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Simultaneous Wireless Information and Power Transfer for IoT

by

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Abstract

Wireless energy transfer technology enables tiny electronic devices in the Internet of Things to harvest energy from radio frequency signals. Radio frequency signals also have been used to carry information in the area of wireless communications for more than one century. Therefore, it is feasible to simultaneously transfer information and energy, from a dual functional access point, to wireless user terminal. Moreover, modern multiple antenna techniques saves both information and energy transmission from the severe channel fading and their performance can be significantly enhanced. However, this benefit high relies on availability and accuracy of channel state information at the transmitter side. To study the impacts of imperfect knowledge of channel on the system performance, a MISO SWIPT system with frequency division duplexing is proposed in this thesis. The trade-off of channel estimation will be studied and evaluated. In order for the system to achieve the optimal performance, a transmission protocol will be developed and evaluated.

Abbreviations

IOT Internet of Things

WPT Wireless power transfer

SWIPT Simultaneously wireless information and power transfer

RF Radio frequency

CSIT Channel state information at the transmitter

TDD Time division duplexing

FDD Frequency division duplexing

MIMO Multiple-input and multiple-output technology

MMSE Minimum mean square error estimation

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Chapter 1

Introduction

The rapid and successful development of integrated circuits and wireless communication technologies have significantly enhanced quality, performance, and interactivity of mobile electronic devices. In the near future, highly-developed electronic devices integrated with communication functionality modules may have the ability to reshape our daily lives. These devices will be embedded into our everyday objects and sense the physical world, collect and exchange data via the Internet. In this scenario, our surroundings no longer are passive things. They can be intelligent instead, capable of interacting with human beings and convey useful information to us, such as environmental temperature, environmental humidity, and human blood pressure. This whole concept based on networks of smart devices is known as the internet of things (IOT) [1] which has attracted a lot of attention from researchers and industries. The IOT offers a variety of solutions to certain applications in different scenarios. Governments can improve the management of city's assets, with IOT, our transportation systems can be more intelligent and efficient, our homes can automatically adjust themselves to the best condition for fitting human needs. The whole physical world will be smart, and our qualities of life will be significantly improved.

In terms of sensor networks, the number of sensors, electronic devices interconnected through the Internet may reach up to 50 billion across the world[2]. Therefore, one of the most demanding challenges of implementing sensor networks is how to provide them with sufficient and stable power supplies. However, existing technologies only provide them with limited operation time.

The most common type of the energy supply for wireless electronic devices is batteries. The traditional solutions of replacing and recharging batteries to prolonging the lifetime of electronic devices are impractical for sensor networks because the number of sensors included in a sensor network is very large and the density of these devices is also high. On the other hand, renewable energy sources, such as the wind and solar, are not able to be fitted into most of application scenarios of the IOT[3-5], since these sources are climate and location independent and unavailable in indoor environments most of the time.

Fortunately, there has been a newly-emerged technology which could address the problem. Radio-Frequency (RF) enabled wireless power transfer (WPT) has great potential to deliver constant and sufficient power to sensor networks over wireless channels[6-22], while other types of power supply are limited by availability and hardware compatibility. By considering the fundamental difference in physical mechanisms, existing WPT technologies are distinguished into three categories: inductive coupling, magnetic resonant and Electromagnetic radiation. Whereas the first two classes involve 'near-field' properties of electromagnetic waves for short distance applications within one meter, the RF-based WPT, whose waveforms are microwaves or lasers, can support long-distance-transmission applications over the range of a few meters to a kilometer by exploiting the radiative 'far-field' properties and the energy broadcasting property. WPT, therefore, should be the best candidate for overcoming the energy constraint of sensor networks and my work will focus on RF-enabled wireless power transfer. According to [23], typical RFID tags could harvest energy 4 meters away from an energy transmitter with approximately 0.6 mW received RF power when RF-enabled wireless power transfer is implemented, and some RF energy harvesting chips are capable of reaching tens of meters line-of-sight effective transmission distance with approximately 0.1 mW received power. Since RF signals have been used as carriers of information in the area of wireless communications for more than one century, there is a possibility that simultaneously transfers information and energy to receivers over the air, which is also known as simultaneously wireless information and power transfer (SWIPT)[17, 24-28].

In modern wireless communication systems, multiple-input and multiple-output technology (MIMO)[29-36], which refers to uses of to multiple antennas at both the transmitter and receiver to multiply the capacity of a radio link by exploiting the degree of freedom, has been an essential element of communication standards. In the best-case scenario, MIMO technique can remove negative effects of the multipath fading channel and significantly increase the information rate over a wireless channel. Besides, the performance of a WPT system (we focus on the amount of energy can be collected on the energy receiver from energy-bearing signals in a WPT system) also can be boosted by implementing MIMO. In general, the energy receiver only can acquire a portion of the total transmitted energy due to the omnidirectional propagation of electromagnetic signals through the transmission path, resulting in a low energy transfer efficiency. By implementing MIMO technique and precoding, the transmitting antenna array is capable of focusing the transmitted energy to a certain direction towards to the receiving device with a desired radiation pattern. Even if there is no clear line of sight, MIMO technique is able to adjust phases of signals through different paths via a radio channel in order to make signals add constructively[21]. As a result of this, the energy transfer efficiency can be significantly enhanced. Nevertheless, benefits of adopting MIMO techniques crucially rely on the availability and accuracy of knowledge of the channel state information at the receiver side (CSIT). One of the existing solutions to obtaining CSIT in a conventional communication system is by estimating uplink channel state based on training signals sent from receivers. Nevertheless, this method is only suitable for systems using Time division duplexing (TDD), a method which separates uplink channels from downlink channels in time domain, because it exploits reciprocity between the forward channel and reverse channel in TDD systems. An alternative solution is the so-called limited feedback method which applies to both time division duplexing and frequency division duplexing (FDD). The Receiver estimates downlink channel based on training sequences sent from the transmitter, and then the receiver sends feedback information, which indicates the transmitter how to perform optimal beamforming, from a quantized codebook. Both solutions involve sending pilot signals during some portion of the estimation phase and training is responsible for costs of time and energy.

Either the energy beamforming gain or the maximum achievable information rate is a strong correlation to the quality of the CSIT. For a training-based scheme, the amount of training affects the amount of available knowledge about the channel, and accordingly, affects the system performance—too little training and the upper bound of the system performance may not be achieved, too much training and there is no sufficient time left for data and energy transmission. Existing work only focused on characteristics (such as capacity) of wireless communication systems[27, 37, 38]. For a SWIPT system, the design goal is not only maximizing the average information transmission rate but also optimizing the energy transfer efficiency.

In my thesis, a point-to-point SWIPT system with MISO adopted is proposed for my study. I will assess the impact of the imperfect CSIT on the performance of the SWIPT system, especially on the amount of net harvested energy (which refers to the total harvested energy offset by the amount of energy consumed during channel estimation). Based on this, I will describe the correlation between the amount of training and the knowledge of the estimated downlink channel vector by mathematical equations. Finally, I will explore the optimal or suboptimal transmission scheme in order for my system to maximize the net harvested energy when only imperfect CSIT is available.

This thesis is organized as follows. In chapter 2, the background of this thesis project is explained. Chapter 3 presents the system model with certain consideration for my study. In chapter 4, the specific transmission protocol is developed and the optimization problem is solved. Chapter 5 demonstrates the specialized numerical result. Finally, chapter 6 draws conclusions and suggests the future work which can improve the thesis.

Notation: In this thesis, $\mathbf{A}^{\mathbf{H}}$, $\mathrm{Tr}(\mathbf{A})$ account for the Hermitian transpose, trace of the matrix $\mathbf{A}$. Matrix $\mathbf{I}_N$ represents an $\mathrm{N} \times \mathrm{N}$ identity matrix. $\mathbb{C}^{M\times N}$ represents the space of $M \times N$ complex matrices. $\mathbb{E}_{\mathbf{X}}[\mathbf{A}]$ represents the expectation with respect to the random matrix $\mathbf{A}$. A complex Gaussian random vector with mean vector μ and covariance matrix Σ is denoted by $CN(\mu, \Sigma)$. $|\mathrm{A}|$ represent the absolute value of a complex scalar and $\| \mathbf{A} \|$ stands for the norm a matrix.

Chapter 2

Background

2.1 Problem definition

Ideal performance and several practical system structures related to SWIPT systems with MIMO have been proposed in [21]. However, maximum performance cannot be achieved under the premise that perfect channel knowledge is available at the transmitter. Moreover, acquiring such CSIT generally is quite challenging for the following reasons. Firstly, most of the previous studies focus on obtaining CSIT in a communication system and lack considerations of energy transfer efficiency. Secondly, a commonly adopted training-related method, which takes advantage of reciprocity between uplink and downlink channels for estimating CSIT, only applies to systems using TDD [39]. This makes acquiring CSIT more challenging for systems using FDD. In addition to these two reasons, while another commonly adopted scheme in a communication system, which is the so-called limited feedback scheme, is applicable for both TDD and FDD based systems, the process of the accurate CSIT estimation consumes unexpected energy which could offset energy harvested by the receiver.

In order for a MIMO SWIPT system using FDD to achieve maximum performance, previous studies show that limited feedback scheme is a realistic solution to obtain CSIT, which can enable transmitters to perform optimal transmission schemes. In terms of limited feedback in traditional communication systems, a receiver firstly estimate downlink channels based on training sequences sent from a transmitter, and then the receiver based on estimated channel information send a certain B bits information as a feedback back to the transmitter, which indicates the optimal beamforming vector from a quantized codebook (typically with size of 2^B) via a feedback channel. Assuming that the feedback channel will not cause any distortions on the feedback information at all, transmitter is able to perform adaptive beamforming based on the B bits feedback [40]. For a joint SWIPT system, not only maximum information transmission rate should be considered, but also maximum net harvested energy should be carefully assessed. It is elemental to analyze the impact of B bits feedback on the receiver.

The Larger size of the codebook can ensure the smaller error of channel estimation when the channel mismatch occurs due to impairments of the transmission channel, and the system performance gain can be accordingly increased[41]. On the other hand, short feedback sequence can reduce the cost of energy and time consumed by sending feedback symbols. The impacts of training are similar to the limited feedback. While more training can increase the amount of channel state information acquired by channel estimation, too much training will consume excessive time and energy resources. In this thesis, I aim to use mathematical equations to explain the relationship between the amount of training and the accuracy of the channel estimation. Based on this equation, I also intend to compute the best training duration which can optimize the system performance.

2.2 Ideal performance of SWIPT and existing solutions

One of the most important studies about the optimal performance of SWIPT systems with implemented MIMO technique has been proposed in[21]. A three nodes SWIPT system model, which is composed of one transmitter, two different types of receiver. One receiver is responsible for information decoding functionality, and another receiver aims to collect energy from RF-based energy symbols. It is believed that ID receiver and EH receiver can be either implemented in the same user terminal or separated into different locations. When the energy harvesting module and the information decoding receiver are integrated into one user terminal and collaborate with each other, the EH receiver is responsible for gaining energy for the user terminal and with the assistance of ID receiver, which usually participates in CSIT estimation, EH receiver could achieve high energy transfer efficiency. In terms of co-located receiver, two effective receiver structures, time-switching, and power-splitting, also presented in their paper. Time-switching means that the energy harvesting terminal and the information receiver work in two orthogonal time slots. For the case of power-splitting, the received signal at the receiving antenna is split into two signal streams with different power level, one sent to EH and another sent to ID. Since the optimal information transmission scheme generally is different from the optimal power transmission scheme (in the sense of this, one optimal design may lead to another poor performance for a SWIPT system), the idea of rate-energy region has been proposed in this paper which is used to evaluate the performance of joint schemes.

Previous studies [39, 42, 43] have investigated CSIT estimation schemes for wireless energy transfer systems or SWIPT systems. In [39], a novel design framework, which maximizes the net harvested energy at energy receivers, has been proposed in order to address the trade-off between channel training and the resulting energy transfer efficiency. One fundamental assumption in their work is channel reciprocity. However, this assumption is held only for systems using TDD. [42] have investigated a feedback-based channel learning method, which is applicable for both TDD and FDD systems, for MIMO wireless energy transfer systems. Due to hardware limitations of energy receivers, it is generally challenging that let energy receivers perform the channel estimation which involves complicated baseband signal process. In this scheme, only one-bit feedback is required and relevant algorithms have been thoroughly presented. Practical hardware design can be consequently simplified. Analysis and simulation show that system performance is more appealing compared to other existing similar works. However, by increasing feedback bits and carefully feedback design, system performance can be further improved. One-bit scheme is only a compromise when energy receivers are lack in baseband signal processing capability. In [43], a MISO SWIPT system is considered with adaptive energy beamforming, and one of their objectives is to maximize energy transfer efficiency. To achieve this, a CSI quantized feedback scheme is proposed to increase the efficiencies of both power and information transmission in their paper. However, without any mathematical proof, the authors simply ignore the fact that feedback consumes energy and time. Moreover, although the authors explore the impact of imperfect CSIT on the corresponding system performance, the accuracy of CSIT is not correlated to feedback design.

Chapter 3

System model

In my thesis, I consider a point-to- point MISO system with FDD, in which a dual functional transmitter with N antenna and an information decoding receiver and an energy harvesting receiver are integrated into one user terminal sharing a single antenna, shown in Fig. 1. The transmitter sends radio frequency signals to the receiving antenna. The ID component and the EH component work in a power-splitting manner. The EH component plays a role of energy supply for the ID receiver, it can gain energy from energy-bearing RF signals. Because the ID Rx and EH Rx are co-located, their channel vectors are identical. It is assumed that the channel coherent time is much greater that every transmission block, which means that the channel state information from the transmitter to the receiver remains constant during every T symbol slots. $\sqrt{\alpha}\,\mathbf{h}$ denotes N dimensional downlink channel vector, where α accounts for the path loss factor and $\mathbf{h} \in \mathbb{C}^{1\times N}$ represents the channel fading vector which elements are independent and identical distributed (i.i.d.) circularly symmetric complex Gaussian with zero mean and unit variance. Moreover, the power splitting unit is employed, splitting the received signal into two signal streams with different power level, ρ out of total power sent to EH Rx and the remaining sent to ID Rx. Without loss of generality, the energy conversion efficiency is assumed to be equal to 1.

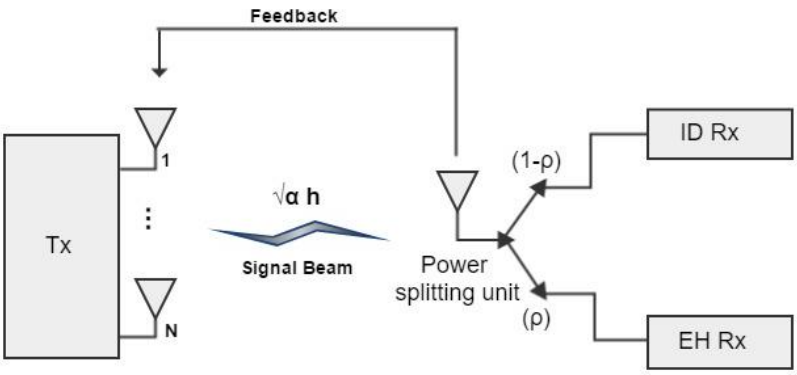

Fig.1. A point-to-point MISO system employing wireless energy and information transfer

Over one coherent time of T symbol slots, the received symbols at the receiving antenna via the downlink channel can be mathematically expressed as

$$y[\mathrm{t}] = \sqrt{\alpha}\mathbf{hx}[\mathrm{t}] + \mathrm{n}[\mathrm{t}], \mathrm{t} = 1,2,\dots,\mathrm{T} \tag{1}$$

where $y[\mathrm{t}]$ is a scalar which represents the received signal over the tth symbol duration; $\mathrm{n}[\mathrm{t}] \in \mathbb{C}^{1\times 1}$ is the additive Gaussian noise at the receiving antenna; $\mathbf{x}[\mathrm{t}] \in \mathbb{C}^{N\times 1}$ is the transmitted signal. It is important to point out that the CSIT has a great effect on both information and energy performance. If the full CSIT is available, the optimal system performance can be achieved. In order to obtain CSIT, one realistic solution is limited feedback (B bits) with a quantized codebook $\mathbf{W}$ of size 2^B. In general, the quantized codebook is designed based on channel phase information and is stored at both transmitter and receiver side[44-46]. The ID receiver receives the training sequence sent by the Tx over τ symbol durations at the beginning of every coherent block. With the received pilot signals, the receiver can estimate the channel and convey the optimal codeword index to Tx by sending B bits information via a feedback channel. When the transmitting beamforming is employed, $\mathbf{x}[\mathrm{t}] = \mathbf{w}[\mathrm{t}]\mathrm{s}[\mathrm{t}]$, where $\mathrm{s} \in \mathbb{C}^{1\times 1}$ are the pseudo-transmit signal with unit power and $\mathbf{w}[\mathrm{t}] \in \mathbb{C}^{N\times 1}$ is the corresponding beamforming vector. $\mathbf{W}[\mathrm{t}] = \mathbf{w}[\mathrm{t}]\mathbf{w}[\mathrm{t}]^{\mathbf{H}}$ is the covariance matrix of the beamforming vector and we have $\mathrm{Tr}\big[\mathbf{W}[\mathrm{t}]\big] = P$ for containing the maximum transmitted power within P. According to the law of energy conservation, the total harvested RF-band energy at the EH receiver over T symbol durations is modelled as

$$Q = \sum_{t=1}^{T} \rho||\sqrt{\alpha}\mathbf{h}\mathbf{w}[\mathrm{t}]\mathrm{s}[\mathrm{t}]||^2 \tag{2}$$

$$= \alpha\rho\mathrm{T}\mathbb{E}[||\mathbf{h}\mathbf{w}[\mathrm{t}]\mathrm{s}[t]||^2] \tag{3}$$

$$= \alpha\rho\mathrm{T}\ \mathrm{Tr}[\mathbf{h}\mathbf{w}[\mathrm{t}]\mathrm{s}[\mathrm{t}]\mathrm{s}[\mathrm{t}]^{\mathbf{H}}\mathbf{w}[\mathrm{t}]^{\mathbf{H}}\mathbf{h}^{\mathbf{H}}] \tag{4}$$

$$= \alpha\rho\mathrm{T}\ \mathrm{Tr}[\mathbf{h}\mathbf{w}[\mathrm{t}]\mathrm{s}[\mathrm{t}]\mathrm{s}[\mathrm{t}]^{\mathbf{H}}\mathbf{w}[\mathrm{t}]^{\mathbf{H}}\mathbf{h}^{\mathbf{H}}] \tag{5}$$

$$= \alpha\rho\mathrm{T}\ \mathrm{Tr}\left[\mathbf{h}^{\mathbf{H}}\mathbf{h}\mathbf{W}[\mathrm{t}]\right] \tag{6}$$

Note that, for simplicity, the term of the additive Gaussian noise is ignored for analyzing the harvested energy. Based on previous work[21], when the perfect CSIT is available, the optimal solution which can maximize the collected energy Q is given by

$$\mathbf{W}^{\star} = P\mathbf{v}_1\mathbf{v}_1^{\mathrm{H}} \tag{7}$$

where $\mathbf{v}_1$ represents the eigenvector corresponding to the maximum eigenvalue of $\mathbf{h}^{\mathbf{H}}\mathbf{h}$. The maximum harvested energy consequently is written by

$$Q_{\max} = \alpha\rho P\lambda_{\max}[\mathbf{h}^{\mathbf{H}}\mathbf{h}] \tag{8}$$

where $\lambda_{\max}[\mathbf{h}^{\mathbf{H}}\mathbf{h}]$ denotes the maximum eigenvalue of $\mathbf{h}^{\mathbf{H}}\mathbf{h}$. By precoding the original transmitted symbol s[t] with the corresponding beamforming vector $\mathbf{w}[\mathrm{t}] = \sqrt{P}\mathbf{v}_1$, the harvested energy Q at the EH receiver can achieve the theoretical maximum value $Q_{\max}$. Note that the harvested energy Q in (6) is dependent of the knowledge of the estimated channel vector $\hat{\mathbf{h}}$. In practice, the factors, including the quantization noise of the quantized codebook and the channel noise, contribute to the channel estimation error. Unfortunately, the perfect CSIT is always unavailable. As a result of this, the performance upper bound in (8) cannot be reached in most of the cases. In this thesis, based on the limited feedback scheme with the quantized codebook, the imperfect CSIT can be obtained in the first phase of the coherent time T. The remaining time of the coherent time T is used to transfer information and energy simultaneously. The fundamental goal of the system is to optimize the harvested energy over the coherent time T. The detailed transmission process will be presented in the next section.

Chapter 4

Transmission scheme and optimizing

In this thesis, the FDD method is considered for separating the uplink channel from the downlink channel. It is assumed that the channel remains constant within the block of T symbols. The transmission protocol and resource allocation are illustrated in Fig.2.

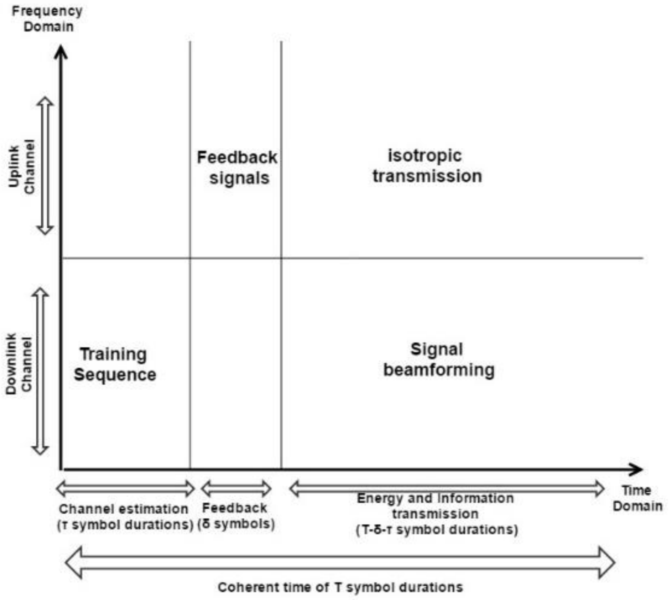

Fig.2. The energy and information transmission protocol for an FDD system

Since the channel realization $\sqrt{\alpha}\mathbf{h}$ is not known to the transmitter, the feedback-based channel estimation is proceeding during the first $\tau + \delta$ symbols of each coherent block, and this is called the channel estimation phase. Within the first τ symbol duration, the transmitter sends orthogonal pilot signals, which is denoted by $\mathbf{t} \in \mathbb{C}^{\tau \times N}$, to the ID receiver via the downlink channel. To achieve a meaningful minimum mean square error estimator of $\mathbf{h}$, at least as many measurements as unknown is required, which implies that $\tau \geq 1$ in the MISO systems. Here, the received training sequence over the τ symbol durations can be written in a vector form by

$$\boldsymbol{y}_{\mathrm{t}} = \sqrt{\frac{P}{N}}\mathbf{t}\sqrt{\alpha}\mathbf{h}^{\mathbf{H}} + \mathbf{n}_{\mathrm{t}} \tag{9}$$

where $\boldsymbol{y}_{\mathrm{t}} \in \mathbb{C}^{\tau\times 1}$ denotes the received signals vector over τ symbols; P is the transmitted power (It is assumed that the P is a constant during the entire T symbols); $\mathbf{n}_{\mathrm{t}} \in \mathbb{C}^{\tau\times 1}$ is the received noise vector at the ID Rx via the downlink channel with independent and identical distribution CSCG entries with zero-mean and $\boldsymbol{\sigma}^{\mathbf{2}}$ variance. Because the first τ symbols are used to channel estimation, there is no energy can be acquired during the τ symbols. However, within the following δ symbols, there is energy will be consumed due to B bits information sent to the transmitter from the ID receiver for conveying optimal codeword index to the transmitter. The length of δ depends on the size of codebook and modulation schemes. Here the energy consumed at the ID receiver due to the feedback bits is written by P_f δ, where P_f is the average transmitted power of feedback symbols.

According to the equation (9), the MMSE estimator $\hat{\mathbf{h}}$ of $\mathbf{h}$ can be written as

$$\hat{\mathbf{h}} = \frac{\sqrt{\alpha P N}}{P\tau\alpha+\sigma^2 N}\mathbf{t}^{\mathbf{H}}\boldsymbol{y}_t \tag{10}$$

Note that $\hat{\mathbf{h}} \in \mathbb{C}^{\mathrm{N}\times 1}$. Correspondingly, the estimation error $\tilde{\mathbf{h}}$ of $\mathbf{h}$ can be expressed as

$$\tilde{\mathbf{h}} = \mathbf{h} - \hat{\mathbf{h}} \tag{11}$$

It is well-known that $\hat{\mathbf{h}}$ and $\tilde{\mathbf{h}}$ are uncorrelated random Gaussian variables due to the orthogonality of the MMSE estimation[47-49]. As a result of this, the entries of $\hat{\mathbf{h}}$ and $\tilde{\mathbf{h}}$ are identical and independent distribution CSCG, with zero mean and different variances. Their variances, $\sigma_{\hat{\mathbf{h}}}^2$ and $\sigma_{\tilde{\mathbf{h}}}^2$, can be expressed as below

$$\sigma_{\hat{\mathbf{h}}}^2 = \frac{\alpha P\tau}{P\tau\alpha+\sigma^2 N} \tag{12}$$

$$\sigma_{\tilde{\mathbf{h}}}^2 = \frac{\sigma^2 N}{P\tau\alpha+\sigma^2 N} \tag{13}$$

It can be clearly observed from the (12) and (13) that increasing the length of the training duration can improve the accuracy of the estimation of $\mathbf{h}$, which is expected. It is also important to point out that the imperfection of the CSIT is caused by the additive noise of the downlink channel during the channel estimation and the mismatch of the feedback process[41, 50]. Here I only captured the impact of the noise on the quality of channel estimation, which refers to the training process. In my thesis, the feedback channel is assumed to be perfect and the estimated channel $\hat{\mathbf{h}}$ can be completely conveyed to the receiver without any losses or distortions. This is not expected in practice.

As soon as the transmitter obtains the downlink channel state information, which may not be perfect in my case, the transmitter is able to implement the optimal transmission strategy to send RF-enabled energy bearing signals within the remaining $T-\tau-\delta$ symbols of the coherent block. Based on (6), the total energy can be collected during this phase can be written by

$$Q = \alpha\rho(\mathrm{T}-\tau-\delta)\,\mathrm{Tr}\left[\mathbf{h}^{\mathbf{H}}\mathbf{h}\mathbf{W}[\mathrm{t}]\right] \tag{14}$$

Since the receiver may not have the complete knowledge of $\mathbf{h}$, the optimal beamforming vector $\mathbf{v}_1$, which is the eigenvector corresponding to the maximum eigenvalue of $\mathbf{h}^{\mathbf{H}}\mathbf{h}$, cannot be correctly computed and the maximum harvested energy cannot be reached. As a result of the imperfect CSIT, given the estimated channel $\hat{\mathbf{h}}$, instead the conditional expectation of the total harvested energy is expressed as

$$\hat{Q} = \mathrm{E}_{\hat{\mathbf{h}}}\,[Q/\hat{\mathbf{h}}] \tag{15}$$

$$= \alpha\rho(T-\tau-\delta)\mathrm{E}_{\hat{\mathbf{h}}}\left[\mathrm{Tr}(\mathbf{h}^{\mathbf{H}}\mathbf{h}\mathbf{W}[\mathrm{t}])\middle|\hat{\mathbf{h}}\right] \tag{16}$$

$$= \alpha\rho(T-\tau-\delta)\,\mathrm{Tr}\left(\left(\left(\hat{\mathbf{h}}^{\mathrm{H}}\hat{\mathbf{h}}\right)+\mathrm{E}_{\tilde{\mathbf{h}}}\left[\tilde{\mathbf{h}}^{\mathbf{H}}\tilde{\mathbf{h}}\right]\right)\mathbf{W}[\mathrm{t}]\right) \tag{17}$$

$$= \alpha\rho(T-\tau-\delta)\,\mathrm{Tr}\left(\left(\left(\hat{\mathbf{h}}^{\mathrm{H}}\hat{\mathbf{h}}\right)+N\sigma_{\tilde{\mathbf{h}}}^{2}\mathbf{I}_N\right)\mathbf{W}[\mathrm{t}]\right) \tag{18}$$

Instead of $\mathbf{h}$, the beamforming vector $\mathbf{v}_1$ is derived from $\hat{\mathbf{h}}^{\mathrm{H}}\hat{\mathbf{h}}$, and $\mathbf{W}[\mathrm{t}] = P\mathbf{v}_1\mathbf{v}_{1.}^{\mathrm{H}}$ Thus, the maximum amount of energy $\hat{Q}$ then become

$$\hat{Q}_{\max} = \alpha\rho(T-\tau-\delta)\,P\left(\Lambda+N\sigma_{\tilde{\mathbf{h}}}^{2}\right) \tag{19}$$

where Λ denotes the largest eigenvalue of $\hat{\mathbf{h}}^{\mathrm{H}}\hat{\mathbf{h}}$, Λ is a random variable. The expiation of $\hat{Q}_{\max}$ can be computed as

$$\bar{Q} = \mathrm{E}_{\hat{\mathbf{h}}}\,[\hat{Q}_{\max}/\hat{\mathbf{h}}] = \alpha\rho(T-\tau-\delta)\,P\big(\mathrm{E}_{\hat{\mathbf{h}}}[\Lambda] + N\sigma_{\hat{\mathbf{h}}}^{2}\big) \tag{20}$$

The properties of the random variable Λ have been thoroughly studied in [51]. The expectation of the maximum eigenvalue Λ is related to the dimension of the vector $\hat{\mathbf{h}}$. For the case of this MISO system, this value is simply equal to the number of the transmit antenna N times the value of the variance of $\hat{\mathbf{h}}$, $\sigma_{\hat{\mathbf{h}}}^{2}$. The cost term, which refers to the energy consumed by sending feedback bits, is added to (20), and (12) (13) are substituted into (20). The average net harvested energy finally is expressed as

$$\bar{Q}_{\mathrm{n}} = \alpha\rho(T-\tau-\delta)\,P\frac{P\tau N+\sigma^{2}N^{2}}{P\tau+\sigma^{2}N} - P_{f}\,\delta \tag{21}$$

The optimal transmit strategy for maximizing the value of $\bar{Q}_{\mathrm{n}}$ can be formulated as the below optimization problem.

$$\text{(P):} \quad \max_{\tau,P_f}\ \bar{Q}_{\mathrm{n}}(\tau,P_f)$$
$$\text{s.t.} \quad 1\le\tau\le \mathrm{T}\ ,$$
$$0\le P_f\le \mathrm{P}_{\max}.$$

Since the feedback channel is assumed to be perfect and the quantization noise of the quantized codebook is not considered here, there are no impacts of the limited feedback method on the quality of the CSIT. Furthermore, the amount of the total acquired energy is not affected by the average power of the feedback symbols in my thesis. To explore the optimal training duration τ, the effects of the δ in the first term of (21) can be reasonably ignored and the second term can be treated as a constant for simplicity. Consequently, the simplified problem is to find the maxima of the function (21) with one variable τ on a closed interval $1\le\tau\le \mathrm{T}$. I calculated the first derivative of it, and I found that the values of the first derivative on the interval $[1,\mathrm{T}]$ can be approximately treated as a negative constant, which implies the maxima of (21) can be reached when $\tau = 1$.

Thus, the solution to the Problem yields $\tau = 1$, which means for the proposed MISO system setting the training duration within each coherent block T equal to 1 is optimal for any P_f. There is an intuitive explanation behind this result. Although increasing τ improves the quality of the CSIT and, accordingly, increases the beamforming gain, the slightly enhanced benefits of the beamforming gain cannot compensate for loss caused by time used for training.

Chapter 5

Numerical Results

In this section, to examine the effectiveness and the performance of the proposed design for the SWIPT system with MISO adopted, the parameters in the practical scenarios are considered and the numerical results are presented. The average transmit power at the transmitter is set to 1 Watts. The distance between the transmit antenna and the receive antenna is assumed to be 15m and the carrier frequency is set to 900 MHz, so the path loss is approximately 55 dB. Moreover, the variance of the additive noise over the training phase is assumed to be -60 dBm. The overall energy conversion efficiency is set to 0.6. The coherent time of the downlink channel is set to 100 symbols. The size of the codebook is 128, so seven symbols are required for the feedback information with BPSK adopted. Furthermore, for simplicity, the cost of the feedback symbols is ignored.

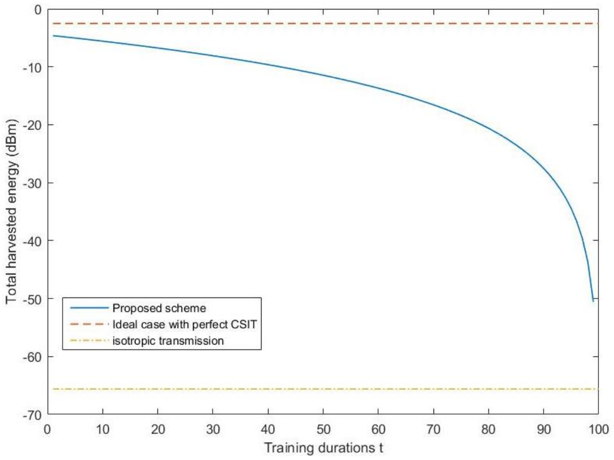

Fig.3. The average net harvested energy vs Training symbols τ with N =5.

Fig.3. shows that the average net harvested energy versus the length of training. The number of transmit antenna is set to five. Two references are presented in

fig.3. For the best-case scenario, which means the perfect CSIT is obtained at the transmitter, the average net harvested energy is optimized by implementing beamforming. For the worst-case scenario, where no CSIT is available, the transmitted signals are of omnidirectional propagation and only a portion of the transmitted energy is harvested. It is shown that the ideal case with the perfect CSIT can achieve the much better performance compared to the case of isotropic transmission. For my proposed scheme, the average net harvested energy linearly decreases as the length of training increases and the maximum value is achieved when τ equals to 1. It is observed that there is no need to spend the extra time on training, only one symbol duration of training can maximize the system performance.

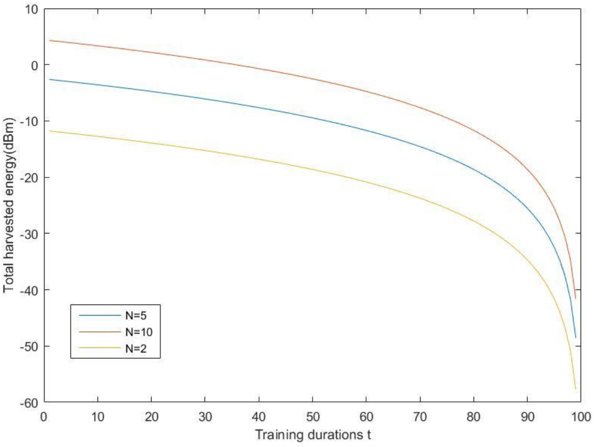

Fig.4. The average net harvested energy vs Training symbols τ with N=2, N=5, and N=10.

It is shown in fig.5. increasing the number of transmit antenna can significantly improve the system performance. When the perfect CSIT is available at the transmitter, the MISO technique can fully exploit the multipath propagation and make signals at the transmitter add constructively. The total amount of acquired energy increases as the number of transmit antenna increases.

Chapter 6

Conclusion

In this thesis, a point-to-point MISO SWIPT system with FDD was proposed. In order for the system to obtain CSIT, training sequences and finite feedback scheme were adopted. Based on a proposed channel estimation error model, I studied the impacts of the channel estimation on the amount of energy can be acquired at the energy harvesting receiver. Furthermore, to maximizing the average net harvested energy, I derived the optimal transmission scheme, which is spending only one symbol duration on training. Even though the additive noise of channel impairs the quality of channel estimation and the benefits of beamforming are affected, spending more time on training fails to increase the total harvested energy. The reason is that the extra harvested energy introduced by the better beamforming cannot compensate the loss caused by time for training.

In fact, not only does the additive noise of the downlink channel affect the quality of channel estimation, but also the imperfection of the feedback channel and the quantization error of codebook have negative effects on the knowledge of the downlink channel at the transmitter. I failed to capture their impacts on the system performance, in my thesis, and I treated these factors as fixed conditions. In my future work, I will assume the feedback channel is imperfect and study the influences of the size of the codebook and the power of the feedback symbol on the performance of the SWIPT system. I also lack practical considerations in my thesis. According to the existing experiments results[52-54], energy harvesting circuits in experiments setups caused the non-linear properties, resulting in mismatches between the theoretical results and the experiments results under some certain conditions. It is necessary to update the current system model so that the characteristics of SWIPT systems can be better studied.

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