WIRELESS POWERED COMMUNICATION NETWORKS

By

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To my loving parents,

Qinxiang Gao and Jinhua Zhang

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Statement of Originality

The work presented in this thesis is the result of original research carried out by myself, in collaboration with my supervisors, while enrolled in the School of Electrical and Information Engineering at the University of Sydney as a candidate for the Master of Philosophy.

These studies were conducted under the supervision of Dr. He Chen and Prof. Yonghui Li. It has not been submitted for any other degree or award in any other university or educational institution.

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Abstract

The limited life time of batteries is a crucial issue in energy-constrained wireless communications. Recently, the radio frequency (RF) wireless energy transfer (WET) technique has been developed as a new practical method to extend the life time of wireless communication networks. Inspired by this, wireless-powered communication network (WPCN) has attracted much attention. Therefore, in this thesis, we consider practical WET and wireless-powered information transmission in WPCNs.

First we investigate a WPCN with two nodes, in which an access point (AP) exchanges information with a wireless-powered user. The user is assumed to have no embedded energy supply and needs to harvest energy from RF signals broadcast by the AP. Differing from existing work that focuses on the design of wireless-powered communication with one-way information flow, we deal with a more general scenario where both the AP and the user have information to transmit. Considering that the AP and user can work in either half-duplex or full-duplex mode as well as having two practical receiver architectures at the user side, we propose five elementary communication protocols for the considered system. Moreover, we define the concept of a throughput region to characterize the tradeoff between the uplink and downlink throughput in all proposed protocols. Numerical simulations are finally performed to compare the throughput regions of the proposed five elementary protocols.

To further the study on WPCN, we investigate a wireless-powered two-way relay system, in which two wireless-powered sources exchange information through a multi-antenna relay. Both sources are assumed to have no embedded energy supply and thus first need to harvest energy from the radio frequency signals broadcast by the relay before exchanging their information via the relay. We aim to maximize the sum throughput of both sources by jointly optimizing the time switching duration, the energy beamforming vector and the precoding matrix at the relay. The formulated problem is non-convex and hard to solve in its original form. Motivated by this, we simplify the problem by reducing the number of variables and by decomposing the

precoding matrix into a transmit vector and a receive vector. We then propose a bisection search, a 1-D search and an iterative algorithm to optimize each variable. Numerical results show that our proposed scheme can achieve higher throughput than the conventional scheme without optimization on the beamforming vector and precoding matrix at the relay.

Due to the high attenuation of RF energy over a long distance, RF based wireless-powered communication is usually designed for low-power scenarios, e.g., wireless-powered sensor networks. Recently, magnetic induction (MI) based WET has been proposed to wirelessly transfer a large amount of energy. Inspired by this, we investigate MI based WET in WPCN. Specifically, we study a MI based wireless-powered relaying network, in which a MI source transmits information to a MI destination, with the help of a MI based wireless powered relay. We propose four active relaying schemes, which consider different relaying modes and different energy harvesting receiver architectures at the relay. We then aim to maximize the end-to-end throughput of each scheme by using a bisection search, a water-filling algorithm, a Lagrange multiplier, quasi-convex programming and an iterative algorithm. We compare the proposed active relaying schemes with passive relaying. Numerical results show that the proposed relaying schemes with a decode-and-forward relaying mode significantly improve the throughput over passive relaying.

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List of Acronyms

AC	alternating current
AF	amplify-and-forward
AP	access point
BC	broadcasting
CSCG	circularly-symmetric Gaussian
CSI	channel state information
DC	direct current
D-C	difference of convex
DF	decode-and-forward
DL	downlink
EH	energy harvesting
ER	energy recycling
ET	energy transfer
FD	full-duplex
HD	half-duplex

ID information decoding

IT information transmission

MA multiple access

MI magnetic induction

MIMO multiple-input-multiple-output

MISO multiple-input-single-output

MRC maximal-ratio combining

PS power splitting

QC quasi-convex

RF radio frequency

SI self-interference

SNR signal-to-noise ratio

SWIPT simultaneous wireless information and power transfer

TS time switching

UL uplink

WET wireless energy transfer

WPC wireless-powered communication

WPCN wireless-powered communication network

List of Symbols and Notations

η	the RF-to-DC energy conversion efficiency
T	the time duration of a transmission block
$\min(A, B)$	the minimum between A and B
$\lvert X \rvert$	the absolute value of X
$\lVert \mathbf{X} \rVert$	the Euclidean norm of $\mathbf{X}$
$\mathbf{X}^T$	the transpose of $\mathbf{X}$
$\mathbf{X}^*$	the complex conjugate of $\mathbf{X}$
$\mathbf{X}^H$	the Hermitian transpose of $\mathbf{X}$
$\mathbb{E}\{X\}$	the statistical expectation of X

List of Publications

The following is a list of publications in refereed conference proceedings produced during my M.Phil. candidature.

Conference Papers

1. Z. Gao, H. Chen, Y. Li, and B. Vucetic, "Wireless-Powered Communications with Two-Way Information Flow: Protocols and Throughput Regions", in 2016 Australian Communications Theory Workshop (AusCTW). Melbourne, Australia, Jan. 2016.

2. Z. Gao, H. Chen, G. Zheng, Y. Li, and B. Vucetic, "Wireless-Powered Two-Way Relaying via A Multi-Antenna Relay with Energy Beamforming", accepted to appear in 2017 IEEE 85th Vehicular Technology Conference (VTC). Sydney, Australia, Jun. 2017.

Chapter 1

Introduction

1.1 Wireless Energy Transfer

The performance of many wireless communications systems is largely constrained by limited energy supply due to a high energy consumption and short battery life. Frequent recharging or replacing batteries may cause a huge cost, and is even infeasible in some applications (e.g., sensors embedded in structures), and can be dangerous or impossible (e.g., devices in toxic environments) [1]. To address this problem, energy harvesting (EH) has emerged as a new solution to extend the network life of energy-constrained wireless networks, where wireless devices can harvest energy from radio frequency (RF) signals in the surrounding environment [2]. Early studies on wireless EH devices mainly focused on renewable energy sources, e.g., solar, wind, thermal, and vibration [3–7]. However, these renewable power sources are unstable since they are typically dependent on weather or climate conditions. Due to the uncertainty and the difficulty in prediction, these renewable energy sources struggle to meet the power quality requirements of wireless devices [8]. A more practical method to implement the EH technique is RF energy transfer, in which a transmitter delivers energy wirelessly to a receiver by leveraging the far-field properties of electromagnetic waves. RF energy transfer is regarded as a low-power long-distance energy transfer, therefore it can be used as the energy supply for low power devices distributed in a relatively wide area [9]. To enable RF energy transfer, an RF energy receiver should be used at the wireless-powered receiver, which consists of a receive antenna to receive the RF signals, an impedance matching circuit to maximize the received power, a rectifier to convert alternating current (AC) into direct current (DC), a filter and a voltage regulator to stabilize the voltage supply. The amount of the harvested energy can be calculated as

$$E = \eta \tau G_R H G_T P, \tag{1.1.1}$$

where P is the transmit power at the transmitter; G_T is the transmit antenna gain; H is the path loss; G_R is the receive antenna gain; τ is the time duration of power transmission and η is the efficiency of energy harvesting.

Apart from RF energy transfer, recent research has also studied another type of wireless energy transfer (WET), termed magnetic induction (MI) based WET. MI based WET enables a transmitter to transfer energy through the induction between two coils with the same resonant frequency, which can be tuned by changing the size of the coils and by selecting components with the appropriate value of inductance and capacitance. MI based WET can transfer a huge amount of energy over a relative short distance, i.e., a few meters, compared with RF WET.

1.2 Wireless-Powered Communication

Inspired by RF WET techniques, a new concept, termed wireless-powered communication (WPC) has been proposed recently, in which wireless terminals communicate using the energy harvested from WET and thus are not constrained by short battery life. Therefore, WPC is a promising technique which can potentially prolong the lifetime of wireless networks. In WPC systems, devices can transmit or receive both energy and information. Motivated by this, simultaneous wireless information and power transfer (SWIPT) has been proposed, which allows a transmitter to transfer both information and energy wirelessly to a receiver simultaneously. Early research on SWIPT assumed that a transmitter can transfer both energy and information to the target without losses [10]. However, the receiver for information decoding (ID) and that for EH are fundamentally different [11]. Thus, in order to practically deliver both energy and information to the receivers, the receivers have to split the received signal into two distinct parts, one for EH and one for ID. Several techniques have been proposed to achieve this signal splitting, e.g., time switching (TS), power splitting (PS), antenna switching, spatial switching and an integrated receiver [2].

It is important to develop efficient protocols for a wireless-powered communication network (WPCN), where one or more nodes in a communication network harvest energy from the surrounding environment and use it to transmit their own signals. Existing communications protocols for the purpose of information transmission may no longer be suitable for WPCNs since the signals in WPCN carry both information and energy. Therefore the features of WPCNs should be analyzed, and new protocols for WPCNs should be proposed to optimize their performance.

1.3 Wireless-Powered Relaying Communication

Wireless-Powered Relaying is an important technology in WPC. Using intermediate relays to forward signals from the source to the destination can extend the transmission distance. A relaying system can significantly improve the performance of a communication system.

The commonly used relaying protocols are amplify-and-forward (AF) relay and decode-and-forward (DF) relay. AF relaying protocol simply amplifies the received signal and then forwards it without decoding whereas DF relay first decodes the information from the received signal and then re-encodes it into a new signal before forwarding it to the destination.

Relay can be used in either one-way or two-way communications. In a one-way relaying network, the source transmits information to the destination with the help of the relay, whereas in a two-way relaying network, two sources exchange information via the relay. Relaying networks can work in either half-duplex (HD) or full-duplex (FD) mode. In HD mode, each devices can either transmit or receive signals, whereas in FD mode, the source or the relay can transmit and receive signals simultaneously. Although the FD technique may double the maximum transmission capacity, it suffers from self-interference (SI) dramatically. Therefore, interference suppression techniques are often used to separate the desired information from the interferences.

1.4 Research Problems and Contributions

The focus of this thesis is on the protocol design, performance analysis and resource allocation in different WPCNs. The research problems and the corresponding contributions are elaborated on as follows.

The *first* research problem we consider is "*what are the practical transmission protocols for a two-way communication system with one wireless-powered user?*". Five protocols are proposed by considering different system settings and architectures, e.g., half-duplex and full-duplex, and different receiver architectures, e.g., time-switching and power-splitting. In addition, an energy recycling technique and an interference suppression technique are considered in these protocols. The optimization problem for the proposed schemes is difficult to solve. The main contributions regarding this research problem include:

- We proposed five elementary protocols for the considered network by considering that the access point (AP) and user can work in either HD or FD mode as well as two practical receiver architectures (i.e., TS and PS) at the user side. All other potential protocols can be treated as combinations of the proposed protocols.
- We defined a new concept of a throughput region to evaluate the performance of the proposed protocols by characterizing the trade-off between uplink (UL) and downlink (DL) throughput.
- We derived the throughput regions of the proposed protocols and compared them via numerical simulations. Numerical results show that the system has a larger throughput region when the PS receiver is adopted. The protocols working in FD mode can outperform those working in HD mode when the SI is

sufficiently suppressed.

The *second* research problem we consider is "*what is the optimal scheme for a two-way relaying network with two wireless-powered sources?*". This research considers two wireless-powered sources exchanging information through a hybrid multi-antenna relay, in which a HD AF multi-antenna relay first transfers energy to both sources, and then the sources exchange their information via the relay. The main contributions regarding this research problem include:

- We proposed a two-way relaying protocol based on the three-node model, and then derived the expression of the total throughput of the considered wireless-powered two-way relaying network.
- We proposed an algorithm to maximize the total throughput under the constraint of peak transmit power at the relay.
- We solved the non-convex optimization of time duration of each time phase, the beamforming vector for energy transfer and the precoding matrix at the relay by alternatingly using a bisection search, 1-D search and difference of convex (D-C) programming.
- The theoretical results are validated by numerical simulations, which show that the proposed two-way relay system achieves a higher total throughput in the case of higher power budget at the relay and lower channel fading due to a higher received signal-to-noise ratio (SNR) at both sources, and the optimization of beamforming vectors significantly improves the transmission capability.

The *third* research problem we consider is "*what is the practical scheme for a MI based wireless-powered active relaying system?*". In this research, we consider a MI source transmitting information to a MI destination via a MI based wireless-powered relay. The main contributions regarding this research problem include:

- We proposed four protocols for the proposed wireless-powered active relaying model, by considering different relaying modes and receiver architectures. We then derived the expression of the throughput for each protocol.
- We solved the formulated problems through alternatingly optimizing each variable by solving close form functions, using a bisection search, water-filling algorithms, Lagrange multipliers, quasi-convex (QC) programming and a new proposed iterative algorithm.
- We showed that the AF-PS scheme always performs worse than the passive relaying scheme, whereas the performance of the AF-TS scheme is slightly better but almost the same as the passive relaying scheme. In addition, the performances of the DF-TS and the DF-PS relaying schemes outperform the passive relaying scheme. The DF-TS scheme performs even better when the distance between the source and destination is longer, which achieves a throughput approximately twice than that of passive relaying.

1.5 Thesis Outline

This thesis consists of six chapters, including the introduction, background, design and analysis of protocols for three WPCNs, and conclusions. The outline of the thesis can be summarized as follows:

Chapter 1 introduces the literature review and motivation for the research, research problems and corresponding contributions.

Chapter 2 illustrates the background of the thesis, including SWIPT, beamforming, and relaying system.

Chapter 3 investigates a two-way communication system consists of an AP and a wireless-powered user. Five protocols are proposed and then optimized to maximize the throughput region of the system.

Chapter 4 investigates a two-way relaying network consists of a hybrid multi-antenna relay and two wireless-powered sources, where the relay first transfers energy to both sources, and then the sources exchange information via the relay. A protocol is proposed and then optimized to maximize the sum throughput of the two sources.

Chapter 5 investigates a MI based one-way relaying network consists of a MI based source, a MI based wireless-powered relay and a MI based destination. Five protocols are proposed and then optimized to maximize the throughput.

Chapter 6 summarizes the main contributions of this thesis and gives conclusions and recommendations for future work.

Chapter 2

Preliminaries

In this chapter, a brief review of some general concepts is provided, in the context of SWIPT, beamforming, and relaying systems, respectively.

2.1 Simultaneous Wireless Information and Power Transfer

The concept of SWIPT is based on the fact that RF signals that carry energy can at the same time be used for transporting information. However, the receiver sensitivities for ID and EH are generally different (e.g., -60 dBm for ID and -10 dBm for EH). Therefore, in order to practically receive both information and energy simultaneously, separated receiver architecture and co-located receiver architecture are commonly used to receive both information and energy.

In separated receiver architecture, the wireless-powered device is usually equipped with multiple antennas. One part of the antenna array is connected to the information decoder, whereas the other part is connected to the energy harvester. Therefore, the wireless-powered devices can simultaneously harvest energy and receive information.

Co-located receiver architecture performs both information and energy reception via the same set of antennas. There are mainly two types of co-located receiver architecture, termed time-switching and power-splitting, respectively. Time-switching architecture allows the device to switch between the information receiver and energy harvester and use one of them at a time, whereas power-splitting architecture allows the device to split the received signal into two streams, one for ID and one for EH.

2.2 Beamforming

Beamforming is a signal processing technique that is applied on antenna arrays for either directional signal transmission or reception. Specifically, in transmission beamforming, the beamformer appropriately sets the magnitude and phase of the transmitted signal at each element in a phased array to constructively interfere the signals at particular angles while destructively interfering the signals at the other angles. In reception beamforming, the beamformer linearly combines the signals received from different antennas to obtain the desired information.

2.2.1 Multiple-Input-Single-Output Beamforming

The term multiple-input-single-output (MISO) beamforming indicates a method to enhance the capacity of wireless information transmission by using multiple transmit antennas and a single receive antenna. Assume that the transmitter transmits a symbol s to the receiver. Then the received signal at the receive antenna can be written as

$$y = \mathbf{h}\mathbf{x} + n, \tag{2.2.1}$$

where $\mathbf{x} = [\alpha_1, \alpha_2, \ldots, \alpha_k]^T s$ is the transmitted signal by k antennas, $\alpha_i \in \mathbb{R}$ denotes the magnitude and phase of the signal at the i^{th} transmit antenna, $\mathbf{h} \in \mathbb{C}^{N\times 1}$ denotes the channel between the transmit antennas and the receive antenna, n denotes the received noise at the receiver and we assume $n \sim \mathcal{CN}(0, \sigma^2)$, where $\mathcal{CN}(0, \sigma^2)$ stands for a circularly-symmetric Gaussian (CSCG) random variable with zero mean and variance σ^2.

MISO beamforming aims to maximize the channel capacity, subject to a limited transmit power, i.e., $P = 1$. Therefore the beamforming problem at the transmitter can be formulated as

$$\max_{\alpha} \quad \log\left(1 + \frac{|\mathbf{hx}|^2}{\sigma^2}\right), \tag{2.2.2}$$

$$s.t. \quad \|\mathbf{x}\|^2 \leq 1. \tag{2.2.3}$$

The optimal solution of this problem is given by

$$\alpha_i = \frac{h_i^*}{\sum\limits_{i=1}^{k} |h_i|^2}, \tag{2.2.4}$$

where h_i is the channel coefficient between the i^{th} transmit antenna and the receive antenna.

2.3 Relaying System

Intermediate relaying is a practical method to extend the transmission distance against the signal attenuation. Relay can be further classified by the work mode (e.g., AF and DF relay), the number of information flows (e.g., one-way and two-way relay) and duplex mode (e.g., HD and FD relay).

2.3.1 One-way relay channel model

In a one-way relaying system, one source transmits information to the destination, with the help of the relay. Both AF and DF relaying schemes are commonly used in a one-way relaying system.

Amplify-and-forward relay

In a typical one-way AF scheme, a transmission block is equally divided into two time slots. The source transmits a signal to the relay in the first time slot. The received signal at the relay in the first time slot can be expressed as

$$y_r = h_1 x + n_r, \tag{2.3.1}$$

where h_1 is the channel coefficient between the source and the relay. x denotes the signal transmitted by the source, and n_r denotes the received noise at the relay.

In the second time slot, the relay amplifies and forwards the received signal to the destination. Therefore the received signal at the destination in the second time slot is given by

$$y_d = h_2 A \left(h_1 x + n_r\right) + n_d, \tag{2.3.2}$$

where h_2 is the channel coefficient between the relay and the destination. A denotes the amplification factor at the relay, n_d denotes the received noise at the destination.

The overall channel capacity of this AF relaying system can be given by

$$C_{AF} = \log\left(1 + \frac{|h_2|^2 A^2 |h_1|^2 |x|^2}{|h_2|^2 A^2 |n_r|^2 + |n_d|^2}\right). \tag{2.3.3}$$

AF relaying requires much less computing than other relaying modes and therefore causes less delay.

Decode-and-forward relay

In a DF relaying scheme, a relay decodes the message transmitted by the source in one time slot, then re-encodes and transmits the message to the destination in the following time slot. The channel capacity of a DF relaying system is expressed as

$$C_{DF} = \min\left\{ \log\left(1 + \frac{|h_1|^2 |x_s|^2}{|n_r|^2}\right), \log\left(1 + \frac{|h_2|^2 |x_r|^2}{|n_d|^2}\right)\right\}, \tag{2.3.4}$$

where x_s denotes the transmitted signal from the source, and x_r denotes the transmitted signal from the relay.

2.3.2 Two-way relay channel model

In a two-way relaying system, two sources exchange information via a relay. Both AF and DF relay are commonly used in two-way relaying systems.

One of the main challenges in two-way relaying schemes is the interference. This is because a source can receive the signal transmitted by itself. The source can overcome the interference by applying either passive suppression or active cancellation.

Passive suppression is a technique to electromagnetically isolate the transmit and receive antennas, and therefore attenuate the signal in the SI channel. Active cancellation is to cancel the SI by injecting a cancellation waveform into the received signal, this requires the source to know the SI channel.

Chapter 3

Wireless-Powered Communications with Two-Way Information Flow: Protocols and Throughput Regions

The recent advance in RF energy transfer has enabled WPC, where wireless devices are powered by dedicated wireless energy transmitters. In this paper, we study a WPC scenario consisting of one AP and one user. The user is assumed to have no embedded energy supply and needs to harvest energy from RF signals broadcast by the AP. Differing from existing research that focuses on the design of WPC with a one-way information flow, we deal with a general scenario where the AP and user need to exchange information with each other. Considering that the AP and user can work in either the HD or the FD mode as well as having two practical receiver architectures at the user side, we propose five elementary communication protocols for the considered system. Moreover, we define the concept of a throughput region to characterize the tradeoff between the uplink and downlink throughput in all proposed protocols. Numerical simulations are finally performed to compare the throughput regions of the proposed five elementary protocols.

3.1 Introduction

Recently, RF energy transfer has been proposed as an alternative and promising technique to extend the lifetime of wireless networks [12]. It refers to a WET process of delivering energy from an energy transmitter wirelessly to charge devices by leveraging the far-field radiative properties of electromagnetic waves. This technique has opened a new research area, termed WPC, which has attracted much attention in wireless communications very recently [11].

Existing research on WPC can be generally categorised into two main directions. One line of work is SWIPT, in which the same RF signal at the transmitter is used to deliver both information and energy to the receiver [1, 13]. The other line of research focuses on designing a new type of network, termed WPCN, in which wireless terminals communicate using the energy harvested from wireless energy transfer [14–17].

In this thesis, we advance the research on WPC by investigating a more general scenario with a two-way information flow, where one hybrid AP and one wireless-powered user exchange information with each other. Specifically, the AP transmits both information and energy to the user in the DL and the user uses the harvested energy to send its information to the AP in the UL. Note that the scenario studied in this paper is the extension of the existing SWIPT and WPCN. Thus, the communication protocols proposed for SWIPT and WPCN may no longer work efficiently in the considered network, and should be redesigned and evaluated by capturing the feature of a two-way information flow. Furthermore, the optimization of resource allocation for this scenario is correspondingly challenging as more tangled variables are dealt with.

The main contributions of this work can be summarised as: **(1)** For the considered network, we propose five elementary protocols by considering that the AP and user can work in either the HD or the FD modes. We also consider two practical receiver architectures (i.e., TS and PS) at the user side. All other potential protocols can be treated as combinations of the proposed protocols. **(2)** In order to characterise the performance of the proposed protocols, we define a new concept of a throughput region characterising the trade-off between UL and DL throughput. **(3)** We then derive the throughput regions of the proposed protocols and compare them via numerical simulations. Numerical results show that the system with PS receiver can achieve a larger throughput region than those with TS receiver. The protocols working in the FD mode can outperform those working in the HD mode when the SI is sufficiently suppressed.

3.2 System Model and Proposed Protocols

We consider a WPCN consisting of one AP and one user. The AP and user have information to transmit to each other. We assume that the user has no embedded energy supply and thus has to harvest energy from the signals broadcast by the AP in the DL before using it for UL information transmission (IT). In this case, the AP needs to perform SWIPT in the DL. To practically realise SWIPT, the received signal should be split into two distinct parts, one for EH and one for ID. Several techniques have been proposed to achieve this signal splitting (e.g., time, power, antenna, and space) [2]. In this paper, we assume either TS or PS receiver architecture is used at the user side.

Each node is assumed to be equipped with two antennas with predetermined

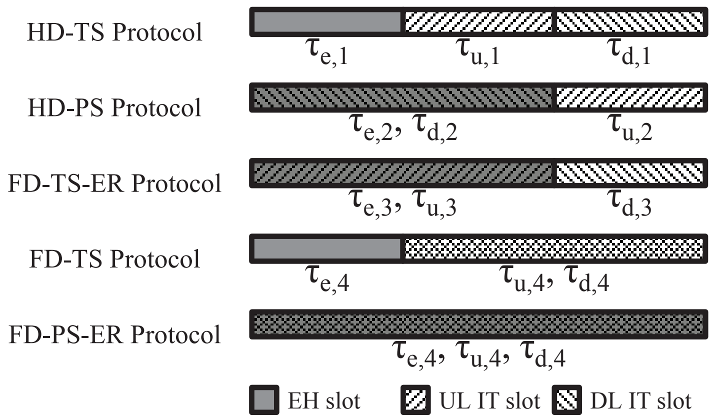


Figure 3.1: Diagram of five elementary protocols for the considered network.

functions. One antenna is used to transmit information and is connected to the IT RF chain. The other antenna is used to receive signal, which is then used for ID and/or EH. In this setup, both nodes can work in either the HD or the FD mode. Specifically, each node can either transmit or receive signals in the HD mode, while each node can transmit and receive signals simultaneously in the FD mode. In the FD mode, each node suffers from SI from its transmit antenna to its receive antenna, which is harmful when the received signal is used for ID. To deal with this, several SI suppression schemes have been proposed in the literature [18]. In contrast, the SI becomes beneficial when the received signal is used for EH and the energy recycling (ER) technique [19] is adopted, in which the user can recycle extra energy from the signals broadcast by itself. We also assume that the user is a low-cost and low-complexity device such that it is only equipped with simple storage (e.g., super-capacitors) to hold the energy harvested within each transmission block and has no capability of performing energy accumulation across different blocks. Moreover, the dual-storage scheme proposed in [20] is adopted to support the user's FD operation.

We use f and h to denote the channel coefficient from the AP to the user and that from the user to the AP, respectively. h_0 and h_u denote the SI channel at the AP and user, respectively, including the transmit signal leakage inside the transceiver as well as its reflected versions from the outside environment. It is assumed that all channels are quasi-static flat-fading, and all channel power gains remain constant during each transmission block. For simplicity, it is further assumed that the full channel state information (CSI) is known perfectly at both the AP and user.

Since the user has no embedded energy supply, the UL IT cannot start ahead of the DL energy transfer. Jointly considering this constraint and the working mode of both nodes as well as the receiver architecture at the user, we propose five elementary transmission protocols for the considered WPCN, as depicted in Fig.3.1. All other potential protocols can be treated as the combinations of the proposed protocols. In the following subsections, we describe the proposed protocols and derive the UL and DL SNR expressions for each protocol.

In the following sections, we use $\tau_{e,i}$, $\tau_{u,i}$ and $\tau_{d,i}$ to denote the time duration of the EH slot, UL IT slot and DL IT slot in protocol i, respectively. $P_{\max}$ denotes the instantaneous power limit of the AP. $P_{e,i}$ denotes the AP transmit power in protocol i during the EH slot with $P_{e,i} \leq P_{\max}$. E_i denotes the amount of energy harvested at the user in protocol i during the EH slot. $P_{u,i}$ is the UL transmit power at the user of protocol i with $P_{u,i} \leq \frac{E_i}{\tau_u}$. $P_{0,i}$ denotes the DL transmit power of the AP in protocol i with $P_{0,i} \leq P_{\max}$. $\eta \in (0, 1)$ denotes the energy conversion efficiency. For convenience, we assume a normalized time duration of each block, i.e., $T = 1$.

3.2.1 HD-TS protocol

In this protocol, both the AP and user work in the HD mode and the TS protocol is used to realize SWIPT in the DL, as shown in Fig.3.1. This protocol includes three time slots, where

$$\tau_{e,1} + \tau_{u,1} + \tau_{d,1} \leq 1. \tag{3.2.1}$$

In the first time slot, the AP transfers energy to the user to enable its UL IT. The received signal at the user is thus given by

$$y_e = f\sqrt{P_{e,1}}x_e + n_u, \tag{3.2.2}$$

where x_e denotes the transmitted signal by the AP, with $\mathbb{E}\left(|x_e|^2\right) = 1$. n_u denotes the noise at the user, which is assumed to be $n_u \sim \mathcal{CN}\left(0, \sigma_u^2\right)$, where $\mathcal{CN}\left(v, \sigma^2\right)$ stands for a CSCG random variable with mean v and variance σ^2. In this work, we consider that the noise power is very small and below the sensitivity of the EH device. The harvested energy at the user can thus be expressed as

$$E_1 = \eta\tau_{e,1}|f|^2 P_{e,1}. \tag{3.2.3}$$

During the second time slot, the user uses the harvested energy to transmit its information to the AP in the UL. The received signal at the AP is expressed as

$$y_0 = h\sqrt{P_{u,1}}x_u + n_0, \tag{3.2.4}$$

where x_u denotes the transmitted signal at the user, with $\mathbb{E}\left(|x_u|^2\right) = 1$. n_0 denotes the noise suffered at the AP, which is assumed to be $n_0 \sim \mathcal{CN}\left(0, \sigma_0^2\right)$. The received SNR at the user can thus be written as

$$\gamma_{u,1} = \frac{|h|^2 P_{u,1}}{\sigma_0^2}. \tag{3.2.5}$$

In the last time slot, the AP transmits information to the user in the DL. The received signal at the user is written as

$$y_u = f\sqrt{P_{0,1}}x_0 + n_u, \tag{3.2.6}$$

where x_0 denotes the transmitted signal at the AP with $\mathbb{E}\left(|x_0|^2\right) = 1$. The received SNR at the AP is given by

$$\gamma_{d,1} = \frac{|f|^2 P_{0,1}}{\sigma_u^2}. \tag{3.2.7}$$

3.2.2 HD-PS Protocol

As shown in Fig.3.1, in this protocol, both the AP and user work in the HD mode and the PS protocol is used to realize SWIPT in the DL. Two time slots are included in this protocol, where

$$\tau_{e,2} = \tau_{d,2}, \tau_{d,2} + \tau_{u,2} \leq 1. \tag{3.2.8}$$

In the first time slot, the AP transfers energy and information to the user simultaneously. The received signal at the user in the first time slot can be expressed as

$$y_u = f\sqrt{P_{0,2}}x_0 + n_u. \tag{3.2.9}$$

Then the user needs to split part of the received energy for EH to ensure the capability of UL communication, and decodes information based on the residual part of the signal. Here we use $\rho_2 \in [0, 1]$ to denote the partition of the received signal used for EH, and $(1 - \rho_2)$ to denote the partition used for decoding DL information. Then the amount of harvested energy at the user is given by

$$E_2 = \eta\tau_{e,2}\rho_2|f|^2 P_{0,2}. \tag{3.2.10}$$

In this case, the received SNR at the user can thus be written as

$$\gamma_{d,2} = \frac{(1 - \rho_2)|f|^2 P_{0,2}}{\sigma_u^2}. \tag{3.2.11}$$

In the second time slot, the user transmits UL information to the AP. The received SNR at the AP is given by

$$\gamma_{u,2} = \frac{|h|^2 P_{u,2}}{\sigma_0^2}. \tag{3.2.12}$$

3.2.3 FD-TS-ER Protocol

In this protocol, two time slots are needed to fulfil the information exchange task, as shown in Fig.3.1, where

$$\tau_{e,3} = \tau_{u,3}, \tau_{u,3} + \tau_{d,3} \leq 1. \tag{3.2.13}$$

In the first time slot, both the AP and user work in the FD mode, where the AP transfers energy to the user in the DL and the user adopts the harvested energy to send information to the AP in the UL at the same time. Note that we assume that the delay caused by the EH circuit is ignorable for simplicity. Furthermore, the user can implement the ER technique [19] to harvest extra energy from the signals broadcast by itself. In the second time slot, the AP conveys its information to the user in the DL. Since the DL energy and information are transferred in two time slots, we can consider that the TS receiver structure is adopted in this protocol. Since the AP works in the FD mode which causes SI at the AP, SI suppression techniques [18] are introduced to tackle the SI. The signal received by the receive antenna at the user during the first time slot is given by

$$y_e = f\sqrt{P_{e,3}}x_e + h_u\sqrt{P_{u,3}}x_u + n_u. \tag{3.2.14}$$

We assume the DL energy signal x_e is independent from the UL information signal x_u. Thus the amount of energy harvested by the user at the first time slot could be expressed by

$$E_3 = \eta\tau_{e,3}\left(|f|^2 P_{e,3} + |h_u|^2 P_{u,3}\right). \tag{3.2.15}$$

Note that the transmit power of the user is constrained by $P_{u,3} \leq \frac{E_3}{\tau_{u,3}}$. We then have the following constraint on $P_{u,3}$

$$P_{u,3} \leq \frac{\eta \left|f\right|^2 P_{e,3}}{1 - \eta \left|h_u\right|^2}. \tag{3.2.16}$$

The AP transfers energy to the user in the first time slot. Meanwhile, it receives UL information from the user. The received signal at the AP at the first time slot is given by

$$y_0 = h\sqrt{P_{u,3}}x_u + \sqrt{\beta_0}h_0\sqrt{P_{e,3}}x_e + n_0, \tag{3.2.17}$$

where $\beta_0 \in [0, 1]$ denotes the SI suppression factor at the AP side. The received SNR at the AP is written as

$$\gamma_{u,3} = \frac{\left|h\right|^2 P_{u,3}}{\sigma_0^2 + \beta_0 \left|h_0\right|^2 P_{e,3}}. \tag{3.2.18}$$

In the second time slot, the AP transmits DL information to the user. Both the AP and user work in the HD mode. The received SNR at the user can be expressed as

$$\gamma_{d,3} = \frac{\left|f\right|^2 P_{0,3}}{\sigma_u^2}. \tag{3.2.19}$$

3.2.4 FD-TS Protocol

As shown in Fig.3.1, in this protocol, each block is divided into two time slots, where

$$\tau_{u,4} = \tau_{d,4}, \tau_{e,4} + \tau_{u,4} \leq 1. \tag{3.2.20}$$

In the first time slot, the AP transfers energy to the user, whereas UL and DL IT are performed simultaneously in the second slot. Similar to the HD-TS Protocol, the power harvested by the user during the first time slot is given by

$$E_4 = \eta \tau_{e,4} \left|f\right|^2 P_{e,4}. \tag{3.2.21}$$

In the second time slot, both the AP and user work in the FD mode. Each node uses one antenna to transmit information while using the other to receive information. The received signals at the AP and user at the second time slot are given by

$$y_0 = h\sqrt{P_{u,4}}x_u + \sqrt{\beta_0}h_0\sqrt{P_{0,4}}x_0 + n_0, \tag{3.2.22}$$

$$y_u = f\sqrt{P_{0,4}}x_0 + \sqrt{\beta_u}h_u\sqrt{P_{u,4}}x_u + n_u, \tag{3.2.23}$$

respectively, where $\beta_u \in [0, 1]$ denotes the SI suppression factor at the user side. The received SNRs at the AP and user are thus given by

$$\gamma_{u,4} = \frac{|h|^2 P_{u,4}}{\sigma_0^2 + \beta_0 |h_0|^2 P_{0,4}}, \tag{3.2.24}$$

$$\gamma_{d,4} = \frac{|f|^2 P_{0,4}}{\sigma_u^2 + \beta_u |h_u|^2 P_{u,4}}, \tag{3.2.25}$$

respectively.

3.2.5 FD-PS-ER Protocol

In this protocol, both the AP and user work in the FD mode, where the PS receiver architecture is adopted at the user. UL IT, DL IT and DL energy transfer are implemented at the same time, which is shown in Fig.3.1, where

$$\tau_{e,5} = \tau_{u,5} = \tau_{d,5} \le 1. \tag{3.2.26}$$

Thus the received signals at the AP and user are given by

$$y_0 = h\sqrt{P_{u,5}}x_u + \sqrt{\beta_0}h_0\sqrt{P_{0,5}}x_0 + n_0, \tag{3.2.27}$$

$$y_u = f\sqrt{P_{0,5}}x_0 + \sqrt{\beta_u}h_u\sqrt{P_{u,5}}x_u + n_u, \tag{3.2.28}$$

respectively.

The user splits part of received energy for EH to ensure the capability of UL IT, and decodes information from the remaining part. The receive antenna of the user can also receive energy from the UL signal broadcast by its transmit antenna. Here we use $\rho_5 \in [0, 1]$ to denote the partition of the received signal that is used for harvesting energy, and $(1 - \rho_5)$ to denote the partition that is used for decoding DL information. Since both nodes suffer from SI, the SI suppression techniques are used in this protocol, where the SI suppression at the user side is implemented after PS and before the ID circuit. Similar to the FD-TS-ER protocol, the energy harvested by the user is given by

$$E_5 = \eta\tau_{e,5}\rho_5 \left(|f|^2 P_{0,5} + |h_u|^2 P_{u,5}\right). \tag{3.2.29}$$

Then, the transmit power at the user should satisfy

$$P_{u,5} \leq \frac{\eta\rho_5 |f|^2 P_{0,5}}{1 - \eta\rho_5 |h_u|^2}. \tag{3.2.30}$$

Then the received SNRs at the AP and user could be given by

$$\gamma_{u,5} = \frac{|h|^2 P_{u,5}}{\sigma_0^2 + \beta_0 |h_0|^2 P_{0,5}}, \tag{3.2.31}$$

$$\gamma_{d,5} = \frac{(1 - \rho_5) |f|^2 P_{0,5}}{\sigma_u^2 + (1 - \rho_5) \beta_u |h_u|^2 P_{u,5}}, \tag{3.2.32}$$

respectively.

3.3 Throughput Regions

In the considered system, it is readily observed that there is a trade-off between the DL throughput and UL throughout due to limited resources. That is, the optimal resource allocation to maximize the DL throughput and to maximize the UL throughput are generally different [1]. To characterize this tradeoff, we define the throughput region for each protocol given by

$$\begin{aligned}\mathcal{C}_i\left(P_{\max}\right) \triangleq \{ & (R_u, R_d) : (3.2.1), (3.2.8), (3.2.13), (3.2.20), (3.2.26), \\ & R_u \leq \tau_{u,i} \log_2\left(1+\gamma_{u,i}\right), R_d \leq \tau_{d,i} \log_2\left(1+\gamma_{d,i}\right), \\ & P_{0,i} \leq P_{\max}, P_{e,i} \leq P_{\max}, P_{u,i} \leq \frac{E_i}{\tau_{u,i}}, \\ & i \in (1,2,3,4,5)\}.\end{aligned} \tag{3.3.1}$$

The optimal trade-off between the maximum UL throughput and maximum DL throughput could be characterized by the boundary of the above throughput region, thus we need to characterize all the boundary throughput pairs of $\mathcal{C}_i\left(P_{\max}\right)$ for any $P_{\max} > 0$.

We let $(R_{UL,i}, R_d)$ and $(R_u, R_{DL.i})$ be the boundary points of the throughput region of protocol i corresponding to the maximum UL and DL throughput, respectively. To characterize the throughput region of each elementary protocol, for each given $R_d \leq R_{DL,i}$, we find the maximum achievable UL throughput R_u. In the following, we derive the throughput region for each protocol.

3.3.1 HD-TS Protocol

It is easy to obtain that the maximum achievable DL throughput is

$$R_{DL,1} = \log_2\left(1 + \frac{|f|^2 P_{\max}}{\sigma_u^2}\right), \tag{3.3.2}$$

when the AP only transmits DL information and the corresponding $R_u = 0$. Similarly, according to [17], the maximum achievable UL throughput can be obtained by solving $\frac{\partial R_u}{\partial \tau_{u,1}} = 0$, which can be expanded as

$$\log_2\left(1 + \Delta\frac{1-\tau_{u,1}}{\tau_{u,1}}\right) + \frac{\tau_{u,1}}{\ln 2}\frac{-\frac{\Delta}{\tau_{u,1}^2}}{1+\Delta\frac{1-\tau_{u,1}}{\tau_{u,1}}} = 0. \tag{3.3.3}$$

where

$$\Delta = \frac{|h|^2 \eta |f|^2 P_{\max}}{\sigma_0^2}. \tag{3.3.4}$$

For simplicity, we assume $\nabla = 1 + \Delta \frac{1-\tau_{u,1}}{\tau_{u,1}}$, then $\tau_{u,1} = \frac{\Delta}{\nabla + \Delta - 1}$. Therefore equation (3.3.3) can be converted to

$$\ln \nabla + \frac{-\nabla - \Delta + 1}{\nabla} = 0. \tag{3.3.5}$$

Then we have

$$\nabla \ln \nabla - \nabla = \Delta - 1, \tag{3.3.6}$$

$$\ln \left(\frac{\nabla}{e} \right) e^{\ln\left(\frac{\nabla}{e}\right)} = \frac{\Delta - 1}{e}, \tag{3.3.7}$$

$$\ln \left(\frac{\nabla}{e} \right) = \mathcal{W} \left(\frac{\Delta - 1}{e} \right), \tag{3.3.8}$$

$$\nabla = \exp \left(\mathcal{W} \left(\frac{\Delta - 1}{e} \right) + 1 \right), \tag{3.3.9}$$

$$\tau_{UL,1} = \frac{\Delta}{\exp \left(\mathcal{W} \left(\frac{\Delta - 1}{e} \right) + 1 \right) + \Delta - 1}, \tag{3.3.10}$$

where $\mathcal{W}(x)$ is the Lambert W function. In this case, the AP transmits no information to the user and therefore $R_d = 0$. The corresponding uplink throughput can be expressed as

$$R_{UL,1} = \frac{\tau_{UL,1}}{\ln 2} \mathcal{W} \left(\frac{\Delta - 1}{e} \right) + 1, \tag{3.3.11}$$

Therefore for each given $R_d \leq R_{DL,1}$, we formulate the optimization problem as

$$\begin{aligned} \mathcal{P}_1 : \quad & \max_{P_{e,1}, P_{u,1}, P_{0,1}, \tau_{e,1}, \tau_{u,1}, \tau_{d,1}} \tau_{u,1} \log_2 (1 + \gamma_{u,1}), \\ s.t. \quad & (3.2.1), (3.2.3), \tau_{d,1} \log_2 (1 + \gamma_{d,1}) \geq R_d, \\ & P_{e,1} \leq P_{\max}, P_{0,1} \leq P_{\max}, P_{u,1} \leq \frac{E_1}{\tau_{u,1}}. \end{aligned} \tag{3.3.12}$$

Since the objective function (3.3.12) is a monotonically increasing function of $P_{e,1}$, the optimal $\hat{P}_{e,1} = P_{\max}$. Similarly, the optimal $\hat{P}_{0,1} = P_{\max}$, $\hat{P}_{u,1} = \frac{E_1}{\tau_{u,1}}$.

For a given $R_d \leq R_{DL,1}$, it is easy to obtain that the optimal $\hat{\tau}_{d,1} = \frac{R_d}{R_{DL,1}}$, and

$\hat{\tau}_{u,1} + \hat{\tau}_{e,1} = 1 - \hat{\tau}_{d,1}$. According to [17], for a given $R_d \in (0, R_{DL,1})$, the optimal $\hat{\tau}_{u,1}$ for $\mathcal{P}_1$ is given by

$$\hat{\tau}_{u,1} = \left(1 - \frac{R_d}{R_{DL,1}}\right) \tau_{UL,1}. \tag{3.3.13}$$

The optimal time duration for the EH slot is thus given by $\hat{\tau}_{e,1} = 1 - \hat{\tau}_{u,1} - \hat{\tau}_{d,1}$. Then the throughput region of the HD-TS protocol could be written as

$$\mathcal{C}_1\left(P_{\max}\right) \triangleq \{(R_u, R_d) : R_u \leq \frac{\hat{\tau}_{u,1} R_{UL,1}}{\tau_{UL,1}}, R_d \leq R_{DL,1}\}. \tag{3.3.14}$$

3.3.2 HD-PS Protocol

The HD-PS protocol is the same as the HD-TS protocol when the system only realizes DL IT. Therefore the maximum achievable DL throughput is given by $R_{DL,2} = R_{DL,1}$, when $R_u = 0$. Similarly, the maximum achievable DL throughput $R_{UL,2} = R_{UL,1}$, when $R_d = 0$ and $\tau_{UL,2} = \tau_{UL,1}$. For each given $R_d \leq R_{DL,2}$, we formulate the optimization problem as

$$\begin{aligned} \mathcal{P}_2 : \quad & \max_{P_{u,2}, P_{0,2}, \tau_{e,2}, \tau_{u,2}, \rho_2} \tau_{u,2} \log_2\left(1 + \gamma_{u,2}\right), \qquad (3.3.15) \\ s.t. \quad & (3.2.8), (3.2.10), \tau_{d,2} \log_2\left(1 + \gamma_{d,2}\right) \geq R_d, \\ & P_{0,2} \leq P_{\max}, P_{u,2} \leq \frac{E_2}{\tau_{u,2}}. \end{aligned}$$

The objective function (3.3.15) is a monotonically increasing function of $P_{u,2}$, thus the optimal $\hat{P}_{u,2} = \frac{E_2}{\tau_{u,2}}$. Similarly, the optimal $\hat{P}_{0,2} = P_{\max}$, and the optimal $\hat{\tau}_{e,2} = 1 - \tau_{u,2}$. Therefore given $\tau_{u,2}$, the optimal PS ratio should satisfy $\tau_{d,2} \log_2\left(1 + \gamma_{d,2}\right) = R_d$. We then have

$$\hat{\rho}_2 = 1 - \frac{\sigma_u^2}{|f|^2 P_{\max}} \left(2^{\frac{R_d}{1-\tau_{u,2}}} - 1\right). \tag{3.3.16}$$

Up to here, the problem $\mathcal{P}_2$ has been simplified as an optimization of only one variable $\tau_{u,2}$. However, due to the complicated structure of the simplified problem, it is currently hard to get the closed form expression of optimal $\hat{\tau}_{u,2}$. However, this can be efficiently solved by a one-dimension exhaustive search. We then can express the boundary throughput pairs of $\mathcal{C}_2$ as

$$\mathcal{C}_2\left(P_{\max}\right) \triangleq \{(R_u, R_d) : R_d \leq R_{DL,2}, \quad R_u \leq \hat{\tau}_{u,2} \log_2\left(1 + \frac{|h|^2 \eta \tau_{e,2} \hat{\rho}_2 |f|^2 P_{\max}}{\hat{\tau}_{u,2}\sigma_0^2}\right)\}. \tag{3.3.17}$$

3.3.3 FD-TS-ER Protocol

Like the HD-TS protocol, the maximum achievable DL throughput $R_{DL,3} = R_{DL,1}$ when $\tau_{d,3} = 1$, and thus $R_u = 0$. The system with the FD-TS-ER protocol can achieve its maximum UL throughput when $\tau_{d,3} = 0$ and thus $R_d = 0$. According to (3.2.16) and (3.2.18), the achievable UL throughput should satisfy

$$R_u \leq \log_2\left(1 + \frac{|h|^2 \eta |f|^2 P_{e,3}}{\left(1 - \eta |h_u|^2\right)\left(\sigma_0^2 + \beta_0 |h_0|^2 P_{e,3}\right)}\right), \tag{3.3.18}$$

where the right-hand side of (3.3.18) is a monotonically increasing function of $P_{e,3}$, thus the AP does not need to control its transmit power during the EH slot. Thus $\hat{P}_{e,3} = P_{\max}$. Then the maximum achievable UL throughput can be expressed as

$$R_{UL,3} = \log_2\left(1 + \frac{|h|^2 \eta |f|^2 P_{\max}}{\left(1 - \eta |h_u|^2\right)\left(\sigma_0^2 + \beta_0 |h_0|^2 P_{\max}\right)}\right). \tag{3.3.19}$$

For each given $R_d \leq R_{DL,3}$, we formulate the problem as

$$\begin{aligned} \mathcal{P}_3: \quad & \max_{P_{u,3}, P_{0,3}, \tau_{u,3}, \tau_{d,3}} \tau_{u,3} \log_2\left(1 + \gamma_{u,3}\right), \\ s.t. \quad & (3.2.13), (3.2.15), \tau_{d,3} \log_2\left(1 + \gamma_{d,3}\right) \geq R_d, \\ & P_{e,3} \leq P_{\max}, P_{0,3} \leq P_{\max}, P_{u,3} \leq \frac{E_3}{\tau_{u,3}}. \end{aligned} \tag{3.3.20}$$

Like the HD-PS Protocol, it is easy to obtain the optimal $\hat{P}_{u,3} = \frac{E_3}{\tau_{u,3}}$, $\hat{P}_{0,3} = P_{\max}$. Thus for each given R_d, the optimal time duration of the DL IT slot is given by $\hat{\tau}_{d,3} = \frac{R_d}{R_{DL,3}}$. The time duration of the UL IT slot is thus given by $\hat{\tau}_{u,3} = 1 - \tau_{d,3}$.

The achievable UL throughput can be expressed as

$$R_u \leq \left(1 - \frac{R_d}{R_{DL,3}}\right) R_{UL,3}. \tag{3.3.21}$$

Then the throughput region of the FD-TS-ER protocol could be written as

$$\mathcal{C}_3\left(P_{\max}\right) \triangleq \{(R_u, R_d) : (3.3.21), R_d \leq R_{DL,3}\}. \tag{3.3.22}$$

3.3.4 FD-TS Protocol

According to (3.2.24), the system achieves the maximum UL throughput when the AP transmits no information to the user, therefore the maximum achievable UL throughput is given by $R_{UL,4} = R_{UL,1}$, when $R_d = 0$. Like the HD-TS protocol, the maximum achievable DL throughput $R_{DL,4} = R_{DL,1}$, when $\tau_{e,4} = 0$, and thus $R_u = 0$. For each given $R_d \leq R_{DL,4}$, we formulate the optimization problem as

$$\begin{aligned} \mathcal{P}_4 : \quad & \max_{P_{e,4}, P_{u,4}, P_{0,4}, \tau_{e,4}, \tau_{d,4}} \tau_{u,4} \log_2\left(1 + \gamma_{u,4}\right), \qquad (3.3.23) \\ s.t. \quad & (3.2.20), (3.2.21), \tau_{d,4} \log_2\left(1 + \gamma_{d,4}\right) \geq R_d, \\ & P_{e,4} \leq P_{\max}, P_{0,4} \leq P_{\max}, P_{u,4} \leq \frac{E_4}{\tau_{u,4}}. \end{aligned}$$

Notice that the objective function (3.3.23) is a monotonically increasing function of $P_{e,4}$, therefore the optimal $\hat{P}_{e,4} = P_{\max}$.

Given R_d and $\tau_{d,4}$, it is easy to obtain that the optimal $\hat{\tau}_{e,4} = 1 - \tau_{d,4}$, and we have

$$P_{0,4} \geq \left(2^{\frac{R_d}{\tau_{d,4}}} - 1\right) \frac{\sigma_u^2 + \beta_u |h_u|^2 P_{u,4}}{|f|^2}. \tag{3.3.24}$$

The UL throughput should satisfy

$$R_u \leq \tau_{d,4} \log_2\left(1 + \frac{|h|^2 P_{u,4}}{\sigma_0^2 + \beta_0 |h_0|^2 P_{0,4}}\right), \tag{3.3.25}$$

where the right-hand side of (3.3.25) is a monotonically increasing function of $P_{u,4}$, thus the optimal $\hat{P}_{u,4} = \frac{E_4}{\tau_{d,4}}$.

Since $\frac{\partial R_u}{\partial P_{0,4}} < 0$, for given $\tau_{d,4}$ and R_d, it is easy to find the optimal DL power is

$$\hat{P}_{0,4} = \left(2^{\frac{R_d}{\tau_{d,4}}} - 1\right)\left(\frac{\sigma_u^2}{|f|^2} + \frac{\beta_u |h_u|^2 (1-\tau_{d,4})\eta P_{\max}}{\tau_{d,4}}\right). \tag{3.3.26}$$

Then $\mathcal{P}_4$ can be converted into

$$\mathcal{P}_5 : \quad \max_{\tau_{d,4}} \tau_{d,4}\log_2\left(1 + \frac{|h|^2\eta|f|^2 P_{\max}(1-\tau_{d,4})}{\tau_{d,4}\left(\sigma_0^2 + \beta_0|h_0|^2\hat{P}_{0,4}\right)}\right), \tag{3.3.27}$$

$$s.t. \quad (3.3.26), R_d \leq R_{DL,4}, 0 \leq \tau_{d,4} \leq 1.$$

Due to the complicated structure of $\mathcal{P}_5$, it is currently hard to get the closed form expression of optimal $\hat{\tau}_{d,4}$. However, this can be efficiently solved by a one-dimension exhaustive search. We then can express the boundary throughput pairs of $\mathcal{C}_2$ as

$$\mathcal{C}_5(P_{\max}) \triangleq \{(R_u, R_d) : R_d \leq R_{DL,5}, \tag{3.3.28}$$

$$R_u \leq \hat{\tau}_{d,4}\log_2\left(1 + \frac{|h|^2\eta|f|^2 P_{\max}(1-\hat{\tau}_{d,4})}{\hat{\tau}_{d,4}\left(\sigma_0^2 + \beta_0|h_0|^2\hat{P}_{0,4}\right)}\right)\}.$$

3.3.5 FD-PS-ER Protocol

Like the FD-TS-ER protocol, the maximum achievable UL throughput $R_{UL,5} = R_{UL,3}$, when $\rho_5 = 1$, and thus $R_{d\max} = 0$. The maximum achievable DL throughput $R_{DL,5} = R_{DL,1}$, when $\rho_5 = 0$, and thus $R_{u\max} = 0$. According to (3.2.31), (3.2.32), the achievable UL and DL throughput can be expressed as

$$R_u \leq \log_2(1 + \gamma_{u,5}), \tag{3.3.29}$$

$$R_d \leq \log_2(1 + \gamma_{d,5}), \tag{3.3.30}$$

respectively. For each given $R_d \le R_{DL,5}$, we formulate the optimization problem as

$$\mathcal{P}_6: \quad \max_{\rho_5, P_{u,5}, P_{0,5}, \tau_{e,5}} \tau_{u,5} \log_2 (1 + \gamma_{u,5}), \tag{3.3.31}$$

$$s.t. \quad (3.2.26), (3.2.29), \tau_{d,5} \log_2 (1 + \gamma_{d,5}) \ge R_d,$$

$$P_{0,5} \le P_{\max}, P_{u,5} \le \frac{E_5}{\tau_{u,5}}.$$

Similar to the FD-TS protocol, the optimal $\hat{P}_{u,5} = \frac{E_5}{\tau_{u,5}}$. It is then easy to obtain the optimal $\hat{\tau}_{e,5} = 1$. Thus given R_d and ρ_5, we have

$$R_u \le \log_2 \left(1 + \frac{|h|^2 \eta \rho_5 |f|^2 P_{0,5}}{\left(1 - \eta \rho_5 |h_u|^2\right) \left(\sigma_0^2 + \beta_0 |h_0|^2 P_{0,5}\right)} \right), \tag{3.3.32}$$

where the right-hand side of (3.3.32) is a monotonically increasing function of $P_{0,5}$, thus the optimal $\hat{P}_{0,5} = P_{\max}$. Then it is easy to find the optimal ρ_5 is

$$\hat{\rho}_5 = \frac{-B - \sqrt{B^2 - 4AC}}{2A}, \tag{3.3.33}$$

where

$$A = |f|^2 P_{\max} |h_u|^2 \eta + \gamma_{d,5} \beta_u |f|^2 P_{\max} |h_u|^2 \eta, \tag{3.3.34}$$

$$B = \gamma_{d,5} |h_u|^2 \eta \sigma_u^2 - |f|^2 P_{\max} - A, \tag{3.3.35}$$

$$C = |f|^2 P_{\max} - \gamma_{d,5} \sigma_u^2. \tag{3.3.36}$$

Then the achievable UL throughput is given by

$$R_u \le \log_2 \left(1 + \frac{|h|^2 \eta \hat{\rho}_5 |f|^2 P_{\max}}{\left(1 - \eta \hat{\rho}_5 |h_u|^2\right) \left(\sigma_0^2 + \beta_0 |h_0|^2 P_{\max}\right)} \right). \tag{3.3.37}$$

Then the throughput region of the FD-PS-ER protocol could be written as

$$\mathcal{C}_5 (P_{\max}) \triangleq \{(R_u, R_d) : (3.3.37), R_d \le R_{DL,5}\}. \tag{3.3.38}$$

3.4 Numerical Results

In this section, we compare the throughput regions of the five proposed protocols analyzed in the previous section. For all simulation examples, the distance-dependent

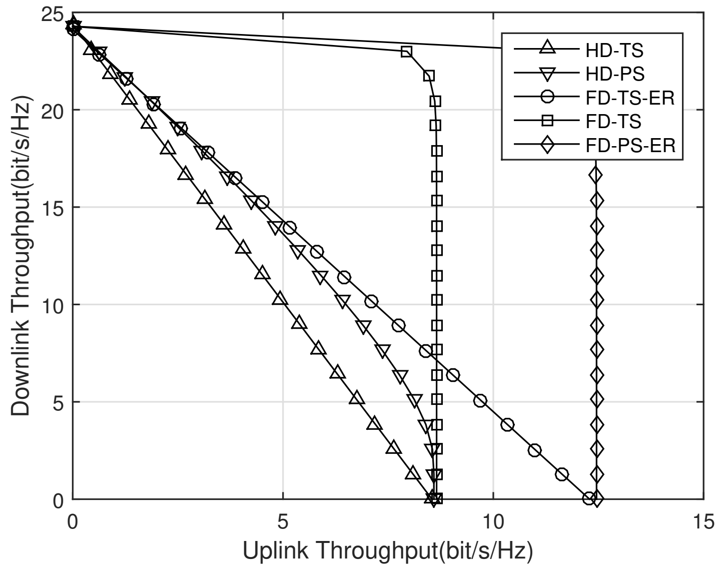


Figure 3.2: Throughput Regions of all proposed Elementary Protocols with the suppression factor $\beta = 0$.

signal attenuations between the AP and the user are set as $\mathbb{E}\left[|f|^2\right] = \mathbb{E}\left[|h|^2\right] = -30$dB. We assume the SI channels $\mathbb{E}\left[|h_0|^2\right] = \mathbb{E}\left[|h_u|^2\right] = -25$dB, which correspond to the case that two omnidirectional antennas are separated by 35 cm in a reflective room [18]. Furthermore, we set the power limit of AP $P_{\max} = 30$dBm, the noise power density is assumed to be -140dBm/Hz, and the average noise power at the AP and user is assumed as $\sigma_0^2 = \sigma_u^2 = -70$dBm over the bandwidth of 10MHz. The SI suppression factors at the AP and user are set to be $\beta_0 = \beta_u = \beta$. The energy conversion efficiency $\eta = 0.5$.

Fig. 3.2, Fig. 3.3 and Fig. 3.4 plot the throughput regions of the five proposed protocols, in which each curve is obtained by averaging over 1000 random channel realizations. In particular, we show the boundaries of throughput region $\mathcal{C}_i$ for all elementary protocols, where the SI suppression factor is set to be 0 (fully cancelled),

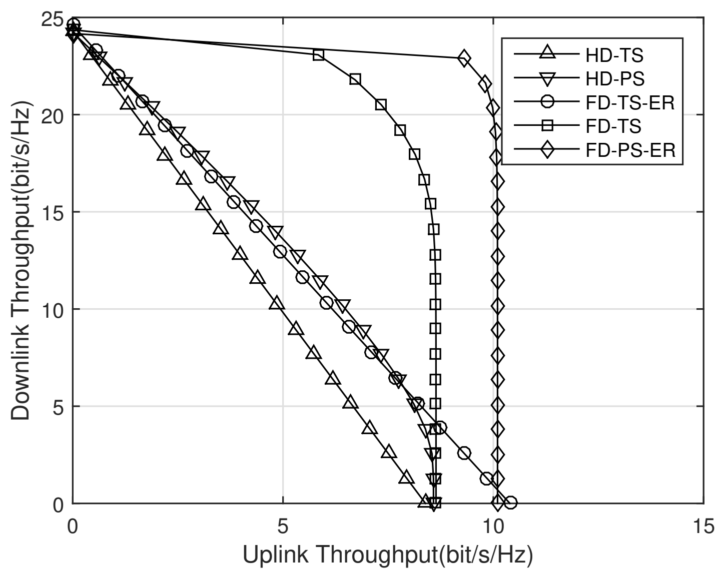


Figure 3.3: Throughput Regions of all proposed Elementary Protocols with the suppression factor $\beta = -75$dB.

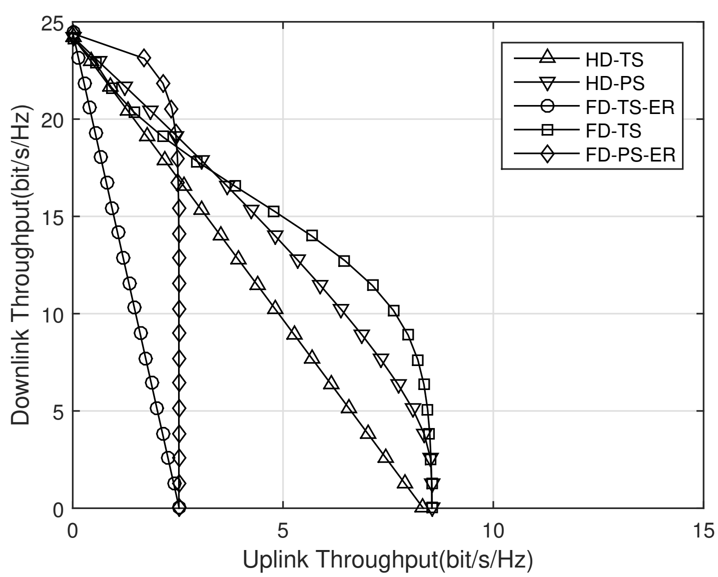


Figure 3.4: Throughput Regions of all proposed Elementary Protocols with the suppression factor $\beta = -45$dB.

-75dB and $\beta = -45$dB, which could be achieved in an ideal case, an anechoic chamber and reflective room, respectively [18].

It is observed that all protocols achieve the same maximum DL throughput when the UL throughput R_u is set to zero. The FD protocols with the ER technique achieve higher UL throughput than those without ER. Furthermore, the system with the FD protocols in general achieves a higher throughput pair than that with the HD protocols under an ideal or anechoic chamber environment. However, the FD protocols suffer from SI and thus perform worse as the SI suppression factor increases. Specifically, the FD protocols with ER suffer dramatically from SI and thus have a significantly smaller throughput region in the case of a reflective room than those without the FD or the ER. In contrast, thanks to the power control at the AP, the FD-TS protocol still outperforms the HD protocols in a reflective room. It can also be observed that the optimized PS receiver achieves a larger throughput region than the TS receiver at the expense of incurring a higher hardware complexity and a higher computational burden for resource allocation.

Chapter 4

Wireless Powered Two-Way Relaying via a Hybrid Multi-Antenna Relay

This chapter investigates WPCN with more wireless-powered nodes. Moreover, a two-way relay channel is considered in this chapter. Specifically, we study a wireless-powered two-way relay system, in which both wireless-powered sources exchange information through a multi-antenna relay. Both sources are assumed to have no embedded energy supply and thus first need to harvest energy from the radio frequency signals broadcast by the relay before exchanging their information via the relay. We aim to maximize the sum throughput of both sources by jointly optimizing the time switching duration, the energy beamforming vector and the precoding matrix at the relay. The formulated problem is non-convex and hard to solve in its original form. To address this, we simplify the problem by reducing the number of variables and by decomposing the precoding matrix into a transmit vector and a receive vector. We then propose a bisection search, a 1-D search and iterative algorithms to optimize each variable. Numerical results show that our proposed scheme can achieve a higher throughput than the conventional scheme without optimization on the beamforming vector and *precoding matrix at the relay.*

4.1 Introduction

Recently, researchers extended the study on SWIPT to relaying networks, in which a wireless powered relay and/or wireless powered sources were considered in a relay system [21–24]. Specifically, [22] studied a two-way relaying system with two wireless powered sources, whereas [23] investigated a two-way relaying system with a wireless powered relay. [24] studied a two-way relaying network with multiple pairs of wireless powered users. All these works considered PS receiver architecture at the wireless powered nodes and aimed to maximize the sum throughput of the sources.

Note that none of these works investigated TS receiver architecture, which has a lower hardware complexity [25] and thus is easy to implement. Motivated by this gap, in this work we investigate a wireless multiple-input-multiple-output (MIMO) two-way relaying system using the TS technique, in which two wireless-powered sources with TS receiver architecture exchange information through a hybrid multi-antenna relay. More specifically, a hybrid relay first transmits wireless energy to both sources in the energy transfer (ET) phase; both sources then use the harvested energy to send their information to the relay in the multiple access (MA) phase; and the relay finally amplifies and forwards the received signals to both sources in the broadcasting (BC) phase.

The studied wireless-powered two-way relay system in this paper is fundamentally different from those in the literature. Compared to existing work using the PS receiver technique, an extra transmit beamforming vector for WET and a new TS factor need to be determined to balance the harvested energy and data throughput of two sources in the considered system setup. In line with existing works, we formulate a total throughput maximization problem under a peak power constraint at the relay. With all optimization variables tangled together, the formulated problem is difficult to solve.

To address this difficult problem, we first prove that the optimal beamforming vector for WET can be parameterized by a single variable. Then we decompose the precoding matrix at the relay into a receive beamforming vector and a transmit beamforming vector. We prove the optimal receive beamforming vector is same as the one for WET. As a result, we transform the optimization of the transmit beamforming vector to a convex problem. Finally we use DC programming [26] to find the optimal solution to the transformed problem.

4.2 System Model

We consider a wireless-powered two-way relay network consisting of a multi-antenna HD relay with N antennas and two wireless-powered sources with a single antenna, as shown in Fig. 4.1. It is assumed that there is no direct link between the two sources. In this system, both sources have no embedded energy supply and thus have to harvest energy from the signals broadcast by the relay before using it for their two-way information exchange via the relay. In this case, the relay needs to transfer both energy and information to the sources. In this paper, we assume that the TS receiver architecture is used at both sources due to its lower hardware complexity and lower computational burden for resource allocation [25]. We assume that both sources have information to transmit to each other. The AF protocol is applied in this system as it achieves lower hardware complexity. We assume all nodes

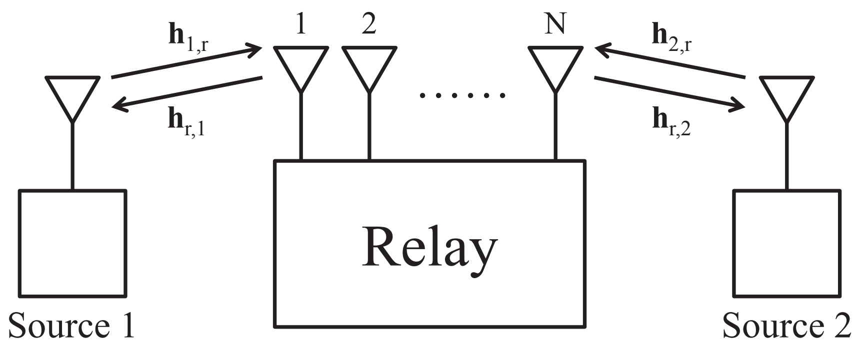


Figure 4.1: System Model.

work in the commonly used HD mode. We use $P_{\max}$ to denote the instantaneous peak power limit of the relay. We use $\mathbf{h}_{i,r} \in \mathbb{C}^{N\times 1}$ and $\mathbf{h}_{r,i} \in \mathbb{C}^{1\times N}$ to denote the channel coefficient from source i to the relay and that from the relay to source i, $i \in \{1,2\}$, respectively. We consider that all channels are quasi-static flat-fading, such that all channel power gains remain constant during each transmission block, denoted by T. Furthermore, the channels are assumed to be reciprocal, i.e., $\mathbf{h}_{i,r} = \mathbf{h}_{r,i}^H$. For simplicity, we follow [27] and assume that the full channel state information is known perfectly at the relay. Without loss of generality, we hereafter consider a normalized time duration of each transmission block, i.e., $T = 1$.

Each transmission block consists of three time phases, namely, the ET phase, MA phase and BC phase, respectively. In the ET phase, the relay broadcasts energy-bearing signals to both sources. The received signal at source i is thus given by

$$y_{e,i} = \mathbf{h}_{r,i}\mathbf{w}_1\sqrt{P_e}x_e + n_i, \tag{4.2.1}$$

where $\mathbf{w}_1 \in \mathbb{C}^{N\times 1}$ is the energy beamforming vector with $\|\mathbf{w}_1\| = 1$. P_e denotes the transmit power of the relay during the ET phase with $P_e \leq P_{\max}$. x_e denotes the transmitted signal by the relay with $\mathbb{E}\left[|x_e|^2\right] = 1$. n_i denotes the noise at source i, which is assumed to be $n_i \sim \mathcal{CN}(0, \sigma_i^2)$, where $\mathcal{CN}(v, \sigma^2)$ stands for a CSCG random variable with mean v and variance σ^2. In this paper, we ignore the amount of energy harvested from noise since its power is normally small and below the sensitivity of the EH devices. The harvested energy at source i can thus be expressed as

$$E_i = \eta\tau|\mathbf{h}_{r,i}\mathbf{w}_1|^2 P_e, \tag{4.2.2}$$

where $\eta \in (0, 1)$ denotes the energy conversion efficiency. $\tau \in [0, 1]$ denotes the time duration of the ET phase. The remaining time in each transmission block is further divided equally into two parts to realize the AF relaying. Therefore the time durations of the MA and BC phases are given by

$$\tau_{MA} = \tau_{BC} = \frac{1-\tau}{2}. \tag{4.2.3}$$

In the MA phase, both sources use their harvested energy to transmit information to the relay. The received signal at the relay is written as

$$\mathbf{y}_r = \mathbf{h}_{1,r}\sqrt{P_1}x_1 + \mathbf{h}_{2,r}\sqrt{P_2}x_2 + \mathbf{n}_r, \tag{4.2.4}$$

where P_i denotes the transmission power of source i during the MA phase, we assume that the sources have no battery to reserve energy for later usage, then we have $P_i \leq \frac{E_i}{\tau_{MA}}$. x_i denotes the transmitted signal by source i with $\mathbb{E}\left[|x_i|^2\right] = 1$. $\mathbf{n}_r$ is a $N \times 1$ vector denoting the noise at the relay with the k_{th} element $n_{r,k} \sim \mathcal{CN}(0, \sigma_r^2)$.

In the BC phase, the relay generates a signal by using precoding matrix $\mathbf{W}_2 \in \mathbb{C}^{N\times N}$ and then broadcasting the signal to both sources. Then according to [27], the transmit power of the relay in the BC phase is given by

$$P_r = P_1\|\mathbf{W}_2\mathbf{h}_{1,r}\|^2 + P_2\|\mathbf{W}_2\mathbf{h}_{2,r}\|^2 + \sigma_r^2\text{trace}\left(\mathbf{W}_2\mathbf{W}_2^H\right). \tag{4.2.5}$$

The received signal at each source is given by

$$y_i = \mathbf{h}_{r,i}\mathbf{W}_2\mathbf{y}_r + n_i. \tag{4.2.6}$$

Each source needs to cancel their own information component from the received signal. Then the received SNR at source i can be written as

$$\gamma_i = \frac{P_j|\mathbf{h}_{r,i}\mathbf{W}_2\mathbf{h}_{j,r}|^2}{\sigma_r^2\|\mathbf{h}_{r,i}\mathbf{W}_2\|^2 + \sigma_i^2}, \tag{4.2.7}$$

where $j = 3 - i$.

Therefore the achievable throughput of source i is given by

$$R_i \leq \tau_{MA}\log_2\left(1 + \gamma_j\right). \tag{4.2.8}$$

4.3 Total Throughput Maximization

In this work, we aim to maximize the total throughput of both sources, subject to the power constraints at the relay and both sources. Mathematically, we can have the following maximization problem

$$\begin{aligned} \mathcal{P}_1 : \max_{\tau, P_e, P_1, P_2, \mathbf{w}_1, \mathbf{W}_2} \quad & R_1 + R_2, \\ s.t. \quad & P_r \leq P_{\max}, P_e \leq P_{\max}, 0 \leq \tau \leq 1, \\ & P_1 \leq \frac{2E_1}{1-\tau}, P_2 \leq \frac{2E_2}{1-\tau}. \end{aligned} \tag{4.3.1}$$

We first express the precoding matrix $\mathbf{W}_2$ as

$$\mathbf{W}_2 = \sqrt{\beta}\mathbf{W}, \tag{4.3.2}$$

where $\mathbf{W}$ is the normalized precoding matrix with $\|\mathbf{W}\|^2 = 1$, $\beta \in \mathbb{R}^+$ is the power amplification ratio of the AF relay. Then given τ, $\mathbf{w}_1$, P_1 and P_2, the transmit power of the relay can be expressed as

$$P_r = \beta\left(P_1\|\mathbf{W}\mathbf{h}_{1,r}\|^2 + P_2\|\mathbf{W}\mathbf{h}_{2,r}\|^2 + \sigma_r^2\text{trace}\left(\mathbf{W}\mathbf{W}^H\right)\right). \tag{4.3.3}$$

The throughput of source i is given by

$$R_i = \left(\frac{1-\tau}{2}\right)\log_2\left(1+\frac{\beta P_i|\mathbf{h}_{r,j}\mathbf{W}\mathbf{h}_{i,r}|^2}{\beta\sigma_r^2\left\|\mathbf{h}_{r,j}\mathbf{W}\right\|^2+\sigma_j^2}\right). \tag{4.3.4}$$

Since $\frac{\partial R_i}{\partial \beta} \geq 0$, according to (4.3.3), for given τ, $\mathbf{w}_1$, P_1 and P_2, the equality of the first constraint holds, thus the optimal precoding matrix $\hat{\mathbf{W}}_2$ should satisfy

$$P_1\left\|\hat{\mathbf{W}}_2\mathbf{h}_{1,r}\right\|^2+P_2\left\|\hat{\mathbf{W}}_2\mathbf{h}_{2,r}\right\|^2+\sigma_r^2\text{trace}\left(\hat{\mathbf{W}}_2\hat{\mathbf{W}}_2^H\right)=P_{\max}. \tag{4.3.5}$$

Similarly, it is easy to obtain that the optimal $\hat{P}_e = P_{\max}$, $\hat{P}_i = \frac{2E_i}{1-\tau}$. Then problem $\mathcal{P}_1$ can be transformed to

$$\begin{aligned}\mathcal{P}_2 : \max_{\tau,\mathbf{w}_1,\mathbf{W}_2} \quad & R_1 + R_2, \\ s.t. \quad & P_r = P_{\max}, P_e = P_{\max}, 0 \leq \tau \leq 1, \\ & P_1 = \frac{2E_1}{1-\tau}, P_2 = \frac{2E_2}{1-\tau}, (4.3.5).\end{aligned} \tag{4.3.6}$$

Unfortunately, the problem (4.3.6) is non-convex and all the variables are coupled together. Motivated by this, in this paper we solve this problem by optimizing τ, $\mathbf{w}_1$ and $\mathbf{W}_2$ alternatingly.

4.3.1 Optimization of the time duration of ET phase τ

It is observed that either R_1 or R_2 is concave function of τ. Thus the optimal τ can be found by solving $\frac{\partial R_1}{\partial \tau} + \frac{\partial R_2}{\partial \tau} = 0$, which can be expanded as

$$\sum_{i=1}^{2}\frac{1-\tau}{2}\log_2\left(1-\Delta_i+\frac{\Delta_i}{1-\tau}\right)=0, \tag{4.3.7}$$

where $\Delta_i = \frac{2\eta|\mathbf{h}_{r,i}\mathbf{w}_1|^2P_e|\mathbf{h}_{r,j}\mathbf{W}_2\mathbf{h}_{i,r}|^2}{\sigma_r^2\|\mathbf{h}_{r,j}\mathbf{W}_2\|^2+\sigma_j^2}$. Let $x = 1-\tau$, the equation above can be further expanded as

$$\ln\left(Ax^2+Bx+C\right)-2\ln x-\frac{Bx+2C}{Ax^2+Bx+C}=0, \tag{4.3.8}$$

where $A = 1-\Delta_1-\Delta_2+\Delta_1\Delta_2$, $B = \Delta_1+\Delta_2-2\Delta_1\Delta_2$ and $C = \Delta_1\Delta_2$.

Due to the complicated structure of equation (4.3.8), it is hard to get a closed form expression for the optimal τ. However, it can be observed that the left-hand side of equation (4.3.8) is a monotonically decreasing function of variable τ and it always has a solution in $[0,1]$, thus this problem can be efficiently solved by a bisection search.

4.3.2 Parameterization of the energy beamforming vector $\mathbf{w}_1$

We can observe that the beamforming vector $\mathbf{w}_1$ is only involved in the terms $|\mathbf{h}_{r,1}\mathbf{w}_1|^2$ and $|\mathbf{h}_{r,2}\mathbf{w}_1|^2$, thus it can be used to balance the signals broadcast to both sources. According to [28], for given τ and $\mathbf{W}_2$, the beamforming vector $\mathbf{w}_1$ for all throughput pairs on the Pareto boundary can be parameterized by $\alpha \in [0,1]$ as

$$\mathbf{w}_1 = \alpha \frac{\prod_{\mathbf{h}_{r,2}^H} \mathbf{h}_{r,1}^H}{\left\| \prod_{\mathbf{h}_{r,2}^T} \mathbf{h}_{r,1}^T \right\|} + \sqrt{1-\alpha^2} \frac{\prod_{\mathbf{h}_{r,2}^H}^{\perp} \mathbf{h}_{r,1}^H}{\left\| \prod_{\mathbf{h}_{r,2}^T}^{\perp} \mathbf{h}_{r,1}^T \right\|}, \tag{4.3.9}$$

where $\prod_{\mathbf{X}} \triangleq \mathbf{X}\left(\mathbf{X}^H\mathbf{X}\right)^{-1}\mathbf{X}^H$, $\prod_{\mathbf{X}}^{\perp} \triangleq \mathbf{I} - \prod_{\mathbf{X}}$, and Pareto boundary is the outermost boundary of the achievable throughput region defined by

$$\begin{aligned} \mathcal{C}\left(P_{\max}\right) \triangleq \{ & (R_1, R_2) : R_1 \leq \tau_{MA}\log_2\left(1+\gamma_1\right), R_2 \leq \tau_{MA}\log_2\left(1+\gamma_2\right), \\ & 0 \leq \tau \leq 1, P_e \leq P_{\max}, P_r \leq P_{\max}, P_1 \leq \frac{2E_1}{1-\tau}, P_2 \leq \frac{2E_2}{1-\tau} \Big\}. \end{aligned} \tag{4.3.10}$$

Therefore, the optimization of the energy beamforming vector can be simplified to an optimization of one scalar variable α, and can be efficiently solved by a one-dimension exhaustive search.

4.3.3 Optimization of the precoding matrix $\mathbf{W}_2$

Similar to [27], considering the fact that each source only transmits a single data stream and the network coding principle encourages mixing rather than separating the data streams from different sources, we decompose $\mathbf{W}_2$ as $\mathbf{W}_2 = \mathbf{w}_t\mathbf{w}_r^H$, where $\mathbf{w}_r$ is the receive beamforming vector and $\mathbf{w}_t$ is the transmit beamforming vector at the relay. Without loss of optimality, we further assume $\|\mathbf{w}_r\| = 1$. As a result, problem $\mathcal{P}_2$ can be converted to

$$\begin{aligned} \mathcal{P}_3 : \max_{\tau,\mathbf{w}_r,\mathbf{w}_t} \quad & \sum_{i=1}^{2} \frac{1-\tau}{2}\log_2\left(1+\frac{\beta P_i|\mathbf{h}_{r,j}\mathbf{w}_t|^2\left|\mathbf{w}_r^H\mathbf{h}_{i,r}\right|^2}{\beta\sigma_r^2|\mathbf{h}_{r,j}\mathbf{w}_t|^2+\sigma_j^2}\right), \\ s.t. \quad & P_r = P_{\max}, P_e = P_{\max}, 0 \le \tau \le 1, \\ & P_1 = \frac{2E_1}{1-\tau}, P_2 = \frac{2E_2}{1-\tau}, \|\mathbf{w}_r\| = 1, \\ & \sum_{i=1}^{2} P_i\|\mathbf{w}_t\|^2\left|\mathbf{w}_r^H\mathbf{h}_{i,r}\right|^2 + \sigma_r^2\|\mathbf{w}_t\|^2 = P_{\max}, \end{aligned} \tag{4.3.11}$$

where $\beta P_i|\mathbf{h}_{r,j}\mathbf{w}_t|^2\left|\mathbf{w}_r^H\mathbf{h}_{i,r}\right|^2$ can be expanded as $\frac{2\beta\eta\tau P_{\max}}{1-\tau}|\mathbf{h}_{r,j}\mathbf{w}_t|^2\left|\mathbf{w}_r^H\mathbf{h}_{i,r}\right|^2|\mathbf{h}_{r,i}\mathbf{w}_1|^2$. It is observed that the receive beamforming vector $\mathbf{w}_r$ is only involved in the terms $\left|\mathbf{w}_r^H\mathbf{h}_{1,r}\right|^2$ and $\left|\mathbf{w}_r^H\mathbf{h}_{2,r}\right|^2$ and can be used to balance the signals received from both sources. Since $\left|\mathbf{w}_r^H\mathbf{h}_{i,r}\right|^2$ and $\left|\mathbf{h}_{r,i}^H\mathbf{w}_1\right|^2$ are in same position, and considering the fact that $|\mathbf{h}_{i,r}|^2 = \left|\mathbf{h}_{r,i}^H\right|^2$, for given τ and $\mathbf{w}_t$, the optimal receive beamforming vector $\hat{\mathbf{w}}_r = \hat{\mathbf{w}}_1$.

We then study how to optimize $\mathbf{w}_t$ with given τ, $\mathbf{w}_1$ and $\mathbf{w}_r$. For convenience, we define a semidefinite matrix $\mathbf{W}_t = \mathbf{w}_t\mathbf{w}_t^H$. Then for any given τ, the problem (4.3.11) becomes

$$\begin{aligned} \mathcal{P}_4 : \max_{\mathbf{W}_t\succeq 0} \quad & F\left(\mathbf{W}_t\right), \\ s.t. \quad & P_r = P_{\max}, P_e = P_{\max}, P_1 = \frac{2E_1}{1-\tau}, P_2 = \frac{2E_2}{1-\tau}, \\ & \sum_{i=1}^{2} P_i \mathrm{trace}\left(\mathbf{W}_t\right)\left|\mathbf{w}_r^H\mathbf{h}_{i,r}\right|^2 + \sigma_r^2 \mathrm{trace}\left(\mathbf{W}_t\right) = P_{\max}. \end{aligned} \tag{4.3.12}$$

where $F(\mathbf{W}_t)$ is defined as

$$F(\mathbf{W}t) = \left(\frac{1-\tau}{2}\right) \times \tag{4.3.13}$$

$$\left\{\log_2\left(1 + \frac{\beta P_1 \text{trace}\left(\mathbf{W}_t \mathbf{h}_{r,2}^H \mathbf{h}_{r,2}\right) \left|\mathbf{w}_r^H \mathbf{h}_{1,r}\right|^2}{\beta\sigma_r^2 \text{trace}\left(\mathbf{W}_t \mathbf{h}_{r,2}^H \mathbf{h}_{r,2}\right) + \sigma_2^2}\right) + \right. \tag{4.3.14}$$

$$\left. \log_2\left(1 + \frac{\beta P_2 \text{trace}\left(\mathbf{W}_t \mathbf{h}_{r,1}^H \mathbf{h}_{r,1}\right) \left|\mathbf{w}_r^H \mathbf{h}_{2,r}\right|^2}{\beta\sigma_r^2 \text{trace}\left(\mathbf{W}_t \mathbf{h}_{1,2}^H \mathbf{h}_{1,2}\right) + \sigma_1^2}\right)\right\}, \tag{4.3.15}$$

which can be expanded as

$$\begin{aligned} F(\mathbf{W}_t) = &\left(\tfrac{1-\tau}{2}\right) \times \\ &\left\{\log_2\left(\left(P_1\left|\mathbf{w}_r^H \mathbf{h}_{1,r}\right|^2 + \sigma_r^2\right) \beta \text{trace}\left(\mathbf{W}_t \mathbf{h}_{r,2}^H \mathbf{h}_{r,2}\right)\right)\right. \\ &-\log_2\left(\beta\sigma_r^2 \text{trace}\left(\mathbf{W}_t \mathbf{h}_{r,2}^H \mathbf{h}_{r,2}\right) + \sigma_2^2\right) \\ &+\log_2\left(\left(P_2\left|\mathbf{w}_r^H \mathbf{h}_{2,r}\right|^2 + \sigma_r^2\right) \beta \text{trace}\left(\mathbf{W}_t \mathbf{h}_{r,1}^H \mathbf{h}_{r,1}\right)\right) \\ &\left.-\log_2\left(\beta\sigma_r^2 \text{trace}\left(\mathbf{W}_t \mathbf{h}_{r,1}^H \mathbf{h}_{r,1}\right) + \sigma_1^2\right)\right\}, \end{aligned} \tag{4.3.16}$$

which has the same form as function (33) in [27], and can be solved similarly through D-C programming [26] to find an optimal solution. Specifically, we can express $F(\mathbf{W}_t)$ as a difference of two concave functions $f(\mathbf{W}_t)$ and $g(\mathbf{W}_t)$, i.e.,

$$F(\mathbf{W}_t) \triangleq \left(\frac{1-\tau}{2}\right) \left(f(\mathbf{W}_t) - g(\mathbf{W}_t)\right), \tag{4.3.17}$$

where

$$\begin{aligned} f(\mathbf{W}_t) \triangleq &\log_2\left(\left(P_1\left|\mathbf{w}_r^H \mathbf{h}_{1,r}\right|^2 + \sigma_r^2\right) \beta \text{trace}\left(\mathbf{W}_t \mathbf{h}_{r,2}^H \mathbf{h}_{r,2}\right)\right) \\ &+ \log_2\left(\left(P_2\left|\mathbf{w}_r^H \mathbf{h}_{2,r}\right|^2 + \sigma_r^2\right) \beta \text{trace}\left(\mathbf{W}_t \mathbf{h}_{r,1}^H \mathbf{h}_{r,1}\right)\right), \\ g(\mathbf{W}_t) \triangleq &\log_2\left(\beta\sigma_r^2 \text{trace}\left(\mathbf{W}_t \mathbf{h}_{r,2}^H \mathbf{h}_{r,2}\right) + \sigma_2^2\right) \\ &+ \log_2\left(\beta\sigma_r^2 \text{trace}\left(\mathbf{W}_t \mathbf{h}_{r,1}^H \mathbf{h}_{r,1}\right) + \sigma_1^2\right). \end{aligned}$$

We then approximate $g(\mathbf{W}_t)$ by a linear function. The first-order approximation of $g(\mathbf{W}_t)$ around the point $\mathbf{W}_{t,k}$ is given by

$$\begin{aligned} g_L(\mathbf{W}_t;\mathbf{W}_{t,k}) = & \frac{1}{\ln 2}\frac{\beta\sigma_r^2 \text{trace}\left(\left(\mathbf{W}_t-\mathbf{W}_{t,k}\right)\mathbf{h}_{r,2}^H\mathbf{h}_{r,2}\right)}{\beta\sigma_r^2\text{trace}\left(\mathbf{W}_{t,k}\mathbf{h}_{r,2}^H\mathbf{h}_{r,2}\right)+\sigma_2^2} \\ & + \frac{1}{\ln 2}\frac{\beta\sigma_r^2 \text{trace}\left(\left(\mathbf{W}_t-\mathbf{W}_{t,k}\right)\mathbf{h}_{r,1}^H\mathbf{h}_{r,1}\right)}{\beta\sigma_r^2\text{trace}\left(\mathbf{W}_{t,k}\mathbf{h}_{r,1}^H\mathbf{h}_{r,1}\right)+\sigma_1^2} \\ & + \log_2\left(\beta\sigma_r^2\text{trace}\left(\mathbf{W}_{t,k}\mathbf{h}_{r,2}^H\mathbf{h}_{r,2}\right)+\sigma_2^2\right) \\ & + \log_2\left(\beta\sigma_r^2\text{trace}\left(\mathbf{W}_{t,k}\mathbf{h}_{r,1}^H\mathbf{h}_{r,1}\right)+\sigma_1^2\right). \end{aligned} \tag{4.3.18}$$

Then the D-C programming can be applied to sequentially solve the following convex problem,

$$\begin{aligned} \mathbf{W}_{t,k+1} = & \arg\max_{\mathbf{W}_t} \quad f(\mathbf{W}_t) - g_L(\mathbf{W}_t;\mathbf{W}_{t,k}), \\ & s.t. \quad \sum_{i=1}^{2} P_i \text{trace}(\mathbf{W}_t)\left|\mathbf{w}_r^H\mathbf{h}_{i,r}\right|^2 + \\ & \qquad \sigma_r^2\text{trace}(\mathbf{W}_t) = P_{\max}. \end{aligned} \tag{4.3.19}$$

Then the problem (4.3.12) can be solved by choosing an initial point $\mathbf{W}_t$ and for $k = 0, 1, \cdots$, and solving (4.3.19) until a termination condition is met. Therefore the decomposition of $\mathbf{W}_t$ leads to the optimal solution $\hat{\mathbf{w}}_t$ for problem (4.3.11).

The overall algorithm to solve problem $\mathcal{P}_2$ is given in the sequence as follows: Initialize with any $\tau, \alpha \in (0,1)$ and a non-zero $\mathbf{w}_t$. Then alternatingly optimize τ by solving (4.3.8), search α by (4.3.9), and optimize $\mathbf{w}_t$ by solving (4.3.19). The worst-case complexity of these searches is $\mathcal{O}\left(\log\left(\frac{1}{\varepsilon_\tau}\right)\right)$, $\mathcal{O}\left(\frac{1}{\varepsilon_\alpha}\right)$ and $\mathcal{O}\left(N^{4.5}\log\left(\frac{1}{\varepsilon_{\mathbf{w}_t}}\right)\right)$, respectively, where ε_τ, ε_α and $\varepsilon_{\mathbf{w}_t}$ is the desired solution accuracy for each variable [27].

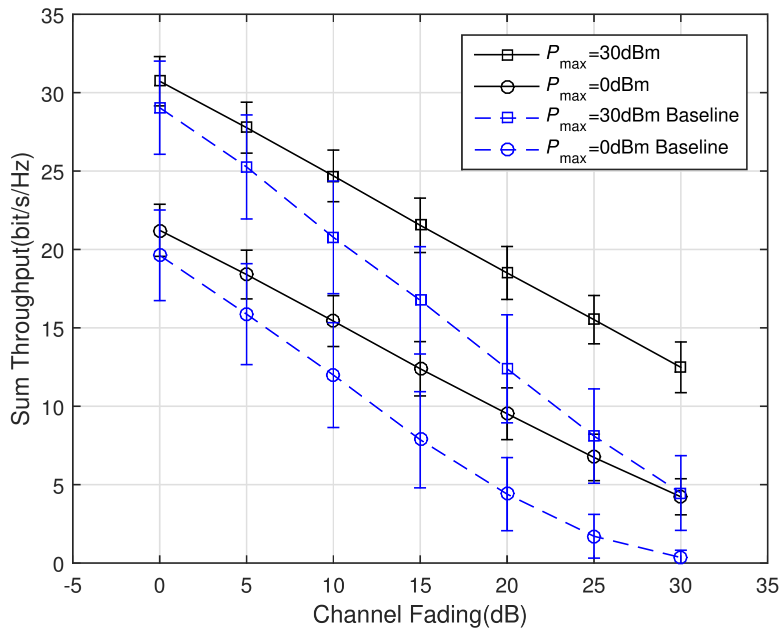


Figure 4.2: Maximum Sum Throughput vs. Channel Fading (dB).

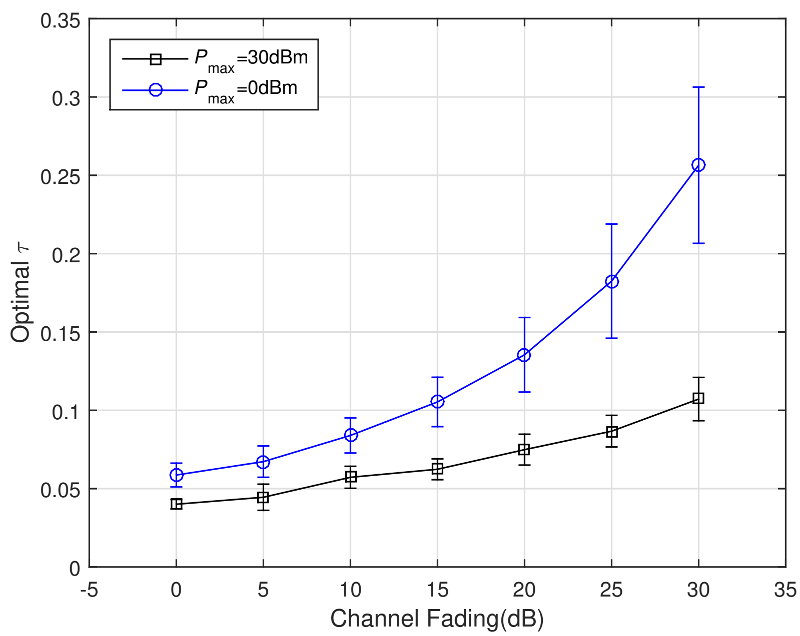


Figure 4.3: Optimal τ vs. Channel Fading (dB).

4.4 Numerical Results

In this section, we provide numerical results to evaluate the performance of the considered wireless-powered two-way relay system. For all simulation results, the noise power density is set to be −140dBm/Hz, and the average noise power at the relay and both sources is assumed as $\sigma_r = \sigma_1 = \sigma_2 = -70$dBm over a bandwidth of 10MHz. The energy conversion efficiency $\eta = 0.5$. The curves in each figure are obtained by averaging over 1000 random channel realizations.

In Fig. 4.2, we show the total throughput against the channel fading, i.e., $\mathbb{E}\left[|\mathbf{h}_{i,r}|^2\right]$ and $\mathbb{E}\left[|\mathbf{h}_{r,i}|^2\right]$, under a different power limit $P_{\max}$. The relay is equipped with two antennas. The distance-dependent signal attenuations between each antenna at the relay and both sources are set as $\mathbb{E}\left[|\mathbf{h}_{i,r}|^2\right] = \mathbb{E}\left[|\mathbf{h}_{r,i}|^2\right] = 0, -1, \ldots, -30$dB. Furthermore, we set the power limit at the relay $P_{\max} = 0$dBm and 30dBm. The blue dash lines are the performance of a benchmark scheme without optimization on $\mathbf{w}_1$, $\mathbf{w}_r$ and $\mathbf{W}_t$, i.e., broadcasting signals equally in all directions. It is observed that the proposed two-way relay system achieves a higher total throughput in the case of a higher power budget at the relay and lower channel fading due to a higher received SNR at both sources, and the optimization of beamforming vectors significantly improves the transmission capability.

In Fig. 4.3, we show the optimal time duration of the ET phase τ against the channel fading for a different power limit $P_{\max}$ with the same parameters used in Fig. 4.2. It is shown that the requirement of time duration of the ET phase τ decreases as the channel fading becomes less severe or the power budget increases since it takes less time to harvest the required energy at the sources when the power of the received signal is higher.

Chapter 5

Magnetic Induction based Wireless Powered Communication System with Active Relaying

The previous two chapters investigated RF based WET in WPCN. However, RF based WPCN presents a variety of challenges due to a high path loss. MI based WET has been proposed to overcome this issue. In this chapter, we study a WPCN scenario, in which a MI source transmits information to a MI destination, with the help of a MI based wireless powered relay. We propose four active relaying schemes, which consider different relaying modes and energy harvesting receiver architectures at the relay. We then aim to maximize the end-to-end throughput of each scheme by using a bisection search, a water-filling algorithm, a Lagrange multiplier, QC programming and an iterative algorithm. We compare the proposed active relaying schemes with passive relaying. Numerical results show that the proposed relaying schemes with a decode-and-forward relaying mode significantly improves the throughput over the passive relaying.

5.1 Introduction

Existing research on WET usually uses RF signals as an energy carrier to transfer energy from the source to destination [29]. However, the energy transfer efficiency in this technique is relative low due to the high path loss and vulnerability in some specific media (e.g., soil) [30]. Thus RF based WET can only support ultra-low power devices. To address this problem, MI based WET, which can efficiently deliver energy in a high power and over a long distance [31], has been proposed as a practical method to realize WET.

As an extension of existing research, we investigate MI based WET. Specifically, a MI source transmits information to a MI destination, with the help of a MI based wireless-powered relay. The relay can work either passively or actively. In this work, we aim to maximize the throughput of the proposed system. Note that the MI based transmission channels are fundamentally different from the conventional RF channel.

To tackle the new problems, we first derive the expression of throughput of five possible schemes that considering different relaying modes and receiver architectures. We then optimize each variable by solving close form functions, using a bisection search, a water-filling algorithms, a Lagrange multipliers, QC programming and an iterative algorithm.

5.2 System Model

In this work, we consider a wireless-powered relay network consists of a MI relay and two MI transceivers (i.e., source and destination), as shown in Fig. 5.1. In this system, the source transmits information to the destination with the help of the relay.

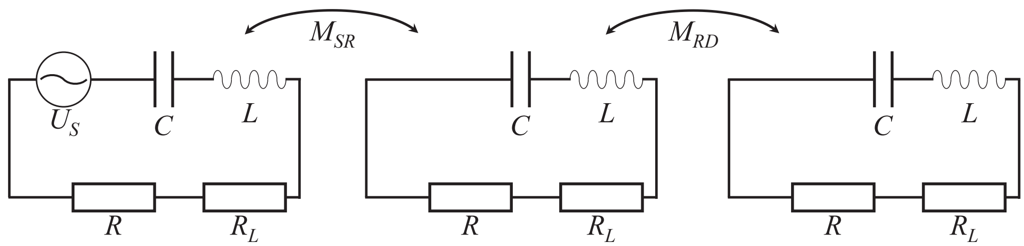


Figure 5.1: System Model.

The source has a power supply with a power limit $P_{\max}$. We assume that the relay has no embedded energy supply and thus has to harvest energy via magnetic WET, and then uses it to forward information to the destination. The resonance circuits of all three devices can be regarded as the series of a resistor with resistance R, a capacitor with capacitance C, an inductor with inductance L, and a load resistor R_L. It is assumed that the inductor and the capacitor are carefully chosen so that their impacts cancel each other at the resonant frequency f_0, i.e.,

$$j2\pi f_0 L + \frac{1}{j2\pi f_0 C} = 0. \tag{5.2.1}$$

The coupling between the source and the relay as well as the relay and the destination are determined by the mutual inductance M_{SR} and M_{RD}, respectively. According to [32], these mutual inductances can be given by

$$M_{SR} = \mu\pi N^2 \frac{a^4}{4r_{SR}^3} J_{SR} G_{SR}, \tag{5.2.2}$$

$$M_{RD} = \mu\pi N^2 \frac{a^4}{4r_{RD}^3} J_{RD} G_{RD}, \tag{5.2.3}$$

respectively, where μ is the magnetic permeability, N is the number of turns of the resonant coil, a is the radius of the coil, $r_{\{\}}$ is the distance between two coils, and $J_{\{\}}$ and $G_{\{\}}$ represent the polarization factor [33] and additional loss factor [32], which can be calculated as

$$J = 2\sin(\theta_t)\sin(\theta_r) + \cos(\theta_t)\cos(\theta_r)\cos(\phi), \tag{5.2.4}$$

$$G = \exp\left(-r2\pi f\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\frac{\sigma^2}{(2\pi f)^2\varepsilon^2}}-1\right)}\right), \tag{5.2.5}$$

respectively, where θ_t and θ_r are the angles between the coil radial directions and the line connecting the two coil centers, respectively, and ϕ is the angle between the two coil radial directions in the plane orthogonal to the line connecting the two coil centers. ε and σ stand for the permittivity and the conductivity of the media, respectively.

According to [30], the power gain among the channel between the source and the relay can be calculated as

$$|H_{SR}(f)|^2 = \left|\frac{Z_g(2\pi f M_{SR})^2 R_L}{\left(Z_g^2+(2\pi f)^2(M_{SR}^2+M_{RD}^2)\right)\left(Z_g^2+(2\pi f M_{RD})^2\right)}\right|, \tag{5.2.6}$$

where $Z_g = j2\pi fL + \frac{1}{j2\pi fC} + R + R_L$ denotes the impedance of the circuit. Similarly, the channel power gain from the source to the destination through passive relay, and from the relay to the destination can be given by

$$|H_{SDp}(f)|^2 = \left|\frac{(2\pi f)^4(M_{SR}M_{RD})^2 R_L}{Z_g\left(Z_g^2+(2\pi f)^2(M_{SR}^2+M_{RD}^2)\right)\left(Z_g^2+(2\pi f M_{RD})^2\right)}\right|, \tag{5.2.7}$$

$$|H_{RD}(f)|^2 = \left|\frac{(2\pi f)^2 M_{RD}^2 R_L}{Z_g\left(Z_g^2+(2\pi f)^2(M_{SR}^2+M_{RD}^2)\right)}\right|, \tag{5.2.8}$$

respectively. As pointed out in [30], there is an additional path loss from the received signal to the transmitted signal at the relay, which can be written as

$$|H_{RR}(f)|^2 = \left|\frac{Z_g}{Z_g^2+(2\pi f)^2(M_{SR}^2+M_{RD}^2)}\right| R_L. \tag{5.2.9}$$

Then the total channel power gain for non regenerative relaying schemes (e.g. AF relaying) can be given by

$$|H_{SDa}(f)|^2 = |H_{SR}(f)|^2 |H_{RR}(f)|^2 |H_{RD}(f)|^2. \tag{5.2.10}$$

The noise power spectral density at the relay and the destination are denoted as $P_{Rn}(f)$ and $P_{Dn}(f)$, respectively.

5.3 Relaying Schemes

There are many possible schemes to realize wireless powered relaying, which are considered different active relaying schemes (e.g., AF relaying, and DF relaying), different relaying modes (e.g., HD and FD) with different EH receiver architectures (e.g., TS and PS) [29]. In this paper, we investigate different active relaying schemes. Both AF and DF relaying modes are considered in this section. Both TS and PS receiver architectures are adopted. For convenience, the time duration of one transmission block is normalized (i.e., each transmission block has a time duration of 1).

5.3.1 Passive Relay

The basic relaying scheme for the proposed system is passive relaying, where the destination receives signals only from the passive relay channel. Then the throughput of passive relaying over the selected bandwidth can be calculated by

$$C_P = \int_B \log_2 \left(1 + \frac{P_{St}(f)\,|H_{SDp}(f)|^2}{P_{Dn}(f)}\right) \mathrm{d}f, \tag{5.3.1}$$

where B is the selected signal bandwidth, and $P_{St}(f)$ is the transmit power spectral density at the source.

5.3.2 Amplify and Forward Relay

The AF relaying mode is discussed in this subsection. AF relay is non-regenerative relay and the simplest active relay that is easy to be realized. We then analyze the properties of the AF relaying scheme.

Time-Switching

In the AF-TS relaying scheme, each transmission block is divided into three time slots. The first slot is used for the source to transmit energy to the relay. The energy received at the relay in the first time slot is given by

$$E_{AF,TS} = \int_B \tau\eta \left(P_{St1}(f)\,|H_{SR}(f)|^2 + P_{Rn}(f)\right) \mathrm{d}f, \tag{5.3.2}$$

where $\tau \in [0,1]$ is the time duration of the first time slot, $\eta \in [0,1]$ denotes the energy conversion efficiency, and $P_{St1}(f)$ is the transmit power spectral density at the source in the first time slot. Simultaneously, the destination can decode information from the signal transmitted by the source via a passive link. Then we derive the received signal to noise ratio (SNR) at the destination in the first time slot as

$$\mathrm{SNR}_{1,AF,TS}(f) = \frac{P_{St1}(f)\,|H_{SDp}(f)|^2}{P_{Dn}(f)}. \tag{5.3.3}$$

The rest time of a block is equally divided, thus the time duration of the second and third time slots is $\frac{1-\tau}{2}$. In the second time slot, the source transmits information to the relay and destination simultaneously, therefore the received SNR at the destination in the second time slot is given by

$$\mathrm{SNR}_{2,AF,TS}(f) = \frac{P_{St2}(f)\,|H_{SDp}(f)|^2}{P_{Dn}(f)}, \tag{5.3.4}$$

where $P_{St2}(f)$ is the transmit power spectral density at the source in the second time slot.

In the third time slot, the relay uses all its harvested energy to amplify and forward the received signal to the destination. The source transmits the same signal at the same time through passive relaying. A MISO beamforming [34] with two transmitters will be performed at the source and the relay. The optimum received SNR at the destination can be given by

$$\mathrm{SNR}_{3,AF,TS}\left(f\right) = \frac{P_{St2}\left(f\right)\left(\left|H_{SDp}\left(f\right)\right| + A\left|H_{SDa}\left(f\right)\right|\right)^2}{A^2{\left|H_{RR}\left(f\right)\right|}^2{\left|H_{RD}\left(f\right)\right|}^2 P_{Rn}\left(f\right) + P_{Dn}\left(f\right)}, \tag{5.3.5}$$

where A is related to the harvested energy at the relay and is expressed as

$$A = \sqrt{\frac{\frac{2E_{AF,PS}}{1-\tau}}{\int_B \left(P_{St2}\left(f\right)\left|H_{SR}\left(f\right)\right|^2 + P_{Rn}\left(f\right)\right)\left|H_{RR}\left(f\right)\right|^2 \mathrm{d}f}}. \tag{5.3.6}$$

Then the destination combines the signals received at the second and third time slots using maximal-ratio combining (MRC), and the overall throughput can be given by

$$C_{AF,TS} = \tau \int_B \log_2\left(1 + \mathrm{SNR}_{1,AF,TS}\left(f\right)\right)\mathrm{d}f + \frac{1-\tau}{2}\int_B \log_2\left(1 + \mathrm{SNR}_{2,AF,TS}\left(f\right) + \mathrm{SNR}_{3,AF,TS}\left(f\right)\right)\mathrm{d}f. \tag{5.3.7}$$

Power-Splitting

In this relaying scheme, each transmission block is divided equally into two slots. In the first time slot, the source sends a signal to the relay. Then the relay divides the received signal into two parts, $\rho \in [0,1]$ of the received signal is used to harvest energy. The harvested energy can be given by

$$E_{AF,PS} = \int_B \frac{1}{2}\eta\rho\left(P_{St}\left(f\right)\left|H_{SR}\left(f\right)\right|^2 + P_{Rn}\left(f\right)\right)\mathrm{d}f, \tag{5.3.8}$$

where $P_{St}\left(f\right)$ is the transmit power spectral density at the source in the first time slot. Simultaneously, the destination receives the signal via passive relaying, the received

SNR at the destination in the first time slot can be expressed as

$$\mathrm{SNR}_{1,AF,PS}(f) = \frac{P_{St}(f)\left|H_{SDp}(f)\right|^2}{P_{Dn}(f)}. \tag{5.3.9}$$

In the second time slot, the relay uses all harvested energy to amplify and forward the received signal to the destination. The source transmits the same signal at the same time through passive relaying. A MISO beamforming is performed at the source and the relay. The optimum received SNR at the destination can be given by

$$\begin{aligned}&\mathrm{SNR}_{2,AF,PS}(f) = \\ &\frac{P_{St}(f)\left(\left|H_{SDp}(f)\right| + A\left|H_{SDa}(f)\right|\right)^2}{A^2\left|H_{RR}(f)\right|^2\left|H_{RD}(f)\right|^2 P_{Rn}(f) + P_{Dn}(f)},\end{aligned} \tag{5.3.10}$$

where A is related to the harvested energy at the relay and can be given by

$$A = \sqrt{\frac{2E_{AF,PS}}{\int_B \left(P_{St}(f)\left|H_{SR}(f)\right|^2 + P_{Rn}(f)\right)\left|H_{RR}(f)\right|^2 \mathrm{d}f}}. \tag{5.3.11}$$

Then the destination combines two signals using MRC, and the overall throughput can be expressed as

$$C_{AF,PS} = \frac{1}{2}\int_B \log_2\left(1 + \mathrm{SNR}_{1,AF,PS}(f) + \mathrm{SNR}_{2,AF,PS}(f)\right)\mathrm{d}f. \tag{5.3.12}$$

5.3.3 Decode and Forward Relay

As pointed out in [35], DF relaying generally has a higher throughput than AF relaying. Here we analyze the properties of DF relaying with TS or PS receiver architecture.

Time-Switching

In the DF-TS relaying scheme, each transmission block is divided into three time slots with a time duration of $\tau_1, \tau_2, 1-\tau_1-\tau_2 \in [0,1]$, respectively. The first time slot is used for the source to transmit energy to the relay. The harvested energy at the relay in the first time slot can be derived as

$$E_{DF,TS} = \int_B \tau_1 \eta \left(P_{St1}(f) \left| H_{SR}(f) \right|^2 + P_{Rn}(f) \right) \mathrm{d}f. \tag{5.3.13}$$

Also the received SNR at the destination in the first time slot is given by

$$\mathrm{SNR}_{1,DF,TS}(f) = \frac{P_{St1}(f) \left| H_{SDp}(f) \right|^2}{P_{Dn}(f)}. \tag{5.3.14}$$

In the second time slot, the source transmits signal to the relay via active link as well as to the destination via a passive link. Then the received SNR at the relay and the destination in the second time slot is given by

$$\mathrm{SNR}_{2,DF,TS}(f) = \frac{P_{St2}(f) \left| H_{SR}(f) \right|^2}{P_{Rn}(f)}, \tag{5.3.15}$$

$$\mathrm{SNR}_{p2,DF,TS}(f) = \frac{P_{St2}(f) \left| H_{SDp}(f) \right|^2}{P_{Dn}(f)}, \tag{5.3.16}$$

respectively.

In the third time slot, the relay uses all the harvested energy to decode and forward the information to the destination, the source transmits the signal to the destination simultaneously. The received SNR at the destination via a passive link in the third time slot can be given by

$$\mathrm{SNR}_{p3,DF,TS}(f) = \frac{P_{St3}(f) \left| H_{SDp}(f) \right|^2}{P_{Dn}(f)}, \tag{5.3.17}$$

where $P_{St3}(f)$ is the transmit power spectral density at the source in the third time slot. According to [36], the optimum received SNR at the destination in the third time slot is given by

$$\begin{aligned} &\mathrm{SNR}_{3,DF,TS}(f) = \\ &\quad \frac{P_{Rt}(f) \left| H_{RD}(f) \right|^2 + P_{St3}(f) \left| H_{SDp}(f) \right|^2}{P_{Dn}(f)} + \\ &\quad \frac{2r \sqrt{P_{Rt}(f) P_{St3}(f)} \left| H_{RD}(f) \right| \left| H_{SDp}(f) \right|}{P_{Dn}(f)}, \end{aligned} \tag{5.3.18}$$

where $P_{Rt}(f)$ is the transmit power spectral density at the relay in the third time slot with $\int_B P_{Rt}(f)\,\mathrm{d}f = \frac{E_{DF,TS}}{1-\tau_1-\tau_2}$, and $r \in [0,1]$ is the correlation between the signals sent by the source and the relay.

Similar to [36], the overall channel capacity of this relaying scheme is given by

$$\begin{aligned}
&C_{DF,TS} = \tau_1 C\left(\mathrm{SNR}_{1,DF,TS}\right) + \min\{\\
&\tau_2 C\left(\mathrm{SNR}_{2,DF,TS}\right) + (1-\tau_1-\tau_2)\, C\left(\left(1-r^2\right)\mathrm{SNR}_{p3,DF,TS}\right),\\
&\tau_2 C\left(\mathrm{SNR}_{p2,DF,TS}\right) + (1-\tau_1-\tau_2)\, C\left(\mathrm{SNR}_{3,DF,TS}\right)\},
\end{aligned} \tag{5.3.19}$$

where $C(x) = \int_B \log_2(1+x)\,\mathrm{d}f$.

Power-Spliting

In the DF-PS relaying scheme, each transmission block is divided into two slots. The time duration of the first time slot is $\tau \in [0,1]$, in which the source sends a signal to the relay. The relay divides the received signal into two parts, $\rho \in [0,1]$ of the received signal is used to harvest energy. Then the harvested energy is given by

$$E_{DF,PS} = \int_B \tau\eta\rho\left(P_{St1}(f)\left|H_{SR}(f)\right|^2 + P_{Rn}(f)\right)\mathrm{d}f. \tag{5.3.20}$$

The received SNR at the relay can be expressed as

$$\mathrm{SNR}_{1,DF,PS}(f) = \frac{(1-\rho)\,P_{St1}(f)\left|H_{SR}(f)\right|^2}{P_{Rn}(f)}. \tag{5.3.21}$$

At the same time, the destination receives the signal through passive relaying, the received SNR at the destination in the first time slot is given by

$$\mathrm{SNR}_{p1,DF,PS}(f) = \frac{P_{St1}(f)\left|H_{SDp}(f)\right|^2}{P_{Dn}(f)}. \tag{5.3.22}$$

In the second time slot, the relay decodes and forwards the information using all its harvested energy. The source transmits the same signal at the same time via passive relaying. The received SNR at the destination via passive link can be given by

$$\mathrm{SNR}_{p2,DF,PS}(f) = \frac{P_{St2}(f)\left|H_{SDp}(f)\right|^2}{P_{Dn}(f)}. \tag{5.3.23}$$

According to [36], the optimum received SNR at the destination can be expressed as

$$\mathrm{SNR}_{2,DF,PS}(f) = \frac{P_{Rt}(f)\left|H_{RD}(f)\right|^2 + P_{St2}(f)\left|H_{SDp}(f)\right|^2}{P_{Dn}(f)} + \frac{2r\sqrt{P_{Rt}(f)\,P_{St2}(f)}\left|H_{RD}(f)\right|\left|H_{SDp}(f)\right|}{P_{Dn}(f)}, \tag{5.3.24}$$

where $P_{Rt}(f)$ is the transmit power spectral density at the relay in the second time slot with $\int_B P_{Rt}(f)\,\mathrm{d}f = \frac{E_{DF,PS}}{1-\tau}$.

Similar to [36], the overall channel capacity of this relaying scheme is given by

$$C_{DF,PS} = \min\{\tau C\left(\mathrm{SNR}_{1,DF,PS}\right) + (1-\tau)\,C\left(\left(1-r^2\right)\mathrm{SNR}_{p2,DF,PS}\right), \tau C\left(\mathrm{SNR}_{p1,DF,PS}\right) + (1-\tau)\,C\left(\mathrm{SNR}_{2,DF,PS}\right)\}. \tag{5.3.25}$$

5.4 Problem Formulation and Optimization

In this section, we aim to maximize the throughput subject to the fixed channel state, i.e., fixed M_{SR} and M_{RD}.

5.4.1 Passive Relay

In the passive relaying scheme, only $P_{St}(f)$ needs to be optimized. According to [30], the optimal $P_{St}(f)$ can be calculated by using a water filling approach, which can be given by

$$P_{St}(f) = \max\left\{\frac{1}{\lambda} - \frac{1}{K(f)}, 0\right\}, \tag{5.4.1}$$

where $K(f) = \frac{\left|H_{SDp}(f)\right|^2}{P_{Dn}(f)}$, which is independent of $P_{St}(f)$, and $\frac{1}{\lambda}$ stands for the water level.

5.4.2 Amplify and Forward Relay

Time-Switching

In the AF-TS relaying scheme, for each set of M_{SR} and M_{RD}, the throughput maximization problem is formulated as

$$\mathcal{P}_1 : \max_{\tau, P_{St1}(f), P_{St2}(f)} C_{AF,TS}, \tag{5.4.2}$$

$$s.t. \quad 0 \leq \tau \leq 1, \tag{5.4.3}$$

$$\int_B P_{St1}(f)\,\mathrm{d}f \leq P_{\max}, \tag{5.4.4}$$

$$\int_B P_{St2}(f)\,\mathrm{d}f \leq P_{\max}. \tag{5.4.5}$$

It is shown that $C_{AF,TS}$ is a convex function of $\frac{\tau}{1-\tau}$. Thus for fixed $P_{St1}(f)$ and $P_{St2}(f)$, the optimization of τ can be done efficiently by a bisection search corresponding to the maximum $C_{AF,TS}$.

In addition, we notice that, for given P_{St2} and τ, $C_{AF,TS}$ is a convex function of $P_{St1}(f)$. Therefore the optimization of $P_{St1}(f)$ can be solved using Lagrange multipliers. Specifically, we discretize the integration within a bandwidth to the sum of finite frequencies, i.e., $C(x) = \sum_B \log_2(1+x)$. We formulate the Lagrange function as

$$\begin{aligned}
&F = \tau \sum\nolimits_B \log_2\left(1 + \mathrm{SNR}_{1,AF,TS}(f)\right) + \\
&\frac{1-\tau}{2} \sum\nolimits_B \log_2\left(1 + \mathrm{SNR}_{2,AF,TS}(f) + \mathrm{SNR}_{3,AF,TS}(f)\right) + \\
&\lambda\left(\sum\nolimits_B P_{St1}(f) - P_{\max}\right),
\end{aligned} \tag{5.4.6}$$

and then solve the following equations

$$\frac{\partial F}{\partial P_{St1}(f)} = 0, f = f_1, f_2, \ldots, f_N, \tag{5.4.7}$$

$$\frac{\partial F}{\partial \lambda} = 0, \tag{5.4.8}$$

where N is the number of discretized frequencies.

Then for fixed τ and $P_{St1}(f)$, the transmit power spectral density $P_{St2}(f)$ can be optimized by applying a water filling algorithm. Specifically, we iteratively optimize $P_{St2}(f)$ by using a water filling algorithm as

$$P_{St2}(f) = \max\left\{\frac{1}{\lambda} - \frac{1}{K(f)}, 0\right\}, \tag{5.4.9}$$

where $K(f) = \frac{\mathrm{SNR}_{2,AF,TS} + \mathrm{SNR}_{3,AF,TS}(f)}{P_{St1}(f)}$, and calculate the value of A in each iteration based on (5.3.6).

Power-Splitting

In this relaying scheme, for each given set of M_{SR} and M_{RD}, the throughput maximization problem can be formulated as

$$\mathcal{P}_2 : \max_{\rho, P_{St}(f)} C_{AF,PS}, \tag{5.4.10}$$

$$s.t. \quad 0 \le \rho \le 1, \int_B P_{St}(f)\,\mathrm{d}f \le P_{\max}. \tag{5.4.11}$$

Notice that ρ is only involved in $\mathrm{SNR}_{2,AF,PS}$, in which both the numerator and the denominator are monotonically increasing functions of ρ in the interval of $[0, 1]$, we denote the numerator and the denominator of (5.3.10) as

$$\mathrm{SNR}_n = P_{St}(f)\left(H_{SDp}(f) + A\left|H_{SDa}(f)\right|\right)^2, \tag{5.4.12}$$

$$\mathrm{SNR}_d = A^2\left|H_{RR}(f)\right|^2\left|H_{RD}(f)\right|^2 P_{Rn}(f) + P_{Dn}(f), \tag{5.4.13}$$

respectively. Then the optimal ρ can be found by solving $\mathrm{SNR}_n(\rho)\frac{\partial \mathrm{SNR}_d(\rho)}{\partial \rho} = \mathrm{SNR}_d(\rho)\frac{\partial \mathrm{SNR}_n(\rho)}{\partial \rho}$.

For fixed ρ, the $P_{St}(f)$ can be optimized by iteratively applying a water filling algorithm similar to (5.4.9), and calculate the value of A in each iteration based on (5.3.11).

5.4.3 Decode and Forward Relay

Time-Switching

In the DF-TS scheme, for each given set of M_{SR} and M_{RD}, the optimization problem can be formulated as

$$\mathcal{P}_3: \max_{\substack{\tau_1, \tau_2, r, P_{Rt}(f) \\ P_{St1}(f), P_{St2}(f), P_{St3}(f)}} C_{DF,TS}, \tag{5.4.14}$$

$$s.t. \quad 0 \leq \tau_1, \tau_2, 1-\tau_1-\tau_2 \leq 1, \tag{5.4.15}$$

$$\int_B P_{St1}(f)\,\mathrm{d}f \leq P_{\max}, \int_B P_{St2}(f)\,\mathrm{d}f \leq P_{\max}, \tag{5.4.16}$$

$$\int_B P_{St3}(f)\,\mathrm{d}f \leq P_{\max}, \int_B P_{Rt}(f)\,\mathrm{d}f \leq \frac{E_{DF,TS}}{1-\tau_1-\tau_2}. \tag{5.4.17}$$

For convenience, we denote

$$C_{1,DF,TS} = \tau_2 C\left(\mathrm{SNR}_{2,DF,TS}\right) + \bar{\tau}_2 C\left(\left(1-r^2\right)\mathrm{SNR}_{p3,DF,TS}\right), \tag{5.4.18}$$

$$C_{2,DF,TS} = \tau_2 C\left(\mathrm{SNR}_{p2,DF,TS}\right) + \bar{\tau}_2 C\left(\mathrm{SNR}_{3,DF,TS}\right), \tag{5.4.19}$$

where $\bar{\tau}_2 = 1-\tau_1-\tau_2$. Then the equation (5.3.19) can be expressed as

$$C_{DF,TS} = \tau_1 C\left(\mathrm{SNR}_{1,DF,TS}\right) + \min\left\{C_{1,DF,TS}, C_{2,DF,TS}\right\}. \tag{5.4.20}$$

Here the transmit power spectral density of the source and the relay in the third time slot can be different, however there will be some correlation between the signal transmitted by the source and the relay, thus there should also be correlations between $P_{St3}(f)$ and $P_{Rt}(f)$. As a result, the optimization of P_{St3} and P_{Rt} depends on each other, which makes the problem extremely hard to solve. To simplify the problem, we assume the transmit power spectral density of the source has the same shape as that of the relay in the third time slot, i.e.,

$$P_{Rt}(f) = AP_{St3}(f), \tag{5.4.21}$$

where $A = \frac{E_{DF,TS}}{P_{\max}(1-\tau_1-\tau_2)}$ is a factor corresponding to the harvested energy at the relay. Note that this assumption always reduces the throughput of the original problem, therefore the optimized throughput will be the lower bound of the maximal throughput. Under the assumption (5.4.21), the equation (5.3.18) can be rewritten as

$$\begin{aligned}&\mathrm{SNR}_{3,DF,PS}(f) = \\ &\quad \frac{P_{St3}(f)\left(A|H_{RD}(f)|^2 + |H_{SDp}(f)|^2\right)}{P_{Dn}(f)} + \\ &\quad \frac{P_{St3}(f)\, 2r\sqrt{A}\,|H_{RD}(f)|\,|H_{SDp}(f)|}{P_{Dn}(f)}.\end{aligned} \tag{5.4.22}$$

Then problem $\mathcal{P}_3$ can be converted to

$$\mathcal{P}_4: \max_{\substack{\tau_1,\tau_2,r,P_{St1}(f)\\ P_{St2}(f),P_{St3}(f)}} C_{DF,TS}, \tag{5.4.23}$$

$$s.t. \quad (5.4.22), 0 \le \tau_1, \tau_2, \bar{\tau}_2 \le 1, \tag{5.4.24}$$

$$\int_B P_{St1}(f)\,\mathrm{d}f \le P_{\max}, \tag{5.4.25}$$

$$\int_B P_{St2}(f)\,\mathrm{d}f \le P_{\max}, \tag{5.4.26}$$

$$\int_B P_{St3}(f)\,\mathrm{d}f \le P_{\max}. \tag{5.4.27}$$

It is shown that $C_{1,DF,TS}$ is a linear function of τ_2, whereas $C_{2,DF,TS}$ is a convex function of τ_2. Similarly, $C_{DF,TS}$ is a convex function of τ_1. Then when all the other parameters are fixed, the optimal τ_1 and τ_2 corresponding to the maximum $C_{DF,TS}$ can be found by a bisection search.

It is also observed that $C_{1,DF,TS}$ is monotonically decreasing as r increases, whereas

$C_{2,DF,TS}$ is a monotonically decreasing function of r. Therefore when all the other parameters are fixed, the optimal r can be found by solving $C_{1,DF,TS} = C_{2,DF,TS}$, which can be solved efficiently using bisection search.

The variable $P_{St1}(f)$ is only involved in $\frac{P_{St1}(f)\left|H_{SDp}(f)\right|^2}{P_{Dn}(f)}$ and thus can be optimized individually by using water filling algorithm as (5.4.9).

For fixed τ_1, τ_2, r, $P_{St1}(f)$ and $P_{St2}(f)$, the terms $\tau_1 C\left(\mathrm{SNR}_{1,DF,TS}\right)$, $\tau_2 C\left(\mathrm{SNR}_{2,DF,TS}\right)$ and $\tau_2 C\left(\mathrm{SNR}_{p2,DF,TS}\right)$ become constants. To obtain the optimal $P_{St3}(f)$, we discretize the integration within a bandwidth to the sum of finite frequencies, i.e., $C(x) = \sum_B \log_2(1+x)$. Then problem $\mathcal{P}_4$ can be converted to

$$\begin{aligned}
\mathcal{P}_5 : & \max_{P_{St3}(f_1,f_2,\ldots,f_N)} \min \\
& \left\{\sum_{f=f_1}^{f_N} \left(\log_2\left(2^{\Delta_1}\left(1+\left(1-r^2\right)\mathrm{SNR}_{p3,DF,TS}\right)\right)\right),\right. \\
& \left.\sum_{f=f_1}^{f_N} \left(\log_2\left(2^{\Delta_2}\left(1+\mathrm{SNR}_{3,DF,TS}\right)\right)\right)\right\}, && (5.4.28) \\
s.t. & \sum_{f=f_1}^{f_N} P_{St3}(f) \le P_{\max}, && (5.4.29)
\end{aligned}$$

where $\Delta_1 = \frac{\tau_2}{\bar{\tau}_2 N}\int_B \log_2\left(1+\mathrm{SNR}_{2,DF,TS}\right)\mathrm{d}f$, and $\Delta_2 = \frac{\tau_2}{\bar{\tau}_2 N}\int_B \log_2\left(1+\mathrm{SNR}_{p2,DF,TS}\right)\mathrm{d}f$. N is the amount of discretized frequencies. Therefore problem $\mathcal{P}_5$ has the same form as the max-min problem (5) in [37], and can be solved accordingly using QC programming.

The optimization of $P_{St2}(f)$ is the same as that of $P_{St3}(f)$.

Power-Splitting

For each set of M_{SR} and M_{RD}, the optimization problem can be formulated as

$$\mathcal{P}_6: \max_{\tau,\rho,r,P_{St1}(f),P_{St2},(f),P_{Rt}(f)} C_{DF,PS}, \tag{5.4.30}$$

$$s.t. \quad 0 \leq \tau, \rho, r \leq 1, \tag{5.4.31}$$

$$\int_B P_{St1}(f)\,\mathrm{d}f \leq P_{\max}, \tag{5.4.32}$$

$$\int_B P_{St2}(f)\,\mathrm{d}f \leq P_{\max}, \tag{5.4.33}$$

$$\int_B P_{Rt}(f)\,\mathrm{d}f \leq \frac{E_{DF,PS}}{1-\tau}. \tag{5.4.34}$$

For convenience, we denote

$$C_{1,DF,PS} = \tau C\left(\mathrm{SNR}_{1,DF,PS}\right) + (1-\tau)\, C\left(\left(1-r^2\right)\mathrm{SNR}_{p2,DF,PS}\right), \tag{5.4.35}$$

$$C_{2,DF,PS} = \tau C\left(\mathrm{SNR}_{p1,DF,PS}\right) + (1-\tau)\, C\left(\mathrm{SNR}_{2,DF,PS}\right). \tag{5.4.36}$$

Then the equation (5.3.25) can be expressed as

$$C_{DF,PS} = \min\left\{C_{1,DF,PS}, C_{2,DF,PS}\right\}. \tag{5.4.37}$$

Here the transmit power spectral density of the source and the relay in the second time slot can be different, however there will be some correlation between the signal transmitted by the source and the relay, thus the $P_{St2}(f)$ and $P_{Rt}(f)$ can not be regarded as individual variables. As a result, the optimization of P_{St2} and P_{Rt} depends on each other, which makes the problem extremely hard to solve. To simplify the problem, we assume the transmit power spectral density of the source has the same shape as that of the relay in the second time slot, i.e.,

$$P_{Rt}(f) = A P_{St2}(f), \tag{5.4.38}$$

where $A = \frac{E_{DF,PS}}{P_{\max}(1-\tau)}$ is a factor corresponding to the harvested energy at the relay. Note that this assumption always reduces the throughput of the original problem, therefore the optimized throughput will be the lower bound of the maximal throughput. Under the assumption (5.4.38), the equation (5.3.24) can be rewritten as

$$\begin{aligned}\mathrm{SNR}_{2,DF,PS}(f) = \\ &\frac{P_{St2}(f)\left(A|H_{RD}(f)|^2 + |H_{SDp}(f)|^2\right)}{P_{Dn}(f)} + \\ &\frac{P_{St2}(f)\,2r\sqrt{A}\,|H_{RD}(f)|\,|H_{SDp}(f)|}{P_{Dn}(f)}.\end{aligned} \tag{5.4.39}$$

Then problem $\mathcal{P}_6$ can be converted to

$$\mathcal{P}_7 : \max_{\tau,\rho,r,P_{St1}(f),P_{St2}(f)} C_{DF,PS}, \tag{5.4.40}$$

$$s.t. \quad (5.4.39), 0 \leq \tau, \rho, r \leq 1, \tag{5.4.41}$$

$$\int_B P_{St1}(f)\,\mathrm{d}f \leq P_{\max}, \tag{5.4.42}$$

$$\int_B P_{St2}(f)\,\mathrm{d}f \leq P_{\max}. \tag{5.4.43}$$

To solve this problem, we alternatingly optimize each variable.

It is observed that $C_{1,DF,PS}$ is monotonically decreasing as r increases, whereas $C_{2,DF,PS}$ is a monotonically decreasing function of r. Therefore for fixed τ, ρ, $P_{St1}(f)$ and $P_{St2}(f)$, the optimal r can be found by solving $C_{1,DF,PS} = C_{2,DF,PS}$, which can be solved efficiently using a bisection search.

Similarly, the optimal ρ can be found by solving $C_{1,DF,PS} = C_{2,DF,PS}$ using a bisection search while all other parameters are fixed.

Then for fixed ρ, r, $P_{St1}(f)$ and $P_{St2}(f)$, $C_{1,DF,PS}$ is a linear function of τ, whereas $C_{2,DF,PS}$ is a convex function of τ, thus the optimal τ corresponding to the maximum $C_{DF,PS}$ can also be found by a bisection search.

For fixed τ, ρ, r and $P_{St1}(f)$, the terms $\tau C(\mathrm{SNR}_{1,DF,PS})$ and $\tau C(\mathrm{SNR}_{p1,DF,PS})$

become constants. To obtain the optimal $P_{St2}(f)$, we discretize the integration within a bandwidth to the sum of finite frequencies, i.e., $C(x) = \sum_B \log_2(1+x)$. Then problem $\mathcal{P}_7$ can be converted to

$$\begin{aligned}
\mathcal{P}_8 : & \max_{P_{St2}(f_1, f_2, \ldots, f_N)} \min \\
& \Big\{ \sum_{f=f_1}^{f_N} \left(\log_2 \left(2^{\Delta_1} \left(1 + \left(1 - r^2\right) \mathrm{SNR}_{p2,DF,PS} \right) \right) \right), \\
& \sum_{f=f_1}^{f_N} \left(\log_2 \left(2^{\Delta_2} \left(1 + \mathrm{SNR}_{2,DF,PS} \right) \right) \right) \Big\}, \qquad (5.4.44) \\
s.t. & \sum_{f=f_1}^{f_N} P_{St2}(f) \le P_{\max}, \qquad (5.4.45)
\end{aligned}$$

where $\Delta_1 = \frac{\tau}{(1-\tau)N} \int_B \log_2\left(1 + \mathrm{SNR}_{1,DF,PS}\right) \mathrm{d}f$, and $\Delta_2 = \frac{\tau}{(1-\tau)N} \int_B \log_2\left(1 + \mathrm{SNR}_{p1,DF,PS}\right) \mathrm{d}f$. N is the number of discretized frequencies. Therefore problem $\mathcal{P}_8$ has the same form as the max-min problem (5) in [37], and can be solved accordingly using QC programming.

For fixed τ, ρ, r and $P_{St2}(f)$, we express equations (5.4.35) and (5.4.36) as

$$\begin{aligned}
C_{1,DF,PS} &= \int_B \tau \log_2\left(1 + \mathrm{SNR}_{1,DF,PS}\right) + \\
&\quad (1-\tau) \log_2\left(1 + \left(1 - r^2\right) \mathrm{SNR}_{p2,DF,PS}\right) \mathrm{d}f \\
&= \int_B \nabla_1(f) \, \mathrm{d}f, \qquad (5.4.46) \\
C_{2,DF,PS} &= \int_B \tau \log_2\left(1 + \mathrm{SNR}_{p1,DF,PS}\right) + \\
&\quad (1-\tau) \log_2\left(1 + \mathrm{SNR}_{2,DF,PS}\right) \mathrm{d}f \\
&= \int_B \nabla_2(f) \, \mathrm{d}f. \qquad (5.4.47)
\end{aligned}$$

It is shown that both $\nabla_1(f)$ and $\nabla_2(f)$ are convex function of $P_{St1}(f)$. Meanwhile $\frac{\partial \nabla_1(f)}{\partial P_{St1}(f)} > 0$ and $\frac{\partial \nabla_2(f)}{\partial P_{St1}(f)} > 0$, therefore $C_{DF,PS}$ is also a convex and monotonically increasing function of $P_{St1}(f)$ for any f within the selected bandwidth, then the optimization of $P_{St1}(f)$ can be done by using the following iterative algorithm. We initialize $P_{St1}(f)$ with a uniform distribution, i.e., $P_{St1}(f) = \frac{P_{\max}}{B}$. Then we calculate the gradient of $C_{DF,PS}$ for all $P_{St1}(f)$ within the selected bandwidth, i.e.,

$$G(f) = \frac{\partial C_{1,DF,PS}}{\partial P_{St1}(f)}, C_{1,DF,PS} \leq C_{2,DF,PS}, \\ \frac{\partial C_{2,DF,PS}}{\partial P_{St1}(f)}, C_{1,DF,PS} > C_{2,DF,PS}. \quad (5.4.48)$$

Then we update the $P_{St1}(f)$ according to the gradients till the desired solution accuracy is achieved, i.e.,

$$\hat{P}_{St1}(f) = P_{St1}(f) + \delta\left(G(f) - \frac{1}{B}\int_{B} G(f)\,\mathrm{d}f\right), \quad (5.4.49)$$

where δ is the step factor, which is carefully selected to balance between the convergence speed and accuracy. Then after each iteration, we adjust $\hat{P}_{St1}(f)$ using

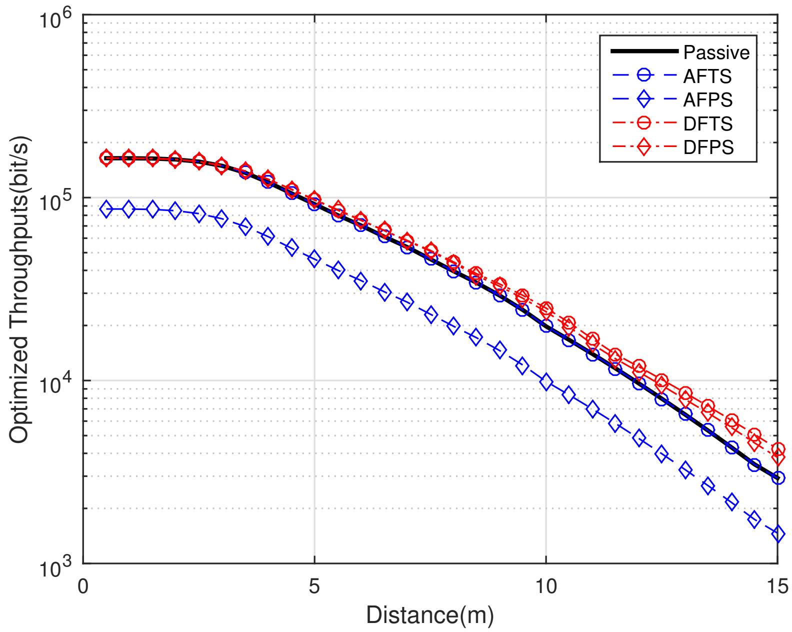
$$\hat{P}_{St1}(f) = \max\left\{\hat{P}_{St1}(f), 0\right\}, \quad (5.4.50)$$

and then normalize the sum power of $\hat{P}_{St1}$ to $P_{\max}$.

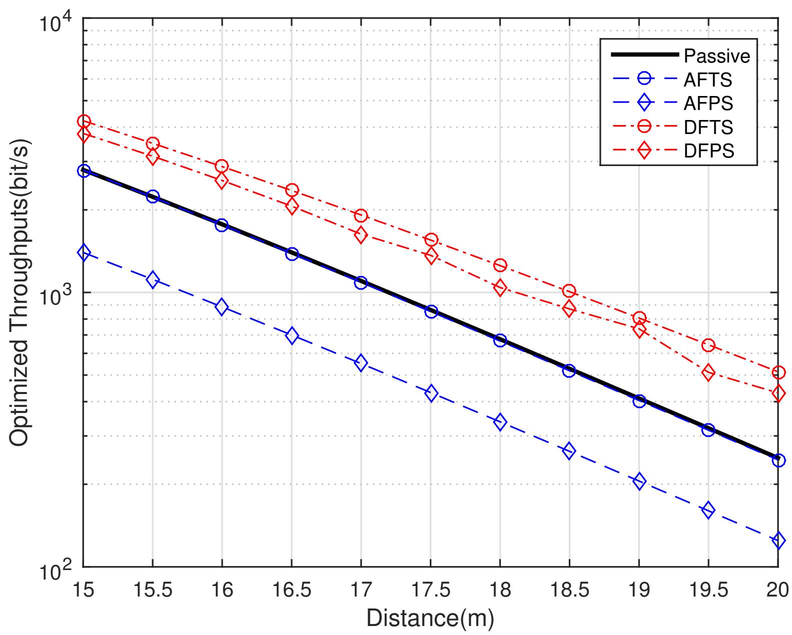
5.5 Numerical Results

In this section, we provide numerical results to demonstrate the performance of the proposed schemes. For all simulation results, we let $\mu = 4\pi \times 10^{-7} H/m$, $\varepsilon = 8.854 \times 10^{-12} F/m$, $\sigma = 8 \times 10^{-15} S/m$. We assume that $R = 10\Omega$ whereas $R_L = 10k\Omega$. Then we set $N = 1000$, $a = 0.25m$. The power limit at the source is set as $P_{\max} = 0.01W$. The noise power spectral density is set as $P_{Rn}(f) = P_{Dn}(f) = 10^{-12} W/Hz$ for all frequencies within the selected bandwidth, where the center frequency is set as $f_0 = 1MHz$ and the bandwidth is $10kHz$. The energy conversion efficiency $\eta = 0.5$.

Fig. 5.2 illustrates the optimized throughput against the distance between the source and destination. In each sample point, the position of the relay is selected to achieve the maximum throughput under the corresponding relaying scheme.



(a)



(b)

Figure 5.2: Optimized Throughput vs. Distance.

In Fig. 5.2(a), we can find that for all relaying schemes, the throughput decreases as the distance increases due to a lower mutual inductance between coils, however the throughputs tend to remain constant when the transmit distance is short. It is also observed that the AF-PS scheme always performs worse than the passive relaying scheme. The reason is that in the AF-PS scheme the transmit block is divided equally into two parts, and the source has to transmit the same signal twice in these two time slots, which increases the redundancy but reduces the throughput. The performance of the AF-TS scheme is slightly better but almost same as the passive relaying scheme. This is because the AF relaying scheme can not significantly improve the throughput when the additional path loss $|H_{RR}(f)|^2$ exists, therefore the optimal τ is close to 1, and the AF-TS scheme almost degrades into a passive relaying scheme. Besides this, we can find that the performances of the DF-TS and DF-PS relaying schemes outperform the passive relaying scheme. The DF-TS scheme is even better when the distance between the source and destination is long.

Fig. 5.2(b) shows more details for the case of long distance. It is observed that the optimized throughput for the DF-TS and DF-PS relaying schemes are approximately twice (3dB) that of passive relaying.

Chapter 6

Conclusions and Future Work

In this thesis, we proposed new protocols for wireless-powered communications, analyzed network performance. The key results and findings are summarized in this chapter. The suggestions for future work are then presented.

6.1 Summary of Results and Insights

In Chapter 3, we proposed five elementary protocols to practically realize WPC between an access point and a wireless-powered user with a two-way information flow. These protocols correspond to the different working modes of two nodes and different receiver architectures at the user. We first defined and then analyzed the throughput region to evaluate the performance of each protocol. Numerical results showed that the power splitting receiver normally performs better than the TS receiver and the FD protocols with energy recycling achieve the highest uplink throughput when SI is well suppressed. Moreover, the performance of the FD protocols highly depends on the SI suppression. Specifically, all the FD protocols outperform the HD protocols when the SI can be fully cancelled or sufficiently suppressed. However, only the performance of the FD-TS protocol is slightly better than that of the HD protocols when the SI suppression is not good enough.

Then, in Chapter 4, we studied a wireless powered two-way relay system consisting of a multi-antenna relay and two sources, where the sources have no embedded energy supply. We proposed an algorithm to maximize the total throughput under the constraint of peak transmit power at the relay. We solved the non-convex optimizations of time duration of each time phase, the beamforming vector for energy transfer and the precoding matrix at the relay by alternatingly using a bisection search, 1-D search and D-C programming.

Next, in Chapter 5, we studied a WPCN scenario, in which a MI source transmits information to a MI destination, with the help of a MI based wireless-powered relay. We proposed four active relaying schemes, which considered different relaying modes and different energy harvesting receiver architectures at the relay. We formulated problems in order to maximize the end-to-end throughput of each scheme. We solved the formulated problems by alternatingly using a bisection search, a water-filling algorithm, a Lagrange multiplier, QC programming and an iterative algorithm. Numerical results showed that the proposed relaying schemes with decode and forward relaying modes significantly improve the throughput over passive relaying.

6.2 Future Work

In Chapter 4 and Chapter 5, we solved non-convex problems by alternatingly optimizing each variable. However, this could lead to a local optimal result instead of a global one. An interesting topic for future work would be the global optimization of these problems.

In Chapter 5, we investigated a MI based wireless-powered relaying network, in which a MI based source transferred information to a MI based destination, with the help of a wireless-powered MI based relay. It will be interesting to investigate a similar system, in which neither the source nor the relay has energy supply, and thus has to harvest energy from the signal broadcast by the destination. This model can be used in wide variety of scenarios, e.g., one or more wireless-powered sensors sending messages to a sink node.

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