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Multiple Antennas and Beamforming for SWIPT Systems

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Abstract

In conventional communication systems, the use of radio frequency (RF) signals is mainly constrained on information transfer. However, RF signals also contain energy and this fact leads to the emergence of various new research areas, like RF-enabled wireless power transfer (WPT) where wireless receivers could harvest energy from RF signals radiated by an energy transmitter. There is another technique that use the same RF signals for energy and information transfer jointly, this technique is regarded as simultaneous wireless information and power transfer (SWIPT).

Although a lot of research efforts have made on these new areas in literature, from practical perspective, further development of WPT and SWIPT still faces some problems like low power transfer efficiency, safety concerns etc. These problems slow down the speed of transforming SWIPT and WPT from theory to practice.

In this article, we first provide an overview of WPT and SWIPT which involves definition of these two paradigms, their possibilities and constrains as well as relevant technologies that are used to achieve efficient WPT and SWIPT. Then we focus on a SWIPT system and we aim to optimize the SWIPT system by maximizing its energy efficiency. A detailed discussion of this optimization problem is provided in this article.

Abbreviations

WPT Wireless power transfer
SWIPT Simultaneous Wireless Information and Power Transfer
RF Radio Frequency
EH Energy Harvesting
ID Information Decoding
MPT Microwave Power Transfer
TDD Time Division Duplexing
FDD Frequency Division Duplexing
CSI Channel State Information
DoFs Degree of Freedom
MIMO Multiple-input and Multiple-output
SNR Signal to Noise Ratio
DC Direct Current
QoS Quality of Service
AWGN Additive Gaussian Noise

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Notations

$\vec{h}$	Channel vector between the transmitter and the information receiver.
$\vec{g}_j$	Channel vector between the transmitter and the j_{th} energy receiver.
$\vec{w}$	Information beamforming vector.
σ_{ant}^2, σ_s^2	Antenna noise and signal processing noise.
ρ	Power splitting factor.
P_{min_j}	Minimum required power of the j_{th} energy receiver.
P_{min}	Minimum required power of information receiver.
P_c	Power consumed for manipulating transmitter itself.
P_1	Power harvested from non-renewable energy source.
P_2	Power harvested from renewable energy source

Chapter 1 Introduction

1.1 Wireless Power Transfer(WPT)

Wireless power transfer (WPT) is the transmission of electrical energy from a power source to an electrical load, such as an electrical power grid or appliance, without the use of conductors like wires or cables [1]. In general, a wireless power system consists of a "transmitter" connected to a source of power such as a power line, which converts the power to a time-varying electromagnetic field, and one or more "receiver" devices which receive the power and convert it back to direct current (DC) or alternating current (AC) which is used by an electrical load [2][3]. There are two main regions of WPT, one is near-field region or non-radiative region, the other is far-field region or radiative region.

Near-field region WPT is mainly facilitated by capacitive coupling (electrostatic induction) between metal electrodes, or via magnetic fields by inductive coupling (electromagnetic induction) between coils of wire [3][4][5][6]. There is no radiative in the near-field region WPT, so the use of near-field region WPT do not arise public health concerns caused by strong electromagnetic radiation. However, if there is no receiving device or absorbing material within their limited range to "couple" to, near-field region WPT is not achievable as no power leaves the transmitter [7]. Besides, the propagation range of near-field region WPT is extremely short and the transmit power decreases with distance exponentially [8][9][10].

The use of RF signals for energy harvesting (EH) enables far-field region WPT. The propagation range in far-field region WPT is more acceptable than the near-field region WPT and energy is radiated by the transmitter no matter there is a receiver to absorb it or not. One specific example of far-field region WPT is microwave power transfer (MPT), MPT takes use of radiative property of microwave to transmit energy, it has long propagation range due to the support of large-scale antenna arrays and high-power microwave generators. Although energy transmission in MPT is not constrained in short distance and the use of large antenna arrays facilitates efficient MPT, MPT or far-field region WPT is not suitable for everyday use because of strong magnitude radiation which results in serious safety concerns.

Despite further development of WPT faces several challenges, the use of WPT is still attractive. As the use of WPT avoids the costly process of installing and displacing power cables in buildings and infrastructures. Besides, it also provides an attractive solution to prolong lifetime of power-limited networks and wireless devices in use, as they can use energy harvested from electromagnetic radiation through WPT to charge batteries. WPT has already been used in simple wireless devices with low energy consumption, for instance, Intel has demonstrated the wireless charging of a temperature and humidity meter as well as a liquid-crystal display by using the signals radiated by a TV station 4 km away [11]. More importantly, WPT makes it possible to eliminate the “last wires” connecting mobile devices to charger, thus, WPT has potential to increase the mobility of wireless devices significantly and improve user experience, besides, in a communication network with WPT, both transmitters and receivers can be supported without external power sources. In addition, WPT is a controllable power transfer method and it can be environmental friendly. In RF-enabled WPT, receivers harvest energy from ambient energy transmitter. The energy source is stable, it is also fully controlled by the transmitter. Besides, transmitter can also harvest energy from the surrounding environment, like solar energy or wind energy, then the harvest energy can be used for manipulating transmitter itself and enable wireless energy transmission between transmitter and receiver.

Although WPT provides a lot of possibilities in both academic and industrial area, it still faces a lot of challenges. In comparison WPT with traditional wireless communication, energy sensitivity in WPT is much more important than in traditional wireless communication. In traditional wireless communication, the goal is to ensure transmit signal can be decoded at receiver side, so the amount of power reaching the receiver is not so important as long as it is sufficient so the signal to noise ratio is high enough that the information can be received intelligibly [4] [5] [12]. In contrast, the amount of energy received at receiver side and the energy efficiency (fraction of transmitted energy that is received) are important in WPT [4].

However, the fact is power transfer efficiency in WPT is relatively low as receivers can only harvest a small amount of energy emitted by the transmitter due to path loss and channel fading. The low conversion rate of radio frequency (RF) signal to direct current (DC) also results in inefficient WPT. Besides, as WPT is initially used for facilitating energy harvesting for critical applications with guaranteed quality of service (QoS), it requires strong electromagnetic radiation which has raised serious public health concerns. Further development of WPT is slow because of these above-mentioned constrains and problems.

Thanks to recent advances in silicon technology and multiple antenna technology that make it possible to solve those above-mentioned problems. The breakthrough in silicon technology has reduced energy demand of simple wireless devices significantly and multiple antenna technology also contributes a lot for reducing total transmit power. Moreover, multiple-antenna devices enable energy beamforming techniques which could shape the transmit waveform at each antenna and control the collected waveforms at receiver side. The beamforming techniques can increase signal reception at receiver side so that the energy efficiency can be improved.

1.2 Simultaneous wireless information and power transfer(SWIPT)

As RF signals can be used not only in energy transfer but information transfer, so, recently, there has been an increasing interest in the integration of wireless power transfer and information transmission. It also motivates the development of a new technology named simultaneous wireless information and power transfer (SWIPT).

SWIPT has ability to achieve significant gains in spectral efficiency as it uses the same RF signal for signal processing and energy harvesting simultaneously, for example, wireless implants could be charged and calibrated concurrently with the same signal, and wireless sensor nodes can be charged with the control signal they received from the access point [13].

As SWIPT has potential to achieve high spectrum efficiency, it seems more attractive than conventional wireless information transfer, however, further development of SWIPT still faces a lot of challenges and the implementation of efficient SWIPT has different requirement on the design of communication system.

Like traditional communication system, system with SWIPT also suffers from channel fading and path loss which result in performance loss. Specifically, in practice, efficiency of power transfer in SWIPT is low and the distance of power transfer in SWIPT is relatively short. Inefficient SWIPT is not able to provide guaranteed quality of service (QoS). In addition to the conventional QoS requirements such as throughput, energy efficiency, fairness, and delay, efficient transfer of energy plays an important role as a new QoS requirement in SWIPT systems. Although energy efficiency in SWIPT can be simply improved by increasing the power of transmit signal, a higher transmit power leads to a larger susceptibility for information leakage due to broadcast nature of wireless channels [14]. Therefore, information security is an important issue in SWIPT system.

Besides, design of receiver side in SWIPT is different from conventional communication network and WPT, as receivers in traditional communication network is unable to simultaneously decode information and harvest energy from the same RF signal emitted by the transmitter due to different nature of signal processing and receiver sensitivities required, it also puts some difficulties in the implementation of information and power transfer jointly.

To improve power transfer efficiency in SWIPT, fading effects need to be abated. Multiple-antennas technology is a promising way to enhance performance over fading channel and the use of this kind of technology in SWIPT is motivated by the fact that they have the potential to improve the energy efficiency of wireless power transfer significantly [14]. The use of multiple-antenna technologies, more specifically, beamforming technologies can align the transmit signal to a certain power receiver to increase signal reception at receiver side.

The implementation of multiple-antennas technologies requires channel state information (CSI) is known to the transmitter side, generally, there are two commonly used CSI acquisition approaches in multiple-antennas systems. One is frequency division duplex (FDD) and the other is time division duplex (TDD).

In FDD, CSI is obtained by feedback from receivers to transmitters, specifically, the feedback is determined by a quantization codebook and accuracy of CSI is determined by size of the quantization codebook. Although a larger size quantization codebook results in more accurate CSI, it also introduces feedback overheads. Therefore, it is not efficient to increase size of quantization codebook to obtain accurate CSI. Instead, for more accurate CSI acquisition at transmitter side, the amount of feedback from receivers need to be increased.

In TDD, CSI can be obtained by making use of channel reciprocity directly. In comparison with FDD, TDD saves feedback resources but transceiver hardware impairment may result in performance loss in TDD.

As receivers in traditional communication system may not be able to facilitate SWIPT, so the implementation of SWIPT requires special receiver structures. There are several special receiver structures that can facilitate SWIPT like separated receiver structure, time switching receiver structure, power splitting receiver structure, antenna switching receiver structure and spatial switching receiver structure, etc. In the following, we provide an overview of these special receiver structures.

Separated Receiver Structure

In separated receiver architecture, an energy harvesting (EH) circuit and an information decoding (ID) circuit are implemented as two separated receivers with separated antennas, which are served by a common multiple antenna transmitter [14]. Both information receiver and energy harvesting receiver have ability to send feedback, for example, information about their energy demand to the transmitter side, so that the transmitter can take use of the limited system resources efficiently. Besides, the availability of channel state information (CSI) at transmitter side also lead to efficient use of limited system resources. Therefore, the use of feedback from receiver side and CSI can optimize achievable energy rate and information rate. Compared with other special receiver structures, separated receiver structure requires low complexities in hardware implementation. It can be simply implemented using off-the-shelf components for the two individual receivers [14].

Time Switching

In time switching receiver structure, each receiver is equipped with an information decoder and an energy harvester. The information decoder and the energy harvester are controlled by a switch. In each time slot, a time switching receiver can switch between energy harvesting circuit and information decoding circuit. In other words, in each time slot, time switching receiver can only use the received signal for either energy harvesting or information decoding. Time switching structure can be facilitated by simple hardware, but it has high demand on accurate information or energy scheduling.

Power Splitting

Receivers equipped with power splitting structure has ability to split the received signal into two power streams according to a certain power splitting factor. Then, these two streams are sent to an energy harvester and an information decoder. One stream is used for harvesting energy and the other stream is used for decoding the modulated information. Compared with time switching technique, power splitting technique has higher demand on hardware, besides, the power splitting factor need to be optimized according to different requirement on the energy demand of information decoding and energy harvesting of the receiver. Although complexities of power splitting structure are higher than time switching structure, it achieves signal processing and energy harvesting simultaneously in each time slot by using the same RF signal.

Antenna Switching

Antenna switching scheme is motivated by using antenna arrays in generating DC powers for reliable device operation. In general, antennas at receiver side are divided into two groups, one group is used for ID and the other group is used for EH [15]. These two groups are controlled by a switch for implementation of SWIPT in antenna domain. The antenna switching technique requires the solution of an optimization problem in each communication frame for optimal assignment of antenna elements to information decoding and energy harvesting [13].

Spatial Switching

Spatial switching (SS) technique can be applied in multiple-input and multiple-output (MIMO) configurations and achieves SWIPT in the spatial domain by exploiting multiple degrees of freedom (DoFs) of the interference channel [16]. As MIMO channel can be decomposed into parallel eigenchannels and each eigenchannel is orthogonal to other eigenchannels, so each channel can be exploited for either information decoding or energy harvesting. At the output of each eigenchannel, there is a switch that drives the channel output to either conventional decoding or the rectification circuit [16].

In this article, we focus on a SWIPT system which is powered by hybrid energy source including non-renewable energy source and renewable energy source. This system consists of a multiple-antenna transmitter and several single-antenna receivers. In the system, separated receiver structure is equipped at receiver side. In other words, there are two types of receivers in the system, one is information receiver, the other one is energy harvesting receiver. The information receiver has power splitting structure, so it can harvest energy and decode information from the same RF signal emitted by the transmitter simultaneously while the energy harvesting receivers can only harvest energy from the transmit signal.

Our aim in this article is to maximize energy efficiency between transmitter and information receiver. This can be implemented by taking use of total harvest power from hybrid energy source properly, besides, the use of multiple antenna technology, more specifically, beamforming technology and control of power splitting factor of the information receiver can also result in significant increase in energy efficiency.

Chapter 2 System Model

2.1 System model

In this article, we consider a SWIPT system which is powered by hybrid energy source, see in figure 2.1.

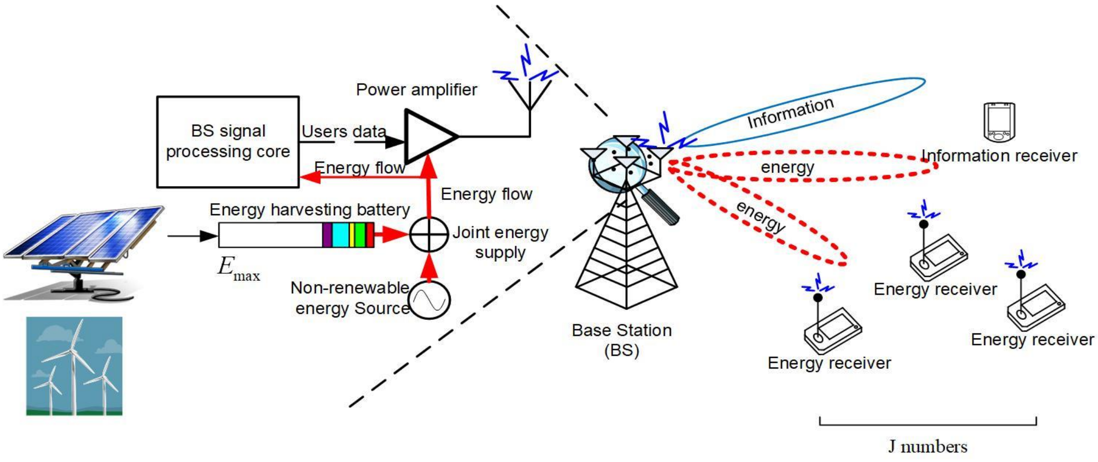

Figure 2.1

The use of renewable energy source like solar or wind make the system green. Stability of the system is ensured by using non-renewable energy source. In the down link of this system, there are J numbers energy harvesting receivers and one information receiver. Both energy harvesting receiver and information receiver are single antenna devices. The energy harvesting receiver can only harvest energy from RF signal emitted by the transmitter while the information receiver has power splitting structure which enables it harvest energy and decode information from the same RF signal emitted by the transmitter jointly.

At transmitter side, the transmitter is equipped with multiple antennas. In the SWIPT system, the transmission process is divided into n time slot, in each time slot, the transmitter first harvest energy from both renewable energy source and non-renewable energy source. Then it uses the harvested power to manipulate itself properly and transmit RF signal to the receiver side.

In conventional communication system, we mainly focus on whether the transmit signal could be decoded at receiver side, as high signal to noise ratio (SNR) of the receive signal lead to better result in information decoding, so the transmitter always emit RF signal that the amount of energy contained by the RF signal is far beyond the energy demand for information decoding at receiver side. In other words, large amount of energy is wasted which lead to inefficient use of limited system resources as transmitter lacks information of energy demand of receivers.

However, decode information is not the only goal in SWIPT system. Both information rate and energy efficiency are important criteria in SWIPT. It is obvious to see that inefficient use of limited system resources leads to low energy efficiency. In order to improve energy efficiency in SWIPT system, separated receiver structure is equipped at the receiver side, as both information receiver and energy harvesting receiver have ability to send information about their energy demand to the transmitter, so the transmitter can avoid waste in power transmission and assign the limited system resources appropriately.

The receive signals at information receiver and the j_{th} energy receiver are shown as below.

$$\mathrm{y} = \vec{h}^H \vec{x} + z_a \tag{2.1}$$

$$y_j = \vec{g_j}^H \vec{x} + z_j \quad \mathrm{j} \in \{1 \ldots \ldots J\} \tag{2.2}$$

where $\vec{x}$ denotes the transmit signal vector, $\vec{h}^H$ is the channel vector between transmitter and information receiver and $\vec{g_j}^H$ is the channel vector between transmitter and the j_{th} energy receiver. Both $\vec{h}^H$ and $\vec{g_j}^H$ has fading and path loss. z_a and z_j are additive Gaussian noises (AWGNs) of information receiver and the j_{th} energy harvesting receiver respectively, with zero mean and variance σ_{ant}^2 and $\sigma_{ant_j}^2$, respectively.

As the transmitter is equipped with multiple antennas, so, we use beamforming technique at transmitter side to increase signal reception at receiver side and achieve efficient SWIPT. The transmit signal vector now is given by

$$\vec{x} = \vec{w}s \tag{2.3}$$

where s is the transmit signal and $\vec{w}$ is the corresponding beamforming vector. We assume without loss of generality so that the energy of transmit signal is normalized to 1.

At receiver side, design of different beamforming vector can result in significant difference on efficiency of energy harvesting and information decoding. Besides, as the information receiver has power splitting structure, we need to take the effect of power splitting factor into consideration. We consider the information receiver splits the received signal into two power streams according to power splitting factor ρ and $1 - \rho$ for information decoding and energy harvesting respectively. See figure 2.2.

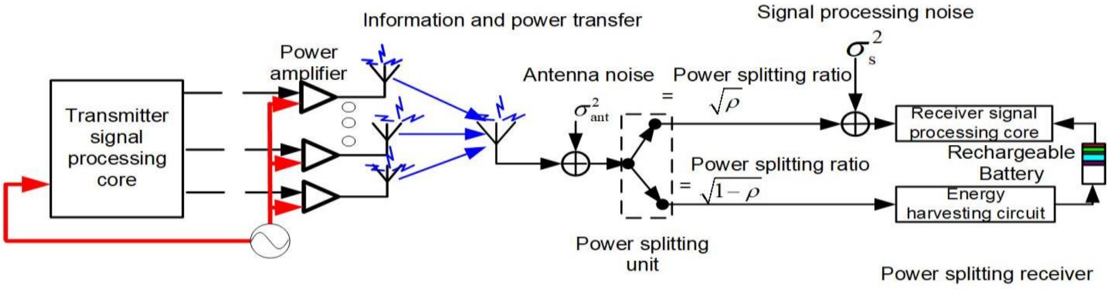

Figure 2.2

We assume the power splitting unit is a perfect passive analog device and the use of it does not introduce extra noise to the information receiver. The range of power splitting factor is from 0 to 1 which indicates that the power splitting unit does not introduce any extra power. The harvested power can be stored or used as a power supply for signal processing through charging the rechargeable battery when the energy provided by transmitter to information receiver is not enough for information decoding.

2.2 System optimization

In this section, we formulate our optimization problem for the SWIPT system. We aim to maximize energy efficiency between information receiver and transmitter. Definition of energy efficiency is given by

$$\frac{log_2(1+SNR)}{P} \tag{2.4}$$

where SNR is the signal to noise ratio of information receiver, P is the total cost at the transmitter side. P consists of two parts energies. One part is energy consumed for manipulating transmitter itself. The other part is power harvested by transmitter from other energy resources. It is shown that increase value of SNR at receiver side and decrease amount of either total transmit power or power consumed by transmitter itself can improve energy efficiency between information receiver and transmitter.

The transmission is divided into n time slot, we use i to indicate the i_{th} time slot. SNR_i indicates SNR of information receiver at the i_{th} time slot which is given by

$$SNR_i = \frac{\rho\left|\vec{h}_i^H\vec{w}_i\right|^2}{\rho\sigma_{ant}^2+\sigma_s^2} \qquad \forall\ i \in \{1 \ldots \ldots n\} \tag{2.5}$$

where ρ is the power splitting factor for information decoding, $\vec{h}_i^H$ is the Hermitian channel between information receiver and transmitter at i_{th} time slot and $\vec{w}_i$ is the corresponding beamforming vector at i_{th} time slot. σ_{ant}^2 is antenna noise power and σ_s^2 is signal processing noise power. Both σ_{ant}^2 and σ_s^2 are constant. It is obvious to see that maximization of SNR_i requires high receive signal power and low noise power, this can be implemented by control the power splitting factor ρ and beamforming vector $\vec{w}_i$. It is feasible to maximize receive signal power of information receiver by the design of beamforming vector. However, increasing of power splitting factor results in increasing in both receive signal power and antenna noise power, in order to get high SNR, the increasing rate of receive signal power is required to exceed the increasing rate of antenna noise power.

At transmitter side, the sum of power consumed by transmitter itself and energy harvested by transmitter from other energy resources is given by

$$P = P_c + P_{1,i} + P_{2,i} \tag{2.6}$$

P_c represents the power consumed by transmitter itself, here, P_c is a constant. $P_{1,i}$ represents harvest power from non-renewable energy source at the i_{th} time slot and $P_{2,i}$ represents harvest power from renewable energy source at the i_{th} time slot. The use of energy harvested from renewable energy source is free of charge as we can use the harvested renewable energy source directly without extra pay. The use of harvested energy from non-renewable energy source at transmitter side requires extra cost, for example, if the harvested energy by the transmitter is produced by fossil fuels, at least, the use of this harvested energy need to pay for the consumption of fossil fuels. We initially aim to reduce the cost at transmitter side, increasing use of renewable energy source is a promising way to achieve this goal, however, this will result in decrease of system stability. As in some occasions, the amount of energy provided by renewable energy source is not able to support the transmitter, sometimes, the total harvest energy from renewable energy source could even be zero, for example, it is impractical to harvest solar energy when the weather is cloudy. In order to ensure stability of the SWIPT system and maximize energy efficiency, there is a trade-off between the use of renewable energy source and non-renewable energy source.

The objective function of the optimization problem is given by

$$\text{maximize} \frac{\sum_{i=1}^{n} log_2(1+SNR_i)}{P_c+\sum_{i=1}^{n}(P_{1,i}+P_{2,i})} \tag{2.7}$$

s.t.

$$\eta_j\left|\vec{g}_i^H\vec{w}_i\right|^2 \geq P_{jmin_i}, \qquad \forall\ i \in \{1 \ldots\ldots n\}$$

$$\eta(1-\rho)\left|\vec{h}_i^H\vec{w}_i\right|^2 \geq P_{min_i} \qquad \forall\ i \in \{1 \ldots\ldots n\}$$

$$0 \leq \rho \leq 1$$

$$||\vec{w}_n||^2 \leq P_{2,n}+P_{1,n}+\left[\left(\sum_{i=1}^{n-1} P_{2,i}+P_{1,i}\right)-\left(\sum_{i=1}^{n-1}||\vec{w}_n||^2\right)\right]$$

The amount of power harvested by information receiver and energy harvesting receiver should larger or equal to the minimum required power of these two kinds of receivers. P_{jmin_i} represents the minimum required power of the j_{th} energy harvesting receiver at i_{th} time slot, P_{min_i} represents the minimum required power of information receiver at the i_{th} time slot. In this article, these two values are known to the transmitter side, as both information receiver and energy harvesting receiver can send feedback which contains their demand of energy to the transmitter. η_j and η is conversion rate of RF signal to direct current (DC) of the j_{th} energy harvesting receiver and information receiver respectively. $\|\vec{w}_n\|^2$ is the total power transmit to the receiver side, the value of it should be small or equal to the amount of power contained in the transmitter. As the transmission process is divide into n time slot, so the amount of power contained in transmitter at the n_{th} time slot is comprised by two parts. One part is harvest power from both renewable energy source and non-renewable energy source at n_{th} time slot which is represented as $P_{2n} + P_{1n}$, the other part is the remained power from the 1_{st} time slot to the $(n-1)_{th}$ time slot. This remained power is represented as $(\sum_{i=1}^{n-1} P_{2i} + P_{1i}) - (\sum_{i=1}^{n-1} \|\vec{w}_n\|^2)$, where $\sum_{i=1}^{n-1} P_{2i} + P_{1i}$ is the remained power from the 1_{st} time slot to the $(n-1)_{th}$ time slot at transmitter side and $\sum_{i=1}^{n-1} \|\vec{w}_n\|^2$is the transmitted power from the 1_{st} time slot to the $(n-1)_{th}$ time slot.

Chapter 3 Preliminary Simulation

In this section, we only consider transmission process at the 1_{st} time slot.

We first focus on the effects of increasing power splitting factor and weight of beamforming vector on SNR of information receiver.

SNR of information receiver at the 1_{st} time slot is given by

$$SNR_1 = \frac{\rho \left| \vec{h}_1^H \vec{w}_1 \right|^2}{\rho \sigma_{ant}^2 + \sigma_s^2} \tag{3.1}$$

In preliminary simulation, we assume channel between transmitter and information receiver is time invariant over the 1_{st} time slot and the energy beam aligns with the direction of the strongest eigenmode of the channel matrix.

We set channel gain of $\vec{h}_1$ equal to 1, the range of power splitting factor is from 0 to 1 and the range of beamforming vector is from 0 to 10. Antenna and signal processing noise power are constant. In the preliminary simulation, we set value of σ_{ant}^2 and σ_s^2 equal to 0.001 and 0.0001 respectively.

The relationship between power splitting factor and beamforming vector with SNR_1 is shown in figure 3.1 and figure 3.2 respectively.

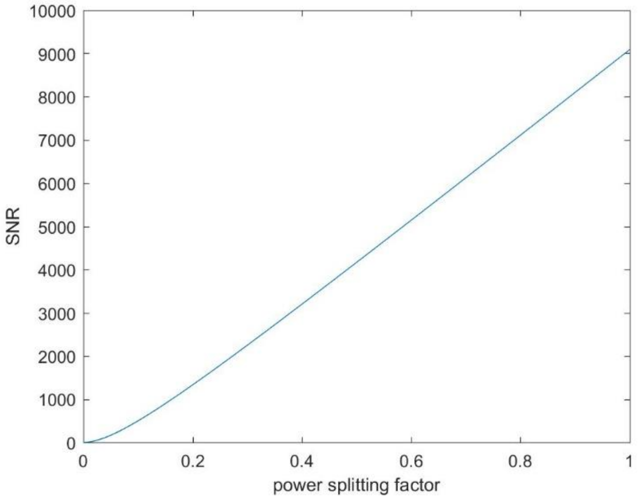

Figure 3.1

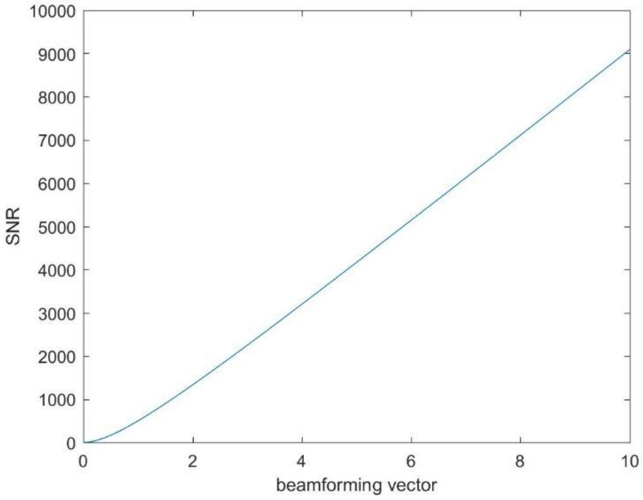

Figure 3.2

Intuitively, the result shows that SNR_1 as a function of power splitting factor ρand beamforming vector $\vec{w}_1$ is a monotone increasing function. Although increasing power splitting factor lead to increase in both receive signal power and antenna noise power, increase of beamforming vector weight make the increasing rate of receive signal power is far beyond the increasing rate of antenna noise power.

As SNR_1 is a monotone increasing function, so $log_2(1+SNR_1)$ is also a monotone increasing function, but the relationship between power splitting factor and beamforming vector with the efficiency of information transmission between transmitter and information receiver is not monotone increasing. We now focus on effect of beamforming and power splitting on efficiency of information transmission and we also consider effect of different use of both renewable energy source and non-renewable energy source on efficiency of information transmission.

We still consider the 1_{st} slot, and the objective function is given by,

$$\text{maximize} \frac{log_2(1+SNR_1)}{P_{1,1}+P_{2,1}+P_c} \qquad (3.2)$$

s. t.

$$C1: \eta_j |\vec{g}_1^H \vec{w}_1|^2 \geq P_{jmin_1}$$

$$C2: \eta(1-\rho)\left|\vec{h}_1^H \vec{w}_1\right|^2 \geq P_{min_1}$$

$$\mathrm{C3:} \quad 0 \leq \rho \leq 1$$

$$C4: \quad \|\vec{w}_1\| \leq P_{2,1}+P_{1,1}$$

For the calculation of SNR_1, value of channel gain, range of power splitting factor and beamforming vector remain same as the previous calculation of SNR_1.

P_c represents power consumed for manipulating transmitter itself, it is a constant and in preliminary simulation, we set the value of it equal to 1W. We assume all settings of parameters in the objective function satisfy constraints C_1 to C_4.

From previous analysis, the use of renewable energy source can increase efficiency of information transmission rate significantly, in the preliminary simulation, we first set the amount of harvest power from renewable energy source equal to zero and change the value of harvest power from non-renewable energy source. Then, we consider a situation that the harvest power from renewable energy source is enough to support signal transmission from transmitter side to receiver side and manipulation of transmitter. The relationship between weight of beamforming vector and efficiency of information transmission is shown in figure 3.3

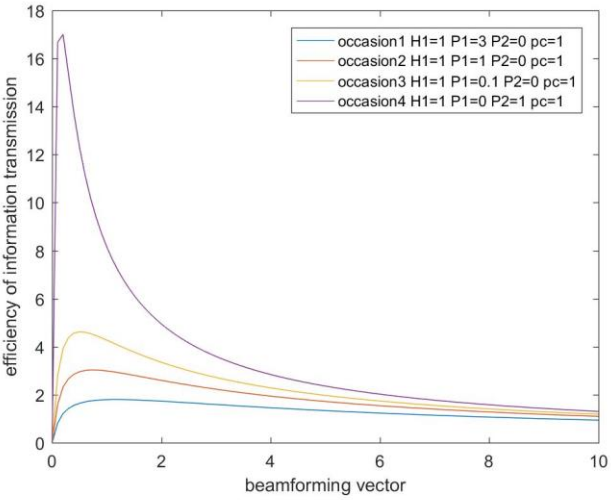

Figure 3.3

It is obvious to see the efficiency of information transmission does not increase with the increase of beamforming vector weight. With increasing weight of beamforming vector, the efficiency of information transmission first keeps increasing, then, it starts to decrease after reaching its maximum value.

In occasion 1, 2 and 3, we consider the transmitter do not harvest power from renewable energy source, so, the value of P2 is equal to 0. P1 is harvest power from non-renewable energy source, we assume at the 1_{st} time slot, energy harvest from non-renewable energy source is used up by the transmitter, so there is no remained power and the value of P1 is submitted into the objective function directly. From figure 5, we can see that increase use of non-renewable energy source lead to efficiency of information transmission decrease.

In occasion 4, we consider the transmitter harvest 1W energy from renewable energy source, and we assume 1W is enough to support the transmitter work properly and transmit signal to receiver side so we do not need to use energy harvest from non-renewable energy source. Besides, energy harvest from renewable energy source is used up by transmitter.

Compare occasion 4 with occasion 2, it is easy to see under the same level of energy demand, the use of renewable energy source can increase the efficiency of information transmission significantly and lead to decrease of beamforming vector weight.

The relationship between power splitting factor and efficiency of information transmission is shown in figure 3.4.

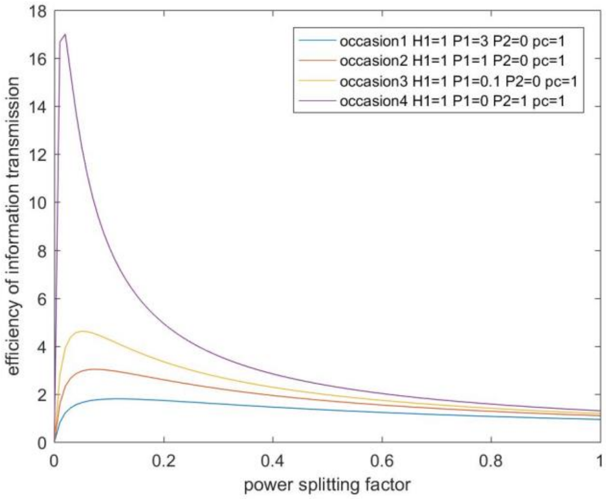

Figure 3.4

The efficiency of information transmission first increases with the increase of power splitting factor, after reaching its highest point, the efficiency of information transmission starts to decrease.

Chapter 4 Preliminary Conclusion

The result of preliminary simulation indicates that it is feasible to maximize efficiency of information transmission between transmitter and information receiver by appropriate design of power splitting factor and beamforming vector. Besides, the use of non-renewable energy source in the SWIPT system increase the efficiency of information transmission significantly. Once we get the maximum value of efficiency of information transmission, we can set the corresponding value of beamforming vector, power splitting factor to reach perpetual maximization of efficiency of information transmission.

Chapter 5

5.1 Solving the optimization problem mathematically

From the result of preliminary simulation, we can see the objective function is a concave function. More specifically, the numerator is concave and the denominator is affine.

As a constrained concave maximization problem is equivalent to a constrained convex minimization problem (through a sign change in the objective), so, alternatively, we may view the problem in (9) as the minimization problem subject to all the constraints. Moreover, constraints C1 and C2 are non-convex, which does not facilitate the design of a computationally efficient beamformer, so, we adopt trace operator and rewrite (2.7) in the following form. For simplicity, we assume ρ is given.

$$\text{minimize} - \frac{\sum_{i=1}^{n} log_2(1 + SNR_i)}{Pc + \sum_{i=1}^{n}\left(P_{1,i} + P_{2,i}\right)} \qquad (5.1)$$

where

$$SNR_i = \frac{\rho \mathrm{Tr}(H_i W_i)}{\rho\sigma_{ant}^2 + \sigma_s^2} \qquad \forall\ i \in \{1 \dots\dots n\}$$

s.t.

$$\text{C1:}\ \mathrm{Tr}(G_i W_i) \geq \frac{P_{jmin_i}}{\eta_j} \qquad \forall\ i \in \{1 \dots\dots n\}$$

$$\text{C2:}\ \mathrm{Tr}(H_i W_i) \geq \frac{P_{min_i}}{\eta(1-\rho)} \qquad \forall\ i \in \{1 \dots\dots n\}$$

$$\text{C3:}\left(\sum_{i=1}^{n} \mathrm{Tr}(W_i)\right) - \sum_{i=1}^{n}(P_{2,i} + P_{1,i}) \leq 0$$

$$\text{C4:}\ \mathrm{W} \succcurlyeq 0$$

$$\text{C5:}\ \mathrm{Rank}(\mathrm{W}) \leq 1$$

Where $\mathrm{W} = \vec{w}_i\vec{w}_i^H$, $\mathrm{G} = \vec{g}_i\vec{g}_i^H$ and $\mathrm{H} = \vec{h}_i\vec{h}_i^H$ $(\vec{h}_i \in C^{N_T \times 1},\ \ \vec{g}_i \in C^{N_T \times 1})$.

Solving problem (5.1) is still not easy due to the presence of inequality constraints, the non-convexity of constraint 5 as well as fractional pattern of the objective function.

According to Werner Dinkelbach theorem [17]:

For the following problems:

$$\max\left\{{N(x)}\Big/{D(x)}\,|x \in S\right\} \qquad (5.2)$$

$$\max\{N(x) - q_0 D(x)|x \in S\} \qquad for\ \ q \in E^1 \qquad (5.3)$$

Where E^n is the Euclidean space of dimension 1 and S be a compact and connected subset of E^n.

$$q_0 = {N(x_0)}\Big/{D(x_0)} = \max\left\{{N(x)}\Big/{D(x)}\,|x \in S\right\}$$

if and only if

$$\mathrm{F}(q_0) = F(q_0, x_0) = \max\{N(x) - q_0 D(x)|x \in S\} = 0$$

Where q_0 is maximum of problem (5.2) and x_0 is a solution vector of problem (5.2) and this theorem is still valid if we replace “max” by “min” [17]

Hence, we further rewrite the objective function,

$$\text{minimize} - \textstyle\sum_{i=1}^{n} log_2(1 + SNR_i) - q \sum_{i=1}^{n}\left(P_{1,i} + P_{2,i}\right) + Pc \qquad (5.4)$$

$\mathrm{s.t.}\qquad \mathrm{C1-C5}$

For computational efficient, we let $\tau_i = Tr(W_i G_i)$ and add another constraint C6, where C6 is

$$\mathrm{C6:}\ \ \tau_i \le Tr(W_i G_i)$$

Eventually, the optimization problem is

$$\text{minimize} - \textstyle\sum_{i=1}^{n} log_2\left(1 + \frac{\rho\tau_i}{\rho\sigma_{ant}+\sigma_s}\right) - q \sum_{i=1}^{n}\left(P_{1,i} + P_{2,i}\right) + Pc \qquad (5.5)$$

$\mathrm{s.t\ \ C1-C6}$

now the only difficulty of solving the optimization problem is due to non-convexity of constraint 5.

Constraints 5 is a combinatorial constrain [18-26]. This constraint is required for finding a global optimal solution [18]. In order to eliminate the effect of the non-convexity, we adopt a semidefinite programming(SDP) relaxation to (5.3) by relaxing constraint 5: $\mathrm{Rank(W)} = 1$ [18]. Then we get

$$\text{minimize} - \textstyle\sum_{i=1}^{n} log_2\left(1 + \frac{\rho\tau_i}{\rho\sigma_{ant}+\sigma_s}\right) - q \sum_{i=1}^{n}\left(P_{1,i} + P_{2,i}\right) + Pc \qquad (5.6)$$

$\mathrm{s.t\ \ C1-C4, C6}$

$$C5{:}\, Rank(W) = 1$$

According to the basic principles of optimization theory, if solution of W is a rank-one matrix, then it is the optimal solution of the original problem.

However, rank of W may larger than one and this lead to the constraint relaxation might not be tight.

In the following, we proof the tightness of the original problem after SDP relaxation via dual problem and KKT conditions of problem (5.6). We also need the Lagragian function of problem (5.6), which is

$$D(W_i,\alpha,\beta,\gamma,\delta,Y) = -\sum_{i=1}^{n} log_2\left(1+\frac{\rho\tau_i}{\rho{\sigma_{ant}}^2+{\sigma_s}^2}\right) - q^{(t)}(\sum_{i=1}^{n}\left(P_{1,i}+P_{2,i}\right)+Pc) + \alpha(\frac{P_{jmin_i}}{\eta_j} - \ \mathrm{Tr}(G_iW_i)) \ + \ \beta(\frac{P_{min_i}}{\eta(1-\rho)} - \mathrm{Tr}(H_iW_i)) \ + \ \gamma_i((\sum_{i=1}^{n}\mathrm{Tr}(W_i)) - \sum_{i=1}^{n}(P_{2,i} + P_{1,i}))+\delta\left(\tau_i - Tr(W_iH_i)\right) - \ \mathrm{Tr}(WY) \quad (5.7)$$

Where $\alpha \geq 0$ is the dual variable for the minimum required power of energy receiver in $C1$. $\beta \geq 0$ is the dual variable for the minimum required power of information receiver in $C2$. $\gamma_i \geq 0,\ i \in (1\cdots\cdots n)$ is the dual variable vector associated with the maximum transmit power in constraint $C3$. The matrix $Y \succcurlyeq 0$ is the dual variable for the semi-definiteness constraint on matrix W.

Now, we do the first order differentiation to W. By KKT condition, we then get:

$$Y^* = -\alpha^*G_i - \beta^*H_i + I_{N_T}\sum_{i=1}^{n}\gamma_i^* - \delta^*H_i$$

$$= -\alpha^*G_i + I_{N_T}\sum_{i=1}^{n}\gamma_i - (\beta^*+\delta^*)H_i$$

$$= A - (\beta^*+\delta^*)\ H_i \quad (5.8)$$

where $\alpha^*,\beta^*,\delta^*,\gamma_i^*,$ are optimal dual variables and we let $A = -\alpha^*G_i + I_{N_T}\sum_{i=1}^{n}\gamma_i$.

Besides, by complementary slackness condition, we get

$$Y^*W_i^* = 0 \quad (5.9)$$

(5.9) is satisfied when the columns of W_i^* lay in the null space of Y^*[19]. Therefore, if $\mathrm{Rank}(Y^*) = N_T - 1$, then the rank of optimal $W^* \neq 0$ must be one and the optimal $\vec{w}_i^*$ can be obtained through eigenvalue decomposition on W^*[19].

Now, we prove the tightness of relaxed optimization problem by contradiction that

A is a full rank matrix with rank N_T [19]. We assume that A is a rank deficient matrix with at least one zero eigenvalue and we denote the associated eigenvector as $\vec{u}$. Without loss of generality, we create a matrix $\mathrm{U} = \vec{u}\vec{u}^H$ from the eigenvector. We then multiply U at both side of (5.8) and apply trace operator, we get

$$\mathrm{Tr}(Y^* U) = Tr(AU) - (\beta^* + \delta^*)Tr(H_i U) \qquad (5.10)$$

$$= -(\beta^* + \delta^*)\mathrm{Tr}(H_i \mathrm{U}) \qquad (5.11)$$

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

We then examine the signs of both side of the equality in (5.11). We first consider the right-hand side. Recall constraint 6 is

$$\mathrm{C6:}\ \tau_i \leq Tr(W_i G_i)$$

and the optimal condition of constraint 6 is $\tau_i^* = Tr(W_i^* G_i)$, according to KKT condition, under the optimal condition, $\delta^* > 0$, hence $\beta^* + \delta^* > 0$. Next, we approve $\mathrm{Tr}(H_i \mathrm{U}) > 0$. Since $\vec{h}_i$ and $\vec{g}_i$ are statistically independent. As a consequence, the probability that H_i and G_i share the same null space is zero which yields $\mathrm{Tr}(H_i \mathrm{U}) \neq 0$. Moreover, $\vec{h}_i \vec{h}_i^H$ is a positive semidefinite matrix thus $\mathrm{Tr}(H_i \mathrm{U})$ must be positive and the right-hand side of (5.11) must be negative.

For the left-hand side of (5.11), Y^* is a positive semidefinite matrix and the left-hand side of (5.11) is non-negative, which contradicts the sign of the right-hand side of (5.11). Therefore, matrix A must be a full rank matrix with rank N_T [19]. We then have

$$\mathrm{Rank}(Y^*) + \mathrm{Rank}\big((\beta^* + \alpha^*)H_i\big) \geq Rank(Y^* + (\beta^* + \alpha^*)H_i) = Rank(A) = N_T$$

$$\mathrm{Rank}(Y^*) \geq N_T - 1 \qquad (21)$$

(21) indicates that $\mathrm{Rank}(Y^*)$ is either N_T or $N_T - 1$. In order to satisfy minimum required power at receiver side, W^* should not equal to zero. Hence, $\mathrm{Rank}(Y^*) = N_T - 1$ and $\mathrm{Rank}(W^*) = 1$

5.2 Conclusion

System parameters

Item	value
ρ: power splitting factor of information receiver	0.5
η: conversion rate of information receiver	0.5
η_j: conversion rate of j_{th} energy receiver	0.5
P_{1i}: Harvested power from non-renewable energy resources	3dB
P_{2i}: Harvested power from renewable energy resources	3dB
P_c: Power consumed by transmitter	1.5e-4

For simulation part, Dinkelbach method is applied.

Important assumption

1. From the 1_{st} time slot to the n_{th} time slot, for any given n, channel $\vec{h}_i$ and channel $\vec{g}_i$ are time invariant.
2. Channel $\vec{h}_i$ and channel $\vec{g}_i$ are statistically independent.
3. $P_{1,i}$ and $P_{2,i}$ is given and for any ith time slot, value of $P_{1,i}$ and $P_{2,i}$ are fixed.
4. For the simulation part, we set the number of information receiver and energy receiver in the system model all equal to 1

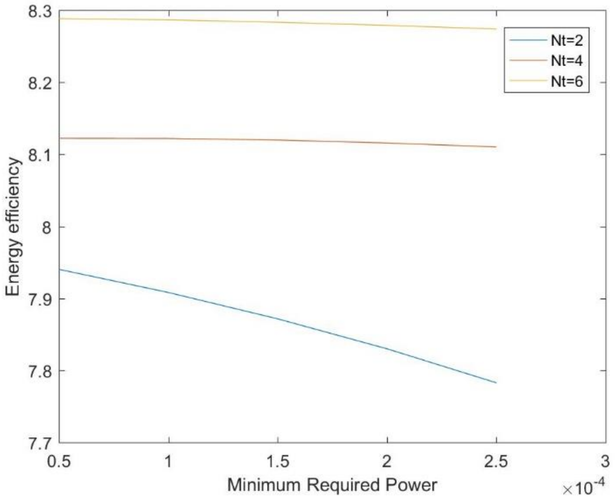

Figure 5.1

Figure 5.1 shows that when increasing the minimum required power at receiver side, energy efficiency will decrease. Moreover, increasing number of antennas at transmitter side can increase the energy efficiency significantly. The gap between $N_T = 2$ and $N_T = 4$ is larger than the gap between $N_T = 4$ and $N_T = 6$ due to channel hardening.

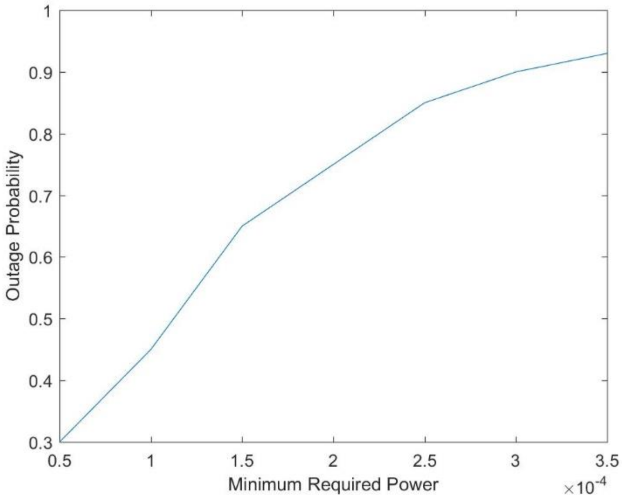

Figure 5.2

Figure 5.2 illustrates that with increasing of minimum required power, outage probability of channel is increasing. The increasing rate of channel outage probability is decreasing because the proposed optimization which utilities the resources efficiently.

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