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Energy-efficient Resource Allocation for IRS-empowered Future Communication Networks

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Abstract

Intelligent reflecting surface (IRS) has become a revolutionary technology in wireless communications system to provide reconfigurable environment and supply better energy efficiency. Previous IRS studies of power efficiency have mainly focused on the performance optimization and harvesting eavesdropper system design without considering the multi-IRS signal reflection. In this thesis, we propose a multiple-RISs-assisted network architecture, where two or more IRS panels are set between the base station and multiple receive terminals by assuming the distance between transmitter and receiver is too far to reach the signal. Thus, the signal can only be propagated by IRS reflection. We are aiming to optimize the system problem formula to find the maximum energy efficiency of this IRS-assisted system. To address the non-convexity of the problem, the alternating optimization method for beamformer and phase shift schedule is needed. The validity of the proposed algorithm approach is demonstrated by simulation results.

Abbreviations

5G	Fifth Generation Communication Network
B5G	Beyond the Fifth Generation Communication Network
6G	Sixth Generation Communication Network
MIMO	Multiple Input Multiple Output
mmWave	Millimeter Wave
UDN	Ultra-dense Network
IRS	Intelligent Reflecting Surface
BS	Base Station
CSI	Channel State Information
SINR	Signal to Interference plus Noise Ratio
SE	Spectral Efficiency
EE	Energy Efficiency
AO	Alternating Optimization
SCA	Successive Convex Approximation
SDP	Semidefinite Programming
SDR	Semidefinite Programming Relaxation
KKT	Karush-Kuhn Tucker

Contents

Chapter 1

Introduction

With the exponentially increasing of smart devices demanding and wireless communication system capacity, the target of fifth generation (5G) wireless network has been accomplished that the network connectivity could support at least 100 billion wireless devices. The capacity of network increased to 1000 times of the previous generation by developing the wireless technologies such as millimeter wave (mmWave), massive multiple input multiple output (MIMO), and user-centric design (UDN) [11]. Compared to 5G, the density of 6G will increase tenfold, the peak rate is expected to reach in Tbit/s level, and the experienced rate should be developed to over 10 Gbit/s [24]. The requirements such that high data rates, high energy efficiency, low latencies, ubiquitous coverage, and robustness of transmission introduced the focus on developing mmWave method in 5G and B5G, since the bandwidths of high frequency are desired for high bit rates. In 6G, it will be even higher that increase from mmWave to THz or visible light spectrum potentially. However, the higher frequency means shorter wavelength. As a result, the ability to sensitive the signal blockage and the reduction of coherence time become two fundamental drawbacks in high frequency technology [14].

Moreover, the growth of traffic volumes and the resulting significant demand for communications quality have raised an urgent need to find a cost-efficient and consumption-efficient solution for future wireless networks. The basic requirements could be summarized as:

- High performance wireless connectivity: Capable to afford the extreme transmit rate with low latency, meanwhile keep the reliability as high as possible.
- Trustworthy capability: Guarantee the safety, security, integrity and privacy of communications.

- Sensing-assisted communication: Provide a high accuracy localization ability, signal reconstruction and sensing to improve the transmit performance, simultaneous mapping.
- Sustainable and green network: Develop the energy efficiency, low power consumption. Reduce the expenditure for installation and maintenance.

Aiming to fulfill the coverage of the usage of mmWave in 5G, THz communication in 6G and the aforementioned requirements, nowadays, intelligent reflecting surface (IRS) have been developed as an innovation technology that is able to significantly develop the performance of wireless communication systems in a cost and consumption-effective manner. The small meta-atom for signal reflection help IRS enhance or interfere the signal by phase adjusting. Meanwhile, it is flexible to equipped on walls and building facades, thus the IRS is desirable to contribute to the communication service coverage. The detailed function and benefits of IRS will be introduced in next chapter.

Chapter 2

Background

2.1 5G and Future Communications

The fifth generation (5G) technologies have become a popular research topic recently containing NOA, M-MIMO, and UDN. That is, a new vision of wireless communications has emerged, including distinct requirements: advanced bandwidth, ultra-reliable and low-latency transmission design, and enormous wireless communications [7].

Therefore, millimeter wave (mmWave) is suitable for 5G transmission since high frequency bands have a lot of unused bandwidth, which could guarantee a higher data rate. Narrow beams are suitable for applications of mmWave and M-MIMO by mounting multiple antennas at the transmitter. Furthermore, the wavelength of radio signal would be decreasing while the frequency increasing. 5G solutions based on short-range communications, such as device-to-device (D2D) communications and ultra-dense network (UDN), can improve wireless power transfer (WPT) efficiency also minimize the energy transfer distance [11]. However, the drawback of high frequency bands is distinct as well. The penetration of high frequency radio through obstacles could be blocked because of the short wavelength, thus the number of antennas for communications would increase continuously, the multiple antennas equipped hardware is impractical.

It is reported in [16], wireless communications network may afford up to billions of users and millions of applications nowadays, the throughput rate is achieved nearly 100 times faster than 2017. In addition, with the development of IoT and related instruments, the amount of IoT devices is estimated to arrive hundreds of billions in next decade. The existing 5G narrow-band IoT (NB-IoT) standard is clearly incapable of meeting the future demands [1].

In addition, 6G technology aims to provide an extreme higher data rate than 5G, the magnitude is expected to develop from 20 Gbps to 1000 Gbps [25], the comparison between 6G and 5G is shown in figure 1:

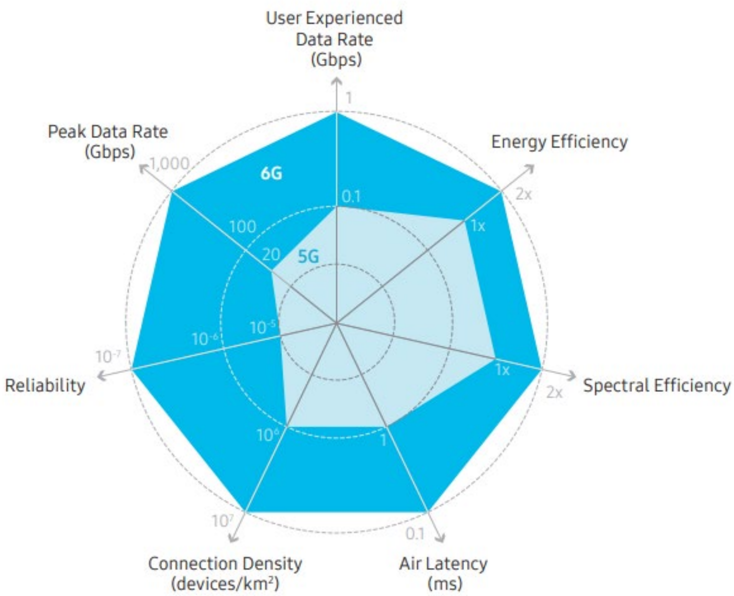

Figure 1. Key requirements comparison between 5G and 6G [25]

It is clear that the communication requirements in 6G are extremely higher than 5G. As we have dedicated that, continuously increasing the number of antennas is the solution to improve the transmission performance based on the principles of current wireless communication technology, however, this method is unfulfillable for high level services.

As a result, a new green communications technology beyond 5G (B5G) or 6G is essential with an exponentially increasing demand for wireless network transmission, that energy consumption and cost on maintenance are no longer sustainable. Specifically, the tradeoff should be made between major relationships among spectrum efficiency (SE) versus energy efficiency (EE), deployment efficiency (DE) versus energy efficiency (EE), delay (DL) versus power (PW), and bandwidth (BW) versus power (PW) [16].

In [14], beamspace was introduced to an important position at mmWave frequency and higher radios in 5G and B5G. MIMO technic is a desired approach in current transmission. However, the multiple access communication in 5G and B5G network is not a simple operation [15]. The traditional information transmission of multiple access system only focuses on the limited number of elements, to apply the system into massive access is difficult for current conventional method.

According to the reports from [7], there is no single technology to fulfill all of 5G requirements. The further research on B5G and the sixth generation (6G) should break out the bounds of existing technology, although the current development of communications method seems does not change too much at present. The technologies should aim to achieve the new requirements. Applications and trends in decades instead of simply following the experience from 5G. However, the challenge bring by innovation is obvious that a new communication paradigm, particularly at physical layer, is necessary, an optical related method could be significant in the future. In addition, wider spectrum utilize is introduced in 6G for higher connectivity requirements, THz and even visible light spectrum will be used in future, an ideal THz related design for transmission equipment is expected to be a combination of photonic, electronic and hybrid transceivers [24].

2.2 Intelligent Reflecting Surface

The RIS is proposed as a man-made passive surface of electromagnetic (EM) material for future communications, it is constructed with software-defined control circuit board, reflecting elements, and copper backplane which shows in figure 2. The software-defined circuit board could control the surface plane electronically by simple integrated electronics. The intention and explicit of signal propagation condition is improved by the precise adjustment in surface, so that the quality of service would be boosted as well [7]. The meta-atom in the reflecting element contains the ability to reflect the signal passively that play a role as the low cost miniature antenna [26].

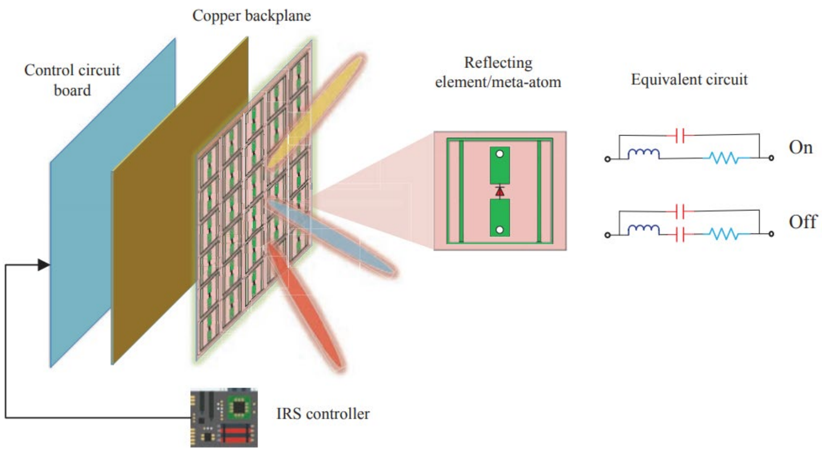

Figure 2. Architecture of IRS [12]

In recent research, the benefits of IRS technology have been verified for a variety of wireless communication applications such as transmission link security for physical layer, full-duplex transmission, mmWave networks, and simultaneous wireless information and power transfer (SWIPT) systems [13]. Moreover, the advantage of electromagnetic properties also including negative refraction, high quality signal at the edge of propagation range. Thus, IRS could maintain the good quality with low power or in the massive access scenario [1]. As IRS only reflects the given signal by passive surface, for wider operation in massive connectivity is using large active surfaces [14], the comparison of IRS and other technologies that candidate for 5G or 6G transmission shows in figure 3.

Technology	Operating mechanism	Duplex	No. of transmit RF chains needed	Hardware cost	Energy consumption	Role
IRS	Passive, reflect	Full duplex	0	Low	Low	Helper
Backscatter	Passive, reflect	Full duplex	0	Very low	Very low	Source
MIMO relay	Active, receive and transmit	Half/full duplex	N	High	High	Helper
Massive MIMO	Active, transmit/receive	Half/full duplex	N	Very high	Very high	Source/ Destination

Figure 3. Comparison of IRS with other related technologies [4]

For energy optimum and power maximization in network, It is found that applying large-scale IRS panels reacts a better method to improve the energy efficiency of system than keeping install the power amplifier or other power-consuming elements which means to add more antennas at the transmitter, since IRS as a passive device that has lower cost, complexity, no require of power-hungry RF chains [15]. These results straightforward indicated the dominance of IRSs compared with traditional wireless designs in terms of both signal transmission performance and power consumption [2]. Moreover, IRS is expected to be applied in further communications network. Two principles of IRS called energy focusing and energy nulling [14], can be involved in signal interference, coverage, capacity and rate improvement.

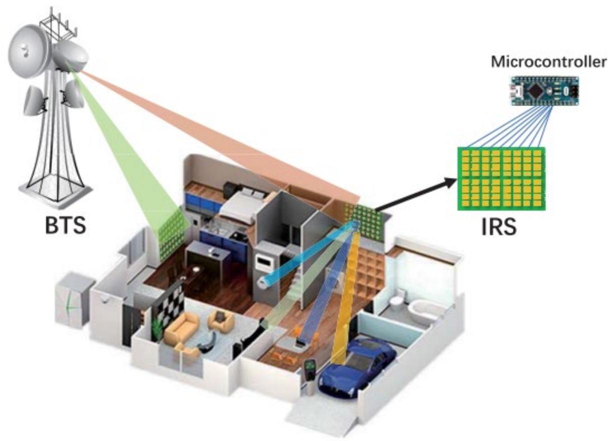

Figure 4. Indoor network with an IRS [15]

As we have indicated before, the short wavelength signal in transmission is affected by walls easily. The model in figure 4 indicates an indoor coverage enhancement method and figure 5 indicates the outdoor (building) m-MIMO transmission system. In these two scenarios, the IRS panels are equipped on the wall that consist of an intelligent wall for signal reflection to avoid signals attenuation during transmission [8]. Instead of reflect signal entirely in the whole surface, a large number of reflecting units inside work separately, which can control the enhance or interfere by phase shifting. This product addresses coverage drawback and the blockage during the propagation. Compared to the large-scale antenna metrics, IRS has the advantage of less power consume, lower cost and complexity [15]. Therefore, IRS is expected as a promising technology for future wireless communications.

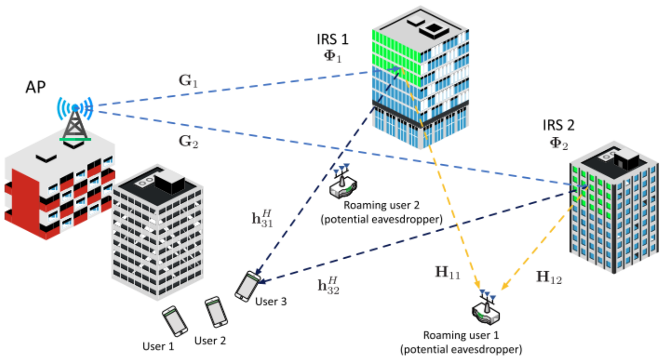

Figure 5. Outdoor multiuser MIMO model with two IRS [6]

According to the preliminary study, this thesis will evaluate the energy passive reflection property of IRS, based on the developed model and optimal algorithm, the energy performance by testing under signal blockage condition will be tested.

2.4 Objectives

Based on the literature review, I noticed that there is a research gap in system modeling. Most of the model that I found from other articles or reports, they only set single IRS panel in the system. If there are two or more IRS penals in the system, the signal vector is still only reflected once by IRS [10]. Therefore, I was interested in exploring how signal transmission will be affected if the signal is reflected by multiple times, how system will be optimized.

In addition, the main topics of green technology in wireless communications are focusing on power consume, transmission security and energy efficiency [11][12]. Energy efficiency was chosen since I was more interested in learning about how energy affected in a long transmission distance especially when the signal is passed by several IRS step by step.

Therefore, refer to my opinion on the system design, to investigating an energy efficiency maximization methodology within a multiple IRS-assisted system eventually became the objectives of this thesis.

Chapter 3

System Model

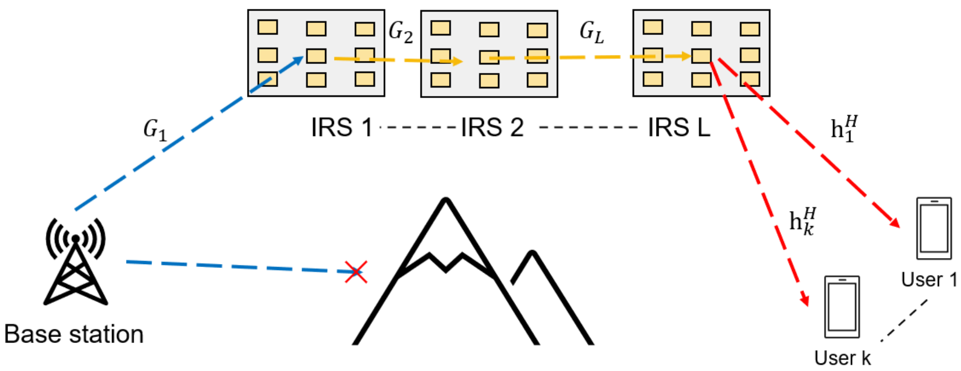

Figure 6. Multi-IRS-assisted energy efficiency maximization communication system

As figure 6 shows, the basic system model of multi-IRS-assisted energy efficiency maximization communications is constructed. In this thesis, assuming that the base station (BS) is equipped with $N > 1$ number of antennas, whereas the user devices equipped single antenna only [17]. Variables M, L and K stand for the number of mounted reflecting elements on each IRS panel, IRS panels for downlink transmission, and the independent users respectively. The set of the K users is denoted by $\mathcal{K} = 1, \ldots, \mathrm{K}$. In addition, the L IRS panels set is denoted as $\mathcal{L} = 1, \ldots, L$. This system model assuming that the distance between users and base station is too far and the signal propagation is blocked by obstacles (e.g., mountains), hence, the channel vector of direct transmission denoted by $\boldsymbol{h}_{d,k} \in \mathbb{C}^{1\times N}$ is unavailable. Moreover, the channel state information (CSI) of each channel is assumed to be perfectly known at the transmitter for energy efficiency or power optimize problem formulation [16]. The baseband equivalent channel $\boldsymbol{h}_{r,k} \in \mathbb{C}^{1\times M}$ denotes the vector between IRS and kth user. $\boldsymbol{G} \in$

$\mathbb{C}^{N\times M}$denotes the channel matrix from BS to IRS. Furthermore, the transmitted signal vector from BS $\boldsymbol{x} \in \mathbb{C}^{N}$, is given by

$$\boldsymbol{x} = \sum_{k=1}^{K} \boldsymbol{w}_k s_k \tag{1}$$

Where $\boldsymbol{w}_k \in \mathbb{C}$ and $s_k \in \mathbb{C}^{N\times 1}$ represents the beamforming vector and information-bearing signal transmitted from the BS to user k respectively, where $\mathbb{E}[|s_k|^2] = 1, \forall k \in \mathcal{K}$. Since the signal is transmitted by multiple IRS panel, the received signal vector at user k is

$$\boldsymbol{y_k} = \boldsymbol{h}_{r,k}^{H}\left(\prod_{l=1}^{L} \boldsymbol{G}_l \boldsymbol{\Phi}_l\right) \sum_{k=1}^{K} \boldsymbol{w}_k s_k + n_k \tag{2}$$

The formula (2) could be simplified by choosing symbols to represent the signal vector that transmitted from BS and IRS reflection. Hence, rewritten the formula (2) in terms of the g and x as

$$y_k = \boldsymbol{g}_k^{H} x + n_k \tag{3}$$

Where define $\boldsymbol{g}_k^{H} = \boldsymbol{h}_{r,k}^{H}(\prod_{l=1}^{L} \boldsymbol{G}_l \boldsymbol{\Phi}_l)$ and $x = \sum_{k=1}^{K} \boldsymbol{w}_k s_k$, respectively.

The phase shift matrix is denoted by $\boldsymbol{\Phi} \in \mathbb{C}^{M\times M}$, $\boldsymbol{\Phi}_l = \mathrm{diag}\left(\beta e^{j\theta_{l1}}, \beta e^{j\theta_{l2}}, \dots, \beta e^{j\theta_{lM}}\right)$. The value of amplitude coefficient $\beta \in [0,1]$ in this thesis is fixed at 1, therefore the beamforming would hold the integrity of original signal without changing the amplitude of original signal, only the phase is adjustable in IRS elements for practical operation. θ_{lm} represents the phase shift of m-th reflecting element in IRS panel l, where $\theta_{lm} \in [0, 2\pi], \forall m \in M$. The variable $n_k \sim \mathcal{CN}(0, \sigma_k^2)$ denotes the additive white Gaussian noise (AWGN) received by k-th user, σ_k^2 is corresponding to the noise energy. Hence, the formula of signal to interference plus noise ratio (SINR) received at user k is given by

$$SINR_k = \frac{|\boldsymbol{g}_k^{H} \boldsymbol{w}_k|^2}{\sum_{i\neq k}^{K} |\boldsymbol{g}_k^{H} \boldsymbol{w}_i|^2 + {\sigma_k}^2} \tag{4}$$

Following the Shannon formula introduced in [18], the total sum achievable throughput or spectral efficiency (SE) of system is given by

$$R = \sum_{k=1}^{K} log_2(1 + SINR_k) \tag{5}$$

Generally, the total power of system would dissipate to BS transmit power, as well as the consumed static power in hardware. It should be noted that there is no transmission power loss in RIS signal reflection since the reflectors would not adjust the amplitude of incoming signal [5]. Therefore, the total consumption power of system that from BS to k users is obtained as

$$P = \sum_{k=1}^{K} \|\boldsymbol{w}_k\|^2 + P_s + LP_I \tag{6}$$

Where P_s represents the consumption static power of BS, and LP_I is the power consumed by the L of IRS panels.

Chapter 4

Design Problem Formulation

This thesis is aiming to maximize the transmit energy efficiency, following the formular which introduced in [11], the optimization problem formulation of energy efficiency with corresponding constraints could be written as

$$maximize_{\{\boldsymbol{w}_k,\Theta_{l,m}\}} = \frac{R}{P} = \frac{\sum_{k=1}^{K} log_2(1 + SINR_k)}{\sum_{k=1}^{K}\|\boldsymbol{w}_k\|^2 + P_s + LP_I} \quad \text{(P1)}$$

s.t.

$$C1: \sum_{k=1}^{K}\|\boldsymbol{w}_k\|^2 \le P_{max}$$

$$C2: 0 \le \Theta_{l,m} \le 2\pi \quad \forall l,m$$

$$C3: SINR_k \ge \mu_{min,k} \quad \forall k \in K$$

The constraint C1 indicates that the total transmit power should be constrained within the total power capability of the system. The constraint C2 indicates the range of phase shift in IRS. The constraint C3 is to maintain the SINR value higher than the expected minimum value to user k in order to guarantee the quality of signal. Based on the definition of convex theory, it could be concluded that, the problem formula and the SINR equation in C3 are not convex.

4.1 Solution of the problem

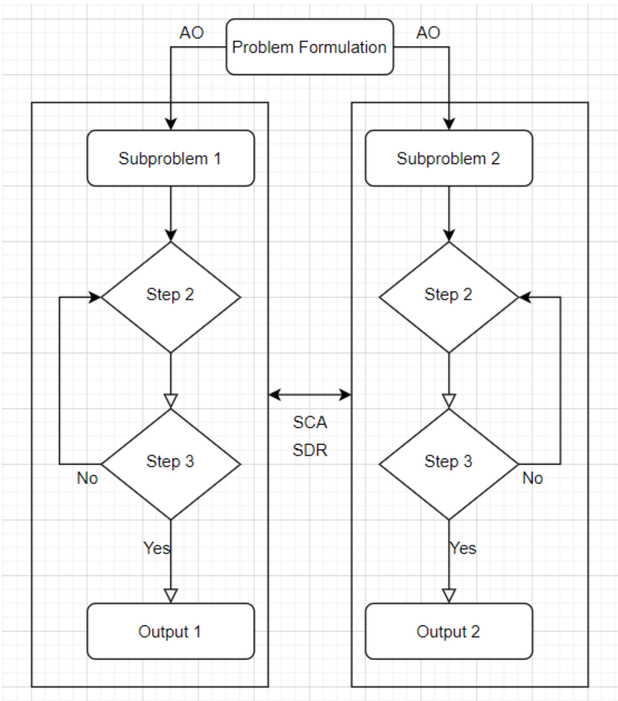

Figure 7. Flow chart of alternating optimization

In this section we start to solve the objective problem by jointly adjusting and optimizing the $\mathbf{\Phi}$, $\boldsymbol{wk}$. Since the beamforming vector and the phase shift are strongly coupled, an algorithm called alternating iteration method is proposed. The figure 7 shows the basic procedure of AO, we split the objective formula into two subproblems which one problem for beamforming vector maximization and another subproblem for phase shift optimization. The subproblem will find the target optimal result while holding the other parameters constant. The optimal values will be interchanged via iteration calculation, the algorithm will be stopped when the function achieve the maximum of iteration or convexity. For the first subproblem, we will apply the theory of Taylor expansion and Dinkelbach's algorithm to handle the non-convexity problem formula, also, we have to adopt SDR to eliminate the rank one constraint. For the second subproblem of phase shift, we could apply SCA and SDR again, but to be noticed that further AO algorithm for multiply formula optimization have to utilized again.

Firstly, we define the numerator and denominator of SINR for a neater formula let $a_k = \sum_{i \neq k}^{K} |\boldsymbol{g}_k^H \boldsymbol{w}_i|^2 + {\sigma_k}^2$, $b_k = |\boldsymbol{g}_k^H \boldsymbol{w}_k|^2$, $\boldsymbol{W}_k = \boldsymbol{w}_k \boldsymbol{w}_k^H$, regenerate the formula of (5) as follow:

$$\begin{aligned} R &= \sum_{k=1}^{K} log_2(1 + \frac{|\boldsymbol{g}_k^H \boldsymbol{w}_k|^2}{\sum_{i \neq k}^{K} |\boldsymbol{g}_k^H \boldsymbol{w}_i|^2 + {\sigma_k}^2}) \\ &= \sum_{k=1}^{K} log_2(1 + \frac{b_k}{a_k}) \\ &= \sum_{k=1}^{K} \log_2(a_k + b_k) - \log_2(a_k) \end{aligned} \tag{8}$$

Therefore, the power efficiency formula and the corresponding constraints could be rewritten as:

$$max_{\{\boldsymbol{W}_k, a_k, b_k\}} = \frac{\sum_{k=1}^{K} \log_2(a_k + b_k) - \log_2(a_k)}{\sum_{k=1}^{K} Tr(\boldsymbol{W}_k) + P_s + LP_I} \tag{9}$$

St.
C1 $\boldsymbol{W}_K \succcurlyeq 0, \ \forall k \in K$

C2 Rank $(\boldsymbol{W}_k) \leq 1, \ \forall k \in K$

C3 $\sum_{k=1}^{K} \mathrm{Tr}(\boldsymbol{W}_k) \leq P_{max}$

C4 $\mathrm{Tr}(\boldsymbol{g}_k \boldsymbol{g}_k^H \boldsymbol{W}_k) \geq b_k, \ \forall k \in K$

C5 $\sum_{i \neq k}^{K} |\boldsymbol{g}_k^H \boldsymbol{w}_i|^2 + {\sigma_k}^2 \geq a_k, \ \forall k \in K$

C6 $\log_2(a_k + b_k) - \log_2(a_k) \geq R_{k,min}$

4.1.1 Subproblem 1 – solve beamforming vector w_k

Firstly, settle the fixed value of phase shift $\boldsymbol{\Phi}$ to the subproblem 1 then we have only one variable $\boldsymbol{W}_k$ in the objection problem now.

The constraint 2 and the numerator part in the function (9) are non-convex. In numerator, the combination of concave and convex function cannot guarantee the convexity of overall function. To address this issue, we can reformulate the formula by apply SCA method. By setting the constant upper bond, we could limit the uncertain part that always contains the convexity property.

Applying Taylor's expansion to set the upper bound:

$$f(x+h) \leq f(x) + hf^{t}\,(x)$$

$$\log_2(a_k) \ \leq \ \frac{(a_k - a_k^t)}{a_k^t \ln(2)} + \log_2(a_k^t) = \ C^{(t)}$$

Where the superscript t stands for the iteration index, so that $C^{(t)}$ refers to the Taylor series of ak in t-th iteration. a_k^t is the feasible value at the t-th iteration.

Therefore, replace the $\log_2(a_k)$ with upper bond, the problem formula should be constraints as:

$$max_{\{\boldsymbol{W}_k, a_k, b_k\}} = \frac{\sum_{k=1}^{K} \log_2(a_k+b_k) - C^{(t)}}{\sum_{k=1}^{K} Tr(\boldsymbol{W}_k) + P_S + LP_I}$$

st. C1 $\boldsymbol{W}_K \succcurlyeq 0, \ \forall k \in K$

C2 Rank $(\boldsymbol{W}_k) \leq 1, \ \forall k \in K$

C3 $\sum_{k=1}^{K} \mathrm{Tr}(\boldsymbol{W}_k) \leq P_{max}$

C4 $\mathrm{Tr}(\boldsymbol{g}_k \boldsymbol{g}_k^H \boldsymbol{W}_k) \geq b_k, \ \forall k \in K$

C5 $\sum_{i \neq k}^{K} |\boldsymbol{g}_k^H \boldsymbol{w}_i|^2 + {\sigma_k}^2 \geq a_k, \ \forall k \in K$

C6 $\log_2(a_k + b_k) - C^{(t)} \geq \ R_{k,min}$

The constraint 2 remains non convexity in the problem formula due to the rank one property. We could apply semidefinite programming relaxation (SDR) to relax the constraint and eliminate it to make it suitable for convex optimization [6] [27]. Once the problem becomes an SDP problem, the SCA algorithm will be guaranteed to converge at the local optimal point. The proof of SDR please refers to the appendix.

Furthermore, the Dinkelbach's method could be proposed to solve the fractional formula of two linear functions aiming to obtain the maximum or minimum ratio. The constraints should linear and variables should continuous in the domain for the Dinkelbach method transform the function as the form of

$$F(x) = \frac{Numerator(x)}{Denominator(x)}$$

$$\Leftrightarrow \mathrm{F}(q_k) = \max(Numerator(x) - q_k Denominator(x) |\, x \in s)$$

Where,

$$q^* = max\frac{R'}{P'}$$

Applying Dinkelbach's algorithm, rewrite the fractional expression into a non-fractional form [9, 10].

$$max_{\{\boldsymbol{W}_k, a_k, b_k\}} = \sum_{k=1}^{K} \log_2(a_k + b_k) - q^* \left(\sum_{k=1}^{K} Tr(\boldsymbol{W}_k) + P_s + LP_I \right) - C^{(t)} \qquad (P2)$$

St. C1 $\boldsymbol{W}_K \succcurlyeq 0,\ \forall k \in K$

C2 $\sum_{k=1}^{K} \mathrm{Tr}(\boldsymbol{W}_k) \leq \mathrm{P_{max}}$

C3 $\mathrm{Tr}(\boldsymbol{g}_k \boldsymbol{g}_k^H \boldsymbol{W}_k) \geq b_k,\ \forall k \in K$

C4 $\sum_{i \neq k}^{K} |\boldsymbol{g}_k^H \boldsymbol{w}_i|^2 + {\sigma_k}^2 \geq a_k,\ \forall k \in K$

C5 $\log_2(a_k + b_k) - \log_2(a_k) \geq \mathrm{R_{k,min}}$

Algorithm 1: SDR Based SCA and Dinkelbach Algorithm
1: Initialize the iteration index i = 1and the maximum iteration value
2: Set the value of phase shift $\boldsymbol{\Phi}$
3: Repeat
4: Solve the formula P2 with the given values, store the updated value of $C^{(t)}$
5. Calculate the q^* and update $q^{*(t)}$
6: Set i = i + 1
7. Until convergence or reach the maximum iteration
8. Gain the new value of $\boldsymbol{W}_k{}^{\boldsymbol{i}}$

4.1.2 Subproblem 2 – solve phase shift $\boldsymbol{\Phi}$

Giver by the known transmit beamforming vector $\boldsymbol{W}_k$ from subproblem 1. Recall the formula of P1, the phase shift $\boldsymbol{\Phi}$ only has impact on the total rate of the system, in other words, solve the maximum value of R is a way to optimize the maximum power efficiency.

$$maximize_{\{w_k,\Theta_{l,m}\}} = \frac{R}{P} = \frac{\sum_{k=1}^{K} log_2(1 + \frac{|\boldsymbol{g}_k^H \boldsymbol{w}_k|^2}{\sum_{i\neq k}^{K}|\boldsymbol{g}_k^H \boldsymbol{w}_i|^2 + \sigma_k{}^2})}{\sum_{k=1}^{K}||\boldsymbol{w}_k||^2 + P_s + LP_I} \qquad (P1)$$

St. $C1$: $\sum_{k=1}^{K}||\boldsymbol{w}_k||^2 \leq P_{max}$

$C2$: $0 \leq \Theta_{l,m} \leq 2\pi \quad \forall l, m$

Therefore, the simplified objective function is:

$$\max_{\Phi} R_k = \sum_{k=1}^{K} \log_2(a_k + b_k) - \log_2(a_k) \qquad (P3)$$

St. $C1 \mid \Phi_l| = 1, \quad \forall l$

C2 $\log_2(a_k + b_k) - \log_2(a_k) \geq \mathrm{R_{k,min}}$

Which $a_k = \sum_{i\neq k}^{K} |\boldsymbol{g}_k^H \boldsymbol{w}_i|^2 + {\sigma_k}^2$, $b_k = |\boldsymbol{g}_k^H \boldsymbol{w}_k|^2$.

And the fundamental format of $\boldsymbol{g}_k^H$ is $\boldsymbol{h}_{r,k}^H(\prod_{l=1}^{L} \boldsymbol{G}_l \boldsymbol{\Phi}_l) = \prod_{l=1}^{L} \boldsymbol{h}_{r,k}^H \boldsymbol{G}_l \boldsymbol{\Phi}_l$, let $\boldsymbol{h}_{r,k}^H \boldsymbol{\Phi}_l = \widetilde{\boldsymbol{v}}\, diag(\boldsymbol{h}_k^H)$ where $\widetilde{\boldsymbol{v}} = [e^{j\theta_{l1}}, e^{j\theta_{l2}}, \dots, e^{j\theta_{lM}}]^H$, $\boldsymbol{f}_l^H = diag(\boldsymbol{h}_k^H)\boldsymbol{G}_l \boldsymbol{w}_k$

The b_k can be reformulated as following:

$$b_k = |\boldsymbol{g}_k^H \boldsymbol{w}_k|^2 = |\prod_{l=1}^{L} \boldsymbol{h}_{r,k}^H \boldsymbol{G}_l \boldsymbol{\Phi}_l \boldsymbol{w}_k\,|^2$$

$$= \left| \prod_{l=1}^{L} \widetilde{\boldsymbol{v}}_l^H\, diag(\boldsymbol{h}_k^H) \boldsymbol{G}_l \boldsymbol{w}_k \boldsymbol{w}_k^H {\boldsymbol{G}_l}^H diag(\boldsymbol{h}_k\,) \widetilde{\boldsymbol{v}}_l \right|^2$$

$$= \left| \prod_{l=1}^{L} \widetilde{\boldsymbol{v}}_l^H \boldsymbol{f}_{l,k}^H \boldsymbol{f}_{l,k} \widetilde{\boldsymbol{v}}_l \right|^2$$

$$= \prod_{l=1}^{L} \mathrm{Tr}\,(\boldsymbol{F}_l \boldsymbol{V}_l)$$

Since we are aiming to investigate the maximum of R, in other words, once the maximum value of b_k is found, a_k would be the minimum, R will achieve maximum. Hence, the object formula is written as following:

$$max_{\{\boldsymbol{V}_l\}} \prod_{l=1}^{L} \mathrm{Tr}\,(\boldsymbol{F}_l \boldsymbol{V}_l) \qquad (P3.2)$$

$$st.\ \ C1 \quad \boldsymbol{V}_l \succcurlyeq 0, \forall l \in L$$

$$C2 \ \ Tr(\boldsymbol{F}_l \boldsymbol{V}_l) > \ b_k - \prod_{j\neq l}^{L} \mathrm{Tr}\,(\boldsymbol{F}_j \boldsymbol{V}_j)$$

$$C3 \quad \boldsymbol{V}_l = 1, \forall l \in L$$

$$C4 \ \ \mathrm{R_{k,min}} \left[\sum_{i\neq k}^{K} Tr(\boldsymbol{F}_{l,i} \boldsymbol{V}_l) + {\sigma_k}^2 \right] - Tr(\boldsymbol{F}_k \boldsymbol{V}_l) \leq 0$$

$$C5 \ \ Rank(\boldsymbol{V}_l) \leq 1$$

Where C4 and C5 are constrained to guarantee the equation $\boldsymbol{V}_l = \widetilde{\boldsymbol{v}}_l \widetilde{\boldsymbol{v}}_l^H$ holds after the optimal structure. It is intuitive that C5 and C2 hold the non-convexity. To remove the C5, apply SDR like we did in subproblem 1. To handle the multiply function in C2, the most straight forward method is to apply the AO again. Another method of SCA algorithm is possible as well. Eigenvalue decomposition (EVD) is introduced to obtain the results by solve $\boldsymbol{V}_l = \boldsymbol{U}\,\boldsymbol{\Lambda}\boldsymbol{U}^{\boldsymbol{H}}$ if we do not apply the SDR, the undesired result could be obtained if $Rank(\boldsymbol{V}_l) > 1$.

Algorithm 2: Double AO Based SDR Algorithm
1: Initialize the iteration index j = 1and the maximum iteration value
2: Set the value of beamforming vector ${\boldsymbol{W}_k}^{\boldsymbol{i}}$
3: Repeat
4: Solve the formula P3.2 with the given values, store the updated value of ${V_l}^{(j)}$
5. Calculate the R_k and update ${b_k}^{(j)}$
6: Set j = j + 1
7. Until convergence or reach the maximum iteration
8. Gain the new value of $\Phi^{\boldsymbol{j}} = \text{Diag(v)}$

Algorithm 3: Alternating Optimization Algorithm
1: Initialize the iteration index t, maximum iteration time t
2: Initialize the phase shift $\Phi^{\boldsymbol{j}}$
3: Repeat
4: Solve P2 by Algorithm 1 and update the temporary result of ${\boldsymbol{W}_k}^{\boldsymbol{i}}$
5: Substitute ${\boldsymbol{W}_k}^{\boldsymbol{i}}$ into beamforming vector, solve P3 by Algorithm 2 and update the result of $\boldsymbol{\Phi}^{\boldsymbol{j+1}}$
6: Set t = t + 1
7: Until convergence or reach the maximum iteration
8: Gain the final optimal value of both beamforming vector and phase shift $\boldsymbol{W}_k, \boldsymbol{\Phi}$

Chapter 5

Simulation Results

Parameter Name	Value
System Bandwidth	200 KHz
Noise Power	-110 dBm
Base Station Power	1 W
IRS Penal Power	1 mW
Number of IRS Panel	2
Carrier Frequency	2.1 GHz
SINR Requirement	10 dB
Channel Realizations	1000

Table 1. Significant parameters of problem simulation

In this section, we evaluate the simulation results of the designed algorithm based on the system model in chapter 3. The simulation model is inspired by the fundamental design from the work in [10], shown in figure 8. The simulation mainly focused on the comparation of average energy efficiency and IRS panel elements, level of transmission power and the number of users.

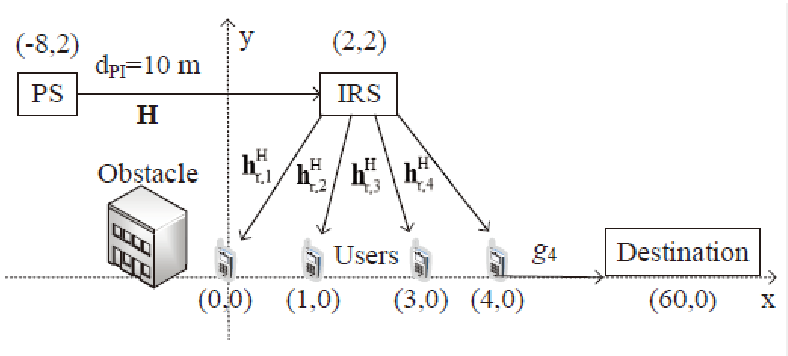

Figure 8. Simulation model in Wu's work [10]

The base station and IRS panels are at the same horizontal level but should be separated long enough in the distance, for the small environmental simulation, 100m is desired. The main configuration of system setup is presented in table 1, the path loss exponent of BS-IRS & IRS-user link is 3 following the TGN models restriction, in addition, all the elements in system are undergoing the same channel fading model.

For the first simulation, we concentrate on the relationship between average system energy efficiency and the maximum power budget in transmission by choosing different amount of IRS elements on two reflection panels. As the figure 9 shown, firstly, the magnitude of average power efficiency continuously rises till the transmission power reach to around 34 dBm level, no matter how IRS elements increases or the number of antenna changes. In other words, the efficiency reaches to the maximum 'saturation' condition under the 34 dBm power budget in this system. In addition, the increasing of IRS elements in panel could develop the energy efficiency significantly when using same transmission power. Also, the result performance better by providing more antenna at the base station. The increasing number of antennas and IRS develop the performance in beamforming; thus the efficiency will be improved as well.

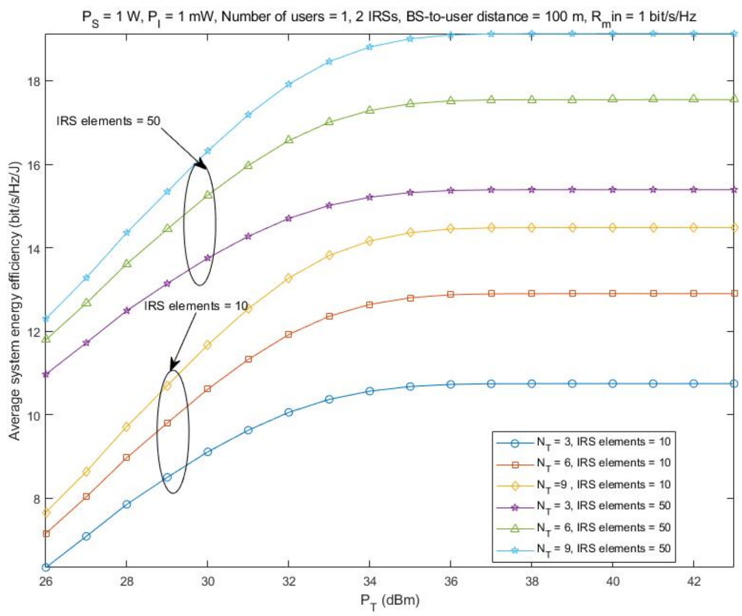

Figure 9. Average system energy efficiency VS transmit power

In the next simulation, we investigate on the influence facts of energy efficiency and number of users at the receiver. Figure 10 indicated that the energy efficiency will achieve the maximum point at the point of two users at receiver. The outstanding dropping accurse if the number of users keep increasing. The notable difference also appears by changing the antenna quantity. Similar with the performance in previous one, the energy efficiency will be developed with the increase of antenna by using more antenna such as 12 instead of 9. In other words, although the energy performance is dropped, compare the performance at the same 26 dBm transmission power level with only one user in simulation 1. The overall performance is still better than single user unless the user's number reach to 5.

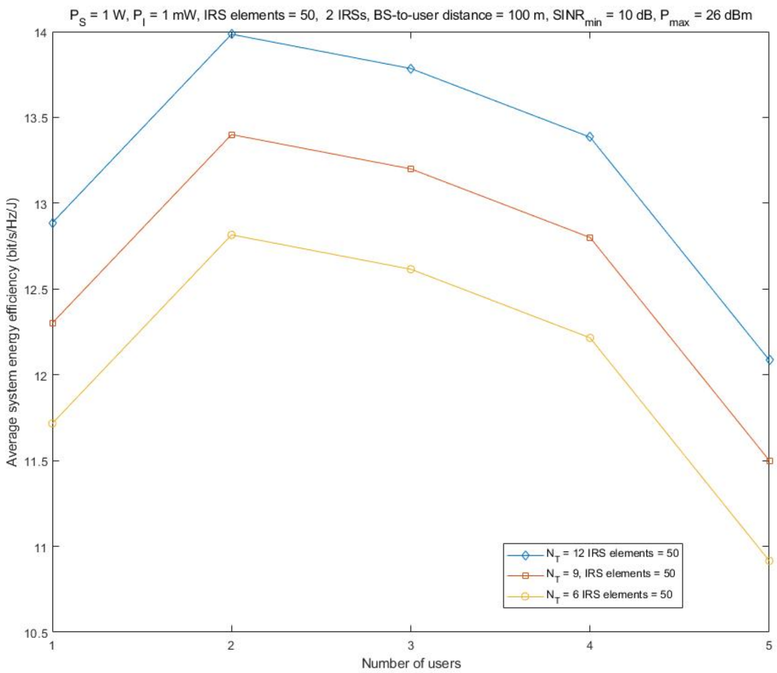

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Figure 10. Average system energy efficiency VS number of users

Chapter 6

Conclusion

6.1 Summary of Results

In this thesis, we design a multi-IRS assist system to investigate the energy efficiency and the influences of resource setting. The two simulation results indicate and confirm the effective improvement among the proposed model and algorithms. The increase of reflection elements and the transmission antenna shows the considerably development on the energy efficiency performance. The results also show that the number of users can be increased to improve the power efficiency but needs to be kept within a reasonable range, otherwise the performance could be affected significantly.

6.2 Future Plan

Although the results present the satisfactory performance under the designed system and algorithm, there are still large number of progresses could be implemented. First of all, I could make comparison between multi-IRS panel and single IRS under the same transmission condition [28]-[32] . I could also make comparison of energy efficiency [31]-[38] between by adding and without the energy harvesting model. Moreover, in the current system model, we only consider about the users and passive IRS elements. At the receiver side, I can investigate on the performance such as security and bit rate by adding time-switching receivers in massive MIMO system [39]-[42]. In a part of certain scenarios of secure transmission system modelling, the extra element named eavesdropper would be added as the undesired receive [43]-47].

For the convexity optimization, I could investigate on other algorithms such as the rest of two methods I proposed in the thesis A. The majority of challenging is that it takes time to studying on convex optimization which is as difficult as learning new knowledges while practicing them to real work. The future research directions on IRS and convex optimization are interesting and challenging.

6.3 Conclusion

In this thesis, we investigated the energy efficiency of the multi-IRS system to ensure the satisfied communication performance for each user under the designed obstruction model. The algorithm is formulated to solve non-convex optimization problem for the maximization of the power efficiency rate of the transmitted signal passes through multiple IRS panels to the user. The convex optimization methods have practical significance for the further study of IRS. The simulation results show the relationship between system efficiency and stability with different number of IRS panels and users. I can learn more about IRS system by changing parameters or adding more constraints and parameters for the future development.

The challenging obstacle in future is subsystem convex optimization and the algorithm design. Also, a lot of mistakes have to be found and correct them with the correct understanding.

Chapter 7

Appendix

As mentioned in the chapter 4, we should apply SDR to eliminate the non-convex rank constraint C2. Moreover, the Slater's constraint and Lagrange dual function should be utilized to prove the convexity and strong duality of problem. Firstly, to prove the SDR is tight, Karush Kuhn Tucker (KKT) should be applied. The Lagrange dual function in terms of beamforming vector $\boldsymbol{W}_k$ is formulated as:

$$\mathcal{L}(\boldsymbol{W}_k, \lambda_1, \lambda_2, \lambda_3, \lambda_4) = \sum\nolimits_{k \in K} log_2(a_k + b_k) - q^* \left(\sum_{k=1}^{K} Tr(\boldsymbol{W}_k) + P_s + LP_I \right) - C^{(t)}$$

$$+\lambda_1 \left(\sum_{k=1}^{K} \mathrm{Tr}(\boldsymbol{W}_k) - \mathrm{Pmax} \right) + \lambda_2 \left(b_k - \mathrm{Tr}(\boldsymbol{g}_k \boldsymbol{g}_k^H \boldsymbol{W}_k) \right) +$$

$$\lambda_3 \left(a_k - \sum_{i \neq k}^{K} |\boldsymbol{g}_k^H \boldsymbol{w}_i|^2 + {\sigma_k}^2 \right) +$$

$$\lambda_4 \left(\log_2(a_k + b_k) - C^{(t)} \right) - Tr(\boldsymbol{Y}\boldsymbol{W}_{\boldsymbol{K}})$$

Where $\lambda_1, \lambda_2, \lambda_3, \lambda_4 > 0$, $\boldsymbol{Y} \succcurlyeq 0$ are the Lagrange dual variables associated with the constraints of C2, C3, C4, C5 respectively. Therefore, the Lagrange dual problem could be rewritten as:

$$\max_{\boldsymbol{Y}_{\boldsymbol{K}}, \lambda_1, \lambda_2, \lambda_3, \lambda_4} \inf_{\boldsymbol{W}_{\boldsymbol{K}}} L$$

Then we concentrate on the KKT conditions by firstly derive the Lagrange function respect to W_k, the value of **Y** will know when the derivative is zero. **I** is identity matrix.

$$\frac{\partial L}{\partial \boldsymbol{W}} = q^* \boldsymbol{I} + \lambda_1 \boldsymbol{I} - \lambda_2 \boldsymbol{g}_k \boldsymbol{g}_k^H + \lambda_3 \boldsymbol{g}_k \boldsymbol{g}_k^H$$

$$\mathbf{Y} = q^*\boldsymbol{I} + \lambda_1\boldsymbol{I} - \lambda_2\boldsymbol{g}_k\boldsymbol{g}_k^H + \lambda_3\boldsymbol{g}_k\boldsymbol{g}_k^H$$

Note that KKT conditions including:

K1: $\boldsymbol{Y} \succcurlyeq 0, \lambda_1, \lambda_2, \lambda_3, \lambda_4 > 0$
K2: $\boldsymbol{Y}\boldsymbol{W}_{\boldsymbol{K}} = 0$
K3: $\boldsymbol{Y} = \boldsymbol{A} - \boldsymbol{H}$

Due to K2 indicates the complementary slackness property, if the dual variables are greater than zero, then K2 can only be satisfied if rank ($\boldsymbol{W}_{\boldsymbol{K}}$) =0. Assuming that the A in K3 is a positive semi-definite matrix, there will be at least one zero eigenvalue. Denote v as the associated eigenvector and let $\boldsymbol{V} = \ vv^H$, multiply the matrix V and apply trace operation on the both sides of K3, then the K3 could be generated as:

$$Tr(\boldsymbol{YV}) = Tr(\boldsymbol{AV}) - Tr(\boldsymbol{HV})$$
$$= \ -Tr(\boldsymbol{HV})$$

Recall that $\boldsymbol{H}$ and $\boldsymbol{g}_k$ are independent and Tr ($\boldsymbol{HV}$) must greater than zero thus this proves the matrix A is a positive definite matrix and full rank. Set Rank(A) = $N_{T.}$ To find the rank of Y, we could follow the theory of inequality and rank of matrices. Since the sum of rank(A) and rank(B) which two matrixes have same dimensions is larger than rank(A+B), the following prove is written as:

$$Rank(A) + Rank(B) \geq Rank(A + B)$$
$$Rank(A) - Rank(B) \leq Rank(A + B)$$

$$Rank(\boldsymbol{Y}) = Rank(-\boldsymbol{Y}) = Rank(-\boldsymbol{A} + \boldsymbol{H}) \geq Rank(\boldsymbol{A}) - Rank(\boldsymbol{H}) \geq N_T - 1$$

As a result, Rank(**W**) $\leq$ 1 where the column of **W** stands for the members of null space of **Y**.

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