MULTI-INPUT MULTI-OUTPUT TWO-WAY RELAYING WITH ADAPTIVE OVERHEARING

BY

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Dedication

To my parents, wife, daughter, brothers, and sisters for their endless support and love.

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THESIS ABSTRACT

NAME: Said O. Alshrafi

TITLE OF STUDY: Multi-Input Multi-Output Two-Way Relaying With Adaptive Overhearing

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Two-way relaying (TWR) is a spectrally efficient protocol, providing a solution to overcome the half-duplex loss in one-way relay channels. Moreover, incorporating the multiple-input multiple-output (MIMO) technology can further improve the spectral efficiency and diversity gain. In addition, the designed protocols can turn overheard interference into useful side information to allow simultaneous transmission of multiple communication flows and increase the spectral efficiency in interference-limited regime.

The aim of this thesis study some extended schemes that would increase the sum-rate of the overhearing scheme by increasing the number of antenna, and exploit the overhearing link. In the first extension of the overhearing scheme, we consider an overhearing scheme for a two-way amplify-and-forward relaying

system consisting of a multi-antenna base station (BS), a multi-antenna relay station (RS), and two user equipment (UEs) with single antenna each, where one is an uplink user while the other is a downlink user. The downlink user receives the signal from the BS, overhears the signal from the uplink user, and exploits the overheard signal to improve the detection of the desired signal. Due to the two-way transmission, the precoding matrix at the RS in the second time slot and the transmit weights at the uplink user over the two-time slots are jointly optimized via an iterative algorithm in the sense of maximizing the minimum signal-to-interference-plus-noise-ratio (SINR). Simulation results show that the increase in number of antennas at the BS provides significant sum-rate gain. In the second extension of the overhearing scheme, the overhearing scheme extended to the scenario with multiple antennas at all terminals, the BS, the RS, and the UEs. The relay precoder in the second time slot and the transmit weight matrices at the uplink user over the two-time slots are again jointly optimized via an iterative algorithm in the sense of maximizing the minimum SINR. The obtained results reveal the significant sum-rate increase due to the use of multiple antennas at the UEs.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Wireless communications is more than a century old field of research and industry, which remains one of the most successful and fast growing fields at present. Being one of the fundamental needs of a human, social interaction through communication stimulates continuous development for connecting people all over the world. Recent progress in technology enables production of tiny devices able to realize very complex signal processing tasks consuming limited power that allows implementation of more and more sophisticated communication technologies.

In recent years, we have witnessed a great success of cellular mobile telephony, which has become an important part of people everyday life in all developed and developing countries. As a consequence, the demand for new audio, video and data services has significantly increased over the past decade and continues growing from year to year. In this perspective, new techniques and tools for fast, efficient and reliable communication over wireless channels are needed.

Cooperative communication, on the other hand, has shown the benefits of allowing reliable communications with an increase of radio coverage. The idea behind cooperative communications is that the direct communication between the source and the destination can be supported by a relay link. With cooperative relaying, the end-to-end transmission in the time domain is divided into two phases, namely, broadcasting and relaying phases. In the broadcasting phase, the source sends data to both relay and destination. In the relaying phase, the relay processes the received data and then forwards it to the destination. The signals received at the destination are combined into one signal to recover the source data. Practical relaying protocols and coding designs have been extensively studied in order to achieve cooperative diversity [1]. Early works on cooperative communications and information theoretic aspects of the relay channel can be traced back to the 1970s [2, 3].

Two-way relaying (TWR) promises improved spectral efficiency compared to one-way relaying. However, TWR efficiently works with symmetric traffic between two terminals. In case one of the terminal is a base station (BS), the suitable traffic scenario for TWR is symmetric uplink-downlink traffic between the BS and an user equipment (UE). The scenarios with asymmetric uplink-downlink traffic actually occur often in a cellular network, for example, a certain UE is downloading videos while another UE is uploading another highly loaded content. For such an asymmetric-traffic scenario, in [4], the authors proposed a single-input single-output (SISO) overhearing scheme for the scenario with one BS, one relay station (RS), one UE with an uplink message, and one UE with a downlink message.

In the first phase, the BS and one of UE (uplink user) transmit their signals. The RS receives, amplifies, precodes and broadcasts a signal in the second phase. The BS cancels its self-interference signal in the received signal and decodes its desired signal. The other UE (downlink user) overhears the signal from the uplink user in the first phase, and uses the overheard signal to cancel the interference in the received signal in the second phase. The advantage of overheard information is to reduce the time slots used and improve the minimum rate of the two users. The aim of this thesis is to extend and analyze the overhearing scheme to multiple antennas. In this thesis, the precoding matrix at the RS and the overhearing weights at the uplink user are jointly optimized to maximize the minimum weighted signal-to-interference-plus-noise-ratio (SINR). The minimum mean square error (MMSE) and MMSE-successive interference cancellation (SIC) are considered at the downlink user. Furthermore, simulation results show that the extended scheme provides significant sum-rate gain compared to the scenario with single-antenna.

1.2 Thesis motivation

In this section, we discuss the main motivation that led to this thesis work and how they are important to the area of research in the relay networks.

Since multiple-input multiple-output (MIMO) systems are able to support high-data rates by combating fading and interference and allowing spatial multiplexing, it is reasonable to exploit the advantages of MIMO systems by accommodating multiple antennas at the RS. The protocol of amplify-and-forward at the RS leads to the low complexity and short delay because digital signal processing is not necessary at the RS during data transmission.

TWR networks have attracted great research interest for its ability of facilitating the data exchange of two terminals. The TWR concept has also been extended to support multi-pair terminals and multi-way transmission. The interested design of the transmission protocol which introduces interference in a way that the receiver can overhear the interference and exploit it as side information to improve the overall spectral efficiency of the network. However, the overhearing scheme consists of one UE overhears the signal from the other UE to improve the detection of the desired signal. To illustrate how to efficiently use the overhearing link, in this thesis, we focus on a scenario with two cell-edge UEs having asymmetric channel, where one UE is uplink user, while the other UE is downlink user, and no direct link between the BS and the UEs.

The common aim of the research in this thesis is to study the capacity of the overhearing scheme with single-antenna and multiple antennas at the users. In addition, joint optimization of the relay precoder and the transmit weight at the uplink user is performed to increase the sum-rate for the scheme. Finally, the sum-rate is increased when increasing the number of antennas in relay networks.

1.3 Thesis contributions

The main contributions of this thesis work are briefly discussed in this section.

- The analysis of the overhearing relay scheme with multiple antennas at both the BS and the RS while the UEs with single-antenna. The downlink user exploits the overheard signal from the uplink user to improve the detection of the desired signal. The MMSE and MMSE-SIC detectors are considered at the downlink user. The relay precoder and the transmit weights at the uplink user are jointly optimized via an iterative algorithm in the sense of maximizing the minimum SINRs. semidefinite relaxation (SDR) technique is applied to the non-convex optimization problems, then we can find the approximate solutions for the optimization problems. CVX MATLB tools is used to find the approximation solution for each optimization problem. Simulation results show that the increase in number of antennas at the BS provides significant sum-rate gain, also, results illustrate the comparison between the optimization of the relay precoder only and the joint optimization of the relay precoder and the transmit weights at the uplink user.

- The overhearing scheme is extended to multiple antennas at the UEs. The downlink user exploits the overhearing signals from the uplink user to improve the detection performance. The MMSE and MMSE-SICs receivers are considered at the downlink user, while the cases of detection is upgraded to more than two cases due to having the multiple streams. Joint optimization of the precoding matrix at the RS and overhearing weight matrices at the uplink user are performed via an iterative algorithm to maximize the minimum SINR. To find the approximate solution of the non-convex problems, we can apply SDR to the optimization problems. The sum-rate performance can be significantly improved compared to the scheme with the case of the multiple antennas at both the BS and the RS and single-antenna at the UEs.

1.4 Thesis outline

The purpose of this thesis is to study the capacity of the overhearing scheme by increasing the number of antennas. This thesis is presented as the following: **Chapter Two** presents the background of relay networks, multiuser MIMO relaying model, wireless channels modeling, capacity of MIMO channels, linear signal detection, precoding techniques in relay networks, and optimization problems. The chapter also presents a literature review related to the cooperative communication, and overhearing schemes. **Chapter Three** presents the first extended overhearing scheme in this thesis. The chapter provides an analysis of the extended scheme, an iterative algorithm to jointly optimize the relay precoding and the overhearing weights at the uplink user, and simulation results for the sum-rate of the extended scheme. **Chapter Four** presents the second scenario for the overhearing scheme with multiple antennas at the users, joint optimization of the relay precoding and the overhearing weight matrices at the uplink user are performed via an iterative algorithm, and simulation results for the MIMO overhearing scheme. Finally, **Chapter Five** concludes the thesis work by highlighting the main contributions of the thesis, and proposing future work on the overhearing scheme.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Background

In this section, the background of topics related to the thesis work is presented.

2.1.1 Relay networks

The classical relay channel model, shown in Fig. 2.1, was first proposed in the information theory literature in the late 1960's and early 70's [5, 2, 3]. However, due to practical constraints little work was carried out on relays [6, 7, 8]. Advances in wireless communications technology have now rekindled interest in relays. Relaying exploits spatial diversity by employing antennas distributed over multiple terminals. Hence, each terminal can have less number of antennas and less number of radio frequency (RF) chains. These terminals combined act as a distributed MIMO system [9]. It has also been shown that relaying can enhance the coverage and capacity of wireless networks [10, 11].

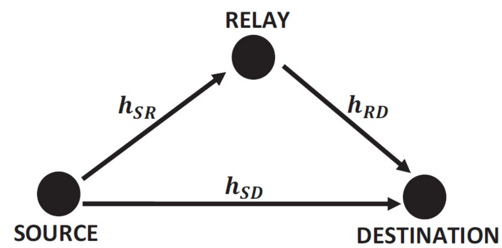

Figure 2.1: A three terminal relay channel with a single source-destination pair aided by a relay.

In particular, relaying can evidently enhance the transmission capacity for users at the edge of a cell. In addition to the other benefits, cooperative relaying reduces energy consumption [12, 13]. Thus, introducing relays can lead to significant improvements in wireless networks.

There are two main strategies of relay deployment: access-point relaying and cooperative relaying. In access-point relaying, fixed relays are deployed as access points which aid users in communicating with source(s) such as base station [14]. In cooperative relaying, users themselves act as relays for different users [6]. Hence, forming a cooperative network and exploiting what is termed as cooperative diversity. The cooperative relaying is mostly limited to literature and still needs more work to make it feasible. On the other hand, fixed access-point relaying is already being incorporated into telecommunications standards. For instance, in Long Term Evolution (LTE)-Advanced systems, fixed access-point relays with only an in-band wireless connection to the back-haul network are to be deployed

[15, 16, 17].

Following on from deployment strategies, there are two main relaying protocols: half-duplex relaying and full-duplex relaying. In full-duplex relaying [18], the relay can transmit and receive at the same time and at the same frequency band. In half-duplex relaying [21], the relay can only either transmit or receive at the same time and at the same frequency band. Thus, transmission in half-duplex relaying is divided into two phases. In the first phase, the source transmits to the relay and in the second phase the relay forwards the received signal to the destination. Half-duplex relaying is currently preferred over full-duplex relaying due to the latter's problem of self-interference which can significantly degrade performance and may render full-duplex relaying infeasible. This limitation of full-duplex relaying stems from the capability of the current radio technology and is expected to improve in future. Hence, throughout this work, half-duplex operation is assumed.

There are two main data processing protocols for relays [8]:

1. **Amplify-and-forward (AF):** These relays first amplify the signal received from the source and then forward it to the destination. The advantage of AF relays is that they are simple to implement. However, the drawback of these relays is that they cannot detect errors in the received signal. Due to their low cost and ease of implementation, they are currently used in signal repeaters [11].

   The received signal at the destination y_D:

$$y_D = g\sqrt{p_R} h_{DR} y_{RS} + n_R, \tag{2.1}$$

where g is the amplification factor, p_R is the average transmit power at the relay, h_{DR} is the channel gain between the relay and the destination, y_{RS} is the received signal at the relay, and n_R is the AWGN noise at the destination.

2. **Decode-and-forward (DF):** These relays first decode the received signal. Then they re-encode the signal; after which it is forwarded to the destination. As the relay decodes the signal, it can detect errors present in the signal. However, this comes at the cost of added complexity which can be difficult to incorporate in relays which usually need to be simple and inexpensive. Moreover, if there is decoding error, it will propagate.

   The received signal at the destination:

$$y_D = \sqrt{p_R} h_{DR} \hat{x} + n_R, \tag{2.2}$$

   where $\hat{x}$ is the decoded signal at the relay.

There are two other types of relay depend on data processing protocols:

1. **Compress-and-Forward relays (CF):** map the received signal into another signal in a reduced signal space, then encode and transmit the compressed signal as a new codeword by taking the signal received at the destination as side information [19].

2. **Compute-and-forward relays:** decode linear functions of received messages according to their observed channel coefficients rather than ignoring

the interference as noise, then forward to the destination [20].

There are three types of relays depending on adaptive strategies and feedback used [21, 22, 23]:

1. **Fixed relaying:** in cooperative link, there is a fixed relay to help terminals in the connection, and the fixed relay is in AF or DF mode. The additional delays in the process of relaying are disadvantage for fixed relaying.

2. **Selection relaying:** this mode makes opportunities for the sender terminals to select a way to transmit signals either cooperative link or direct link depend on a threshold determined by using the channel-state information (CSI). The disadvantage is network will be highly dynamic and unstable, so this mode is less reliable than the first mode (fixed relaying).

3. **Incremental relaying:** that exploits the limited feedback from the receiver or relay to improve the spectral efficiency of both the first mode (fixed relaying) and the second mode (selection relaying).

2.1.2 Resource allocation

Resource allocation is prospected to be an integral part of the next generation wireless systems to achieve high data rate and quality of service (QoS) demands. The importance of resource allocation stems from the fact that resources available to a wireless communication system are limited. These resources include bandwidth, time, and power. It is essential to utilize these resources as efficiently as possible. The spectrum (bandwidth) is of particular importance as it is shared across multiple service providers and is the main bottleneck impeding the performance of wireless networks [24].Thus, it is desirable to exploit any sources of gain available in the system and to allocate these resources to maximize this exploitation.

Channel allocation is the process of allocating a particular wireless channel at a specific time and at a specific frequency to a specific node for transmission or reception. This is particularly important in multi-user systems in which multiple users compete for system resources. Hence, multi-user scheduling [25], i.e, allocating the system resources either partially or fully to a user for a fixed time and frequency, has to be carried out.

Power allocation, which is well known to enhance system performance [26], merging communication systems, such as LTE, are aided by adaptive transmission schemes (i.e, modulation and coding) and dynamic resource allocation and multi-user scheduling methods [27].

CSI is information which represents the state of a communication link from the transmit to the receiver. This information describes the propagation of signal, and the combined effect of, for example, scattering, fading, and power decay with distance. There are two cases in cooperative networks [28]:

1. **Full CSI:** CSI is available to all terminals (source, relays, and destination), the transmitted power in every terminal can be optimally allocated, that improves the efficiency of the transmission with time-varying channels.

2. **Partial CSI:** when the environment is highly dynamic, then it's difficult to use full CSI, because every terminal will track the change, then change the transmitted power. The power allocation depends on partial CSI, CSI won't be known at all terminals.

The performance analysis was studied for two-node relay system in [29], there was only cooperative link with AF mode and fixed gain relay, authors derived generic closed-form equation for the outage probability and the average probability of error, and explore the effect of the relay saturation on the performance under some consideration. In [30], the performance of two terminals relay system with AF relay over flat Rayleigh fading channels was modeled, authors derived and applied some new closed-form expressions for the statistics of the harmonic mean of two independent exponential random variables (RVs), the average Bit Error Rate (BER) expression for binary differential Phase Shift Keying (PSK) was presented in [30], and there were comparison between regenerative and non-regenerative systems.

Closed-form expressions for the statistics of the harmonic mean of two independent and identically distributed ($i.i.d$) gamma variates, and the probability density function (PDF) was derived in [31], then the performance analysis for outage probability expressions, and general expressions for average BER was tested depend on the results while it was using AF relay over flat Nakagami fading channels.

The capacity of AF multiple terminals relaying networks based on different adaptive transmission schemes over Nakagami fading channels was considered in [32], authors derived approximation expressions for the capacity, and approximation for the probability of outage. In [33], authors compared between direct link and cooperative link, the result was a lower transmit power and a higher outage capacity for the cooperative link.

In [34], authors studied the ergodic capacity in Rayleigh fading for multiple relays with AF or DF relay, and perfect CSI at the receiver. they used Jensen's inequality and the harmonic-geometric means inequality to determine two upper bounds and derive the ergodic capacity for both AF and DF relaying mode. The upper and lower bounds for outage, ergodic capacity and power allocation were studied in [35] over Rayleigh-fading channels.

2.1.3 Multiuser MIMO R]relaying model

The presence of multiple users in relaying schemes has raised a great interest due to the good results obtained in both performance and capacity. The main drawback of this kind of schemes is that the transceiver design becomes more difficult because they have to share resources such as transmission power or bandwidth.

Multiuser MIMO (MU-MIMO) multi-hop networks can be classified as either downlink or uplink. Fig. 2.2 shows the uplink system where k users with M_U antennas send data through a fixed relay equipped with M_R antennas, which after the performing of the appropriate relaying strategy forwards the signal to the BS equipped with M_B receive antennas.

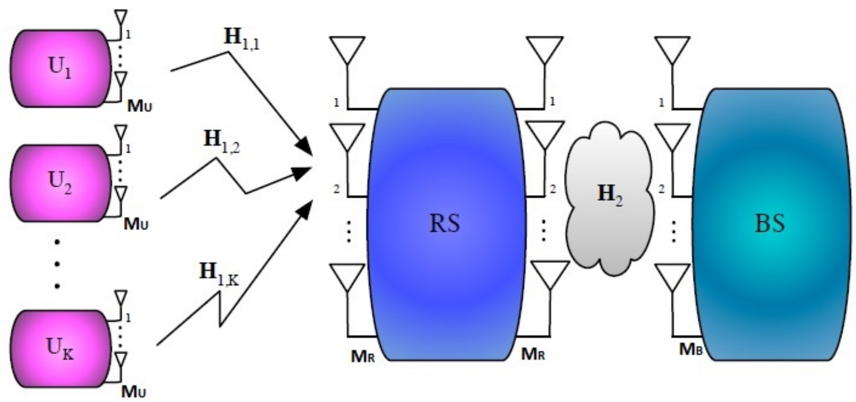

Figure 2.2: MIMO-MAC relaying system diagram with k users with M_U antennas each, a relay equipped with M_R antennas and an M_B-antennas BS.

In the same way, Fig. 2.3 shows the downlink or broadcast channel where an M_B-antenna BS sends information to k multi-antenna users across a relay station equipped with M_R antennas. For both transmission schemes, the communication

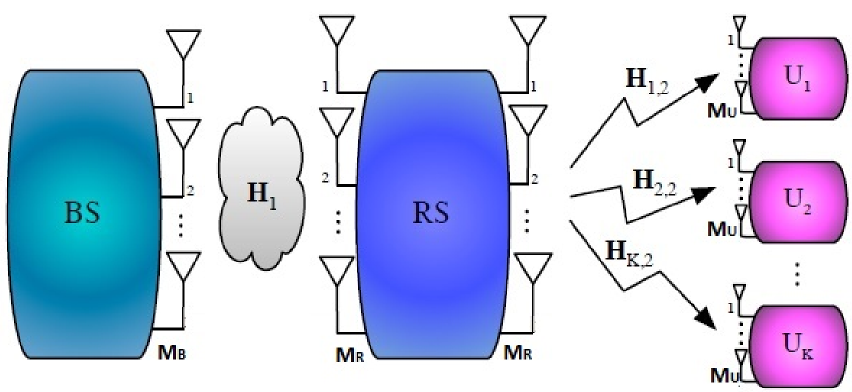

Figure 2.3: MIMO-BC relaying system diagram with k users, each one with M_U antennas, a relay equipped with M_R antennas and an M_B-antenna BS.

is assumed half-duplex. In [36], the uplink MU-MIMO relaying scheme is analyzed for a multihop system where the terminals are multi-antenna ones. Following the MMSE criterion, the optimal relaying matrix is derived at each relay. As happens with single-user relaying systems, the research focuses on the design of the precoding matrices at the BS and the RS. An example of this is described in [37], where the filters are designed for the mean square error (MSE) minimization from the BS to the end users.

In [38] and [39], a theoretical analysis is presented to obtain the optimal precoding matrices that maximize the sum-rate. While [38] evaluates both uplink and downlink channels, [39] pays attention to the broadcast channel (BC) scenario in order to get upper and lower bounds of the achievable sum-rate assuming zero forcing-dirty paper coding (ZF-DPC). In order to overcome DPC's complexity, Tomlinson-Harashima precoding (THP) is proposed at the BS with adaptive modulation.

For MU-MIMO relaying systems, the capacity computation is more complex because multiple access channel (MAC) and BC concepts are combined. The uplink multiuser relaying capacity is analyzed in [40], where outer bounds for a discrete memoryless multiple access relay channels are obtained for CF and AF strategies. The sum-rate for the downlink channel is studied in [41] for single-antenna users and a multi-antenna fixed relay. The proposed algorithms compute the achievable sum-rate based on dirty paper coding (DPC), for which a lower bound is derived.

2.1.4 Wireless channels modeling

The communication channel provides the connection between the transmitter and the receiver. It may represent different physical media, from aqueous molecular medium to optical fiber. In this thesis we focus on RF, which have several distinguishing properties:

- **Pathloss:** when propagating, the radio waves that carry the signal are scattered in all directions. Therefore, only a limited portion of the radiated power reaches the receiver.

- **Shadowing:** this effect is created by large objects in the surrounding (e.g., buildings, tunnels, hills) leading to worsening of the channel conditions even when the transmitter and the receiver are close to each other.

- **Multipath fading:** when the signal from the transmitter to the receiver propagates, radio waves experience reflection, scattering, and diffraction from various objects on their way. Therefore, they arrive at the receiver via multiple paths with different delay and phase rotation in each path, thereby interfering each other. This causes small-scale fluctuations of the received signal power.

These channel effects are summarized as signal fading. This phenomenon is often modeled as block fading; that is, the channel gain is assumed to be constant during a block of several consecutive discrete time instants ($t \in \{0, ..., T_{coh}\}$), and the channel gains of different blocks are assumed to be *i.i.d.* The length of such block, T_{coh}, is called the coherence time of the channel.

In wireless communication literature, the effect of fading is broadly divided into the following two phenomena, depending on the interrelation between the symbol duration and the coherence interval of the channel.

- **Slow fading:** the variations of the channel gain are random, but slow in comparison to the symbol rate, i.e, coherence time of the channel is larger than several symbol durations. This situation is often modeled by the quasi static scenario, where the channel gains are random but are assumed to be constant over the transmission duration.

- **Fast fading:** channel variations are fast, so that a codeword length spans a large number of coherence intervals. As this number increases, the fading process becomes ergodic; that is, averaging over time becomes equivalent to averaging over an ensemble of fading realizations. Hence, the randomness of the channel may be averaged out over time allowing for constant long-term transmission rates.

SISO channels

A SISO channel is between a pair of transceiver, and each one has a single-antenna for the transmitter and the receiver [42].

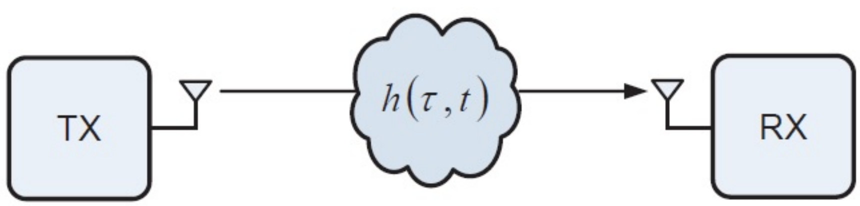

Figure 2.4: A SISO wireless channel.

The SISO channel is described by the impulse response as:

$$h(\tau,t) = \sum_{n=0}^{N} \alpha_n(t) e^{-j\phi_n(t)} \delta(\tau - \tau_n(t)), \tag{2.3}$$

$h(\tau, t)$ is the channel response at time t to an impulse at time $t - \tau$, N is multi-path component, α_n is attenuation, and τ_n is delay. ϕ_n is phase shift due to delay and Doppler spread.

For time-invariant channels, the expression in (2.3) reduced to

$$h(\tau) = \sum_{n=0}^{N} \alpha_n e^{-j\phi_n} \delta(\tau - \tau_n) \tag{2.4}$$

In general, the received signal is modeled as follows [43]:

$$y = hx + n_{SISO}, \tag{2.5}$$

where x, h, and n_{SISO} refer to the data signal mapped onto symbols by using a modulation scheme, channel gain, and additive white Gaussian noise (AWGN), respectively.

MIMO channels

A MIMO channel is the wireless channel between a multiple-antenna transmitter-receiver pair. For MIMO wireless system, the system has M_T transmit antennas,

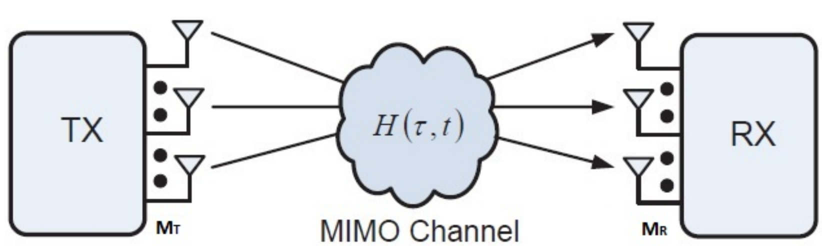

Figure 2.5: A MIMO wireless channel.

and M_R receive antennas, the invariant channel response is matrix $H \in \mathbb{C}^{M_R \times M_T}$ of complex channel gains. The output of the MIMO channel is modeled as:

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n}, \tag{2.6}$$

where $\mathbf{y} \in \mathbb{C}^{M_R \times 1}$, $\boldsymbol{H} \in \mathbb{C}^{M_R \times M_T}$, and $\mathbf{n} \in \mathbb{C}^{M_R \times 1}$ represent the received signal, channel matrix, and AWGN, respectively.

2.1.5 Capacity of MIMO channels

The enormous interests in MIMO systems are mainly inspired by the significant information-theoretical results reported in pioneering works by [44] and [45], independently, where the authors have proved that the capacity of MIMO system scales linearly with the minimum number of the transmit or receive antennas.

For the system described in (2.6), the mutual information expression was derived in [44, 45] as

$$I = \log_2 det\left(I + \frac{1}{\sigma^2}\boldsymbol{H}\boldsymbol{Q}_x\boldsymbol{H}^H\right), \tag{2.7}$$

therefore, the channel capacity is given by

$$C = \max_{Tr\left\{\boldsymbol{Q}_x\right\} \leq p_T} I, \tag{2.8}$$

where the optimization is taken on the signal covariance matrix $\boldsymbol{Q}_x = E[\boldsymbol{x}\boldsymbol{x}^H]$ with p_T being the total transmit power.

Capacity of multiuser MIMO multiple access channel

The system model in Fig. 2.6 consists of the BS with M_B antennas, and k users and each user is equipped with M_U antennas. The received signals at the BS is given by

$$\boldsymbol{y}_B = \sum_{i=1}^{k} \boldsymbol{H}_{Bi}\boldsymbol{x}_i + \boldsymbol{n}, \tag{2.9}$$

where $\boldsymbol{H}_{Bi} \in \mathbb{C}^{M_B \times M_U}$ is channel matrix from the i^{th} user to the BS.

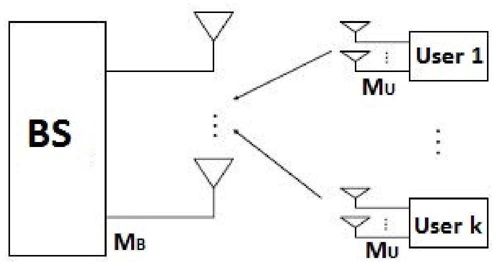

Figure 2.6: The MAC channel model.

Joint decoding is that decoding of all signals is performed simultaneously and cooperatively. While independent decoding is that different signals are decoded independently and in parallel and the signal from other users are treated as noise. Let $\boldsymbol{Q}_{x,i} = E[\boldsymbol{x}_i\boldsymbol{x}_i^H]$ be the covariance matrix of the signal for user i, and p_T is the power constraint applied to the i^{th} user. The capacity region for joint decoding is given by

$$\sum_{i=1}^{k} \boldsymbol{R}_i \leq \log_2 det \left[\boldsymbol{I} + \sum_{i=1}^{k} \boldsymbol{H}_{Bi}\boldsymbol{Q}_{x,i}\boldsymbol{H}_{Bi}^H \right]. \tag{2.10}$$

In the case of independent decoding, let $\boldsymbol{Q}_{y,i} = E[\boldsymbol{y}\boldsymbol{y}^H]$ be the covariance matrix of received signal for user i, the achievable rate is given by

$$\boldsymbol{R}_i \leq \log_2 \left(\frac{det\left(\boldsymbol{Q}_{y,i}\right)}{det\left(\boldsymbol{Q}_{y,i} - \boldsymbol{Q}_{x,i}\right)} \right) \text{for } i = 1, \ldots, k, \tag{2.11}$$

since the signals from other users are considered as noise for user i. Fig.2.7 shows the capacity region of the MAC system for two users. The maximum sum-rate capacity achieved through independent decoding will be less than that via the joint decoding.

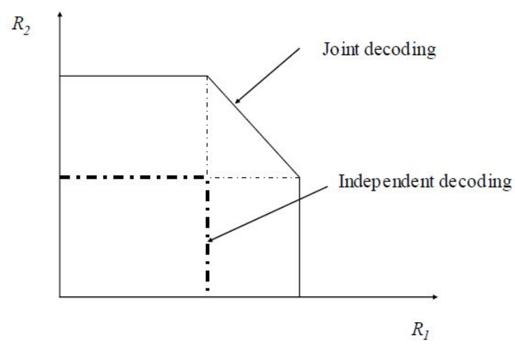

Figure 2.7: The capacity region of a MAC channel for two users.

Capacity of multiuser MIMO broadcast channel

In Fig.2.8, the BS with M_B antennas transmits a column vector signal to k users and each user has M_U antennas. The received signal for the i^{th} user is expressed as

$$\boldsymbol{y}_i = \boldsymbol{H}_{iB}\boldsymbol{x} + \boldsymbol{n}_i, \tag{2.12}$$

where $\boldsymbol{H}_{iB} \in \mathbb{C}^{M_U \times M_B}$ is channel matrix from the BS to the i^{th} user.

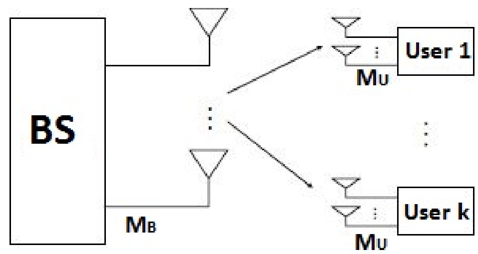

Figure 2.8: The BC channel model.

In MU-MIMO BC channel, the idea of DPC can be applied at the transmitter when choosing codewords for different users in transmission [46]. The capacity region is achievable via DPC scheme in transmission:

$$(\boldsymbol{R}_1, \ldots, \boldsymbol{R}_k) : \boldsymbol{R}_i \leq \log_2 \left(\frac{det\left(\boldsymbol{I} + \sum_{i=j}^{k} \boldsymbol{H}_{jB} \boldsymbol{Q}_i \boldsymbol{H}_{jB}^{H}\right)}{det\left(\boldsymbol{I} + \sum_{i=j+1}^{k} \boldsymbol{H}_{jB} \boldsymbol{Q}_i \boldsymbol{H}_{jB}^{H}\right)} \right) \text{for} j = 1, \ldots, k, \tag{2.13}$$

where $\boldsymbol{Q}_i = E[\boldsymbol{x}_i \boldsymbol{x}_i^H]$ denotes the input covariance matrix for user i. $\boldsymbol{Q} = [\boldsymbol{Q}_1, \ldots, \boldsymbol{Q}_k]$ is a set of positive semidefinite covariance matrices satisfying constraint $\sum_{i=1}^{k} Tr\left\{\boldsymbol{Q}_i\right\} \leq p$. It is difficult to compute the MIMO BC capacity because the rate expression in (2.13) is neither a concave nor a convex of the covariance matrices [47, 48].

2.1.6 Linear detection scheme

A linear detector first separates the data streams with a linear filter and then decodes each stream independently. The computational complexity of linear MIMO detection is small in comparison to other detection schemes. However, the BER performance is significantly worse compared to maximum likelihood (ML) detection. Examples of linear detectors are Zero Forcing (ZF) and MMSE filters apply an inverse of the channel to the received signal in order to restore the transmitted signal [49]. These linear filters can be implemented at a low complexity.

ZF detector

The ZF detector inverts the effect of the channel matrix $\boldsymbol{H}$ where the received signal at the destination is $\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{n}$. The corresponding channel filter matrix $\boldsymbol{W}_{ZF}$ is given by

$$\boldsymbol{W}_{ZF} = \left(\boldsymbol{H}^H \boldsymbol{H}\right)^{-1} \boldsymbol{H}^H. \tag{2.14}$$

Thus, the estimate of $\hat{\boldsymbol{x}}$ is expressed as

$$\hat{\boldsymbol{x}}_{ZF} = \boldsymbol{W}_{\boldsymbol{ZF}}\boldsymbol{y} = \boldsymbol{x} + \left(\boldsymbol{H}^H \boldsymbol{H}\right)^{-1} \boldsymbol{H}^H \boldsymbol{n} = \boldsymbol{x} + \hat{\boldsymbol{n}}_{ZF}, \tag{2.15}$$

The ZF detection removes the interference and it is the ideal detector when the channel is noiseless. However, in a real system, the noise is enhanced and correlated by $\boldsymbol{W}_{ZF}$, which is the main reason for the poor BER performance of ZF detection at lower SNR. This phenomenon is known as noise-enhancement [50].

MMSE detector

The MMSE detector considers the noise power in the interference cancellation and therefore shows a slightly better performance. It reduces the effect of noise-enhancement by minimizing the total error, including the noise term. It finds out the estimate $\hat{\boldsymbol{x}}_{MMSE}$ of the transmitted symbol vector $\boldsymbol{x}$ as

$$\begin{aligned}\hat{\boldsymbol{x}}_{MMSE} &= \boldsymbol{W}_{\boldsymbol{MMSE}}\,\boldsymbol{y} = \left(\boldsymbol{H}^H\boldsymbol{H} + \sigma_n^2\boldsymbol{I}\right)^{-1}\boldsymbol{H}^H\boldsymbol{y} \\ &= \hat{\boldsymbol{x}} + \left(\boldsymbol{H}^H\boldsymbol{H} + \sigma_n^2\boldsymbol{I}\right)^{-1}\boldsymbol{H}^H n = \hat{\boldsymbol{x}} + \hat{\boldsymbol{n}}_{MMSE},\end{aligned} \tag{2.16}$$

where $\boldsymbol{W}_{MMSE} = \left(\boldsymbol{H}^H\boldsymbol{H} + \sigma_n^2\boldsymbol{I}\right)^{-1}\boldsymbol{H}^H$ is the channel filter matrix.

The MMSE detector suffers less from the noise-enhancement and therefore achieves a better BER performance in comparison to ZF detection.

Successive interference cancellation detectors

The SIC technique was initially adopted by the Vertical-Bell Laboratories Layered Space-Time (V-BLAST) system [51]. In contrast to the basic ZF and MMSE detectors, SIC detects the transmitted streams sequentially. It chooses the sub-stream with largest SNR and removes the interference of each detected stream before continuing the detection process. The performance of the SIC algorithm is generally better than ZF and MMSE filters.

However, the streams are processed sequentially, one after another. This allows slicing the estimate $\hat{y}_i$ to $\hat{x}_i$ immediately after its computation and using the result to cancel out its influence on the subsequent streams.

ML detectors

Under the assumption that all transmit symbol vectors are equally likely, ML decoding is the optimum MIMO detection scheme in terms of minimizing the symbol error rate (SER) [50]. The Euclidean distance between the product of all possible transmitted signal vectors and the received signal vector is calculated by ML detector with the channel matrix $\boldsymbol{H}$, then finding the minimum distance. The ML detection determines the estimate of the transmitted signal vector $\boldsymbol{x}$ as

$$\hat{\boldsymbol{x}}_{ML} = \arg\min \|\boldsymbol{x} - \boldsymbol{H}\boldsymbol{y}\|^2 , \tag{2.17}$$

where $\|\boldsymbol{x} - \boldsymbol{H}\boldsymbol{y}\|^2$ is the ML metric.

2.1.7 Precoding techniques in relay networks

With the aim of reducing the receiver complexity and due to the lack of cooperation between users, the signal processing complexity is transferred to the BS by means of a processing stage called precoding. If the BS knows the channel, the interference can be suppressed before transmission. Combining the precoding phase and the linear precoding at the relay, each user will receive an optimized interference-free signal.

Linear precoding

Linear precoding multiplies the user signal by a matrix which targets a trade-off between interference nulling and noise reduction. Mainly, linear precoders can be classified as either ZF or MMSE based precoders.

ZF cancels the interference among the users completely by inverting the channel matrix, it achieves a good performance at high SNR environments or when the number of users is large enough [52]. The main drawback of ZF is the power increment of the precoded symbols, mainly for ill-conditioned channels [52], which requires the use of a large power-reduction factor, impacting directly in the detection SNR.

If a limited interference or crosstalk between different user streams is admitted, more efficient solutions can be achieved. The optimal regularization factor is derived in [53] following an MMSE or *Wiener* problem formulation. This solution finds a trade-off between noise enhancement and interference by means of a regularized inverse of the channel.

Non-Linear precoding

Non-linear precoding techniques improve the performance of linear processing [54]. The main drawback of these schemes is that the implementation is more complex due to the algorithms.

As it can be seen in [52], DPC derives the capacity of the interfering channels when the interference is known at the transmitter. The main problem of DPC is that the increased complexity makes the implementation impossible. In order to reduce the computational cost, Tomlinson-Harashima precoding (THP) and vector precoding (VP), both non-linear techniques are generally used, which tend to reach DPC's performance at lower computational cost.

2.1.8 Kronecker product

Let $A \in \mathbb{R}^{(m\times n)}$ and $B \in \mathbb{R}^{(p\times q)}$ then the Kronecker product denoted by $\otimes$ is given by

$$A \otimes B = \begin{bmatrix} a_{11}B & \dots & a_{1n}B \\ \vdots & \ddots & \vdots \\ a_{m1}B & \dots & a_{mn}B \end{bmatrix}_{(mp)\times(nq)} . \tag{2.18}$$

2.1.9 Optimization problems

The standard form of a convex optimization problem can be expressed as

$$\begin{aligned} \max_{\boldsymbol{x}} \quad & f_o(x) \\ \text{s.t.} \quad & f_i(x) \leq 0, \quad i = 1, \dots, m, \\ & h_i(x) = 0, \quad i = 1, \dots, p, \end{aligned} \tag{2.19}$$

where the optimization variable of the problem is x, the functions $f_o, \dots, f_m$ and $h_1, \dots, h_p$ are convex functions and linear functions, respectively. The objective function is f_o, also, $f_i(x) \leq 0, i = 1, \ldots, m$, and $h_i(x) = 0, i = 1, \ldots, p$ are the inequality constraints and the equality constraints, respectively. The domain of the optimization problem (2.19) is the set of points for which the objective and the constraints are defined and is denoted as

$$D = \cap_{i=0}^{m} \text{domain}(f_i) \bigcap \cap_{i=0}^{p} \text{domain}(h_i). \tag{2.20}$$

If $x \in D$ satisfies all the constraints, then it is a feasible point. If there is a feasible point, then the problem is feasible problem, and infeasible otherwise. The solution of the optimization problem or the optimal value is achieved at the optimal point x^* if and only if

$$f_o(x^*) \leq f_o(x), \forall x \in D. \tag{2.21}$$

Quadratic programming

The optimization problem can be quadratic programming (QP) if the objective function of the problem is quadratic and and the constraint are affine. A QP can be formulated as

$$\begin{aligned} \min_{\boldsymbol{x}} \quad & \boldsymbol{x}^T \boldsymbol{P} \boldsymbol{x} + \boldsymbol{q}^T \boldsymbol{x} + r \\ \text{s.t.} \quad & \boldsymbol{G}\boldsymbol{x} \leq \boldsymbol{h} \\ & \boldsymbol{A}\boldsymbol{x} = b, \end{aligned} \tag{2.22}$$

where $\boldsymbol{P} \in \mathbb{S}_+^n$, $\boldsymbol{G} \in \mathbb{R}^{m \times n}$, and $\boldsymbol{A} \in \mathbb{R}^{p \times n}$.

Quadratically constrained quadratic programming

The optimization problem is called a quadratically constrained quadratic programming (QCQP), when both the objective and the constraints are quadratic. A QCQP can be expressed as

$$\begin{aligned} \min_{\boldsymbol{x}} \quad & \boldsymbol{x}^T \boldsymbol{P_o} \boldsymbol{x} + \boldsymbol{q_o}^T \boldsymbol{x} + r_o \\ \text{s.t.} \quad & \boldsymbol{x}^T \boldsymbol{P_i} \boldsymbol{x} + \boldsymbol{q_i}^T \boldsymbol{x} + r_i \leq 0 \quad i = 1, \ldots, m \\ & \boldsymbol{A}\boldsymbol{x} = b, \end{aligned} \tag{2.23}$$

where $\boldsymbol{P}_i \in \mathbb{S}^n_+, i = 1, \ldots, m.$ a QCQP, a quadratic convex function is minimized over a feasible region that is the intersection of ellipsoids. In QCQP, by setting $\boldsymbol{P}_i = 0, i = 1, \ldots, m$ in the constraints of (2.23), an linear programing (LP) can be obtained.

2.1.10 Semidefinite programming (SDP)

SDR [55] is a powerful for non-convex optimization problems, particularly non-convex QCQPs in the form as,

$$\begin{aligned} \min_{\boldsymbol{x}} \quad & \boldsymbol{x}^H \boldsymbol{C} \boldsymbol{x} \\ \text{s.t.} \quad & \boldsymbol{x}^H \boldsymbol{G}_i \boldsymbol{x} \geq g_i, \quad i = 1, \ldots, m \\ & \boldsymbol{x}^H \boldsymbol{F}_i \boldsymbol{x} = f_i, \quad i = 1, \ldots, p \\ & \boldsymbol{x}^H \boldsymbol{L}_i \boldsymbol{x} \leq l_i, \quad i = 1, \ldots, q, \end{aligned} \tag{2.24}$$

where $\boldsymbol{C}$, $\boldsymbol{G}_i$, $\boldsymbol{F}_i$, and $\boldsymbol{L}_i$ are general Hermitian matrices. Because the problem is non-convex, it is very difficult to solve, which means that it can not be solved in polynomial time, or equivalently the running time required to solve this problem is not a polynomial expression of the problem size [55]. However, an approximation technique can be used to solve this problem by first converting it to an equivalent problem as

$$\begin{aligned}
\min_{\boldsymbol{X}} \quad & Tr\left(\boldsymbol{C}\boldsymbol{X}\right) \\
\text{s.t.} \quad & Tr\left(\boldsymbol{G}_i\boldsymbol{X}\right) \geq g_i, \qquad i = 1, \dots, m \\
& Tr\left(\boldsymbol{F}_i\boldsymbol{X}\right) = f_i, \qquad i = 1, \dots, p \\
& Tr\left(\boldsymbol{L}_i\boldsymbol{X}\right) \leq l_i, \qquad i = 1, \dots, q \\
& \boldsymbol{X} \geq 0, rank(\boldsymbol{X}) = 1,
\end{aligned} \tag{2.25}$$

where $\boldsymbol{X} = \boldsymbol{x}^H\boldsymbol{x}$. Although the problem is still non-convex. It becomes convex when the constraint $rank(\boldsymbol{X}) = 1$ is dropped. Therefore, (2.25) is approximated by (2.26), which is called SDR.

$$\begin{aligned}
\min_{\boldsymbol{X}} \quad & Tr\left(\boldsymbol{C}\boldsymbol{X}\right) \\
\text{s.t.} \quad & Tr\left(\boldsymbol{G}_i\boldsymbol{X}\right) \geq g_i, \quad i = 1, \dots, m \\
& Tr\left(\boldsymbol{F}_i\boldsymbol{X}\right) = f_i, \quad i = 1, \dots, p \\
& Tr\left(\boldsymbol{L}_i\boldsymbol{X}\right) \leq l_i, \quad i = 1, \dots, q \\
& \boldsymbol{X} \geq 0.
\end{aligned} \tag{2.26}$$

Let $\boldsymbol{X}^*$ be the optimal solution to (2.26). If $rank(\boldsymbol{X}^*) = 1$, then there must be a $\boldsymbol{x}^*$ such that $\boldsymbol{X}^* = \boldsymbol{x}^*\boldsymbol{x}^{*H}$, and $\boldsymbol{x}^*$ is the optimal solution to (2.24). Otherwise, we must extract a $\boldsymbol{x}^*$, which is feasible to (2.24), from $\boldsymbol{x}^*$ [55]. One widely used method to extract $\boldsymbol{x}^*$ is called eigenvalue approximation [55], which works as follows. First, decomposite $\boldsymbol{X}^*$ by eigenvalues $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_r$, where $r = rank(\boldsymbol{X}^*)$. Then, choose λ_1 and its corresponding eigenvector q_1 to build $\hat{\boldsymbol{x}} = \sqrt{\lambda_1}q_1$ as the solution to (2.24) if it is feasible. Otherwise, map $\hat{\boldsymbol{x}}$ to its nearby feasible point to (2.24) as the solution.

2.2 Literature Review

In this section, the literature review about the relay networks and overhearing scheme is introduced.

2.2.1 Cooperative communication

The fundamental form of the cooperative communication (relay channel), was firstly introduced by van der Meulen in 1968 [2]. Further, Cover and El Gamal analyzed the relay channel from the information-theoretic point of view and developed several fundamental relaying strategies [3]. The main idea of the relay channel is that a relay station can overhear the signal from the transmitter and retransmit it towards the receiver. In this way, the relay channel then can be regarded as superposition of a broadcast channel [56], [57] and a multiple access channel [58], [59] well investigated before. Cover and El Gamal provoked high interest to the cooperative communication, which remains a hot topic within the area of communication theory. Interested reader is referred to [60] and references there for an excellent overview of the topic.

In general, there are three types of nodes in the cooperative communications terminology. The source (S), the destination (D), and the relay (R) nodes. The aim is to transmit information from the source to the destination node via employing the relay network in order to improve the quality of the overall transmission. The following different models of relaying can be classified into

- S to (R;D); (S;R) to D (The most general form).
- S to R; (S;R) to D (D ignores the signal of S node in the first phase).
- S to (R;D); R to D (S does not transmit in the second phase).
- S to R; R to D (Multi-hop communication).

The first model is the most general one and it was employed by the majority of the early works in the are of cooperative communications. The second and the third model are simplified models that were introduced mainly for analytical tractability. For example, they derived a simplified expression for the outage probability analysis and the design of the space-time codes for fading relay channels [8, 21, 9]. The last model is much older as well as simpler than the other three and is commonly referenced as multi-hop communications.

Within the context of cooperative communications, the AF strategy was firstly introduced and investigated by Lanemann et al. in [8]. The most frequently used regenerative relaying strategy is DF, originally introduced in [3]. The main idea of the DF strategy is that the received signal, firstly, decoded at the relay, then re-encoded and retransmitted to the receiver. Another type of regenerative strategies is CF, also initially suggested in [3]. The idea here is that the relay quantizes the received signal and encodes the samples into a new message which is forwarded to the destination serving as additional redundancy for the signal received directly from the source.

A one-way relay receives from or transmits to a single user at a given time. But a two-way relay communicates with two users simultaneously. A more general multi-way relay receives from or transmits to multiple users simultaneously.

In a one-way relay network with half-duplex, four time-slots are needed for a

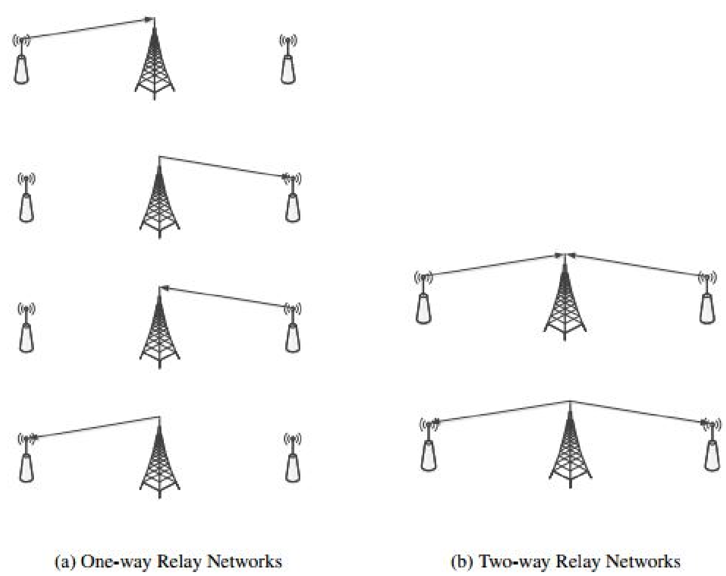

Figure 2.9: Comparison of one-way and two-way relay networks.

single data transfer between two end terminals. This results in loss of spectral efficiency. However, TWR networks which uses interference cancellation or physical layer network coding requires only two-time slots to transfer data between two end users [61, 62]. Thus a TWR doubles the data rate compared to an one-way relay. A comparison of signal transfer steps of an one-way relay with a TWR is shown in Fig.2.9.

In the first time slot both the end users transmit their respective data to the relay. In the second time-slot, the relay will amplify and forward the received signal to end users. End users receive their own transmitted signal and the signal transmitted by the other user. As end users know their own transmitted signal, using basic signal processing they can easily decode the transmitted message of the other user. Removal of this self-interference is known as network coding [61, 62].

Previous studies on AF MIMO relaying largely assume that the instantaneous CSI is available at the relay [63, 64]. An extra signal processing requirement at the relay is the most significant drawback of this technique. This is contradictory to the objective of using AF MIMO relaying as a less complex relaying protocol. The authors in [65, 66, 67] discuss systems with an alternative approach, which employ a fixed gain at the relay. This technique is often referred to as non-coherent or fixed-gain AF relaying.

2.2.2 Overhearing schemes

Authors in [68] proposed a multi-user relaying with two UEs, while one UE overhears the signal or the data from the other UE perfectly. However, it is difficult to apply in a practical situation, because the overhearing link is noisy. The proposed overhearing relay schemes in [69, 70] were more realistic, the authors assumed the scheme with two UE, one UE has a good direct link to the BS and the other UE has no direct link to the BS. In [69], a non-linear receiver considered to exploit the overhearing signal from the other UE where the overhearing interference is decoded first then cancel the interference signal from the received signal, while [70] uses a linear receiver to suppress the overhearing interference. Also, a cooperative cognitive radio network in [71] uses a linear receiver.

The overhearing scheme in [72] considered two UEs at the cell edge, one UE was uplink user while the other UE was downlink user. Also, the scheme was with single-antenna at all nodes and no direct link between the BS and the UEs. The downlink user overhears the signal from the other user and exploits it to cancel the interference from the uplink user. If the overheard signal is weaker than the desired signal at the downlink user, then MMSE applied to decode the desired signal. In addition, if the interference signal is stronger than the desired signal, then MMSE-SIC is applied to decode the overheard signal before detecting the desired signal. The authors in [72] proposed an iterative algorithm to optimize the precoding matrix at the RS. The rate for that scheme significantly improved compared to the scheme without the overhearing link.

In [73], the authors extended the overhearing scheme in [72] to the scenario with multiple antennas at the RS. Also, they jointly optimized the relay precoder in the second time slot and the weights of transmit power at the uplink user over two-time slots. The sum-rate for the extended scheme in [73] was larger than the overhearing scheme with single-antenna at all terminals in [72]. In this thesis, we focus on the overhearing scheme in [73], and we want to extend the scheme to multiple antennas at all terminals. In [74], the overhearing scheme in [73] is extended to the scheme with more than one multi-antenna relay in parallel.

The overhearing scheme for multi-cell shared relay network was considered in [75]. they assumed three cells, where each cell has two UEs, one is in downlink reception mode and the other is in uplink transmission mode. In addition, All the UEs and the RS are at the cell-edge. The precoding matrices at the BSs and the RS were determined by interference alignment such that all interference signal is suppressed.

CHAPTER 3

ADAPTIVE OVERHEARING IN TWO-WAY RELAYING CHANNELS

3.1 Introduction

This chapter contains an overhearing model for TWR with multi-antenna at the BS and the RS and two single-antenna users, where one user is in transmission mode (uplink user) and the other user is in reception mode (downlink user). In addition, there is no direct link between the BS and the users, and the downlink user overhears the signal from the uplink user and exploits the overheard signal to improve the detection performance. The MMSE and MMSE-SIC receivers at the downlink user are utilized to detect the desired signal. Moreover, the relay precoding matrix and the transmit weights at the uplink user are jointly optimized via an iterative algorithm in the sense of maximizing the minimum SINR. Simulation results show that the joint design of the relay precoder and the overhearing weights at the uplink user provides significant sum-rate gain over the overhearing scheme with different scenarios for equal and unequal number of antennas at the BS and the RS.

The reminder of this chapter is arranged as follows: Section 3.2 describes the system model and the channel model; Section 3.3 provides the analysis of the MMSE receiver; Section 3.4 formulates the problem for the precoding matrix at the relay station and the transmit weights for the uplink user; Section 3.5 discusses the simulation results for different scenarios; Section 3.6 state the conclusions.

3.2 The overhearing system model with single antenna at the users

The system model for this chapter is extended from the scheme in [73]. The asymmetric TWR channel consisting of a BS with M_B antennas, an AF relay with M_R antennas, and single-antenna for the two UEs, where one is in uplink transmission mode (uplink user) wile the other is in downlink reception mode (downlink user) as shown in Fig. 3.1. The UEs are at the cell-edge, and there is no direct link between the BS and the UEs.

The overhearing scheme with AF relay is half-duplex, so the communication will be in the two-time slots. In the first time slot or the MAC slot, the BS and UE1

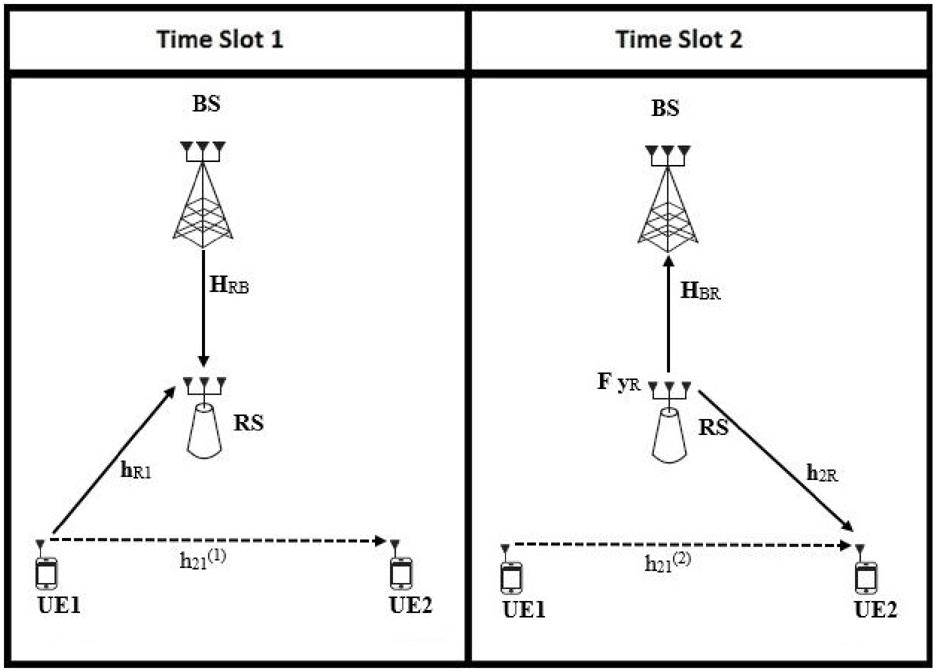

Figure 3.1: The system model.

send the signal $\sqrt{p_s}\boldsymbol{v}_B x_2$, $w_1 x_1$ to the RS, respectively, wile UE2 overhears the signal from UE1. The received signal at the RS and UE2 are expressed as

$$\begin{aligned} \boldsymbol{y}_R &= \sqrt{p_s}\boldsymbol{H}_{RB}\boldsymbol{v}_B x_2 + w_1 \boldsymbol{h}_{R1} x_1 + \boldsymbol{n}_R, \\ y_2^{(1)} &= w_1 h_{21}^{(1)} x_1 + n_2^{(1)}, \end{aligned} \tag{3.1}$$

respectively, where the notations in (3.1) are defined as the following:

- $\boldsymbol{H}_{RB} \in \mathbb{C}^{M_R \times M_B}$ is the channel coefficient matrix from the BS to the RS.
- $\boldsymbol{h}_{R1} \in \mathbb{C}^{M_R \times 1}$ is the channel coefficient column vector from UE1 to the RS.
- h_{21} is the overhearing channel coefficient from UE1 to UE2.
- $\sqrt{p_s}$ is the total transmit power at the BS and defined as $p_s = Tr\{p_1, p_2, ..., p_{M_B}\}$.

- $\boldsymbol{v}_B = [1; 1; ...; 1]^T_{M_{B\times 1}}$.
- w_1 is the transmit weight at UE1 in the first time slot.
- x_1 is the unit-power signal from UE1 to the BS.
- x_2 is the unit-power signal from the BS to UE2.
- $\boldsymbol{n}_R \in \mathbb{C}^{M_R\times 1} \sim \mathcal{CN}(0, I_{M_R})$ and $n_2^{(1)} \in \mathbb{C}^{1\times 1} \sim \mathcal{CN}(0, 1)$ are the AWGN at the RS and UE2 in the first time slot, respectively.

After the relay receives the signals, the RS multiplies the received signals by the precoding matrix $\boldsymbol{F} \in \mathbb{C}^{M_R X M_R}$ in the second time slot or the BC slot, then retransmits $\boldsymbol{F}\boldsymbol{y}_R$. In addition, UE1 sends again x_1 with a different weight w_2 to UE2 to improve the cancellation of the interference at the UE2, and UE2 receives the overheard signal $w_2 x_1$ and $\boldsymbol{F}\boldsymbol{y}_R$. The transmit power constraint at the RS is given by

$$\begin{aligned} p_{RT} =& Tr\{(\boldsymbol{F}\boldsymbol{y}_R)^H (\boldsymbol{F}\boldsymbol{y}_R)\} \\ =& Tr\{\left(\sqrt{p_s}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B x_2 + w_1\boldsymbol{F}\boldsymbol{h}_{R1}x_1 + \boldsymbol{F}\boldsymbol{n}_R\right)^H \\ & \left(\sqrt{p_s}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B x_2 + w_1\boldsymbol{F}\boldsymbol{h}_{R1}x_1 + \boldsymbol{F}\boldsymbol{n}_R\right)\} \\ =& p_s Tr\{\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B\} + w_1^2 Tr\{\boldsymbol{h}_{R1}^H\boldsymbol{F}^H\boldsymbol{F}\boldsymbol{h}_{R1}\} + Tr\{\boldsymbol{F}^H\boldsymbol{F}\} \leq p_R, \end{aligned} \tag{3.2}$$

where p_R is the maximum transmit power at the RS, $\mathbb{E}[x_1^* x_1] = \mathbb{E}[x_1 x_1^*] = \mathbb{E}[x_2^* x_2] = \mathbb{E}[x_2 x_2^*] = 1$, and $\mathbb{E}\left[\boldsymbol{n}_R^H\boldsymbol{n}_R\right] = \mathbb{E}\left[\boldsymbol{n}_R\boldsymbol{n}_R^H\right] = I_{M_R}$.

The received signal at the BS and UE2 in the second time slot are

$$\begin{aligned}
\boldsymbol{y}_B &= \boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{y}_R + \boldsymbol{n}_B \\
&= \sqrt{p_s}\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B x_2 + w_1\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{h}_{R1}x_1 + \boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{n}_R + \boldsymbol{n}_B, \\
y_2^{(2)} &= \boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{y}_R + w_2 h_{21}^{(2)} x_1 + n_2^{(2)} \\
&= \sqrt{p_s}\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B x_2 + w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}x_1 + w_2 h_{21}^{(2)} x_1 + \boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{n}_R + n_2^{(2)},
\end{aligned} \tag{3.3}$$

respectively, where

- $\boldsymbol{H}_{BR} \in \mathbb{C}^{M_B \times M_R}$ is the channel coefficient matrix from the RS to the BS.
- $\boldsymbol{h}_{2R} \in \mathbb{C}^{1 \times M_R}$ is the channel coefficient row vector from the RS to UE2.
- $\boldsymbol{n}_B \in \mathbb{C}^{M_B \times 1} \sim \mathcal{CN}(0, I_{M_B})$ and $n_2^{(2)} \in \mathbb{C}^{1 \times 1} \sim \mathcal{CN}(0, 1)$ are the AWGN at the RS and UE2 in the BC slot, respectively.

3.3 Signal-To-Interference-Plus-Noise-Ratio

Here, it is assumed that the BS knows the channel coefficient matrix from the BS to the RS, then the BS exploits a self-interference cancellation to cancel $\sqrt{p_s}\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B x_2$ from the received signal. Thus, the received signal consists of the desired signal and the noise, so the expression in (3.3) reduces to

$$\boldsymbol{y}_B = w_1\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{h}_{R1}x_1 + \boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{n}_R + \boldsymbol{n}_B. \tag{3.4}$$

Then, the SNR at BS can be easily obtained as

$$
\begin{aligned}
SNR_B &= \frac{\text{Power of the desired signal}}{\text{Power of the noise}} \\
&= \frac{(w_1 \boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{h}_{R1}x_1)(w_1 \boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{h}_{R1}x_1)^H}{(\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{n}_R)(\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{n}_R)^H + (\boldsymbol{n}_B)(\boldsymbol{n}_B)^H} \\
&= \frac{(w_1 \boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{h}_{R1}x_1)\left(x_1^* \boldsymbol{h}_{R1}^H \boldsymbol{F}^H \boldsymbol{H}_{BR}^H w_1^*\right)}{(\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{n}_R)\left(\boldsymbol{n}_R^H \boldsymbol{F}^H \boldsymbol{H}_{BR}^H\right) + (\boldsymbol{n}_B)\left(\boldsymbol{n}_B^H\right)} \\
&= \frac{w_1^2 \|\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{h}_{R1}\|^2}{\|\boldsymbol{H}_{BR}\boldsymbol{F}\|^2 + M_B},
\end{aligned}
\tag{3.5}
$$

where the notation $\|.\|$ denotes the Frobenius norm of a matrix.

The received signals at UE2 over the two-time slots can be written as

$$
\begin{aligned}
\boldsymbol{y}_2 = \begin{bmatrix} y_2^{(1)} \\ y_2^{(2)} \end{bmatrix} &= \begin{bmatrix} w_1 h_{21}^{(1)} \\ w_1 \boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1} + w_2 h_{21}^{(2)} \end{bmatrix} x_1 \\
&+ \begin{bmatrix} 0 \\ \sqrt{p_s}\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B \end{bmatrix} x_2 + \begin{bmatrix} n_2^{(1)} \\ \boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{n}_R + n_2^{(2)} \end{bmatrix} \\
&= \boldsymbol{h}_1 x_1 + \boldsymbol{h}_2 x_2 + \boldsymbol{n}_2.
\end{aligned}
\tag{3.6}
$$

Now, UE2 applies MMSE to the received signals to decode the desired signal x_2, while x_1 is the interference signal over the two-time slots. Therefore, we obtain the SINRs for the signals, $SINR_1$ and $SINR_2$ represented for x_1 and x_2, respectively, as

$$
\begin{aligned}
SINR_1 &= \boldsymbol{h}_1^H \Big[\mathbb{E}[(\boldsymbol{h}_2 x_2 + \boldsymbol{n}_2)(\boldsymbol{h}_2 x_2 + \boldsymbol{n}_2)^H]\Big]^{-1} \boldsymbol{h}_1 \\
&= \frac{w_1^2 \left|h_{21}^{(1)}\right|^2 (p_s |\boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B|^2 + \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + 1)}{p_s |\boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B|^2 + \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + 1} + \\
&\quad \frac{\left|w_1 \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{h}_{R1} + w_2 h_{21}^{(2)}\right|^2}{p_s |\boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B|^2 + \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + 1},
\end{aligned}
\tag{3.7}
$$

$$
\begin{aligned}
SINR_2 &= \boldsymbol{h}_2^H \Big[\mathbb{E}[(\boldsymbol{h}_1 x_1 + \boldsymbol{n}_2)(\boldsymbol{h}_1 x_1 + \boldsymbol{n}_2)^H]\Big]^{-1} \boldsymbol{h}_2 \\
&= \frac{\left(p_s \boldsymbol{v}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{h}_{2R}^H \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B\right)\left(w_1^2 \left|h_{21}^{(1)}\right|^2 + 1\right)}{\left(\boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + 1\right)\left(w_1^2 \left|h_{21}^{(1)}\right|^2 + 1\right) + \left|w_1 \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{h}_{R1} + w_2 h_{21}^{(2)}\right|^2}.
\end{aligned}
\tag{3.8}
$$

The derivations of the SINRs expression are given in Appendix 3.A.

When UE2 decodes the desired signal, there are two possible cases:

- **MMSE detection:** is applied when the $SINR_2$ for the desired x_2 is stronger than the $SINR_1$ for the interference signal x_1.

- **MMSE-SIC detection:** if the $SINR_1$ is weaker than the $SINR_2$, MMSE-SIC is applied to detect the x_1 first, then remove it from the received signals to improve the $SINR_2$ for the desired x_2, thus UE2 can detect the desired signal.

In MMSE-SIC, when UE2 decode the interference signal x_1, the received signal an be expressed as

$$\hat{\boldsymbol{y}}_2 = \begin{bmatrix} 0 \\ \sqrt{p_s}\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B \end{bmatrix} x_2 + \begin{bmatrix} n_2^{(1)} \\ \boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{n}_R + n_2^{(2)} \end{bmatrix}. \tag{3.9}$$

Then, it easy to decode the desired signal x_2, and the SNR at UE2 in this case is

$$\begin{aligned} SNR_2 &= \frac{p_s \boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H}{1+\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H} \\ &= \frac{p_s|\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B|^2}{1+\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H}. \end{aligned} \tag{3.10}$$

3.4 Optimization of the relay precoder and the transmit weights for uplink user

The precoding matrix at the RS in the second time slot and the overhearing transmit weights at the UE1 over the two-time slots are jointly optimized to maximize the minimum weighted SINR for two cases, the linear MMSE and MMSE-SIC receivers at UE2. The transmit weights can expressed as $\boldsymbol{w} = [w_1, w_2]^T$, and the weight factors for uplink and downlink are β^{UL} and β^{DL}, respectively.

Now, we can optimize the relay precoder and the transmit weights in an adaptive way for each case. At first of the optimization, the transmit weights $\boldsymbol{w}$ are optimized for a given the precoding matrix $\boldsymbol{F}$, then, the relay precoder is optimized for given the transmit weights.

3.4.1 Optimization of $\boldsymbol{w}$ for given $\boldsymbol{F}$

The optimization of $\boldsymbol{w}$ for the two cases, linear MMMSE, and MMSE-SIC are considered at UE2, where the relay precoder is given. The first case (MMSE), when the $SINR_2$ for the desired signal is stronger than the $SINR_1$ for the interference signal. Thus, the linear MMSE detector is employed at UE2 to decode the desired signal x_2. The optimization of $\boldsymbol{w}$ is formulated as

$$\begin{aligned} \max_{\boldsymbol{w}} \quad & min\{\beta^{UL} SNR_B, \beta^{DL} SINR_2\} \\ \text{s.t.} \quad & SINR_2 > SINR_1, \\ & \boldsymbol{w}^H \boldsymbol{w} \leq p_w, w_1^H w_1 \leq p_{w_1}, \end{aligned} \tag{3.11}$$

where $p_{w_1} = \dfrac{p_R - p_s Tr\{\boldsymbol{v}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B\} - Tr\{\boldsymbol{F}^H \boldsymbol{F}\}}{Tr\{\boldsymbol{h}_{R1}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{h}_{R1}\}}$ from the power constraint at the RS, and p_w is the total sum-transmit power at UE1 over the two-time slots.

In case of the MMSE-SIC receiver at UE2, the SINR for the desired signal is weaker than the SINR of the interference signal. The uplink signal x_1 needs to decodable at both the BS and UE2, so, the SINR for x_1 is given by $min(SNR_B, SINR_1)$. Thus the optimization problem for this case is formulated as

$$
\begin{aligned}
\max_{\boldsymbol{w}} \quad & min\{\beta^{UL} min(SNR_B, SINR_1), \beta^{DL} SNR_2\} \\
\text{s.t.} \quad & SINR_2 \leq SINR_1, \\
& \boldsymbol{w}^H \boldsymbol{w} \leq p_w, w_1^H w_1 \leq p_{w_1},
\end{aligned}
\tag{3.12}
$$

Now, the precoding matrix at the RS is known, so, SNR_B in (3.5), $SINR_1$ in (3.7), and $SINR_2$ in (3.8) can be rewritten in terms of $\boldsymbol{w}$ as

$$
\begin{aligned}
SNR_B &= b.\boldsymbol{w}^H A \boldsymbol{w}, \\
SINR_1 &= \boldsymbol{w}^H [C + \frac{1}{e_1} \boldsymbol{d}^* \boldsymbol{d}^T] \boldsymbol{w}, \\
SINR_2 &= \frac{e_2(1 + \boldsymbol{w}^H C \boldsymbol{w})}{g(1 + \boldsymbol{w}^H C \boldsymbol{w}) + \boldsymbol{w}^H \boldsymbol{d}^* \boldsymbol{d}^T \boldsymbol{w}},
\end{aligned}
\tag{3.13}
$$

where

$$
\begin{aligned}
A &= \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \\
b &= \frac{\|\boldsymbol{H}_{BR} \boldsymbol{F} \boldsymbol{h}_{R1}\|^2}{\|\boldsymbol{H}_{BR} \boldsymbol{F}\|^2 + M_B}, \\
C &= \left| h_{21}^{(1)} \right|^2 A, \\
\boldsymbol{d} &= [\boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{h}_{R1}, h_{21}^{(2)}]^T, \\
e_1 &= p_s |\boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B|^2 + \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + 1, \\
e_2 &= p_s \boldsymbol{v}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{h}_{2R}^H \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B \\
& and, \\
g &= \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + 1.
\end{aligned}
\tag{3.14}
$$

3.4.2 Optimization of $\boldsymbol{F}$ for given $\boldsymbol{w}$

The optimization of the precoding matrix at the RS is derived in the sense of maximizing minimum weighted SINR, for given the transmit weights at UE1. The optimization with linear MMSE receiver at UE2 for $SIN_2 > SINR_1$, the optimization problem of $\boldsymbol{F}$ for given $\boldsymbol{w}$ is formulated as

$$\begin{aligned} \max_{\boldsymbol{F}} \quad & min\{\beta^{UL}(SNR_B, \beta^{DL}SINR_2\} \\ \text{s.t.} \quad & SINR_2 > SINR_1, \\ & p_s Tr\{\boldsymbol{v}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B\} + w_1 Tr\{\boldsymbol{h}_{R1}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{h}_{R1}\} + Tr\{\boldsymbol{F}^H \boldsymbol{F}\} \leq p_R, \end{aligned} \tag{3.15}$$

where the second constraint follows from the power constraint at the RS.

In the case of the MMSE-SIC receiver at UE2, when $SINR_2 \leq SINR_1$, the optimization problem is expressed as

$$\begin{aligned} \max_{\boldsymbol{F}} \quad & min\{\beta^{UL} min(SNR_B, SINR_1), \beta^{DL}SNR_2\} \\ \text{s.t.} \quad & SINR_2 \leq SINR_1, \\ & p_s Tr\{\boldsymbol{v}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B\} + w_1 Tr\{\boldsymbol{h}_{R1}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{h}_{R1}\} + Tr\{\boldsymbol{F}^H \boldsymbol{F}\} \leq p_R. \end{aligned} \tag{3.16}$$

To simplify the optimization of the relay precoder $\boldsymbol{F}$, we need to set the precoding matrix into vector form instead of matrix form. Therefore, the relay precoder can be expressed as $\boldsymbol{f} = vec\{\boldsymbol{F}\}$. To express SNR_B in (3.5), $SINR_1$ in (3.7), $SINR_2$

in (3.8), SNR_2 in (3.10), and the power constraint at the RS in (3.2) with respect of $\boldsymbol{f}$ by using the Kronecker product. Th numerator of SNR_B in (3.5) can be rewritten in term of $\boldsymbol{f}$ as:

$$
\begin{aligned}
&w_1^2\|\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{h}_{R1}\|^2 = w_1^2 Tr\left\{\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{h}_{R1}\boldsymbol{h}_{R1}^H\boldsymbol{F}^H\boldsymbol{H}_{BR}^H\right\} \\
&= w_1^2 Tr\left\{\boldsymbol{H}_{BR}^H\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{h}_{R1}\boldsymbol{h}_{R1}^H\boldsymbol{F}^H\right\} = w_1^2 vec\left\{\boldsymbol{H}_{BR}^H\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{h}_{R1}\boldsymbol{h}_{R1}^H\boldsymbol{F}^H\right\} \\
&= vec\{\boldsymbol{F}\}^H w_1^2(\boldsymbol{H}_{BR}^H\boldsymbol{H}_{BR}) \otimes (\boldsymbol{h}_{R1}\boldsymbol{h}_{R1}^H) vec\{\boldsymbol{F}\} \\
&= \boldsymbol{f}^H w_1^2(\boldsymbol{H}_{BR}^H\boldsymbol{H}_{BR}) \otimes (\boldsymbol{h}_{R1}\boldsymbol{h}_{R1}^H)\boldsymbol{f}.
\end{aligned}
\tag{3.17}
$$

Th denominator of SNR_B in (3.5) can be rewritten in term of $\boldsymbol{f}$ as:

$$
\begin{aligned}
&\|\boldsymbol{H}_{BR}\boldsymbol{F}\|^2 + M_B = Tr\left\{\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{H}_{BR}^H\right\} + M_B \\
&= Tr\left\{\boldsymbol{H}_{BR}^H\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{F}^H\right\} + M_B = vec\left\{\boldsymbol{H}_{BR}^H\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{F}^H\right\} + M_B \\
&= vec\{\boldsymbol{F}\}^H (\boldsymbol{H}_{BR}^H\boldsymbol{H}_{BR}) \otimes (I_{M_R}) vec\{\boldsymbol{F}\} + M_B \\
&= \boldsymbol{f}^H(\boldsymbol{H}_{BR}^H\boldsymbol{H}_{BR}) \otimes (I_{M_R})\boldsymbol{f} + M_B.
\end{aligned}
\tag{3.18}
$$

The terms in the numerator of $SINR_1$ in (3.7) can be rewritten in term of $\boldsymbol{f}$ as:

$$p_s|\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B|^2 = p_s Tr\left\{\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H\right\}$$

$$= p_s Tr\left\{\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\right\} = p_s vec\left\{\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\right\}$$

$$= \boldsymbol{f}^H p_s(\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}) \otimes (\boldsymbol{H}_{RB}\boldsymbol{v}_B\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H)\boldsymbol{f},$$

$$\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H = Tr\left\{\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H\right\} = Tr\left\{\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\right\} = vec\left\{\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\right\}$$

$$= \boldsymbol{f}^H(\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}) \otimes (I_{M_R})\boldsymbol{f},$$

and

$$\left|w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1} + w_2 h_{21}^{(2)}\right|^2 = Tr\left\{\left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1} + w_2 h_{21}^{(2)}\right)\left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1} + w_2 h_{21}^{(2)}\right)^H\right\}$$

$$= Tr\left\{\left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1} + w_2 h_{21}^{(2)}\right)\left(\boldsymbol{h}_{R1}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H w_1^* + h_{21}^{(2)*}w_2^*\right)\right\}$$

$$= Tr\left\{\left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}\boldsymbol{h}_{R1}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H w_1^*\right) + \left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}h_{21}^{(2)*}w_2^*\right)\right\} +$$

$$Tr\left\{\left(w_2 h_{21}^{(2)}\boldsymbol{h}_{R1}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H w_1^*\right) + \left(w_2 h_{21}^{(2)}h_{21}^{(2)*}w_2^*\right)\right\}$$

$$= \left(\boldsymbol{f} + \frac{w_2 h_{21}^{(2)}}{w_1}\left((\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}) \otimes (\boldsymbol{h}_{R1}\boldsymbol{h}_{R1}^H)\right)^{-1} vec\{\boldsymbol{h}_{R1}\boldsymbol{h}_{2R}\}^*\right)^H$$

$$\left(|w_1|^2(\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}) \otimes (\boldsymbol{h}_{R1}\boldsymbol{h}_{R1}^H)\right)$$

$$\left(\boldsymbol{f} + \frac{w_2 h_{21}^{(2)}}{w_1}\left((\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}) \otimes (\boldsymbol{h}_{R1}\boldsymbol{h}_{R1}^H)\right)^{-1} vec\{\boldsymbol{h}_{R1}\boldsymbol{h}_{2R}\}^*\right)$$

$$+\left|h_{21}^{(2)}w_2\right|^2 - \left|h_{21}^{(2)}w_2\right|^2 vec\{\boldsymbol{h}_{R1}\boldsymbol{h}_{2R}\}^T\left((\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}) \otimes (\boldsymbol{h}_{R1}\boldsymbol{h}_{R1}^H)\right)^{-1} vec\{\boldsymbol{h}_{R1}\boldsymbol{h}_{2R}\}^*$$

$$+\left|h_{21}^{(1)}w_1\right|^2. \tag{3.19}$$

The term of the numerator of $SINR_2$ in (3.8) can be rewritten in term of $\boldsymbol{f}$ as:

$$\left(p_s\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B\right) = p_sTr\left\{\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B\right\}$$
$$= p_sTr\left\{\boldsymbol{H}_{RB}\boldsymbol{v}_B\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}\boldsymbol{F}\right\} = p_svec\left\{\boldsymbol{H}_{RB}\boldsymbol{v}_B\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}\boldsymbol{F}\right\}$$
$$= \boldsymbol{f}^Hp_s(\boldsymbol{H}_{RB}\boldsymbol{v}_B\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H)\otimes(\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R})\boldsymbol{f}. \tag{3.20}$$

The power constraint at the RS in (3.2) can be rewritten in term of $\boldsymbol{f}$ as:

$$\begin{aligned} p_{RT} =& p_sTr\{\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B\} + w_1^2Tr\{\boldsymbol{h}_{R1}^H\boldsymbol{F}^H\boldsymbol{F}\boldsymbol{h}_{R1}\} + Tr\{\boldsymbol{F}^H\boldsymbol{F}\} \leq p_R \\ =& p_svec\{\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B\} + w_1^2vec\{\boldsymbol{h}_{R1}^H\boldsymbol{F}^H\boldsymbol{F}\boldsymbol{h}_{R1}\} + vec\{\boldsymbol{F}^H\boldsymbol{F}\} \leq p_R \\ =& \boldsymbol{f}^H\left(p_s(I_{M_R})\otimes(\boldsymbol{H}_{RB}^*\boldsymbol{v}_B^*\boldsymbol{v}_B^T\boldsymbol{H}_{RB}^T) + w_1^2(I_M)\otimes(\boldsymbol{h}_{R1}^*\boldsymbol{h}_{R1}^T) + I_{M_R^2}\right)\boldsymbol{f} \leq p_R \end{aligned} \tag{3.21}$$

Thus, SNR_B in (3.5), $SINR_1$ in (3.7), $SINR_2$ in (3.8), SNR_2 in (3.10), and the relay power constraint in (3.2) can be rewritten in terms of $\boldsymbol{f}$ as

$$\begin{aligned} SNR_B &= \frac{\boldsymbol{f}^H\boldsymbol{K}_1\boldsymbol{f}}{M_B + \boldsymbol{f}^H\boldsymbol{K}_2\boldsymbol{f}}, \\ SINR_1 &= \frac{\boldsymbol{f}^H\left[\left|h_{21}^{(1)}w_1\right|^2(\boldsymbol{K}_3+\boldsymbol{K}_4)\right]\boldsymbol{f} + \tilde{\boldsymbol{f}}^H|w_1|^2\boldsymbol{K}_5\tilde{\boldsymbol{f}} + l_3}{1+\boldsymbol{f}^H(\boldsymbol{K}_3+\boldsymbol{K}_4)\boldsymbol{f}}, \\ SINR_2 &= \frac{\boldsymbol{f}^H\left[\left(1+\left|h_{21}^{(1)}w_1\right|^2\right)\boldsymbol{K}_6\right]\boldsymbol{f}}{\boldsymbol{f}^H\left[\left(1+\left|h_{21}^{(1)}w_1\right|^2\right)\boldsymbol{K}_4\right]\boldsymbol{f} + \tilde{\boldsymbol{f}}^H|w_1|^2\boldsymbol{K}_5\tilde{\boldsymbol{f}} + l_3}, \\ SNR_2 &= \frac{\boldsymbol{f}^H\boldsymbol{K}_3\boldsymbol{f}}{1+\boldsymbol{f}^H\boldsymbol{K}_4\boldsymbol{f}}, \\ p_{RT} &= \boldsymbol{f}^HO\boldsymbol{f} \leq p_R, \end{aligned} \tag{3.22}$$

where

$$
\begin{aligned}
\boldsymbol{K}_1 &= w_1^2(\boldsymbol{H}_{BR}^H\boldsymbol{H}_{BR}) \otimes (\boldsymbol{h}_{R1}\boldsymbol{h}_{R1}^H),\\
\boldsymbol{K}_2 &= (\boldsymbol{H}_{BR}^H\boldsymbol{H}_{BR}) \otimes (I_{M_R}),\\
\boldsymbol{K}_3 &= p_s(\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}) \otimes (\boldsymbol{H}_{RB}\boldsymbol{v}_B\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H),\\
\boldsymbol{K}_4 &= (\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}) \otimes (I_{M_R}),\\
\boldsymbol{K}_5 &= (\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}) \otimes (\boldsymbol{h}_{R1}\boldsymbol{h}_{R1}^H),\\
\boldsymbol{K}_6 &= p_s(\boldsymbol{H}_{RB}\boldsymbol{v}_B\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H) \otimes (\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}),\\
\boldsymbol{K}_7 &= (I_{M_R}) \otimes (\boldsymbol{H}_{RB}^*\boldsymbol{v}_B^*\boldsymbol{v}_B^T\boldsymbol{H}_{RB}^T),\\
\boldsymbol{K}_8 &= w_1^2(I_M) \otimes (\boldsymbol{h}_{R1}^*\boldsymbol{h}_{R1}^T),\\
l_1 &= vec\{\boldsymbol{h}_{R1}\boldsymbol{h}_{2R}\},\\
l_2 &= \frac{w_2h_{21}^{(2)}}{w_1}\boldsymbol{K}_5^{-1}l_1^*,\\
l_3 &= \left|h_{21}^{(2)}w_2\right|^2 - \left|h_{21}^{(2)}w_2\right|^2 l_1^T\boldsymbol{K}_5^{-1}l_1^* + \left|h_{21}^{(1)}w_1\right|^2,\\
\tilde{\boldsymbol{f}} &= \boldsymbol{f} + l_2,\\
\text{and,}\boldsymbol{O} &= \boldsymbol{K}_7 + \boldsymbol{K}_8 + I_{M_R^2}.
\end{aligned}
\tag{3.23}
$$

3.4.3 Iterative optimization

All the optimization problems in (3.11), (3.12), (3.15), and (3.16) are non-convex, because of the expression of the SINRs, and the non-convex quadratic constraints, so, we can not find a simple solution for those problems. There are different techniques to convert a non-convex optimization problem to a convex problem, one of the option is applying SDR to all problems. In this thesis, SDR is applied to problems in (3.11), (3.12), (3.15), and (3.16), then the modified problems now can be solved in a polynomial time by the SDP.

The first step in deriving an SDR is to observe that $\boldsymbol{x}^T\boldsymbol{A}\boldsymbol{x} = Tr\left\{\boldsymbol{x}^T\boldsymbol{A}\boldsymbol{x}\right\} = Tr\left\{\boldsymbol{A}\boldsymbol{x}\boldsymbol{x}^T\right\}$. In particular, both the objective function and constraints are linear in the matrix $\boldsymbol{w}\boldsymbol{w}^H$, and $\boldsymbol{f}\boldsymbol{f}^H$. Thus, by introducing variables $\boldsymbol{W}' = \boldsymbol{w}\boldsymbol{w}^H$ and $\boldsymbol{F}' = \boldsymbol{f}\boldsymbol{f}^H$. $\boldsymbol{W}'$, and $\boldsymbol{F}'$ are rank-one symmetric positive semidefinite matrix. Then, we add two constraints for each problem, and the constraints are for rank-one and the variable should be positive semidefinite. However, the rank-one constraint is difficult constraint, thus, we drop it. Therefore all optimization problems are known as an SDR, so, it can be solved. We can solve the problems in MATLAB with the code given in A CVX Code for SDR.

The optimization problems in (3.11), (3.12), (3.15), and (3.16) can be respectively expressed as

$$\begin{aligned}
&\text{find} \quad \boldsymbol{W}' \\
&\text{s.t.} \quad Tr\left\{\boldsymbol{W}'(\beta^{UL}b.A)\right\} \geq r, Tr\left\{\boldsymbol{W}'\beta^{DL}\left(C + \frac{1}{e_1}\boldsymbol{d}^*\boldsymbol{d}^T\right)\right\} \leq r, \\
&\qquad Tr\left\{\boldsymbol{W}'\left[\beta^{DL}e_2C - rgC - r\boldsymbol{d}^*\boldsymbol{d}^T\right]\right\} \geq rg - \beta^{DL}e_2, \\
&\qquad Tr\left\{\boldsymbol{W}'A\right\} \leq p_{w_1}, Tr\left\{\boldsymbol{W}'\right\} \leq p_w,
\end{aligned} \tag{3.24}$$

$$\begin{aligned}
&\text{find} \quad \boldsymbol{W}' \\
&\text{s.t.} \quad Tr\left\{\boldsymbol{W}'(\beta^{UL}b.A)\right\} \geq r_{SIC}, Tr\left\{\boldsymbol{W}'\right\} \leq p_w, \\
&\qquad Tr\left\{\boldsymbol{W}'\beta^{DL}\left(C + \frac{1}{e_1}\boldsymbol{d}^*\boldsymbol{d}^T\right)\right\} \geq r_{SIC}, \\
&\qquad Tr\left\{\boldsymbol{W}'\left[\beta^{DL}e_2C - r_{SIC}gC - r_{SIC}\boldsymbol{d}^*\boldsymbol{d}^T\right]\right\} \leq \\
&\qquad r_{SIC}g - \beta^{DL}e_2, Tr\left\{\boldsymbol{W}'A\right\} \leq p_{w_1},
\end{aligned} \tag{3.25}$$

$$\begin{aligned}
&\text{find} \quad \boldsymbol{F}' \\
&\text{s.t.} \quad Tr\left\{\boldsymbol{F}'\left(\beta^{UL}\boldsymbol{K}_1 - r\boldsymbol{K}_2\right)\right\} \geq M_B r, \\
&\qquad Tr\left\{\boldsymbol{F}'\left[\left(\left|h_{21}^{(1)}w_1\right|^2 - r\right)\boldsymbol{K}_{34}\right] + \tilde{\boldsymbol{F}}'|w_1|^2\boldsymbol{K}_5\right\} \geq r/\beta^{DL} - l_3, \\
&\qquad Tr\left\{\boldsymbol{F}'\left[\left(1 + \left|h_{21}^{(1)}w_1\right|^2\right)\left(\beta^{DL}\boldsymbol{K}_6 - r\boldsymbol{K}_4\right)\right] - \tilde{\boldsymbol{F}}'r|w_1|^2\boldsymbol{K}_5\right\} \\
&\qquad \leq r_{SIC}l_3, Tr\left\{\boldsymbol{F}'O\right\} \leq p_R.
\end{aligned} \tag{3.26}$$

$$\begin{aligned}
&\text{find} \quad \boldsymbol{F}' \\
&\text{s.t.} \quad Tr\left\{\boldsymbol{F}'\left(\beta^{UL}\boldsymbol{K}_1 - r_{SIC}\boldsymbol{K}_2\right)\right\} \geq M_B r_{SIC}, \\
&\qquad Tr\left\{\boldsymbol{F}'\left[\left(\left|h_{21}^{(1)}w_1\right|^2 - r_{SIC}\right)\boldsymbol{K}_{34}\right] + \tilde{\boldsymbol{F}}'|w_1|^2\boldsymbol{K}_5\right\} \geq \\
&\qquad r_{SIC}/\beta^{DL} - l_3, Tr\left\{\boldsymbol{F}'\left(\boldsymbol{K}_3 - r_{SIC}\boldsymbol{K}_4\right)\right\} \geq r_{SIC}, \\
&\qquad Tr\left\{\boldsymbol{F}'\left[\left(1 + \left|h_{21}^{(1)}w_1\right|^2\right)\left(\beta^{DL}\boldsymbol{K}_6 - r_{SIC}\boldsymbol{K}_4\right)\right]\right\} - \\
&\qquad Tr\left\{\tilde{\boldsymbol{F}}'r_{SIC}|w_1|^2\boldsymbol{K}_5\right\} \leq r_{SIC}l_3, Tr\left\{\boldsymbol{F}'O\right\} \leq p_R,
\end{aligned} \tag{3.27}$$

where the notation of $\boldsymbol{K}_{34}$ is $\boldsymbol{K}_3 - \boldsymbol{K}_4$, $r = min\{\beta^{UL}SNR_B, \beta^{DL}SINR_2\}$, and $r_{SIC} = min\{\beta^{UL}min(SNR_B, SINR_1), \beta^{DL}SNR_2\}$ are the rates accounting for the cost functions of (3.5), (3.7), (3.8), and (3.10).

We iteratively optimize $\boldsymbol{F}$ and $\boldsymbol{w}$ solving the problems (3.24), (3.25), (3.26), and (3.27) as shown in Algorithm 1.

Algorithm 1: Minimum weighted SNR/SINR maximization

---

1 **Initialization:**

- Select initial $\boldsymbol{f}_i$ and $\boldsymbol{w}_i$ randomly.
- Set $\epsilon > 0$.

MMSE and MMSE-SIC detection at UE2:
Initialize r_{min} and r_{max}, and set $\epsilon' > 0$
read current;
repeat
  Set $r_i = \frac{1}{2}(r_{max} + r_{min})$ and $i = 0$
  repeat
    Set $r = r_i$, $\boldsymbol{f} = \boldsymbol{f}_i$, and $\boldsymbol{w} = \boldsymbol{w}_i$
    Solve (3.24) for MMSE or (3.25) for MMSE-SIC
    Solution $\boldsymbol{w}$ for $i + 1$
    Solve (3.26) for MMSE or (3.27) for MMSE-SIC
    Solution $\boldsymbol{f}$ for $i + 1$
    Increase i by 1
    MMSE: by using (3.5) and (3.8) obtain
    $r_i = min\{\beta^{UL}SNR_B, \beta^{DL}SINR_2\}$
    MMSE-SIC: by using (3.5), (3.7) and (3.10) obtain
    $r_{SIC,i} = min\{\beta^{UL}min(SNR_B, SINR_1), \beta^{DL}SNR_2\}$
  until $\frac{|r_i - r_{i-1}|}{r_{i-1}} \leq \epsilon'$;
  if r_i *is feasible* **then**
    $r_{min} = r_i$
  else
    else $r_{max} = r_i$
  end
until $r_{max} - r_{min} \leq \epsilon$;
Minimum Weighted SNR/SINR: $max(r, r_{SIC})$

3.5 Simulation Results And Discussions

In this section of thesis work, simulation results of the extended overhearing relay scenario are performed and analyzed.

We assume that each channel coefficient or noise component is $\sim \mathcal{CN}(0,1)$, and the threshold is set to $\epsilon = \epsilon' = 0.01$. Also, we initialize the vector of $\boldsymbol{f}$ and $\boldsymbol{w}$ randomly. The weight factors are set to be $\beta^{UL} = \beta^{DL} = 1$, and $p_1 = p_w$. The sum-rate is defined as $R_{sum} = \frac{1}{2}\big(\log_2(1+SNR_B) + \log_2(1+SINR)\big)$, where SNR_B is given in (3.5), while $SINR$ in the case of MMSE is given in (3.8), and for MMSE-SIC case is given in (3.10).

The simulation results for this chapter are performed for two scenarios. In the first scenario, we simulate the system with optimization of the precoding matrix at the RS only, while in the other scenario, we jointly optimize the relay precoder and the overhearing weights at UE1.

3.5.1 Simulation results with $\boldsymbol{F}$ optimization

The simulation results are performed with optimization of the precoding matrix at the RS only to demonstrate later the effect of the optimization of the transmit weights at UE1, and how the trend of the sum-rate curves will be. The overhearing weight at UE1 is a half of p_1 for each time slot ($w_1 = w_2 = \frac{p_1}{2}$).

In Fig. 3.2, and Fig. 3.3, it is shown that the sum-rates for the overhearing

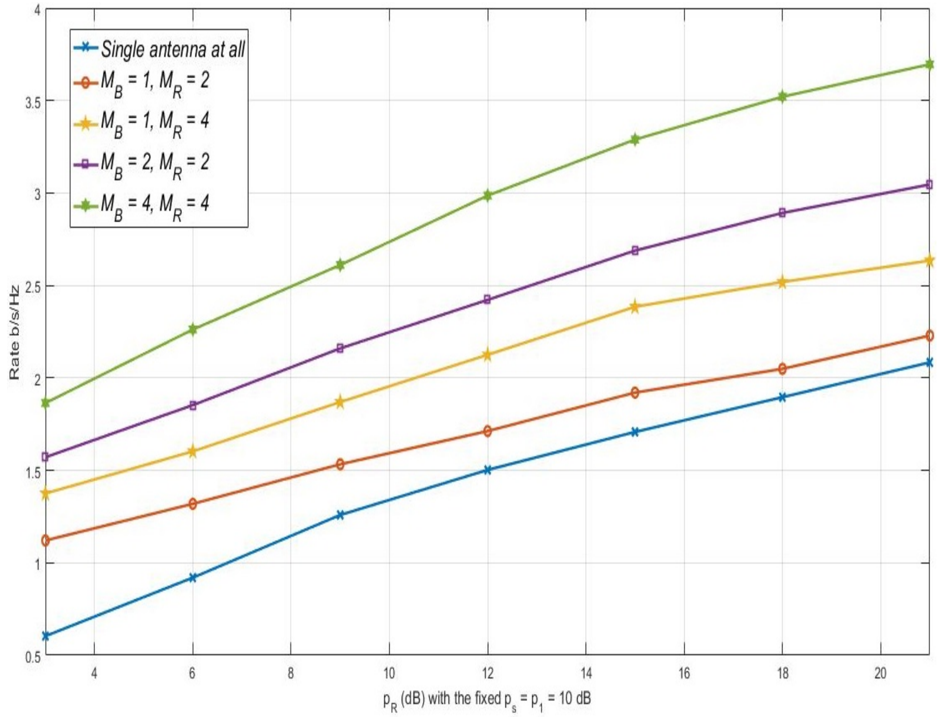

Figure 3.2: Sum-rates of the TWR overhearing schemes with respect to p_R for fixed $p_s = p_1 = 10$ dB.

scheme versus p_R for fixed $p_s = p_1 = 10$ dB and $p_s = p_1$ with fixed $p_R = 10$ dB. We observe that increasing number of antennas at the BS provides more gain compared to the sum-rate for the scenario with multi-antenna only at the RS. However, the sum-rates at high SNR are almost going to saturation. The comparison between the sum-rat in the case of multi-antenna at both the BS and the RS and multi-antenna at only the RS is illustrated for different number of antennas.

In Fig. 3.2, the sum-rate for the case of $M_B = M_R = 2$ is greater than the sum-rate for $M_B = 1$ and $M_R = 2$. For examples, at $p_R = 18$ dB, the gain is increased by 0.85 b/s/Hz, also, the sum-rate increases by 1 b/s/Hz when increasing the number of antennas to four at both the BS and RS.

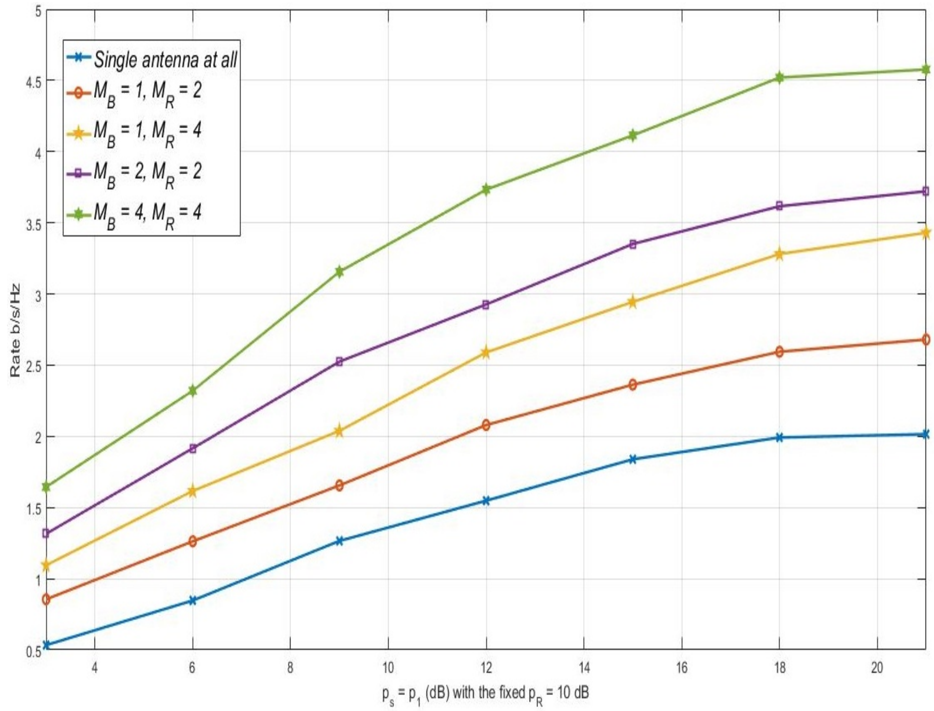

Figure 3.3: Sum-rates of the TWR overhearing schemes with respect to $p_s = p_1$ for fixed $p_R = 10$ dB.

In addition, the gin is 0.65 b/s/Hz when increasing the number of antennas at both the BS and the RS from $M_B = M_R = 2$ to $M_B = M_R = 4$, while the sum-rate is increased by 0.45 b/s/Hz when increasing M_R to 4 and $M_B = 1$. Fig. 3.3 shows the sum-rate for $M_B = M_R = 2$ increases by 1.1 b/s/Hz at $p_s = p_1 = 18$ dB compared with the case of $M_B = 1$ and $M_R = 2$.

3.5.2 Simulation results with $\boldsymbol{F}$ and $\boldsymbol{w}$ joint optimization

The relay precoder $\boldsymbol{F}$ and the overhearing weights $\boldsymbol{w}$ are jointly optimized in the simulation results for this section.

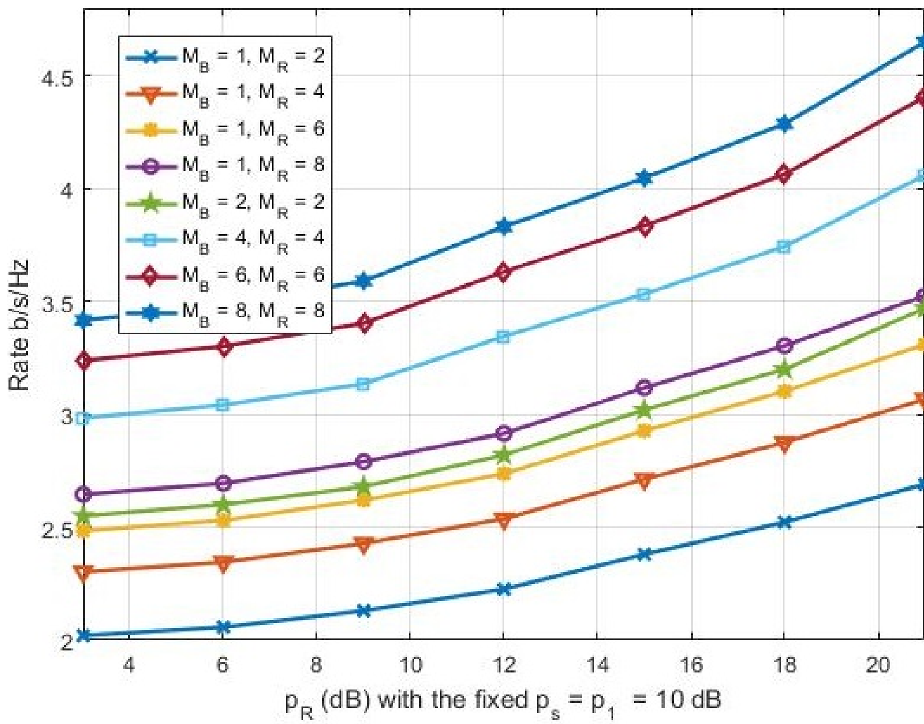

Figure 3.4: Sum-rates of the TWR overhearing schemes with respect to p_R for fixed $p_s = p_1 = 10$ dB.

Fig. 3.4 and Fig. 3.5 illustrate the sum-rates versus the transmit power at the relay p_R with fixed $p_s = p_1 = 10$ dB in the cases of multiple antennas at both the BS and the RS ($M_B = M_R$) and multiple antennas only at the RS with different number of antennas.

The sum-rate for the case of multi-antenna at both the BS and the RS is higher than the sum-rate for multiple antennas only at the RS, also, when increasing the number of antennas. For examples, at $p_R = 18$ dB, the gain is 0.4 b/s/Hz in the case of $M_B = M_R = 2$ and $M_B = 1$ and $M_R = 2$, while the gain is 1.2 at $p_s = p_1 = 18$ dB in Fig. 3.5. In addition, when increasing the number of antennas, the gain will be more. For example, increasing the number of antennas to $M_B = M_R = 8$ as compared to $M_B = 1$ and $M_R = 8$, increases the sum-rate

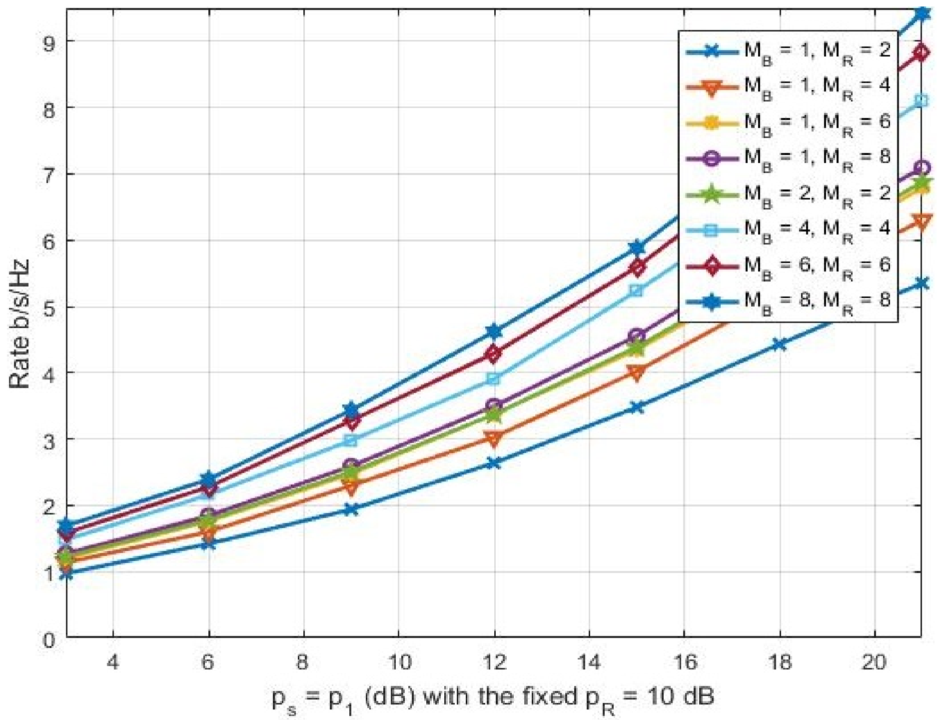

Figure 3.5: Sum-rates of the TWR overhearing schemes with respect to $p_s = p_1$ for fixed $p_R = 10$ dB.

by 1.7 b/s/Hz.

In the case of $M_B \neq M_R$, it can be observed that the increasing number of antennas at the BS results is more gain than increasing the number of antennas at the RS as shown in Fig. 3.6, and Fig. 3.7. The sum-rate for $M_B = 4$ and $M_R = 2$ is higher than the sum-rate for $M_B = 2$ and $M_R = 4$.

The increase of gain at the high SNR is more the increase of gain at the low SNR. For example, for the comparison between $M_B = M_R = 2$ and $M_B = M_R = 8$, the sum-rate in Fig. 3.5 at $p_s = p_1 = 21$ dB is increased by 2.7 b/s/Hz, while the sum-rate at $p_s = p_1 = 3$ dB is raised by 0.5 b/s/Hz. Also the sum-rate for $M_B = 1$ and $M_R = 8$ still is lower than the sum-rate for $M_B = M_R = 4$.

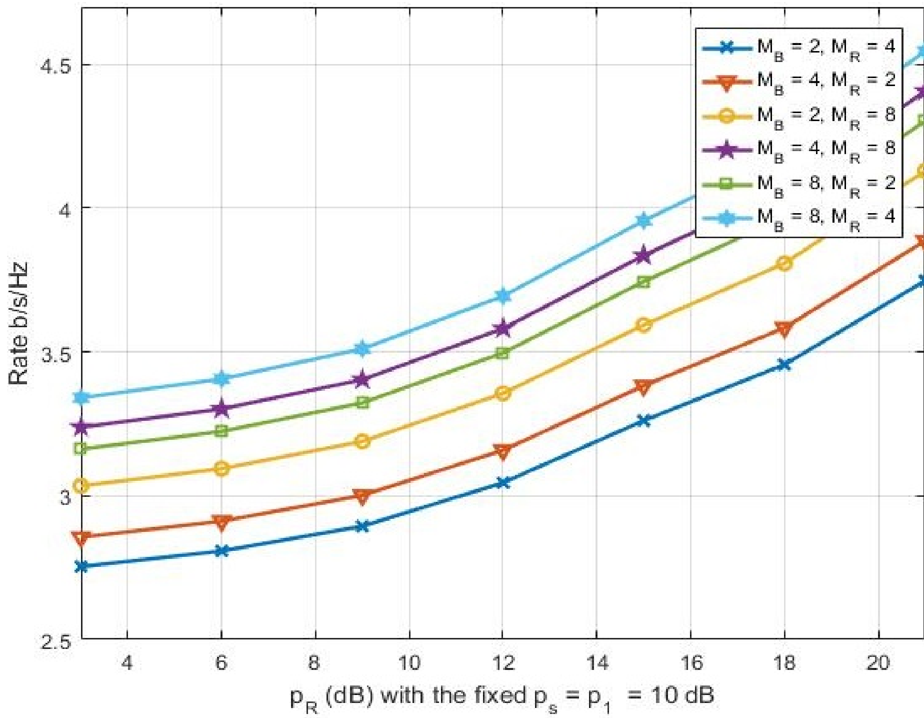

Figure 3.6: Sum-rates comparison over p_R for fixed $p_s = p_1 = 10$ dB with different number of antenna at the BS and the RS.

Furthermore, the sum-rate versus $p_s = p_1$ is higher than the sum-rate versus p_r, this is because the larger the transmit power $p_s = p_1$, the higher interference received at UE2.

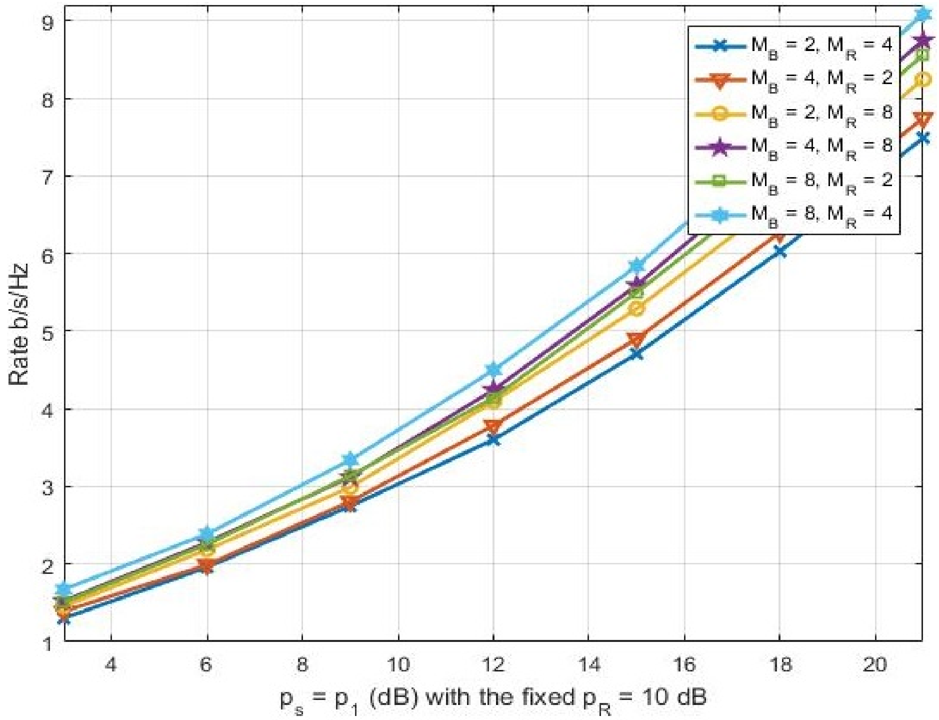

Figure 3.7: Sum-rates comparison over $p_s = p_1$ for fixed $p_R = 10$ dB with different number of antenna at the BS and the RS.

3.6 Conclusions

In this chapter, we considered two-way-relaying overhearing scheme, and extended it to the scenario of multiple antennas at both the base station and the relay station. Also, joint optimization for the precoding matrix at the relay station in the second time slot and the overhearing weights at the uplink user is performed. The simulation results demonstrate high gain of the sum-rate with multiple antennas at the base station relative to multiple antennas at the relay station, which because of having less interference at the base station.

CHAPTER 4

ADAPTIVE MIMO OVERHEARING IN TWO-WAY RELAYING CHANNELS

4.1 Introduction

In this chapter, an overhearing relay model for TWR with multi-antenna at all terminals, where one user transmits the signals or data to the BS and the other user receives the signals from the BS. In addition, there is no direct link between the BS and the users, and the downlink user overhears the signals from the uplink user and exploits the overheard signals to improve the detection performance. The downlink user detects the desired signals by using MMSE and MMSE-SICs detectors. Moreover, we jointly optimize the relay precoder in the second time slot and the transmit weight power matrices at the uplink user in both time slots. Joint optimization is performed via an iterative algorithm in the sense of maximizing the minimum SINR. Simulation results show that the joint design of the relay precoder and overhearing weight matrices provides significant sum-rate gain compared to the overhearing scheme with multiple antennas at both the BS and the RS and single-antenna at the UEs.

The reminder of this chapter is arranged as follows: section 4.2 describes the system model and the channel model; section 4.3 provides the analysis of SINRs; section 4.4 formulates the problems for the relay precoder and transmit weight matrices for the uplink user; section 4.5 discusses the simulation results for the overhearing relay scheme; section 4.6 state the conclusions.

4.2 The overhearing system model with multiple antennas at the users

The system model for this chapter is extended from the scheme in chapter 3 . The scheme consists of the BS (M_B antennas), the RS (M_R antennas), and the two UEs (M_U antennas). All terminals with multiple antennas as shown in Fig. 4.1, so, the connection between the BS and end users is MIMO link. AF relay assists the BS and UEs to communicate to each others. One of the user is uplink user, while the other UE is downlink user, and the two UEs are at the cell-edge and no direct link between the UEs and the BS. The communication will be in two-time slots. In the MAC slot, the BS and UE1 transmit the signals $\sqrt{p_s}\boldsymbol{I}_B\boldsymbol{x}_2$, $\boldsymbol{W}_1\boldsymbol{x}_1$

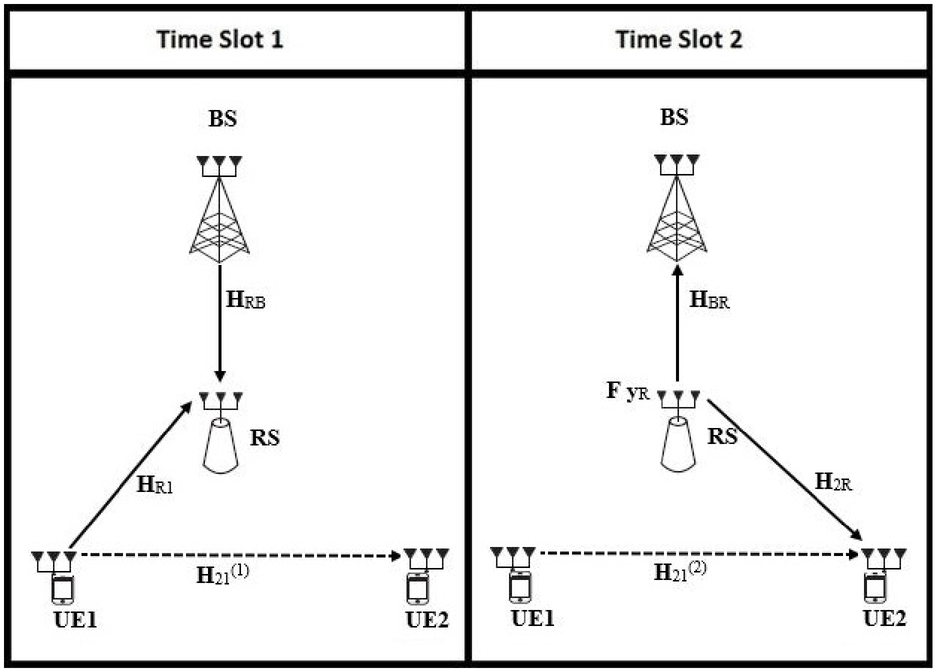

Figure 4.1: The system model.

to the RS, respectively, wile UE2 overhears the signals from UE1. The received signal at the RS and UE2 in the first time slot can be expressed as

$$\begin{aligned} \boldsymbol{y}_R &= \sqrt{p_s}\boldsymbol{H}_{RB}\boldsymbol{I}_B\boldsymbol{x}_2 + \boldsymbol{W}_1\boldsymbol{H}_{R1}\boldsymbol{x}_1 + \boldsymbol{n}_R, \\ \boldsymbol{y}_2^{(1)} &= \boldsymbol{W}_1\boldsymbol{H}_{21}^{(1)}\boldsymbol{x}_1 + \boldsymbol{n}_2^{(1)}, \end{aligned} \tag{4.1}$$

where the notations in (4.1) are defined as the following:

- $\boldsymbol{H}_{RB} \in \mathbb{C}^{M_R \times M_B}$ is the channel coefficient matrix from the BS to the RS.
- $\boldsymbol{H}_{R1} \in \mathbb{C}^{M_R \times M_U}$ is the channel coefficient matrix from UE1 to the RS.
- $\boldsymbol{H}_{21}$ is the overhearing channel coefficient matrix from UE1 to UE2.
- $\sqrt{p_s}$ is the total transmit power at the BS and defined as $p_s = Tr\{p_1, p_2, ..., p_{M_B}\}$.

- $\boldsymbol{W}_1$ is the weight transmit matrix at UE1 in the first time slot.

- $\boldsymbol{x}_1$ is the unit-power signal from UE1 to the BS.

- $\boldsymbol{x}_2$ is the unit-power signal from the BS to UE2.

- $\boldsymbol{I}_B = \boldsymbol{I}_{M_B}$ is the identity matrix.

- $\boldsymbol{n}_R \in \mathbb{C}^{M_R \times 1} \sim \mathcal{CN}(0, I_{M_R})$ and $\boldsymbol{n}_2^{(1)} \in \mathbb{C}^{M_U \times 1} \sim \mathcal{CN}(0, I_{M_U})$ are the AWGN at the RS and UE2 in the first time slot, respectively.

In the second time slot, The RS multiplies the received signals by the precoding matrix $\boldsymbol{F} \in \mathbb{C}^{M_R X M_R}$, then broadcasts $\boldsymbol{F}\boldsymbol{y}_R$. Also, UE1 transmits again $\boldsymbol{x}_1$ with a different weight matrix $\boldsymbol{W}_2$ to UE2 as overheard signals to improve the cancellation of the interference signals at the UE2. The transmit power constraint at the RS is given by

$$\begin{aligned}
p_{RT} =& Tr\{(\boldsymbol{F}\boldsymbol{y}_R)^H (\boldsymbol{F}\boldsymbol{y}_R)\} \\
=& Tr\{\left(\sqrt{p_s}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{I}_B\boldsymbol{x}_2 + \boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{W}_1\boldsymbol{x}_1 + \boldsymbol{F}\boldsymbol{n}_R\right)^H \\
&\left(\sqrt{p_s}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{I}_B\boldsymbol{x}_2 + \boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{W}_1\boldsymbol{x}_1 + \boldsymbol{F}\boldsymbol{n}_R\right)\} \\
=& p_s Tr\{\boldsymbol{I}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{I}_B\} + Tr\{\boldsymbol{W}_1^H\boldsymbol{H}_{R1}^H\boldsymbol{F}^H\boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{W}_1\} \\
&+ Tr\{\boldsymbol{F}^H\boldsymbol{F}\} \leq p_R, \\
=& p_s Tr\{\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{F}\boldsymbol{H}_{RB}\} + Tr\{\boldsymbol{W}_1^H\boldsymbol{H}_{R1}^H\boldsymbol{F}^H\boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{W}_1\} + Tr\{\boldsymbol{F}^H\boldsymbol{F}\} \leq p_R,
\end{aligned} \tag{4.2}$$

where p_R is the maximum transmit power at the RS, $\mathbb{E}\left[\boldsymbol{x}_1^H\boldsymbol{x}_1\right] = \mathbb{E}\left[\boldsymbol{x}_1\boldsymbol{x}_1^H\right] = I_{M_U}, \mathbb{E}\left[\boldsymbol{x}_2^H\boldsymbol{x}_2\right] = \mathbb{E}\left[\boldsymbol{x}_2\boldsymbol{x}_2^H\right] = I_{M_B}$, and $\mathbb{E}\left[\boldsymbol{n}_R^H\boldsymbol{n}_R\right] = \mathbb{E}\left[\boldsymbol{n}_R\boldsymbol{n}_R^H\right] = I_{M_R}$.

The received signals at the BS and UE2 in the BC slot are, respectively.

$$\begin{aligned}
\boldsymbol{y}_B &= \boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{y}_R + \boldsymbol{n}_B \\
&= \sqrt{p_s}\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{I}_B\boldsymbol{x}_2 + \boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{W}_1\boldsymbol{x}_1 + \boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{n}_R + \boldsymbol{n}_B, \\
\boldsymbol{y}_2^{(2)} &= \boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{y}_R + \boldsymbol{H}_{21}^{(2)}\boldsymbol{W}_2\boldsymbol{x}_1 + \boldsymbol{n}_2^{(2)} \\
&= \sqrt{p_s}\boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{I}_B\boldsymbol{x}_2 + \boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{W}_1\boldsymbol{x}_1 + \boldsymbol{H}_{21}^{(2)}\boldsymbol{W}_2\boldsymbol{x}_1 + \boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{n}_R + \boldsymbol{n}_2^{(2)},
\end{aligned} \tag{4.3}$$

where

- $\boldsymbol{H}_{BR} \in \mathbb{C}^{M_B \times M_R}$ is the channel coefficient matrix from the RS to the BS.
- $\boldsymbol{H}_{2R} \in \mathbb{C}^{M_U \times M_R}$ is the channel coefficient matrix from the RS to UE2.
- $\boldsymbol{n}_B \in \mathbb{C}^{M_B \times 1} \sim \mathcal{CN}(0, I_{M_B})$ and $\boldsymbol{n}_2^{(2)} \in \mathbb{C}^{M_U \times 1} \sim \mathcal{CN}(0, I_{M_U})$ are AWGN at the RS and UE2 in the BC slot, respectively.

4.3 Signal-To-Interference-Plus-Noise-Ratio

Due to the complexity associated with applying MMSE-SIC with ranking, it is assumed that each terminal has two antennas, and the streams is approximated as Gaussian distribution [76, 77].

Notation: If we have a matrix A with size of $p \times q$, the notation of $A[i]$ referred to the i^{th} column vector of A, for example: $A = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix}_{2\times 2}$, Thus, $A[1] = \begin{bmatrix} 1 \\ 3 \end{bmatrix}_{2\times 1}$, and $A[2] = \begin{bmatrix} 2 \\ 4 \end{bmatrix}_{2\times 1}$.

The BS knows the channel coefficient matrix from the BS to the RS, and exploits the self-interference cancellation to cancel its signals $\sqrt{p_s}\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{I}_B\boldsymbol{x}_2$ from the received signal. Thus, the received signal at the BS consists of the desired signals and the noise, so the expression of $\boldsymbol{y}_B$ in (4.3) reduces to

$$\boldsymbol{y}_B = \boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{x}_1 + \boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{n}_R + \boldsymbol{n}_B. \tag{4.4}$$

Thus, the BS decodes the strongest stream first, then removes that stream from the received signal before detection of the other stream. The SINR and SNR at the BS can be expressed as

$$\begin{aligned} SINR_{B,i} &= \frac{\left\|\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{W}_1[i]\right\|^2}{\left\|\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{W}_1[j]\right\|^2 + \left\|\boldsymbol{H}_{BR}\boldsymbol{F}\right\|^2 + M_B}, \\ &\text{and} \\ SNR_{B,j} &= \frac{\left\|\boldsymbol{H}_{BR}\boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{W}_1[j]\right\|^2}{\left\|\boldsymbol{H}_{BR}\boldsymbol{F}\right\|^2 + M_B}, \end{aligned} \tag{4.5}$$

where the i^{th} stream is stronger than the j^{th} stream and **for all the notation in this chapter**. The received signals at UE2 over two-time slots can be written as

$$\begin{aligned}
\boldsymbol{Y}_2 = \begin{bmatrix} \boldsymbol{y}_2^{(1)} \\ \boldsymbol{y}_2^{(2)} \end{bmatrix} &= \begin{bmatrix} \boldsymbol{H}_{21}^{(1)}\boldsymbol{W}_1 & 0s \\ \boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{W}_1 + \boldsymbol{H}_{21}^{(2)}\boldsymbol{W}_2 & \sqrt{p_s}\boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{I}_B \end{bmatrix} \begin{bmatrix} \boldsymbol{x}_1 \\ \boldsymbol{x}_2 \end{bmatrix} \\
&+ \begin{bmatrix} \boldsymbol{n}_2^{(1)} \\ \boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{n}_R + \boldsymbol{n}_2^{(2)} \end{bmatrix} \\
&= \boldsymbol{H}_1\boldsymbol{x}_1 + \boldsymbol{H}_2\boldsymbol{x}_2 + \boldsymbol{n}_2.
\end{aligned} \tag{4.6}$$

Now, UE2 applies MMSE to the received signals to decode the desired signals $\boldsymbol{x}_2$, while $\boldsymbol{x}_1$ is the interference signals over the two-time slots. Therefore, we obtain the SINRs for each stream. $SINR_{1,1}$ and $SINR_{1,2}$ for $\boldsymbol{x}_1$, and $SINR_{2,1}$ and $SINR_{2,2}$ for $\boldsymbol{x}_2$. The SINRs of the i^{th} stream can be expressed as

$$\begin{aligned}
SINR_{1,i} &= \frac{\left\|\boldsymbol{H}_1[i]\right\|^2}{\left\|\boldsymbol{H}_1[j]\right\|^2 + \sum_{k=1}^{M_B=2}\left\|\boldsymbol{H}_2[k]\right\|^2 + \|\boldsymbol{n}_2\|^2} \\
&= \frac{\left\|\boldsymbol{H}_{21}^{(1)}\boldsymbol{W}_1[i]\right\|^2 + \left\|\left(\boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{W}_1 + \boldsymbol{H}_{21}^{(2)}\boldsymbol{W}_2\right)[i]\right\|^2}{\left\|\boldsymbol{H}_{21}^{(1)}\boldsymbol{W}_1[j]\right\|^2 + \left\|\left(\boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{W}_1 + \boldsymbol{H}_{21}^{(2)}\boldsymbol{W}_2\right)[j]\right\|^2 + Z_{x2} + \varphi},
\end{aligned} \tag{4.7}$$

$$
\begin{aligned}
SINR_{2,i} &= \frac{\text{Power of the desired signal}}{\text{Power of the interference and the noise}} \\
&= \frac{\left\|\boldsymbol{H}_2[i]\right\|^2}{\left\|\boldsymbol{H}_2[j]\right\|^2 + \sum_{k=1}^{M_U=2}\left\|\boldsymbol{H}_1[k]\right\|^2 + \left\|\boldsymbol{n}_2\right\|^2} \\
&= \frac{\frac{p_s}{M_B}\left\|\boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{I}_B[i]\right\|^2}{\frac{p_s}{M_B}\left\|\boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{I}_B[j]\right\|^2 + Z_{x1} + \varphi},
\end{aligned} \tag{4.8}
$$

where $Z_{x1} = \sum_{k=1}^{M_U=2}\left(\left\|\boldsymbol{H}_{21}^{(1)}\boldsymbol{W}_1[k]\right\|^2 + \left\|\left(\boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{W}_1 + \boldsymbol{H}_{21}^{(2)}\boldsymbol{W}_2\right)[k]\right\|^2\right)$, $Z_{x2} = \sum_{k=1}^{M_B=2}\frac{p_s}{M_B}\left\|\boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{I}_B[k]\right\|^2$, and $\varphi = \left\|\boldsymbol{I}_2 + \boldsymbol{H}_{2R}\boldsymbol{F}\right\|^2 + M_U$.

When UE2 decodes the desired signal, it is assumed that six cases are given in Table. 4.1. UE2 decodes a stream whatever is, then remove that stream from the received signal. Thus, the interference terms of the SINRs for the other streams will change according to the stream or streams were decoded. For example, in the case of the MMSE, the strongest SINR for the symbol of $x_{2,1}$, UE2 decodes the stream of $x_{2,1}$ first, then $SINR_{2,2}$ reduces to

$$
SINR_{2,2} = \frac{\frac{p_s}{M_B}\left\|\boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{I}_B[2]\right\|^2}{Z_{x1} + \left\|\boldsymbol{I}_2 + \boldsymbol{H}_{2R}\boldsymbol{F}\right\|^2 + M_U}. \tag{4.9}
$$

Another example, UE2 decodes all symbols except $x_{2,2}$, thus, the $SNR_{2,2}$ can be written as

$$
SNR_{2,2} = \frac{\frac{p_s}{M_B}\left\|\boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{I}_B[2]\right\|^2}{\left\|\boldsymbol{I}_2 + \boldsymbol{H}_{2R}\boldsymbol{F}\right\|^2 + M_U}. \tag{4.10}
$$

Case	Ranking of the signals	Ranking of the signals	Ranking of the signals	Ranking of the signals
MMSE	$SINR_{2,1}$ $SINR_{2,2}$ $SINR_{1,1}$ $SINR_{1,2}$	$SINR_{2,1}$ $SINR_{2,2}$ $SINR_{1,2}$ $SINR_{1,1}$	$SINR_{2,2}$ $SINR_{2,1}$ $SINR_{1,1}$ $SINR_{1,2}$	$SINR_{2,2}$ $SINR_{2,1}$ $SINR_{1,2}$ $SINR_{1,1}$
MMSE-SIC1	$SINR_{1,1}$ $SINR_{1,2}$ $SINR_{2,1}$ $SINR_{2,2}$	$SINR_{1,1}$ $SINR_{1,2}$ $SINR_{2,2}$ $SINR_{2,1}$	$SINR_{1,2}$ $SINR_{1,1}$ $SINR_{2,1}$ $SINR_{2,2}$	$SINR_{1,2}$ $SINR_{1,1}$ $SINR_{2,2}$ $SINR_{2,1}$
MMSE-SIC2	$SINR_{1,1}$ $SINR_{2,1}$ $SINR_{2,2}$ $SINR_{1,2}$	$SINR_{1,1}$ $SINR_{2,2}$ $SINR_{2,1}$ $SINR_{1,2}$		
MMSE-SIC3	$SINR_{1,2}$ $SINR_{2,1}$ $SINR_{2,2}$ $SINR_{1,1}$	$SINR_{1,2}$ $SINR_{2,2}$ $SINR_{2,1}$ $SINR_{1,1}$		
MMSE-SIC4	$SINR_{2,1}$ $SINR_{1,1}$ $SINR_{1,2}$ $SINR_{2,2}$	$SINR_{2,1}$ $SINR_{1,2}$ $SINR_{1,1}$ $SINR_{2,2}$		
MMSE-SIC5	$SINR_{2,2}$ $SINR_{1,1}$ $SINR_{1,2}$ $SINR_{2,1}$	$SINR_{2,2}$ $SINR_{1,2}$ $SINR_{1,1}$ $SINR_{2,1}$		

Table 4.1: The scenarios of the ranking of the SINRs.

4.4 Optimization of the precoding matrix at the relay and the transmit weight matrices for uplink user

The precoding matrix at the RS in the second time slot and the overhearing weight matrices at the UE1 over the two-time slots are jointly optimized to maximize the minimum weighted SINR for six cases or scenarios in the Table 4.1. The overhearing weight matrices are $\boldsymbol{W}_1$ and $\boldsymbol{W}_2$, so, we have two optimization variables for overhearing weights. In addition, the weight factors for uplink and downlink are β^{UL} and β^{DL}, respectively.

Now, we can optimize the relay precoder and the transmit weights in an adaptive way for each case. At first of the optimization, the transmit weight matrices $\boldsymbol{W}_1$ and $\boldsymbol{W}_2$ are optimized for a given the precoding matrix $\boldsymbol{F}$, then, the relay precoder is optimized for given the transmit weights.

4.4.1 Optimization of $\boldsymbol{W}_1$ and $\boldsymbol{W}_2$ for given $\boldsymbol{F}$

The optimization of $\boldsymbol{W}_1$ and $\boldsymbol{W}_2$ for all cases of the ranking of the SINRs, linear MMMSE, and MMSE-SICs are considered at UE2, where the precoding matrix at the RS is given. The optimization problem for $\boldsymbol{W}_1$ and $\boldsymbol{W}_2$ is formulated for each case in the Table 4.1 as:

- MMSE

$$\begin{aligned}
\max_{\boldsymbol{W}_1,\boldsymbol{W}_2} \quad & min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}\}, \beta^{DL} min\{SINR_{2,1}, SINR_{2,2}\}\} \\
\text{s.t.} \quad & SINR_{2,1} \geq r, SINR_{2,2} \geq r, \\
& SINR_{1,1} < r, SINR_{1,2} < r, \\
& SINR_{B,1} \geq r, SINR_{B,2} \geq r, \\
& \boldsymbol{W}_1^H \boldsymbol{W}_1 \leq \frac{p_w}{2}, \boldsymbol{W}_2^H \boldsymbol{W}_2 \leq \frac{p_w}{2}, \boldsymbol{W}_1^H \boldsymbol{W}_1 \leq p_{w_1},
\end{aligned} \tag{4.11}$$

- MMSE-SIC1

$$\begin{aligned}
\max_{\boldsymbol{W}_1,\boldsymbol{W}_2} \quad & min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}, SINR_{1,2}\}, \\
& \beta^{DL} min\{SINR^*_{2,1}, SINR^*_{2,2}\}\} \\
\text{s.t.} \quad & SINR_{2,1} < r_{SIC1}, SINR_{2,2} < r_{SIC1}, \\
& SINR_{1,1} \geq r_{SIC1}, SINR_{1,2} \geq r_{SIC1}, \\
& SINR^*_{2,1} \geq r_{SIC1}, SINR^*_{2,2} \geq r_{SIC1}, \\
& SINR_{B,1} \geq r_{SIC1}, SINR_{B,2} \geq r_{SIC1}, \\
& \boldsymbol{W}_1^H \boldsymbol{W}_1 \leq \frac{p_w}{2}, \boldsymbol{W}_2^H \boldsymbol{W}_2 \leq \frac{p_w}{2}, \boldsymbol{W}_1^H \boldsymbol{W}_1 \leq p_{w_1},
\end{aligned} \tag{4.12}$$

- MMSE-SIC2

$$
\begin{aligned}
\max_{\boldsymbol{W}_1,\boldsymbol{W}_2} \quad & min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}\}, \\
& \beta^{DL} min\{SINR^{**}_{2,1}, SINR^{**}_{2,2}\}\} \\
\text{s.t.} \quad & SINR_{2,1} < r_{SIC2}, SINR_{2,2} < r_{SIC2}, \\
& SINR_{1,1} \geq r_{SIC2}, SINR_{1,2} < r_{SIC2}, \\
& SINR^{**}_{2,1} \geq r_{SIC2}, SINR^{**}_{2,2} \geq r_{SIC2}, \\
& SINR_{B,1} \geq r_{SIC2}, SINR_{B,2} \geq r_{SIC2}, \\
& \boldsymbol{W}_1^H \boldsymbol{W}_1 \leq \frac{p_w}{2}, \boldsymbol{W}_2^H \boldsymbol{W}_2 \leq \frac{p_w}{2}, \boldsymbol{W}_1^H \boldsymbol{W}_1 \leq p_{w_1},
\end{aligned}
\tag{4.13}
$$

- MMSE-SIC3

$$
\begin{aligned}
\max_{\boldsymbol{W}_1,\boldsymbol{W}_2} \quad & min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,2}\}, \\
& \beta^{DL} min\{SINR^{***}_{2,1}, SINR^{***}_{2,2}\}\} \\
\text{s.t.} \quad & SINR_{2,1} < r_{SIC3}, SINR_{2,2} < r_{SIC3}, \\
& SINR_{1,1} < r_{SIC3}, SINR_{1,2} \geq r_{SIC3}, \\
& SINR^{***}_{2,1} \geq r_{SIC3}, SINR^{***}_{2,2} \geq r_{SIC3}, \\
& SINR_{B,1} \geq r_{SIC3}, SINR_{B,2} \geq r_{SIC3}, \\
& \boldsymbol{W}_1^H \boldsymbol{W}_1 \leq \frac{p_w}{2}, \boldsymbol{W}_2^H \boldsymbol{W}_2 \leq \frac{p_w}{2}, \boldsymbol{W}_1^H \boldsymbol{W}_1 \leq p_{w_1},
\end{aligned}
\tag{4.14}
$$

- MMSE-SIC4

$$\begin{aligned}
\max_{\boldsymbol{W}_1, \boldsymbol{W}_2} \quad & min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}, SINR_{1,2}\}, \\
& \beta^{DL} min\{SINR_{2,1}, SNR_{2,2}\}\} \\
\text{s.t.} \quad & SINR_{2,1} \geq r_{SIC4}, SINR_{2,2} < r_{SIC4}, \\
& SINR_{1,1} \geq r_{SIC4}, SINR_{1,2} \geq r_{SIC4}, \\
& SNR_{2,2} \geq r_{SIC4}, \\
& SINR_{B,1} \geq r_{SIC4}, SINR_{B,2} \geq r_{SIC4}, \\
& \boldsymbol{W}_1^H \boldsymbol{W}_1 \leq \frac{p_w}{2}, \boldsymbol{W}_2^H \boldsymbol{W}_2 \leq \frac{p_w}{2}, \boldsymbol{W}_1^H \boldsymbol{W}_1 \leq p_{w_1},
\end{aligned} \tag{4.15}$$

- MMSE-SIC5

$$\begin{aligned}
\max_{\boldsymbol{W}_1, \boldsymbol{W}_2} \quad & min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}, SINR_{1,2}\}, \\
& \beta^{DL} min\{SNR_{2,1}, SINR_{2,2}\}\} \\
\text{s.t.} \quad & SINR_{2,1} < r_{SIC5}, SINR_{2,2} \geq r_{SIC5}, \\
& SINR_{1,1} \geq r_{SIC5}, SINR_{1,2} \geq r_{SIC5}, \\
& SNR_{2,1} \geq r_{SIC5}, \\
& SINR_{B,1} \geq r_{SIC5}, SINR_{B,2} \geq r_{SIC5}, \\
& \boldsymbol{W}_1^H \boldsymbol{W}_1 \leq \frac{p_w}{2}, \boldsymbol{W}_2^H \boldsymbol{W}_2 \leq \frac{p_w}{2}, \boldsymbol{W}_1^H \boldsymbol{W}_1 \leq p_{w_1},
\end{aligned} \tag{4.16}$$

where p_w is the total sum-transmit power at UE1 over the two-time slots, and $p_{w_1} = \frac{p_R - p_s Tr\{\boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{RB}\} - Tr\{\boldsymbol{F}^H \boldsymbol{F}\}}{Tr\{\boldsymbol{H}_{R1}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{R1}\}}$, $SINR_{2,i}^{*}$ is without interference from symbols $x_{1,1}$ and $x_{1,2}$, $SINR_{2,i}^{**}$ is without interference from symbol

$x_{1,2}$, $SINR^{***}_{2,i}$ is without interference from symbol $x_{1,1}$, and the rates accounting for the functions of (4.11), (4.12), (4.13), (4.14), (4.15), and (4.16) are

$r = min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}\}, \beta^{DL} min\{SINR_{2,1}, SINR_{2,2}\}\}$,

$r_{SIC1} = min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}, SINR_{1,2}\}, \beta^{DL} min\{SINR^{*}_{2,1}, SINR^{*}_{2,2}\}\}$,

$r_{SIC2} = min\{min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}\}, \beta^{DL} min\{SINR^{**}_{2,1}, SINR^{**}_{2,2}\}$,

$r_{SIC3} = min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,2}\}, \beta^{DL} min\{SINR^{***}_{2,1}, SINR^{***}_{2,2}\}\}$,

$r_{SIC4} = min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}, SINR_{1,2}\}, \beta^{DL} min\{SINR_{2,1}, SNR_{2,2}\}\}$,

and

$r_{SIC5} = min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}, SINR_{1,2}\}, \beta^{DL} min\{SNR_{2,1}, SINR_{2,2}\}\}$,

respectively.

To simplify the optimization of the overhearing weight matrices $\boldsymbol{W}_1$ and $\boldsymbol{W}_2$, we need to set $\boldsymbol{W}_1$ and $\boldsymbol{W}_2$ into vector form instead of matrix form. Therefore, the transmit weights can be expressed as $\boldsymbol{w}_1 = vec\{\boldsymbol{W}_1\}$ and $\boldsymbol{w}_2 = vec\{\boldsymbol{W}_2\}$.

We need to express SINRs with respect of $\boldsymbol{w}_1$ and $\boldsymbol{w}_2$. The SINRs can be rewritten as

$$
\begin{aligned}
SINR_{1,i} &= \frac{\left(\boldsymbol{w}_1^H \boldsymbol{K}_1 A_i \boldsymbol{w}_1\right) + \left(\boldsymbol{w}_{12}^H[i] B \boldsymbol{w}_{12}[i]\right)}{\left(\boldsymbol{w}_1^H \boldsymbol{K}_1 A_j \boldsymbol{w}_1\right) + \left(\boldsymbol{w}_{12}^H[j] B \boldsymbol{w}_{12}[j]\right) + \sum_{k=1}^{M_B=2} c_k + d + M_U}, \\
SINR_{2,i} &= \frac{c_i}{c_j + \sum_{k=1}^{M_U=2} \left(\left(\boldsymbol{w}_1^H \boldsymbol{K}_1 A_k \boldsymbol{w}_1\right) + \left(\boldsymbol{w}_{12}^H[k] B \boldsymbol{w}_{12}[k]\right)\right) + d + M_U}, \\
SINR_{B,i} &= \frac{\boldsymbol{w}_1^H \boldsymbol{K}_2 A_i \boldsymbol{w}_1}{\boldsymbol{w}_1^H \boldsymbol{K}_2 A_j \boldsymbol{w}_1 + e + M_B},
\end{aligned}
\tag{4.17}
$$

where the notation in (4.17) are referred to as

$$
\begin{aligned}
\boldsymbol{K}_1 &= (\boldsymbol{H}_{21}^{(1)H}\boldsymbol{H}_{21}^{(1)}) \otimes (I_{M_U}),\\
\boldsymbol{K}_1 &= (\boldsymbol{H}_{BR}^{H}\boldsymbol{F}^{H}\boldsymbol{F}\boldsymbol{H}_{BR}) \otimes (\boldsymbol{H}_{R1}\boldsymbol{H}_{R1}^{H}),\\
A_1 &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, A_2 = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},\\
B &= \begin{bmatrix} \boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{H}_{R1}^{H}\boldsymbol{F}^{H}\boldsymbol{H}_{2R}^{H} & \boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{R1}\boldsymbol{H}_{21}^{(2)H} \\ \boldsymbol{H}_{21}^{(2)}\boldsymbol{H}_{R1}^{H}\boldsymbol{F}^{H}\boldsymbol{H}_{21}^{H} & \boldsymbol{H}_{21}^{(2)}\boldsymbol{H}_{21}^{(2)H} \end{bmatrix}, \qquad (4.18)\\
c_1 &= \frac{p_s}{M_B}\left\|\boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{I}_B[1]\right\|^2,\\
c_2 &= \frac{p_s}{M_B}\left\|\boldsymbol{H}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{I}_B[2]\right\|^2,\\
d &= \|\boldsymbol{I}_2 + \boldsymbol{H}_{2R}\boldsymbol{F}\|^2, e = \|\boldsymbol{H}_{2R}\boldsymbol{F}\|^2,
\end{aligned}
$$

and

$$
\boldsymbol{w}_{12}^{H}[i] = \begin{bmatrix} \boldsymbol{w}_1^{H}[i] & \boldsymbol{w}_2^{H}[i] \end{bmatrix}.
$$

4.4.2 Optimization of $\boldsymbol{F}$ for given $\boldsymbol{W}_1$ and $\boldsymbol{W}_2$

The optimization of the relay precoder is derived in the sense of maximizing minimum weighted SINR, for given the transmit weight matrices at UE1. The optimization problem of $\boldsymbol{F}$ for given $\boldsymbol{W}_1$ and $\boldsymbol{W}_2$ is formulated for each case as

- MMSE

$$\begin{aligned}
\max_{F} \quad & min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}\}, \beta^{DL}min\{SINR_{2,1}, SINR_{2,2}\}\} \\
\text{s.t.} \quad & SINR_{2,1} \geq r, SINR_{2,2} \geq r, \\
& SINR_{1,1} < r, SINR_{1,2} < r, \\
& SINR_{B,1} \geq r, SINR_{B,2} \geq r, \\
& p_s Tr\{\boldsymbol{I}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{I}_B\} + Tr\{\boldsymbol{W}_1^H \boldsymbol{H}_{R1}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{R1} \boldsymbol{W}_1\} \\
& + Tr\{\boldsymbol{F}^H \boldsymbol{F}\} \leq p_R,
\end{aligned} \tag{4.19}$$

- MMSE-SIC1

$$\begin{aligned}
\max_{F} \quad & min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}, SINR_{1,2}\}, \\
& \beta^{DL}min\{SINR^*_{2,1}, SINR^*_{2,2}\}\} \\
\text{s.t.} \quad & SINR_{2,1} < r_{SIC1}, SINR_{2,2} < r_{SIC1}, \\
& SINR_{1,1} \geq r_{SIC1}, SINR_{1,2} \geq r_{SIC1}, \\
& SINR^*_{2,1} \geq r_{SIC1}, SINR^*_{2,2} \geq r_{SIC1}, \\
& SINR_{B,1} \geq r_{SIC1}, SINR_{B,2} \geq r_{SIC1}, \\
& p_s Tr\{\boldsymbol{I}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{I}_B\} + Tr\{\boldsymbol{W}_1^H \boldsymbol{H}_{R1}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{R1} \boldsymbol{W}_1\} \\
& + Tr\{\boldsymbol{F}^H \boldsymbol{F}\} \leq p_R,
\end{aligned} \tag{4.20}$$

- MMSE-SIC2

$$
\begin{aligned}
\max_{F} \quad & min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}\}, \\
& \beta^{DL} min\{SINR^{**}_{2,1}, SINR^{**}_{2,2}\}\} \\
\text{s.t.} \quad & SINR_{2,1} < r_{SIC2}, SINR_{2,2} < r_{SIC2}, \\
& SINR_{1,1} \geq r_{SIC2}, SINR_{1,2} < r_{SIC2}, \\
& SINR^{**}_{2,1} \geq r_{SIC2}, SINR^{**}_{2,2} \geq r_{SIC2}, \\
& SINR_{B,1} \geq r_{SIC2}, SINR_{B,2} \geq r_{SIC2}, \\
& p_s Tr\{\boldsymbol{I}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{I}_B\} + Tr\{\boldsymbol{W}_1^H \boldsymbol{H}_{R1}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{R1} \boldsymbol{W}_1\} \\
& + Tr\{\boldsymbol{F}^H \boldsymbol{F}\} \leq p_R,
\end{aligned}
\tag{4.21}
$$

- MMSE-SIC3

$$
\begin{aligned}
\max_{F} \quad & min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,2}\}, \\
& \beta^{DL} min\{SINR^{***}_{2,1}, SINR^{***}_{2,2}\}\} \\
\text{s.t.} \quad & SINR_{2,1} < r_{SIC3}, SINR_{2,2} < r_{SIC3}, \\
& SINR_{1,1} < r_{SIC3}, SINR_{1,2} \geq r_{SIC3}, \\
& SINR^{***}_{2,1} \geq r_{SIC3}, SINR^{***}_{2,2} \geq r_{SIC3}, \\
& SINR_{B,1} \geq r_{SIC3}, SINR_{B,2} \geq r_{SIC3}, \\
& p_s Tr\{\boldsymbol{I}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{I}_B\} + Tr\{\boldsymbol{W}_1^H \boldsymbol{H}_{R1}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{R1} \boldsymbol{W}_1\} \\
& + Tr\{\boldsymbol{F}^H \boldsymbol{F}\} \leq p_R,
\end{aligned}
\tag{4.22}
$$

- MMSE-SIC4

$$
\begin{aligned}
\max_{F} \quad & min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}, SINR_{1,2}\},\\
& \beta^{DL}min\{SINR_{2,1}, SNR_{2,2}\}\}\\
\text{s.t.} \quad & SINR_{2,1} \geq r_{SIC4}, SINR_{2,2} < r_{SIC4},\\
& SINR_{1,1} \geq r_{SIC4}, SINR_{1,2} \geq r_{SIC4},\\
& SNR_{2,2} \geq r_{SIC4},\\
& SINR_{B,1} \geq r_{SIC4}, SINR_{B,2} \geq r_{SIC4},\\
& p_s Tr\{\boldsymbol{I}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{I}_B\} + Tr\{\boldsymbol{W}_1^H \boldsymbol{H}_{R1}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{R1} \boldsymbol{W}_1\}\\
& + Tr\{\boldsymbol{F}^H \boldsymbol{F}\} \leq p_R,
\end{aligned}
\tag{4.23}
$$

- MMSE-SIC5

$$
\begin{aligned}
\max_{F} \quad & min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}, SINR_{1,2}\},\\
& \beta^{DL}min\{SNR_{2,1}, SINR_{2,2}\}\}\\
\text{s.t.} \quad & SINR_{2,1} < r_{SIC5}, SINR_{2,2} \geq r_{SIC5},\\
& SINR_{1,1} \geq r_{SIC5}, SINR_{1,2} \geq r_{SIC5},\\
& SNR_{2,1} \geq r_{SIC5},\\
& SINR_{B,1} \geq r_{SIC5}, SINR_{B,2} \geq r_{SIC5},\\
& p_s Tr\{\boldsymbol{I}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{I}_B\} + Tr\{\boldsymbol{W}_1^H \boldsymbol{H}_{R1}^H \boldsymbol{F}^H \boldsymbol{F} \boldsymbol{H}_{R1} \boldsymbol{W}_1\}\\
& + Tr\{\boldsymbol{F}^H \boldsymbol{F}\} \leq p_R,
\end{aligned}
\tag{4.24}
$$

To simplify the optimization of the relay precoder, we need to set the precoding matrix into vector form instead of matrix form. Therefore, the relay precoder can be expressed as $\boldsymbol{f} = vec\{\boldsymbol{F}\}$. The SINRs and the power constraint at the RS can be rewritten in term of $\boldsymbol{f}$ as

$$\begin{aligned}
SINR_{1,i} &= \frac{g_i + \tilde{\boldsymbol{f}}^H L_i \tilde{\boldsymbol{f}}}{g_j + \tilde{\boldsymbol{f}}^H L_j \tilde{\boldsymbol{f}} + \sum_{k=1}^{M_B=2}\left(\boldsymbol{f}^H \boldsymbol{K}_{7(k)} \boldsymbol{f}\right) + \tilde{\boldsymbol{f}}^H Q \tilde{\boldsymbol{f}} + M_U},\\
SINR_{2,i} &= \frac{\boldsymbol{f}^H \boldsymbol{K}_{7(i)} \boldsymbol{f}}{\boldsymbol{f}^H K_{7(j)} \boldsymbol{f} + \sum_{k=1}^{M_U=2}\left(g_k + \tilde{\boldsymbol{f}}^H L_k \tilde{\boldsymbol{f}}\right) + \tilde{\boldsymbol{f}}^H Q \tilde{\boldsymbol{f}} + M_U},\\
SINR_{B,i} &= \frac{\boldsymbol{f}^H \boldsymbol{K}_{9(i)} \boldsymbol{f}}{\boldsymbol{f}^H \boldsymbol{K}_{9(j)} \boldsymbol{f} + \boldsymbol{f}^H \boldsymbol{K}_{10} \boldsymbol{f} + M_B},\\
p_{RT} &= \boldsymbol{f}^H O \boldsymbol{f} \leq p_R,
\end{aligned} \tag{4.25}$$

where

$$\begin{aligned}
\boldsymbol{K}_{3(i)} &= (\boldsymbol{H}_{2R}^H \boldsymbol{H}_{2R}) \otimes (\boldsymbol{H}_{R1} \boldsymbol{W}_1[i] \boldsymbol{W}_1^H[i] \boldsymbol{H}_{R1}^H),\\
\boldsymbol{K}_{4(i)} &= (\boldsymbol{H}_{21}^{(2)H}) \otimes (\boldsymbol{H}_{21}^{(2)} \boldsymbol{H}_{R1} \boldsymbol{W}_1[i] \boldsymbol{W}_2^H[i]),\\
\boldsymbol{K}_{5(i)} &= (\boldsymbol{H}_{2R}^H \boldsymbol{H}_{R1}^H) \otimes (\boldsymbol{H}_{21}^{(2)} \boldsymbol{W}_2[i] \boldsymbol{W}_1^H[i]),\\
\boldsymbol{K}_{6(i)} &= (\boldsymbol{H}_{21}^{(2)H} \boldsymbol{W}_2^H[i] \boldsymbol{W}_2[i] \boldsymbol{H}_{21}^{(2)}) \otimes (I_{M_R}),\\
\boldsymbol{K}_{7(i)} &= \frac{p_s}{M_B}(\boldsymbol{H}_{2R}^H \boldsymbol{H}_{2R}) \otimes (\boldsymbol{H}_{RB} I_{M_B}[i] I_{M_B}^H[i] \boldsymbol{H}_{RB}^H),\\
\boldsymbol{K}_8 &= (\boldsymbol{H}_{2R}^H \boldsymbol{H}_{2R}) \otimes (I_{M_R}),\\
\boldsymbol{K}_{8.1} &= (\boldsymbol{H}_{2R}^H) \otimes (I_{M_R}),\\
\boldsymbol{K}_{8.2} &= (I_{M_R}) \otimes (\boldsymbol{H}_{2R}),\\
\boldsymbol{K}_{9(i)} &= (\boldsymbol{H}_{BR}^H \boldsymbol{H}_{BR}) \otimes (\boldsymbol{H}_{R1} \boldsymbol{W}_1[i] \boldsymbol{W}_1^H[i] \boldsymbol{H}_{R1}^H),
\end{aligned} \tag{4.26}$$

$$
\begin{aligned}
&\boldsymbol{K}_{10} = (\boldsymbol{H}_{BR}^{H}\boldsymbol{H}_{BR}) \otimes (I_{M_R}),\\
&\boldsymbol{K}_{11} = (\frac{p_s}{M_B} I_{M_R}) \otimes (\boldsymbol{H}_{RB}^{H}\boldsymbol{H}_{RB}),\\
&\boldsymbol{K}_{12} = (\boldsymbol{W}_1\boldsymbol{W}_1^{H}) \otimes (\boldsymbol{H}_{R1}^{H}\boldsymbol{H}_{R1}),\\
&\quad g_1 = \left\|\boldsymbol{H}_{21}^{(1)}\boldsymbol{W}_1[1]\right\|^2, g_2 = \left\|\boldsymbol{H}_{21}^{(1)}\boldsymbol{W}_1[2]\right\|^2,\\
&\quad L_1 = \begin{bmatrix} \boldsymbol{K}_{3(1)} & \boldsymbol{K}_{4(1)} \\ \boldsymbol{K}_{5(1)} & \boldsymbol{K}_{6(1)} \end{bmatrix}, L_2 = \begin{bmatrix} \boldsymbol{K}_{3(2)} & \boldsymbol{K}_{4(2)} \\ \boldsymbol{K}_{5(2)} & \boldsymbol{K}_{6(2)} \end{bmatrix},\\
&\quad O = \boldsymbol{K}_{11} + \boldsymbol{K}_{12} + I_{M_R^2},\\
&\quad Q = \begin{bmatrix} I_{M_R^2} & \boldsymbol{K}_{8.1} \\ \boldsymbol{K}_{8.2} & \boldsymbol{K}_{8} \end{bmatrix},\\
&\quad \boldsymbol{v}_f = [1;1;\ldots;1]_{M_R\times 1},\\
&\text{and}\\
&\tilde{\boldsymbol{f}}^{H} = [\boldsymbol{f}^{H}\boldsymbol{v}_f^{T}]_{(1\times M_R^2)}.
\end{aligned} \tag{4.26}
$$

4.4.3 Iterative optimization

All the optimization problems from (4.11) to (4.16), and from (4.19) to (4.24) are non-convex, because of the expression of the SINRs, and the non-convex quadratic constraints, so, we can not find a simple solution for those problems. There are different techniques to convert a non-convex optimization problem to a convex problem, one of the option is applying SDR to all problems. In this thesis, SDR is applied to all problems, then the modified problems now can be solved in a polynomial time by SDP.

Now, we use $\boldsymbol{W}_1' = \boldsymbol{w}_1\boldsymbol{w}_1^H$, $\boldsymbol{W}_2' = \boldsymbol{w}_2\boldsymbol{w}_2^H$ and $\boldsymbol{F}' = \boldsymbol{f}\boldsymbol{f}^H$. Thus, we can solve the optimization problems in MATLAB with the code given in A CVX Code for SDR. The optimization problems from (4.11) to (4.16), and from (4.19) to (4.24) can be expressed in a convex SDR as given in Appendix 4.A. We iteratively optimize $\boldsymbol{F}$, $\boldsymbol{W}_1$, and $\boldsymbol{W}_2$ solving all problems as given in Appendix 4.A in Algorithm 2.

Algorithm 2: Minimum weighted SNR/SINR maximization

Initialization:

- Select initial $\boldsymbol{f}_i$, $\boldsymbol{w}_{1i}$, and $\boldsymbol{w}_{2i}$ randomly.
- Set $\epsilon > 0$.

MMSE and MMSE-SICs detection at UE2:
Initialize r_{min} and r_{max}, and set $\epsilon' > 0$
read current;
repeat
    Set $r_i = \frac{1}{2}(r_{max} + r_{min})$ and $i = 0$
    repeat
        Set $r = r_i$, $\boldsymbol{f} = \boldsymbol{f}_i$, $\boldsymbol{w}_1 = \boldsymbol{w}_{1i}$, and $\boldsymbol{w}_2 = \boldsymbol{w}_{1i}$
        Solve the problem of $\boldsymbol{w}_1$ and $\boldsymbol{w}_2$ for each case given in Appendix 4.A
        Solution $\boldsymbol{w}_1$ and $\boldsymbol{w}_2$ for $i + 1$
        Solve the problem of $\boldsymbol{f}$ for each case given in Appendix 4.A
        Solution $\boldsymbol{f}$ for $i + 1$
        Increase i by 1

- MMSE: by using (4.5) and (4.8) obtain $r_i = min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}\}, \beta^{DL} min\{SINR_{2,1}, SINR_{2,2}\}\}$
- MMSE-SIC1: by using (4.5), (4.7) and (4.8) obtain $r_{SIC1,i} = min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}, SINR_{1,2}\}, \beta^{DL} min\{SINR^{*}_{2,1}, SINR^{*}_{2,2}\}\}$
- MMSE-SIC2: by using (4.5), (4.7) and (4.8) obtain $r_{SIC2,i} = min\{min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}\}, \beta^{DL} min\{SINR^{**}_{2,1}, SINR^{**}_{2,2}\}$
- MMSE-SIC3: by using (4.5), (4.7) and (4.8) obtain $r_{SIC3,i} = min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,2}\}, \beta^{DL} min\{SINR^{***}_{2,1}, SINR^{***}_{2,2}\}\}$
- MMSE-SIC4: by using (4.5), (4.7) and (4.8) obtain $r_{SIC4,i} = min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}, SINR_{1,2}\}, \beta^{DL} min\{SINR_{2,1}, SNR_{2,2}\}\}$
- MMSE-SIC5: by using (4.5), (4.7) and (4.8) obtain $r_{SIC5,i} = min\{\beta^{UL}\{SNR_{B,1}, SNR_{B,2}, SINR_{1,1}, SINR_{1,2}\}, \beta^{DL} min\{SNR_{2,1}, SINR_{2,2}\}\}$

    until $\frac{|r_i - r_{i-1}|}{r_{i-1}} \leq \epsilon'$;
    if r_i *is feasible* **then**
        $r_{min} = r_i$
    else
        else $r_{max} = r_i$
    end
until $r_{max} - r_{min} \leq \epsilon$;
Minimum Weighted SNR/SINR:
$max(r, r_{SIC1}, r_{SIC2}, r_{SIC3}, r_{SIC4}, r_{SIC5})$

4.5 Simulation Results And Discussions

In this section of thesis work, simulation results of extended MIMO overhearing channel scenario are performed and analyzed.

We assume that each channel coefficient or noise component is $\sim \mathcal{CN}(0,1)$, and the threshold is set to $\epsilon = \epsilon' = 0.01$. Also, we initialize the vector of $\boldsymbol{f}$, $\boldsymbol{w}_1$ and $\boldsymbol{w}_2$ randomly. The weight factors are set to be $\beta^{UL} = \beta^{DL} = 1$, and $p_1 = p_w$. The sum-rate is defined as $R_{sum} = \frac{1}{2}\left[\sum_{k=1}^{2}\left(\log_2\left(1+SINR_{B,k}\right)\right)+\sum_{k=1}^{2}\left(\log_2\left(1+SINR_{2,k}\right)\right)\right]$, where $SINR_{B,i}$ is given in (4.5), while $SINR_{2,i}$ is in (4.8), and it depends on the case.

4.5.1 Simulation results with joint optimization of the relay precoder and the overhearing weight matrices

In here, the results of the joint optimization of $\boldsymbol{F}$, $\boldsymbol{w}_1$, and $\boldsymbol{w}_2$ are presented.

Fig. 4.2, and Fig. 4.3 illustrate the sum-rate versus the transmit power at the RS for fixed $p_s = p_1 = 10$ dB and $p_s = p_1$ with fixed $p_R = 10$ dB. The trend of the sum-rate curve for the scenario with multiple antennas at all terminals is the same trend as the scenario with multiple-antenna at both the BS and the RS. The sum-rate for the MIMO overhearing scheme is larger than the sum-rate for the scenario with only multi-antenna at both the BS and the RS as expected.

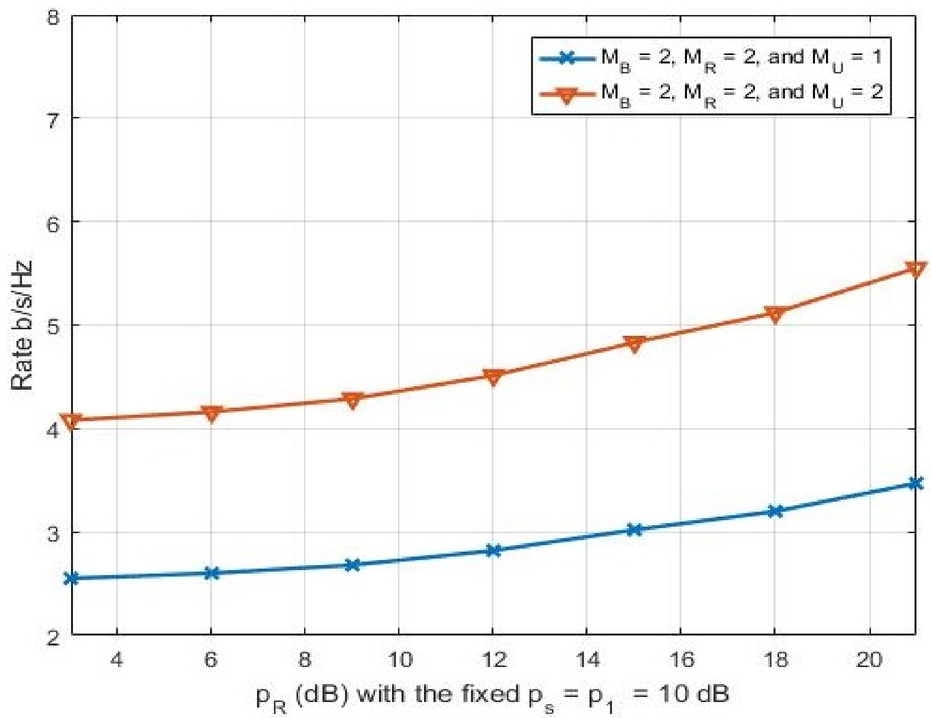

Figure 4.2: Sum-rates of the TWR overhearing schemes with respect to p_R for fixed $p_s = p_1 = 10$ dB.

Also, the gain at high SNR is larger than the gain at low SNR. The gain for the scenario with multiple antennas at the UEs is better compared to the scenario with single-antenna at the UEs, for example, at $p_R = 18$ dB, the gain is increased by 1.9 b/s/Hz, also, the sum-rate increases by 4.5 b/s/Hz at $p_s = p_1 = 18$ dB. Furthermore, the sum-rate versus $p_s = p_1$ is higher than the sum-rate versus p_r, this is because the larger the transmit power $p_s = p_1$, the higher interference received at UE2.

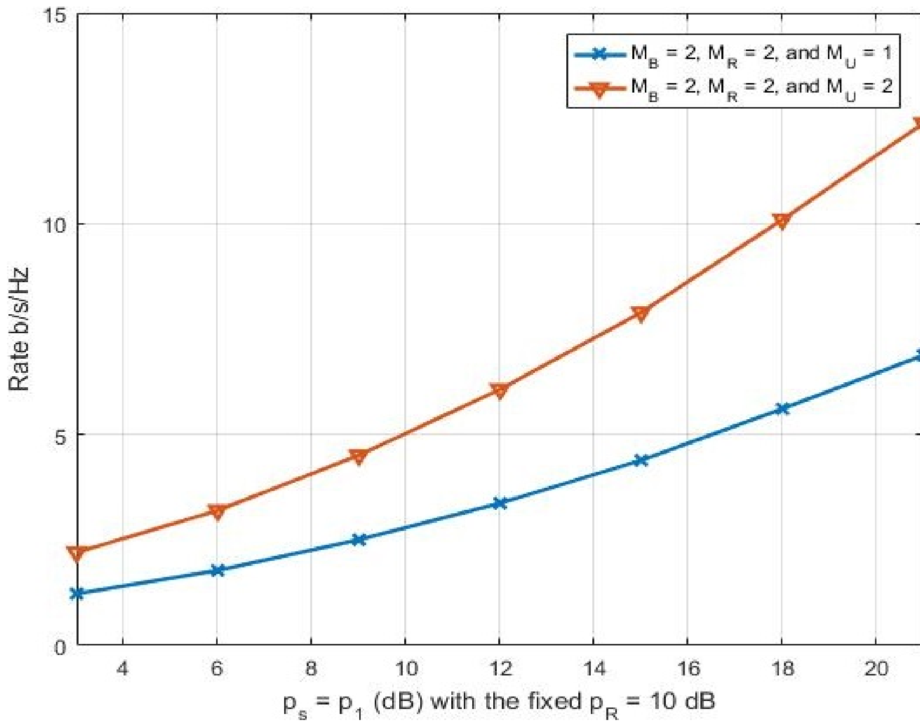

Figure 4.3: Sum-rates of the TWR overhearing schemes with respect to $p_s = p_1$ for fixed $p_R = 10$ dB.

4.6 Conclusions

In this chapter, we considered two-way-relaying overhearing scheme, and extended it to the scenario of multiple antennas at all the terminals. Also, the precoding matrix at the relay station in the second time slot and the overhearing weight matrices at the uplink user are jointly optimized to maximize the minimum weighted SINR. The iteration algorithm is performed by using SDR technique to solve the optimization problems. The simulation results demonstrate high gain of the sum-rate of the extended scheme with multiple antennas at the users compared to the scenario with single-antenna at the users.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

In this chapter, we conclude the thesis work presented in the previous chapters. In addition, we propose some interesting topics in the overhearing scheme to be considered in our future research.

5.1 Conclusions

5.1.1 Adaptive overhearing in two-way relaying channels

The overhearing relay scheme is extended to the scenario of multiple antennas at both the BS and the RS and single antenna at the users. The downlink user overhears the signal from the uplink user over the two-time slots, and exploits it in the detection of the desired signal. Also, the MMSE and MMSE-SIC detectors are considered at the downlink user. The BS exploits the self-interference cancellation, then the received signal is interference free. The precoding matrix in the second time slot and the transmit weights at the uplink user over the two-time slots are jointly optimized to maximize the minimum weighted SINR via the iterative algorithm. SDR technique is applied to the non-convex optimization problems, then we can find the approximation solutions for the optimization problems. CVX MATLB tools is used to find the approximation solution for each optimization problem. The sum-rates of the extended overhearing scheme are shown in the simulation results. The sum-rate increases when increasing the number of antennas at both the BS and the RS. Furthermore, the sum-rates are shown with different number of antennas in two cases; the first case, the number of antennas at the BS is equal to the number of antennas at the RS, while it is not equal in the second case.

5.1.2 Adaptive MIMO overhearing in Two-way relaying channels

The extended overhearing scheme is presented with multiple antennas at all terminals, the BS, the RS, and the users. The downlink user overhears the signals from the uplink user over the two-time slots to improve the detection of the desired signal. However, the MMSE and MMSE-SICs receivers are considered at the downlink user, where the ranking of the SINRs are assumed. The ranking of the SINRs depend on the values of the SINRs, so that the strongest SINR is the first one, and the last SINR is the weakest SINR. The precoding matrix in the second time slot and the transmit weights at the uplink user over the two-time slots are again jointly optimized to maximize the minimum weighted SINR via the iterative algorithm, also, SDR is applied to find the solution for each optimization problem. The sum-rate for the MIMO overhearing scheme is larger than the sum-rate for the scenario with multi-antenna at both the BS and the RS and single-antenna at the users.

5.2 Future Work

There are many open research problems for the capacity of TWR that need to be investigated and evaluated under different system models and parameters. In some extensions of the studied problems in this thesis are proposed as follows:

- The sum-rate increases when increasing the number of antennas. In this respect, the overhearing scheme can be with the scenario of increasing the number of antennas to more than two antennas at both the BS and the RS, or more than two antennas at all terminals.
- The study of the performance of the MIMO overhearing relay scheme in multi-cell scenario.
- An asymptotic analysis for the MIMO overhearing scheme can be performed to study the capacity of large scale MIMO overhearing relay.
- The extension of the MIMO overhearing scheme in cognitive relay networks.

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APPENDIX A

THE DERIVATIONS OF THE SINRS

$$\begin{aligned}
SINR_1 &= \boldsymbol{h}_1^H\Big[\mathbb{E}[(\boldsymbol{h}_2x_2+\boldsymbol{n}_2)(\boldsymbol{h}_2x_2+\boldsymbol{n}_2)^H]\Big]^{-1}\boldsymbol{h}_1\\
&= \boldsymbol{h}_1^H\Big[\mathbb{E}[(\boldsymbol{h}_2x_2+\boldsymbol{n}_2)((\boldsymbol{h}_2x_2)^H+\boldsymbol{n}_2^H)]\Big]^{-1}\boldsymbol{h}_1\\
&= \boldsymbol{h}_1^H\Big[\mathbb{E}[\boldsymbol{h}_2x_2x_2^*\boldsymbol{h}_2^H]+\mathbb{E}[\boldsymbol{h}_2x_2\boldsymbol{n}_2^H]+\mathbb{E}[\boldsymbol{n}_2x_2^*\boldsymbol{h}_2^H]+\mathbb{E}[\boldsymbol{n}_2\boldsymbol{n}_2^H]\Big]^{-1}\boldsymbol{h}_1\\
&= \boldsymbol{h}_1^H\Big[\mathbb{E}[\boldsymbol{h}_2x_2x_2^*\boldsymbol{h}_2^H]+\mathbb{E}[\boldsymbol{n}_2\boldsymbol{n}_2^H]\Big]^{-1}\boldsymbol{h}_1\\
&= \boldsymbol{h}_1^H\Big[\begin{bmatrix}0 & 0\\ 0 & p_s\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H\end{bmatrix}+\begin{bmatrix}1 & 0\\ 0 & \boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H+1\end{bmatrix}\Big]^{-1}\boldsymbol{h}_1\\
&= \boldsymbol{h}_1^H\Big[\begin{bmatrix}1 & 0\\ 0 & p_s\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H+\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H+1\end{bmatrix}\Big]^{-1}\boldsymbol{h}_1\\
&= \boldsymbol{h}_1^H\begin{bmatrix}1 & 0\\ 0 & \dfrac{1}{p_s\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H+\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H+1}\end{bmatrix}\boldsymbol{h}_1
\end{aligned} \tag{A.1}$$

$$
\begin{aligned}
&= \begin{bmatrix} h_{21}^{(1)*} w_1^* & \left(w_1 \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{h}_{R1} + w_2 h_{21}^{(2)} \right)^H \end{bmatrix} \\
&\quad \begin{bmatrix} 1 & 0 \\ 0 & \dfrac{1}{p_s \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B \boldsymbol{v}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + 1} \end{bmatrix} \boldsymbol{h}_1 \\
&= \begin{bmatrix} h_{21}^{(1)*} w_1^* & \dfrac{\left(w_1 \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{h}_{R1} + w_2 h_{21}^{(2)} \right)^H}{p_s \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B \boldsymbol{v}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + 1} \end{bmatrix} \boldsymbol{h}_1 \\
&= \begin{bmatrix} h_{21}^{(1)*} w_1^* & \dfrac{\left(w_1 \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{h}_{R1} + w_2 h_{21}^{(2)} \right)^H}{p_s \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B \boldsymbol{v}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + 1} \end{bmatrix} \\
&\begin{bmatrix} w_1 h_{21}^{(1)} \\ w_1 \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{h}_{R1} + w_2 h_{21}^{(2)} \end{bmatrix} \\
&= \frac{w_1^2 \left| h_{21}^{(1)} \right|^2 \left(p_s \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B \boldsymbol{v}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + 1 \right)}{p_s \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B \boldsymbol{v}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + 1} + \\
&= \frac{\left| w_1 \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{h}_{R1} + w_2 h_{21}^{(2)} \right|^2}{p_s \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B \boldsymbol{v}_B^H \boldsymbol{H}_{RB}^H \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + 1}, \\
&= \frac{w_1^2 \left| h_{21}^{(1)} \right|^2 \left(p_s \left| \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B \right|^2 + \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + 1 \right) + \left| w_1 \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{h}_{R1} + w_2 h_{21}^{(2)} \right|^2}{p_s \left| \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{H}_{RB} \boldsymbol{v}_B \right|^2 + \boldsymbol{h}_{2R} \boldsymbol{F} \boldsymbol{F}^H \boldsymbol{h}_{2R}^H + 1},
\end{aligned}
\tag{A.1}
$$

$$
\begin{aligned}
SINR_2 &= \boldsymbol{h}_2^H\Big[\mathbb{E}[(\boldsymbol{h}_1x_1+\boldsymbol{n}_2)(\boldsymbol{h}_1x_1+\boldsymbol{n}_2)^H]\Big]^{-1}\boldsymbol{h}_2\\
&= \boldsymbol{h}_2^H\Big[\mathbb{E}[(\boldsymbol{h}_1x_1+\boldsymbol{n}_2)((\boldsymbol{h}_1x_1)^H+\boldsymbol{n}_2^H)]\Big]^{-1}\boldsymbol{h}_1\\
&= \boldsymbol{h}_2^H\Big[\mathbb{E}[\boldsymbol{h}_1x_1x_1^*\boldsymbol{h}_1^H]+\mathbb{E}[\boldsymbol{h}_1x_1\boldsymbol{n}_2^H]+\mathbb{E}[\boldsymbol{n}_2x_1^*\boldsymbol{h}_1^H]+\mathbb{E}[\boldsymbol{n}_2\boldsymbol{n}_2^H]\Big]^{-1}\boldsymbol{h}_2\\
&= \boldsymbol{h}_2^H\Big[\mathbb{E}[\boldsymbol{h}_1x_1x_1^*\boldsymbol{h}_1^H]+\mathbb{E}[\boldsymbol{n}_2\boldsymbol{n}_2^H]\Big]^{-1}\boldsymbol{h}_2\\
&= \boldsymbol{h}_2^H\Big[\begin{bmatrix} w_1^2\left|h_{21}^{(1)}\right|^2 & w_1h_{21}^{(1)}\left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}+w_2h_{21}^{(2)}\right)^H\\ \left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}+w_2h_{21}^{(2)}\right)h_{21}^{(1)*}w_1^* & \left|w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}+w_2h_{21}^{(2)}\right|^2\end{bmatrix}\\
&\quad+\begin{bmatrix}1 & 0\\ 0 & \boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H+1\end{bmatrix}\Big]^{-1}\boldsymbol{h}_2\\
&= \boldsymbol{h}_2^H\Big[\begin{bmatrix} w_1^2\left|h_{21}^{(1)}\right|^2+1 & w_1h_{21}^{(1)}\left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}+w_2h_{21}^{(2)}\right)^H\\ \left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}+w_2h_{21}^{(2)}\right)h_{21}^{(1)*}w_1^* & \left|w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}+w_2h_{21}^{(2)}\right|^2+\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H+1\end{bmatrix}\dots\\
&\Big]^{-1}\boldsymbol{h}_2\\
&= \boldsymbol{h}_2^H\frac{1}{\left(w_1^2\left|h_{21}^{(1)}\right|^2+1\right)\left(\left|w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}+w_2h_{21}^{(2)}\right|^2+\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H+1\right)-}\dots\\
&\quad\frac{}{\left(w_1h_{21}^{(1)}\left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}+w_2h_{21}^{(2)}\right)^H\right)\left(\left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}+w_2h_{21}^{(2)}\right)h_{21}^{(1)*}w_1^*\right)}\\
&\quad\begin{bmatrix}\left|w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}+w_2h_{21}^{(2)}\right|^2+\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H+1 & -w_1h_{21}^{(1)}\left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}+w_2h_{21}^{(2)}\right)^H\\ -\left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1}+w_2h_{21}^{(2)}\right)h_{21}^{(1)*}w_1^* & w_1^2\left|h_{21}^{(1)}\right|^2+1\end{bmatrix}\boldsymbol{h}_2
\end{aligned}
\tag{A.2}
$$

$$
\begin{aligned}
&= \frac{1}{\left(\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H + 1\right)\left(w_1^2\left|h_{21}^{(1)}\right|^2 + 1\right) + \left|w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1} + w_2h_{21}^{(2)}\right|^2} \\
&\begin{bmatrix} 0s^H & \sqrt{p_s}\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H \end{bmatrix} \\
&\begin{bmatrix} \left|w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1} + w_2h_{21}^{(2)}\right|^2 + \boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H + 1 & -w_1h_{21}^{(1)}\left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1} + w_2h_{21}^{(2)}\right)^H \\ -\left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1} + w_2h_{21}^{(2)}\right)h_{21}^{(1)*}w_1^* & w_1^2\left|h_{21}^{(1)}\right|^2 + 1 \end{bmatrix}\boldsymbol{h}_2 \\
&= \frac{1}{\left(\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H + 1\right)\left(w_1^2\left|h_{21}^{(1)}\right|^2 + 1\right) + \left|w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1} + w_2h_{21}^{(2)}\right|^2} \\
&\begin{bmatrix} \left(\sqrt{p_s}\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H\right)\left(-\left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1} + w_2h_{21}^{(2)}\right)h_{21}^{(1)*}w_1^*\right) \\ \left(\sqrt{p_s}\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H\right)\left(w_1^2\left|h_{21}^{(1)}\right|^2 + 1\right) \end{bmatrix}^T \boldsymbol{h}_2 \\
&= \frac{1}{\left(\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H + 1\right)\left(w_1^2\left|h_{21}^{(1)}\right|^2 + 1\right) + \left|w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1} + w_2h_{21}^{(2)}\right|^2} \\
&\begin{bmatrix} \left(\sqrt{p_s}\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H\right)\left(-\left(w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1} + w_2h_{21}^{(2)}\right)h_{21}^{(1)*}w_1^*\right) \\ \left(\sqrt{p_s}\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H\right)\left(w_1^2\left|h_{21}^{(1)}\right|^2 + 1\right) \end{bmatrix}^T \\
&\begin{bmatrix} 0s \\ \sqrt{p_s}\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B \end{bmatrix} \\
&\frac{\left(p_s\boldsymbol{v}_B^H\boldsymbol{H}_{RB}^H\boldsymbol{F}^H\boldsymbol{h}_{2R}^H\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{H}_{RB}\boldsymbol{v}_B\right)\left(w_1^2\left|h_{21}^{(1)}\right|^2 + 1\right)}{\left(\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{F}^H\boldsymbol{h}_{2R}^H + 1\right)\left(w_1^2\left|h_{21}^{(1)}\right|^2 + 1\right) + \left|w_1\boldsymbol{h}_{2R}\boldsymbol{F}\boldsymbol{h}_{R1} + w_2h_{21}^{(2)}\right|^2}.
\end{aligned}
\tag{A.2}
$$

APPENDIX B

APPLYING SDR TO THE OPTIMIZATION PROBLEMS

Applying SDR to the problems from (4.11) to (4.16) and from (4.19) to (4.24), the feasibility problems for them can be respectively written as follows:

$$
\begin{aligned}
\text{find} \quad & \boldsymbol{W}'_1, \boldsymbol{W}'_2 \\
\text{s.t.} \quad & Tr\left\{r\boldsymbol{W}'_1\left(-\boldsymbol{K}_1A_1 - \boldsymbol{K}_1A_2\right) - r\boldsymbol{W}_{12}[1]'B - r\boldsymbol{W}_{12}[2]'B\right\} \geq \\
& r(c_2 + d + M_U) - \beta^{DL}c_1, \\
& Tr\left\{r\boldsymbol{W}'_1\left(-\boldsymbol{K}_1A_1 - \boldsymbol{K}_1A_2\right) - r\boldsymbol{W}_{12}[1]'B - r\boldsymbol{W}_{12}[2]'B\right\} \geq \\
& r(c_1 + d + M_U) - \beta^{DL}c_2, \\
& Tr\left\{\boldsymbol{W}'_1\left(\beta^{DL}\boldsymbol{K}_1A_1 - r\boldsymbol{K}_1A_2\right) + \beta^{DL}\boldsymbol{W}_{12}[1]'B - r\boldsymbol{W}_{12}[2]'B\right\} < \\
& r\left(c_1 + c_2 + d + M_U\right), \\
& Tr\left\{\boldsymbol{W}'_1\left(\beta^{DL}\boldsymbol{K}_1A_2 - r\boldsymbol{K}_1A_1\right) + \beta^{DL}\boldsymbol{W}_{12}[2]'B - r\boldsymbol{W}_{12}[1]'B\right\} < \\
& r\left(c_1 + c_2 + d + M_U\right), \\
& Tr\left\{\boldsymbol{W}'_1\left(\beta^{UL}\boldsymbol{K}_2A_1 - r\boldsymbol{K}_2A_2\right)\right\} \geq r\left(e + M_B\right), \\
& Tr\left\{\boldsymbol{W}'_1\left(\beta^{UL}\boldsymbol{K}_2A_2 - r\boldsymbol{K}_2A_1\right)\right\} \geq r\left(e + M_B\right), \\
& Tr\left\{\boldsymbol{W}'_1\right\} \leq \frac{p_w}{2}, Tr\left\{\boldsymbol{W}'_2\right\} \leq \frac{p_w}{2}, Tr\left\{\boldsymbol{W}'_1\right\} \leq p_{w_1},
\end{aligned}
\tag{B.1}
$$

$$
\begin{aligned}
\text{find} \quad & \boldsymbol{W}_1', \boldsymbol{W}_2' \\
\text{s.t.} \quad & Tr\left\{r_{SIC1}\boldsymbol{W}_1'\left(-\boldsymbol{K}_1A_1 - \boldsymbol{K}_1A_2\right) - r_{SIC1}\boldsymbol{W}_{12}[1]'B - r_{SIC1}\boldsymbol{W}_{12}[2]'B\right\} \\
& < r_{SIC1}(c_2 + d + M_U) - \beta^{DL}c_1, \\
& Tr\left\{r_{SIC1}\boldsymbol{W}_1'\left(-\boldsymbol{K}_1A_1 - \boldsymbol{K}_1A_2\right) - r_{SIC1}\boldsymbol{W}_{12}[1]'B - r_{SIC1}\boldsymbol{W}_{12}[2]'B\right\} \\
& < r_{SIC1}(c_1 + d + M_U) - \beta^{DL}c_2, \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{DL}\boldsymbol{K}_1A_1 - r_{SIC1}\boldsymbol{K}_1A_2\right) + \beta^{DL}\boldsymbol{W}_{12}[1]'B - r_{SIC1}\boldsymbol{W}_{12}[2]'B\right\} \\
& \geq r_{SIC1}\left(c_1 + c_2 + d + M_U\right), \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{DL}\boldsymbol{K}_1A_2 - r_{SIC1}\boldsymbol{K}_1A_1\right) + \beta^{DL}\boldsymbol{W}_{12}[2]'B - r_{SIC1}\boldsymbol{W}_{12}[1]'B\right\} \\
& \geq r_{SIC1}\left(c_1 + c_2 + d + M_U\right), \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{UL}\boldsymbol{K}_2A_1 - r_{SIC1}\boldsymbol{K}_2A_2\right)\right\} \geq r_{SIC1}\left(e + M_B\right), \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{UL}\boldsymbol{K}_2A_2 - r_{SIC1}\boldsymbol{K}_2A_1\right)\right\} \geq r_{SIC1}\left(e + M_B\right), \\
& Tr\left\{\boldsymbol{W}_1'\right\} \leq \frac{p_w}{2}, Tr\left\{\boldsymbol{W}_2'\right\} \leq \frac{p_w}{2}, Tr\left\{\boldsymbol{W}_1'\right\} \leq p_{w_1},
\end{aligned}
\tag{B.2}
$$

$$
\begin{aligned}
\text{find} \quad & \boldsymbol{W}_1', \boldsymbol{W}_2' \\
\text{s.t.} \quad & Tr\left\{r_{SIC2}\boldsymbol{W}_1'\left(-\boldsymbol{K}_1 A_1 - \boldsymbol{K}_1 A_2\right) - r_{SIC2}\boldsymbol{W}_{12}[1]'B - r_{SIC2}\boldsymbol{W}_{12}[2]'B\right\} \\
& < r_{SIC2}(c_2 + d + M_U) - \beta^{DL}c_1, \\
& Tr\left\{r_{SIC2}\boldsymbol{W}_1'\left(-\boldsymbol{K}_1 A_1 - \boldsymbol{K}_1 A_2\right) - r_{SIC2}\boldsymbol{W}_{12}[1]'B - r_{SIC2}\boldsymbol{W}_{12}[2]'B\right\} \\
& < r_{SIC2}(c_1 + d + M_U) - \beta^{DL}c_2, \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{DL}\boldsymbol{K}_1 A_1 - r_{SIC2}\boldsymbol{K}_1 A_2\right) + \beta^{DL}\boldsymbol{W}_{12}[1]'B - r_{SIC2}\boldsymbol{W}_{12}[2]'B\right\} \\
& \geq r_{SIC2}\left(c_1 + c_2 + d + M_U\right), \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{DL}\boldsymbol{K}_1 A_2 - r_{SIC2}\boldsymbol{K}_1 A_1\right) + \beta^{DL}\boldsymbol{W}_{12}[2]'B - r_{SIC2}\boldsymbol{W}_{12}[1]'B\right\} \\
& < r_{SIC2}\left(c_1 + c_2 + d + M_U\right), \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{UL}\boldsymbol{K}_2 A_1 - r_{SIC2}\boldsymbol{K}_2 A_2\right)\right\} \geq r_{SIC2}\left(e + M_B\right), \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{UL}\boldsymbol{K}_2 A_2 - r_{SIC2}\boldsymbol{K}_2 A_1\right)\right\} \geq r_{SIC2}\left(e + M_B\right), \\
& Tr\left\{r_{SIC2}\boldsymbol{W}_1'\left(-\boldsymbol{K}_1 A_1\right) - r_{SIC2}\boldsymbol{W}_{12}[1]'B\right\} \geq r_{SIC2}(c_2 + d + M_U) - \beta^{DL}c_1, \\
& Tr\left\{r_{SIC2}\boldsymbol{W}_1'\left(-\boldsymbol{K}_1 A_1\right) - r_{SIC2}\boldsymbol{W}_{12}[1]'B\right\} \geq r_{SIC2}(c_1 + d + M_U) - \beta^{DL}c_2, \\
& Tr\left\{\boldsymbol{W}_1'\right\} \leq \frac{p_w}{2}, Tr\left\{\boldsymbol{W}_2'\right\} \leq \frac{p_w}{2}, Tr\left\{\boldsymbol{W}_1'\right\} \leq p_{w_1},
\end{aligned}
\tag{B.3}
$$

$$
\begin{aligned}
\text{find} \quad & \boldsymbol{W}_1', \boldsymbol{W}_2' \\
\text{s.t.} \quad & Tr\left\{r_{SIC3}\boldsymbol{W}_1'\left(-\boldsymbol{K}_1A_1 - \boldsymbol{K}_1A_2\right) - r_{SIC3}\boldsymbol{W}_{12}[1]'B - r_{SIC3}\boldsymbol{W}_{12}[2]'B\right\} \\
& < r_{SIC3}(c_2 + d + M_U) - \beta^{DL}c_1, \\
& Tr\left\{r_{SIC3}\boldsymbol{W}_1'\left(-\boldsymbol{K}_1A_1 - \boldsymbol{K}_1A_2\right) - r_{SIC3}\boldsymbol{W}_{12}[1]'B - r_{SIC3}\boldsymbol{W}_{12}[2]'B\right\} \\
& < r_{SIC3}(c_1 + d + M_U) - \beta^{DL}c_2, \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{DL}\boldsymbol{K}_1A_1 - r_{SIC3}\boldsymbol{K}_1A_2\right) + \beta^{DL}\boldsymbol{W}_{12}[1]'B - r_{SIC3}\boldsymbol{W}_{12}[2]'B\right\} \\
& < r_{SIC3}\left(c_1 + c_2 + d + M_U\right), \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{DL}\boldsymbol{K}_1A_2 - r_{SIC3}\boldsymbol{K}_1A_1\right) + \beta^{DL}\boldsymbol{W}_{12}[2]'B - r_{SIC3}\boldsymbol{W}_{12}[1]'B\right\} \\
& \geq r_{SIC3}\left(c_1 + c_2 + d + M_U\right), \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{UL}\boldsymbol{K}_2A_1 - r_{SIC3}\boldsymbol{K}_2A_2\right)\right\} \geq r_{SIC3}\left(e + M_B\right), \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{UL}\boldsymbol{K}_2A_2 - r_{SIC3}\boldsymbol{K}_2A_1\right)\right\} \geq r_{SIC3}\left(e + M_B\right), \\
& Tr\left\{r_{SIC3}\boldsymbol{W}_1'\left(-\boldsymbol{K}_1A_2\right) - r_{SIC3}\boldsymbol{W}_{12}[2]'B\right\} \geq r_{SIC3}(c_2 + d + M_U) - \beta^{DL}c_1, \\
& Tr\left\{r_{SIC3}\boldsymbol{W}_1'\left(-\boldsymbol{K}_1A_2\right) - r_{SIC3}\boldsymbol{W}_{12}[2]'B\right\} \geq r_{SIC3}(c_1 + d + M_U) - \beta^{DL}c_2, \\
& Tr\left\{\boldsymbol{W}_1'\right\} \leq \frac{p_w}{2}, Tr\left\{\boldsymbol{W}_2'\right\} \leq \frac{p_w}{2}, Tr\left\{\boldsymbol{W}_1'\right\} \leq p_{w_1},
\end{aligned}
\tag{B.4}
$$

$$
\begin{aligned}
\text{find} \quad & \boldsymbol{W}'_1, \boldsymbol{W}'_2 \\
\text{s.t.} \quad & Tr\left\{r_{SIC4}\boldsymbol{W}'_1\left(-\boldsymbol{K}_1A_1-\boldsymbol{K}_1A_2\right)-r_{SIC4}\boldsymbol{W}_{12}[1]'B-r_{SIC4}\boldsymbol{W}_{12}[2]'B\right\} \\
& \geq r_{SIC4}(c_2+d+M_U)-\beta^{DL}c_1, \\
& Tr\left\{r_{SIC4}\boldsymbol{W}'_1\left(-\boldsymbol{K}_1A_1-\boldsymbol{K}_1A_2\right)-r_{SIC4}\boldsymbol{W}_{12}[1]'B-r_{SIC4}\boldsymbol{W}_{12}[2]'B\right\} \\
& < r_{SIC4}(c_1+d+M_U)-\beta^{DL}c_2, \\
& Tr\left\{\boldsymbol{W}'_1\left(\beta^{DL}\boldsymbol{K}_1A_1-r_{SIC4}\boldsymbol{K}_1A_2\right)+\beta^{DL}\boldsymbol{W}_{12}[1]'B-r_{SIC4}\boldsymbol{W}_{12}[2]'B\right\} \\
& \geq r_{SIC4}\left(c_1+c_2+d+M_U\right), \\
& Tr\left\{\boldsymbol{W}'_1\left(\beta^{DL}\boldsymbol{K}_1A_2-r_{SIC4}\boldsymbol{K}_1A_1\right)+\beta^{DL}\boldsymbol{W}_{12}[2]'B-r_{SIC4}\boldsymbol{W}_{12}[1]'B\right\} \\
& \geq r_{SIC4}\left(c_1+c_2+d+M_U\right), \\
& Tr\left\{\boldsymbol{W}'_1\left(\beta^{UL}\boldsymbol{K}_2A_1-r_{SIC4}\boldsymbol{K}_2A_2\right)\right\} \geq r_{SIC4}\left(e+M_B\right), \\
& Tr\left\{\boldsymbol{W}'_1\left(\beta^{UL}\boldsymbol{K}_2A_2-r_{SIC4}\boldsymbol{K}_2A_1\right)\right\} \geq r_{SIC4}\left(e+M_B\right), \\
& Tr\left\{\boldsymbol{W}'_1\right\} \leq \frac{p_w}{2}, Tr\left\{\boldsymbol{W}'_2\right\} \leq \frac{p_w}{2}, Tr\left\{\boldsymbol{W}'_1\right\} \leq p_{w_1},
\end{aligned}
\tag{B.5}
$$

$$
\begin{aligned}
\text{find} \quad & \boldsymbol{W}_1', \boldsymbol{W}_2' \\
\text{s.t.} \quad & Tr\left\{r_{SIC5}\boldsymbol{W}_1'\left(-\boldsymbol{K}_1A_1 - \boldsymbol{K}_1A_2\right) - r_{SIC5}\boldsymbol{W}_{12}[1]'B - r_{SIC5}\boldsymbol{W}_{12}[2]'B\right\} \\
& < r_{SIC5}(c_2 + d + M_U) - \beta^{DL}c_1, \\
& Tr\left\{r_{SIC5}\boldsymbol{W}_1'\left(-\boldsymbol{K}_1A_1 - \boldsymbol{K}_1A_2\right) - r_{SIC5}\boldsymbol{W}_{12}[1]'B - r_{SIC5}\boldsymbol{W}_{12}[2]'B\right\} \\
& \geq r_{SIC5}(c_1 + d + M_U) - \beta^{DL}c_2, \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{DL}\boldsymbol{K}_1A_1 - r_{SIC5}\boldsymbol{K}_1A_2\right) + \beta^{DL}\boldsymbol{W}_{12}[1]'B - r_{SIC5}\boldsymbol{W}_{12}[2]'B\right\} \\
& \geq r_{SIC5}\left(c_1 + c_2 + d + M_U\right), \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{DL}\boldsymbol{K}_1A_2 - r_{SIC5}\boldsymbol{K}_1A_1\right) + \beta^{DL}\boldsymbol{W}_{12}[2]'B - r_{SIC5}\boldsymbol{W}_{12}[1]'B\right\} \\
& \geq r_{SIC5}\left(c_1 + c_2 + d + M_U\right), \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{UL}\boldsymbol{K}_2A_1 - r_{SIC5}\boldsymbol{K}_2A_2\right)\right\} \geq r_{SIC5}\left(e + M_B\right), \\
& Tr\left\{\boldsymbol{W}_1'\left(\beta^{UL}\boldsymbol{K}_2A_2 - r_{SIC5}\boldsymbol{K}_2A_1\right)\right\} \geq r_{SIC5}\left(e + M_B\right), \\
& Tr\left\{\boldsymbol{W}_1'\right\} \leq \frac{p_w}{2}, Tr\left\{\boldsymbol{W}_2'\right\} \leq \frac{p_w}{2}, Tr\left\{\boldsymbol{W}_1'\right\} \leq p_{w_1},
\end{aligned}
\tag{B.6}
$$

$$
\begin{aligned}
\text{find} \quad & \boldsymbol{F}' \\
\text{s.t.} \quad & Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(1)} - r\boldsymbol{K}_{7(2)}\right) - r\tilde{\boldsymbol{F}}'\left(L_1 + L_2 + Q\right)\right\} \geq \\
& r\left(g_1 + g_2 + M_U\right), \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(2)} - r\boldsymbol{K}_{7(1)}\right) - r\tilde{\boldsymbol{F}}'\left(L_1 + L_2 + Q\right)\right\} \geq \\
& r\left(g_1 + g_2 + M_U\right), \\
& Tr\left\{\tilde{\boldsymbol{F}}'\left(\beta^{DL}L_1 + rL_2 + rQ\right) - r\boldsymbol{F}'\left(\boldsymbol{K}_{7(1)} + \boldsymbol{K}_{7(2)}\right)\right\} < \\
& r\left(g_2 + M_U\right) - \beta^{DL}g_1, \\
& Tr\left\{\tilde{\boldsymbol{F}}'\left(\beta^{DL}L_2 + rL_1 + rQ\right) - r\boldsymbol{F}'\left(\boldsymbol{K}_{7(1)} + \boldsymbol{K}_{7(2)}\right)\right\} < \\
& r\left(g_1 + M_U\right) - \beta^{DL}g_2, \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{UL}\boldsymbol{K}_{9(1)} - r\boldsymbol{K}_{9(2)} - r\boldsymbol{K}_{10}\right)\right\} \geq M_B r, \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{UL}\boldsymbol{K}_{9(2)} - r\boldsymbol{K}_{9(1)} - r\boldsymbol{K}_{10}\right)\right\} \geq M_B r, \\
& Tr\left\{\boldsymbol{F}'O\right\} \leq p_R,
\end{aligned}
\tag{B.7}
$$

$$
\begin{aligned}
&\text{find} \quad \boldsymbol{F}' \\
&\text{s.t.} \quad Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(1)} - r_{SIC1}\boldsymbol{K}_{7(2)}\right) - r_{SIC1}\tilde{\boldsymbol{F}}'\left(L_1 + L_2 + Q\right)\right\} < \\
&\qquad r_{SIC1}\left(g_1 + g_2 + M_U\right), \\
&\qquad Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(2)} - r_{SIC1}\boldsymbol{K}_{7(1)}\right) - r_{SIC1}\tilde{\boldsymbol{F}}'\left(L_1 + L_2 + Q\right)\right\} < \\
&\qquad r_{SIC1}\left(g_1 + g_2 + M_U\right), \\
&\qquad Tr\left\{\tilde{\boldsymbol{F}}'\left(\beta^{DL}L_1 + r_{SIC1}L_2 + rQ\right) - r_{SIC1}\boldsymbol{F}'\left(\boldsymbol{K}_{7(1)} + \boldsymbol{K}_{7(2)}\right)\right\} \geq \\
&\qquad r_{SIC1}\left(g_2 + M_U\right) - \beta^{DL}g_1, \\
&\qquad Tr\left\{\tilde{\boldsymbol{F}}'\left(\beta^{DL}L_2 + r_{SIC1}L_1 + rQ\right) - r_{SIC1}\boldsymbol{F}'\left(\boldsymbol{K}_{7(1)} + \boldsymbol{K}_{7(2)}\right)\right\} \geq \\
&\qquad r_{SIC1}\left(g_1 + M_U\right) - \beta^{DL}g_2, \\
&\qquad Tr\left\{\boldsymbol{F}'\left(\beta^{UL}\boldsymbol{K}_{9(1)} - r_{SIC1}\boldsymbol{K}_{9(2)} - r_{SIC1}\boldsymbol{K}_{10}\right)\right\} \geq M_B r_{SIC1}, \\
&\qquad Tr\left\{\boldsymbol{F}'\left(\beta^{UL}\boldsymbol{K}_{9(2)} - r_{SIC1}\boldsymbol{K}_{9(1)} - r_{SIC1}\boldsymbol{K}_{10}\right)\right\} \geq M_B r_{SIC1}, \\
&\qquad Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(1)} - r_{SIC1}\boldsymbol{K}_{7(2)}\right) - r_{SIC1}\tilde{\boldsymbol{F}}'Q\right\} < M_U r_{SIC1}, \\
&\qquad Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(2)} - r_{SIC1}\boldsymbol{K}_{7(1)}\right) - r_{SIC1}\tilde{\boldsymbol{F}}'Q\right\} < M_U r_{SIC1}, \\
&\qquad Tr\left\{\boldsymbol{F}'O\right\} \leq p_R,
\end{aligned} \tag{B.8}
$$

$$
\begin{aligned}
\text{find} \quad & \boldsymbol{F}' \\
\text{s.t.} \quad & Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(1)} - r_{SIC2}\boldsymbol{K}_{7(2)}\right) - r_{SIC2}\tilde{\boldsymbol{F}}'\left(L_1 + L_2 + Q\right)\right\} < \\
& r_{SIC2}\left(g_1 + g_2 + M_U\right), \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(2)} - r_{SIC2}\boldsymbol{K}_{7(1)}\right) - r_{SIC2}\tilde{\boldsymbol{F}}'\left(L_1 + L_2 + Q\right)\right\} < \\
& r_{SIC}\left(g_1 + g_2 + M_U\right), \\
& Tr\left\{\tilde{\boldsymbol{F}}'\left(\beta^{DL}L_1 + r_{SIC2}L_2 + rQ\right) - r_{SIC2}\boldsymbol{F}'\left(\boldsymbol{K}_{7(1)} + \boldsymbol{K}_{7(2)}\right)\right\} \geq \\
& r_{SIC2}\left(g_2 + M_U\right) - \beta^{DL}g_1, \\
& Tr\left\{\tilde{\boldsymbol{F}}'\left(\beta^{DL}L_2 + r_{SIC2}L_1 + rQ\right) - r_{SIC2}\boldsymbol{F}'\left(\boldsymbol{K}_{7(1)} + \boldsymbol{K}_{7(2)}\right)\right\} < \\
& r_{SIC2}\left(g_1 + M_U\right) - \beta^{DL}g_2, \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{UL}\boldsymbol{K}_{9(1)} - r_{SIC2}\boldsymbol{K}_{9(2)} - r_{SIC2}\boldsymbol{K}_{10}\right)\right\} \geq M_B r_{SIC2}, \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{UL}\boldsymbol{K}_{9(2)} - r_{SIC2}\boldsymbol{K}_{9(1)} - r_{SIC2}\boldsymbol{K}_{10}\right)\right\} \geq M_B r_{SIC2}, \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(1)} - r_{SIC2}\boldsymbol{K}_{7(2)}\right) - r_{SIC2}\tilde{\boldsymbol{F}}'\left(L_1 + Q\right)\right\} \geq \\
& r_{SIC2}\left(g_1 + M_U\right), \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(2)} - r_{SIC2}\boldsymbol{K}_{7(1)}\right) - r_{SIC2}\tilde{\boldsymbol{F}}'\left(L_1 + Q\right)\right\} \geq \\
& r_{SIC}\left(g_1 + M_U\right), \\
& Tr\left\{\boldsymbol{F}'O\right\} \leq p_R,
\end{aligned} \tag{B.9}
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$$
\begin{aligned}
\text{find} \quad & \boldsymbol{F}' \\
\text{s.t.} \quad & Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(1)} - r_{SIC3}\boldsymbol{K}_{7(2)}\right) - r_{SIC3}\tilde{\boldsymbol{F}}'\left(L_1 + L_2 + Q\right)\right\} < \\
& r_{SIC3}\left(g_1 + g_2 + M_U\right), \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(2)} - r_{SIC3}\boldsymbol{K}_{7(1)}\right) - r_{SIC3}\tilde{\boldsymbol{F}}'\left(L_1 + L_2 + Q\right)\right\} < \\
& r_{SIC}\left(g_1 + g_2 + M_U\right), \\
& Tr\left\{\tilde{\boldsymbol{F}}'\left(\beta^{DL}L_1 + r_{SIC3}L_2 + rQ\right) - r_{SIC3}\boldsymbol{F}'\left(\boldsymbol{K}_{7(1)} + \boldsymbol{K}_{7(2)}\right)\right\} < \\
& r_{SIC3}\left(g_2 + M_U\right) - \beta^{DL}g_1, \\
& Tr\left\{\tilde{\boldsymbol{F}}'\left(\beta^{DL}L_2 + r_{SIC3}L_1 + rQ\right) - r_{SIC3}\boldsymbol{F}'\left(\boldsymbol{K}_{7(1)} + \boldsymbol{K}_{7(2)}\right)\right\} \geq \\
& r_{SIC3}\left(g_1 + M_U\right) - \beta^{DL}g_2, \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{UL}\boldsymbol{K}_{9(1)} - r_{SIC3}\boldsymbol{K}_{9(2)} - r_{SIC3}\boldsymbol{K}_{10}\right)\right\} \geq M_B r_{SIC3}, \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{UL}\boldsymbol{K}_{9(2)} - r_{SIC3}\boldsymbol{K}_{9(1)} - r_{SIC3}\boldsymbol{K}_{10}\right)\right\} \geq M_B r_{SIC3}, \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(1)} - r_{SIC3}\boldsymbol{K}_{7(2)}\right) - r_{SIC3}\tilde{\boldsymbol{F}}'\left(L_2 + Q\right)\right\} \geq \\
& r_{SIC3}\left(g_2 + M_U\right), \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(2)} - r_{SIC3}\boldsymbol{K}_{7(1)}\right) - r_{SIC3}\tilde{\boldsymbol{F}}'\left(L_2 + Q\right)\right\} \geq \\
& r_{SIC}\left(g_2 + M_U\right), \\
& Tr\left\{\boldsymbol{F}'O\right\} \leq p_R,
\end{aligned}
\tag{B.10}
$$

$$
\begin{aligned}
\text{find} \quad & \boldsymbol{F}' \\
\text{s.t.} \quad & Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(1)} - r_{SIC4}\boldsymbol{K}_{7(2)}\right) - r_{SIC4}\tilde{\boldsymbol{F}}'\left(L_1 + L_2 + Q\right)\right\} \geq \\
& r_{SIC4}\left(g_1 + g_2 + M_U\right), \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(2)} - r_{SIC4}\boldsymbol{K}_{7(1)}\right) - r_{SIC4}\tilde{\boldsymbol{F}}'\left(L_1 + L_2 + Q\right)\right\} < \\
& r_{SIC}\left(g_1 + g_2 + M_U\right), \\
& Tr\left\{\tilde{\boldsymbol{F}}'\left(\beta^{DL}L_1 + r_{SIC4}L_2 + rQ\right) - r_{SIC4}\boldsymbol{F}'\left(\boldsymbol{K}_{7(1)} + \boldsymbol{K}_{7(2)}\right)\right\} \geq \\
& r_{SIC4}\left(g_2 + M_U\right) - \beta^{DL}g_1, \\
& Tr\left\{\tilde{\boldsymbol{F}}'\left(\beta^{DL}L_2 + r_{SIC4}L_1 + rQ\right) - r_{SIC4}\boldsymbol{F}'\left(\boldsymbol{K}_{7(1)} + \boldsymbol{K}_{7(2)}\right)\right\} \geq \\
& r_{SIC4}\left(g_1 + M_U\right) - \beta^{DL}g_2, \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{UL}\boldsymbol{K}_{9(1)} - r_{SIC4}\boldsymbol{K}_{9(2)} - r_{SIC4}\boldsymbol{K}_{10}\right)\right\} \geq M_B r_{SIC4}, \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{UL}\boldsymbol{K}_{9(2)} - r_{SIC4}\boldsymbol{K}_{9(1)} - r_{SIC4}\boldsymbol{K}_{10}\right)\right\} \geq M_B r_{SIC4}, \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(2)}\right) - r_{SIC4}\tilde{\boldsymbol{F}}'Q\right\} \geq M_U r_{SIC}, \\
& Tr\left\{\boldsymbol{F}'O\right\} \leq p_R,
\end{aligned}
\tag{B.11}
$$

$$
\begin{aligned}
\text{find} \quad & \boldsymbol{F}' \\
\text{s.t.} \quad & Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(1)} - r_{SIC5}\boldsymbol{K}_{7(2)}\right) - r_{SIC5}\tilde{\boldsymbol{F}}'\left(L_1 + L_2 + Q\right)\right\} < \\
& r_{SIC5}\left(g_1 + g_2 + M_U\right), \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(2)} - r_{SIC5}\boldsymbol{K}_{7(1)}\right) - r_{SIC5}\tilde{\boldsymbol{F}}'\left(L_1 + L_2 + Q\right)\right\} \geq \\
& r_{SIC}\left(g_1 + g_2 + M_U\right), \\
& Tr\left\{\tilde{\boldsymbol{F}}'\left(\beta^{DL}L_1 + r_{SIC5}L_2 + rQ\right) - r_{SIC5}\boldsymbol{F}'\left(\boldsymbol{K}_{7(1)} + \boldsymbol{K}_{7(2)}\right)\right\} \geq \\
& r_{SIC5}\left(g_2 + M_U\right) - \beta^{DL}g_1, \qquad\qquad \text{(B.12)} \\
& Tr\left\{\tilde{\boldsymbol{F}}'\left(\beta^{DL}L_2 + r_{SIC5}L_1 + rQ\right) - r_{SIC5}\boldsymbol{F}'\left(\boldsymbol{K}_{7(1)} + \boldsymbol{K}_{7(2)}\right)\right\} \geq \\
& r_{SIC5}\left(g_1 + M_U\right) - \beta^{DL}g_2, \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{UL}\boldsymbol{K}_{9(1)} - r_{SIC5}\boldsymbol{K}_{9(2)} - r_{SIC5}\boldsymbol{K}_{10}\right)\right\} \geq M_B r_{SIC5}, \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{UL}\boldsymbol{K}_{9(2)} - r_{SIC5}\boldsymbol{K}_{9(1)} - r_{SIC5}\boldsymbol{K}_{10}\right)\right\} \geq M_B r_{SIC5}, \\
& Tr\left\{\boldsymbol{F}'\left(\beta^{DL}\boldsymbol{K}_{7(1)}\right) - r_{SIC5}\tilde{\boldsymbol{F}}'Q\right\} \geq M_U r_{SIC}, \\
& Tr\left\{\boldsymbol{F}'O\right\} \leq p_R.
\end{aligned}
$$

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