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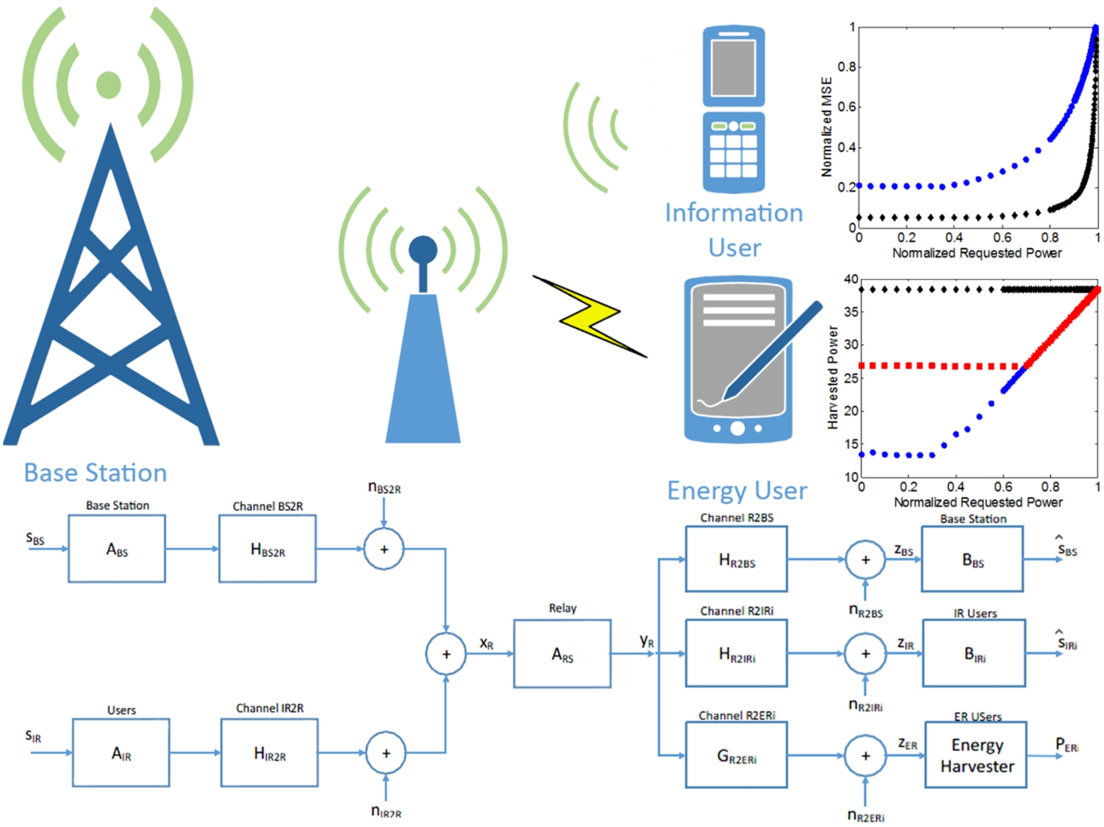

Simultaneous Information and Power Transfer

in Multiple Antenna Relay Channels

Master's thesis in communication engineering

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Department of Signals and Systems
CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

Simultaneous wireless information and power transfer (SWIPT) is an emerging technology that has received significant attention recently. In a communication system with SWIPT capabilities, both of these tasks, information and power transfer is done over wireless medium simultaneously instead of making these separately. In addition to providing a reliable alternative to powering communication networks solely with batteries or with cables, SWIPT capabilities bring increased mobility and prolong network uptime.

In this thesis, SWIPT in a multiple-antenna relay system with multiple users is studied. The relay is used for increasing communication range for the information receivers (IRs) as well as powering the energy harvesting receivers (ERs) that demand power. We focus on the design of the amplify-and-forward strategy at the relay (relay precoder) and the precoder at the base station. The minimum mean-square error (MMSE) is used as the performance criterion for information transfer. We consider two main scenarios: i) one-way relay system and ii) two-way relay system.

For the one-way relay system, the relay amplify-and-forward strategy (relay precoder) to minimize the MMSE from the base station to the information user while satisfying energy harvesting constraints at the energy harvesting users is investigated. For the two-way relay system, minimizing the MMSE from the information users to the base station while satisfying the signal-to-interference-plus-noise-ratio (SINR) constraints at the information users and the energy harvesting constraints at the ERs is considered. Here the precoders at the base station and the relay are optimized jointly.

These problem formulations lead to non-convex optimization problems. Due to limitations of the available approaches for solving these problems, a novel numerical approach is proposed. Using the proposed technique, the trade-offs between the MMSE and the energy harvesting constraints are found. The results show that it is important to design novel transmission techniques in order to deliver information and energy simultaneously more efficiently. The performance of the proposed designs is also compared with the performance of the some existing techniques in the literature that is developed for some special scenarios and it is observed that the proposed designs provide the same performance with these existing techniques in these special cases. The rate of the convergence of the proposed method is also investigated and it is found suitable for solving the mentioned problems.

Keywords: MIMO channel, two-way relay systems, simultaneous information and power transfer (SWIPT), amplify-and-forward strategy, minimum mean square error (MMSE), non-convex optimization problem

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KOOROS MOABBER, 7 June 2015, Gothenburg, Sweden

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Introduction

Wireless communication is the fastest growing segment of the communication industry [1]. Laptops, cellular phone, wireless sensor network, remote media and many other applications and businesses become a critical part of everybody's life in most countries of the world. This explosive growth and demand for higher throughput in addition to the inherent complexity of wireless propagation environments bring more technical challenges in designing and implementing robust wireless systems.

Multiple antenna techniques improve the performance of wireless connections from both capacity and reliability aspects. MIMO systems send the same data in different propagation paths, which is called spatial diversity, to achieve diversity gain and improve reliability of the system. Besides, these systems transmit different portions of the data, which is named spatial-multiplexing, to attain multiplexing gain and improve the data rate [1].

Relaying, in cooperation with base station, is a promising strategy and cost effective solution to extend coverage range and overcome the losses due to different factors, including fading and interference. The most known relaying strategies are amplify-and-forward (AF), decode-and-forward (DF) and compressed-and-forward. In amplify-and-forward strategy, relay stations amplify the received signal from the source and forward it to the destination. Relays with decode-and-forward strategy listen for a transmitted signal from source and decode it. In the case of correct decoding, relays forward signal to the destination. The compressed-and-forward strategy allows the relay station to compress received signal and forward it without decoding [2],[3]. Amplify-and-forward relay strategy is promising due to its low complexity compared to other strategies [4].

Two common protocols for relay transmission are one-way (OWRT) and two-way (TWRT). In one-way relay transmission, one transmission from source to destination occupies two channels at the same time. Hence, OWRT suffers from the half spectral efficiency [5]. In two-way relay transmission protocol, source and destination send signals at the same time to the relay and relay transmit received signals to both source and destination, therefore this protocol improves the poor spectral efficiency of OWRT [4]. Two-way relay transmission due to self-interference cancellation by network coding and improving spectral efficiency has received significant interest [6],[7].

In addition, energy-constrained wireless systems (ECWS) typically use batteries. Recharging of these batteries is expensive, inconvenient and sometimes impossible. Hence, recovering energy from other resources is an appropriate, safe and environment-friendly solution for ECWS. Due to some limitations of natural resources like solar or wind for ECWS, wireless power transfer looks very promising. Radio frequency (RF) signals can be a practical source of energy for low power consumption applications such as sensor networks [8].

Simultaneous wireless information and power transfer (SWIPT) is an interesting area that has attracted many significant attentions recently [9]. The SWIPT concept was introduced first in [10] that showed there was a fundamental trade-off between reliable transferred information and the rate of harvested energy in a single Gaussian channel. This research has been extended later to frequency selective channels [11]. Practical schemes in receivers for allowing SWIPT were proposed in [12],[13]. In these papers two methods of time switching (TS) and power splitting (PS) for this purpose have been suggested. Getting better efficiency by using multiple antenna techniques was focused in [8]. In all these studies, channel state information (CSI) was available in transmitter, but imperfect CSI has also been investigated in [14],[15].

In [16] achievable throughput of SWIPT in relay systems with two TS and PS methods in the delay-limited and delay-tolerant destinations have been investigated. Energy harvesting in multiple relay system in an analog network coding based on two-way relay system has been studied in [17]. In this study, a comparison between SWIPT and sub-time slot information and energy splitting has been done. In [18], short-term throughput maximization and transmission completion time minimization as criteria for two-way relay system has been examined. The results showed the importance of TS and PS in short-term throughput maximization in two-way relay systems. In [19], wireless information and power transfer in MIMO channel under Rician fading has been investigated.

In this thesis, SWIPT in a multiple antenna relay system with two-way amplify-and-forward strategy for multiple users is considered. The main aim of this thesis is to design precoders for the base station (BSP), for relay (RP) or for base station and relay jointly (BSRP) to transfer information with minimum error from information users to base station while requested power transfers from relay to energy harvesting users (ER) and satisfy signal-to-interference-plus-noise ratio (SINR) demands at information receivers (IRs).

To achieve this goal, relay systems are modeled and optimization problems for mentioned scenarios (BSP, RP and BSRP) are formulated. A new technique to solve these problems is proposed. Simulations are carried out to demonstrate the performance of SWIPT in different scenarios by the proposed technique.

The following notation is used throughout the thesis. Uppercase and lowercase letters denote matrices, and column/row vectors respectively. The complex conjugate transpose and transpose of a matrix A are denoted by A^H and A^T. The operators $E(.)$,

$tr(.)$, $rank(.)$ and $det(.)$ denote the expectation, trace, rank and determinant operators respectively. Identity matrix has been denoted with suitable dimensions. $\mathbb{C}^{m \times n}$ denotes the space of $m \times n$ matrices with complex entries. Positive semi-definite ordering is denoted by $\succeq$, where $A \succeq 0$ denotes a Hermitian positive semi-definite matrix.

2

Linear Precoder and Amplify-and-Forward Strategies

2.1 Simultaneous Wireless Information and Power Transfer in MIMO Channel without Relay

In this chapter three different scenarios including information transfer, power transfer and simultaneous information and power transfer in MIMO channel will be modeled, formulated and optimization problems will be defined. Besides, analytical solutions for some scenarios and methodologies for solving these optimization problems are introduced.

2.1.1 Information Transfer in MIMO Channel

In this section, the system model for information transfer is introduced and all mathematical equations that describe the system are explained. Finally, the optimization problem and methodologies for solving them are presented.

System Model

In Figure 2.1, the model of the system is shown. In this model, the transmitter uses a linear precoder ($A_{IR} \in \mathbb{C}^{n_t \times n_s}$) to precode the input information (s_n) and sends it through MIMO channel ($H_{IR2IR} \in \mathbb{C}^{n_r \times n_t}$) which is subject to noise ($n_{IR2IR} \in \mathbb{C}^{n_r \times n_r}$). The receiver, by using the suitable estimator ($B_{IR} \in \mathbb{C}^{n_s \times n_r}$), forms an estimate of sent information ($\hat{s}_n$) from the received signal.

As it has been mentioned before, the transmitter precodes the input information as follows

$$x = A_{IR}.s_n \tag{2.1}$$

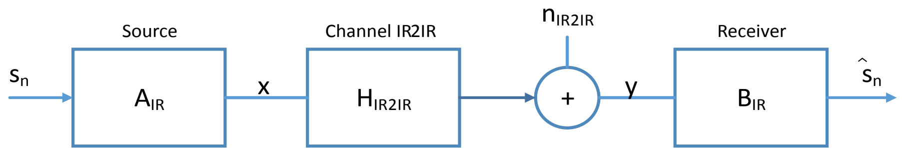


Figure 2.1: System model for information transfer

Received signal at the input of the receiver is as follows

$$y = H_{IR2IR}.A_{IR}.s_n + n_{IR2IR} \tag{2.2}$$

The receiver forms an estimate of the sent signal

$$\hat{s}_n = B_{IR}.(H_{IR2IR}.A_{IR}.s_n + n_{IR2IR}) \tag{2.3}$$

MMSE Estimation Problem

In this section, minimum mean square error (MMSE) estimation to form the estimate of information data is explained. The target is to minimize the following error

$$Error = E[\|\hat{s}_n - s_n\|^2] \tag{2.4}$$

This error can be written in following format

$$Error = E[\|B_{IR}.(H_{IR2IR}.A_{IR}.s_n + n_{IR2IR}) - s_n\|^2] \tag{2.5}$$

By the using derivative with respect to B_{IR}, B_{IR} can be obtained as

$$\frac{\partial Error}{\partial B_{IR}} = 0 \Rightarrow B_{IR} = K_{sy}.K_y^{-1} \tag{2.6}$$

In this equation, K_{sy}, the co-variance of input information and received signal in receiver and K_y, the co-variance of received signal can be written as

$$K_{sy} = K_s.A_{IR}^H.H_{IR2IR}^H \tag{2.7}$$

$$K_y = H_{IR2IR}.A_{IR}.K_s.A_{IR}^H.H_{IR2IR}^H + K_n \tag{2.8}$$

In the two recent equations, K_s and K_n are the co-variance of input information and the co-variance of noise respectively.
By replacing equation (2.6) in (2.5) and considering $E[\|Z\|^2] = E[tr(Z.Z^H)] = tr(E[Z.Z^H])$, the error can be expressed by

$$Error = tr(K_s - K_{sy}.K_y^{-1}.K_{sy}^H) \tag{2.9}$$

Precoder Optimization for Information Transfer

The delivered power by source can be written as

$$P_S = E[\|x\|^2] = tr(A_{IR}.K_s.A_{IR}^H) \tag{2.10}$$

Now the MMSE optimization problem, by considering limited power of source for sending information, can be written as

$$\begin{aligned} \min_{A_{IR}} \quad & tr(K_s - K_{sy}.K_y^{-1}.K_{sy}^H) && (2.11a)\\ \text{s.t.} \quad & tr(A_{IR}.K_s.A_{IR}^H) \leq P_{Source}^{Max} && (2.11b) \end{aligned}$$

In the next section analytical solution for solving this optimization problem will be explained.

Analytical Solution

In this section, the analytical solution for solving (2.11) is explained. By using Woodbury Identity which can be expressed as [11]

$$(A - U.C^{-1}.V)^{-1} = A^{-1} + A^{-1}.U.(C - V.A^{-1}.U)^{-1}.V.A^{-1} \tag{2.12}$$

and by replacing equation (2.7) and (2.8) and supposing $K_n = \sigma^2_{n_{IR2IR}} \cdot I$ and $K_s = I$, this optimization problem can be simplified as

$$\begin{aligned} \min_{A_{IR}} \quad & tr(I + \frac{1}{\sigma^2_{n_{IR2IR}}} A_{IR}^H.H_{IR2IR}^H.H_{IR2IR}.A_{IR})^{-1} && (2.13a)\\ \text{s.t.} \quad & tr(A_{IR}.A_{IR}^H) \leq P_{Source}^{Max} && (2.13b) \end{aligned}$$

By considering the following lemma [20]

$$tr(I_{n*n} + A_{n*m}.B_{m*n})^{-1} = tr(I_{m*m} + B_{m*n}.A_{n*m})^{-1} + n - m \tag{2.14}$$

the optimization problem can be written in the format of

$$\begin{aligned} \min_{A_{IR}} \quad & tr(I + \frac{1}{\sigma^2_{n_{IR2IR}}} H_{IR2IR}.A_{IR}.A_{IR}^H.H_{IR2IR}^H)^{-1} + n_s - n_r && (2.15a)\\ \text{s.t.} \quad & tr(A_{IR}.A_{IR}^H) \leq P_{Source}^{Max} && (2.15b) \end{aligned}$$

Now by considering $K_{A_{IR}} = A_{IR}.A_{IR}^H$ the optimization problem will be expressed as

$$\begin{aligned} \min_{A_{IR}} \quad & tr(I + \frac{1}{\sigma^2_{n_{IR2IR}}} H_{IR2IR}.K_{A_{IR}}.H_{IR2IR}^H)^{-1} + n_s - n_r && (2.16a)\\ \text{s.t.} \quad & tr(K_{A_{IR}}) \leq P_{Source}^{Max} && (2.16b)\\ & K_{A_{IR}} \succeq 0 && (2.16c)\\ & rank(K_{A_{IR}}) \leq n_s && (2.16d) \end{aligned}$$

This is a non-convex problem due to the rank constraint. Hence, solving this optimization problem by available tool (CVX tool [21], [22], [23]) is not possible so the relaxed format of this problem can be formed as

$$\min_{A_{IR}} \quad tr(I + \frac{1}{\sigma^2_{n_{IR2IR}}} H_{IR2IR}.K_{A_{IR}}.H^H_{IR2IR})^{-1} + n_s - n_r \tag{2.17a}$$

$$\text{s.t.} \quad tr(K_{A_{IR}}) \leq P^{Max}_{Source} \tag{2.17b}$$

$$K_{A_{IR}} \succeq 0 \tag{2.17c}$$

The optimal solution to the (2.16)problem has the form $K_{A_{IR}} = V_{H_{IR2IR}}.\Lambda_{K_{A_{IR}}}.V^H_{H_{IR2IR}}$ where $V_{H_{IR2IR}}$ is obtained from $H_{IR2IR} = U_{H_{IR2IR}}.\Lambda^{1/2}_{H_{IR2IR}}.V^H_{H_{IR2IR}}$.
In recent expressions $\Lambda_{H_{IR2IR}} = diag(h_1,h_2,...,h_{n_s}), h_1 \geq h_2 \geq ... \geq h_{n_s} \geq 0$ and $\Lambda_{K_{A_{IR}}} = diag(p_1,p_2,...,p_{n_s})$ where p_i obtained from the standard 'Water Filling Method'. Water filling method allocates power in constant level v that makes $\sum_{i=1}^{n_s} p_i = P^{Max}_{Source}$ when v is obtained by

$$p_i = \left(\frac{v}{\sqrt{h_i}} - \frac{1}{h_i}\right)^+, i = 1,...,n_s \tag{2.18}$$

The optimum value of the objective function is $Error^{Min} = \sum_{i=1}^{n}(1/(h_i.p_i))$. Finally, $A_{IR} = V_{H_{IR2IR}}.\Lambda_{K_{A_{IR}}}{}^{1/2}$ could simply be found. Depending on n_s and rank of $K_{A_{IR}}$ some zero padding for A_{IR} may be needed.

Methodology

In this section, different methodologies to solve optimization problem are introduced. Although an optimal solution can be found analytically, these methodologies for solving the optimization problem support and verify numerical solutions and algorithms for original relay problem.

'A and B' Method [19]

In this method, optimization problem is rewritten in a new format and the algorithm will be described. The error in (2.5) can be expressed as

$$\begin{aligned} Error =& E[\|B_{IR}.(H_{IR2IR}.A_{IR}.s_n + n_{IR2IR}) - s_n\|^2] && (2.19a)\\ =& E[\|I - B_{IR}.H_{IR2IR}.A_{IR}\|^2] + tr(B_{IR}.K_n.B^H_{IR}) && (2.19b)\\ =& n_s + tr(B_{IR}.H_{IR2IR}.A_{IR}.A^H_{IR}.H^H_{IR2IR}.B^H_{IR})\\ & - 2Re[tr(B_{IR}.H_{IR2IR}.A_{IR})] + tr(B_{IR}.K_n.B^H_{IR}) && (2.19c) \end{aligned}$$

Hence, a new optimization problem with relaxation $K_{A_{IR}} \succeq A_{IR}.A^H_{IR}$ instead of $K_{A_{IR}} = A_{IR}.A^H_{IR}$ can be shown as

$$\begin{aligned} \min_{A_{IR}} \quad & n_s + tr(B_{IR}.H_{IR2IR}.K_{A_{IR}}.H^H_{IR2IR}.B^H_{IR})\\ & - 2Re[tr(B_{IR}.H_{IR2IR}.A_{IR})] + tr(B_{IR}.K_n.B^H_{IR}) && (2.20a)\\ \text{s.t.} \quad & tr(K_{A_{IR}}) \leq P^{Max}_{Source} && (2.20b)\\ & K_{A_{IR}} \succeq A_{IR}.A^H_{IR} && (2.20c) \end{aligned}$$

The algorithm for solving the mentioned optimization problem is:

Algorithm IT(A,B):

- ***Initialize*** *Choose* A_{IR} *and update* B_{IR}
- ***Repeat***
  - *solve optimization problem (2.20) and find* A_{IR}
  - *update* B_{IR}
- ***Until*** *No improvements in objective function*

'A and AH' Method
In this method, a new fixed variable A_{IRH} as replacement of A_{IR}^H in optimization problem is used. The algorithm is illustrated as

Algorithm IT(A,AH):

- ***Initialize*** A_{IR}, A_{IRH} *and* $\varepsilon_{A_{IR}}$
- ***Repeat***

- *Solve following convex problem and find* A_{IR}

$$\min_{A_{IR}} \quad tr(I + \frac{1}{\sigma^2_{n_{IR2IR}}} A_{IRH}.H^H_{IR2IR}.H_{IR2IR}.A_{IR})^{-1} \tag{2.21a}$$

$$\text{s.t.} \quad tr(A_{IR}.A_{IRH}) \leq P^{Max}_{Source} \tag{2.21b}$$

$$\left\| vec(A_{IR} - A^H_{IRH}) \right\|^2 \leq \varepsilon_{A_{IR}} \tag{2.21c}$$

- *Change* $\varepsilon_{A_{IR}}$ *to get first feasible* A_{IR}
- *Update* $A_{IRH} = A_{IR}^H$
- *If no improvement in objective function then choose smaller* $\varepsilon_{A_{IR}}$

- ***Until*** $\varepsilon_{A_{IR}} \leq \varepsilon^{Tg}_{A_{IR}}$

The value of $\varepsilon_{A_{IR}}$ changes adaptively. Initial large value makes the optimization problem relaxed and final small value ($\varepsilon_{A_{IR}} \leq \varepsilon^{Tg}_{A_{IR}}$) assures that $A_{IR}^H = A_{IRH}$.

2.1.2 Power Transfer in MIMO Channel

In this section, the system for power transfer is introduced and all mathematical equations that describe the system are explained. Finally, the optimization problem is expressed.

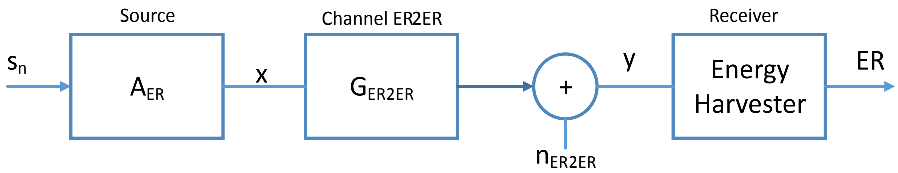


Figure 2.2: System model for power transfer

System Model

In Figure 2.2 , the model of system is shown. In this model, the source or transmitter uses a linear precoder ($A_{ER} \in \mathbb{C}^{n_t \times n_s}$) to precode the input information (s_n) and sends it through MIMO channel ($G_{ER2ER} \in \mathbb{C}^{n_r \times n_t}$) with noise ($n_{ER2ER} \in \mathbb{C}^{n_r \times n_r}$). Receiver by using the energy harvester gathers energy. Received signal at the receiver can be written as

$$y = G_{ER2ER}.A_{ER}.s_n + n_{ER2ER} \tag{2.22}$$

By considering $E[\|Z\|^2] = E[tr(Z \cdot Z^H)] = tr(E[Z \cdot Z^H])$ and supposing $\eta = 1$ when η is the efficiency of energy harvester, harvested power can be expressed by

$$P_{ER} = \eta.E[\|y\|^2] = tr(G_{ER2ER}.A_{ER}.K_s.A_{ER}^H.G_{ER2ER}^H) + tr(K_{n_{ER2ER}}) \tag{2.23}$$

Optimization of the Precoder for Power Transfer

In this section finding A_{ER}, that maximizes the harvested power in the receiver, is the objective function of this optimization problem. Besides, the limited power of source should be considered also. The optimization problem by supposing $tr(K_{n_{ER2ER}}) \approx 0$ and $K_s = I$ can be expressed as

$$\max_{A_{ER}} \quad tr(G_{ER2ER}.A_{ER}.A_{ER}^H.G_{ER2ER}^H) \tag{2.24a}$$

$$\text{s.t.} \quad tr(A_{ER}.A_{ER}^H) \leq P_{Source}^{Max} \tag{2.24b}$$

Analytical Solution

In this section, $A_{ER}.A_{ER}^H$ is replaced by K_{EH} therefore the optimization problem can be rewritten as

$$\max_{A_{ER}} \quad tr(G_{ER2ER}.K_{EH}.G_{ER2ER}^H) \tag{2.25a}$$

$$\text{s.t.} \quad tr(K_{EH}) \leq P_{Source}^{Max} \tag{2.25b}$$

$$K_{EH} \succeq 0 \tag{2.25c}$$

The optimal solution to such a problem has a form of $K_{EH} = P_{Source}^{Max}.v_{\lambda 1}.v_{\lambda 1}^H$ where $v_{\lambda 1}$ corresponds to the first column of $V_{G_{ER2ER}}$. $V_{G_{ER2ER}}$ is obtained by SVD form of $G_{ER2ER} = U_{G_{ER2ER}}.\Lambda_{G_{ER2ER}}.V_{G_{ER2ER}}$ where $\Lambda_{G_{ER2ER}} = diag(g_1,g_2,...,g_n), g_1 \geq g_2 \geq ... \geq g_n \geq 0$. The optimal value of the objective function is $Power^{Max} = P_{Source}^{Max}.g_1$ and optimal precoder is $A_{ER} = \begin{bmatrix} \sqrt{P_{Source}^{Max}}.v_{\lambda 1} & \mathbf{0} \end{bmatrix}$ [8].

Methodology

The 'A and AH' is explained in this section to verify the performance of this method for transferring power which is a simplified format of the optimization problem of the relay.
'A and AH' Method
In this method, a new fixed variable A_{ERH} as replacement of A_{ER}^H in optimization problem is used. The algorithm is denoted as

Algorithm PT(A,AH):

- ***Initialize*** A_{ER}, A_{ERH} *and* $\varepsilon_{A_{ER}}$
- ***Repeat***

\- *Solve following convex problem and find* A_{ER}

$$\begin{aligned} \max_{A_{ER}} \quad & tr(G_{ER2ER}.A_{ER}.A_{ERH}.G_{ER2ER}^H) && (2.26a) \\ \text{s.t.} \quad & tr(A_{ER}.A_{ERH}) \leq P_{Source}^{Max} && (2.26b) \\ & \left\| vec(A_{ER} - A_{ERH}^H) \right\|^2 \leq \varepsilon_{A_{ER}} && (2.26c) \end{aligned}$$

\- *Change* $\varepsilon_{A_{ER}}$ *to get first feasible* A_{ER}

\- *Update* $A_{ERH} = A_{ER}^H$

\- *If no improvement in objective function then choose smaller* $\varepsilon_{A_{ER}}$

- ***Until*** $\varepsilon_{A_{ER}} \leq \varepsilon_{A_{ER}}^{Tg}$

2.1.3 Simultaneous Information and Power Transfer in MIMO Channel

In this section two models of simultaneous wireless information and power transfer (SWIPT) are introduced and two possible optimization problems are explained.

System Model

There are two models for simultaneous information and power transfer. In the first model that is shown in Figure 2.3, information and energy harvesting users are separated. The source or transmitter uses a linear precoder ($A_S \in \mathbb{C}^{n_t \times n_s}$) to precode the input information (s_n) and sends it through two different MIMO channels correspond to information user and energy harvesting user ($H_{S2IR} \in \mathbb{C}^{n_{r_{IR}} \times n_t}$ and $G_{S2ER} \in \mathbb{C}^{n_{r_{ER}} \times n_t}$) with noise ($n_{S2IR} \in \mathbb{C}^{n_{r_{IR}} \times n_{r_{IR}}}$ and $n_{S2ER} \in \mathbb{C}^{n_{r_{ER}} \times n_{r_{ER}}}$). Similar to section 2.1.1 and 2.1.2, the received signal after the estimator in the information user and the received energy in the energy harvesting user is formulated as

$$\hat{s}_n = B_{IR}.(H_{S2IR}.A_S.s_n + n_{S2IR}) \tag{2.27}$$

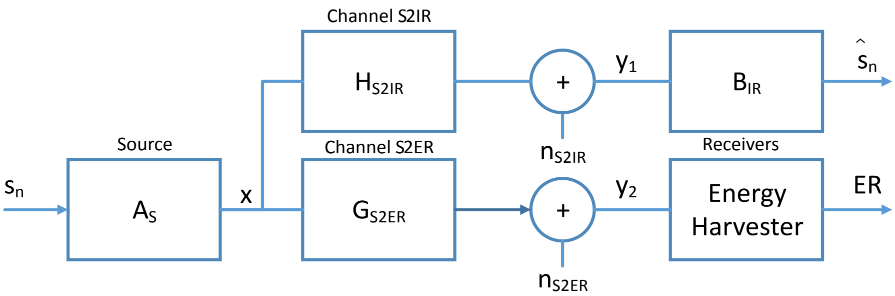


Figure 2.3: System model for SWIPT (model 1)

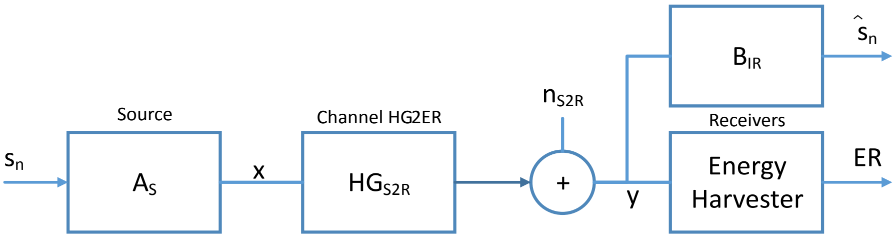


Figure 2.4: System model for SWIPT (model 2)

$$P_{ER} = tr(G_{S2ER}.A_S.K_s.A_S^H.G_{S2ER}^H) + tr(K_{n_{S2ER}}) \tag{2.28}$$

In the second model that is shown in Figure 2.4, information and energy harvesting users are co-located. The source or transmitter uses a linear precoder ($A_S \in \mathbb{C}^{n_t \times n_s}$) to precode the input information (s_n) and sends it through a MIMO channel ($HG_{S2R} \in \mathbb{C}^{n_{rR} \times n_t}$) with noise ($n_{S2R} \in \mathbb{C}^{n_{rR} \times n_{rR}}$). For this model following equations model the system

$$\hat{s}_n = B_{IR}.(HG_{S2R}.A_S.s_n + n_{S2R}) \tag{2.29}$$

$$P_{ER} = tr(HG_{S2R}.A_S.K_s.A_S^H.HG_{S2R}^H) + tr(K_{n_{S2R}}) \tag{2.30}$$

Since this model is a particular case of the previous model, only the first model will be investigated in following sections.

MMSE Estimation Problem

In this optimization problem, minimizing mean square error at the information user while satisfying energy harvesting and transmission power constraints is the target. This problem is formulated as

$$\min_{A_S} \quad tr(K_s - K_s.A_S^H.H_{S2IR}^H.(H_{S2IR}.A_S.K_s.A_S^H.H_{S2IR}^H + K_n)^{-1}.H_{S2IR}.A_S.K_s) \tag{2.31a}$$

$$\text{s.t.} \quad tr(G_{S2ER}.A_S.K_s.A_S^H.G_{S2ER}^H) \geq P_{ER}^{Req} \tag{2.31b}$$

$$tr(A_S.K_s.A_S^H) \leq P_{Source}^{Max} \tag{2.31c}$$

In this problem P_{ER}^{Req} is requested power from the energy harvesting user. This problem is non-convex because of energy harvesting constraint.

Methodology

Two methodologies, 'A and B' method and 'A and AH' method, are applicable. By assuming $K_n = \sigma^2_{n_{S2IR}}.I$ and $K_s = I$, optimization problem can be rewritten as

$$\begin{aligned}
\min_{A_S} \quad & tr(I - A_S^H.H_{S2IR}^H.(H_{S2IR}.A_S.A_S^H.H_{S2IR}^H + \sigma^2_{n_{S2IR}})^{-1}.H_{S2IR}.A_S) && (2.32a)\\
\text{s.t.} \quad & tr(G_{S2ER}.A_S.A_S^H.G_{S2ER}^H) \geq P_{ER}^{Req} && (2.32b)\\
& tr(A_S.A_S^H) \leq P_{Source}^{Max} && (2.32c)
\end{aligned}$$

This optimization problem by using Woodbury Identity (2.12), lemma (2.14) and $K_{A_S} = A_S.A_S^H$ can be expressed as

$$\begin{aligned}
\min_{A_{IR}} \quad & tr(I + \frac{1}{\sigma^2_{n_{S2IR}}}H_{S2IR}.K_{A_S}.H_{S2IR}^H)^{-1} + n_s - n_{r_{IR}} && (2.33a)\\
\text{s.t.} \quad & tr(G_{S2ER}.K_{A_S}.G_{S2ER}^H) \geq P_{ER}^{Req} && (2.33b)\\
& tr(K_{A_S}) \leq P_{Source}^{Max} && (2.33c)\\
& K_{A_S} \succeq 0 && (2.33d)\\
& rank(K_{A_S}) \leq n_s && (2.33e)
\end{aligned}$$

It can be shown that lower and upper limits for information error and harvested power are the limits are calculated for optimization problems in (2.16) and (2.25) [8].

'A and B' Method

In this method, by assuming $K_{A_S} \succeq A_S.A_S^H$ instead of $K_{A_S} = A_S.A_S^H$, the optimization problem (2.31) is given by

$$\begin{aligned}
\min_{A_S} \quad & n_s + tr(B_{IR}.H_{S2IR}.K_{A_S}.H_{S2IR}^H.B_{IR}^H)\\
& - 2Re[tr(B_{IR}.H_{S2IR}.A_S)] + tr(B_{IR}.K_n.B_{IR}^H) && (2.34a)\\
\text{s.t.} \quad & tr(G_{S2ER}.K_{A_S}.G_{S2ER}^H) \geq P_{ER}^{Req} && (2.34b)\\
& tr(K_{A_S}) \leq P_{Source}^{Max} && (2.34c)\\
& K_{A_S} \succeq A_S.A_S^H && (2.34d)
\end{aligned}$$

The algorithm for 'A and B' method is expressed as

Algorithm SWIPT(A,B):

- ***Initialize*** *Choose A_S and update B_{IR}*
- ***Repeat***

- *solve optimization problem (2.34) and find* A_S
- *update* B_{IR}

- ***Until*** *No improvements in objective function*

'A and AH' Method
This method is very similar to information transfer. In (2.33), the A_S^H is replaced by A_{SH} and algorithm is defined as

Algorithm $SWIPT$*(A,AH) version 1:*

- ***Initialize*** A_S, A_{SH} *and* ε_{A_S}
- ***Repeat***

- *Solve following convex problem and find* A_S

$$\begin{aligned} \min_{A_S} \quad & tr(I + \frac{1}{\sigma^2_{n_{S2IR}}} A_{SH}.H^H_{S2IR}.H_{S2IR}.A_S)^{-1} && (2.35a) \\ \text{s.t.} \quad & tr(G_{S2ER}.A_S.A_{SH}.G^H_{S2ER}) \geq P^{Req}_{ER} && (2.35b) \\ & tr(A_S.A_{SH}) \leq P^{Max}_{Source} && (2.35c) \\ & \left\| vec(A_S - A^H_{SH}) \right\|^2 \leq \varepsilon_{A_S} && (2.35d) \end{aligned}$$

- *Change* ε_{A_S} *to get first feasible* A_S
- *Update* $A_{ASH} = A_S^H$
- *If no improvement in objective function then choose smaller* ε_{A_S}

- ***Until*** $\varepsilon_{A_S} \leq \varepsilon^{Tg}_{A_S}$

This version of optimization problem in recent algorithm by using $K_{A_S} = A_S.A_S^H$ and relaxation $K_{A_S} \succeq A_S.A_S^H$ can be rewritten as

Algorithm $SWIPT$*(A,AH) version 2:*

- ***Initialize*** A_S, A_{SH} *and* ε_{A_S}
- ***Repeat***

- *Solve following convex problem and find* A_S

$$
\begin{aligned}
\min_{A_S} \quad & tr(I + \frac{1}{\sigma^2_{n_{S2IR}}} A_{SH}.H^H_{S2IR}.H_{S2IR}.A_S)^{-1} && \text{(2.36a)} \\
\text{s.t.} \quad & tr(G_{S2ER}.K_{A_S}.G^H_{S2ER}) \geq P^{Req}_{ER} && \text{(2.36b)} \\
& tr(K_{A_S}) \leq P^{Max}_{Source} && \text{(2.36c)} \\
& K_{A_S} \succeq A_S.A_{SH} && \text{(2.36d)} \\
& \left\| vec(A_S - A^H_{SH}) \right\|^2 \leq \varepsilon_{A_S} && \text{(2.36e)}
\end{aligned}
$$

- *Change* ε_{A_S} *to get first feasible* A_S

- *Update* $A_{ASH} = A^H_S$

- *If no improvement in objective function then choose smaller* ε_{A_S}

- ***Until*** $\varepsilon_{A_S} \leq \varepsilon^{Tg}_{A_S}$

Numerical experiments show that both versions of this algorithm lead to the same results but the second version converges faster.

2.2 Simultaneous Information and Power Transfer in MIMO Channel with Relay Amplify-and-Forward Strategy

In this chapter, two systems, one-way and two-way information and power transfer with relay amplify-and-forward strategy in MIMO channel are defined and modeled. Optimization problems and methodologies to solve them are introduced.

2.2.1 One-Way Information and Power Transfer with Relay Amplify-and-Forward Strategy

In one-way information and power transfer which is illustrated in Figure 2.5, the base station sends information to relay and relay precodes, amplifies and forwards this signal to information user (IR) and energy harvesting user (ER). In this section, the system model for one-way information and power transfer with relay will be explained. Optimization problem and algorithm for solving it are described.

System Model

In Figure 2.6 and Figure 2.7, the model of system for two different time slots is shown. In the first time slot, the base station sends signal carrying information to relay. In the second time slot, relay adopts the amplify-and-forward strategy to forward to the information user that needs information and the energy harvesting user.

In this model, $H_{BS2R} \in \mathbb{C}^{N_{rx\_R} \times N_{tx\_BS}}$ is channel matrix from base station to relay, $H_{R2IR} \in \mathbb{C}^{N_{tx\_R} \times N_{rx\_IR}}$ is MIMO channel matrix from relay to the information user, $G_{R2ER} \in \mathbb{C}^{N_{rx\_ER} \times N_{tx\_R}}$ is MIMO channel matrix from relay to energy harvesting user, $A_{BS} \in \mathbb{C}^{N_{tx\_BS} \times N_{s\_BS}}$ is precoder at the base station, $A_{RS} \in \mathbb{C}^{N_{tx\_R} \times N_{rx\_R}}$ is precoding

Figure 2.5: One-way relay system with base station and information and energy harvesting users

matrix in the relay, $s_{BS} \in \mathbb{C}^{N_{s\_BS} \times 1}$, $n_{BS2R} \in \mathbb{C}^{N_{rx\_R} \times 1}$ is additive Gaussian noise with $\mathcal{N}(0,\sigma^2_{BS2R}.I)$ distribution in the MIMO channel from base station to relay, n_{R2IR} is additive Gaussian noise with $\mathcal{N}(0,\sigma^2_{R2IR}.I)$ distribution in the MIMO channel from relay to the information user and n_{R2ER} is channel noise with $\mathcal{N}(0,\sigma^2_{R2ER}.I)$ distribution from relay to energy harvesting user.

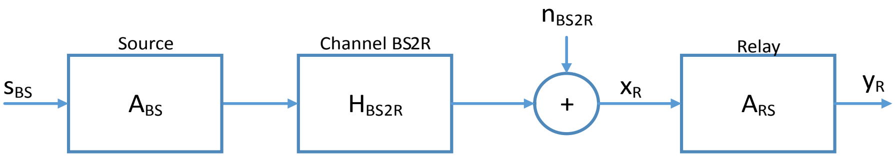


Figure 2.6: System model for the first time slot

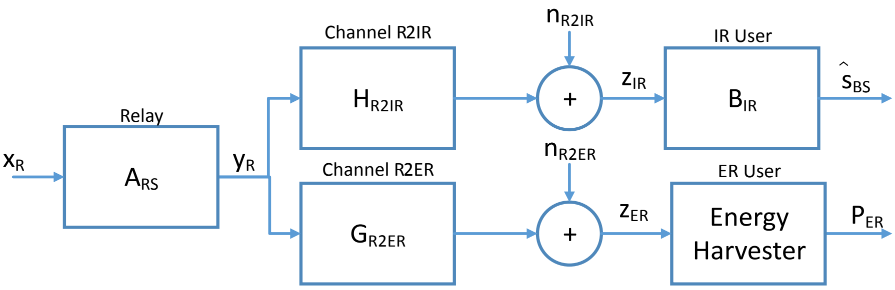


Figure 2.7: System model for the second time slot

Following equation expresses the received signal at the relay input in the first time slot

$$x_R = H_{BS2R}.A_{BS}.s_{BS} + n_{BS2R} \tag{2.37}$$

In second time slot, relay applies precoding and then forwards x_R as follows

$$y_R = A_{RS}.x_R = A_{RS}.(H_{BS2R}.A_{BS}.s_{BS} + n_{BS2R}) \tag{2.38}$$

The relay output power is P_R and it is expressed as

$$P_R = tr(A_{RS}.(H_{BS2R}.A_{BS}.A^H_{BS}.H^H_{BS2R} + \sigma^2_{BS2R}\, I).A^H_{RS}) \tag{2.39}$$

The received signal by the information user is as follows

$$z_{IR} = H_{R2IR}.y_R + n_{R2IR} \tag{2.40}$$

At the IR user, an estimate of s_{BS} is formed as follows

$$\hat{s}_{BS} = B_{IR}.(H_{R2IR}.y_R + n_{R2IR}) \tag{2.41}$$

B_{IR} is the estimator used in the information user to recover sent information. $\hat{s}_{BS}$ can be written as

$$\hat{s}_{BS} = B_{IR}.(H_{R2IR}.A_{RS}.(H_{BS2R}.A_{BS}.s_{BS} + n_{BS2R}) + n_{R2IR}) \tag{2.42}$$

Received signal at the ER user is given by

$$z_{ER} = G_{R2ER}.y_R + n_{R2ER} \tag{2.43}$$

Expression (2.43) can be rewritten as

$$z_{ER} = G_{R2ER}.A_{RS}.(H_{BS2R}.A_{BS}.s_{BS} + n_{BS2R}) + n_{R2ER} \tag{2.44}$$

Energy harvesting user uses the received signal for accumulating energy. The harvested power by the ER is given by

$$P_{ER} = E_{ER}\left(\|G_{R2ER}.y_R + n_{R2ER}\|^2\right) \tag{2.45}$$

$$P_{ER} = tr\left(T_3^H.T_3\right) + T_4 \tag{2.46}$$

When T_3 and T_4 are defined as follows

$$T_3 = G_{R2ER}.A_{RS}.H_{BS2R}.A_{BS} \tag{2.47}$$

$$T_4 = tr(A_{RS}^H.G_{R2ER}^H.G_{R2ER}.A_{RS}).\sigma_{BS2R}^2 + \sigma_{R2ER}^2.n_{ER} \tag{2.48}$$

MMSE Estimation Problem

In this section, optimization of relay precoder in one-way relay system with amplify-and-forward strategy is the main focus. IR user aims to minimize mean square error of the base station sent information and received signal. To achieve this goal, MMSE receiver at the information user is considered. Therefore, total MSE can be stated as

$$MSE_{BS2IR} = E_{IR}\left(\|\hat{s}_{BS} - s_{BS}\|^2\right) \tag{2.49}$$

With some simple manipulations, minimum total MSE can be rewritten in following format.

$$MSE_{BS2IR} = tr\left((I + T_2^H.T_1.T_2)^{-1}\right) \tag{2.50}$$

T_1 and T_2 are expressed as

$$T_1 = (H_{R2IR}.A_{RS}.A_{RS}^H.H_{R2IR}^H.\sigma_{BS2R}^2 + \sigma_{R2IR}^2.I)^{-1} \tag{2.51}$$

$$T_2 = H_{R2IR}.A_{RS}.H_{BS2R}.A_{BS} \tag{2.52}$$

Hence, an optimal estimator in the information user can be written as

$$B_{IR} = T_2^H.\left(T_2.T_2^H + T_1^{-1}\right)^{-1} \tag{2.53}$$

Furthermore, relay has restricted transmission power (P_R^{Max}) to send signals to the information and energy harvesting users that should be considered as a constraint for the optimization problem. Finally, the energy harvesting user requests a certain amount of power (P_{ER}^{Req}) that is another constraint. Briefly, the optimization problem is formulated as (2.54). In this optimization problem, the suitable precoding in the relay is found. This precoder should be designed to minimize error for sent information from the base station to the information user while satisfying the power transfer constraint for the energy harvesting user and relay limited transmission power constraint.

$$\min_{A_{RS}} \quad MSE_{BS2IR} \tag{2.54a}$$
$$Subject\ to:$$
$$P_R \leq P_R^{Max} \tag{2.54b}$$
$$P_{ER} \geq P_{ER}^{Req} \tag{2.54c}$$

This optimization problem is not convex because of non-convex objective function and constraints.

Methodology

Only 'A and AH' method is applicable for such an optimization problem. To solve the problem, $K_{A_{RS}^H} = A_{RS}^H.A_{RS}$ is introduced and (2.54) is rewritten in following format:

$$T_1 = (H_{R2IR}.A_{RS}.A_{RS}^H.H_{R2IR}^H.\sigma_{BS2R}^2 + \sigma_{R2IR}^2.I)^{-1} \tag{2.55a}$$
$$T_2 = H_{R2IR}.A_{RS}.H_{BS2R}.A_{BS} \tag{2.55b}$$
$$\min_{A_{RS}} \quad tr\left((I + T_2^H.T_1.T_2)^{-1}\right) \tag{2.55c}$$
$$Subject\ to:$$
$$tr(A_{BS}^H.H_{BS2R}^H.K_{A_{RS}^H}.H_{BS2R}.A_{BS} + \sigma_{BS2R}^2.K_{A_{RS}^H}) \leq P_R^{Max} \tag{2.55d}$$
$$tr(A_{BS}^H.H_{BS2R}^H.A_{RS}^H.G_{R2ER}^H.G_{R2ER}.A_{RS}.H_{BS2R}.A_{BS})$$
$$+ tr(A_{RS}^H.G_{R2ER}^H.G_{R2ER}.A_{RS}).\sigma_{BS2R}^2 + \sigma_{R2ER}^2 \geq P_{ER}^{Req} \tag{2.55e}$$
$$K_{A_{RS}^H} = A_{RS}^H.A_{RS} \tag{2.55f}$$

This problem is relaxed by replacing $K_{A_{RS}^H} \succeq A_{RS}^H.A_{RS}$ with $K_{A_{RS}^H} = A_{RS}^H.A_{RS}$. By this relaxation, it is possible to make one of the constraints as a convex function. As it has been mentioned earlier, the inequality $K_{A_{RS}^H} - A_{RS}^H.A_{RS} \succeq 0$ denotes positive semi definite matrix.

$$
\begin{aligned}
& T_1 = (H_{R2IR}.A_{RS}.A_{RS}^H.H_{R2IR}^H.\sigma_{BS2R}^2 + \sigma_{R2IR}^2.I)^{-1} && \text{(2.56a)}\\
& T_2 = H_{R2IR}.A_{RS}.H_{BS2R}.A_{BS} && \text{(2.56b)}\\
\min_{A_{RS}} \quad & tr\left((I + T_2^H.T_1.T_2)^{-1}\right) && \text{(2.56c)}\\
& Subject\ to: \\
& tr(A_{BS}^H.H_{BS2R}^H.K_{A_{RS}^H}.H_{BS2R}.A_{BS} + \sigma_{BS2R}^2.K_{A_{RS}^H}) \leq P_R^{Max} && \text{(2.56d)}\\
& tr(A_{BS}^H.H_{BS2R}^H.A_{RS}^H.G_{R2ER}^H.G_{R2ER}.A_{RS}.H_{BS2R}.A_{BS}) \\
& + tr(A_{RS}^H.G_{R2ER}^H.G_{R2ER}.A_{RS}).\sigma_{BS2R}^2 + \sigma_{R2ER}^2 \geq P_{ER}^{Req} && \text{(2.56e)}\\
& K_{A_{RS}^H} - A_{RS}^H.A_{RS} \succeq 0 && \text{(2.56f)}
\end{aligned}
$$

Finally, A_{RS}^H is replaced by a new variable A_{RSH}. The reason for this replacement is the objective function in (2.56) that is a non-convex function.

$$
\begin{aligned}
& T_1 = (H_{R2IR}.A_{RS}.A_{RS}^H.H_{R2IR}^H.\sigma_{BS2R}^2 + \sigma_{R2IR}^2.I)^{-1} && \text{(2.57a)}\\
& T_2 = H_{R2IR}.A_{RS}.H_{BS2R}.A_{BS} && \text{(2.57b)}\\
& T_6 = A_{BS}^H.H_{BS2R}^H.A_{RSH}.H_{R2IR}^H && \text{(2.57c)}\\
\min_{A_{RS}} \quad & tr\left((I + T_6.T_1.T_2)^{-1}\right) && \text{(2.57d)}\\
& Subject\ to: \\
& tr(A_{BS}^H.H_{BS2R}^H.K_{A_{RS}^H}.H_{BS2R}.A_{BS} + \sigma_{BS2R}^2.K_{A_{RS}^H}) \leq P_R^{Max} && \text{(2.57e)}\\
& tr(A_{BS}^H.H_{BS2R}^H.A_{RSH}.G_{R2ER}^H.G_{R2ER}.A_{RS}.H_{BS2R}.A_{BS}) \\
& + tr(A_{RSH}.G_{R2ER}^H.G_{R2ER}.A_{RS}).\sigma_{BS2R}^2 + \sigma_{R2ER}^2 \geq P_{ER}^{Req} && \text{(2.57f)}\\
& K_{A_{RS}^H} - A_{RS}^H.A_{RS} \succeq 0 && \text{(2.57g)}\\
& \|vec(A_{RS} - A_{RSH}^H)\|^2 \leq \varepsilon_{A_{RS}} && \text{(2.57h)}
\end{aligned}
$$

In this formula $\varepsilon_{A_{RS}}$ is an adaptive threshold value with a sufficient small target threshold value ($\varepsilon_{A_{RS}}^{Tg}$) that insures to reach $A_{RS}^H \approx A_{RSH}$. $\varepsilon_{A_{RS}}$ is adaptively changed throughout iterations. At initialization, a large threshold $\varepsilon_{A_{RS}}$ is chosen.

Hence, the overall algorithm for solving this optimization problem is demonstrated below. In this algorithm first A_{RS} is initialized so $A_{RSH} = A_{RS}^H$. $\varepsilon_{A_{RS}}$ is set to a relatively large initial value since larger values for $\varepsilon_{A_{RS}}$ makes the problem more relaxed. After finding the first feasible answer for A_{RS}, A_{RSH} is updated by $A_{RSH} = A_{RS}^H$. This procedure continues until no improvement in the objective function can be reached. Then a smaller value $\varepsilon_{A_{RS}}$ is selected until it becomes less than targeted value ($\varepsilon_{A_{RS}}^{Tg}$).

Algorithm $SWIPT\_ROW(A,AH)$:

- ***Initialize*** *A_{RS}, A_{RSH} and $\varepsilon_{A_{RS}}$*

- ***Repeat***

  - *Calculate expression*
    $T_1 = (H_{R2IR}.A_{RS}.A_{RS}^H.H_{R2IR}^H.\sigma_{BS2R}^2 + \sigma_{R2IR}^2.I)^{-1}$
  - *Define expression*
    $T_2 = H_{R2IR}.A_{RS}.H_{BS2R}.A_{BS}$
    $T_6 = A_{BS}^H.H_{BS2R}^H.A_{RSH}.H_{R2IR}^H$
  - *Solve following convex problem and find* A_{RS}

$$\min_{A_{RS}} \quad tr\left((I + T_6.T_1.T_2)^{-1}\right) \tag{2.58a}$$

$$Subject\ to:$$

$$tr(A_{BS}^H.H_{BS2R}^H.K_{A_{RS}^H}.H_{BS2R}.A_{BS} + \sigma_{BS2R}^2.K_{A_{RS}^H}) \leq P_R^{Max} \tag{2.58b}$$

$$tr(A_{BS}^H.H_{BS2R}^H.A_{RSH}.G_{R2ER}^H.G_{R2ER}.A_{RS}.H_{BS2R}.A_{BS}) + tr(A_{RSH}.G_{R2ER}^H.G_{R2ER}.A_{RS}).\sigma_{BS2R}^2 + \sigma_{R2ER}^2 \geq P_{ER}^{Req} \tag{2.58c}$$

$$K_{A_{RS}^H} - A_{RS}^H.A_{RS} \succeq 0 \tag{2.58d}$$

$$\|vec(A_{RS} - A_{RSH}^H)\|^2 \leq \varepsilon_{A_{RS}} \tag{2.58e}$$

  - *Change* $\varepsilon_{A_{RS}}$ *to get first feasible* A_{RS}
  - *Update* $A_{RSH} = A_{RS}^H$
  - *If no improvement in objective function then choose smaller* $\varepsilon_{A_{RS}}$

  Until $\varepsilon_{A_{RS}} \leq \varepsilon_{A_{RS}}^{Tg}$

2.2.2 Two-Way Information and Power Transfer with Relay Amplify-and-Forward Strategy

In two-way information and power transfer (Figure 2.8), the information users and base station send the information to relay that precodes, amplifies and forwards information of information users to base station and information of base station to the information users. Besides, power transfers to the energy harvesting users simultaneously. In this section, the system model and equations for two-way information and power transfer with relay amplify-and-forward strategy will be explained. Due to possible precoding in the base station, relay and join base station and relay, different optimization problems and algorithms for solving them are described.

System Model

In Figure 2.9 and Figure 2.10, the model of system for two different time slots is shown. In the first time slot, the information users and the base station send information to the relay. In the second time slot, relay uses a linear precoder to amplify and forward

Figure 2.8: Two-way relay system with base station, information and power transfer users

received signals. The precoded signal is sent to the base station, the information users and the energy harvesting users. In this model, $s_{BS} \in \mathbb{C}^{N_{s\_BS} \times 1}$ is information data to the base station, $s_{IRi} \in \mathbb{C}^{N_{s\_IRi} \times 1}$ is information data at user i, $A_{BS} \in \mathbb{C}^{N_{tx\_BS} \times N_{s\_BS}}$ is base station precoder, $A_{IRi} \in \mathbb{C}^{N_{tx\_IRi} \times N_{s\_IRi}}$ is the precoder in the information user i, $H_{BS2R} \in \mathbb{C}^{N_{rx\_R} \times N_{tx\_BS}}$ is the MIMO channel matrix from the base station to the relay, $H_{IRi2R} \in \mathbb{C}^{N_{rx\_R} \times N_{tx\_IRi}}$ is the MIMO channel matrix from the information user i to the relay, $n_{BS2R} \in \mathbb{C}^{N_{rx\_R} \times 1}$ is additive Gaussian noise with $\mathcal{N}(0,\sigma^2_{BS2R}.I)$ distribution in the MIMO channel from the base station to the relay, $n_{IRi2R} \in \mathbb{C}^{N_{rx\_R} \times 1}$ is additive Gaussian noise with $\mathcal{N}(0,\sigma^2_{IR2R}.I)$ distribution in the MIMO channel from the information users to the relay, $A_{RS} \in \mathbb{C}^{N_{tx\_R} \times N_{rx\_R}}$ is precoding matrix in the relay, $H_{R2BS} \in \mathbb{C}^{N_{rx\_BS} \times N_{tx\_R}}$ is the MIMO channel matrix from the relay to the base station, $H_{R2IRi} \in \mathbb{C}^{N_{rx\_IRi} \times N_{tx\_R}}$ is the MIMO channel matrix from the relay to the information user i, $G_{R2ERi} \in \mathbb{C}^{N_{rx\_ERi} \times N_{tx\_R}}$ is the MIMO channel matrix from the relay to the energy harvesting user i, n_{R2BS} is additive Gaussian noise with $\mathcal{N}(0,\sigma^2_{R2BS}.I)$ distribution in the MIMO channel from the relay to the base station, n_{R2IRi} is additive Gaussian noise with $\mathcal{N}(0,\sigma^2_{R2IR}.I)$ distribution in the MIMO channel from the relay to the information user, n_{R2ERi} is channel noise with $\mathcal{N}(0,\sigma^2_{R2ER}.I)$ distribution in the MIMO channel from the relay to the energy harvesting user and B_{BS} and B_{IR_i} are estimators of received signals in base station and information user i respectively.

In the first time slot, both base station and the information users transmit the information to relay. The received signal at the input of the relay is formulated as

$$x_R = H_{BS2R}.A_{BS}.s_{BS} + n_{BS2R} + H_{IR2R}.A_{IR}.s_{IR} + n_{IR2R} \tag{2.59}$$

In this equation $H_{IR2R} = \left[H_{IR_1 2R} \mid H_{IR_2 2R} \mid ... \mid H_{IR_{N_{MU}} 2R} \right]$ where $H_{IR_i 2R}$ is the channel matrix from information user i to relay, N_{MU} is the number of users. A_{IR_i} and P_i are precoder in information user and transmitted power by user i. The equation can be rewritten in following format

$$x_R = H_{BS2R}.A_{BS}.s_{BS} + n_{BS2R} + \sum_{i=1}^{N_{MU}} (H_{IR_i 2R}.A_{IR_i}.s_{IR_i} + n_{IR_i 2R}) \tag{2.60}$$

In the second time slot, the relay applies amplify-and-forward strategy on received signal

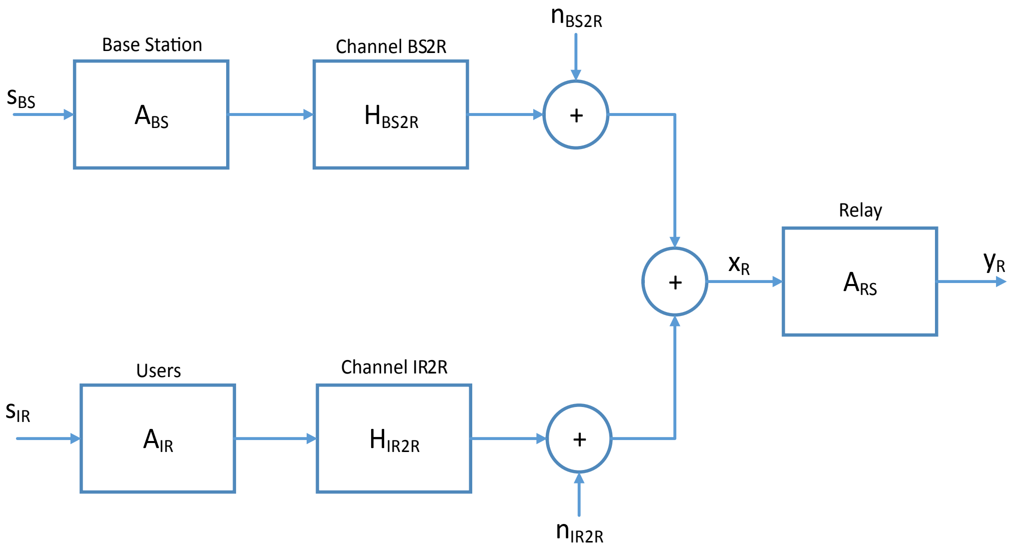


Figure 2.9: System model for the first time slot

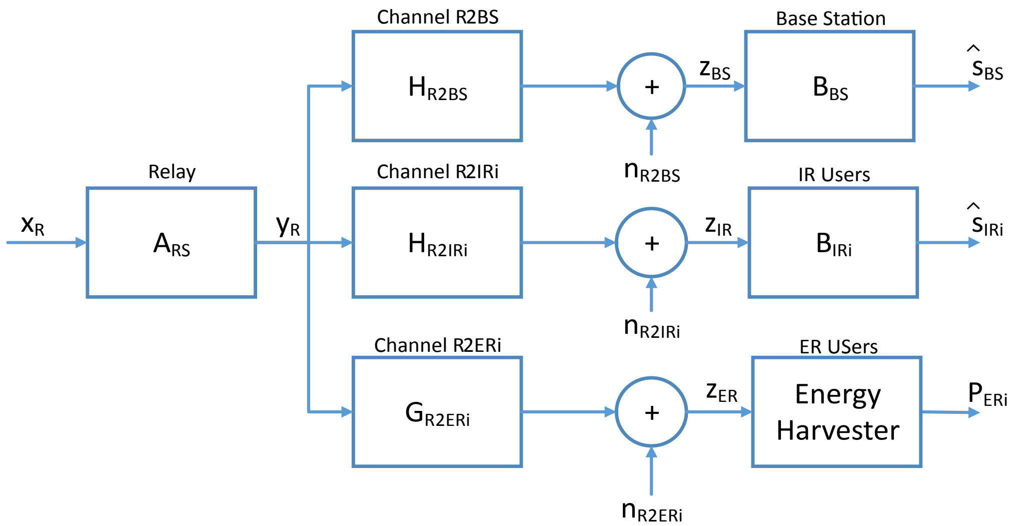


Figure 2.10: System model for the second time slot

from information users and the base station as

$$y_R = A_{RS}.\left(H_{BS2R}.A_{BS}.s_{BS} + n_{BS2R} + H_{IR2R}.A_{IR}.s_{IR} + n_{IR2R}\right) \tag{2.61}$$

The signal received at the base station at the second time slot is given by

$$\begin{aligned} z_{BS} &= H_{R2BS}.y_R + n_{R2BS} \\ &= H_{R2BS}.A_{RS}.(H_{BS2R}.A_{BS}.s_{BS} + n_{BS2R} + H_{IR2R}.A_{IR}.s_{IR} \\ &\quad + n_{IR2R}) + n_{R2BS} \end{aligned} \tag{2.62}$$

A part of the received signal in the base station is related to the sent signal to the relay by the base station. Therefore, the back propagated self-interference term can be eliminated

$$\begin{aligned}\hat{z}_{BS} &= H_{R2BS}.y_R + n_{R2BS} \\ &= H_{R2BS}.A_{RS}.(H_{IR2R}.A_{IR}.s_{IR} + n_{IR2R}) + n_{R2BS} \qquad (2.63)\end{aligned}$$

The base station uses estimator B_{BS} to extract information that has been sent to relay from information users

$$\hat{s}_{BS} = B_{BS}.H_{R2BS}.A_{RS}.(H_{IR2R}.A_{IR}.s_{IR} + n_{IR2R}) + n_{R2BS} \qquad (2.64)$$

It should be mentioned that the base station and relay power are given by

$$\begin{aligned}P_{BS} &= tr(A_{BS}.K_{s_{BS}}.A_{BS}^H) \qquad (2.65a) \\ P_R &= tr(A_{RS}.(H_{BS2R}.A_{BS}.K_{s_{BS}}.A_{BS}^H.H_{BS2R}^H).A_{RS}^H) \\ &\quad + tr(A_{RS}.(H_{IR2R}.A_{IR}.K_{s_{IR}}.A_{IR}^H.H_{IR2R}^H).A_{RS}^H) \\ &\quad + tr(A_{RS}.(\sigma_{n_{BS2R}}^2 + \sigma_{n_{IR2R}}^2).A_{RS}^H) \qquad (2.65b)\end{aligned}$$

When the $K_{s_{BS}}$ is the co-variance matrix of information data at the base station and $K_{s_{IR}}$ is the co-variance matrix of information data at the information users. Information users receive the following signal

$$\begin{aligned}z_{IR} &= H_{R2IR}.y_R + n_{R2IR} \\ &= H_{R2IR}.A_{RS}.(H_{BS2R}.A_{BS}.s_{BS} + n_{BS2R} + H_{IR2R}.A_{IR}.s_{IR} \\ &\quad + n_{IR2R}) + n_{R2IR} \\ &= H_{R2IR}.A_{RS}.\left(H_{BS2R}.A_{BS}.s_{BS} + n_{BS2R} + \sum_{i=1}^{N_{MU}} (H_{IR_i2R}.A_{IR_i}.s_{IR_i} + n_{IR_i2R})\right) \\ &\quad + n_{R2IR} \qquad (2.66)\end{aligned}$$

The base station transmitted signal is recovered by B_{IR} estimator in information users

$$\begin{aligned}\hat{s}_{IR} &= B_{IR}.\left(H_{R2IR}.y_R + n_{R2IR}\right) \\ &= B_{IR}.(H_{R2IR}.A_{RS}.(H_{BS2R}.A_{BS}.s_{BS} + n_{BS2R} + H_{IR2R}.A_{IR}.s_{IR} \\ &\quad + n_{IR2R}) + n_{R2IR}) \qquad (2.67)\end{aligned}$$

The received signal by user k is

$$\begin{aligned}z_{IR_k} &= \sum_{i=1}^{N_{MU}} (H_{R2IR_k}.A_{RS}.H_{BS2R}.A_{BS_i}.s_{BS_i}) + H_{R2IR}.A_{RS}.n_{BS2R} \\ &\quad + \sum_{i=1}^{N_{MU}} H_{R2IR_k}.A_{RS}.(H_{IR_i2R}.A_{IR_i}.s_{IR_i} + n_{IR_i2R}) + n_{R2IR} \qquad (2.68)\end{aligned}$$

Here, $H_{R2IR} = \left[H_{R2IR_1}; H_{R2IR_2}; ...; H_{R2IR_{N_{MU}}}\right]$ where H_{R2IR_i} is the MIMO channel matrix from relay to user i and $A_{BS} = [A_{BS_1} \mid A_{BS_2} \mid ... \mid A_{BS_{N_{MU}}}]$ where A_{BS_i} is the base station precoder for information data belongs to user i. A part of the received signal at the information user k is related to the sent signal to the relay by the same user. Therefore, the back propagated self-interference term can be eliminated

$$\begin{aligned} z_{IR_k} &= H_{R2IR_k}.A_{RS}.H_{BS2R}.A_{BS_k}.s_{BS_k} \\ &+ \sum_{i\neq k}(H_{R2IR_k}.A_{RS}.H_{BS2R}.A_{BS_i}.s_{BS_i}) + H_{R2IR}.A_{RS}.n_{BS2R} \\ &+ \sum_{i\neq k} H_{R2IR_k}.A_{RS}.(H_{IR_i2R}.A_{IR_i}.s_{IR_i} + n_{IR_i2R}) + n_{R2IR} \end{aligned} \tag{2.69}$$

The estimated signal for user k is

$$\begin{aligned} \hat{s}_{IR_k} &= B_{IR_k}.(H_{R2IR_k}.A_{RS}.H_{BS2R}.A_{BS_k}.s_{BS_k}) \\ &+ B_{IR_k}.\left(\sum_{i\neq k}(H_{R2IR_k}.A_{RS}.H_{BS2R}.A_{BS_i}.s_{BS_i}) + H_{R2IR}.A_{RS}.n_{BS2R}\right) \\ &+ B_{IR_k}.\left(\sum_{i\neq k} H_{R2IR_k}.A_{RS}.(H_{IR_i2R}.A_{IR_i}.s_{IR_i} + n_{IR_i2R}) + n_{R2IR}\right) \end{aligned} \tag{2.70}$$

By supposing $K_{s_{BS}} = I$, $K_{s_{IR}} = I$, $K_{n_{BS2R}} = \sigma^2_{BS2R}.I$, $K_{n_{IR2R}} = \sigma^2_{IR2R}.I$ and $K_{n_{R2IR_k}} = \sigma^2_{R2IR_k}.I$, signal-to-interference-plus- noise ratio (SINR) for user k is defined by

$$Sig_{BS2IR_k} = |H_{R2IR_k}.A_{RS}.H_{BS2R}.A_{BS_k}|^2 \tag{2.71a}$$

$$Int_{BS2IR_k} = \sum_{i\neq k} |H_{R2IR_k}.A_{RS}.H_{BS2R}.A_{BS_i}|^2 \tag{2.71b}$$

$$N_{BS2IR} = |H_{R2IR}.A_{RS}|^2.\sigma^2_{n_{BS2R}} \tag{2.71c}$$

$$Int_{IR2IR_k} = \sum_{i\neq k} |H_{R2IR_k}.A_{RS}.H_{IR_i2R}.A_{IR_i}|^2 \tag{2.71d}$$

$$N_{IR2IR_k} = |H_{R2IR}.A_{RS}|^2.\sigma^2_{n_{IR2R}} + \sigma^2_{n_{R2IR_k}} \tag{2.71e}$$

$$SINR_k = \frac{Sig_{BS2IR_k}}{Int_{BS2IR} + Int_{IR2IR_k} + N_{BS2IR} + N_{IR2IR_k}} \tag{2.71f}$$

Finally, the energy harvesting users get the following signal at their inputs

$$\begin{aligned} z_{ER} &= G_{R2ER}.y_R + n_{R2ER} \\ &= G_{R2ER}.A_{RS}.(H_{BS2R}.A_{BS}.s_{BS} + n_{BS2R} + H_{IR2R}.A_{IR}.s_{IR} \\ &+ n_{IR2R}) + n_{R2ER} \end{aligned} \tag{2.72}$$

The received signal by user k is

$$\begin{aligned} z_{ER_k} &= \sum_{i=1}^{N_{MU}} (G_{R2ER_k}.A_{RS}.H_{BS2R}.A_{BS_i}.s_{BS_i}) + G_{R2ER}.A_{RS}.n_{BS2R} \\ &+ \sum_{i=1}^{N_{MU}} H_{R2ER_k}.A_{RS}.(H_{IR_i2R}.A_{IR_i}.s_{IR_i} + n_{IR_i2R}) + n_{R2ER} \end{aligned} \tag{2.73}$$

Here, $G_{R2ER} = [G_{R2IR_1}; G_{R2ER_2}; ...; G_{R2ER_n}]$ where G_{R2ER_i} is i row of G_{R2ER}. The power of received signals is formulated as

$$\begin{aligned} P_{ER} &= E(\|z_{ER}\|^2) \\ &= tr(G_{R2ER}.A_{RS}.H_{BS2R}.A_{BS}.K_{s_{BS}}.A_{BS}^H.H_{BS2R}^H.A_{RS}^H.G_{R2ER}^H) \\ &+ tr(G_{R2ER}.A_{RS}.H_{IR2R}.A_{IR}.K_{s_{IR}}.A_{IR}^H.H_{IR2R}^H.A_{RS}^H.G_{R2ER}^H) \\ &+ tr(G_{R2ER}.A_{RS}.K_{n_{BS2R}}.A_{RS}^H.G_{R2ER}^H) \\ &+ tr(G_{R2ER}.A_{RS}.K_{n_{IR2R}}.A_{RS}^H.G_{R2ER}^H) \\ &+ tr(K_{n_{R2ER}}) \end{aligned} \tag{2.74a}$$

$$\begin{aligned} &= tr(G_{R2ER}.A_{RS}.H_{BS2R}.A_{BS}.A_{BS}^H.H_{BS2R}^H.A_{RS}^H.G_{R2ER}^H) \\ &+ tr(G_{R2ER}.A_{RS}.H_{IR2R}.A_{IR}.A_{IR}^H.H_{IR2R}^H.A_{RS}^H.G_{R2ER}^H) \\ &+ tr(G_{R2ER}.A_{RS}.A_{RS}^H.G_{R2ER}^H).\sigma_{n_{BS2R}}^2 \\ &+ tr(G_{R2ER}.A_{RS}.A_{RS}^H.G_{R2ER}^H).\sigma_{n_{IR2R}}^2 \\ &+ n_{ER}.\sigma_{n_{R2ER}}^2 \end{aligned} \tag{2.74b}$$

The received energy by user k can be rewritten as

$$\begin{aligned} P_{ER_k} &= tr(G_{R2ER_k}.A_{RS}.H_{BS2R}.A_{BS}.A_{BS}^H.H_{BS2R}^H.A_{RS}^H.G_{R2ER_k}^H) \\ &+ tr(G_{R2ER_k}.A_{RS}.H_{IR2R}.A_{IR}.A_{IR}^H.H_{IR2R}^H.A_{RS}^H.G_{R2ER_k}^H) \\ &+ tr(G_{R2ER_k}.A_{RS}.A_{RS}^H.G_{R2ER_k}^H).(\sigma_{n_{BS2R}}^2 + \sigma_{n_{IR2R}}^2) \\ &+ \sigma_{n_{R2ER_k}}^2 \end{aligned} \tag{2.75}$$

In the next section, the optimization problem will be discussed and formulated.

MMSE Estimation Problem

In this section, minimum mean square error (MMSE) to retrieve the sent information data from information users to base station when the SINR from base station to each user is more than required SINR and the power in each energy harvesting user is more than requested power are the target.

The total MMSE from data which has been sent by information users to base station is given by

$$MSE_{IR2BS} = E_{BS}\left(\|\hat{s}_{BS} - s_{IR}\|^2\right) \tag{2.76}$$

This equation is summarized to [ref: (2.9)]

$$\begin{aligned} MSE_{IR2BS} &= tr(K_{s_{IR}} - K_{s_{IR}y_{BS}}.K_{y_{BS}}^{-1}.K_{s_{IR}y_{BS}}^{H}) \\ &= tr(I + K_{s_{IR}y_{BS}}.(K_{y_{BS}} - K_{s_{IR}y_{BS}}^{H}.K_{s_{IR}y_{BS}})^{-1}.K_{s_{IR}y_{BS}}^{H})^{-1} \end{aligned} \tag{2.77}$$

where $K_{s_{IR}y_{BS}}$ is given by

$$K_{s_{IR}y_{BS}} = A_{IR}^{H}.H_{IR2R}^{H}.A_{RS}^{H}.H_{R2BS}^{H} \tag{2.78}$$

and $K_{y_{BS}}$ is expressed as

$$\begin{aligned} K_{y_{BS}} &= H_{R2BS}.A_{RS}.H_{IR2R}.A_{IR}.A_{IR}^{H}.H_{IR2R}^{H}.A_{RS}^{H}.H_{R2BS}^{H} \\ &+ H_{R2BS}.A_{RS}.K_{n_{BS2R}}.A_{RS}^{H}.H_{R2BS}^{H} \\ &+ H_{R2BS}.A_{RS}.K_{n_{IR2R}}.A_{RS}^{H}.H_{R2BS}^{H} \\ &+ K_{n_{R2BS}} \end{aligned} \tag{2.79}$$

Hence, the total MMSE is equal to

$$\begin{aligned} T1 &= \big(H_{R2BS}.A_{RS}.(K_{n_{BS2R}} + K_{n_{IR2R}}).A_{RS}^{H}.H_{R2BS}^{H} + K_{n_{R2BS}}\big)^{-1} \\ &= \Big(H_{R2BS}.A_{RS}.(\sigma_{n_{BS2R}}^{2} + \sigma_{n_{IR2R}}^{2}).A_{RS}^{H}.H_{R2BS}^{H} + \sigma_{n_{R2BS}^{2}}.I\Big)^{-1} \end{aligned} \tag{2.80a}$$

$$MSE_{IR2BS} = tr(I + K_{s_{IR}y_{BS}}.T1.K_{s_{IR}y_{BS}}^{H})^{-1} \tag{2.80b}$$

Since SINR from base station to each user should be more than $SINR_{k}^{Req}$, the received power for the energy harvesting user must be more than $P_{ER_k}^{Req}$, the base station transmission power is limited to P_{BS}^{Max} and the transmission power of relay is also limited to P_{R}^{Max}, the optimization problem is expressed by

$$\min_{A_{RS},A_{BS}} \quad tr(I + K_{s_{IR}y_{BS}}.T1.K_{s_{IR}y_{BS}}^{H})^{-1} \tag{2.81a}$$

$$Subject\ to:$$

$$SINR_k \geq SINR_k^{Req}, \quad \forall k = 1,...,N_{MU} \tag{2.81b}$$

$$P_{ER_k} \geq P_{ER_k}^{Req}, \quad \forall k = 1,...,N_{MU} \tag{2.81c}$$

$$P_{BS} \leq P_{BS}^{Max} \tag{2.81d}$$

$$P_{R} \leq P_{R}^{Max} \tag{2.81e}$$

In this problem, the objective function, SINR and energy constraints are non-convex. In the next section a new method for solving this non-convex problem is introduced.

Methodology

In this section, 'A and AH' method for solving the optimization problem is focused. The optimization problem with some small manipulations and supposing $\sigma_{n_{X2R}}^{2} = \sigma_{n_{BS2R}}^{2} +$

$\sigma^2_{n_{IR2R}}$ is rewritten as

$$T1 = \Big(H_{R2BS}.A_{RS}.\sigma^2_{n_{X2R}}.A^H_{RS}.H^H_{R2BS} + \sigma_{n^2_{R2BS}}.I\Big)^{-1} \tag{2.82a}$$

$$\min_{A_{RS},A_{BS}} tr(I + A^H_{IR}.H^H_{IR2R}.A^H_{RS}.H^H_{R2BS}.T1.H_{R2BS}.A_{RS}.H_{IR2R}.A_{IR})^{-1} \tag{2.82b}$$

$$Subject\ to:$$

$$\begin{aligned} & tr(H^H_{R2IR_K}.H_{R2IR_K}.(A_{RS}.(H_{BS2R}.A_{BS_k}.A^H_{BS_k}.H^H_{BS2R} \\ & - SINR^{Req}_k.(\sum_{i\neq k}(H_{BS2R}.A_{BS_i}.A^H_{BS_i}.H^H_{BS2R} + H_{IR_i2R}.H^H_{IR_i2R}.|A_{IR_i}|^2) \\ & + \sigma^2_{n_{X2R}}.I)).A^H_{RS}) \geq SINR^{Req}_k.\sigma^2_{n_{R2IR_k}}, \quad \forall k = 1,...,N_{MU} \end{aligned} \tag{2.82c}$$

$$\begin{aligned} & tr(G_{R2ER_k}.A_{RS}.H_{BS2R}.A_{BS}.A^H_{BS}.H^H_{BS2R}.A^H_{RS}.G^H_{R2ER_k}) \\ & + tr(G_{R2ER_k}.A_{RS}.H_{IR2R}.A_{IR}.A^H_{IR}.H^H_{IR2R}.A^H_{RS}.G^H_{R2ER_k}) \\ & + tr(G_{R2ER_k}.A_{RS}.A^H_{RS}.G^H_{R2ER_k}).\sigma^2_{n_{X2R}} \\ & + \sigma^2_{n_{R2ER_k}} \geq P^{Req}_{ER_k}, \quad \forall k = 1,...,N_{MU} \end{aligned} \tag{2.82d}$$

$$tr(A_{BS}.A^H_{BS}) \leq P^{Max}_{BS} \tag{2.82e}$$

$$\begin{aligned} & tr((H_{BS2R}.A_{BS}.K_{s_{BS}}.A^H_{BS}.H^H_{BS2R}).A^H_{RS}.A_{RS}) \\ & + tr((H_{IR2R}.A_{IR}.K_{s_{IR}}.A^H_{IR}.H^H_{IR2R}).A^H_{RS}.A_{RS}) \\ & + \sigma^2_{n_{X2R}}.tr(A^H_{RS}.A_{RS}) \leq P^{Max}_R \end{aligned} \tag{2.82f}$$

Three different methodologies and algorithms for base station precoding, relay precoding and joint base station and relay precoding scenarios for this optimization problem are considered. Therefore the optimization problem methodology for each scenario is explained separately.

Base Station Precoding

In this scenario, the precoding is conducted in base station and relay uses an arbitrary constant precoding. Due to limited transmission power of relay $A_{RS} = \sqrt{\alpha}.\hat{A}_{RS}$ with suitable $\alpha \geq 0$ satisfies the power constraint of the relay. By replacing $K_{A_{BS}} = A_{BS}.A^H_{BS}$, this optimization problem can be expressed as

$$T1 = \Big(\alpha.H_{R2BS}.\hat{A}_{RS}.\sigma^2_{n_{X2R}}.\hat{A}^H_{RS}.H^H_{R2BS} + \sigma_{n^2_{R2BS}}.I\Big)^{-1} \tag{2.83a}$$

$$\min_{\alpha, A_{BS}} tr(I + \alpha.A^H_{IR}.H^H_{IR2R}.\hat{A}^H_{RS}.H^H_{R2BS}.T1.H_{R2BS}.\hat{A}_{RS}.H_{IR2R}.A_{IR})^{-1} \tag{2.83b}$$

$Subject\ to:$

$$\begin{aligned}
&tr(H^H_{R2IR_K}.H_{R2IR_K}.(\alpha.\hat{A}_{RS}.(H_{BS2R}.A_{BS_k}.A^H_{BS_k}.H^H_{BS2R} \\
&- SINR^{Req}_k.(\sum_{i\neq k}(H_{BS2R}.A_{BS_i}.A^H_{BS_i}.H^H_{BS2R} + H_{IR_i2R}.H^H_{IR_i2R}.|A_{IR_i}|^2) \\
&+ \sigma^2_{n_{X2R}}.I)).\hat{A}^H_{RS}) \geq SINR^{Req}_k.\sigma^2_{n_{R2IR_k}}, \quad \forall k = 1,...,N_{MU}
\end{aligned} \tag{2.83c}$$

$$\begin{aligned}
&tr(\alpha.G_{R2ER_k}.\hat{A}_{RS}.H_{BS2R}.A_{BS}.A^H_{BS}.H^H_{BS2R}.\hat{A}^H_{RS}.G^H_{R2ER_k}) \\
&+ tr(\alpha.G_{R2ER_k}.\hat{A}_{RS}.H_{IR2R}.A_{IR}.A^H_{IR}.H^H_{IR2R}.\hat{A}^H_{RS}.G^H_{R2ER_k}) \\
&+ tr(\alpha.G_{R2ER_k}.\hat{A}_{RS}.\hat{A}^H_{RS}.G^H_{R2ER_k}).\sigma^2_{n_{X2R}} \\
&+ \sigma^2_{n_{R2ER_k}} \geq P^{Req}_{ER_k}, \quad \forall k = 1,...,N_{MU}
\end{aligned} \tag{2.83d}$$

$$tr(K_{A_{BS}}) \leq P^{Max}_{BS} \tag{2.83e}$$

$$\begin{aligned}
&tr(\alpha.\hat{A}_{RS}.H_{BS2R}.A_{BS}.K_{s_{BS}}.A^H_{BS}.H^H_{BS2R}.\hat{A}^H_{RS}) \\
&+ tr(\alpha.\hat{A}_{RS}.H_{IR2R}.A_{IR}.K_{s_{IR}}.A^H_{IR}.H^H_{IR2R}.\hat{A}^H_{RS}) \\
&+ \sigma^2_{n_{X2R}}.tr(\alpha.\hat{A}_{RS}.\hat{A}^H_{RS}) \leq P^{Max}_{R}
\end{aligned} \tag{2.83f}$$

$$K_{A_{BS}} - A_{BS}.A^H_{BS} = 0 \tag{2.83g}$$

$$\tag{2.83h}$$

By supposing $K_{s_{BS}} = I$ and $K_{s_{IR}} = I$, replacing $K_{A_{BS}} \succeq A_{BS}.A^H_{BS}$ with $K_{A_{BS}} = A_{BS}.A^H_{BS}$ for relaxation and substituting $A_{BSH} = A^H_{BS}$ in 'A and AH' method, the convex problem is given by

$$T1 = \Big(\alpha.H_{R2BS}.\hat{A}_{RS}.\sigma^2_{n_{X2R}}.\hat{A}^H_{RS}.H^H_{R2BS} + \sigma_{n^2_{R2BS}}.I\Big)^{-1} \tag{2.84a}$$

$$\min_{\alpha,A_{BS}} tr(I + \alpha.A^H_{IR}.H^H_{IR2R}.\hat{A}^H_{RS}.H^H_{R2BS}.T1.H_{R2BS}.\hat{A}_{RS}.H_{IR2R}.A_{IR})^{-1} \tag{2.84b}$$

$Subject\ to:$

$$\begin{aligned}
&tr(H^H_{R2IR_K}.H_{R2IR_K}.(\alpha.\hat{A}_{RS}.(H_{BS2R}.A_{BS_k}.A_{BSH_k}.H^H_{BS2R}\\
&- SINR^{Req}_k.(\sum_{i\neq k}(H_{BS2R}.A_{BS_i}.A_{BSH_i}.H^H_{BS2R} + H_{IR_i2R}.H^H_{IR_i2R}.|A_{IR_i}|^2)\\
&+ \sigma^2_{n_{X2R}}.I)).\hat{A}^H_{RS}) \geq SINR^{Req}_k.\sigma^2_{n_{R2IR_k}}, \quad \forall k = 1,...,N_{MU}
\end{aligned} \tag{2.84c}$$

$$\begin{aligned}
&tr(\alpha.G_{R2ER_k}.\hat{A}_{RS}.H_{BS2R}.A_{BS}.A_{BSH}.H^H_{BS2R}.\hat{A}^H_{RS}.G^H_{R2ER_k})\\
&+ tr(\alpha.G_{R2ER_k}.\hat{A}_{RS}.H_{IR2R}.A_{IR}.A^H_{IR}.H^H_{IR2R}.\hat{A}^H_{RS}.G^H_{R2ER_k})\\
&+ tr(\alpha.G_{R2ER_k}.\hat{A}_{RS}.\hat{A}^H_{RS}.G^H_{R2ER_k}).\sigma^2_{n_{X2R}}\\
&+ \sigma^2_{n_{R2ER_k}} \geq P^{Req}_{ER_k}, \quad \forall k = 1,...,N_{MU}
\end{aligned} \tag{2.84d}$$

$$tr(K_{A_{BS}}) \leq P^{Max}_{BS} \tag{2.84e}$$

$$\begin{aligned}
&tr(\alpha.\hat{A}_{RS}.H_{BS2R}.A_{BS}.A_{BSH}.H^H_{BS2R}.\hat{A}^H_{RS})\\
&+ tr(\alpha.\hat{A}_{RS}.H_{IR2R}.A_{IR}.A^H_{IR}.H^H_{IR2R}.\hat{A}^H_{RS})\\
&+ \sigma^2_{n_{X2R}}.tr(\alpha.\hat{A}_{RS}.\hat{A}^H_{RS}) \leq P^{Max}_R
\end{aligned} \tag{2.84f}$$

$$K_{A_{BS}} - A_{BS}.A^H_{BS} \succeq 0 \tag{2.84g}$$

$$\|vec(A_{BS} - A^H_{BSH})\|^2 \leq \varepsilon_{A_{BS}} \tag{2.84h}$$

An adaptive algorithm for selecting suitable value for $\varepsilon_{A_{BS}}$ with initial large value and final small target threshold value ($\varepsilon^{Tg}_{A_{BS}}$) guarantees that $A^H_{BS} \approx A_{BSH}$. Objective function is monotonically decreasing function respect to $\alpha \geq 0$. Therefore, the problem is re-expressed

$$
\begin{aligned}
&\max_{\alpha, A_{BS}} \ \alpha && (2.85a)\\
&Subject\ to:\\
&\qquad tr(H^H_{R2IR_K}.H_{R2IR_K}.(\alpha.\hat{A}_{RS}.(H_{BS2R}.A_{BS_k}.A_{BSH_k}.H^H_{BS2R}\\
&\qquad - SINR^{Req}_k.(\sum_{i\neq k}(H_{BS2R}.A_{BS_i}.A_{BSH_i}.H^H_{BS2R} + H_{IR_i2R}.H^H_{IR_i2R}.|A_{IR_i}|^2)\\
&\qquad + \sigma^2_{n_{X2R}}.I)).\hat{A}^H_{RS}) \geq SINR^{Req}_k.\sigma^2_{n_{R2IR_k}}, \quad \forall k = 1,...,N_{MU} && (2.85b)\\
&\qquad tr(\alpha.G_{R2ER_k}.\hat{A}_{RS}.H_{BS2R}.A_{BS}.A_{BSH}.H^H_{BS2R}.\hat{A}^H_{RS}.G^H_{R2ER_k})\\
&\qquad + tr(\alpha.G_{R2ER_k}.\hat{A}_{RS}.H_{IR2R}.A_{IR}.A^H_{IR}.H^H_{IR2R}.\hat{A}^H_{RS}.G^H_{R2ER_k})\\
&\qquad + tr(\alpha.G_{R2ER_k}.\hat{A}_{RS}.\hat{A}^H_{RS}.G^H_{R2ER_k}).\sigma^2_{n_{X2R}}\\
&\qquad + \sigma^2_{n_{R2ER_k}} \geq P^{Req}_{ER_k}, \quad \forall k = 1,...,N_{MU} && (2.85c)\\
&\qquad tr(K_{A_{BS}}) \leq P^{Max}_{BS} && (2.85d)\\
&\qquad tr(\alpha.\hat{A}_{RS}.H_{BS2R}.A_{BS}.A_{BSH}.H^H_{BS2R}.\hat{A}^H_{RS})\\
&\qquad + tr(\alpha.\hat{A}_{RS}.H_{IR2R}.A_{IR}.A^H_{IR}.H^H_{IR2R}.\hat{A}^H_{RS})\\
&\qquad + \sigma^2_{n_{X2R}}.tr(\alpha.\hat{A}_{RS}.\hat{A}^H_{RS}) \leq P^{Max}_R && (2.85e)\\
&\qquad K_{A_{BS}} - A_{BS}.A^H_{BS} \succeq 0 && (2.85f)\\
&\qquad \|vec(A_{BS} - A^H_{BSH})\|^2 \leq \varepsilon_{A_{BS}} && (2.85g)
\end{aligned}
$$

This optimization problem is convex respect to A_{BS}. By supposing $A_{BS} = \frac{\hat{A}_{BS}}{\sqrt{\alpha}}$ the problem is solved in MATLAB CVX tool easier.

$$\max_{\alpha, A_{BS}} \ \alpha \tag{2.86a}$$

$$Subject\ to:$$

$$tr(H^H_{R2IR_K}.H_{R2IR_K}.(\hat{A}_{RS}.(H_{BS2R}.\hat{A}_{BS_k}.\hat{A}_{BSH_k}.H^H_{BS2R} - SINR^{Req}_k.(\sum_{i\neq k}(H_{BS2R}.\hat{A}_{BS_i}.\hat{A}_{BSH_i}.H^H_{BS2R} + \alpha.H_{IR_i2R}.H^H_{IR_i2R}.|A_{IR_i}|^2) + \alpha.\sigma^2_{n_{X2R}}.I)).\hat{A}^H_{RS}) \geq SINR^{Req}_k.\sigma^2_{n_{R2IR_k}}, \quad \forall k = 1,...,N_{MU} \tag{2.86b}$$

$$tr(G_{R2ER_k}.\hat{A}_{RS}.H_{BS2R}.\hat{A}_{BS}.\hat{A}_{BSH}.H^H_{BS2R}.\hat{A}^H_{RS}.G^H_{R2ER_k}) + tr(\alpha.G_{R2ER_k}.\hat{A}_{RS}.H_{IR2R}.A_{IR}.A^H_{IR}.H^H_{IR2R}.\hat{A}^H_{RS}.G^H_{R2ER_k}) + tr(\alpha.G_{R2ER_k}.\hat{A}_{RS}.\hat{A}^H_{RS}.G^H_{R2ER_k}).\sigma^2_{n_{X2R}} + \sigma^2_{n_{R2ER_k}} \geq P^{Req}_{ER_k}, \quad \forall k = 1,...,N_{MU} \tag{2.86c}$$

$$tr(\hat{K}_{A_{BS}}) \leq \alpha.P^{Max}_{BS} \tag{2.86d}$$

$$tr(\hat{A}_{RS}.H_{BS2R}.\hat{K}_{A_{BS}}.H^H_{BS2R}.\hat{A}^H_{RS}) + tr(\alpha.\hat{A}_{RS}.H_{IR2R}.A_{IR}.A^H_{IR}.H^H_{IR2R}.\hat{A}^H_{RS}) + \sigma^2_{n_{X2R}}.tr(\alpha.\hat{A}_{RS}.\hat{A}^H_{RS}) \leq P^{Max}_R \tag{2.86e}$$

$$\hat{K}_{A_{BS}} - \hat{A}_{BS}.\hat{A}^H_{BS} \succeq 0 \tag{2.86f}$$

$$\|vec(\hat{A}_{BS} - \hat{A}^H_{BSH})\|^2 \leq \alpha.\varepsilon_{A_{BS}} \tag{2.86g}$$

The algorithm for solving this optimization problem is

Algorithm SWIPT_RTW_BS(A,AH):

- **Initialize**
  - *Calculate value* $\hat{A}_{RS} = \sqrt{\alpha}.A_{RS}$ *for arbitrary* A_{RS} *and* α
  - *Initialize* $\hat{A}_{BS}$, $\hat{A}_{BSH}$ *and* $\varepsilon_{A_{BS}}$
- **Repeat**
  - *Solve the convex problem (2.86) to find* A_{BS} *and* α
  - *Change* $\varepsilon_{A_{BS}}$ *to get first feasible* A_{BS}
  - *Update* $\hat{A}_{BSH} = \hat{A}^H_{BS}$
  - *If no improvement in objective function then choose smaller* $\varepsilon_{A_{BS}}$
- **Until** $\varepsilon_{A_{BS}} \leq \varepsilon^{Tg}_{A_{BS}}$
- **Update** $A_{BS} = \hat{A}_{BS}.\sqrt{\alpha}$

Relay Precoding
In this scenario, the precoding is done in the relay and the base station uses an arbitrary constant precoding. By replacing $K_{A_{RS}^H} = A_{RS}^H.A_{RS}$ in (2.82), this optimization problem can be expressed as

$$T1 = \Big(H_{R2BS}.A_{RS}.\sigma^2_{n_{X2R}}.A_{RS}^H.H_{R2BS}^H + \sigma_{n^2_{R2BS}}.I\Big)^{-1} \tag{2.87a}$$

$$\min_{A_{RS}} tr(I + A_{IR}^H.H_{IR2R}^H.A_{RS}^H.H_{R2BS}^H.T1.H_{R2BS}.A_{RS}.H_{IR2R}.A_{IR})^{-1} \tag{2.87b}$$

$$Subject\ to:$$

$$\begin{aligned}
&tr(H_{R2IR_K}^H.H_{R2IR_K}.(A_{RS}.(H_{BS2R}.A_{BS_k}.A_{BS_k}^H.H_{BS2R}^H \\
&- SINR_k^{Req}.(\sum_{i\neq k}(H_{BS2R}.A_{BS_i}.A_{BS_i}^H.H_{BS2R}^H + H_{IR_i2R}.H_{IR_i2R}^H.|A_{IR_i}|^2) \\
&+ \sigma^2_{n_{X2R}}.I)).A_{RS}^H) \geq SINR_k^{Req}.\sigma^2_{n_{R2IR_k}}, \quad \forall k = 1,...,N_{MU}
\end{aligned} \tag{2.87c}$$

$$\begin{aligned}
&tr(G_{R2ER_k}.A_{RS}.H_{BS2R}.A_{BS}.A_{BS}^H.H_{BS2R}^H.A_{RS}^H.G_{R2ER_k}^H) \\
&+ tr(G_{R2ER_k}.A_{RS}.H_{IR2R}.A_{IR}.A_{IR}^H.H_{IR2R}^H.A_{RS}^H.G_{R2ER_k}^H) \\
&+ tr(G_{R2ER_k}.A_{RS}.A_{RS}^H.G_{R2ER_k}^H).\sigma^2_{n_{X2R}} \\
&+ \sigma^2_{n_{R2ER_k}} \geq P_{ER_k}^{Req}, \quad \forall k = 1,...,N_{MU}
\end{aligned} \tag{2.87d}$$

$$tr(A_{BS}.A_{BS}^H) \leq P_{BS}^{Max} \tag{2.87e}$$

$$\begin{aligned}
&tr((H_{BS2R}.A_{BS}.K_{s_{BS}}.A_{BS}^H.H_{BS2R}^H).K_{A_{RS}^H}) \\
&+ tr((H_{IR2R}.A_{IR}.K_{s_{IR}}.A_{IR}^H.H_{IR2R}^H).K_{A_{RS}^H}) \\
&+ \sigma^2_{n_{X2R}}.tr(K_{A_{RS}^H}) \leq P_R^{Max}
\end{aligned} \tag{2.87f}$$

$$K_{A_{RS}^H} = A_{RS}^H.A_{RS} \tag{2.87g}$$

By replacing $K_{A_{RS}^H} \succeq A_{RS}^H.A_{RS}$ instead of $K_{A_{RS}^H} = A_{RS}^H.A_{RS}$ for relaxation and substituting $A_{RSH} = A_{RS}^H$ in 'A and AH' method, it is possible to make the problem convex as follows

$$T1 = \Big(H_{R2BS}.A_{RS}.\sigma^2_{n_{X2R}}.A_{RSH}.H^H_{R2BS} + \sigma_{n^2_{R2BS}}.I\Big)^{-1} \tag{2.88a}$$

$$\min_{A_{RS}} tr(I + A^H_{IR}.H^H_{IR2R}.A_{RSH}.H^H_{R2BS}.T1.H_{R2BS}.A_{RS}.H_{IR2R}.A_{IR})^{-1} \tag{2.88b}$$

Subject to :

$$\begin{aligned}
&tr(H^H_{R2IR_K}.H_{R2IR_K}.(A_{RS}.(H_{BS2R}.A_{BS_k}.A^H_{BS_k}.H^H_{BS2R}\\
&-SINR^{Req}_k.(\sum_{i\neq k}(H_{BS2R}.A_{BS_i}.A^H_{BS_i}.H^H_{BS2R} + H_{IR_i2R}.H^H_{IR_i2R}.|A_{IR_i}|^2)\\
&+\sigma^2_{n_{X2R}}.I)).A_{RSH}) \geq SINR^{Req}_k.\sigma^2_{n_{R2IR_k}}, \quad \forall k = 1,...,N_{MU} && (2.88c)\\
&tr(G_{R2ER_k}.A_{RS}.H_{BS2R}.A_{BS}.A^H_{BS}.H^H_{BS2R}.A_{RSH}.G^H_{R2ER_k})\\
&+tr(G_{R2ER_k}.A_{RS}.H_{IR2R}.A_{IR}.A^H_{IR}.H^H_{IR2R}.A_{RSH}.G^H_{R2ER_k})\\
&+tr(G_{R2ER_k}.A_{RS}.A_{RSH}.G^H_{R2ER_k}).\sigma^2_{n_{X2R}}\\
&+\sigma^2_{n_{R2ER_k}} \geq P^{Req}_{ER_k}, \quad \forall k = 1,...,N_{MU} && (2.88d)\\
&tr(A_{BS}.A^H_{BS}) \leq P^{Max}_{BS} && (2.88e)\\
&tr((H_{BS2R}.A_{BS}.K_{s_{BS}}.A^H_{BS}.H^H_{BS2R}).K_{A^H_{RS}})\\
&+tr((H_{IR2R}.A_{IR}.K_{s_{IR}}.A^H_{IR}.H^H_{IR2R}).K_{A^H_{RS}})\\
&+\sigma^2_{n_{X2R}}.tr(K_{A^H_{RS}}) \leq P^{Max}_R && (2.88f)\\
&K_{A^H_{RS}} - A^H_{RS}.A_{RS} \succeq 0 && (2.88g)\\
&\|vec(A_{RS} - A^H_{RSH})\|^2 \leq \varepsilon_{A_{RS}} && (2.88h)
\end{aligned}$$

Choosing $\varepsilon_{A_{RS}}$ with initial large value and final small target threshold value ($\varepsilon^{Tg}_{A_{RS}}$) assures that $A^H_{RS} \approx A_{RSH}$. The algorithm for solving this optimization problem is

Algorithm SWIPT_RTW_RS(A,AH):

- ***Initialize*** A_{RS}, A_{RSH} *and* $\varepsilon_{A_{RS}}$
- ***Repeat***
  - *Solve convex problem (2.88) to find* A_{RS}
  - *Change* $\varepsilon_{A_{RS}}$ *to get first feasible* A_{RS}
  - *Update* $A_{RSH} = A^H_{RS}$
  - *If no improvement in objective function then choose smaller* $\varepsilon_{A_{RS}}$
- ***Until*** $\varepsilon_{A_{RS}} \leq \varepsilon^{Tg}_{A_{RS}}$

Joint Base Station and Relay Precoding
In this scenario, the precodings are conducted in both base station and relay. The

optimization problem is composed of (2.86) for the base station optimization and (2.88) for the relay optimization. The algorithm for solving these joint optimization problems is outlined as follows.

Algorithm $SWIPT\_RTW\_BSRS(A,AH)$:

- ***Initialize*** $\hat{A}_{BS}$, $\hat{A}_{BSH}$, A_{RS}, A_{RSH}, $\varepsilon_{A_{BS}}$, *and* $\varepsilon_{A_{RS}}$
- ***Repeat***
  - ***Repeat***
    - *Solve convex problem (2.88) to find* A_{RS}
    - *Change* $\varepsilon_{A_{RS}}$ *to get first feasible* A_{RS}
    - *Update* $A_{RSH} = A_{RS}^{H}$
    - *If no improvement in objective function then choose smaller* $\varepsilon_{A_{RS}}$
  - ***Until*** $\varepsilon_{A_{RS}} \leq \varepsilon_{A_{RS}}^{Tg}$
    - *Calculate value* $\hat{A}_{RS} = \sqrt{\alpha}.A_{RS}$ *for* A_{RS} *and arbitrary* α
  - ***Repeat***
    - *Solve convex problem (2.86) to find* $\hat{A}_{BS}$
    - *Change* $\varepsilon_{A_{BS}}$ *to get first feasible* $\hat{A}_{BS}$
    - *Update* $\hat{A}_{BSH} = \hat{A}_{BS}^{H}$
    - *If no improvement in objective function then choose smaller* $\varepsilon_{A_{BS}}$
  - ***Until*** $\varepsilon_{A_{BS}} \leq \varepsilon_{A_{BS}}^{Tg}$
  - ***Update*** $A_{BS} = \hat{A}_{BS}.\sqrt{\alpha}$
- ***Until*** no improvement in objective functions

3

Numerical Results

3.1 Simultaneous Wireless Information and Power Transfer in MIMO Channel without Relay

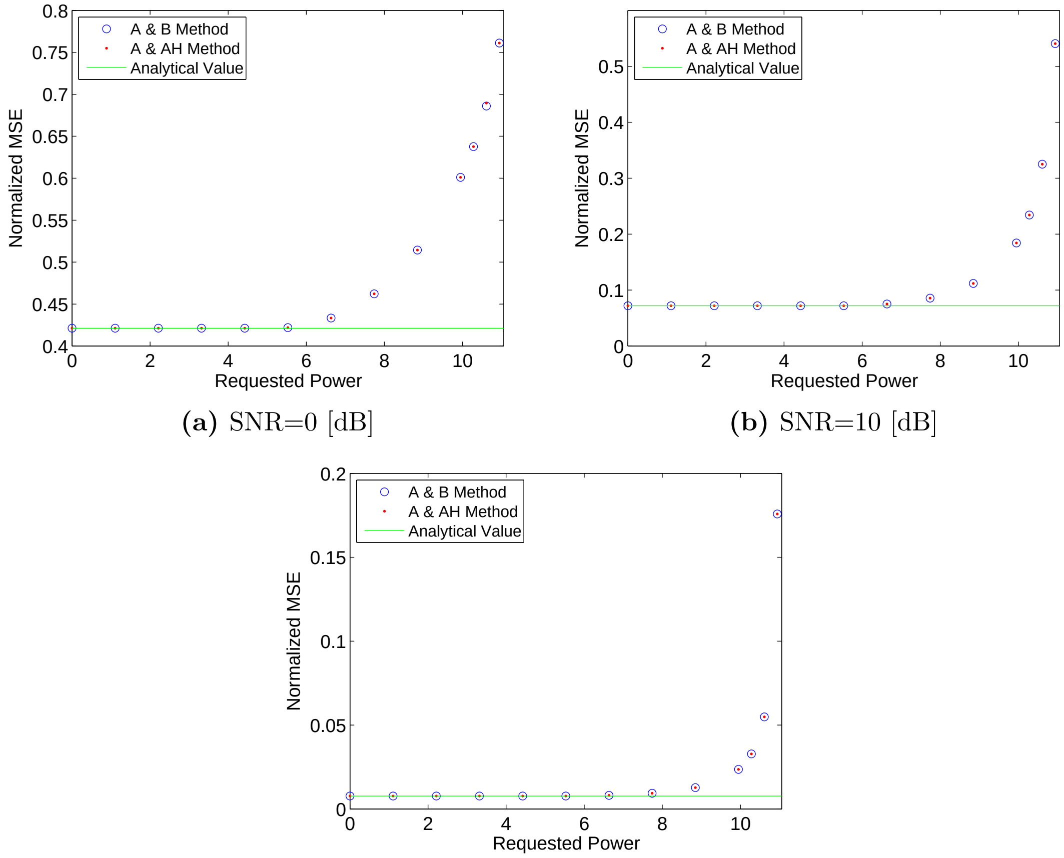
In this chapter, numerical results for information and power transfer to information user and the energy harvesting user without relay will be presented. For some of the scenarios considered here, optimum analytical results are available. These optimum analytic values and performance of the known methodology ('A and B' method) are compared to proposed methodology ('A and AH' method) to verify it. The stability and convergence of these methodologies are compared.

3.1.1 MMSE Results

In Figure 3.1, the results for normalized MSE versus requested power for different channel signal to noise ratio (SNR) for $nt = 5$ and $ns = 4$ are shown. The circle and dot present the 'A and B' and 'A and AH' methods simulation results. The result illustrates that both 'A and B' and 'A and AH' methods give very close results. Hence, the new introduced 'A and AH' method appears promising methodology.

The green line shows the minimum possible MSE that is calculated analytically. When the requested power is small, results of both methods are very close to minimum achievable MSE due to all power of source is consumed for transmitting the information with minimum error.

Moreover, these figures show that there is trade-off between MMSE and energy demands. Besides, by increasing the requested power, the mean square error starts increasing from a knee point that is called K-point. The reason is before this K-point, the source information signals can deliver power to energy harvesting user. By requesting more power than K-point, a part of the source power is used for sending power to the energy harvesting user instead of minimizing MMSE.



(a) SNR=0 [dB]

(b) SNR=10 [dB]

(c) SNR=20 [dB]

Figure 3.1: Normalized MSE versus requested power

Finally, these results also demonstrate that by increasing the SNR, the K-point shifts to higher requested power (to the right hand). The reason is that in higher SNR, more portion of power can be sent to the energy harvesting user before error starts increasing.

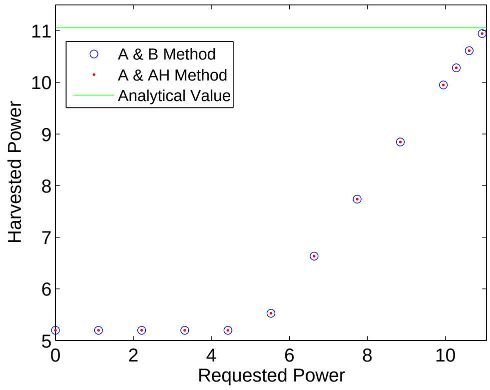
3.1.2 Energy Results

In Figure 3.2, the results for harvested power for different channel signal to noise ratio have been displayed.

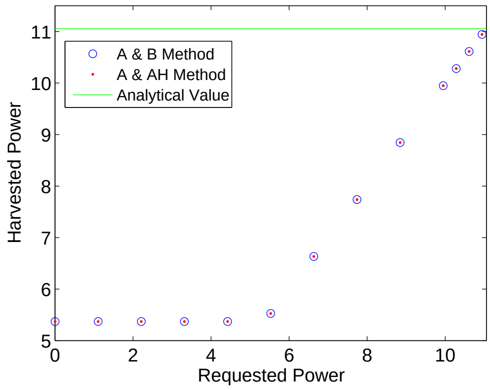
The green line, that shows the maximum achievable power, is calculated analytically therefore the maximum requested power should reach the maximum achievable one.

Besides, minimum harvested powers for different SNRs are the same. It is due to that harvested power from noise is negligible and ignored, Hence as shown earlier it is independent of SNR.

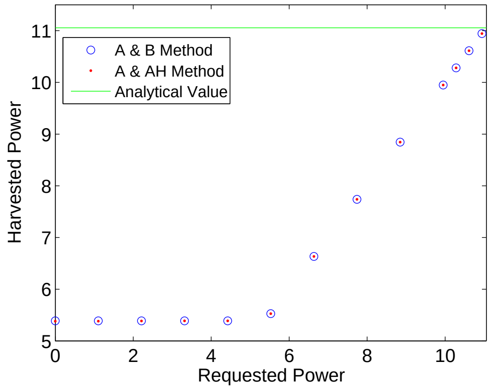
Finally, both ‘A and B’ and ‘A and AH’ methodologies produce the same harvested power results so the new methodology ‘A and AH’ seems promising.



(a) SNR=0 [dB]



(b) SNR=10 [dB]



(c) SNR=20 [dB]

Figure 3.2: Harvested power versus requested power

The results of normalized MSE versus requested power for different n_s is shown in Figure 3.3. The reason for this difference is that estimating less number of variables (n_s) with the same channel (n_t) outcomes lower MSE.

3.1.3 Convergence Results

In Figure 3.4, the convergence status of normalized MSE versus iteration number in 'A and B' and 'A and AH' methods is given. In this figure each curve presents different requested power. The 'A and B' method is converged with less iterations in comparison with 'A and AH' method but 'A and B' Method takes around 198[s] in comparison with 138[s] in 'A and AH' method. The reason is that the complexity of 'A and B' method is higher than 'A and AH' method.

In Figure 3.5 the convergence process of A_{SH} to A_S^H for different requested power in 'A and AH' method is presented. Some oscillations with different amplitudes in convergence process is due to updating A_{SH} by A_S^H and adaptive method for updating ϵ_{A_S}.

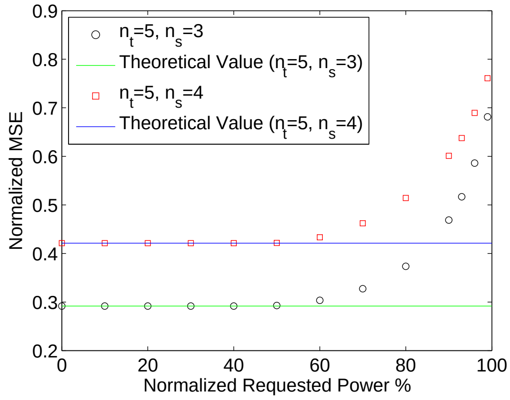
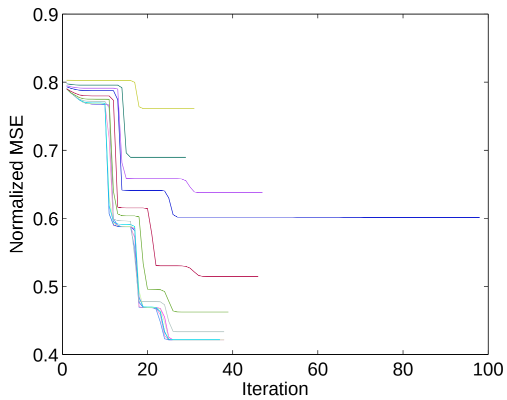
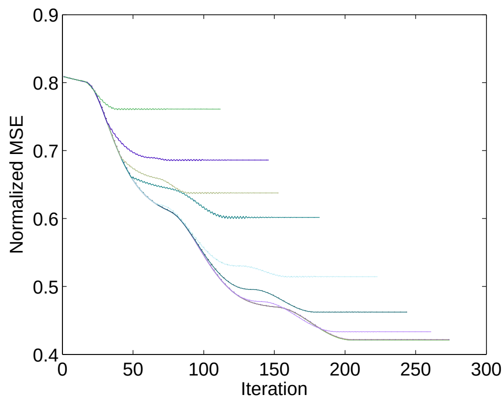


Figure 3.3: Normalized MSE versus requested power



(a) 'A and B' method



(b) 'A and AH' method

Figure 3.4: Convergence status of normalized MSE

The effects of these oscillations in normalized MSE and harvested power are negligible (Figure 3.4). Many different experiments with different energy demands have been tested and it has been observed that convergence always happened $|A_{SH} - A_S^H|^2 \leq \epsilon_{A_S}^{Tg}$. It has been observed that for higher requested power this convergence is faster due to K_{A_S} has a lower rank.

3.2 Simultaneous Wireless Information and Power Transfer in MIMO Channel with Relay Amplify-and-Forward Strategy

In this chapter, numerical results for one-way and two-way information and power transfer to information and energy harvesting users with relay amplify-and-forward strategy

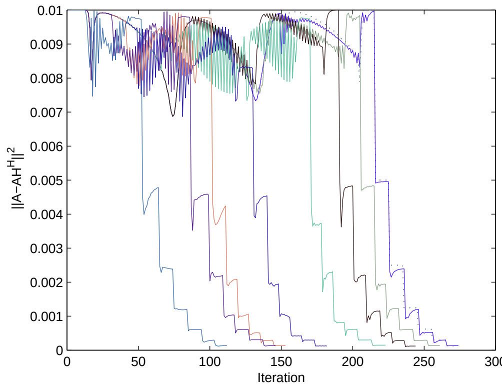


Figure 3.5: Convergence process

will be presented. Convergence results of these strategies are discussed also.

3.2.1 Relay Precoding for One-Way Relay System

MMSE Results for Relay Precoding

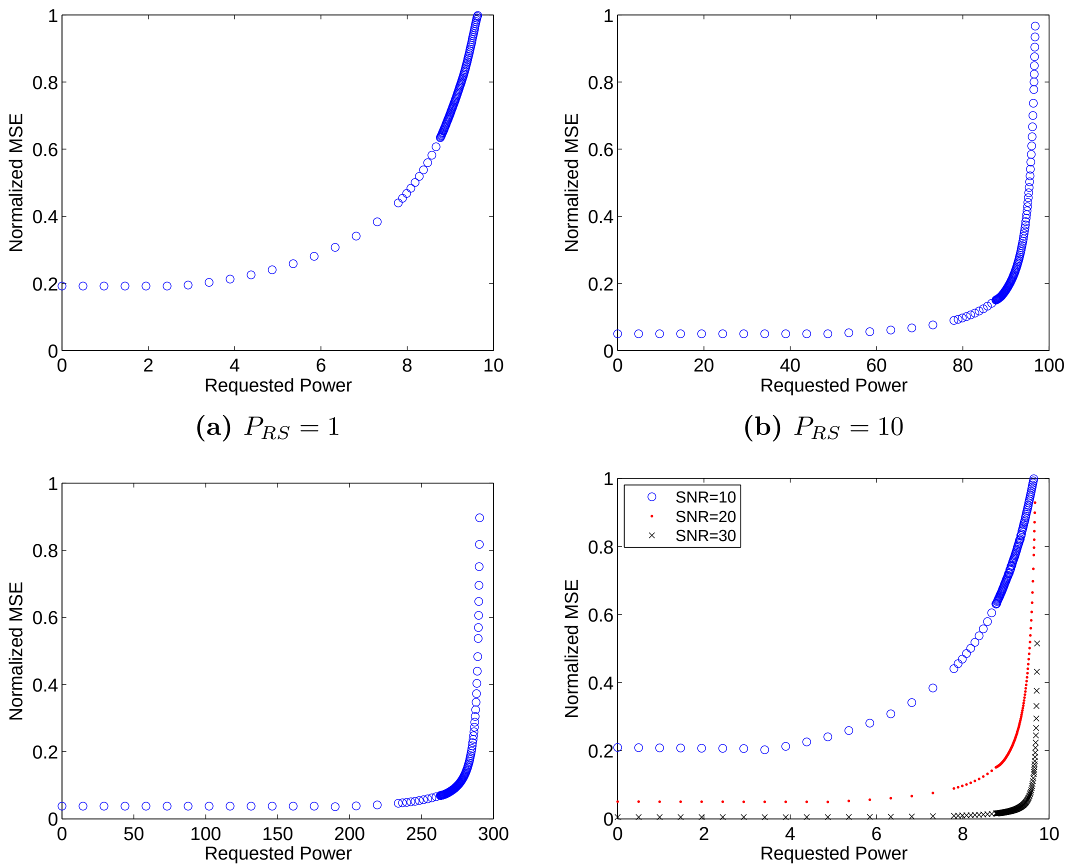
In this section, numerical results of relay precoding for simultaneous one-way information and power transfer with relay amplify-and-forward strategy are presented. All channels are complex MIMO channels with complex Gaussian noise with zero mean and equal variances ($\sigma^2_{BS2R} = \sigma^2_{IR2R} = \sigma^2_{R2BS} = \sigma^2_{R2IR} = \sigma^2_{R2ER}$). Base station, information user, energy harvesting user and relay have 2 antennas.

In Figure 3.6a, Figure 3.6b and Figure 3.6c, MSE at information user versus requested power for three different relay power are shown. Due to limited power in the relay, if the relay uses a precoding that deliver more power to the energy harvesting user, the error at the information user increases.

In Figure 3.6d, MSE in information user versus requested power in the energy harvesting user for three different SNR is presented. As SNR increases, since less power is needed to maintain error in low level, more power of relay can be transferred to the energy harvesting users when SNR is higher since less power is needed to maintain error low.

Energy Results for Relay Precoding

In Figure 3.7, the harvested power versus requested power by energy harvesting user has been presented. At the beginning (flat part of blue curve), although the energy harvesting user has requested lower power, more power could be harvested by this user due to signals that transfer information to information user can deliver power to this user. At K-point, the relay has to use some of its power to send energy to energy harvesting user even if this results in increasing MSE values at information user. Hence, as it has been shown in Figure 3.6, error starts to increase. In Figure 3.7a, Figure 3.7b



(a) $P_{RS} = 1$ **(b)** $P_{RS} = 10$

(c) $P_{RS} = 30$ **(d)** Different SNR

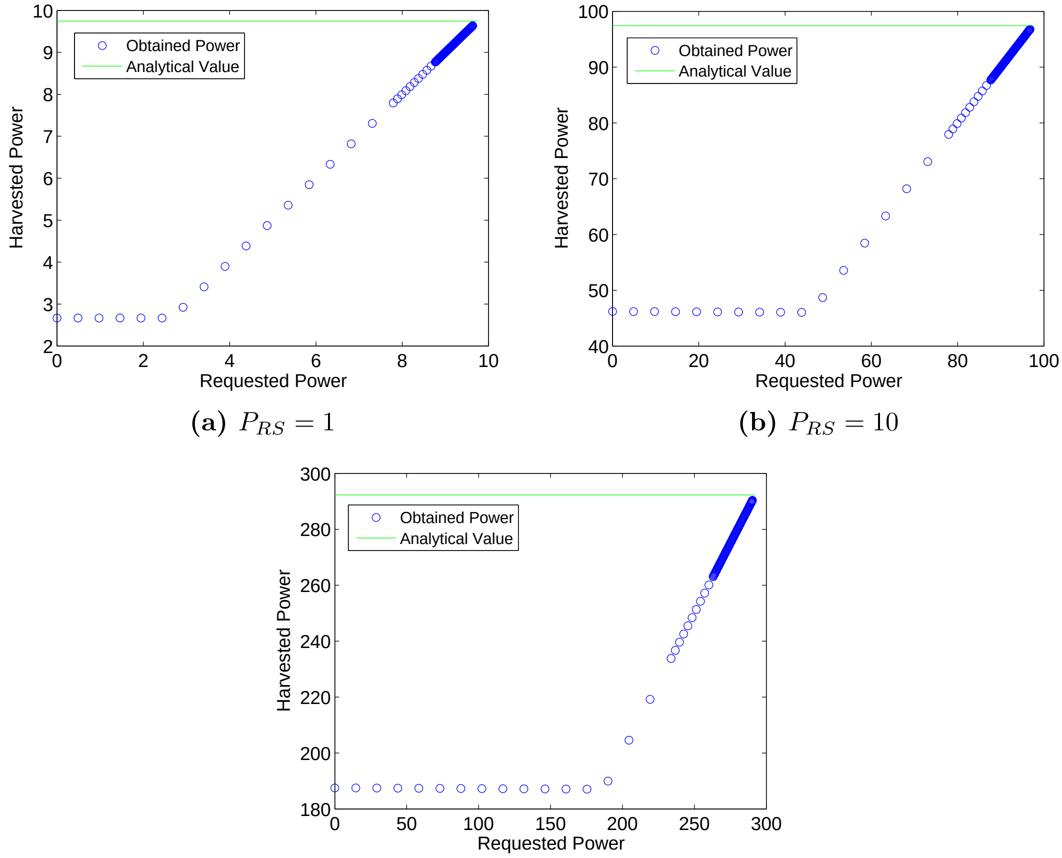
Figure 3.6: Normalized MSE versus requested power

and Figure 3.7c, it has been observed that the start of increasing changes in these curves happen for higher requested power values when P_R is larger. The reason is if the relay has higher power, it can transfer more power to the energy harvesting users when the error at information user is low.

Convergence Results for Relay Precoding

In Figure 3.8, the obtained threshold value versus requested power has been shown. This figure illustrates that optimization procedure has converged for all values of requested power since obtained threshold value is always lower than its target value (10^{-4}).

In Figure 3.9a and Figure 3.9b the elapsed time (Core i7 CPU) and mean square error for different target threshold value ($\varepsilon_{A_{RS}}^{Tg}$) have been presented. These figures illustrate that by choosing a proper target threshold value, an acceptable precision for MSE in less time is achievable.



(a) $P_{RS} = 1$ (b) $P_{RS} = 10$

(c) $P_{RS} = 30$

Figure 3.7: Harvested power versus requested power

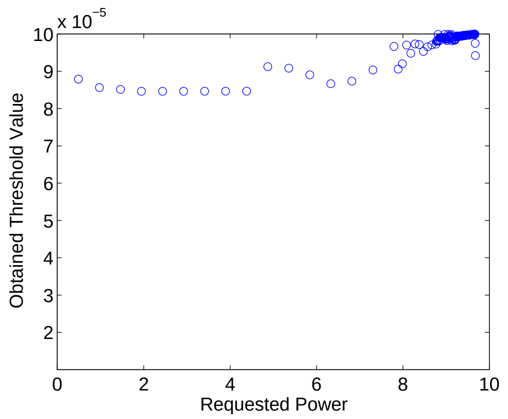
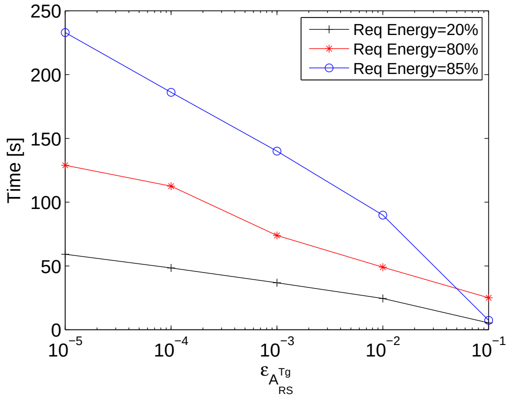
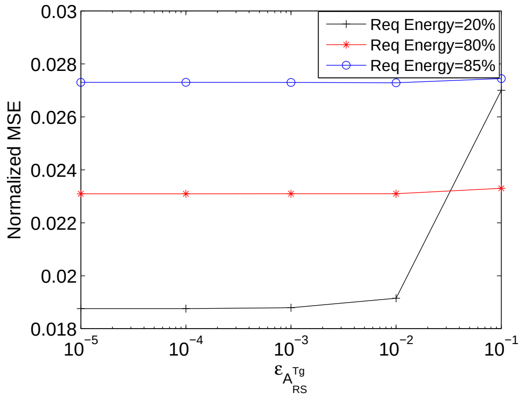


Figure 3.8: Obtained threshold value versus requested power



(a) Time versus $\epsilon_{A_{RS}}^{Tg}$



(b) Normalized MSE versus $\epsilon_{A_{RS}}^{Tg}$

Figure 3.9: Convergence status of normalized MSE

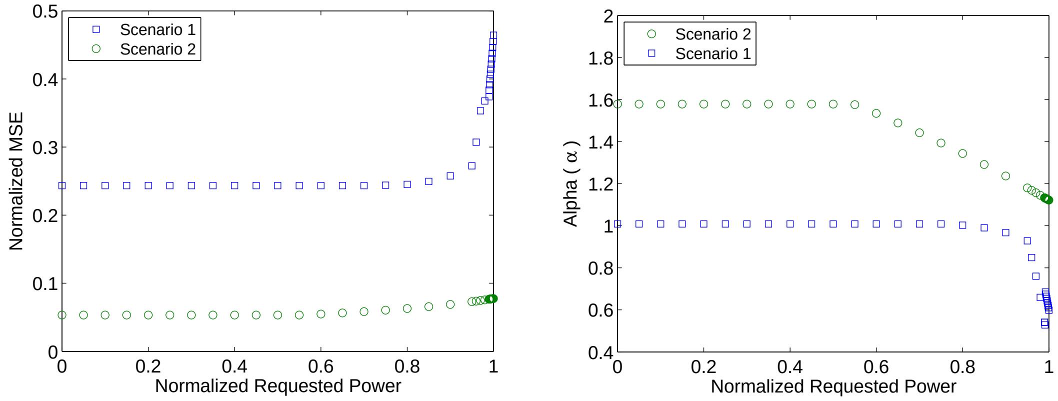
3.2.2 Base Station Precoding for Two-Way Relay System

MMSE and SINR Results for Base Station Precoding

In this section, numerical results of information and power transfer for two-way relay system with amplify-and-forward strategy, when only base station precoding is implemented, are given. Two information users and two energy harvesting users each has one antenna is considered as a scenario. All channels are complex MIMO channels with complex Gaussian noise with zero mean and equal variances ($\sigma_{BS2R}^2 = \sigma_{IR2R}^2 = \sigma_{R2BS}^2 = \sigma_{R2IR}^2 = \sigma_{R2ER}^2$). As it has been explained before, the fixed value of A_{RS} and initial value of A_{BS} are very important to guarantee the high performance of system and fast convergence respectively. It is supposed that base station knows the channel state therefore A_{BS} is optimized for MMSE from base station to relay. A_{IR_i} is optimized for MMSE from information users to relay when P_i is maximum deliverable power of user i. Finally, $P_{BS}^{Max} = 10$ and $P_R^{Max} = 10$ are supposed.

The results for normalized MSE and α for two scenarios have shown in Figure 3.10a and Figure 3.10b. In the first scenario, the fixed A_{RS} is set by identity matrix and in the second one, it is set by minimizing MSE from information users to the base station. As it is expected, the normalized mean square error increases and α decreases by requesting more power by energy harvesting users. The Minimum of MSE and rate of its increment are directly depended on fixed value of A_{RS}. A_{BS} has limited and indirect effects on minimum mean square error from information users to the base station since its effects are on noise portion of this mean square error and a small portion of relay transmission power.

SINR's for both users for scenario one are shown in Figure 3.11a and Figure 3.11b. The same figures for scenario two are demonstrated in Figure 3.11c and Figure 3.11d. As it has been presented, the SINR constraint is always fulfilled. Increasing requested power by energy harvesting users causes a larger portion of relay transmission power is



(a) Normalized MSE **(b)** Alpha (α)

Figure 3.10: Normalized MSE and α versus normalized requested power

focused on users instead of base station therefore SINR increases.

Energy Results for Base Station Precoding

In Figure 3.12a and in Figure 3.12b, harvested power when A_{RS} is the Identity matrix, and Figure 3.12c and Figure 3.12d, harvested power when A_{RS} is specified by the method in scenario two, are shown. Maximum possible harvested powers are calculated by a numerical algorithm that is explained in Appendix A.

Delivering more power to energy harvesting users causes the higher MMSE from information users to base station due to the limited relay transmission power. Furthermore, before K-point, although harvesting users request for lower power, higher power can be delivered. When A_{RS} is set by scenario two, Although MMSE from information users to base station increases negligible, by optimizing precoder in the base station, higher power can be harvested by energy harvesting users.

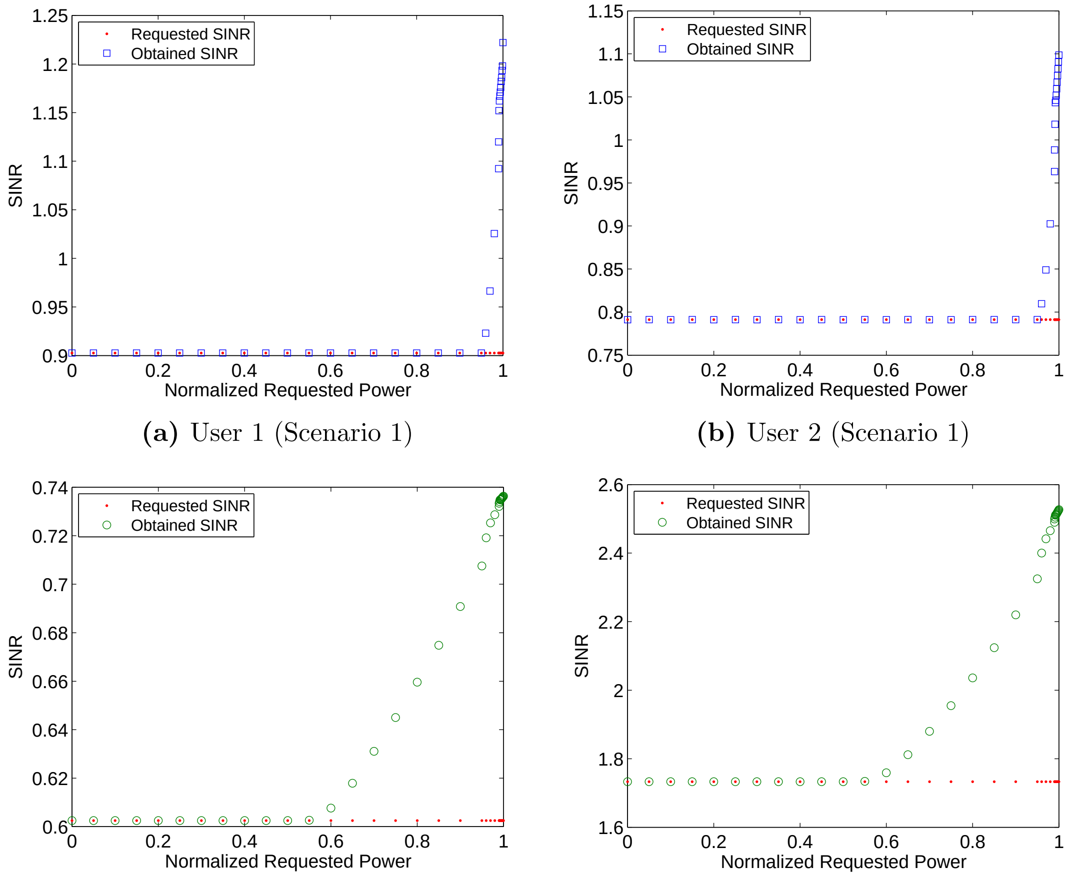
Convergence Results for Base Station Precoding

In Figure 3.13, the obtained threshold value versus normalized requested power is shown. This figure shows that optimization problem has been converged for all demanded power for both A_{RS} values.

3.2.3 Relay Precoding for Two-Way Relay System

MMSE and SINR Results for Relay Precoding

In this section, numerical results of information and power transfer for two-way relay system with amplify-and-forward strategy, when only relay precoding is optimized, are presented. All noise specification and users arrangements are the same as base station precoding. It is supposed that the base station knows the channel state information



(a) User 1 (Scenario 1)

(b) User 2 (Scenario 1)

(c) User 1 (Scenario 2)

(d) User 2 (Scenario 2)

Figure 3.11: SINR versus normalized requested power

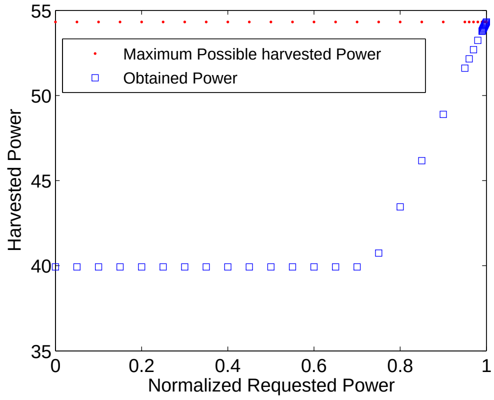
therefore A_{BS} is optimized for MMSE from the base station to the relay. A_{IR_i} is set for MMSE from information user i to relay when maximum transmission power of user i (P_i) constraint is fulfilled (Appendix A).

The result for normalized MSE from information users to base station versus normalized requested power is demonstrated in Figure 3.14a. It is observed that by requesting more power by energy harvesting users, the mean square errors increases. Moreover, requesting different ratios of maximum SINR (SINR Ratio) affect the MSE negligibly.

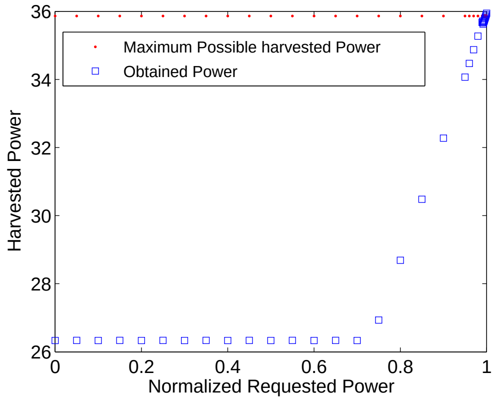
In addition, mean square error from information users to the base station increases if the power of base station increases since transmitted signals by base station have more power than transmitted signals by information users when they are received at the relay.

Finally, observation in (Figure 3.14b) demonstrates that MSE when the $P_{BS} = P_i = 5$ is less than when $P_{BS} = 5, P_i = 1$ since the received signal from the base station and information users have the same level of power.

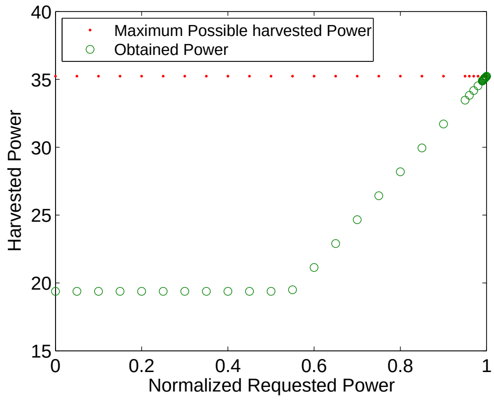
The SINR's are illustrated in Figure 3.15. Although requested SINR constraint is



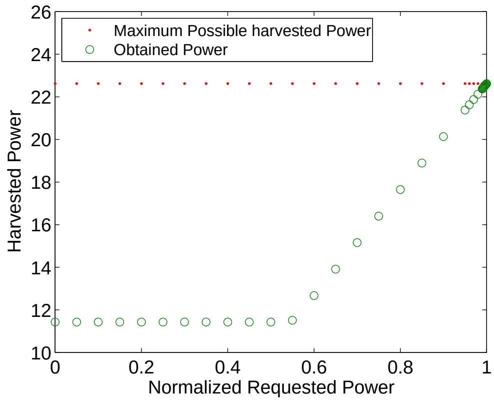
(a) User 1 (Scenario 1)



(b) User 2 (Scenario 1)



(c) User 1 (Scenario 2)



(d) User 2 (Scenario 2)

Figure 3.12: Harvested power versus normalized requested power

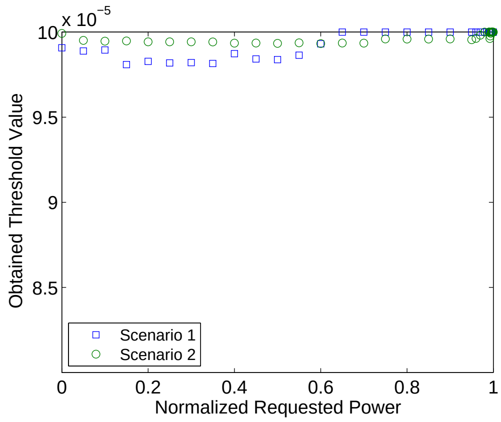
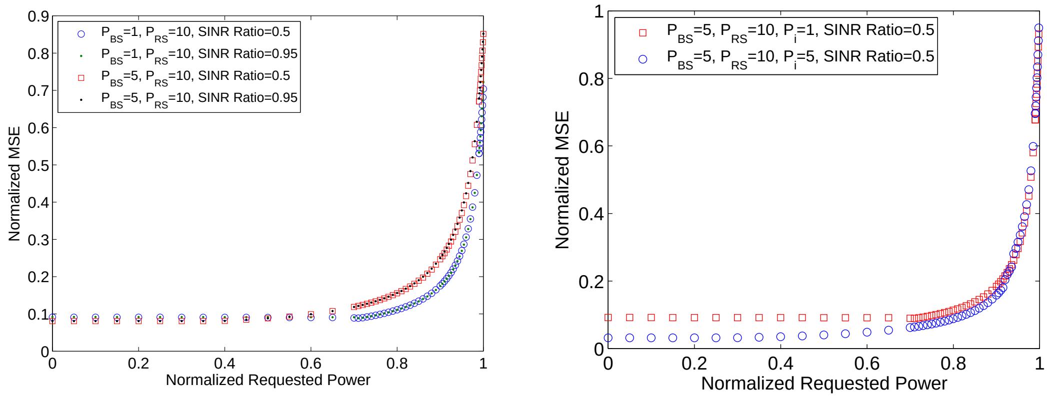


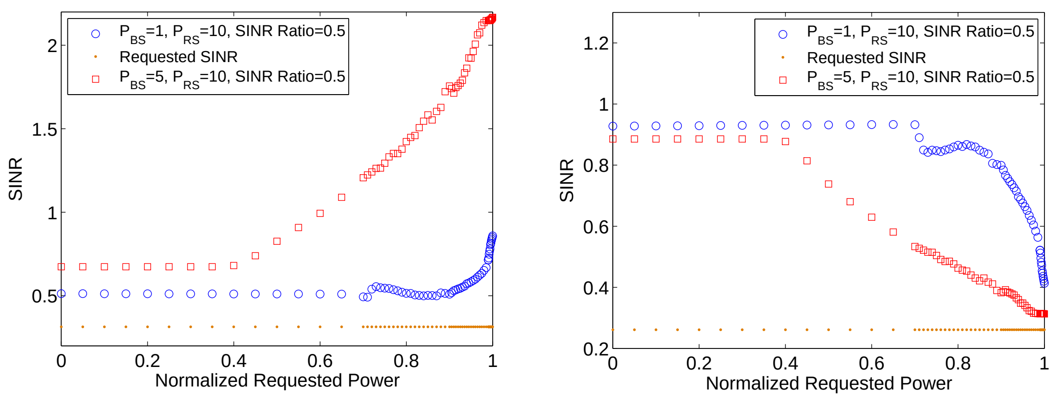
Figure 3.13: Obtained threshold value versus normalized requested power



(a) P_{BS} and SINR Ratio effects

(b) P_i effect

Figure 3.14: Normalized MSE versus normalized requested power



(a) User 1

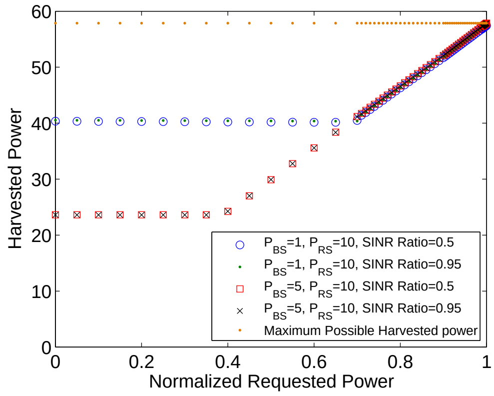
(b) User 2

Figure 3.15: SINR versus normalized requested power

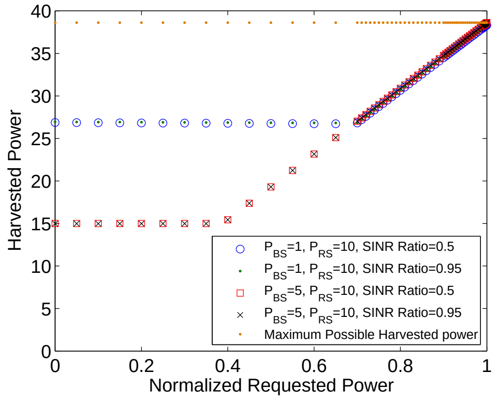
always fulfilled, depending on A_{RS} precoding the SINR can change since the requested SINR is less than maximum possible SINR for each user.

Energy Results for Relay Precoding

In Figure 3.16a and Figure 3.16b, harvester power for user 1 and user 2 are shown. Maximum possible harvested powers are calculated by a numerical algorithm that is explained in Appendix A. As it is expected, delivering more power to energy harvesting users leads to higher MMSE from information users to base station. Furthermore, before K-point, although harvesting users request for lower power, higher power can be delivered. Finally, when the base station power is higher, due to difference between received signal from the base station and information users at the relay, more power is needed



(a) User 1



(b) User 2

Figure 3.16: Harvested power versus normalized requested power

to minimize MSE from information users to the base station. Hence, due to the limited power of relay, delivered powers to energy harvesting users are lower.

Convergence Results for Relay Precoding

In Figure 3.17, the obtained threshold value versus normalized requested power is given when the $\epsilon_{A_{RS}}^{Tg}$ is 10^{-4}. The result shows that this method is converged for all requested power.

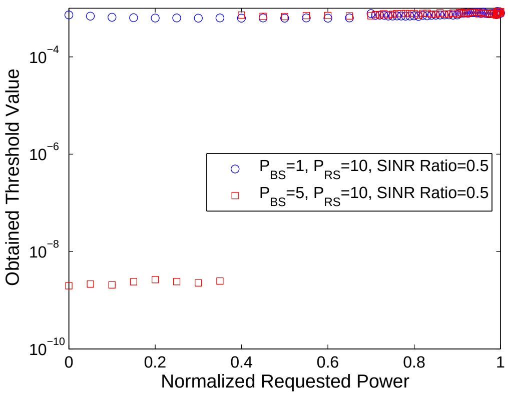


Figure 3.17: Obtained threshold value versus normalized requested power

3.2.4 Joint Base Station and Relay Precoding for Two-Way Relay System

In this section, numerical results of information and power transfer for two-way relay system with amplify-and-forward strategy when both base station precoding and relay precoding are optimized are described. The same conditions used in base station precoding section are adopted if something else is not specifically mentioned. A_{IR_i} is set for MMSE from information users to relay. A_{BS} and A_{RS} are calculated by $SWIPT\_RTW\_BSRS(A,AH)$ algorithm in chapter 2. In this section, the results for base station precoding, relay precoding and joint base station and relay precoding for fixed SINR are compared and pros and cons of them are explained.

MMSE Results for Base Station and Relay Precoding

In Figure 3.18, normalized MSE's versus normalized requested power for base station precoding, relay precoding and joint base station and relay precoding are demonstrated. For all scenarios, the same SINR and relay and base station transmission powers have been considered ($P_{BS}^{Max} = 1$ and $P_{R}^{Max} = 10$). The results show that MMSE of joint base station and relay precoding is better than sole base station precoding or only relay precoding. The MMSE for the relay precoding is closer than the base station precoding to joint base station and relay precoding.

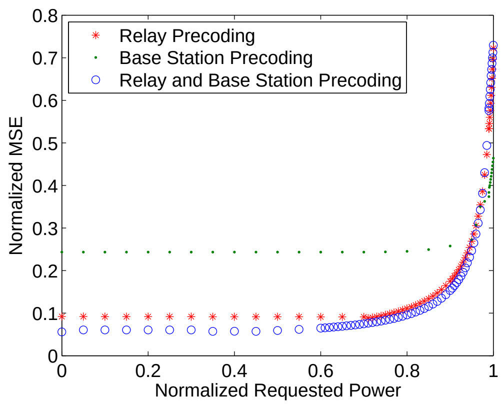
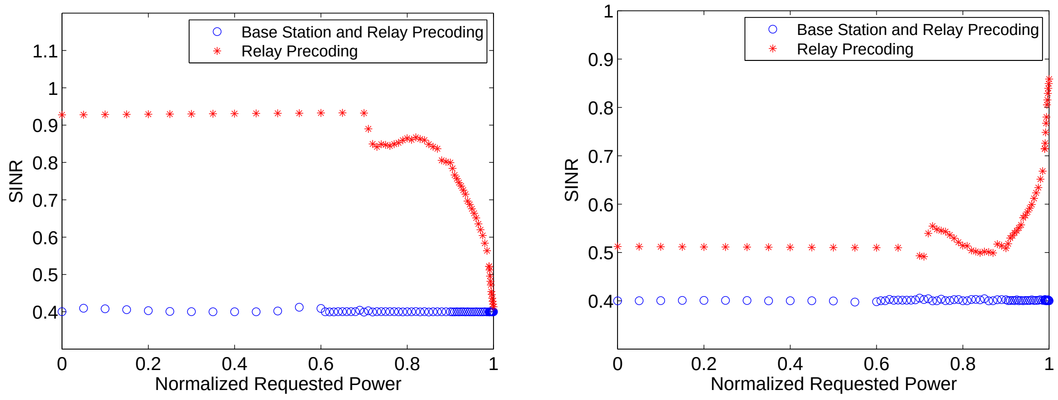


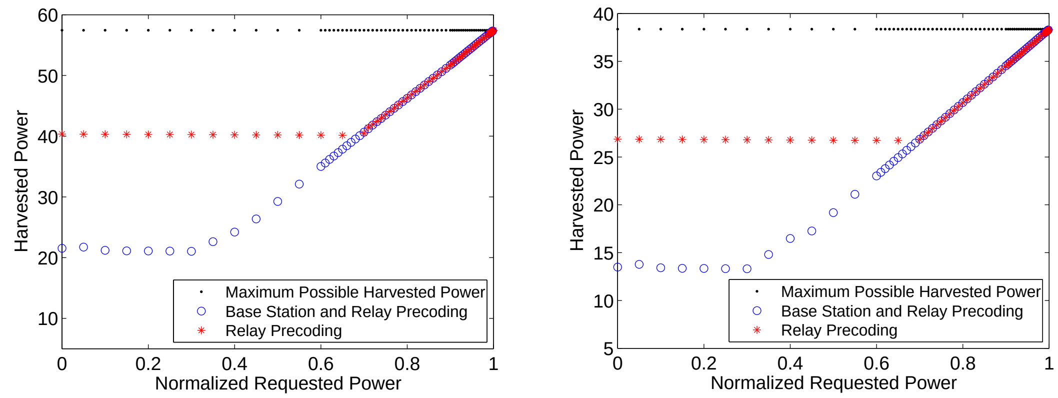
Figure 3.18: Normalized MSE versus normalized requested power

The SINR of relay precoding and joint base station and relay precoding for users is shown in Figure 3.19. Requested SINR for both methods is the same. SINR in relay precoding is higher than joint base station and relay precoding since base station precoder in the sole relay precoding is fixed for minimum mean square error from base station to relay so always maximum power of base station is consumed to minimize this error. In the joint base station and relay precoding, base station precoder is adjusted to use optimal base station power based on requested SINR.



(a) User 1 (b) User 2

Figure 3.19: SINR versus normalized requested power



(a) User 1 (b) User 2

Figure 3.20: Harvested power versus normalized requested power

Energy Results for Base Station and Relay Precoding

In Figure 3.20, the harvested powers for both users and for both relay precoding and joint base station and relay precoding are shown. In low requested power, the deliverable energy from joint base station and relay precoding is less than sole relay precoding since in the joint base station and relay precoding, the relay and base station adjust their transmission powers to obtain requested SINR at information users and requested power at energy harvesting users therefore lower relay transmission power implies lower harvested power.

Requested power	0	20	40	60	80	100
A_{RS} iteration numbers	83	74	61	35	19	7
A_{BS} iteration numbers	25	20	18	6	3	1

Table 3.1: The iteration for A_{BS} and A_{RS} calculations

Convergence Results for Base Station and Relay Precoding

In Figure 3.21, obtained threshold values versus normalized requested power for sole relay precoding and joint base station and relay precoding are illustrated. The target threshold value is $\epsilon_{BS}^{Tg} = \epsilon_{RS}^{Tg} = 10^{-3}$. Due to lower rank of relay precoder in joint base station and relay precoding when more power is requested, convergence is faster and threshold value is more stable.

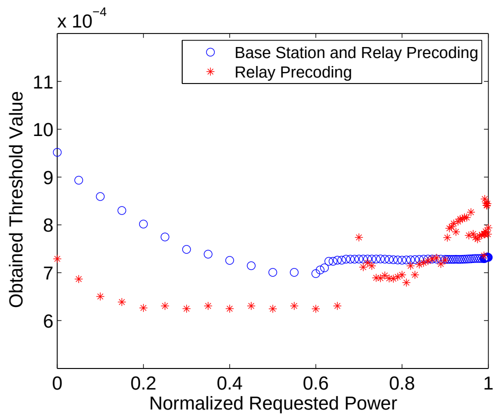


Figure 3.21: Obtained threshold value versus normalized requested power

In table 3.1 the number of iterations for A_{BS} and A_{RS} calculations is presented. The results in this table show that A_{RS} convergence is more challenging than A_{BS} convergence. It is seen that by increasing the requested power, the number of iterations for A_{BS} and A_{RS} decreases rapidly especially for A_{BS}.

4

Discussions

In this thesis, SWIPT in a multiple-antenna relay system with multiple users was studied. The relay was used for increasing communication range for the information receivers (IR) as well as powering the energy harvesting receivers (ER) that demand power. We focused on the design of the amplify-and-forward strategy at the relay (relay precoder) and the precoder at the base station. The minimum mean-square error (MMSE) was used as the performance criterion for information transfer. Two main scenarios has been considered: I) simultaneous wireless information and power transfer in MIMO channel without relay and II) simultaneous wireless information and power transfer in MIMO channel with relay amplify-and-forward strategy. In information and power transfer without relay, source directly sent precoded signal that could transfer information to IR and power to ER.

In simultaneous wireless information and power transfer in MIMO channel with relay two systems has been considered: i) one-way relay system and ii) two-way relay system. For the one-way relay system, the relay amplify-and-forward strategy (relay precoder) to minimize the MMSE from the base station to the information user while satisfying energy harvesting constraints at the energy harvesting users is investigated. For the two-way relay system, minimizing the MMSE from the information users to the base station while satisfying the signal-to-interference-plus-noise ratio (SINR) constraints at the information users and the energy harvesting constraints at the ERs was considered. Here the precoder at the base station and the relay precoder was optimized jointly.

These two scenarios led to non-convex optimization problems and needed an approach to solve them. A novel proposed numerical technique was used to present the trade-offs between the MMSE and the energy harvesting constraints. Details of systems, their models and numerical results for these scenarios are explained as follows.

I) Simultaneous wireless information and power transfer in MIMO channel without relay:

In this scenario, a system with a transmitter, information user (IR) and energy harvesting user (ER) was considered. In this optimization problem by using minimum mean square error (MMSE) method, the error from transmitter to information user was minimized. In the same time, requested power by the energy harvesting user was transferred. Analytic expressions for extreme values, minimum MSE or maximum harvested power, were provided. A new method ('A and AH') was proposed and compared with other methods from the literature.

In numerical part, mean square errors (MSE) and harvested power versus requested power for different signal to noise ratio (SNR) were found by using different methods. The results presented that MMSE met analytic extreme and by increasing requested power, MSE was increased due to the limited power of the transmitter. Besides, received power in low requested power was more than what requested and in maximum met the analytic extreme.

In addition, when the requested power by energy harvester was low, the MSE was almost constant. By requesting more power, the mean square error started to increase from a knee point that was called K-point. It has been observed that the K-point in MSE and harvested power shifted to more requested power due to more portion of power can be sent to the energy harvesting user before the error starts increasing. It has been seen that estimating less number of variables with the same channel resulted lower MSE. Finally, by comparing the MSE, harvested power of these two methods, the new introduced method was verified.

II) Simultaneous wireless information and power transfer in MIMO channel with relay amplify-and-forward strategy

Due to complexity of the problem, the relay problem has been divided into two systems a) one-way relay system and b) two-way relay system. For both systems, relay amplify-and-forward strategy has been presented.

a) *One-way relay system*

In one-way information and power transfer with relay amplify-and-forward strategy, system has been consisted of a base station that sends information, a relay that received base station sent signal, amplified and forwarded it, an information user that received the relay signal and estimated base station sent information and an energy harvesting user that harvested power from its received signal. The model of this system was presented. In this problem, the error of received information from the base station to the information user has been minimized when the energy harvesting user could get the requested power. An algorithm for solving this optimization problem has been developed.

In numerical part of this investigation, MSE from base station to information user versus requested power for different relay power and SNR was shown. In this system, similar to what has been seen in scenario I, when energy harvesting user wanted more power, MSE to information user increased. Besides, if relay had lower power, MSE K-Point shifted toward lower requested power since relay had lower power to maintain MSE constant.

Furthermore, if channel noise was small (high SNR), more power of relay can be transferred to the energy harvesting users since less power was needed to maintain error in low level. This effect could be seen in harvested power due to similar reason. The obtained threshold value that indicates the precision of ('A and AH') method illustrated that this method converges. Finally, it is observed that by choosing a proper target threshold value, an acceptable precision for MSE in less time is achievable.

b) *Two-way relay system*

In two-way information and power transfer with relay amplify-and-forward strategy, the system consisted of a base station, relay and information and energy harvesting users. In the first time slot, the information users and the base station sent the precoded information to the relay. In the second time slot, the relay amplified and forwarded received signals to the base station, information users and energy harvesting users simultaneously. In this sub-scenario, the data error from multi-users to base station through relay by choosing suitable linear precoders and MSE method was minimized when obtained signal-to-interference-plus-noise ratio (SINR) from base station to information users were more than the requested value and requested power by energy harvesting users could be harvested. To investigate this system three different scenarios have been considered b-1) Base station precoding for two-way relay system, b-2) Relay precoding for two-way relay system and b-3) Base station and relay precoding for two-way relay system.

b-1) *Base station precoding for two-way relay system*

In the base station precoding model, in the first time slot, base station precoded input information and send the signal to relay. Simultaneously, information users sent their signals to relay. In the second time slot, relay only had fixed precoding but it could amplify the received signal and forward it to base station, information users and energy harvesting users.

In the numerical results of base station precoding, two scenarios based on the precoder used in the relay were considered: 1) with fixed precoding that minimizes MSE from information users to base station and 2) with the identity matrix. Results presented that choosing initial fixed precoding in relay had a large effect on MSE. Besides, results have shown that base station precoding had a limited and small effect on MSE from information users to base station, especially when fixed precoder in relay minimized MSE from information users to base station. It has been observed that increasing requested power by energy harvesting users caused a larger portion of relay power focused on users instead of base station therefore SINR increased.

Besides, requesting more power by energy harvesting users increased the MSE from information users to base station due to the limited power of relay. When relay was initialized by optimized fixed precoder, the MMSE from information users to base station increased negligible when higher power delivered to the energy harvesting users. Harvested power when the relay was initialized with optimized fixed precoder was smaller since the power of relay was concentrated on minimizing MSE from information users to base station. Relay precoding has affected the maximum possible harvested power because of indirect and partial effect of base station precoding on the transmitted signal from relay. Finally, obtained threshold value versus requested power illustrated the convergence of ('A and AH') method.

b-2) *Relay precoding for two-way relay system*

In the relay precoding model, base station precoder was fixed and in the first time slot sent the fixed precoded signal to relay. In the same time slot information users sent their signals to relay. In the second time slot, relay used linear precoder and amplified and forwarded received signal to base station, information and energy harvesting users.

In the numerical results of relay precoding, base station precoder was fixed and initialized to minimize MSE from base station to relay. It has been demonstrated that by requesting more power by energy harvesting users, the MSE from information users to base station increased and requesting different SINR affected the MSE negligibly. In addition, mean square error from information users to base station increased if the power of base station increases since the power of base station transmitted signal was more than power of information users and it affected the received signal of information users in relay input.

Furthermore; It has been presented that for high value of base station power if the power of information users were increased, the MSE from information users to base station was decreased. It has been seen that when the requested SINR's were less than the maximum possible obtainable SINR's, the SINR's can change between users when requested SINR's were always fulfilled. In addition, delivering more power to energy harvesting users caused a high MSE from information users to base station due to the limited power of relay. Finally, when the base station power was higher, due to difference between received signal from the base station and information users at the relay, more power was needed to minimize the MSE from information users to base station. Consequently, power delivered to the energy harvesting users was lower.

b-3) *Base station and relay precoding for two-way relay system*

In the base station and relay precoding model, in the first time slot, information in base station precoded and sent to relay. In the same time slot, information users sent their information to relay. In the second time slot, relay amplified and forwarded the received signal to base station, information and energy harvesting users. Three different optimization problems for these three models were presented. The introduced novel method ('A and AH') for solving these optimization problems were applied.

In the numerical results of base station and relay precoding, two scenarios of fixed requested SINR and adaptive one have been presented. The first scenario was suitable when comparison between different precoding was needed. The second scenario let information users get higher SINR if it is possible.

In the fixed requested SINR scenario, MSE for base station and relay precoding has been compared with base station and relay precoding. The results showed that MMSE of base station and relay precoding is better than two other ones. This illustrates that proper relay precoding can compensate for using a base station precoder that has not developed with full awareness of the system requirements. Additionally, for relay precoding and base station and relay precoding, The comparison between SINR's was done for fixed requested SINR. SINR in relay precoding was higher than base station and relay precoding since base station precoder in the first scenario was fixed for minimum mean square error from base station to relay so always maximum power of base station was used to minimize this error but in the second scenario, base station precoder is adjusted to use optimal base station power based on requested SINR. It was observed that in low requested power, the deliverable energy from base station and relay precoding was less than relay precoding since in base station and relay precoding, the relay and base station adjust their powers to obtain requested SINR for information users and requested power for energy harvesting users so the lower relay power implies lower harvested power when it is not requested. It has been observed that for higher requested power, convergence happened with a smaller number of iterations.

In the adaptive requested SINR scenario, adaptive and fixed requested SINR were compared. It has been discovered that fixed and adaptive requested SINR didn't affect the MSE's versus requested power. By looking at base station and relay power, it has been observed that in the adaptive algorithm used power from base station and relay varied based on how much SINR or power for energy harvesting requested. For fixed SINR, base station power changes were very small. Relay power for fixed SINR varied depending on requested power for energy harvesting users. For adaptive SINR, this power differed due to requested power or SINR. Finally, it has been observed that in harvested power versus requested power, a rapid change due to relay power change happened.

5

Conclusions

In this thesis, linear precoder for SWIPT in point-to-point and relay systems have been investigated. These problem formulations lead to non-convex optimization problems. A novel numerical method for solving them was proposed.

For SWIPT in point-to-point systems, a new method ('A and AH') was suggested. Trade-offs between the energy harvested and the MMSE were quantified. Results were compared with a recent work from the literature ('A and B' method). It has been observed that proposed approach obtains the same results with the literature method. Convergence of the proposed method was investigated through numerical experiments and it has been observed that by adjusting the threshold value of ('A and AH') method, faster convergence with no significant change in the results was possible. Moreover, it was seen that ('A and AH') method was faster than ('A and B') method.

For SWIPT in one-way relay systems with amplify-and-forward strategy, the earlier method from the literature ('A and B' method) didn't apply for these systems but the proposed approach ('A and AH' method) was applicable. The trade-offs between energy harvesting demands and the MMSE was quantified. Effects of different SNRs and relay transmission powers have been investigated.

For SWIPT in two-way relay systems with amplify-and-forward strategy, sole base station precoding, sole relay precoding and joint precoding were compared. It has been observed that for obtaining the best trade-offs between the MMSE and energy harvested, joint base station and relay precoding was needed. It was observed that the trade-offs obtained by sole relay precoding were close to the trade-offs obtained by joint optimization. Hence, it was conducted that optimization of the relay precoding was more important than optimization of the base station precoding. Finally, it was observed that convergence of the relay precoder was more challenging than that of base station precoder in joint optimization problem.

For future work, SWIPT in two-way relay systems with amplify-and-forward strategy when channel state information (CSI) is imperfect or outdated should be explored.

Moreover, multi-relay systems when users and multiple relays determine how to cooperatively transfer energy and information can be studied. Finally, extracting experimental results by implementation of these scenarios in actual hardware can be investigated.

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A

Other Optimization Algorithms

In this appendix four algorithms for optimization of precoder in users and base station, maximum obtainable power and maximum SINR which have been used in some scenarios are explained.

A.1 Users Precoding Optimization Algorithm

In this section the optimization problem and algorithm of A_{IR_i} when each user has limited power P_i are discussed. The optimization problem is sending the information to relay with minimum error when the power is limited. It means that each user knows the channel state and adjusts its linear precoder for minimum mean square error from user to relay. The optimization problem for user i is expressed as (A.1).

$$\min_{A_{IR_i}} \quad tr(I + \frac{1}{\sigma^2_{n_{IR_i 2R}}} A^H_{IR_i}.H^H_{IR_i 2R}.H_{IR_i 2R}.A_{IR_i})^{-1} \tag{A.1a}$$

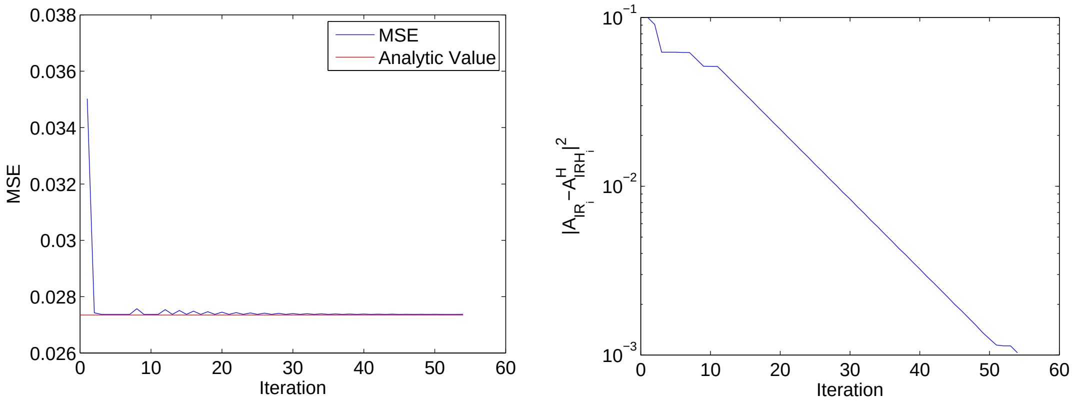
$$\text{s.t.} \quad tr(A_{IR_i}.A^H_{IR_i}) \leq P_i^{Max} \tag{A.1b}$$

This problem can solve analytically or 'A and AH' algorithm which is given by:

Algorithm A_{IR_i}(A,AH):

- ***Initialize*** *A_{IR_i}, A_{IRH_i} and $\varepsilon_{A_{IR_i}}$*
- ***Repeat***

\- *Solve following convex problem and find A_{IR_i}*



(a) Normalized MSE **(b)** Convergence process

Figure A.1: A_{IR_i} optimization results

$$\min_{A_{IR_i}} \quad tr(I + \frac{1}{\sigma^2_{n_{IR_i2R}}} A_{IRH_i}.H^H_{IR_i2R}.H_{IR_i2R}.A_{IR_i})^{-1} \tag{A.2a}$$

$$\text{s.t.} \quad tr(A_{IR_i}.A_{IRH_i}) \leq P_i^{Max} \tag{A.2b}$$

$$\left\|vec(A_{IR_i} - A^H_{IRH_i})\right\|^2 \leq \varepsilon_{A_{IR_i}} \tag{A.2c}$$

- *Change* $\varepsilon_{A_{IR_i}}$ *to get first feasible* A_{IR_i}
- *Update* $A_{IRH_i} = A^H_{IR_i}$
- *If no improvement in objective function then choose smaller* $\varepsilon_{A_{IR_i}}$

- ***Until*** $\varepsilon_{A_{IR_i}} \leq \varepsilon^{Tg}_{A_{IR_i}}$

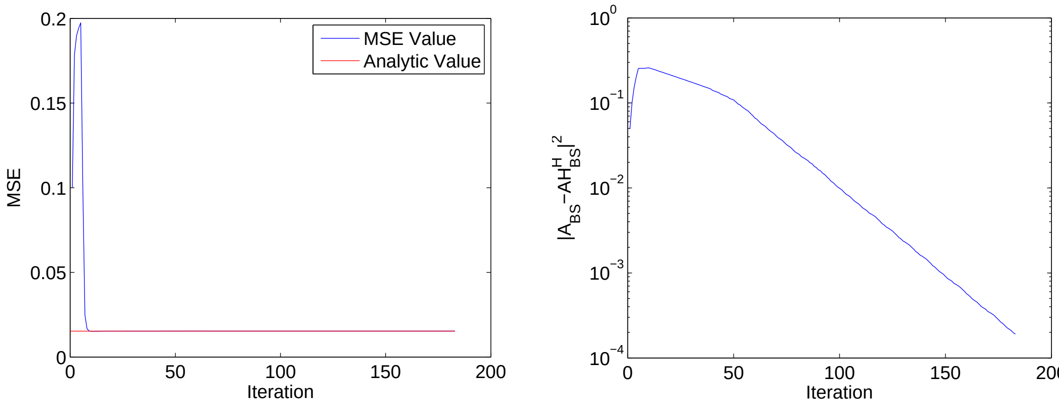
The numerical results including normalized MSE and convergence are shown in Figure A.1. The comparison between analytic results, algorithm results and convergence process show that results are correct. In two-way relay amplify and forward strategies , this optimization affects MMSE from users to base station.

A.2 Base Station Precoding Optimization Algorithm

In this section the MMSE from base station to relay optimization problem and algorithm are explained. If the base station knows the state of channel between base station and relay, it can use a linear precoder to optimize transmitted signal to have minimum error from base station to relay. The optimization problem is formulated as

$$\min_{A_{BS}} \quad tr(I + \frac{1}{\sigma^2_{n_{BS2R}}} A^H_{BS}.H^H_{BS2R}.H_{BS2R}.A_{BS})^{-1} \tag{A.3a}$$

$$\text{s.t.} \quad tr(A_{BS}.A^H_{BS}) \leq P^{Max}_{BS} \tag{A.3b}$$



(a) Normalized MSE

(b) Convergence process

Figure A.2: A_{BS} optimization results

For this purpose the MMSE algorithm has been used

Algorithm $A_{BS}(A,AH)$:

- ***Initialize*** A_{BS}, A_{BSH_i} *and* $\varepsilon_{A_{BS}}$
- ***Repeat***

- *Solve following convex problem and find* A_{BS}

$$\min_{A_{BS}} \quad tr(I + \frac{1}{\sigma^2_{n_{BS2R}}} A_{BSH}.H^H_{BS2R}.H_{BS2R}.A_{BS})^{-1} \tag{A.4a}$$

$$\text{s.t.} \quad tr(A_{BS}.A_{BSH}) \leq P_i^{Max} \tag{A.4b}$$

$$\left\|vec(A_{BS} - A^H_{BSH})\right\|^2 \leq \varepsilon_{A_{BS}} \tag{A.4c}$$

- *Change* $\varepsilon_{A_{BS}}$ *to get first feasible* A_{BS}
- *Update* $A_{BSH} = A^H_{BS}$
- *If no improvement in objective function then choose smaller* $\varepsilon_{A_{BS}}$

- ***Until*** $\varepsilon_{A_{BS}} \leq \varepsilon^{Tg}_{A_{BS}}$

Results are given in Figure A.2a and Figure A.2b. The effect of this optimization is seen in SINR when two-way relay system is used.

A.3 Maximum Power Optimization Algorithm

In this section, the optimization problem and algorithm for maximum power that can be transferred to users are explained. This algorithm is needed for numerical reason when specific percentage of maximum transferable power is requested. The maximum power depends on channel and the power of source that in one-way and two-way relay systems is relay. The optimization problem for A_{RS} is written as (A.5). Similar optimization problem can be written for A_{BS}.

$$\begin{aligned}
& T1 = tr(G_{R2ER_k}.A_{RS}.H_{BS2R}.A_{BS}.A_{BS}^H.H_{BS2R}^H.A_{RSH}.G_{R2ER_k}^H) \\
& \quad + tr(G_{R2ER_k}.A_{RS}.H_{IR2R}.A_{IR}.A_{IR}^H.H_{IR2R}^H.A_{RSH}.G_{R2ER_k}^H) \\
& \quad + tr(G_{R2ER_k}.A_{RS}.A_{RSH}.G_{R2ER_k}^H).\sigma_{n_{X2R}}^2 \\
& \quad + \sigma_{n_{R2ER_k}}^2 && \text{(A.5a)} \\
& \max_{A_{RS},\alpha} \; \alpha.T1 && \text{(A.5b)} \\
& Subject\ to: \\
& \sum_{i=1}^{N_{MU}} (\alpha_i) = 1 && \text{(A.5c)} \\
& tr(H_{R2IR_K}^H.H_{R2IR_K}.(A_{RS}.(H_{BS2R}.A_{BS_k}.A_{BS_k}^H.H_{BS2R}^H \\
& \quad - SINR_k^{Req}.(\sum_{i\neq k}(H_{BS2R}.A_{BS_i}.A_{BS_i}^H.H_{BS2R}^H + H_{IR_i2R}.H_{IR_i2R}^H.|A_{IR_i}|^2) \\
& \quad + \sigma_{n_{X2R}}^2.I)).A_{RSH}) \geq SINR_k^{Req}.\sigma_{n_{R2IR_k}}^2, \quad \forall k = 1,...,N_{MU} && \text{(A.5d)} \\
& tr((H_{BS2R}.A_{BS}.A_{BS}^H.H_{BS2R}^H).K_{A_{RS}^H}) \\
& \quad + tr((H_{IR2R}.A_{IR}.A_{IR}^H.H_{IR2R}^H).K_{A_{RS}^H}) \\
& \quad + \sigma_{n_{X2R}}^2.tr(K_{A_{RS}^H}) \leq P_R^{Max} && \text{(A.5e)} \\
& K_{A_{RS}^H} - A_{RS}^H.A_{RS} \succeq 0 && \text{(A.5f)} \\
& \|vec(A_{RS} - A_{RSH}^H)\|^2 \leq \varepsilon_{A_{RS}} && \text{(A.5g)}
\end{aligned}$$

The algorithm is outlined as follows.

Algorithm $P_{RS}^{Max}(A,AH)$*:*

- ***Initialize*** α, A_{RS}, A_{RSH} *and* $\varepsilon_{A_{RS}}$
- ***Repeat***
  - ***Repeat***
    - *Solve convex problem (A.5) to find* A_{RS}
    - *Change* $\varepsilon_{A_{RS}}$ *to get first feasible* A_{RS}

  - *Update* $A_{RSH} = A_{RS}^H$
  - *If no improvement in objective function then choose smaller* $\varepsilon_{A_{RS}}$
- ***Until*** $\varepsilon_{A_{RS}} \leq \varepsilon_{A_{RS}}^{Tg}$
- ***Solve*** *convex problem (A.5) to find* α

- ***Until*** no improvement in objective functions

In Figure A.3, for specific case, the variations of power between two users is presented. This variations depend on MIMO channel matrix. Small variations for harvested power for user 1 and 2 exist that are not seen in this figure.

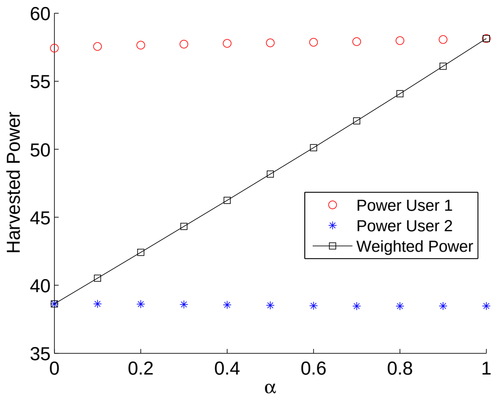


Figure A.3: Variation of user powers and weighted power

A.4 Maximum SINR Optimization Algorithm

In this section, main part of optimization problem and algorithm for maximizing SINR's for users are explained. The actual algorithm with minimum requested SINR is more complex. This algorithm is used for numerical reason. The optimization problem for A_{RS} is written as (A.6).

$$tr(H_{R2IR_K}^H.H_{R2IR_K}.(A_{RS}.(H_{BS2R}.A_{BS_k}.A_{BS_k}^H.H_{BS2R}^H$$
$$- SINR_k.(\sum_{i\neq k}(H_{BS2R}.A_{BS_i}.A_{BS_i}^H.H_{BS2R}^H + H_{IR_i2R}.H_{IR_i2R}^H.|A_{IR_i}|^2)$$
$$+ \sigma_{n_{X2R}}^2.I)).A_{RSH}) \geq SINR_k.\sigma_{n_{R2IR_k}}^2, \quad \forall k = 1,...,N_{MU} \tag{A.6a}$$

$$\max_{A_{RS}} \beta \tag{A.6b}$$

$Subject\ to:$

$$SINR_k \geq \beta, \quad \forall k = 1,...,N_{MU} \tag{A.6c}$$

$$tr(G_{R2ER_k}.A_{RS}.H_{BS2R}.A_{BS}.A_{BS}^H.H_{BS2R}^H.A_{RSH}.G_{R2ER_k}^H)$$
$$+ tr(G_{R2ER_k}.A_{RS}.H_{IR2R}.A_{IR}.A_{IR}^H.H_{IR2R}^H.A_{RSH}.G_{R2ER_k}^H)$$
$$+ tr(G_{R2ER_k}.A_{RS}.A_{RSH}.G_{R2ER_k}^H).\sigma_{n_{X2R}}^2$$
$$+ \sigma_{n_{R2ER_k}}^2 \geq P_{ER_k}^{Req}, \quad \forall k = 1,...,N_{MU} \tag{A.6d}$$

$$tr((H_{BS2R}.A_{BS}.A_{BS}^H.H_{BS2R}^H).K_{A_{RS}^H})$$
$$+ tr((H_{IR2R}.A_{IR}.A_{IR}^H.H_{IR2R}^H).K_{A_{RS}^H})$$
$$+ \sigma_{n_{X2R}}^2.tr(K_{A_{RS}^H}) \leq P_R^{Max} \tag{A.6e}$$

$$K_{A_{RS}^H} - A_{RS}^H.A_{RS} \succeq 0 \tag{A.6f}$$

$$\|vec(A_{RS} - A_{RSH}^H)\|^2 \leq \varepsilon_{A_{RS}} \tag{A.6g}$$

The algorithm is similar to what has been presented in maximizing power for users.

Algorithm $SINR_{RS}^{Max}(A,AH)$*:*

- ***Initialize*** A_{RS}, A_{RSH} *and* $\varepsilon_{A_{RS}}$
- ***Repeat***
  - *Solve convex problem (A.6) to find* A_{RS}
  - *Change* $\varepsilon_{A_{RS}}$ *to get first feasible* A_{RS}
  - *Update* $A_{RSH} = A_{RS}^H$
  - *If no improvement in objective function then choose smaller* $\varepsilon_{A_{RS}}$
- ***Until*** $\varepsilon_{A_{RS}} \leq \varepsilon_{A_{RS}}^{Tg}$
- ***Update*** $SINR's$

B

SINR Adaptive Algorithm for Joint Base Station and Relay Precoding

In this appendix, an adaptive algorithm for calculating maximum obtainable SINR in each iteration of base station and relay precoding for two-way relay algorithm is explained. This algorithm is needed when power transferring higher priority than SINR. Users can get maximum possible SINR (not fixed one) when precoders in base station and relay change in each iteration. This adaptive SINR is calculated by method which was mentioned in Appendix A and should not be less than specific value.

The algorithm of base station and relay precoding for two-way relay system is rewritten as follows.
Algorithm $SWIPT\_RTW\_BSRS$(A,AH):

- ***Initialize*** $\hat{A}_{BS}$, $\hat{A}_{BSH}$, A_{RS}, A_{RSH}, $\varepsilon_{A_{BS}}$, *and* $\varepsilon_{A_{RS}}$
- ***Repeat***
  - ***Repeat***
    - *Solve convex problem (2.88) to find* A_{RS}
    - *Change* $\varepsilon_{A_{RS}}$ *to get first feasible* A_{RS}
    - *Update* $A_{RSH} = A_{RS}^H$
    - *If no improvement in objective function then choose smaller* $\varepsilon_{A_{RS}}$
  - ***Until*** $\varepsilon_{A_{RS}} \leq \varepsilon_{A_{RS}}^{Tg}$
    - *Calculate value* $\hat{A}_{RS} = \sqrt{\alpha}.A_{RS}$ *for* A_{RS} *and arbitrary* α
  - ***Repeat***

- *Solve convex problem (2.86) to find* $\hat{A}_{BS}$
- *Change* $\varepsilon_{A_{BS}}$ *to get first feasible* $\hat{A}_{BS}$
- *Update* $\hat{A}_{BSH} = \hat{A}_{BS}^H$
- *If no improvement in objective function then choose smaller* $\varepsilon_{A_{BS}}$

– ***Until*** $\varepsilon_{A_{BS}} \leq \varepsilon_{A_{BS}}^{Tg}$

– ***Update*** $A_{BS} = \hat{A}_{BS}.\sqrt{\alpha}$

– ***Update*** *SINR to maximum obtainable value respect to* A_{RS}

- ***Until*** no improvement in objective functions

In Figure B.1, normalized MSE versus normalized requested power for fixed and adaptive requested SINR are presented. It is observed that this adaptation doesn't affect the MMSE.

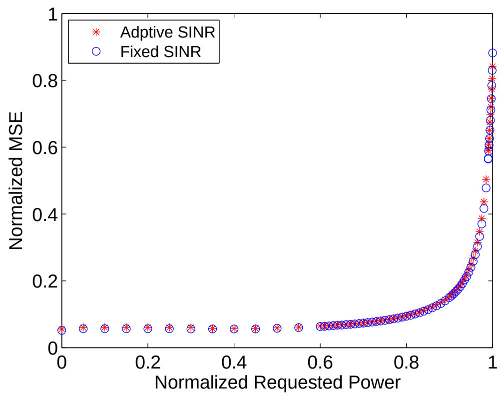


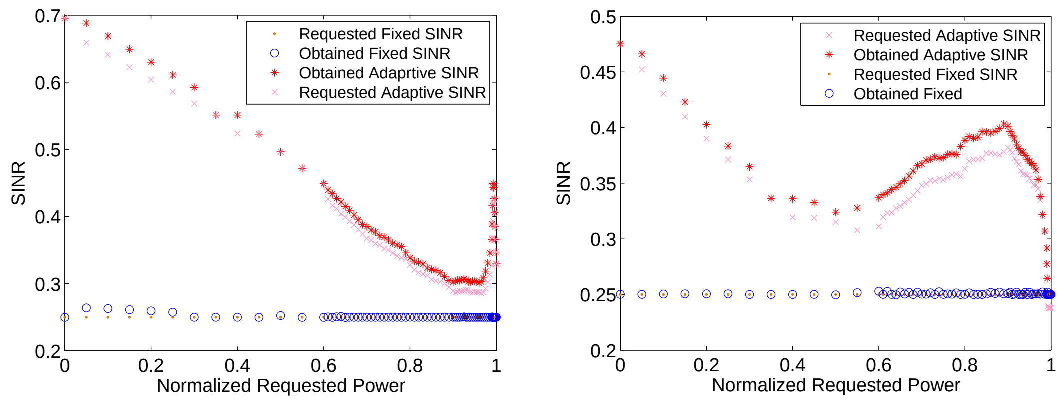
Figure B.1: Normalized MSE versus normalized requested power

In Figure B.2, SINR's for fixed and adaptive methods are demonstrated. Minimum requested SINR is supposed to be 0.25. Since the SINR threshold value is adaptive, higher SINR can be achieved when different power is requested.

In Figure B.3, the power of base station and relay are shown. In adaptive algorithm based on how much SINR or power for energy harvesting requested, used power from base station and relay vary. For fixed SINR, base station power changes are very small. Relay power for fixed SINR varies depending on requested power for energy harvesting users. For adaptive SINR, this power differs due to requested power or SINR.

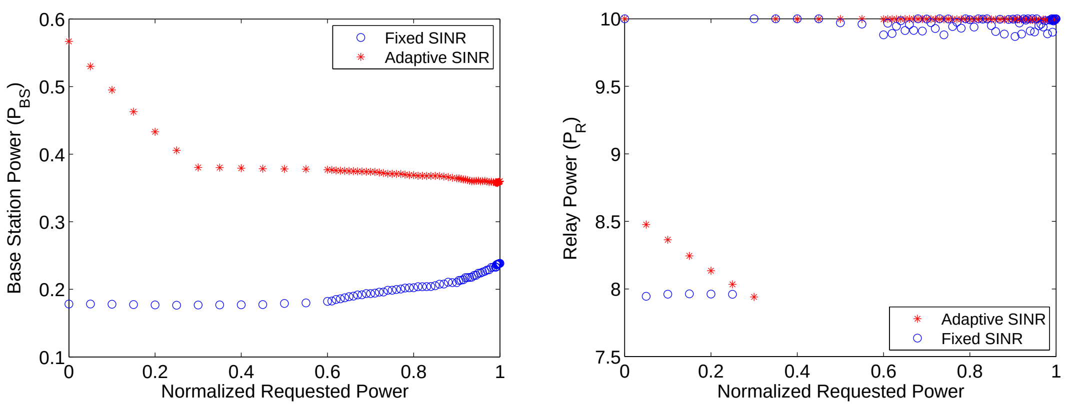
In Figure B.4, the harvested power in fixed and adaptive scenarios are shown. After certain amount of requested power, obtained power changes rapidly, it is due to rapid changes in relay power.

Finally, in Figure B.5, obtained threshold values versus requested power for both fixed and adaptive SINR are illustrated. Although for both fixed and adaptive SINR, the (A,AH) method has converged, obtained threshold value for adaptive SINR is higher due to higher power of base station.



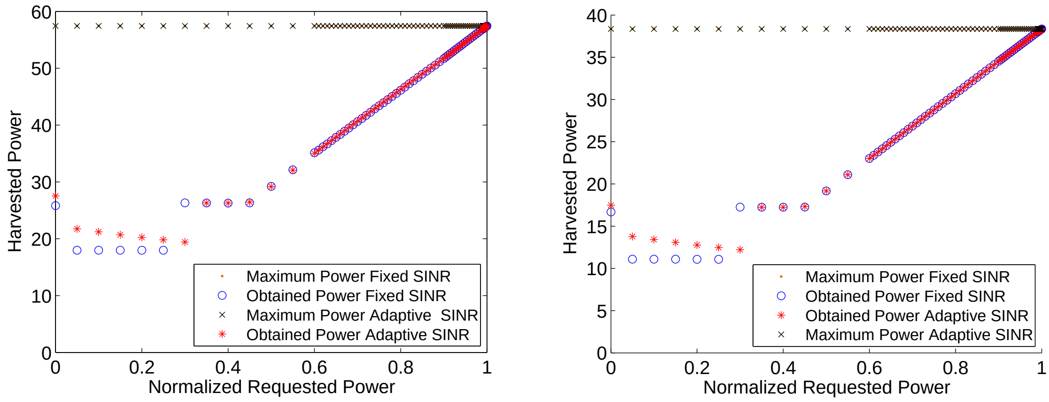
(a) User 1 **(b)** User 2

Figure B.2: SINR versus normalized requested power



(a) Base Station Power **(b)** Relay Power

Figure B.3: SINR versus normalized requested power



(a) User 1 **(b)** User 2

Figure B.4: Harvested power versus normalized requested power

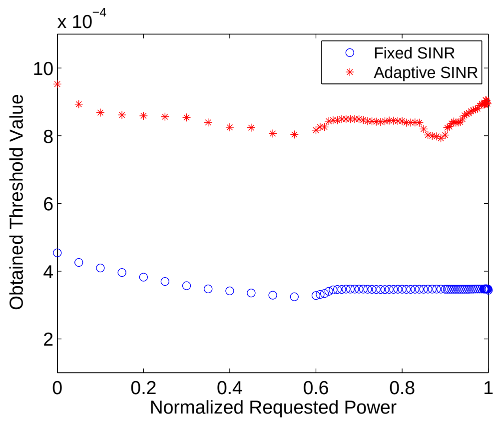


Figure B.5: Obtained threshold value versus normalized requested power