm called wireless powered communication network (WPCN) which transfer energy in downlink and transfer information in the uplink.

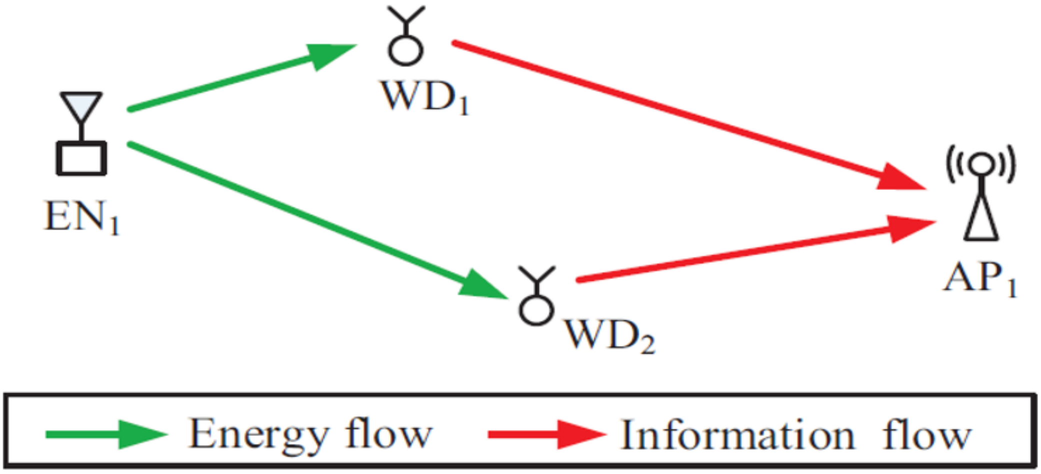

Figure 6. The system model of WPCN

As shown in figure.6, in a WPCN system, the energy node (or energy access point) transmits wireless energy to wireless devices (WD) in the downlink. Then, the wireless devices harvest energy from EN and use the energy to send information to the information access point. Compare with SWIPT, WPCN reduce the power burden on information transmitter by using pure energy access point.

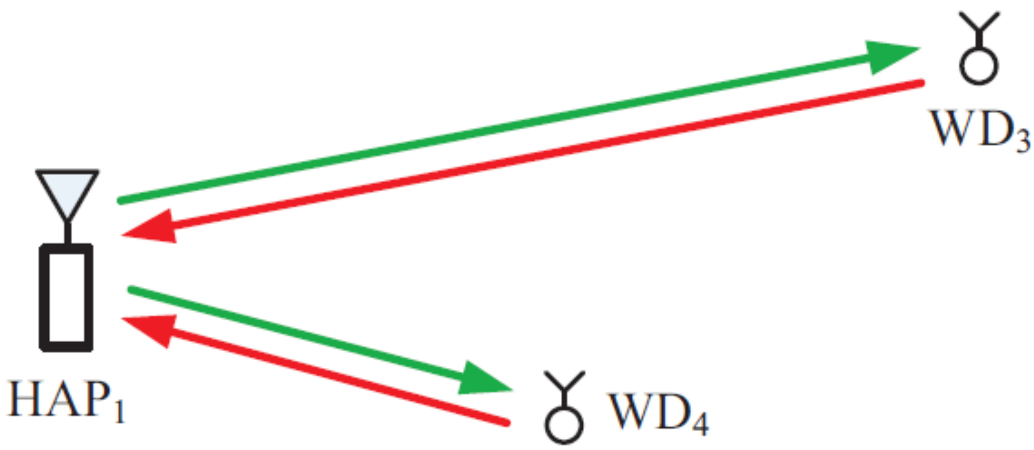

Figure 7. The system model of HAP

It can also integrate the EN and AP into a Hybrid access point (HAP) like figure. This structure can save the production fee, but it brings a double-near-far problem when two wireless devices have different distance away from HAP. Compare with the near user, far user harvests less energy in the downlink but needs to consume more energy to transmit information to HAP in the uplink, which is not fair.

2.1.5. Key Techniques in Wireless Powered Communication Network

To make WPCN or SWIPT system more efficient, some key techniques are introduced in [6] and [7].

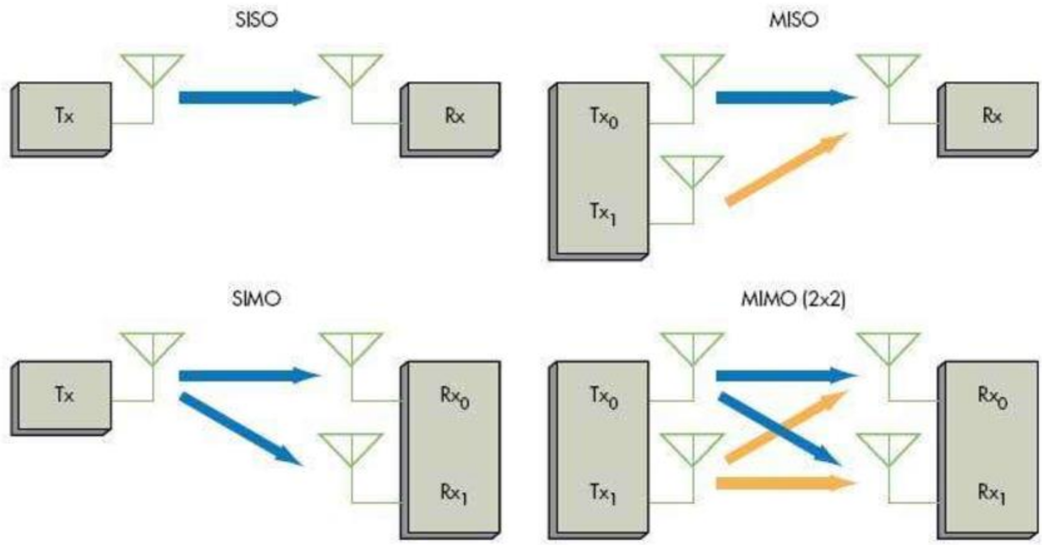

Figure 8. The model of SISO, MISO, SIMO, MIMO(2x2)

As shown in the figure. Multiple-input-multiple-output (MIMO) is a kind of technique that uses multiple antennas to transmit and receive signals at transmitter and receiver, respectively. MIMO technology can be broadly divided into two categories [7], spatial diversity and spatial multiplexing. Multiple antennas are used to increase the spatial diversity to overcome the channel fading. Signals that carry the same information are sent to receiver through different path, then multiple independent fading signals are received in the receiver, which can increase the reliability of reception and the quality of services. Different with spatial diversity, spatial multiplexing divides the high rate date flow into multiple low rate flows at the transmitter and send these low rate data flows by different transmitting antennas in the same frequency band. It can exponentially increase the information rate without increasing the bandwidth.

Because of these obvious advantages, we also apply the MIMO technology in this paper.

Only using the MIMO technology is not enough. WPT generally requires highly direction transmission [6]. For fixed large devices, dish or horn high-gain antennas are used to focus the energy in a narrow energy beams towards the receiver to increase the energy efficiency. For mobile devices, energy beamforming is more suitable in dynamic channel environment.

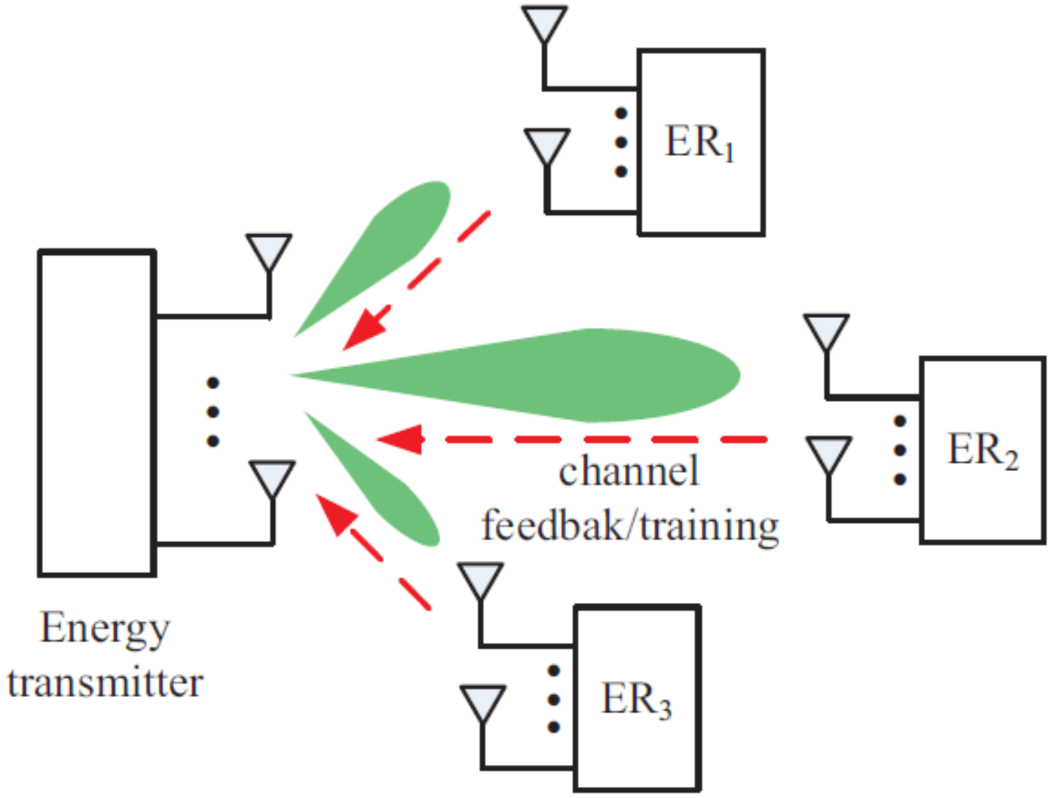

Figure 9. The model of energy beamforming

In order to maximize the received power, transmitter need to know the channel state information (CSI), which include the magnitude and phase shift from the energy transmitter to the energy receiver (ER). And the CSI can be normally obtained by channel estimation and channel feedback. After transmitter knows the CSI, it uses multiple antennas to focus strong energy beam in the communication direction to increase the SNR and focus week energy beam in the interference direction to decrease the co-channel interference.

The signal-interference-plus-noise ratio at the receiver can be greatly increased by applying the MIMO and energy beamforming. So, we can apply these two technologies in SWIPT or WPCN systems to improve the performance of the system.

2.2. Cognitive Radio Part

2.2.1. Cognitive Radio

In [8], the concept of cognitive radio was first proposed, cognitive radio was considered a highly intelligent Radio Knowledge Representation Language (RKRL)-based wireless telecommunication system. RKRL was used to provide a standard way to represent a variety of radio resources and protocols (include software modules, communication protocols, customer requirements, application scenarios, etc.), which make the reset of radio etiquette more convenient. In this paper, Dr. Mitola proposed a cognitive cycle model. the outside world provides stimuli and the cognitive ratio extracts the available contextual cues necessary for the performance of its assigned tasks base on these stimuli. As we can see in the figure.1, the main steps include observe, learn, plan, decide and act. This kind of cognitive radio requires wireless communication system can aware and reconfigure all possible system parameters, so it was called full cognitive radio (FCR).

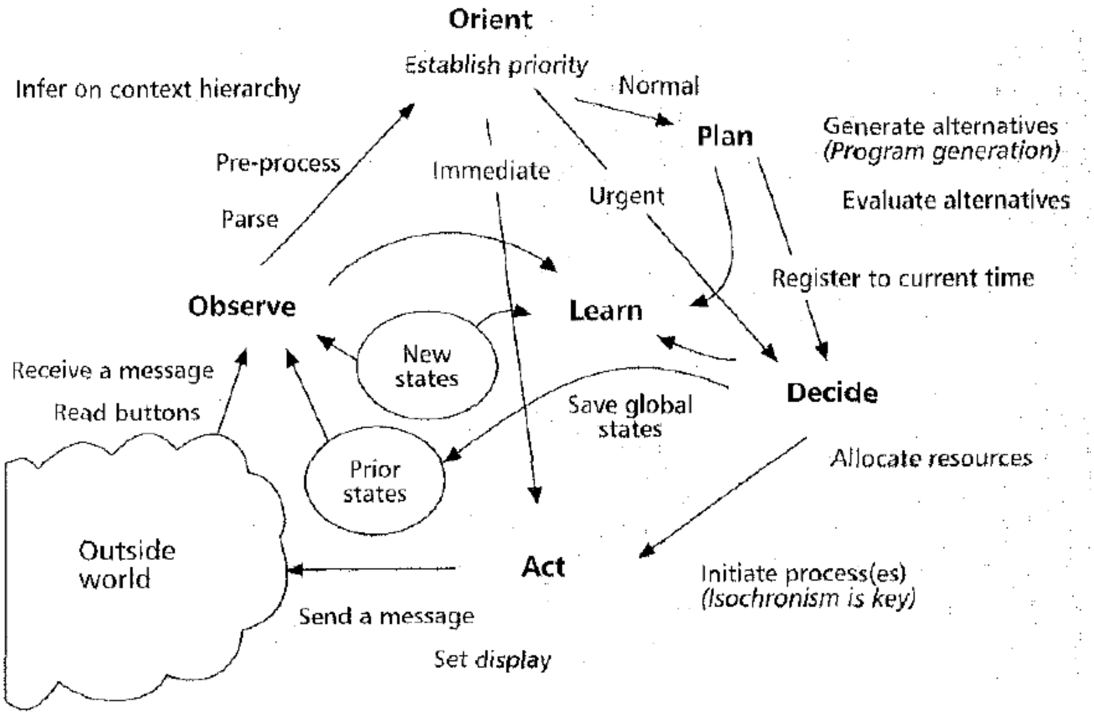

Figure 10. The cognitive cycle model proposed by Dr. Mitola

In addition to the cognitive radio proposed by Dr. Mitola, there is a kind of spectrum-sensing cognitive radio (SSCR). According to the survey results of the Federal Communications Commission (FCC), the utilization rate of large number of authorized spectrum is very low. On the other side, the demand for wireless communications is growing greatly, which results in the shortage of spectrum resources. SSCR is main used to solve the problem caused by the limit spectrum resources and the low utilization rate of authorized spectrum. In SSCR system, unauthorized user is called secondary user (SU). SU can know the authorized channel is idle or busy in a given time period or area by spectrum sensing. If the authorized channel is idle, it exists a spectrum hole (SH) in this channel and the SU can use the detected SH to communicate. It can greatly increase the utilization rate of the spectrum.

In [9], author defined the cognitive radio as a kind of intelligent wireless communication system. It can sense the surrounding environment, then make the state of internal system can be adapted to the change of surrounding environment by reconfiguring its own system operation parameters (include transmitting power, carrier frequency, modulation scheme, etc.). The author also proposed a kind of cognitive cycle. As we can see in the figure.2, the cognition process can be divided into three main functions: (1) Radio-scene analysis, it mainly includes the interference temperature estimation and spectrum holes detection. (2) Channel identification, it mainly includes the channel state information (CSI) estimation and channel capacity prediction. (3) Transmit-power control and dynamic spectrum management.

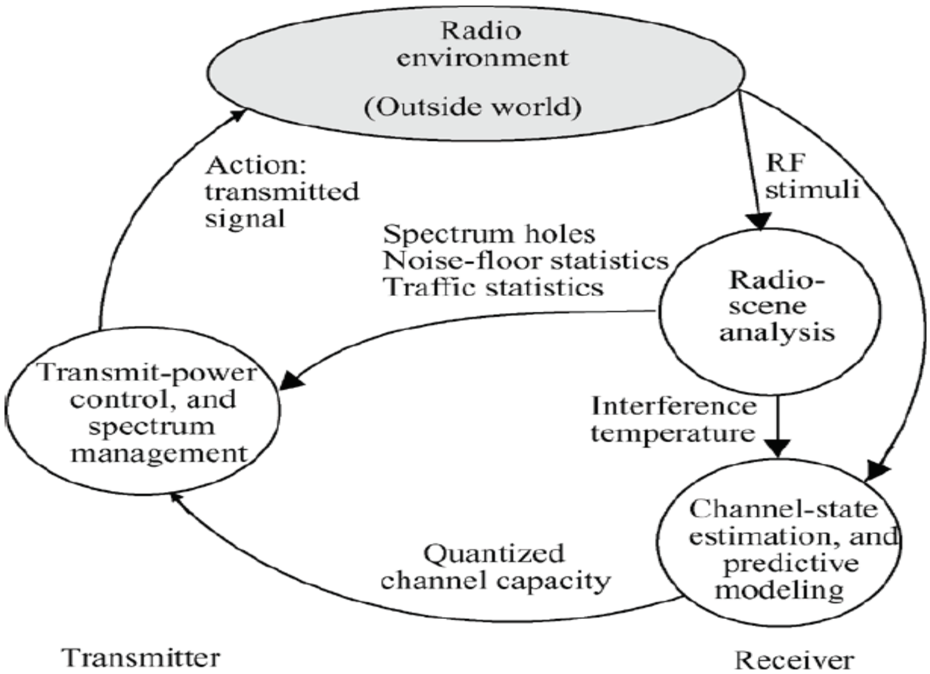

Figure 11. The cognitive cycle model proposed by S. Haykin

The receiver takes charge of function (1) and (2) and the transmitter is responsible for function (3).

Federal Communication Commission also gave its definition of cognitive radio [11]: cognitive radio is a kind of radio that can interact with external environment and adjust the parameters of the transmitter. Cognitive radio was seen as a key technique for the implementation of next-generation networks. It makes heterogeneous radio system have the opportunity to share spectrum resource. The main functions of cognitive radio are summarized as follows [12]:

(1) Spectrum sensing, which is used to detect the SH to realize spectrum sharing mechanism without introducing harmful interference to primary user.
(2) Spectrum management, which is used to find the best available spectrum to meet users' communication requirements.
(3) Spectrum switching, which is used to ensure the seamless communication service during switching the frequency band.
(4) Spectrum sharing, which is used to ensure the fairness of spectrum scheduling.

According to different spectrum sharing method, cognitive ratio can be further divided into two categories [10]: overlay cognitive radio (OCR) and underlay cognitive radio (UCR). For OCR, the secondary user is allowed to use the authorized frequency band only when the primary user is not using this frequency band, which means that the cognitive user can only use the detected spectrum hole to communicate. For UCR, the secondary user can access all the authorized frequency band under the condition that the quality of service for primary user is higher than the requirements.

2.2.2. Cooperation Cognitive Radio Network

In recent years, a kind of new paradigm for cognitive radio system called cooperative cognitive radio networks (CCRN) has been advocated. CCRN further improve the efficiency of cognitive radio network through the information- level cooperation between primary user and second user. CCRN enables some unlicensed secondary users to help relaying primary traffic for primary users when they are allowed to access the frequency band. The transmission rate of the primary users can be greatly increased because of the improvement of the diversity. And the second users which provide the relaying service can also get paid. This results in a “win-win” situation. [13] proposed a new two-time-slot spectrum sharing protocol. The primary user uses part of power to send the information in the first time slot, and uses the rest of power to send a copy in the secondary time slot. The secondary user receives primary user’s message in the first time slot, then it allocates different power to send primary user’s information and its own information in the second time slot. This method increases the diversity of the communication. The primary receiver can compare the messages received in two time slot, which increases the quality of the service.

Secondary user act as a relay in CCRN, and CCRN can be treated as a relay-assisted network. Base on different operation mode, relay can be divided into two types [14]: amplify-and-forward (AF) relay and decode-and-forward (DF) relay. AF relay only linearly amplify the received signal, which can implement the spatial diversity. But it also amplifies the noise in the channel. For DF relay, it will recode the received signal firstly, then re-encode it and send this message to receiver. So, it will not amplify the noise in the channel. But it may mistakenly recode the received signal when the quality of the communication is bad. So, when the quality of the communication is good, it is suitable to apply the DF relay (secondary user) in the CCRN to further increase the SNR of the system.

2.3. Combination of Cooperative Cognitive Radio Network and Wireless Powered Communication

At present, SWIPT and CCRN technologies are both the hot topic in wireless communication area. But the performance of CCRN system is limited by the power constraint of the wireless devices especially the secondary users. With the development of wireless energy transfer, this problem can be solved by applying the SWIPT technology into CCRN system. [15] studied the information and energy cooperation in CCRN. The primary transmitter sends information to second transmitter for relaying service, which can also feed the secondary transmitter at the same time. So, the spectrum resources can be better utilized. This mechanism is particularly suitable and useful when the secondary transmitter is energy constrained and has good channel quality. [15] also compared the performance of power splitting scheme and time switching scheme in wireless powered CCRN systems. Base on the simulation results, the system applying power splitting scheme performs better when the system has a high efficiency of energy transfer. The simulation results also prove that the system enabling both energy-level and information-level cooperation in CCRN outperforms than the system only applying information cooperation.

Chapter 3: System Design

3.1. Overview of System Model

In this paper, we consider a CCRN system with a decode-and-forward (DF) relay, and the relay is powered by both primary transmitter and multi-antenna wireless EAPs. In order to improve the efficiency of both energy and information transfer, we also apply MIMO and energy beamforming technology into the system. In this system, secondary users have the access to share the spectrum with primary users. In return, secondary user need to provide relaying service for primary user to increase the spatial diversity.

This wireless powered CCRN system consists of primary user, secondary user and EAPs. The primary user can be divided into primary transmitter and primary receiver, which is denoted by PU and PR in the figures and functions. Similarly, the secondary user can be divided into secondary transmitter and secondary receiver, which can be denoted by SU and SR. And the ST is energy constrained, which is powered by harvesting energy from EAP and PT. PT and PR only have one antenna. And ST and SR are equipped with M and N antennas, respectively. There are K EAPs in the system, and we denote the number of antennas at the k-th EAP is N_k . The communication process can be divided into two time slots. At the first time slot, PT use a fraction of power to transmit signal to PR, ST and SR. Both PR and ST receive the signal, then recode the signal to get information. And ST keep harvesting energy from PR and EAP during the first time slot. In the second time slot, the PT use the rest of power to send a copy of the previous signal to PR. And ST use the harvested energy to re-encode PT's message and send it together with its own message to PR and SR. The system model is shown as below.

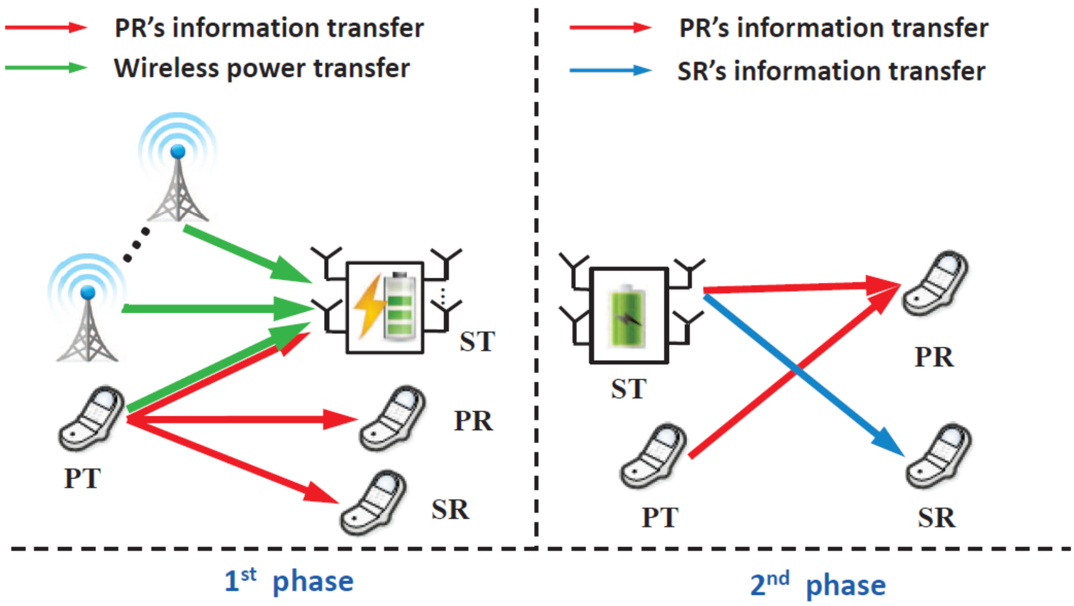

Figure 12. The system model of this project

3.2. The First Time Slot

The signal transmitted from PT is denoted by s. And we use s_k to denote the energy signal transmitted from the k-th EAP. $x_k \in C^{N_k \times 1}$ is the energy beamforming vector from the k-th EAP. So, $x_k s_k$ can be used to denote the energy signal from the k-th EAP.

We also introduce a parameter ρ_k to indicate the selection of the EAPs. When $\rho_k = 1$, it means that the k-th EAP is selected to provide energy for ST. When $\rho_k = 0$, it means that the k-th EAP is not selected to provide energy for ST.

When the PR is receiving the signal sent from PT, it will also receive the energy signal sent from EAP. In order to cancel the interference caused by energy signal, we make all EAPs transmit constant energy signal. So, energy signal can be easily distinguished in the PT, which increase the efficiency of decoding process.

So, the signal received at PR is expressed as:

$$y_{PR}^{(1)} = h_{pp}\sqrt{\beta P_p} s + n_{PR}^{(1)} \quad (1)$$

The h_{pp} in this function denotes the channel from the PT to the PR. P_p is the total power that the PT can use over the two time slot. And β is the power allocation ratio, which means PT can use β part of the total power to transmit the signal in the first time slot and use the rest part of power to transmit a copy of previous signal in the second time slot. In addition, the $n_{PR}^{(1)}$ is the circularly symmetric complex Gaussian additive noise at the PR in the first time slot. So, it can be added directly with $h_{PP}\sqrt{\beta P_P s}$.

The interference at SR caused by energy signal can also be canceled by the same method as previous. So, the received signal at the SR can be expressed as:

$$y_{SR}^{(1)} = \boldsymbol{h}_{ps}\sqrt{\beta P_P} s + \boldsymbol{n}_{SR}^{(1)} \quad (2)$$

It is worth to point out the $\boldsymbol{n}_{SR}^{(1)}$ is a vector, it is because SR has M antennas. So, for each antenna, there will be a circularly symmetric complex Gaussian additive noise. ($\boldsymbol{n}_{SR}^{(1)} \sim \mathcal{CN}(0, \sigma_{PR}^2 \boldsymbol{I})$). And we use the $\boldsymbol{h}_{ps}$ to denote the channel from the PT to the SR.

For ST applying power splitting scheme, the received signal is divided into two streams. Base on the power splitting ratio ρ . ρ part of the received signal is harvested and stored in the battery. And the rest part $(1 - \rho)$ of the signal is decoded by the information receiver. The signal goes into the information receiver can be expressed as:

$$y_{SR}^{(1)} = \sqrt{1-\rho}\left(\boldsymbol{h}_{p,ST}\sqrt{\beta P_P} s + \boldsymbol{n}_a\right) + \boldsymbol{n}_c \quad (3)$$

The $\boldsymbol{h}_{p,ST}$ represents the channel from the PS to the ST. $\boldsymbol{h}_{p,ST}$ is also a receiver because ST has N antennas. And $\boldsymbol{n}_a$ is the circularly symmetric complex Gaussian additive noise at antennas. $\boldsymbol{n}_c$ is the processing noise at the information receiver.

The energy signal transmitted from kth-EAPs can be expressed as:

$$\rho_k \boldsymbol{H}_{k,ST} \boldsymbol{x}_k s_k \quad (4)$$

Then, we can use $\sum_{k=1}^{k} \rho_k \boldsymbol{H}_{k,ST} \boldsymbol{x}_k s_k$ to represent the overall energy signal transmitted from EAPs. After power splitting process, the received energy signal at the energy receiver is given by $\sqrt{1-\rho} \sum_{k=1}^{k} \rho_k \boldsymbol{H}_{k,ST} \boldsymbol{x}_k s_k$. Where $\boldsymbol{H}_{k,ST}$ is a $N \times N_k$ matrix, which represents the channel from the kth EAP to the ST.

3.3. The Second Time Slot

The EAPs stop transmitting energy signal to ST. After decoding the information sent from PU, the ST re-encode PU's information with its own information. Then, ST sends this message to PR and SR. The re-encoded message can be expressed as:

$$\boldsymbol{x}_{ST}^{(2)} = \boldsymbol{w}_p s + \boldsymbol{q}_s \quad (5)$$

In this function, $\boldsymbol{w}_p$ denotes the beamforming vector from the ST to the PR. And $\boldsymbol{q}_s$ is the signal including secondary user's information, which is aimed for MIMO transmission.

We have mentioned that the ST stop harvesting energy in the second time slot. It can only use the energy harvested before to do energy beamforming and send messages. So, it should be a power constraint:

$$\mathrm{Tr}(\boldsymbol{Q}_s) + \left\|\boldsymbol{w}_p\right\|^2 \leq \eta\rho P_{EH}(\beta) \quad (6)$$

$$P_{EH}(\beta) = P_0 \sum_{k=1}^{k} \rho_k \left\|\boldsymbol{H}_{k,ST} \boldsymbol{x}_k s_k\right\|^2 + \beta P_p \left\|h_{p,ST}\right\|^2 \quad (7)$$

Where $Q_s = \mathbb{E}[q_s q_s^H]$. And $P_{EH}(\beta)$ is the harvested power in the first time slot. $\sum_{k=1}^{k} \rho_k \left\|\boldsymbol{H}_{k,ST} \boldsymbol{x}_k s_k\right\|^2$ is the received power from EAPs and $\beta P_p \left\|h_{p,ST}\right\|^2$ is the harvested energy from PT. η is the energy harvesting efficiency at the energy receiver.

For PT, it uses the rest of power to send a copy of previous signal. The signal sent by PT can be expressed as:

$$x_{PT}^{(2)} = \sqrt{(1-\rho)P_p} s \quad (8)$$

So, the received signal at the PR in the second time slot can be expressed as:

$$y_{PR}^{(2)} = h_{pp}\sqrt{(1-\rho)P_p} s + \boldsymbol{g}_{sp}^H \boldsymbol{x}_{ST}^{(2)} + n_{PR}^{(2)} \quad (9)$$

In this function, $h_{pp}\sqrt{(1-\rho)P_p} s$ represents the received signal from PT, and h_{pp} denotes the channel from the PT to the PR. $\boldsymbol{g}_{sp}^H \boldsymbol{x}_{ST}^{(2)}$ represents the signal sent from ST, and $\boldsymbol{g}_{sp}^H$ denotes the channel from the ST to the PR. $n_{PR}^{(2)}$ is the additive noise at the antenna.

For SR, the received signals at the receiver are sent from PT and ST, which can be expressed as:

$$y_{SR}^{(2)} = \boldsymbol{G}_{ss} \boldsymbol{x}_{ST}^{(2)} + \boldsymbol{h}_{ps}\sqrt{(1-\beta)P_p} s + \boldsymbol{n}_{SR}^{(2)} \quad (10)$$

$$y_{SR}^{(2)} = \boldsymbol{G}_{ss}\boldsymbol{q}_s + \boldsymbol{G}_{ss}\boldsymbol{w}_p s + \boldsymbol{h}_{ps}\sqrt{(1-\beta)P_p} s + \boldsymbol{n}_{SR}^{(2)} \quad (11)$$

$$y_{SR}^{(2)} = \boldsymbol{G}_{ss}\boldsymbol{q}_s + \left(\boldsymbol{G}_{ss}\boldsymbol{w}_p + \boldsymbol{h}_{ps}\sqrt{(1-\beta)P_p}\right)s + \boldsymbol{n}_{SR}^{(2)} \quad (12)$$

In this function, $\boldsymbol{G}_{ss}$ is a $\mathrm{M} \times \mathrm{N}$ matrix, which represents the MIMO channel from the ST to the SR. $\boldsymbol{n}_{SR}^{(2)}$ denotes the circularly symmetric complex Gaussian additive noise at the SR.

3.4. Problem statement

We have mentioned before that the ST provides relaying services for PU to increase the spatial diversity. And the PR decodes the information from the two signal received in different time slot. We assume maximum ratio combining method is applied in the PR.

For simplicity, we can transform the equation of received signal at the PR into a new form. The transformation progress is shown as below:

$$y_{PR}^{(2)} = h_{pp}\sqrt{(1-\rho)P_p} s + \boldsymbol{g}_{sp}^H \boldsymbol{x}_{ST}^{(2)} + n_{PR}^{(2)} \quad (13)$$

$$y_{PR}^{(2)} = h_{pp}\sqrt{(1-\rho)P_p} s + \boldsymbol{g}_{sp}^H \boldsymbol{w}_p s + g_{sp}^H \boldsymbol{q}_s + n_{PR}^{(2)} \quad (14)$$

$$y_{PR}^{(2)} = \boldsymbol{g}_{sp}^H \boldsymbol{q}_s + \left(\boldsymbol{g}_{sp}^H \boldsymbol{w}_p + h_{pp}\sqrt{(1-\beta)P_p}\right)s + n_{SR}^{(2)} \quad (15)$$

$$y_{PR}^{(2)} = \boldsymbol{g}_{sp}^H \boldsymbol{q}_s + h_{PP}'^H w_p' s + \boldsymbol{n}_{SR}^{(2)} \quad (16)$$

Where the $h_{PP}'^H = [\boldsymbol{g}_{sp}^H, h_{pp}]$ and the $w_p' = [\boldsymbol{w}_p^H,\ \sqrt{(1-\beta)P_p}]^H$. These computations are mathematical equivalent.

So, the signal-to-interference-plus-noise (SINR) ratio at the PR can be expressed as:

$$SINR_{PR} = \frac{\beta P_p |h_{pp}|^2}{\sigma_{PR}^2} + \frac{|\boldsymbol{h}_{pp}' \boldsymbol{w}_p'|^2}{\boldsymbol{g}_{sp}^H \boldsymbol{Q}_s g_{sp} + \sigma_{PR}^2} \quad (17)$$

Where the $\frac{\beta P_p |h_{pp}|^2}{\sigma_{PR}^2}$ is the SINR at the PR in the first time slot, and the $\frac{|\boldsymbol{h}_{pp}' \boldsymbol{w}_p'|^2}{\boldsymbol{g}_{sp}^H \boldsymbol{Q}_s g_{sp} + \sigma_{PR}^2}$ is the SINR at the PR in the second time slot. By applying MRC method, they can be directly added to get the final $SINR_{PR}$.

The achievable information rate can be calculated by using the equation shown as bellow.

$$\mathrm{r} = \frac{1}{2}\log_2(1 + SINR) \quad (18)$$

Then, the maximum achievable rate for the PR can be obtained, which is expressed as:

$$r_{PR} = \frac{1}{2}\log_2\left(1 + \frac{\beta P_p |h_{pp}|^2}{\sigma_{PR}^2} + \frac{|\boldsymbol{h}_{pp}' \boldsymbol{w}_p'|^2}{\boldsymbol{g}_{sp}^H \boldsymbol{Q}_s g_{sp} + \sigma_{PR}^2}\right) \quad (19)$$

But the maximum achieve rate for the PR is limited by the maximum achievable rate for ST. So. The actual achievable maximum rate for the PR is the minim one between $\frac{1}{2}\log_2(1 + SINR_{ST})$ and $\frac{1}{2}\log_2(1 + SINR_{PR})$. It can be expressed as:

$$r_{PR} = min\left\{\frac{1}{2}\log_2\left(1+\frac{\beta P_p|h_{pp}|^2}{\sigma_{PR}^2}+\frac{|\boldsymbol{h}'_{pp}\boldsymbol{w}'_p|^2}{\boldsymbol{g}_{sp}^H\boldsymbol{Q}_s g_{sp}+\sigma_{PR}^2}\right),\frac{1}{2}\log_2\left(1+\frac{(1-\rho)\beta\|h_{p.ST}\|^2}{(1-\rho)\sigma_a^2+\sigma_c^2}\right)\right\} \quad (20)$$

For the SR, we assume the interference caused by PU's signal is canceled. So, the maximum achievable rate can be calculated by the same method, which is expressed as:

$$r_{SR} = \frac{1}{2}\log_2\left(\mathbf{I}+\frac{G_{ss}Q_sG_{ss}^H}{\sigma_{SR}^2}\right) \quad (21)$$

This paper assume that the ST can get paid by providing relaying services for the PU. And we aim to maximize the payoff by jointly design the beamforming vector, power splitting ratio, power allocation factor and the selections of EAPs. We assume that the ST gets paid base on the rate of PR, and introduce a reward parameter c_1. At the same time, it need to pay for the harvested energy from EAPs base on how much power it harvested. We also introduce a consumption parameter c_2. Then, the payoff of the ST can be denoted by $c_1 r_{PR} - c_2\eta\rho P_{EH}(\beta)$.

The payoff maximization problem can be expressed as bellow.

Problem A:

$$\max_{\boldsymbol{w}_p,Q_s,\rho,\beta,\{\rho_k\}} c_1 r_{PR} - c_2\eta\rho P_{EH}(\beta) \quad (22a)$$

$$\text{Subject to} \quad r_{PR} \geq R_{PR} \quad (22b)$$

$$r_{SR} \geq R_{SR} \quad (22c)$$

$$\boldsymbol{w}'_p = [\boldsymbol{w}_p^H,\ \sqrt{(1-\beta)P_p}]^H \quad (22d)$$

$$\rho_k \in \{0,\ 1\},\ \forall\, k \quad (22e)$$

$$\mathrm{Tr}(\boldsymbol{Q}_s) + \|\boldsymbol{w}_p\|^2 \leq \eta\rho P_{EH}(\beta) \quad (22f)$$

$$0 \leq \beta \leq 1,\ 0 \leq \rho \leq 1,\ \boldsymbol{Q}_s \geq \mathbf{0} \quad (22g)$$

Where R_{PR} is the rate requirement of the PR, and R_{SR} is the rate requirement of the SR. $\boldsymbol{w}'_p$ is the mathematical equivalent form of the beamforming vector from ST to PR.

Chapter 4: Solutions to the Problem

As we mentioned before, all the EAPs transmit constant energy signal so that the energy signal can be easily distinguished by the receiver. We assume the interference caused by energy signal can be perfectly canceled at PR, ST and SR. So, in this optimization problem, the selections of the EAPs only influence the power of received energy signal ($P_{EH}(\beta)$). The optimal EAPs selection can be calculated by the MATLAB. So, we can reduce the original optimization problem to

Problem B:

$$\max_{\boldsymbol{w}_p, Q_s, \rho, \beta} \mathrm{c}_1 r_{PR} - \mathrm{c}_2 \eta \rho P_{EH}(\beta) \quad (23a)$$

Subject to

$$r_{PR} \geq R_{PR} \quad (23b)$$

$$r_{SR} \geq R_{SR} \quad (23c)$$

$$\boldsymbol{w}_p' = [\boldsymbol{w}_p^H, \sqrt{(1-\beta)P_p}]^H \quad (23d)$$

$$\rho_k \in \{0, 1\}, \forall k \quad (23e)$$

$$\mathrm{Tr}(\boldsymbol{Q}_s) + \left\|\boldsymbol{w}_p\right\|^2 \leq \eta \rho P_{EH}(\beta) \quad (23f)$$

$$0 \leq \beta \leq 1, \ 0 \leq \rho \leq 1, \ \boldsymbol{Q}_s \geq \boldsymbol{0} \quad (23g)$$

4.1. The feasible rate region of the PR and SR.

In order to solve the problem B, we first calculate the feasible rate region of the PR and SR. For the PR, there is a maximization problem C, which is shown as below.

Problem C:

$$\max_{\boldsymbol{w}_p, Q_s, \rho, \beta} r_{PR} \quad (24)$$

Subject to

$$r_{PR} \geq R_{PR} \quad (24a)$$

$$\mathrm{Tr}(\boldsymbol{Q}_s) + \left\|\boldsymbol{w}_p\right\|^2 \leq \eta \rho P_{EH}(\beta) \quad (24b)$$

$$0 \leq \beta \leq 1, \ 0 \leq \rho \leq 1, \ \boldsymbol{Q}_s \geq \boldsymbol{0} \quad (24c)$$

By solving the optimization C, we can get the maximum achieve rate for PR, which can be denoted by R_{PR-Max}. The rate requirement should be less than or equal to the R_{PR-Max}. Then, for any given effective rate requirements, we calculate the corresponding maximum rate for SR. The optimization problem D for SR is shown below.

Problem D:

$$\max_{\boldsymbol{w}_p, Q_s, \rho, \beta} r_{SR} \quad (25)$$

Subject to

$$r_{PR} \geq R_{PR} \quad (25a)$$

$$r_{SR} \geq R_{SR} \quad (25c)$$

$$\mathrm{Tr}(\boldsymbol{Q}_s) + \|\boldsymbol{w}_p\|^2 \leq \eta\rho P_{EH}(\beta) \quad (25d)$$

$$0 \leq \beta \leq 1,\ 0 \leq \rho \leq 1,\ \boldsymbol{Q}_s \geq \boldsymbol{0} \quad (25e)$$

The maximum r_{PR} for given power allocation factor β and R_{PR} can be obtained by solving problem D, and we denote it by R_{SR-Max}. And we can use the MATLAB to plot the feasible region for R_{PR} and R_{SR}.

Progress for solving problem C is shown below.

$$r_{PR} \geq R_{PR} \quad (26)$$

The above function can be expanded to:

$$\frac{1}{2}\log_2(1 + SINR_{PR}) \geq \frac{1}{2}\log_2(1 + SINR_{R-PR}) \quad (27)$$

Where $SINR_{R-PR}$ is the corresponding SINR requirement for R_{PR}. Because of the properties of the log function, the above function can be equivalent to:

$$SINR_{PR} \geq SINR_{R-PR} \quad (28)$$

So, we introduce a slack variable t to solve the problem C. The problem C can be transformed to:

Problem E

$$\max_{\boldsymbol{w}_p, \boldsymbol{Q}_s, \rho, \beta} t \quad (29a)$$

Subject to

$$\frac{\beta P_p|h_{pp}|^2}{\sigma_{PR}^2} + \frac{|\boldsymbol{h}'_{pp}\boldsymbol{w}'_p|^2}{\boldsymbol{g}_{sp}^H\boldsymbol{Q}_s\boldsymbol{g}_{sp} + \sigma_{PR}^2} \geq t \quad (29b)$$

$$\frac{(1-\rho)\beta\|h_{p.ST}\|^2}{(1-\rho)\sigma_a^2 + \sigma_c^2} \geq t \quad (29c)$$

$$\mathrm{Tr}(\boldsymbol{Q}_s) + \|\boldsymbol{w}_p\|^2 \leq \eta\rho P_{EH}(\beta) \quad (29d)$$

$$0 \leq \beta \leq 1,\ 0 \leq \rho \leq 1,\ \boldsymbol{Q}_s \geq \boldsymbol{0} \quad (29e)$$

It is obvious that t achieves the maximum value when (1) is equal to (2). When $\boldsymbol{Q}_s = 0$, there is no SINR requirement for the SR, t can be obtained by:

$$\frac{\beta P_p|h_{pp}|^2}{\sigma_{PR}^2} + \frac{|\boldsymbol{h}'_{pp}\boldsymbol{w}'_p|^2}{\sigma_{PR}^2} - t = 0 \quad (30)$$

At the same time,

$$(1-\rho)\beta\|h_{p.ST}\|^2 = \left((1-\rho)\sigma_a^2 + \sigma_c^2\right)t \quad (31)$$

$$\beta\|h_{p.ST}\|^2 - \rho\beta\|h_{p.ST}\|^2 = (\sigma_a^2 + \sigma_c^2)t - \rho\sigma_a^2 t \quad (32)$$

$$\rho = \frac{\sigma_a^2 t - \beta\|h_{p.ST}\|^2 + \sigma_c^2}{\sigma_a^2 t - \beta\|h_{p.ST}\|^2} \quad (33)$$

$$\rho = 1 + \frac{\sigma_c^2}{\sigma_a^2 t - \beta\|h_{p.ST}\|^2} \quad (34)$$

With t numerically solved, the maximum achievable rate of PR can be calculated by $R_{PR} = \frac{1}{2}\log_2(1 + t)$. For given β, the (29b) is convex. So, the problem C can be solved by using the CVX toolbox in MATLAB. And the problem D can also be solved by introducing the

$\boldsymbol{W}'_p = \boldsymbol{w}'_p \boldsymbol{w}'^{H}_p$ and ignoring the rank constraint.

4.2. Progress for solving problem B

With the help of slack variable t, Function $c_1 r_{PR} - c_2 \eta \rho P_{EH}(\beta)$ can be transformed to

$$c_1 \frac{1}{2}\log_2(1+t) - c_2 \eta \rho P_{EH}(\beta) \qquad (35)$$

And $r_{PR} \geq R_{PR}$ can also be transformed to

$$\frac{1}{2}\log_2(1+t) \geq R_{PR} \qquad (36)$$

$$\log_2(1+t) \geq 2R_{PR} \qquad (37)$$

$$t \geq 2^{2R_{PR}} - 1 \qquad (38)$$

So, for given β, the problem B can be transformed to:

$$\max_{\boldsymbol{w}_p, \boldsymbol{Q}_s, \rho, \beta} c_1 \frac{1}{2}\log_2(1+t) - c_2 \eta \rho P_{EH}(\beta) \qquad (39a)$$

Subject to

$$\frac{\beta P_p |h_{pp}|^2}{\sigma_{PR}^2} + \frac{|\boldsymbol{h}'_{pp}\boldsymbol{w}'_p|^2}{\boldsymbol{g}_{sp}^H \boldsymbol{Q}_s \boldsymbol{g}_{sp} + \sigma_{PR}^2} \geq t \qquad (39b)$$

$$\frac{(1-\rho)\beta \|h_{p.ST}\|^2}{(1-\rho)\sigma_a^2 + \sigma_c^2} \geq t \qquad (39c)$$

$$t \geq 2^{2R_{PR}} - 1 \qquad (39d)$$

$$r_{SR} \geq R_{SR} \qquad (39e)$$

$$\boldsymbol{w}'_p = [\boldsymbol{w}_p^H, \sqrt{(1-\beta)P_p}]^H \qquad (39f)$$

$$\rho_k \in \{0, 1\}, \forall k \qquad (39g)$$

$$\mathrm{Tr}(\boldsymbol{Q}_s) + \|\boldsymbol{w}_p\|^2 \leq \eta \rho P_{EH}(\beta) \qquad (39h)$$

$$0 \leq \rho \leq 1, \boldsymbol{Q}_s \geq \boldsymbol{0} \qquad (39i)$$

After convex optimization and testing optimal β sweeping over [0, 1], the problem B can be solved by MATLAB. Then we consider the selection of EAPs to solve the problem A.

4.3. The selection of the EAPs

The selection of the EAPs influences the total power of the received energy signal ($P_{EH}(\beta)$). It also influences the payoff of the ST ($c_1 r_{PR} - c_2 \eta \rho P_{EH}(\beta)$). For each EAP, there are only two statuses. When $\rho_k = 1$, it means that the k-th EAP is selected to provide energy for ST. When $\rho_k = 0$, it means that the k-th EAP is not selected to provide energy for ST. So, there are 2^k situations for k EAPs. We can use MATLAB to simulate all the situations and get the corresponding payoff. Then, the optimal payoff value can be obtained by comparing all the results.

However, when the number of all the EAPs increases, the operation time and cost increase exponentially. In this paper, we also introduce an algorithm which can greatly decrease the computational complexity. Besides, this algorithm can still achieve good performance. The outline of the algorithm is shown as below.

Table 1 The proposed algorithm to reduce operation complexity

1. Set R_{PR} and R_{SR}.
2. Set $\{\rho_1, \rho_1, \cdots\cdots, \rho_k\} = \{1,1,\cdots\cdots,1\}$. Calculate the payoff P_a.
3. Set $\mathrm{i} \leftarrow \mathrm{k}$.
4. Set $\rho_\mathrm{i} = 0$, calculate the corresponding payoff P_b.
5. If $P_b \leq P_a$, set $\{\alpha_1, \alpha_2, \cdots\cdots, \alpha_k\} \leftarrow \{\rho_1, \rho_1, \cdots\cdots, \rho_k\}$, go to procedure 6. If $P_b \geq P_a$, set $\mathrm{i} \leftarrow \mathrm{i} - 1$, $P_a \leftarrow P_b$, and go back to procedure 4.
6. Set $\{\rho_1, \rho_1, \cdots\cdots, \rho_k\} = \{0,0,\cdots\cdots,0\}$. Calculate the corresponding payoff P_c.
7. Set $\mathrm{j} \leftarrow 1$.
8. Set $\rho_j = 1$, calculate the corresponding payoff P_d.
9. If $P_d \leq P_c$, set $\{\beta_1, \beta_2, \cdots\cdots, \beta_k\} \leftarrow \{\rho_1, \rho_1, \cdots\cdots, \rho_k\}$, go to procedure 10. If $P_d \geq P_c$, set $\mathrm{j} \leftarrow \mathrm{j} + 1$, $P_c \leftarrow P_d$, and go back to procedure 8.
10. If $P_b \geq P_d$, return $\{\alpha_1, \alpha_2, \cdots\cdots, \alpha_k\}$. If $P_b < P_d$, return $\{\beta_1, \beta_2, \cdots\cdots, \beta_k\}$.

The algorithm is greedy-based. At first, we input the R_{PR} and R_{SR} to ensure the QOS of the system. In procedure 2, it turns on all the EAPs and calculates the payoff P_a. In procedure 3 to 4, it turns off the k-th EAP and calculates the corresponding payoff P_b under this condition. In procedure 5, if the P_b is larger than the P_a, it will turn off the (k-1)th EAPs and enter a loop. In procedure 4 to 5, by comparing the latest payoff with the former one, this algorithm keeps turning off the EAPs one by one until the payoff decreases and records the selection of EAPs $\{\alpha_1, \alpha_2, \cdots\cdots, \alpha_k\}$ at this time.

In procedure 6 to 9, this algorithm turns on the EAPs in a reverse order. It also records the selection of EAPs $\{\beta_1, \beta_2, \cdots\cdots, \beta_k\}$ after it jumped out of the loop. By comparing the payoffs for these two recorded selections, this algorithm chooses the larger one and returns the corresponding selection of EAPs in procedure 10.

This algorithm can achieve a good performance because it is greedy-based. And it only need to compare at most $(2 \times \mathrm{k})$ situations, which is much simpler than comparing 2^k situations. It can greatly save the operation cost and increase the efficiency of the system.

Chapter 5: Results and Analysis

In this part, some numerical results are provided to prove the effectiveness of the presented algorithm. We also analyze the simulation results to evaluate the impact of different parameters on system parameters.

The system model is based on polar coordinates and the unit distance is m. The ST is chosen to be the origin of the polar coordinate. According to the above setting, the PT is located at (-5,0). PR and SR are located at (5, $\frac{1}{6}\pi$) and (5, $\frac{11}{6}\pi$). And the EAPs are assumed to be uniformly distributed in a circle. The circle has radius 8 m and it is centered at origin. The channel models consist of both small-scale fading and large-scale. The small-scale fading is multi-path fading that following independent identically distributed complex Gaussian distribution with zero mean and unit variance. The large-scale fading is given by a simple path loss model with a path loss exponent of 2.5 in addition to 30dB free space attenuation.

And the setting of the system parameter is shown below:

5.1. The feasible rate region

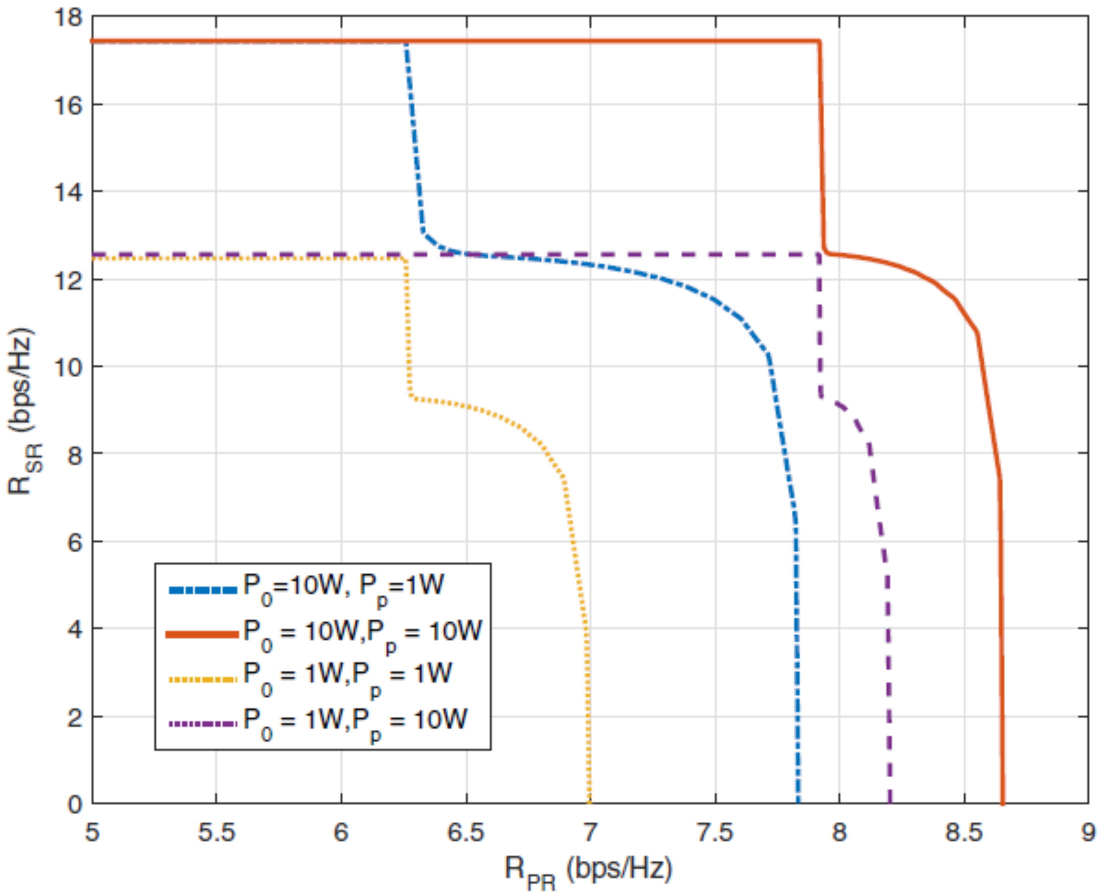

Figure 13. The simulation of feasible rate region

The setting of the system parameter is shown below:

$$c_1 = 0 \text{ (dB)},\ c_2 = 20 \text{ (dB)},\ \eta = 0.5;$$
$$M = N = 3,\ K=10,\ N_k = 10;$$
$$P_0 = 10\text{W or 1W},\ P_p = 10\text{W or 1W};$$
$$\sigma_a^2 = -170\text{dBm},\ \sigma_c^2 = -130\text{dBm},\ \sigma_a^2 + \sigma_c^2 = \sigma_{PR}^2 = \sigma_{SR}^2$$

And in this simulation, we assume all the EAPs are selected for wireless power transferring.

In the situation of P_0 = 1W, P_p = 1W (the yellow dotted line), it can be observed that the R_{SR} remain stable before the R_{PR} increases to about 6.25bps/Hz. Then, R_{SR} decreases rapidly with the increase of R_{PR} and drops to 0bps/Hz when R_{PR} reaches 7bps/Hz. This is because ST need to allocate more power to guarantee the QOS for PU when the R_{PR} increases. So, the maximum achievable rate for SU decreases because of the power constraint for ST.

In the situation of P_0 = 10W, P_p = 1W (the blue dotted line), it can be observed that it has the similar trend with the first situation. But the maximum achievable rates for both PR and SR increases compared with the previous case. This is because P_0 increases to 10W. So, ST can harvest more energy from the EAPs and higher rates can be achieved.

In the situation of P_0 = 1W, P_p = 10W (the purple dotted line), the maximum achievable rate for PR is higher than it in the second situation. This is because ST can only harvest power in the first time slot, but PT allocates part of available power to transmit a copy of previous signal in the second time slot. Part of the power are used to increase the SINR at PR only.

In the situation of P_0 = 10W, P_p = 10W (the red solid line), it can be seen that this region is the largest in all the situations. Both EAPs and PT can provide more energy for direct communication and relaying communication. So, the maximum rates for PR and SR also increase.

5.2. The relationship between the payoff and the cost parameter under different conditions

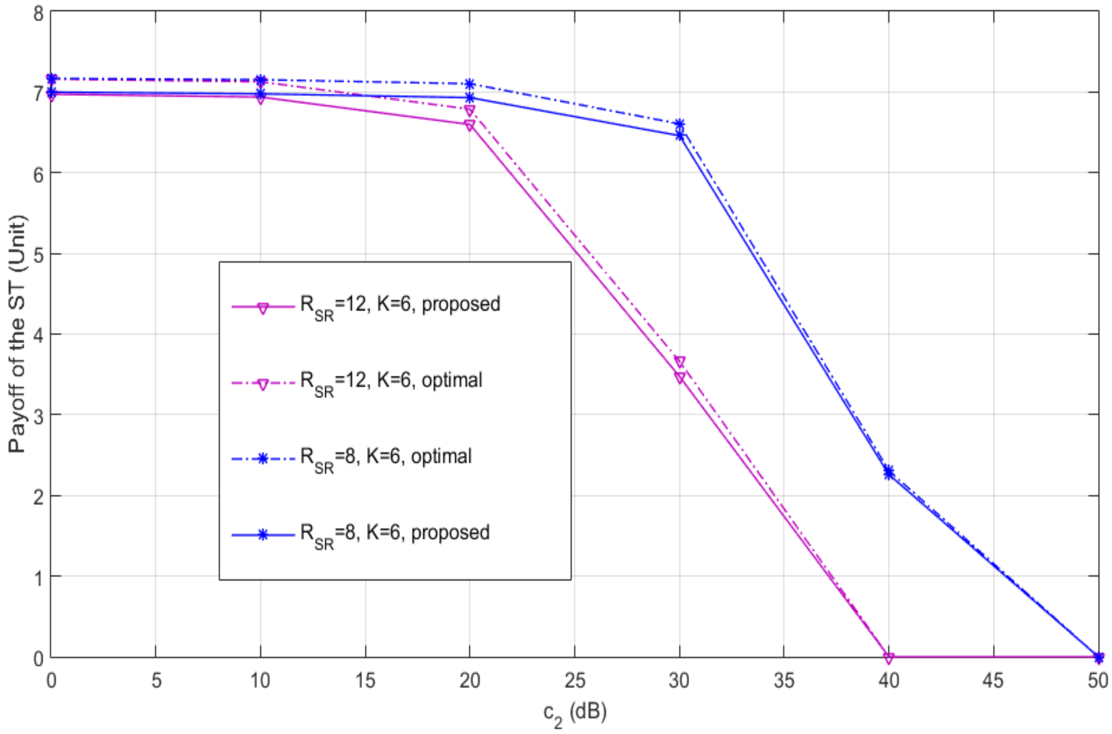

Figure 14. The relationship between the payoff and the cost parameter under different conditions

The setting of the system parameter is shown below:

$$c_1 = 0\ (\mathrm{dB}),\ R_{PR} = 4,\ \mathrm{K} = 6,\ \eta = 0.5;$$
$$\mathrm{M} = \mathrm{N} = 3,\ \mathrm{K}=10,\ N_k = 10;$$
$$P_0 = 10\mathrm{W},\ P_p = 1\mathrm{W};$$
$$\sigma_a^2 = \text{-}170\mathrm{dBm},\ \sigma_c^2 = \text{-}130\mathrm{dBm},\ \sigma_a^2 + \sigma_c^2 = \sigma_{PR}^2 = \sigma_{SR}^2$$

This figure describes the change of the payoff of ST with the increase of the cost parameter. We firstly consider the situations that apply optimal selections of EAPs. When $R_{SR} = 8$, the payoff keeps stable when the value of cost parameter is small. Then, payoff starts to decrease when $c_2 = 20$ (dB) and decreases to 0 when $c_2 = 50$ (dB). The increase of the c_2 means that ST has to pay more for the harvested energy. So, the payoff of ST decreases.

When $R_{SR} = 12$, it has the similar trend with the previous situation. But it starts to decrease earlier than the previous situation. This is because the payoff depends on the rate for PR. When R_{SR} increases, ST has to allocate more energy to make sure the QOS at the SR. For the same reason, payoff decreases to 0 when $c_2 = 40$ (dB), which is earlier than the previous situation.

When the proposed algorithm is applied (which are represented by the solid line), it can be observed that trends for proposed algorithm are almost the same as the trends for optimal scheme. But there is small gap between the optimal scheme and the proposed algorithm. This is due to the proposed algorithm simplify the process of the selection of EAPs. The simulation result proves that the proposed algorithm can still achieve good performance.

Besides, with the increase of c_2, the gap between optimal scheme and proposed algorithm become smaller. This phenomenon can be explained as follows. Under the condition of meeting the rate requirement of PR and SR, ST tries to select fewer EAPs to save the cost when the c_2 is high. At last, ST may choose only one EAPs, and it can also be simply achieved by the proposed algorithm.

5.3. The relationship between rate requirement for PR and the payoff of ST under different conditions.

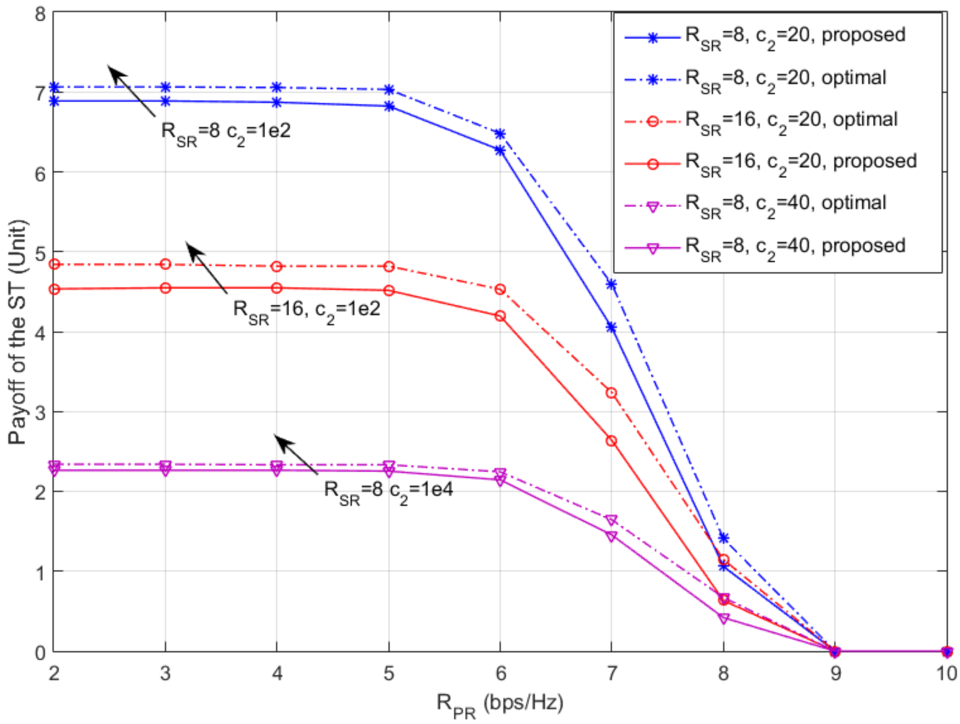

Figure 15. The relationship between the rate requirement of PR and the payoff of ST under different conditions

The setting of the system parameter is shown below:

$$c_1 = 0 \text{ (dB)},\ c_2 = 20 \text{ or } 40 \text{ (dB)},\ R_{SR} = 8 \text{ or } 16,\ \text{K} = 5,\ \eta = 0.5;$$
$$\text{M} = \text{N} = 3,\ \text{K}=10,\ N_k = 10;$$
$$P_0 = 10\text{W},\ P_p = 1\text{W};$$
$$\sigma_a^2 = \text{-}170\text{dBm},\ \sigma_c^2 = \text{-}130\text{dBm},\ \sigma_a^2 + \sigma_c^2 = \sigma_{PR}^2 = \sigma_{SR}^2$$

This figure describes the relationship between R_{PR} and the payoff of ST under different conditions.

We consider the optimal scheme (the dotted lines) firstly. It can be seen that the payoff keeps stable when the rate requirement of PR is low. Then, the payoff starts to decrease when the rate requirement gets higher. And the payoff decreases to 0 when R_{PR} = 9. This can be explained as follows. ST need to harvest more energy to achieve the higher rate requirement for PR. But the cost parameter is much larger than the rewarded parameter, so total payoff decreases and finally drops to 0.

As expected, the blue line is above the orange line all the time. Compared with the situation R_{SR} = 8, the ST need to allocate more energy to ensure the rate requirement of SR when R_{SR} = 16. So, its payoff is always less than the payoff when R_{SR} = 8.

When c_2 increases to 40 (dB), ST has to pay more for the harvesting energy, which decreases the payoff. So, the purple line is always below the red line.

Then we consider the proposed algorithm (the solid lines), it can be observed that the proposed algorithm has the similar trend with the optimal scheme. Besides, for the same reason we mentioned in the analysis of the second simulation, the gap between optimal scheme and proposed algorithm is relatively small when the value of cost parameter is high.

Chapter 6: Conclusion

This paper investigated the wireless powered CCRN, in which the ST provide DF relaying services for the PU and it harvests energy from both information signals and energy signals. In return for the relaying services, the SU can access the authorized frequency band and send its own messages together with PU's messages. The combination of WPCN and CCRN solves the power constrained problem and increases the utilization rate of spectrum resources. Meanwhile, this project aims to maximize the payoff of ST by jointly designing the beamforming vectors, power splitting ratio, power allocation factor and the selection of EAPs under the condition of meeting the power constraint for ST and the rate requirement of PR and SR. In the step of selecting EAPs, we also introduced a greedy-based algorithm to reduce the operation complexity. And the proposed algorithm can achieve good performance, which can be proved by the simulation results.

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Appendices

I verify that I am the sole author of the programs contained in this folder, except where explicitly stated to the contrary.
Shoutian Wu, 24/08/2017

Main

```
clc; clear all;
K=6; %the number of EAP within the reach of the ST
perm=dec2bin(0:2^K-1); %generate an (2^K-1)-by-K char arrays that consist of all K-bit combinations of binary input
%convert char arrays 'perm' to numerical arrays 'Perm'
Perm=zeros(size(2^K,K));
for pp=1:2^K
    for kk=1:K
        Perm(pp,kk)=str2double(perm(pp,kk));
    end
end
N=3;
M=3;
L=10; %the number of antenna each EAP is equipped with
%Deployment of the EAPs, PT, ST, PU and SU assuming a polar coordinate
%system originated at the ST (CR relay)
d_pST=5; %distance between the PT and the ST
d_sp=5;
d_ss=5;
R_max=8; %furtherest radius of an EAP that the ST can have active access to
s=rng;
rng(10, 'twister');
rho_EAP_ST=R_max*sqrt(rand([1,1,K]));
beta_array=linspace(.01,1,99);
scale_factor=1e-8;
% n=20; % the preset length(R_PU_array) that decides how many points are targetted for a given beta;
Pp=1;
P0=10/scale_factor;
noise_antenna=1e-14/scale_factor;
% noise_antenna=1e-4;
noise_conv=1e-10/scale_factor;
% noise_conv=1;
noise_PU=noise_antenna+noise_conv;
noise_SU=noise_PU;
eta=.5;
c1=1;
c2_array=[0 logspace(0,5,6)];
c2_array=c2_array*scale_factor;

trial_Max=100;
```

```
rho_star_array=zeros(K,length(c2_array),trial_Max);
beta_star_array=zeros(trial_Max,length(c2_array));
payoff_star_array=zeros(trial_Max,length(c2_array));

rho_co_star_array=zeros(K,length(c2_array),trial_Max);
beta_co_star_array=zeros(trial_Max,length(c2_array));
payoff_co_star_array=zeros(trial_Max,length(c2_array));


% rho_grd_array=zeros(K,length(R_PU_array));
% payoff_grd_array=zeros(1,length(R_PU_array));
%
% rho_co_grd_array=zeros(K,length(R_PU_array));
% payoff_co_grd_array=zeros(1,length(R_PU_array));


R_PU=4;
R_SU=4;



% load channel_gain;

%%
tic;
for ii=1:trial_Max
    ii
    [h_pST, g_sp, G_ss, h_pp, h_ps, H_EAP_ST]=channel_generation(N, M, K, L, d_pST,
d_sp, d_ss, rho_EAP_ST);
    h_pST=h_pST/sqrt(scale_factor);
    h_pp=h_pp/sqrt(scale_factor);
    g_sp=g_sp/sqrt(scale_factor);
    G_ss=G_ss/sqrt(scale_factor);


    % generate the spectral radius for individual EB, i.e., each corresponding
    % to one N-by-L matrix "H_{k,ST}
    lambda=zeros(K,1);
    for kk=1:K
        [U, Lambda, V]=svd(H_EAP_ST(:,:,kk),'econ');
        lambda(kk)=max(diag(Lambda).^2);
    end
    [sorted_lambda,sorted_I]=sort(lambda,'descend');
```

```
    % generate the spectral radius for cooperative EB, i.e., each corresponding
    % to one N-by-\sum_{k=1}^K L_k large matrix with the sparsity patter
    % specified by each row of perm
    % H=zeros(N,L*K);
    lambda_perm=zeros(2^K,1);
    for pp=1:2^K-1
        H=zeros(N,L*K);
        for kk=1:K
            if Perm(pp,kk)
                H(:,kk*L+1:(kk+1)*L)=H_EAP_ST(:,:,kk);
            end
        end
        lambda_perm(pp)=eigs(H'*H,1);
    end
    H=reshape(H_EAP_ST,[N,K*L]);
    lambda_perm(2^K)=max(eig(H'*H));

    payoff_star_array_temp=zeros(size(c2_array));
    rho_star_array_temp=zeros(K,length(c2_array));
    beta_star_array_temp=zeros(size(c2_array));

    payoff_co_star_array_temp=zeros(size(c2_array));
    rho_co_star_array_temp=zeros(K,length(c2_array));
    beta_co_star_array_temp=zeros(size(c2_array));

    for nn=1:length(c2_array)
        %           nn
        c2=c2_array(nn);
        payoff_array=zeros(1,size(perm,1));
        Status_array=cell(1,size(perm,1));
        payoff_co_array=zeros(1,size(perm,1));
        Status_co_array=cell(1,size(perm,1));
        % Maximize ST's payoff by exhaustive search over 2^K's enumeration of
\rho\in{0,1}^{K\times 1}
        for pp=1:2^K
            rho=Perm(pp,:).';
            % rho=ones(K,1);
            [Qs, w_prime_p, varrho, beta, payoff_array(pp), Flag,
Status_array{pp}]=maximize_payoff(P0, Pp, noise_antenna, noise_conv, noise_PU,
noise_SU, h_pp, g_sp, eta, h_pST, G_ss, lambda, rho, R_PU, R_SU, c1, c2, scale_factor);
            [Qs_co, w_prime_p_co, varrho_co, beta_co, payoff_co_array(pp), Flag_co,
Status_co_array{pp}]=maximize_payoff_co(P0, Pp, noise_antenna, noise_conv, noise_PU,
noise_SU, h_pp, g_sp, eta, h_pST, G_ss, lambda_perm(pp), R_PU, R_SU, c1, c2, scale_factor);
        end
```

```
        I_solved=ind2sub(size(Status_array), strmatch('Solved', Status_array, 'exact')); % I_solved is an index array corresponding to the 'Solved' status
        [payoff, I_cut]=max(payoff_array(I_solved)); % I_cut indicates the index of the maximum payoff in the 'Solved'-only payoff_array
        if isempty(payoff)
            payoff_star_array_temp(nn)=-Inf;
        else

            I=I_solved(I_cut); % I indicates the index of the maximum payoff in the orginal payoff_array
            rho_star_array_temp(:,nn)=Perm(I,:).';
            [Qs_star, w_prime_p_star, varrho_star, beta_star_array_temp(nn), payoff_star_array_temp(nn), Flag_star, Status_star]=maximize_payoff(P0, Pp, noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, lambda, rho_star_array_temp(:,nn), R_PU, R_SU, c1, c2, scale_factor);
            %              payoff_grd_array;rho_grd_array
        end

        I_co_solved=ind2sub(size(Status_co_array), strmatch('Solved', Status_co_array, 'exact'));
        [payoff_co, I_co_cut]=max(payoff_co_array(I_co_solved));
        if isempty(payoff_co)
            payoff_co_star_array_temp(nn)=-Inf;
        else
            I_co=I_co_solved(I_co_cut);
            rho_co_star_array_temp(:,nn)=Perm(I_co,:).';
            [Qs_co_star, w_prime_p_co_star, varrho_co_star, beta_co_star_array_temp(nn), payoff_co_star_array_temp(nn), Flag_co_star, Status_co_star]=maximize_payoff_co(P0, Pp, noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, lambda_perm(I_co), R_PU, R_SU, c1, c2, scale_factor);
            %              payoff_co_grd_array;rho_co_grd_array
        end




        %           % Maximize ST's payoff by greedy search from dropping the \rho\in{0,1} that corresponds to the least spectral radius (spectral radius herein means maximum eigenvalues of H'*H)
        %          % For non-cooperative EB, the heuristic scheme turns off the EAP in line
        %          % with the decreasing order of lambda
```

```
%
%           kk=K;
%           rho=ones(K,1); % start the greedy search from the all-on case
%           payoff=payoff_array(2^K); % the all-on case corresponds to the last row of Perm
%           payoff_previous=-1e3;
%           while ~isinf(payoff)&&(payoff-payoff_previous>=0)
%               if kk % kk indicates the preceding kk EAPs turned on
%                   rho(kk)=0; % turn off the kkth EAP
%                   payoff_previous=payoff;
%                   [Qs, w_prime_p, varrho, beta, payoff, Flag]=maximize_payoff(P0, Pp, noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, sorted_lambda, rho, R_PU, R_SU, c1, c2, scale_factor);
%                   kk=kk-1;
%               else
%                   rho_grd_array(:,nn)=zeros(K,1);
%                   payoff_grd_array(nn)=payoff;
%                   break;
%               end
%           end
%
%           if (kk&&(kk~=K))||(kk==0&&isinf(payoff))
%               rho(kk+1)=1;
%               rho_grd=zeros(K,1);
%               rho_grd(sorted_I)=rho;
%               rho_grd_array(:,nn)=rho_grd;
%               payoff_grd_array(nn)=payoff_previous;
%           else if kk==K
%                   rho_grd_array(:,nn)=zeros(K,1);
%                   payoff_grd_array(nn)=-Inf;
%               else
%               end
%           end
%
%
%
%           % For cooperative EB, the heuristic scheme turns off the EAP in line
%           % with the more and more sparse matrix H
%            H=reshape(H_EAP_ST,[N,K*L]); % start the cooperative EB matrix (from across all EAPs to the ST) with all EAPs turned on
%           lambda_perm_grd=zeros(K,1);
%           for kk=1:K
%               H(:,(K-kk)*L+1:(K-kk+1)*L)=zeros(N,L); % Sparsify the kkth block matrix from the reverse side of full H with an N-by-L zero matrix
```

```
%                   lambda_perm_grd(kk)=eigs(H'*H,1); % kk correspondes to the total number of EAPs turned off from the reverse side of full H
%               end
%
%               kk=1;
%               payoff_co=payoff_co_array(2^K); % the all-on case corresponds to the last row of Perm
%               payoff_co_previous=-1e3;
%               while ~isinf(payoff_co)&&(payoff_co-payoff_co_previous>=0)
%                   if kk~=(K+1) % kk indicates the kk-th largest spectrum radius in the ascending "sorted_lambda_perm_grd
%                       payoff_co_previous=payoff_co;
%                          [Qs_co, w_prime_p_co, varrho_co, beta_co, payoff_co, Flag_co]=maximize_payoff_co(P0, Pp, noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, lambda_perm_grd(kk), R_PU, R_SU, c1, c2);
%                       kk=kk+1;
%                   else
%                       rho_co_grd_array(:,nn)=zeros(K,1);
%                       payoff_co_grd_array(nn)=payoff_co;
%                       break;
%                   end
%               end
%
%               if kk==1
%                   rho_co_grd_array(:,nn)=zeros(K,1);
%                   payoff_co_grd_array(nn)=-Inf;
%               else if ((kk~=1)&&(kk~=K+1))||((kk==K+1)&&isinf(payoff_co))
%                       rho_co_grd=ones(K,1);
%                       rho_co_grd(K-(kk-2)+3:K)=0;
%                       rho_co_grd_array(:,nn)=rho_co_grd;
%                       payoff_co_grd_array(nn)=payoff_co_previous;
%                   else
%                   end
%               end

    end
    payoff_star_array(ii,:)=max(payoff_star_array_temp,0);
    rho_star_array(:,:,ii)=rho_star_array_temp;
    beta_star_array(ii,:)=beta_star_array_temp;

    payoff_co_star_array(ii,:)=max(payoff_co_star_array_temp,0);
    rho_co_star_array(:,:,ii)=rho_co_star_array_temp;
    beta_co_star_array(ii,:)=beta_co_star_array_temp;
end
```

```
payoff_star_array_mean=sum(payoff_star_array)/trial_Max;
payoff_co_star_array_mean=sum(payoff_co_star_array)/trial_Max;
save('payoff_vs_c2_R_SU_4_K_6_09_04_2016.mat');
eclipsed_fixed_beta=toc;

%                    plot(R_PU_array,max(0,payoff_star_array),'--bo',R_PU_array,max(0,payoff_co_star_array),'--b*',R_PU_array,max(0,payoff_grd_array),'-bo',R_PU_array,max(0,payoff_co_grd_array),'-b*','LineWidth',.5);
%    set(gca, 'FontSize',12);
%    xlabel('R_{PU} (bps/Hz)');
%    ylabel('Payoff of the ST (Unit)');
%    legend('EB-optimal','CoEB-optimal','EB-proposed','CoEB-proposed');
%    grid on; hold on;
```

Maximize_payoff

```
function [Qs_star, w_prime_p_star, varrho_star, beta_star, payoff_eqv_star, Flag, Status]=maximize_payoff(P0, Pp, noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, lambda, rho, R_PU, R_SU, c1, c2, scale_factor)
%Given the turn-on indicators of \rho\in{0,1}^{K\times 1}, maximize the
%payoff for the ST via a one-dim search over beta\in [.01, 1]
[M,N]=size(G_ss);
K=length(lambda);
h_prime_pp=[g_sp;h_pp];
H_prime_pp=h_prime_pp*h_prime_pp';
G_sp=g_sp*g_sp';
E=[eye(N) zeros(N,1)]; %w_p=E*w_prime_p
I_N_plus_one=eye(N+1);
U_N_plus_one=diag(I_N_plus_one(:,N+1));
myfun=@WaterFilling;
Qs_star=myfun(G_ss, noise_SU, R_SU);
G_ss=mat2cell(G_ss,M,N);

% beta_array=linspace(.05,1,20);
beta_array=1;
% payoff_array=zeros(size(beta_array));
payoff_eqv_array=zeros(size(beta_array));
% t_min=R_PU;
for ii=1:length(beta_array)
    beta=beta_array(ii);
    %Feasibility check whether the current \rho's support the required pair of
    %(R_PU, R_SU)
    [R_PU_max]=equation_solution(beta, P0, Pp, noise_antenna, noise_conv, noise_PU, h_pp, g_sp, eta, h_pST, lambda, rho, zeros(N), scale_factor);
    if R_PU>R_PU_max*.98
        flag=0; %mark the feasibility of (P1) for given beta given current rho
    else

        g_sp=mat2cell(g_sp,N);
        h_pST=mat2cell(h_pST,N);
        lambda=mat2cell(lambda,K);
        rho=mat2cell(rho,K);
        [~, Qs_max, varrho_max, R_SU_max]=maximum_R_SU(beta, P0, Pp, noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, lambda, rho, R_PU, scale_factor);
        g_sp=cell2mat(g_sp);
        h_pST=cell2mat(h_pST);
```

```
            lambda=cell2mat(lambda);
            rho=cell2mat(rho);
            if R_SU>R_SU_max
                flag=0;
            else
                flag=1;

                P_EH=(P0*rho.'*lambda+beta*Pp*norm(h_pST)^2);
                %                       t=(R_PU_max+t_min)/2;

                cvx_begin quiet
                variable W_prime_p(N+1,N+1) hermitian
                variable varrho
                %                       variable beta nonnegative
                variables t x%achievable SINR of PU via the DF CR-enabled relay is denoted
by 't'
                %                       expression P_EH
                maximize c1/2*log(1+t)/log(2)-c2*eta*varrho*P_EH
%                  maximize c1*t-c2*eta*varrho*P_EH
                subject to
                %                             norm([(1-varrho)-(beta*Pp*norm(h_pST)^2-(2^(2*t)-
1)*noise_antenna);...
                %                                                   2*sqrt((2^(2*t)-1)*noise_conv)])<=(1-
varrho)+(beta*Pp*norm(h_pST)^2-(2^(2*t)-1)*noise_antenna)
                beta*Pp*norm(h_pST)^2/noise_antenna-
(beta*Pp*norm(h_pST)^2*noise_conv/noise_antenna)*inv_pos(x)-t>=0
                x==noise_antenna*(1-varrho)+noise_conv

beta*Pp*abs(h_pp)^2/noise_PU+real(trace(H_prime_pp*W_prime_p))/(real(trace(G_sp*Q
s_star))+noise_PU)-t>=0
                t>=2^(2*R_PU)-1
                real(trace((E'*E)*W_prime_p))/scale_factor<=eta*varrho*P_EH-
real(trace(Qs_star))/scale_factor
                real(trace(U_N_plus_one*W_prime_p))==(1-beta)*Pp
                varrho>=0
                varrho<=.999
                %                       beta<=1
                W_prime_p==hermitian_semidefinite(N+1)
                cvx_end
            end
        end
        if~flag
            %               payoff_array(ii)=-Inf;
            payoff_eqv_array(ii)=-Inf;
```

```
        else
%                   payoff_array(ii)=c1*t-c2*eta*varrho*P_EH;
            payoff_eqv_array(ii)=1/2*c1*log(1+t)/log(2)-c2*eta*varrho*P_EH;
        end
end

% [payoff_star, I_star]=max(payoff_array);
[payoff_eqv_star, I_eqv_star]=max(payoff_eqv_array);

if isinf(payoff_eqv_star)||isnan(payoff_eqv_star)
        Flag=0; %mark the feasibility of (P1) for all beta's given current rho
        w_prime_p_star=zeros(N,1);
        varrho_star=0;
        beta_star=1;
        payoff_eqv_star=-Inf;
        Status='Infeasible';

else
        Flag=1;
        beta_star=beta_array(I_eqv_star);
        P_EH_star=(P0*rho.'*lambda+beta_star*Pp*norm(h_pST)^2);

%       cvx_begin quiet
%       variable W_prime_p(N+1,N+1) hermitian
%       variable varrho
%       %                   variable beta nonnegative
%       variables t x%achievable SINR of PU via the DF CR-enabled relay
%       %                   expression P_EH
%       %                   maximize c1*log(1+t)/log(2)-c2*eta*varrho*P_EH
%       maximize c1*t-c2*eta*varrho*P_EH_star
%       subject to
%           %                           norm([(1-varrho)-(beta*Pp*norm(h_pST)^2-(2^(2*t)-
1)*noise_antenna);...
%               %                                       2*sqrt((2^(2*t)-1)*noise_conv)])<=(1-
varrho)+(beta*Pp*norm(h_pST)^2-(2^(2*t)-1)*noise_antenna)
%                                               beta_star*Pp*norm(h_pST)^2/noise_antenna-
(beta_star*Pp*norm(h_pST)^2*noise_conv/noise_antenna)*inv_pos(x)-t>=0
%                                       %       (1-varrho)*beta_star*Pp*norm(h_pST)^2/((1-
varrho)*noise_antenna+noise_conv)
%       x==noise_antenna*(1-varrho)+noise_conv
%
beta_star*Pp*abs(h_pp)^2/noise_PU+real(trace(H_prime_pp*W_prime_p))/(real(trace(G_
sp*Qs_star))+noise_PU)-t>=0
%       t>=2^(2*R_PU)-1
```

```
%                               real(trace((E'*E)*W_prime_p))/scale_factor<=eta*varrho*P_EH-
real(trace(Qs_star))/scale_factor
%       real(trace(U_N_plus_one*W_prime_p))==(1-beta_star)*Pp
%       varrho>=0
%       varrho<=.999
%       %               beta<=1
%       W_prime_p==hermitian_semidefinite(N+1)
%       cvx_end

    Status=cvx_status;
    if strncmp('Inaccurate/Solved',Status,17)
        if                                  beta*Pp*norm(h_pST)^2/noise_antenna-
(beta*Pp*norm(h_pST)^2*noise_conv/noise_antenna)*inv_pos(x)-t>=0
            Status='Solved';
        else
        end
    else
    end
    W_prime_p_star=W_prime_p;
    [U,Lambda,V]=svd(W_prime_p_star);
    w_prime_p_star=sqrt(Lambda(1,1))*U(:,1);
    varrho_star=varrho;
    payoff_eqv_star=1/2*c1*log(1+t)/log(2)-c2*eta*varrho_star*P_EH_star;
end


end
```

Maximize_payoff_heur

```
function [payoff_grd, rho_grd]=maximize_payoff_heur(P0, Pp, noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, sorted_lambda, sorted_I, R_PU, R_SU, c1, c2, scale_factor, payoff_full, payoff_empty)
%UNTITLED2 Summary of this function goes here
% Maximize ST's payoff by greedy search from dropping the \rho\in{0,1} that corresponds to the least spectral radius (spectral radius herein means maximum eigenvalues of H'*H)
% For non-cooperative EB, the heuristic scheme turns off the EAP in line
% with the decreasing order of lambda
K=length(sorted_lambda); % lambda is sorted in descending order
kk=K;
rho=ones(K,1); % start the greedy search from the all-on case
payoff=payoff_full; % the all-on case corresponds to the last row of Perm
payoff_previous=-1e5;
flag=0;
while ~isinf(payoff)&&(payoff-payoff_previous>=0)
    if kk % kk indicates the preceding kk EAPs turned on
        rho(kk)=0; % turn off the kkth EAP
        payoff_previous=payoff;
        [Qs, w_prime_p, varrho, beta, payoff, Flag, Status]=maximize_payoff(P0, Pp, noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, sorted_lambda, rho, R_PU, R_SU, c1, c2, scale_factor);
        if strncmp('Inaccurate/Solved',Status,17)
            payoff=payoff_previous;
        else
        end
        kk=kk-1;
    else
        rho_grd_d=zeros(K,1);
        payoff_grd_d=payoff;
        flag=1;
        break;
    end
end
if ~flag
    if kk==K
        rho_grd_d=zeros(K,1);
        payoff_grd_d=-Inf;
    else
    rho(kk+1)=1;
```

```
        rho_grd_d=zeros(K,1);
        rho_grd_d(sorted_I)=rho;
        payoff_grd_d=payoff_previous;
        end
else
end



sorted_lambda=sorted_lambda.';
sorted_I=sorted_I.';
kk=1;
rho=zeros(K,1); % start the greedy search from the all-on case
payoff=payoff_empty; % the all-off case corresponds to the first row of Perm
payoff_previous=-1e5;
flag=0;
while isinf(payoff)||(payoff-payoff_previous>=0)
        if kk~=K+1 % kk indicates the (K-1+kk) EAPs in the reverse order turned off
                rho(kk)=1; % turn on the kkth EAP
                payoff_previous=payoff;
                [Qs, w_prime_p, varrho, beta, payoff, Flag, Status]=maximize_payoff(P0, Pp, noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, fliplr(sorted_lambda).', rho, R_PU, R_SU, c1, c2, scale_factor);
                if strncmp('Inaccurate/Solved',Status,17)
                        payoff=payoff_previous;
                else
                end
                kk=kk+1;
        else if isinf(payoff)
                        rho_grd_a=zeros(K,1);
                else
                rho_grd_a=ones(K,1);
                end
                payoff_grd_a=payoff;
                flag=1;
                break;
        end
end

if    ~flag
        rho(kk-1)=0;
        rho_grd_a=zeros(K,1);
        rho_grd_a(fliplr(sorted_I).')=rho;
        payoff_grd_a=payoff_previous;
```

```
else
end


[payoff_grd, I_alter]=max([payoff_grd_d, payoff_grd_a]);
if I_alter==1
	rho_grd=rho_grd_d;
else
	rho_grd=rho_grd_a;
end


end
```

Maximum_R_SU

```
function [w_prime_p_star, Qs_star, varrho_star, R_SU_star]=maximum_R_SU(beta, P0, Pp,
noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, lambda, rho,
R_PU, scale_factor)


%UNTITLED2 Summary of this function goes here
%Detailed explanation goes here
%Convert the indexed cell-type variable to its corresponding vector form
g_sp=cell2mat(g_sp);
h_pST=cell2mat(h_pST);
% H_EAP_ST=cell2mat(H_EAP_ST);
G_ss=cell2mat(G_ss);
lambda=cell2mat(lambda);
rho=cell2mat(rho);

h_pST=h_pST*sqrt(scale_factor);
h_pp=h_pp*sqrt(scale_factor);
g_sp=g_sp*sqrt(scale_factor);
G_ss=G_ss*sqrt(scale_factor);
Pp=Pp/scale_factor;

[M,N]=size(G_ss);
% K=size(H_EAP_ST,3);
P_EH=P0*rho.'*lambda+beta*Pp*norm(h_pST)^2;
% sum_EH=0;
% for kk=1:K
%       sum_EH=sum_EH+norm(H_EAP_ST(:,:,kk)*x(:,kk))^2;
% end
h_prime_pp=[g_sp;h_pp];
H_prime_pp=h_prime_pp*h_prime_pp';
G_sp=g_sp*g_sp';
E=[eye(N) zeros(N,1)]; %w_p=E*w_prime_p
I_N_plus_one=eye(N+1);
U_N_plus_one=diag(I_N_plus_one(:,N+1));

cvx_begin quiet
variable W_prime_p(N+1,N+1) hermitian
variable Qs(N,N) hermitian
variable varrho
maximize det_rootn(eye(M)+G_ss*Qs*G_ss'/noise_SU)
subject to
```

```
(1-varrho)*beta*Pp*norm(h_pST)^2>=(2^(2*R_PU)-1)*((1-
varrho)*noise_antenna+noise_conv)
%                                                   beta*Pp*norm(h_pST)^2/noise_antenna-
(beta*Pp*norm(h_pST)^2*(noise_conv/noise_antenna))*inv_pos(x)>=2^(2*R_PU)-1
% x==noise_antenna*(1-varrho)+noise_conv
trace(H_prime_pp*W_prime_p)>=(2^(2*R_PU)-1-
beta*Pp*abs(h_pp)^2/noise_PU)*(real(trace(G_sp*Qs))+noise_PU)
trace(Qs)+trace((E'*E)*W_prime_p)<=eta*varrho*P_EH;
trace(U_N_plus_one*W_prime_p)==(1-beta)*Pp
varrho>=0
varrho<=1
W_prime_p==hermitian_semidefinite(N+1)
Qs==hermitian_semidefinite(N)
cvx_end

if    strncmp('Infeasible',cvx_status,10)
      w_prime_p_star=num2cell(zeros(N+1,1),1);
      Qs_star=num2cell(zeros(N),[1,2]);
      varrho_star=num2cell(0);
      R_SU_star=0;
else
Qs=Qs*scale_factor;
W_prime_p_star=W_prime_p;
[U,Lambda,V]=svd(W_prime_p_star);
w_prime_p_star=num2cell(sqrt(Lambda(1,1))*U(:,1),1);
Qs_star=num2cell(Qs,[1,2]);
varrho_star=num2cell(varrho);
% R_SU_star=1/2*(M*log2(cvx_optval));
R_SU_star=1/2*log2(real(det(eye(M)+G_ss*(Qs/scale_factor)*G_ss'/noise_SU)));
end

end
```

WaterFilling

```
function [Qs] = WaterFilling(G_ss, noise_SU, R_SU)
%WaterFilling solutions for power minimization problem subject to a QoS
%constraint on the SU's achievable rate
%     Apply bi-section over the multiplier \lambda on the classical
%     water-filling solutions of power allocations given by
%     p_i^*=(\lambda/ln2-1/\sigma_i)^+, where \sigma_i's are eigen-values of
%     G_ss^H*G_ss
% tic;
[M,N]=size(G_ss);
r=min(M,N);
[V,D]=eig(G_ss'*G_ss);
[sigma,Index]=sort(diag(D),'descend');
sigma=sigma(1:r);
V=V(:,Index);
V=V(:,1:r);
lambda_max=1e8;
lambda_min=log(2)*noise_SU/max(sigma);
epsilon=1e-8;
lambda_lb=lambda_min;
lambda_ub=lambda_max;
lambda=(lambda_lb+lambda_ub)/2;
lambda_temp=0;
while(abs(lambda-lambda_temp)>epsilon)
        p_array=max(0,lambda/log(2)-noise_SU./sigma);
        if 1/2*log2(det(diag(1+p_array.*sigma/noise_SU)))>R_SU
            lambda_ub=lambda;
        else
            lambda_lb=lambda;
        end
        lambda_temp=lambda;
        lambda=(lambda_lb+lambda_ub)/2;
end

p_star_array=max(0,lambda/log(2)-noise_SU./sigma);
Qs=V*diag(p_star_array)*V';
% P_min=real(trace(Qs));
% 'bi-section:'
% display(P_min)
% t1=toc;
```

```
% %Verified by cvx as follows
% tic;
% cvx_begin quiet
% variable Qs(N,N) hermitian
% minimize trace(Qs)
% subject to
% det_rootn(eye(N)+G_ss*Qs*G_ss'/noise_SU)>=exp(2*log(2)*R_SU/N);
% Qs==hermitian_semidefinite(N)
% cvx_end
%
% P_min=trace(Qs);
% 'cvx:'
% display(P_min);
% t2=toc;
end
```

Channel_generation

```
function [h_pST, g_sp, G_ss, h_pp, h_ps, H_EAP_ST]=channel_generation(N, M, K, L, d_pST,
d_sp, d_ss, rho_EAP_ST)
%channel generation for the wireless powered CR cooperation system
A0=1e-3; d0=1;
alpha=2.5; %exponential factor for the simple pathloss model
theta_sp=pi/6;
theta_ss=11*pi/6;
d_pp=sqrt(d_pST^2+d_sp^2-2*d_pST*d_sp*cos(pi-theta_sp));
d_ps=sqrt(d_pST^2+d_ss^2-2*d_pST*d_ss*cos(pi-theta_ss));
% rho_EAP_ST=R_max*sqrt(rand([1,1,K]));
% theta_EAP_ST=2*pi*rand(K,1);
% the large-scale fading factor, i.e., the pathloss for respective channel
% gain
beta_pST=A0*(d_pST/d0).^(-alpha);
beta_sp=A0*(d_sp/d0).^(-alpha);
beta_ss=A0*(d_ss/d0).^(-alpha);
beta_pp=A0*(d_pp/d0).^(-alpha);
beta_ps=A0*(d_ps/d0).^(-alpha);
beta_EAP_ST=A0*(rho_EAP_ST/d0).^(-alpha);
% channel_gain_model=sqrt(path_loss)*Rayleigh fading
h_pST=sqrt(beta_pST)*(sqrt(2)/2*complex(randn(N,1),randn(N,1)));
g_sp=sqrt(beta_sp)*(sqrt(2)/2*complex(randn(N,1),randn(N,1)));
G_ss=sqrt(beta_ss)*(sqrt(2)/2*complex(randn(M,N),randn(M,N)));
h_pp=sqrt(beta_pp)*(sqrt(2)/2*complex(randn(1),randn(1)));
h_ps=sqrt(beta_ps)*(sqrt(2)/2*complex(randn(M,1),randn(M,1)));
H_EAP_ST=repmat(sqrt(beta_EAP_ST),N,L,1).*(sqrt(2)/2*complex(randn(N,L,K),randn(N,L,
K)));

% save('channel_gain','h_pST','g_sp','G_ss','h_pp','h_ps','H_EAP_ST');
end
```

Equation_solution

```
function [t_star] = equation_solution(beta, P0, Pp, noise_antenna, noise_conv, noise_PU,
h_pp, g_sp, eta, h_pST, lambda, rho, Qs, scale_factor)
%Find the maximum achievable rate for the PU given rho_k's and Qs by the
%equation regarding t
%   t is obtained by looking for the unique "zeros" of a monotonically
%   decreasing function in terms of t
% K=size(H_EAP_ST,3);
P_EH=P0*rho.'*lambda+beta*Pp*norm(h_pST)^2;

t_ub=1/2*log2(1+beta*Pp*norm(h_pST)^2/(noise_antenna+noise_conv));
t_lb=1/2*log2(1+beta*Pp*abs(h_pp)^2/noise_PU);
t_array=linspace(t_lb,t_ub,1e4);
varrho=@(t)1-noise_conv*(2.^(2*t)-1)./(beta*Pp*norm(h_pST)^2-
noise_antenna*(2.^(2*t)-1));
myfun=@(t)(sqrt((eta*varrho(t)*P_EH-
real(trace(Qs))/scale_factor)*scale_factor)*norm(g_sp)+sqrt((1-
beta)*Pp)*abs(h_pp)).^2/(real(g_sp'*Qs*g_sp)+noise_PU)+beta*Pp*abs(h_pp)^2/noise_P
U-(2.^(2*t)-1);

%The argument that yields the least square of the difference between LHS
%and RHS of the closed-form equation
[ls, I_ls]=min(abs(myfun(t_array)).^2);
t_star=t_array(I_ls);
end
```

Heuristic_main

```
clc; clear all;
K=6; %the number of EAP within the reach of the ST
perm=dec2bin(0:2^K-1); %generate an (2^K-1)-by-K char arrays that consist of all K-bit combinations of binary input
%convert char arrays 'perm' to numerical arrays 'Perm'
Perm=zeros(size(2^K,K));
for pp=1:2^K
        for kk=1:K
                Perm(pp,kk)=str2double(perm(pp,kk));
        end
end
N=3;
M=3;
L=10; %the number of antenna each EAP is equipped with
%Deployment of the EAPs, PT, ST, PU and SU assuming a polar coordinate
%system originated at the ST (CR relay)
d_pST=5; %distance between the PT and the ST
d_sp=5;
d_ss=5;
R_max=8; %furtherest radius of an EAP that the ST can have active access to
s=rng;
rng(10, 'twister');
rho_EAP_ST=R_max*sqrt(rand([1,1,K]));
beta_array=linspace(.01,1,99);
scale_factor=1e-8;
% n=20; % the preset length(R_PU_array) that decides how many points are targetted for a given beta;
Pp=1;
P0=10/scale_factor;
noise_antenna=1e-14/scale_factor;
% noise_antenna=1e-4;
noise_conv=1e-10/scale_factor;
% noise_conv=1;
noise_PU=noise_antenna+noise_conv;
noise_SU=noise_PU;
eta=.5;
c1=1;
c2_array=[0 logspace(0,5,6)];
c2_array=c2_array*scalar_factor;

trial_Max=100;
```

```
rho_grd_array=zeros(K,length(c2_array),trial_Max);
% beta_grd_array=zeros(trial_Max,length(R_PU_array));
payoff_grd_array=zeros(trial_Max,length(c2_array));

rho_co_grd_array=zeros(K,length(c2_array),trial_Max);
% beta_co_grd_array=zeros(trial_Max,length(R_PU_array));
payoff_co_grd_array=zeros(trial_Max,length(c2_array));


% rho_grd_array=zeros(K,length(R_PU_array));
% payoff_grd_array=zeros(1,length(R_PU_array));
%
% rho_co_grd_array=zeros(K,length(R_PU_array));
% payoff_co_grd_array=zeros(1,length(R_PU_array));


R_PU=4;
R_SU=4;



% load channel_gain;

%%
tic;
for ii=1:trial_Max
    ii
    [h_pST, g_sp, G_ss, h_pp, h_ps, H_EAP_ST]=channel_generation(N, M, K, L, d_pST,
d_sp, d_ss, rho_EAP_ST);
    h_pST=h_pST/sqrt(scale_factor);
    h_pp=h_pp/sqrt(scale_factor);
    g_sp=g_sp/sqrt(scale_factor);
    G_ss=G_ss/sqrt(scale_factor);


    % generate the spectral radius for individual EB, i.e., each corresponding
    % to one N-by-L matrix "H_{k,ST}
    lambda=zeros(K,1);
    for kk=1:K
        [U, Lambda, V]=svd(H_EAP_ST(:,:,kk),'econ');
        lambda(kk)=max(diag(Lambda).^2);
    end
    [sorted_lambda,sorted_I]=sort(lambda,'descend');
```

```
% generate the spectral radius for cooperative EB, i.e., each corresponding
% to one N-by-\sum_{k=1}^K L_k large matrix
H=reshape(H_EAP_ST,[N,K*L]);
lambda_perm=zeros(2^K,1);
lambda_perm(2^K)=max(eig(H'*H));

payoff_grd_array_temp=zeros(size(c2_array));
rho_grd_array_temp=zeros(K,length(c2_array));
%       beta_grd_array_temp=zeros(size(R_PU_array));

payoff_co_grd_array_temp=zeros(size(c2_array));
rho_co_grd_array_temp=zeros(K,length(c2_array));
%       beta_co_grd_array_temp=zeros(size(R_PU_array));

for nn=1:length(c2_array)
    %           nn
    c2=c2_array(nn);
    %           payoff_array=zeros(1,size(perm,1));
    %           Status_array=cell(1,size(perm,1));
    %           payoff_co_array=zeros(1,size(perm,1));
    %           Status_co_array=cell(1,size(perm,1));
    % Maximize ST's payoff by exhaustive search over 2^K's enumeration of \rho\in{0,1}^{K\times 1}

    rho_full=ones(K,1);
    [Qs, w_prime_p, varrho, beta, payoff_full, Flag, Status]=maximize_payoff(P0, Pp, noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, lambda, rho_full, R_PU, R_SU, c1, c2, scale_factor);
    rho_empty=zeros(K,1);
    [Qs, w_prime_p, varrho, beta, payoff_empty, Flag, Status]=maximize_payoff(P0, Pp, noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, lambda, rho_empty, R_PU, R_SU, c1, c2, scale_factor);
    [payoff_grd_array_temp(nn), rho_grd_array_temp(:,nn)]=maximize_payoff_heur(P0, Pp, noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, sorted_lambda, sorted_I, R_PU, R_SU, c1, c2, scale_factor, payoff_full, payoff_empty);



    [Qs_co, w_prime_p_co, varrho_co, beta_co, payoff_co_full, Flag_co, Status_co]=maximize_payoff_co(P0, Pp, noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, lambda_perm(2^K), R_PU, R_SU, c1, c2, scale_factor);
    [Qs_co, w_prime_p_co, varrho_co, beta_co, payoff_co_empty, Flag_co, Status_co]=maximize_payoff_co(P0, Pp, noise_antenna, noise_conv, noise_PU, noise_SU,
```

```
h_pp, g_sp, eta, h_pST, G_ss, lambda_perm(1), R_PU, R_SU, c1, c2, scale_factor);
            [payoff_co_grd_array_temp(nn),
rho_co_grd_array_temp(:,nn)]=maximize_payoff_co_heur(P0,        Pp,        noise_antenna,
noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, h_pST, G_ss, H_EAP_ST, R_PU, R_SU, c1,
c2, scale_factor, payoff_co_full, payoff_co_empty);

      end
      payoff_grd_array(ii,:)=payoff_grd_array_temp;
      rho_grd_array(:,:,ii)=rho_grd_array_temp;
      %        beta_grd_array(ii,:)=beta_grd_array_temp;

      payoff_co_grd_array(ii,:)=payoff_co_grd_array_temp;
      rho_co_grd_array(:,:,ii)=rho_co_grd_array_temp;
      %        beta_co_grd_array(ii,:)=beta_co_grd_array_temp;
end

% payoff_grd_array_mean=sum(payoff_grd_array)/trial_Max;
% payoff_co_grd_array_mean=sum(payoff_co_grd_array)/trial_Max;
save('heuristic_payoff_vs_c2_R_SU_4_K_6_09_04_2016.mat');
eclipsed_fixed_beta=toc;

%                                                   plot(R_PU_array,max(0,payoff_star_array),'--
bo',R_PU_array,max(0,payoff_co_star_array),'--b*',R_PU_array,max(0,payoff_grd_array),'-
bo',R_PU_array,max(0,payoff_co_grd_array),'-b*','LineWidth',.5);
%        set(gca, 'FontSize',12);
%        xlabel('R_{PU} (bps/Hz)');
%        ylabel('Payoff of the ST (Unit)');
%        legend('EB-optimal','CoEB-optimal','EB-proposed','CoEB-proposed');
%        grid on; hold on;
```

Feasible_region

```
%Charaterize the feasible region of (R_PU, R_SU)'s
%by obtaining the maxium achievable R_SU for each R_PU through solving problem (P0-1), where the feasible range of R_PU is given by solving problem (P0-2)
clc; clear all;
K=10; %the number of EAP within the reach of the ST
N=3;
M=3;
L=10; %the number of antenna each EAP is equipped with
d_pST=5; %distance between the PT and the ST
d_sp=5;
d_ss=5;
R_max=8; %furtherest radius of an EAP that the ST can have active access to
s=rng;
rng(10, 'twister');
rho_EAP_ST=R_max*sqrt(rand([1,1,K]));
beta_array=linspace(.01,1,100);
n=20; % the preset length(R_PU_array) that decides how many points are targetted for a given beta;
scale_factor=1e-8;
% n=20; % the preset length(R_PU_array) that decides how many points are targetted for a given beta;
Pp=10;
P0=10/scale_factor;
noise_antenna=1e-14/scale_factor;
% noise_antenna=1e-4;
noise_conv=1e-10/scale_factor;
% noise_conv=1;
noise_PU=noise_antenna+noise_conv;
noise_SU=noise_PU;
eta=.5;
%feasibility problem to find the maximum permissive R_PU, i.e., (P0-2') by
%CVX, and the semi-closed form solutions, respectively

% x=zeros(L,K);
% %total harvested power when all EAP are all turned on
% sum_EH=0;
% for kk=1:K
%       [U, Lambda, V]=svd(H_EAP_ST(:,:,kk),'econ');
%       x(:,kk)=sqrt(P0)*V(:,1);
%       sum_EH=sum_EH+norm(H_EAP_ST(:,:,kk)*x(:,kk))^2;
% end
```

```
[h_pST, g_sp, G_ss, h_pp, h_ps, H_EAP_ST]=channel_generation(N, M, K, L, d_pST, d_sp, d_ss, rho_EAP_ST);
h_pST=h_pST/sqrt(scale_factor);
h_pp=h_pp/sqrt(scale_factor);
g_sp=g_sp/sqrt(scale_factor);
G_ss=G_ss/sqrt(scale_factor);

lambda=zeros(K,1);
for kk=1:K
    [U, Lambda, V]=svd(H_EAP_ST(:,:,kk),'econ');
    lambda(kk)=max(diag(Lambda).^2);
end
rho=ones(K,1);

H_EAP_ST_cell=num2cell(repmat(H_EAP_ST,1,1,1,n),[1,2,3]);
H_EAP_ST_array=cell(1,n);
H_EAP_ST_array(1,:)=H_EAP_ST_cell(1,1,1,:);
G_ss_cell=num2cell(repmat(G_ss,1,1,n),[1,2]);
G_ss_array=cell(1,n);
G_ss_array(1,:)=G_ss_cell(1,1,:);
% x_cell=num2cell(repmat(x,1,1,n),[1,2]);
% x_array=cell(1,n);
% x_array(1,:)=x_cell(1,1,:);
w_prime_p_array=cell(1,n);
Qs_array=cell(1,n);
varrho_array=cell(1,n);
R_PU_array=zeros(length(beta_array),n);
R_SU_array=zeros(length(beta_array),n);
Qs=zeros(N);


for ii=1:length(beta_array)
    beta=beta_array(ii)
    t_min=1/2*log2(1+beta*Pp*abs(h_pp)^2/noise_PU);
    % [w_prime_p,Qs,rho,t_cvx] = Feasible_R_PU(beta, Pp, noise_antenna, noise_conv, noise_PU, h_pp, g_sp, eta, H_EAP_ST, h_pST, x);
    [t_equation] = equation_solution(beta, P0, Pp, noise_antenna, noise_conv, noise_PU, h_pp, g_sp, eta, h_pST, lambda, rho, Qs, scale_factor); %the maxium achievable rate for the PU given rho_k's and Qs

    %Characterize the Pareto boundary of the achievable(R_PU, R_SU)'s given beta
    R_PU_array(ii,:)=linspace(t_min,t_equation*.999,n);

    % use loop to plot (R_PU, R_SU)'s boundary
```

```
% for ll=1:length(R_PU_array)
% [w_prime_p, Qs, rho, R_SU_array(ll)]=maximum_R_SU(beta, Pp, noise_antenna, noise_conv, noise_PU, noise_SU, h_pp, g_sp, eta, H_EAP_ST, h_pST, G_ss, x, R_PU_array(ll));
%end

%use "arrayfun" to plot (R_PU, R_SU)'s boundary
%B(i)=maximum_R_SU(A(i)), in which B can be either a cell array or
%an array, but the returned value is stored in B(i), while the input is taken as A(i).
[w_prime_p_array, Qs_array, varrho_array, R_SU_array(ii,:)]=arrayfun(@maximum_R_SU, beta*ones(1,n), P0*ones(1,n), Pp*ones(1,n), noise_antenna*ones(1,n), noise_conv*ones(1,n), noise_PU*ones(1,n), noise_SU*ones(1,n), h_pp*ones(1,n), num2cell(repmat(g_sp,1,n),1), eta*ones(1,n),...
    num2cell(repmat(h_pST,1,n),1), G_ss_array, num2cell(repmat(lambda,1,n),1), num2cell(repmat(rho,1,n),1), R_PU_array(ii,:), scale_factor*ones(1,n));
end

plot(R_PU_array_bound,R_SU_array_bound,'-ob', 'MarkerSize',4);
plot(max(R_PU_array_bound)*ones(1,5),linspace(0,min(R_SU_array_bound),5),'-ob');
plot(linspace(0,min(R_PU_array_bound),5),max(R_SU_array_bound)*ones(1,5),'-ob');
set(gca, 'FontSize',12);
xlabel('R_{PU} (bps/Hz)');
ylabel('R_{SU} (bps/Hz)');
% legend('\beta=.75');
grid on; hold on;
```

Feasible_R_PU

```
function [w_prime_p_star,Qs_star,rho_star,t_star] = Feasible_R_PU(beta, Pp, noise_antenna, noise_conv, noise_PU, h_pp, g_sp, eta, H_EAP_ST, h_pST, x)
% Find the maximum achievable R_PU via bi-section over t solving a
% feasibility problem
%   Detailed explanation goes here
N=length(g_sp);
K=size(H_EAP_ST,3);
sum_EH=0;
for kk=1:K
    sum_EH=sum_EH+norm(H_EAP_ST(:,:,kk)*x(:,kk))^2;
end
h_prime_pp=[g_sp;h_pp];
H_prime_pp=h_prime_pp*h_prime_pp';
G_sp=g_sp*g_sp';
E=[eye(N) zeros(N,1)]; %w_p=E*w_prime_p
I_N_plus_one=eye(N+1);
U_N_plus_one=diag(I_N_plus_one(:,N+1));


t_ub=beta*Pp*norm(h_pST)^2/(noise_antenna+noise_conv);
t_lb=beta*Pp*abs(h_pp)^2/noise_PU;
epsilon=1e-6;
% t_array=linspace(t_lb,t_ub,1e2);
t=(t_lb+t_ub)/2;
t_previous=0;


while abs(t-t_previous)>epsilon&&t<=t_ub
    rho=1-t*noise_conv/(beta*Pp*norm(h_pST)^2-t*noise_antenna);

    cvx_begin quiet
    variable W_prime_p(N+1,N+1) hermitian
    variable Qs(N,N) hermitian
    maximize 0
    subject to

beta*Pp*abs(h_pp)^2/noise_PU*(real(trace(G_sp*Qs))+noise_PU)+trace(H_prime_pp*W_prime_p)==t*(real(trace(G_sp*Qs))+noise_PU)
    trace(Qs)+trace((E'*E)*W_prime_p)<=eta*rho*(sum_EH+beta*Pp*norm(h_pST)^2)
    trace(U_N_plus_one*W_prime_p)==(1-beta)*Pp
    W_prime_p==hermitian_semidefinite(N+1)
```

```
    Qs==hermitian_semidefinite(N)
    cvx_end

    if strncmp('Solved',cvx_status,6)&&(cvx_optval==0)
        t_lb=t;
        Qs_star=Qs;
        rho_star=rho;
        t_star=t;
        W_prime_p_star=W_prime_p;
    else
        t_ub=t;
    end
    t_previous=t;
    t=(t_lb+t_ub)/2;

end

[U,Lambda,V]=svd(W_prime_p_star);
w_prime_p_star=sqrt(Lambda(1,1))*U(:,1);

end
```