SCHOOL OF ELECTRICAL ENGINEERING

AND TELECOMMUNICATIONS

Beamforming Design for Energy-efficient IRS-assisted Systems

by

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Abstract

Intelligent Reflecting Surface (IRS) has a series of advantages including low power consumption and convenient deployment. It is likely to become the backbone of communication system design in the future. In order to improve the energy efficiency and security quality of IRS-aided communication systems, as well as to guarantee practicality and stability, an information-security-oriented, artificial-noise (AN) -assisted maximum resource allocation algorithm for energy-efficient IRS networks is proposed. This algorithm is applicable to classical multiple-input single-output IRS-assisted cellular communication systems. A non-linear, multivariate coupled energy-efficient maximum system resource allocation model is developed to simultaneously satisfy the constraint of the user's security threshold secrecy rate, the base station (BS) maximum transmit power and continuous phase shift.

Contents

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Symbols Descriptions And Key Notations

This section is about these basic symbols and notations in this paper. Symbol **|·|** represents the absolute value of a vector, and $\|\cdot\|^2$ means a vector's l_2 Euclidian norm. Then, *diag*(·) is the diagonal operator. Moreover, $[\mathbf{A}]_{m,m}$ means the (m,m)-entry of matrix **A.** $\boldsymbol{a}^T$, $\boldsymbol{a}^H$ will denote the transpose and conjugate transpose of vector ***a***. In addition, the **Tr(·)** are calculating the trace of a matrix. $C^{I\times J}$ represents the complex matrix with I rows and J columns. Moreover, $\mathbf{H}^N$ is the meaning of the N-dimension Hermitian matrices. As for symbols ≜and ~, the meanings of them are "defined as" and "distributed as" in this report.

Chart of Symbol Descriptions

w	beamforming vector
R_{min}	user's minimum threshold secrecy rate
x	signal transmitted from the base station
M	the quantity of antennas at base station
N	the quantity of IRS reflecting elements
P_{cost}	power consumption of system
H_{BI}	channel matrix (base station to IRS)
h_{BU}	channel matrix (base station to user)
h_{IU}	channel matrix (IRS to user)
P_{total}	the total power budget
P_{max}	maximum transmit power of base station
h_{IE}	from IRS to eavesdropper channel matrix
h_{BE}	from base station to eavesdropper channel martix
Θ	phase shift matrix
q	IRS phase shift vector

Introduction

When time has come to the 21st century, the era of information has officially arrived. The new generation of communication technology has invited this trend into this information age. For example, massive MIMO and millimeter wave technology are both advanced technology with potential [14]. However, when it comes to the ultimate pursuit of communication speed, the energy consumption and energy efficiency of communication networks is an unavoidable problem. Compared with the traditional 4G communication, the speed improvement of the 5G communication system can be said to be quite significant. However, its costs of both energy and fund are really high, under which condition it requires careful consideration. Luckily, in recent years, the birth of the IRS declares that the communication network with high efficiency and low consumption is no longer a fantasy.

In short, IRS is a quickly rising technology which is significantly low-cost and energy-saved. The reflective elements of IRS are usually placed between the base station and the users. Its working mode is coordinated by a software controller [8]-[16]. Since each element independently changes the phase and amplitude of the incident signal, the designer may make reasonable use of this feature to make the users receive the signal transmitted by the base station better. Also, IRS can modify the parameters of the wireless channel through controllable reflections, which is incompatible with the existing transmitter/receiver wireless link. Due to the characters of IRS which is independent of RF chain short working distance, with low cost and low energy consumption, it can be deployed without considering interference management [14].

From an implementation standpoint, the IRS also has great advantages. First of all, the small size of the IRS makes it easy to install everywhere such as walls, roofs, ceilings and so on. In addition, as a supplementary device, the IRS does not need to modify the hardware when it is deployed in the existing wireless system. Therefore, it is really convenient to integrate the IRS into the wireless network, which shows its high compatibility. In terms of security, different from the traditional communication mode, due to its controllability, IRS can not only enhance the received power of legitimate users, but also disrupt the received power of the hidden eavesdroppers [1]. The security and stability of the system will be greatly improved. improve.

Thus, the research on IRS-assisted secure communication is particularly important and imperative.

Meanwhile, resource allocation (RA) is also a significant issue in the consideration of IRS communication system design. Because in the IRS system, proper resource allocation can improve the quality of the signal received by the user. Through the design of beamforming and the adjustment of IRS phase shift, the energy distribution of the whole system will reach a theoretically optimal state. However, the research on IRS system resource allocation is still in its infancy. Because there are many aspects which need to be considered in resource allocation, involving security, effectiveness and other aspects. In the literature [16], a IRS model of Multiple-Input-Single-Output (MISO) with single user takes into account the transmit power constraints of the base station, and proposes a resource allocation algorithm that maximizes the received power of the user. The literature [17] is based on the self-sustainable IRS, with the joint design and phase shift at the access point, as well as energy harvesting for the beamformer in order to make rate promotion. In [15], as for an IRS assisted multiple-input-single-output (MISO) networks and independent cooperative interference. Energy efficiency is maximized by designing transmit and interference beamforming and infrared spectral phase shift matrices. Although these algorithms have shown advantages in some aspects, experts have few consideration for the user's QoS and the threshold of the received signal.

The technology of communications is moving so quickly that people cannot keep with its pace leisurely. Meanwhile, the requirements of security performance has become an issue that worth thinking about. In wireless communication systems, physical layer security has become a new research topic in the field of information security. Artificial noise (AN) assisted physical layer security communication technology is a classic method to enhance the security performance of wireless communication by using multiple antennas to transmit and receive so as to ensure the security performance of wireless communication information in the physical layer [1].

In conclusion, in an IRS-aided system, it is urgent to find an algorithm which takes into account both the energy efficiency of the system and the security. There are several reasons for it. First of all, in a particular communication system, the improvement of energy efficiency means the improvement of transmission rate along with the reduction of energy consumption at the same time, which is especially significant when the experts evaluate the performance of a system.

Secondly, in practical applications, communication systems are not ideal and uninterrupted, where will usually be several eavesdroppers hidden in the system, whose existence will threaten the security of users. It would be totally unacceptable if vital confidence were stolen by eavesdroppers.

In summary, in order to promote the energy efficiency and security of the intelligent reflector system, this paper will illustrate an IRS energy efficiency maximum resource allocation algorithm that takes into account the system security under the condition of artificial noise interference.

Background

The Next Generation Communication Technology

The existing 4G LTE (Long Term Evolution) brings users a great mobile broadband experience through a new all-IP, flat network architecture [20]. The purpose of wireless data transmission at a high rate is achieved. However, it is not tough to find that some current applications, such as AR, VR, mobile multimedia, etc. , have been suddenly limited by the lack of 4G development pace. The high complexity, expensive hardware cost and key issues such as energy consumption cannot be solved [21]. To this end, the 5G network comes into being. 5G achieves all-round improvements in a fairly high rate. Quite a number of technical indicators seem to have been upgraded in ways that were previously unimaginable. Throughout the evolution of communication technologies, meeting the communication needs of users is the primary goal of each generation of system evolution, and new communication technologies are the driving force for each generation of system evolution.

From 1G to 5G, in order to increase speed and capacity, wireless communication is always expanding towards more spectrum and higher frequency bands. Looking at the future 6G technology, its early stage may be the expansion and deepening of 5G, based on AI and the Internet of Things (IoT), communication network and intelligence are more closely integrated, such as virtual reality, augmented reality, artificial intelligence and other functions can be well realized [22]. Promoted by these emerging materials and integration technologies, coupled with new theories proposed by experts, the long-term evolution of 6G will lead to new breakthroughs that are completely different from previous eras.

At the same time, software and open-source trends are pouring into the field of mobile communications. In the future 6G era, new methods as software-defined-radio (SDR) and software-defined networking (SDN) are expected to enter a mature stage, which means that from 5G to 6G, the upgrade of telecommunication infrastructure is more convenient, which can be achieved based on cloud resources and software upgrades [23].

Physical Structures of IRS

Briefly speaking, Intelligent Reflecting Surface (IRS) can be described as just flat surfaces consisting of low-cost passive reflective elements placed between the base station and the user (i.e. from the transmitter to the receiver) shown in Fig.1. Each element is capable of independently changing the amplitude of the incident signal. As for its concrete structure physic layers, it can be divided into three parts to explain [23].

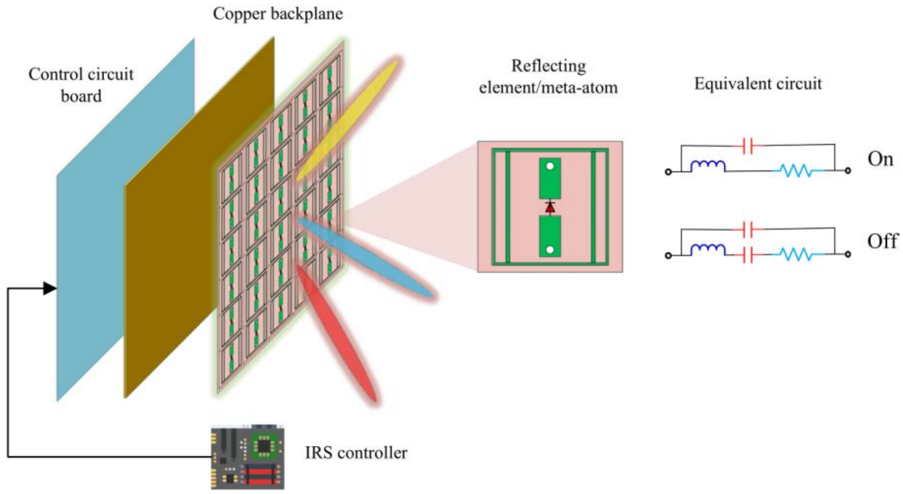

Fig1. Basic IRS model

Cited from R. Zhang's work in 2020 [12]

The first physic layer of IRS is the surface contacting with the electromagnetic waves directly, on which there are a lot of reflecting units working, which are able to control the phase of the reflecting units in order to adjust the direction of the incident waves.

The second layer is called as contact backplane, which is mainly for preventing the leakage of electromagnetic wave signals behind the reflecting surface which improves the reflective efficiency. It is a protective component of the whole structure.

The third layer is used to modulate the reflective surface and the controller, which can be made of FPGA (Field Programmable Gate Array) to regulate the phase shift of the reflective unit on the surface by controlling the transmitted signal; or the controller (such as installing some sensors on it) can also be used for sensing the environments, which can help the IRS to switch between reflective mode and intelligent awareness. For instance, the reflecting unit consists of a diode, is adjusted to obtain a 1-bit phase switch (e.g. 0 and π) by means of the diode bias voltage.

The essential difference between IRS and existing communication relays is "reflecting". Traditional relays can be summarized as "transmitting, and receiving" in essence, with few reference to the concept of “reflection”. However, IRS depends on pure reflection, the place of its innovation is the term - “reflecting.”

The term “intelligent” in IRS also has a double meaning: the hardware is reconfigurable in terms of intelligent reflecting units. The software is also intelligent in terms of signal processing, beamforming design, artificial intelligence, and convex optimisation.

	IRS	**AF Relay**	**DF Relay**	**Full-duplex Relay**
With RF Chains?	No	Yes	Yes	Yes
SP Capability?	No	No	Yes	Yes
Noise?	No	Yes	Yes	Yes
Duplex	Full	Half	Half	Full
Hardware cost	Low	Median	High	Very high
Power Consumption	Low	Median	High	Very high

Fig.2 IRS vs. Relays in some characteristics

Cited from C.Pan’s work in 2020

Types of Intelligent Reflecting Surface: Active and Passive

Traditional passive IRS

Traditional passive IRS is composed of passive components, each of which only reflects the input signal (such as phase shift, amplitude modulation) without transmitting the signal. [24] Under the dense component deployment, IRS may be regarded as a continuous surface, each point is capable of receiving and reflecting signals, which can be controlled by software to complete the intelligent configuration of the wireless system. Passive IRS almost conducts no power consumption. Ideally, it hardly consumes any energy source. It is not affected by receiver noise and power amplifier devices when it receives signals, which reduces the processing and amplification of noise. Passive IRS is also by far the most common type.

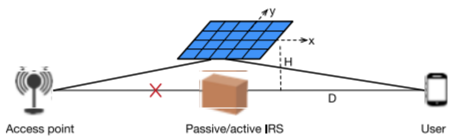

Fig.3 An IRS-aided wireless communication systems, with active or passive IRS

Cited from C. You's work in 2021 [13]

Active IRS

In fact, most existing IRS operates in a passive state. Therefore, it is only able to reflect signals from passive loads. Passive IRS operates in full-duplex (FD) mode with no amplification noise or self-interference effects [24]. It has a higher frequency spectrum and is more energy-efficient than some traditional active relays. However, a new IRS has recently been proposed as a latecomer called active IRS. Active IRS uses low-cost, easy-to-implement hardware to amplify the reflected signal which is able to overcome a major of the other problems that exist with passive IRS, such as signal phase adjustment. Active IRS consists of a number of active reflective elements, including some negative resistive elements such as negative impedance converters, asymmetric current reflectors, etc, which are all capable of amplifying the power of the incident signal [25]. As for active RIS, the noise introduced by active devices is not as negligible as passive IRS. Therefore, its signal model is also significantly different from passive IRS.

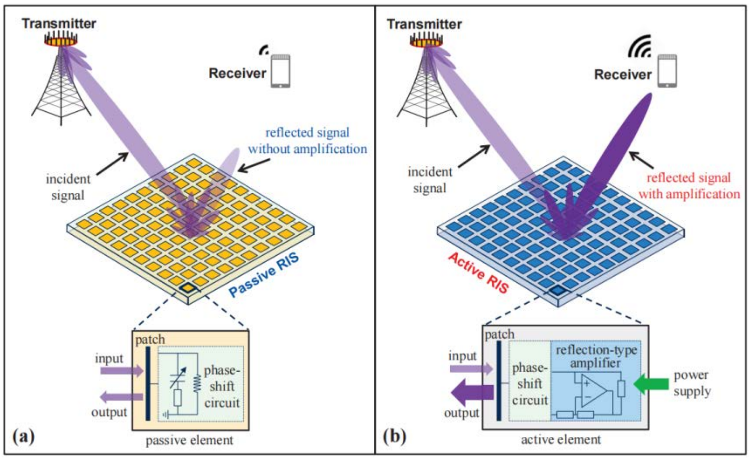

Fig.4 Comparison between (a) the existing passive and (b) the proposed active IRS (RIS).

Cited from R. Schober's work in 2021 [14]

IRS Hardware Implementation

In practice, the communication quality of wireless systems still depends on the performance of channels. Referring to the theories of wireless communication, the electromagnetic waves will be influenced by reflection, diffraction and path loss in the wireless channel before it reaches the receiver. In traditional perspectives, the channel is considered to be unpredictable and cannot be adjusted. Thus a probabilistic model is usually established for the channel estimation. Overall, most of the communication technologies proposed in many research work such as system diversities, and channel coding, is applied to cancel the influence of the channel without changing it [27].

How to achieve IRS hardware regulation? The discovery of hardware devices related to IRS is mainly concentrating on the new theory of "metasurface". Specifically, the designer can modify the amplitude and phase shift of its reflection accordingly by appropriately designing the elements, including shape, size, orientation, order of arrangement, etc. As for applications in wireless communication systems, the reflection coefficient of the unit is adjustable to adapt to the dynamic wireless channel generated by the users, which requires real-time reconfiguration. At this time, PIN diodes in analog circuits [22] are put to good use. It is in each element that controls its bias voltage via the DC feed line and then switches it between "on" and "off" - two status shown in the equivalent circuit, resulting in a phase shift difference. Therefore, the phase shifts of the IRS elements may be achieved independently through a software controller [28].

In addition, the amplitude of the reflected signal needs also to be regulated. In the design of its hardware, variable resistive loads are generally chosen to regulate the amplitude. Variable loads allow the resistance in each element to be changed so that different parts of the incident signal energy are dissipated, achieving a controlled reflection amplitude. For the practical user, the amplitude and phase of each element must be able to be adjusted effectively. Thus the designer must effectively reduce the size (integration) of the circuit used for this function [29]. This is necessary to meet the requirements of large-scale IRS configurations.

However, the hardware implementation of IRS research just stays at the stage of simulation. In other words, this depends on experimental verification of the results of theoretical analysis so far. It is not exactly accurate because it is out of the realm of practical application. Therefore, the hardware implementation of IRS is still a long way off. The first thing to prove is the consistency between the practice and simulation results. Only when this is secured will the IRS have a chance to play its part in the future [18].

Significance of Information Security

It is generally accepted that information security refers to the reliability and survival of the communication network itself (i.e. the bearer network and the service network) in the process of information delivery using the services provided by the network. Different interpretations of network security can be made from different perspectives. In a general sense, network security refers to both information security and control security. The international standards define information security as "the integrity, availability, confidentiality and reliability of information".

Recently, the popularity and evolution of communication systems have changed the way people communicate with information and communication networks, as a major carrier of information transfer, are closely related to a variety of social and economic life in the process of promoting information technology. On the one hand, this connection brings great social and economic value. However, on the other hand, it also means great potential danger. In the event of a security incident in the communication network, there is a risk that communication between thousands of people may be blocked, bringing unforeseen losses in social and economic value. When it comes to the future development prospects of information security, first of all, we consider the relationship between information rate and information security. In the future, information transmission will be high-speed and instantaneous. How to ensure at the same time high speed and confidentiality of the best communication will become a top priority. In addition, the emergence of the IRS will also bring new challenges to information security. IRS as a benchmark in the new generation of communication technology, because of its integration and easy installation characteristics, is bound to be the first to bear the brunt. Therefore, the importance of information security in the future is indeed self-evident [4].

System Model

First, set up an IRS-aided MISO security communication system with a single user (in Fig.4). This system consists of a base station (BS) containing M antennas, an IRS reflector element, a single-antenna user and an active eavesdropper. The IRS contains N reflectors connected to the base station through an IRS controller whose parameters can be regulated. The IRS first receives the signals from the base station, reflecting the hybrid signal to the receiving end of user through the planar array source. In this case, the received signal of the user and the eavesdropper should include both the direct link signal from the base station to the user or eavesdropper and the indirect link signal from the base station to them through the IRS. Assuming that the coefficients of these channels from the base station to IRS, from IRS and the base station to user, from the IRS and base station to the eavesdropper are $\mathbf{H_{BI}} \in C^{N\times M}$, $\mathbf{h_{BU}} \in C^{M\times 1}$, $\mathbf{h_{IU}} \in C^{N\times 1}$, $\mathbf{h_{IE}} \in C^{N\times 1}$ and $\mathbf{h_{BE}} \in C^{M\times 1}$ respectively:

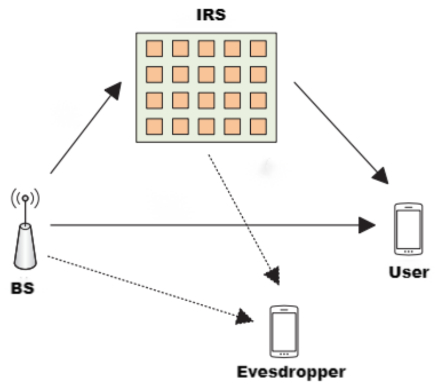

Fig. 5 An IRS-assisted MISO system with an active eavesdropper (AN assisted)

Furthermore, to guarantee secure communication, the BS generates and transmits a vector $\mathbf{z} \in \mathbf{C^M}$ to disturb eavesdroppers. In general, the vector $\mathbf{z}$ is modeled as a complex Gaussian random vector with zero mean, and the covariance matrix $\mathbf{Z} \in \mathbf{H^M}$, $\mathbf{Z} \geq 0$ .While the base station transmits a message to the user, then the user receives the signals from both BS and the IRS.Therefore, the signal received by the user and the eavesdropper is:

$$y_{user} = \mathbf{h_{IU}}^{H}\Theta\mathbf{H_{BI}}\,(\mathbf{wx} + \mathbf{z}) + \mathbf{h_{BU}}^{H}\mathbf{w(x+z)} + n_u \quad (1)$$

$$y_{eavesdropper} = \mathbf{h_{IE}}^{H}\Theta\mathbf{H_{BI}}\,(\mathbf{wx} + \mathbf{z}) + \mathbf{h_{BE}}^{H}\mathbf{w(x+z)} + n_e \quad (2)$$

According to the Shannon formula, data rate of the user is:

$$\mathrm{R_u} = \log_2\left(1+\frac{(\mathbf{h}_{\mathbf{IU}}^{\mathbf{H}}\mathbf{\Theta}\mathbf{H}_{\mathbf{BI}}+\mathbf{h}_{\mathbf{BU}}^{\mathbf{H}})\mathbf{W}(\mathbf{H}_{\mathbf{BI}}{}^{\mathbf{H}}\mathbf{\Theta}^{\mathbf{H}}\mathbf{h}_{\mathbf{IU}}+\mathbf{h}_{\mathbf{BU}})}{\mathrm{Tr}(\mathbf{H}_{\mathbf{BI}}{}^{\mathbf{H}}\mathbf{\Theta}^{\mathbf{H}}\mathbf{h}_{\mathbf{IU}}^{\mathbf{H}}\mathbf{h}_{\mathbf{IU}}\mathbf{\Theta}\mathbf{H}_{\mathbf{BI}}\mathbf{Z})+\sigma_U^2}\right) \tag{3}$$

Data rate of the eavesdropper is:

$$\mathrm{R_e} = \log_2\left(1+\frac{(\mathbf{h}_{\mathbf{IE}}^{\mathbf{H}}\mathbf{\Theta}\mathbf{H}_{\mathbf{BI}}+\mathbf{h}_{\mathbf{BE}}^{\mathbf{H}})\mathbf{W}(\mathbf{H}_{\mathbf{BI}}{}^{\mathbf{H}}\mathbf{\Theta}^{\mathbf{H}}\mathbf{h}_{\mathbf{IE}}+\mathbf{h}_{\mathbf{BE}})}{\mathrm{Tr}(\mathbf{H}_{\mathbf{BI}}{}^{\mathbf{H}}\mathbf{\Theta}^{\mathbf{H}}\mathbf{h}_{\mathbf{IE}}^{\mathbf{H}}\mathbf{h}_{\mathbf{IE}}\mathbf{\Theta}\mathbf{H}_{\mathbf{BI}}\mathbf{Z})+\sigma_E^2}\right) \tag{4}$$

Thus, the secrecy rate can be written as:

$$\mathrm{R_s} = \mathrm{R_u} - \mathrm{R_e} \tag{5}$$

The total power transmit budget of this system can be written as:

$$\mathrm{P_{total}} = (\mathbf{W}^2 + \mathrm{P_{cost}}) \tag{6}$$

Problem Formulation

In order to improve data transfer rate and energy utilization, a resource allocation problem to maximize energy efficiency is established as follows:

$$\max_{W,\ \Theta} \frac{R_U(\mathbf{W},\mathbf{\Theta})}{P_{total}} \tag{7}$$

$$\text{s.t.} \quad C_1 : R_S \geq R_{min} \tag{8}$$

$$C_2 : \|\mathbf{w}\|^2 + \mathrm{Tr}\,(\mathbf{Z}) \leq P_{\max} \tag{9}$$

$$C_3 : 0 \leq \mathbf{\Theta_n} \leq 2\pi, \forall n = 1,2,\cdots,N \tag{10}$$

$$C_4 : \mathbf{Z} \geq \mathbf{0} \tag{11}$$

Where C_1 is to keep the minimum secrecy rate greater than threshold. C_2 represents the maximum transmitting power constraint of the base station. C_3 represents the phase shift constraint of the intelligent reflecting surface. C_4 is the requirement of the artificial noise (AN). Obviously, Equation (7) is a nonlinear optimization problem with multi-variable coupling. It is hard to obtain the global optimal solution directly.

Solution

In an IRS system, the alternating iteration method is widely uesd to solve the beamforming vector and phase shift problem [1]-[6]. Since the relationship between the beamforming vector emitted by the base station and the phase shift of the smart reflecting surface is strongly coupled. Therefore, conducting the following algorithm ,which first fix the phase shift **Θ** to solve the beamforming vector **W**, and then fix the beamforming vector **W** to obtain the phase shift **Θ** [1]-[4].

Subproblem 1

Fix the phase shift Θ to solve the beamforming vector W

When the phase shift is fixed, the process of beamforming vector design can be write in this form:

$$\max_{w} \frac{B\log_2\left(1+K_U(w)\right)}{w^H w+P_{cost}} \quad (12)$$

$$C_2 : \| w \|^2 + Tr(z) \leqslant P_{\max} \text{ s.t. } \overline{C_1} : \log_2 \frac{1+K_U(w)}{1+K_E(w)} \geqslant R_{\min}$$

In this subproblem, the original problem (7) can be re-represented as the above formula.

Among the above formula:

$$K_U(w) = w^H \Phi_n w$$
$$K_E(w) = w^H \Phi_E w$$

$$\Phi_U = \frac{\left|\left(h_{IU}{}^H \Theta H_{BI} + h_{BU}^H\right)\right|^2}{\mathrm{Tr}(H_{BI}^H \Theta^H h_{IU}{}^H h_{IU} \Theta H_{BI} Z) + \sigma_U^2}$$
$$\Phi_E = \frac{\left|\left(h_{IE}{}^H \Theta H_{BI} + h_{BE}^H\right)\right|^2}{\mathrm{Tr}(H_{BI}^H \Theta^H h_{IE}{}^H h_{IE} \Theta H_{BI} Z) + \sigma_E^2}$$

Equation (12) is still non-convex. Therefore, it is necessary to use successive convex approximation (SCA) method to obtain the approximation first, and then use Dinkelbach method to transform the fraction into parameter subtraction.

To maximize the energy efficiency, we first introduce auxiliary variables j and k.

Thus:

$$\log_2\left(1 + \frac{j}{k}\right) = \log_2(j+k) - \log_2(k) \qquad (14)$$

In this $K_U(w) = j/k$

Then we use SCA method, first set up an upper bound

$$\log_2(j) \le C^{(t)} \qquad (15)$$

According to the Taylor expansion:

$$\text{If } f''(x) \le 0, f(x) \le f(x_0) + f'(x_0)(x - x_0) \qquad (16)$$

The above equation holds if the function is differentiable second order at x_0, and the equality sign holds if and only if $x=x_0$

Define f (x) = $\log_2$ (j)

Then we calculate the first and second order of the Taylor expansion:

$$f'(x) = \frac{1}{j\ln(2)'}$$
$$f''(x) = -\frac{1}{j^2\ln(2)} < 0.$$

Therefore, according to the first-order Taylor approximation:

$$\log_2(j) \leq \log_2\left(j^{(t)}\right) + \frac{1}{j^{(t)}\ln(2)}\left(j - j^{(t)}\right) = C^{(t)}.$$

where the equality holds when j is equal to $j^{(t)}$. $C^{(t)}$ is the Taylor series of $\log_2(j)$ in the t-th iteration. $j^{(t)}$ is the value of j which has been processes t-th iteration. Then we use $C^{(t)}$ to replace the upper bound.

Then formula (12) can be written as

$$\max_{w} \frac{\log_2(j+k) - C^{(t)}}{\mathrm{Tr}(\boldsymbol{W}) + P_{cost}} \tag{17}$$

At this time, using Dinkelbach method to turn this fraction into a subtraction. In this case, the system energy efficiency η is defined. When η is given, the corresponding beamforming vector w in (9) can be solved.

$$\max_{w} B\log_2(j+k) - C^{(t)} - \eta\left(w^H w + P_{cost}\right) \tag{18}$$

$$\text{s.t. } \bar{C}_1 : log_2 \frac{(j+k) - C^{(t)}}{1 + K_E(w)} \geqslant R_{\min}$$

$$C_2 : \|w\|^2 + \mathrm{Tr}(z) \leqslant P_{\max}$$

Then at this point, we define $\boldsymbol{W} = \boldsymbol{w^H w}$

$$\max_{w} B\,\mathrm{lb}(1 + \mathrm{Tr}(\Phi_{\mathrm{U}}\boldsymbol{W})) - \eta(\mathrm{Tr}(\boldsymbol{W}) + P_{\mathrm{c}}) \tag{19}$$

$$s.t.\ \widetilde{\mathrm{C}}_1 : \mathrm{Tr}(\Phi_{\mathrm{U}}\boldsymbol{W}) - 2^{R_{\min}}\,\mathrm{Tr}(\Phi_{\mathrm{E}}\boldsymbol{W}) \geqslant 2^{R_{\min}} - 1$$

$$\widetilde{\mathrm{C}_2} : \mathrm{Tr}(\boldsymbol{W}) + \mathrm{Tr}(\boldsymbol{Z}) \leqslant P_{\max}$$

$$\mathrm{C}_4 : \mathrm{Rank}(\boldsymbol{W}) \leq 1$$

The above problem is a standard SDP problem The constraint C_4 is a non-convex rank constraint that makes the problem difficult, and the semi-definite relaxation (SDR) method is used to eliminate the constraint. Consequently, problem (19) can be solved by the convex optimization solver such as CVX. For a detailed procedure for the proof of the rank constraint, it isin the appendix for details.

Subproblem 2

Fix the beamforming vector W to solve the phase shift Θ

After the beamforming vector **W** in subproblem 1 is defined, we use this **W** to solve the phase shift Θ.

First, we should define sorts of new variables:

$$\boldsymbol{\alpha}_{\text{user}} = \mathbf{h}_{\mathbf{BU}}{}^{\mathbf{H}}\mathbf{w}$$

$$\boldsymbol{\alpha}_{\text{eavesdropper}} = \mathbf{h}_{\mathbf{BE}}{}^{\mathbf{H}}\mathbf{w}$$

$$\beta_{\text{user}} = \mathbf{diag}\{\mathbf{h}_{\mathbf{IU}}{}^{\mathbf{H}}\}\mathbf{H}_{\mathbf{BI}}\mathbf{w}$$

$$\beta_{\text{eavesdropper}} = \mathbf{diag}\{\mathbf{h}_{\mathbf{IE}}{}^{\mathbf{H}}\}\mathbf{H}_{\mathbf{BE}}\mathbf{w}$$

In this case, the communication rate of both user and eavesdropper side are represented as in this way:

$$R_{\mathrm{U}} = B\log_2\left(1 + \frac{\left|\boldsymbol{q}^{\mathrm{H}}\boldsymbol{\alpha}_{\text{user}} + \beta_{\text{user}}\right|^2}{\mathrm{Tr}\left(H_{BI}^{H}\Theta^{H}h_{IU}^{H}h_{IU}\Theta H_{BI}Z\right) + \sigma_{\mathrm{U}}^2}\right)$$

$$R_{\mathrm{E}} = B\log_2\left(1 + \frac{\left|\boldsymbol{q}^{\mathrm{H}}\boldsymbol{\alpha}_{\text{eavesdropper}} + \beta_{\text{eavesdropper}}\right|^2}{\mathrm{Tr}\left(H_{BI}^{H}\Theta^{H}h_{IE}{}^{H}h_{IE}\Theta H_{BI}Z\right) + \sigma_{\mathrm{E}}^2}\right)$$

At this time, introducing an auxiliary variable $\mathbf{q} = [\ \mathbf{q}^{\mathbf{H}} \quad 1\ ]$, then the problem (7) can be written as：

$$\max_{\bar{q}} \frac{B\,\mathrm{lb}\left(1 + \overline{\boldsymbol{q}}^{\mathrm{H}}\boldsymbol{G}_{\mathrm{U}}\overline{\boldsymbol{q}}\right)}{P_{\text{total}}} \tag{20}$$

$$s.t.\ \hat{\mathrm{C}}_1 : \mathrm{Tr}\left(\overline{\boldsymbol{q}}^{\mathrm{H}}\boldsymbol{G}_{\mathrm{U}}\overline{\boldsymbol{q}}\right) - 2^{R_{\min}}\,\mathrm{Tr}\left(\overline{\boldsymbol{q}}^{\mathrm{H}}\boldsymbol{G}_{\mathrm{E}}\overline{\boldsymbol{q}}\right) \geqslant 2^{R_{\min}} - 1$$

$$\widehat{\mathrm{C}}_3 : |\bar{q}_m| = 1, \forall m = 1, 2, \cdots, N+1$$

Among these, the terms in the above equation are:

$$\boldsymbol{G}_{\mathrm{U}} = \frac{1}{\sigma_{\mathrm{U}}^2}\begin{bmatrix} \boldsymbol{a}_{\mathrm{user}}\boldsymbol{\alpha}_{\mathrm{user}}{}^{\mathrm{H}} & \boldsymbol{\alpha}_{\mathrm{user}}\,\beta\,{}^{\mathrm{H}}_{\mathrm{user}} \\ \beta\,{}_{\mathrm{user}}\boldsymbol{\alpha}^{\mathrm{H}}_{\mathrm{user}} & \beta\,|_{\mathrm{user}}|^2 \end{bmatrix}$$

$$\boldsymbol{G}_{\mathrm{E}} = \frac{1}{\sigma_{\mathrm{E}}^2}\begin{bmatrix} \boldsymbol{\alpha}_{\mathrm{eavesdropper}}\boldsymbol{\alpha}^{\mathrm{H}}_{\mathrm{eavesdropper}} & \boldsymbol{\alpha}_{\mathrm{eavesdropper}}\,\beta^{\mathrm{H}}_{\mathrm{eavesdropper}} \\ \beta_{\mathrm{eavesdropper}}\boldsymbol{\alpha}^{\mathrm{H}}_{\mathrm{eavesdropper}} & \beta|_{\mathrm{eavesdropper}}|^2 \end{bmatrix}$$

$$\left|\boldsymbol{q}^{\mathrm{H}}\boldsymbol{\alpha}_{\mathrm{user}} + \beta\,{}_{\mathrm{user}}\right|^2 = \overline{\boldsymbol{q}}^{\mathrm{H}}\boldsymbol{G}_{\mathrm{U}}\overline{\boldsymbol{q}}$$

$$\left|\boldsymbol{q}^{\mathrm{H}}\boldsymbol{\alpha}_{\mathrm{eavesdropper}} + \beta\,{}_{\mathrm{eavesdropper}}\right|^2 = \overline{\boldsymbol{q}}^{\mathrm{H}}\boldsymbol{G}_{\mathrm{E}}\overline{\boldsymbol{q}}$$

Under this condition, problem (20) can be written as:

$$\max_{Q} \frac{B\log_2(1+\mathrm{Tr}(\boldsymbol{Q}\boldsymbol{G}_U))}{P_{\mathrm{total}}} \tag{21}$$

$$s.t.\, \widetilde{\mathrm{C}}_1 : \mathrm{Tr}(\Phi_{\mathrm{U}}\boldsymbol{W}) - 2^{R_{\min}}\,\mathrm{Tr}(\Phi_{\mathrm{E}}\boldsymbol{W}) \geqslant 2^{R_{\min}} - 1$$

$$\widehat{\mathrm{C}}_2 : \boldsymbol{Q}(n,n) = 1$$
$$\mathrm{C}_3 : \mathrm{Rank}(\boldsymbol{Q}) = 1$$

The solution method of problem (21) is roughly the same. CVX can be used to find the optimal solution. However, after adopting the SDR method for the rank constraint in problem (16), the rank-one solution is not obtained. Therefore that we adopt SVD to obtain the solution we need. For the energy efficiency problem of fractions, we usually use SCA, Dinkelbach method and SCA-SDR method to solve it. Among them, Dinkelbach method is really effective in solving the optimal solution of energy efficiency, which can increase the accuracy and reduce the complexity. The requirement for the number of iterations should be controlled within 10, i.e., the maximum value of iterations i_m=10.

Summary of the algorithm

In summary, the energy efficiency maximization algorithm using alternating iterations can be summarized as the following steps:

Step 1 Initialization :IRS phase shift defined as $q^0 = (q^0{}_1, q^0{}_2 ... ,q^0{}_N)$, the initial iteration number $i_0 = 0$, the maximum number $i_m = 10$, the initial energy efficiency value $\eta_0 = 0$, and the convergence accuracy is $\varepsilon = 10^{-5}$.

Step 2 Successive Convex Approximation (SCA method) Algorithm*

Step 3 for i = 0,1,…,do.

Step 3.1 The beamforming vectors $\mathbf{w}_i$ are obtained by solving problem (10) according to the given phase shift $\boldsymbol{q}^{i-1}$ and energy efficiency η_i 。

Step 3.2 Using SDR, $\mathbf{W}_i$ is a SDP problem can be solved by CVX .

Step 3.3 Using $\boldsymbol{w}_i$ to solve the formula (21) to get the phase shift solution $\boldsymbol{Q}_i$ by CVX

Step 3.4 Processing SVD method of $\boldsymbol{Q}_i = \boldsymbol{U}_i \boldsymbol{\Sigma} \boldsymbol{U}_0$ to get $\boldsymbol{q}_i$

Step 4 if the value of objective function in problem (21) converges

break

else

i= i+1

end

Step 5 end

Note: i is not exceeding i_m。

Simulation and Results

In order to verify the effectiveness of this algorithm in practical applications, a simulation of the algorithm is required. Firstly, we build a simulation model based on *Q. Wu*'s work as shown in Fig 6. This simulation focuses on the results of the average energy efficiency under different number of antennas, maximum transmit power budge, different number of IRS elements reflectors and the conditions where is an eavesdropper. The base station is at the same level as the IRS, and the user and the eavesdropper are also at the same level. Denote the horizontal distance between the base station and user by d. Throughout the simulation results, we focus our attention on the relationship between overall energy efficiency and overall power budget, how this algorithm compares to the baseline scenario, and how user additions and subtractions change the energy efficiency. Focusing on the energy efficiency performance of this algorithm in the IRS system.

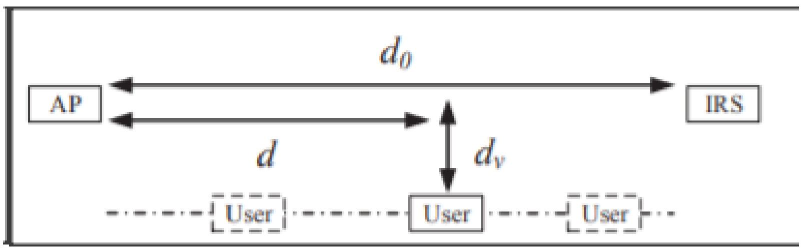

Fig.6 Initial system model (without eavesdropper)

Cited from Q.Wu's work in 2021 [4]

The distance from the base station to the user is $d_{BU} = d^2 + d_v^2$, the distance to the eavesdropper is $d_{BE} = d^2{}_{hE} + d_v^2$, the distance from the IRS to the user is $d_{IU} = (d_{BI}\text{-}d)^2 + d^2$, and the distance to the eavesdropper is $d_{IE} = (d_{BI}\text{-}d_{hE})^2 + d^2$. The defined path loss is $L\,(d)= T_0\,(d/d_0)^{-\alpha}$. T_0 = -10dB denotes the path loss at a distance of d_0 = 1 m. Then d denotes the communication link distance and $\boldsymbol{\alpha}$ represents the path loss index. $\boldsymbol{\alpha}_{BU} = \boldsymbol{\alpha}_{BE} = 6$ for the path loss from the base station to the user and the eavesdropper, $\boldsymbol{\alpha}_{BI} = \boldsymbol{\alpha}_{IU} = \boldsymbol{\alpha}_{IE} = 4$ for the path loss from the base station to the IRS and from the IRS to the user and the eavesdropper, respectively.

The simulation parameters are shown below**.**

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
σ^2_U	-80	L	30/60	α_{BI}	4	d_{BI}	51
σ^2_E	-80	α_{BU}	6	α_{IE}	4	d_v	2
N_t	3/6/9	α_{BE}	6	α_{IU}	4	d_{HE}	20

Table 1 simulation parameters and values

Fig. 7 shows that the relationship between the energy efficiency of the user and the maximum power budget for different number of antennas. As shown in the figure, in the proposed scheme, with the continuous increase of the maximum power budget threshold, the energy efficiency of users also gradually increases, and finally tends to be flat. Compared with the baseline scheme, the energy efficiency of users will not decline rapidly after increasing to the threshold, which reflects the superiority of this scheme. The reason is that when the transmission power budget of the base station increases, the power it can allocate to the users also increases, which will increase the transmission rate at the same time, resulting in the energy efficiency of the user side gradually increases with the power threshold. Energy efficiency will eventually level off due to saturation effects.

Besides, the increasing number of transmitting antennas improves the accuracy of beamforming. Therefore, the energy efficiency will increase with the number of antennas. However, while the number of transmitting antennas exceeds a constant value, then the effect of increasing the amount of antennas N_T will no longer be significant. This is because the channel capacity grows logarithmically with respect to N_T, and because of the nature of the logarithmic function, this will make the increase less obvious.

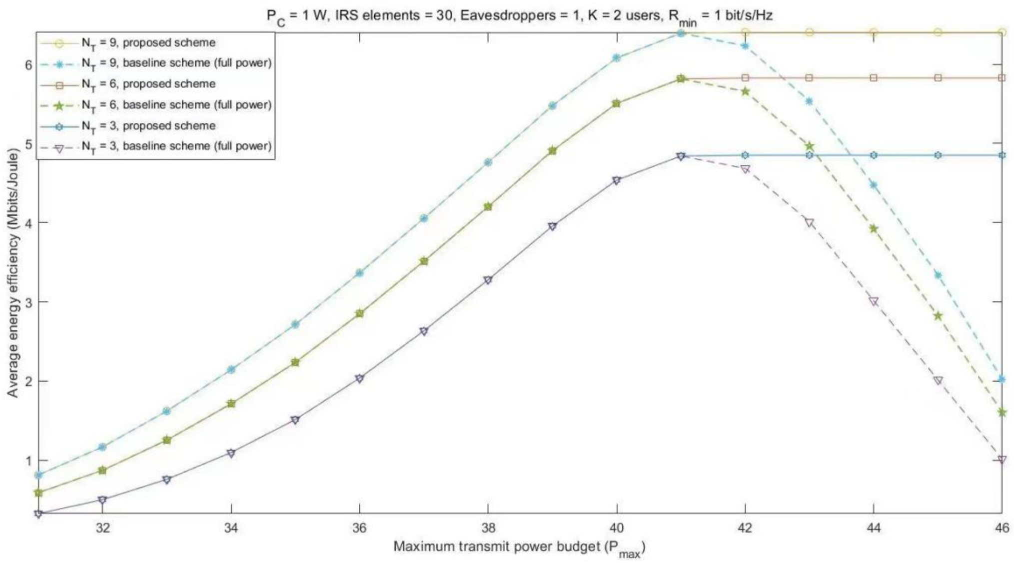

Fig. 7 Relationship between average energy efficiency and maximum transmit power budget (under different numbers of antennas)

Fig 8 indicates that the the average energy efficiency under the condition of increasing number of users when the number of antennas and IRS elements changes. Assume there is an eavesdropper. When the the number IRS elements of 30, the users can reach an average energy efficiency up to 6.8. However, if it increase to 60, users can reach an efficiency improved to 7.5. This shows that average efficiency can be increased when the number of element is doubled. The reason of this situation is that the number of elements increased means that more elements received signal energy from the base station. When the number of re-users is less than 3, with the increase of the number of users, the system energy efficiency will reach the peak when the number of users is 3. Then as the number of users grows, the energy efficiency will decline.

To sum up, it can be seen from the existing simulation results that even if increasing the transmission power budget can improve the overall energy efficiency to a certain extent, it cannot be increased without limit. It could also lead to a rapid decline in efficiency. The same is true for increasing the number of antennas N_T. When the number of antennas increases beyond a certain point, the efficiency gains are no longer significant.

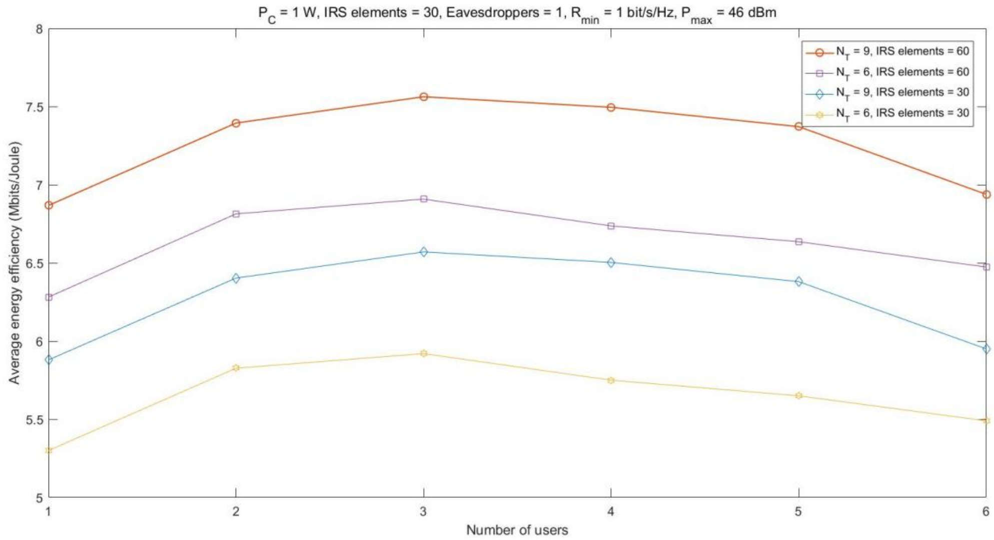

Fig. 8 Relationship between average energy efficiency and numbers of users (under different numbers of antennas and IRS elements)

Conclusion

This report is based on the IRS simulation model proposed by *Derrick Ng* [1] and *Q.Wu* [16], as well as the algorithm model proposed by *Q. Liu* [4], which is extended and improved on this basis. For the first half of the algorithm, the SCA algorithm steps are added to enable it to be applied in a variety of scenarios. In the theory of communication technology, IRS research results can only be said to be at the surface stage. Energy efficiency has been a lingering issue for MISO cellular communication systems. Only by focusing on energy efficiency can we lay the foundation for deep thinking about other performance. In other words, energy efficiency is the leading parameter in the research of communication systems. In this paper, the design of a beamforming vector based on the energy efficiency requirements of MISO cellular systems is studied. In the presence of an eavesdropper, the energy efficiency maximization model is established under the conditions of the secrecy threshold rate and other constraints. Dinkelbach, as the core method in this algorithm, transforms the division formula into the addition and subtraction formula to calculate. After that, adopt the continuous alternating iteration method find the beamforming vector $\mathbf{W}$ and phase shift $\mathbf{\Theta}$. It can be seen from the simulation results that the algorithm shows considerable energy efficiency and stability under different number of users and different simulation parameters. Therefore, the algorithm has high security and reliability. The proposed algorithm has practical significance for the study of IRS, while further research is needed for the addition of other parameters and the existence of more constraints.

The difficulty in this algorithm lies in mathematical modeling. I found an appropriate method by consulting materials, referring to the literature provided by the professor, and adding my own extracurricular learning.

Future works

The study in this paper is based on the analysis of the channel parameters, the lack of the actual channel estimation, as well as the channel itself state error. Especially the channel estimation of MISO cellular systems with eavesdroppers needs to be studied in the future. In addition, the proposed algorithm research is based on energy efficiency maximization, and future research can be based on SNR or data rate, so that it can be applied to beam shaping algorithms that reflect overall optimization.

IRS is still in the critical stage of transformation from theoretical research to practical construction [2]. In fact, research and understanding of IRS is still in its infancy. The research on IRS and its hardware configuration is not mature. Therefore, it is difficult to combine theory with reality.

Appendix

One of the difficulties encountered in the design of the algorithm is the non-convex rank constraint. To prove that SDR is tight, Slater's constraints need to be satisfied. In fact, in optimization theory, the objective function is generally convex function. Therefore, how to eliminate the rank constraint and transform it into an SDP problem is the whole key.

In order to prove that SDR is tight, Karush-Kuhn-Tucker (KKT) conditions should be studied. Therefore, first write the Lagrangian function of the target:

$$\begin{aligned} L(\boldsymbol{W}, \lambda_1, \lambda_2) = -\log_2(j+k) - C^{(t)} + q[\mathrm{Tr}(\boldsymbol{W}) + P_{cost}] + \\ \lambda_1(\mathrm{Tr}(\boldsymbol{W}) + \mathrm{Tr}(\boldsymbol{Z}) - P_{\max}) + \lambda_2(R_{\min} - \log_2(j+k) - \\ C^{(t)}\Big) - \mathrm{Tr}(\boldsymbol{Y}\boldsymbol{W}) \end{aligned} \tag{22}$$

Where Y and λ_1, λ_2 are the dual variables corresponding to the constraints C4 and C1, C2, of the optimization problem. The Lagrangian derived above is used for solving dual problem of the initial one.

Therefore, the dual problem can be stated as:

$$\max_{Y, \lambda_1, \lambda_2} \inf_{W} L \tag{23}$$

The derivative of the dual function with respect to **W,** according to KKT conditions, when the Lagrange is equal to zero：

$$\frac{\partial L}{\partial \boldsymbol{W}} = q\boldsymbol{I} + \lambda_1 \boldsymbol{I} - \lambda_2 \,\mathrm{Tr}(\boldsymbol{\Phi}_U) - \boldsymbol{Y} \tag{24}$$

$$\boldsymbol{Y} = q\boldsymbol{I} + \lambda_1 \boldsymbol{I} - \lambda_2 \Phi_U \tag{25}$$

where I is an identity matrix including the following requirements:

$$\boldsymbol{Y} \succcurlyeq 0, \lambda_1, \lambda_2 \geq 0 \tag{26}$$

At this time, we further study the KKT condition and consider the complementary relaxation method. Complementary relaxation method shows that if a dual variable is greater than zero, its corresponding primal constraint must be equality constraint. Conversely, if the primal constraint is greater than zero, then the corresponding dual variable must be strictly equal.

$$\boldsymbol{Y}\boldsymbol{W} = 0 \tag{27}$$

The rank of the optimal beamforming matrix ***W*** will be not exceeding one when the rank of Y is exceeding the number of transmission antennas (dimension of W-1).

In order to solve the rank problem, rewrite the matrix as:

$$\boldsymbol{Y} = \boldsymbol{C} - \boldsymbol{H} \tag{28}$$

In this case, we need to prove that the matrix C is positive definite.

First of all, consider the case that B is a positive semi-definite matrix. When the B matrix is positive semi-definite, B exists a zero eigenvalue λ at least. Multiply both sides of the equation by a matrix $\boldsymbol{\Lambda} = \boldsymbol{\lambda\lambda^H}$.

Then take the trace of the matrix on both sides, and get the following equation:

$$\mathrm{Tr}\,(\boldsymbol{Y}\boldsymbol{V}) = -\mathrm{Tr}\,(\boldsymbol{H}\boldsymbol{V}) + \mathrm{Tr}\,(\boldsymbol{C}\boldsymbol{V})$$

$$= -\mathrm{Tr}\,(\boldsymbol{H}\boldsymbol{V})$$

Matrices **H** and $\boldsymbol{\Phi}_U$ are independent and Tr (***HV***) must be exceeding zero.

Actually, Tr (***YV***) is no less than thus the two inequalities contradict each other which proves matrix ***C*** is a positive definite matrix and full-rank. Rank (***C***) = N_T.

As for the solution of Rank (***Y***), first we talk about two matrices **P** and **Q** whose dimensions is equal. Due to theory of inequality and rank of matrices, the summation of rank between **P** and **Q** must be larger than the rank of the matrix (***P***+***Q***).

$$\mathrm{Rank}\,(\boldsymbol{P}) + \mathrm{Rank}\,(\boldsymbol{Q}) \geq \mathrm{Rank}\,(\boldsymbol{P} + \boldsymbol{Q}).$$

Therefore，

$$\mathrm{Rank}\,(\boldsymbol{P} + \boldsymbol{Q}) + \mathrm{Rank}\,(-\boldsymbol{Q}) \geq \mathrm{Rank}\,(\boldsymbol{P})$$

$$\mathrm{Rank}\,(\boldsymbol{P} + \boldsymbol{Q}) \geq \mathrm{Rank}\,(\boldsymbol{P}) - \mathrm{Rank}\,(\boldsymbol{Q})$$

Similarly, the rank of matrix ***Y*** can be solved as:

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

Consequently, $\mathrm{Rank}\,(\boldsymbol{W}) \leq 1$.

*** Successive Convex Approximation (SCA) Algorithm**

1. **Initialization**: Set **w**= $\mathbf{w_0}$, iteration global number i = 1, iteration variable C

2. **Repeat**

3. **Beamforming Optimization**: Initialize branch iteration number m = 1,j,k. Solve the objective function (17) for given j^i , then store the intermediate solution j, store $C^{(t)}$.

4. **Repeat**

5. Set i = i + 1, j^i = j, C = $C^{(t)}$

6. **Until** convergence.

7. Set j^*= j^t

References

[1] Xu, D., Yu, X., Sun, Y., Ng, D.W.K. and Schober, R., 2019, December. Resource allocation for secure IRS-assisted multiuser MISO systems. In 2019 IEEE Globecom Workshops (GC Wkshps) (pp. 1-6). IEEE.

[2] Yu, X., Xu, D., Ng, D.W.K. and Schober, R., 2021. IRS-assisted green communication systems: Provable convergence and robust optimization. IEEE Transactions on Communications, 69(9), pp.6313-6329.

[3] Yu, X., Xu, D., Sun, Y., Ng, D.W.K. and Schober, R., 2020. Robust and secure wireless communications via intelligent reflecting surfaces. IEEE Journal on Selected Areas in Communications, 38(11), pp.2637-2652.

[4] Liu, Q., Yang, J., Xu, Y., Li, G. and Sun, H., 2020, August. Energy-efficient resource allocation for secure IRS networks with an active eavesdropper. In 2020 IEEE/CIC International Conference on Communications in China (ICCC) (pp. 1-5). IEEE

[5] Hu, S., Wei, Z., Cai, Y., Liu, C., Ng, D.W.K. and Yuan, J., 2021. Robust and secure sum-rate maximization for multiuser MISO downlink systems with self-sustainable IRS. IEEE Transactions on Communications, 69(10), pp.7032-7049.

[6] Qi, Q., Chen, X. and Ng, D.W.K., 2019. Robust beamforming for NOMA-based cellular massive IoT with SWIPT. IEEE Transactions on Signal Processing, 68, pp.211-224.

[7] Cai, Y., Wei, Z., Li, R., Ng, D.W.K. and Yuan, J., 2020. Joint trajectory and resource allocation design for energy-efficient secure UAV communication systems. IEEE Transactions on Communications, 68(7), pp.4536-4553.

[8] Wu, Q., Xu, J., Zeng, Y., Ng, D.W.K., Al-Dhahir, N., Schober, R. and Swindlehurst, A.L.,

2021. A comprehensive overview on 5G-and-beyond networks with UAVs: From communications to sensing and intelligence. IEEE Journal on Selected Areas in Communications.

[9] Wei, Z., Yang, L., Ng, D.W.K., Yuan, J. and Hanzo, L., 2019. On the performance gain of NOMA over OMA in uplink communication systems. IEEE Transactions on Communications, 68(1), pp.536-568.

[10] Sun, Y., Xu, D., Ng, D.W.K., Dai, L. and Schober, R., 2019. Optimal 3D-trajectory design and resource allocation for solar-powered UAV communication systems. IEEE Transactions on Communications, 67(6), pp.4281-4298.

[11] Liu, C., Liu, X., Ng, D.W.K. and Yuan, J., 2021. Deep residual learning for channel estimation in intelligent reflecting surface-assisted multi-user communications. IEEE Transactions on Wireless Communications, 21(2), pp.898-912.

[12] Cai, Y., Wei, Z., Hu, S., Liu, C., Ng, D.W.K. and Yuan, J., 2022. Resource Allocation and 3D Trajectory Design for Power-Efficient IRS-Assisted UAV-NOMA Communications. IEEE Transactions on Wireless Communications.

[13] Xu, W., Yang, Z., Ng, D.W.K., Levorato, M. and Eldar, Y.C., 2022. Edge Learning for B5G Networks with Distributed Signal Processing: Semantic Communication, Edge Computing, and Wireless Sensing. arXiv preprint arXiv:2206.00422.

[14] J. Chen, Y. Liang, Y. Pei, and H. Guo, “Intelligent reflecting surface:A programmable wireless environment for physical layer security,” arXivpreprint arXiv:1905.03689, 2019.

[15] Q. Wu and R. Zhang, “Weighted sum power maximization for intelligent reflecting surface aided SWIPT,” IEEE Wireless Commun. Lett., vol. 9,no. 5, pp. 570–590, May 2020.

[16] Q. Wu and R. Zhang, Intelligent reflecting surface enhanced wireless network:joint active and passive beamforming design[C] / / Proceedings of IEEE Global Com- munications Conference (GLOBECOM). Abu Dhabi: IEEE,2018:1-6

[17] Hu, S., Liu, C., Wei, Z., Cai, Y., Ng, D. W. K., & Yuan, J. (2021). Beamforming Design for Intelligent Reflecting Surface-Enhanced Symbiotic Radio Systems. arXiv preprint arXiv:2110.10316.

[18] Khalili, A., Zargari, S., Wu, Q., Ng, D. W. K., & Zhang, R. (2021). Multi-objective resource allocation for IRS-aided SWIPT. IEEE Wireless Communications Letters, 10(6), 1324-1328.

[19] Hui, S. Y., & Yeung, K. H. (2003). Challenges in the migration to 4G mobile systems. IEEE Communications magazine, 41(12), 54-59.

[20] Frattasi, S., Fathi, H., Fitzek, F. H., Prasad, R., & Katz, M. D. (2006). Defining 4G technology from the users perspective. IEEE network, 20(1), 35-41.

[21] Saad, W., Bennis, M., & Chen, M. (2019). A vision of 6G wireless systems: Applications, trends, technologies, and open research problems. IEEE network, 34(3), 134-142.

[22] Letaief, K. B., Chen, W., Shi, Y., Zhang, J., & Zhang, Y. J. A. (2019). The roadmap to 6G: AI empowered wireless networks. IEEE communications magazine, 57(8), 84-90.

[23] Q. Wu and R. Zhang, “Towards Smart and Reconfigurable Environment: Intelligent Reflecting Surface Aided Wireless Networks,” IEEE Communications Magazine, January 2020.

[24] You, C., & Zhang, R. (2021). Wireless communication aided by intelligent reflecting surface: Active or passive?. IEEE Wireless Communications Letters, 10(12), 2659-2663.

[25] Zhang, Z., Dai, L., Chen, X., Liu, C., Yang, F., Schober, R., & Poor, H. V. (2021). Active RIS vs. passive RIS: Which will prevail in 6G?. arXiv preprint arXiv:2103.15154.

[26] Zhu, J., Ng, D. W. K., Wang, N., Schober, R., & Bhargava, V. K. (2017). Analysis and design of secure massive MIMO systems in the presence of hardware impairments. IEEE Transactions on Wireless Communications, 16(3), 2001-2016.

[27] Ning, B., Tian, Z., Chen, Z., Han, C., Yuan, J., & Li, S. (2021). Prospective beamforming technologies for ultra-massive MIMO in terahertz communications: A tutorial. arXiv preprint arXiv:2107.03032.

[28] Wu, Q., & Zhang, R. (2019, May). Beamforming optimization for intelligent reflecting surface with discrete phase shifts. In ICASSP 2019-2019 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP) (pp. 7830-7833). IEEE.

[29] Zhou, S., Xu, W., Wang, K., Di Renzo, M., & Alouini, M. S. (2020). Spectral and energy efficiency of IRS-assisted MISO communication with hardware impairments. IEEE Wireless Communications Letters, 9(9), 1366-1369.

[30] S. Li, B. Duo, M. D. Renzo, M. Tao, and X. Yuan, “Robust secure UAV communications with the aid of reconfigurable intelligent surfaces,” IEEE Trans. Wireless Commun., vol. 20, no. 10, pp. 6402–6417, Oct. 2021, doi: 10.1109/TWC.2021.3073746.

[31] C. Wu, S. Yan, X. Zhou, R. Chen, and J. Sun, “Intelligent reflecting surface (IRS)-aided covert communication with Warden’s statistical CSI,” IEEE Wireless Commun. Lett., vol. 10, no. 7, pp. 1449–1453, Jul. 2021.

[32] Xu, D., Yu, X., Sun, Y., Ng, D.W.K. and Schober, R., 2020. Resource allocation for IRS-assisted full-duplex cognitive radio systems. IEEE Transactions on Communications,

68(12), pp.7376-7394.

[33] Mu, X., Liu, Y., Guo, L., Lin, J. and Al-Dhahir, N., 2021. Capacity and optimal resource allocation for IRS-assisted multi-user communication systems. IEEE Transactions on Communications, 69(6), pp.3771-3786.

[34] Cai, Y., Wei, Z., Hu, S., Ng, D.W.K. and Yuan, J., 2020, June. Resource allocation for power-efficient IRS-assisted UAV communications. In 2020 IEEE International Conference on Communications Workshops (ICC Workshops) (pp. 1-7). IEEE.

[35] Khalili, A., Zargari, S., Wu, Q., Ng, D. W. K., & Zhang, R. (2021). Multi-objective resource allocation for IRS-aided SWIPT. IEEE Wireless Communications Letters, 10(6), 1324-1328.

[36] Zheng, B. and Zhang, R., 2021. IRS meets relaying: Joint resource allocation and passive beamforming optimization. IEEE Wireless Communications Letters, 10(9), pp.2080-2084.

[37] Cao, H., Li, Z. and Chen, W., 2021. Resource allocation for IRS-assisted wireless powered communication networks. IEEE Wireless Communications Letters, 10(11), pp.2450-2454.

[38] Chen, J., Xie, Y., Mu, X., Jia, J., Liu, Y. and Wang, X., 2022. Energy Efficient Resource Allocation for IRS Assisted CoMP Systems. IEEE Transactions on Wireless Communications.

[39] Forouzanmehr, M., Akhlaghi, S., Khalili, A. and Wu, Q., 2021. Energy efficiency maximization for IRS-assisted uplink systems: Joint resource allocation and beamforming design. IEEE Communications Letters, 25(12), pp.3932-3936

[40] Mohamed, Z. and Aïssa, S., 2021, March. Resource allocation for energy-efficient cellular communications via aerial IRS. In 2021 IEEE Wireless Communications and Networking Conference (WCNC) (pp. 1-6). IEEE.

[41] Zuo, J., Liu, Y., Qin, Z. and Al-Dhahir, N., 2020. Resource allocation in intelligent reflecting surface assisted NOMA systems. IEEE Transactions on Communications, 68(11), pp.7170-7183.

[42] Fu, H., Feng, S. and Ng, D.W.K., 2021, June. Resource allocation design for IRS-aided downlink MU-MISO RSMA systems. In 2021 IEEE International Conference on Communications Workshops (ICC Workshops) (pp. 1-6). IEEE.

[43] Rezaei, A., Khalili, A., Jalali, J., Shafiei, H. and Wu, Q., 2022. Energy-Efficient Resource Allocation and Antenna Selection for IRS-assisted Multi-Cell Downlink Networks. IEEE Wireless Communications Letters.

[44] Hua, M., Wu, Q. and Poor, H.V., 2022. Power-Efficient Passive Beamforming and Resource Allocation for IRS-Aided WPCNs. IEEE Transactions on Communications, 70(5), pp.3250-3265.

[45] Liu, Z., Zhao, S., Wu, Q., Yang, Y. and Guan, X., 2021. Joint trajectory design and resource allocation for IRS-assisted UAV communications with wireless energy harvesting. IEEE Communications Letters, 26(2), pp.404-408.

[46] Zhang, H., He, X., Wu, Q. and Dai, H., 2021, May. Spectral graph theory based resource allocation for IRS-assisted multi-hop edge computing. In IEEE INFOCOM 2021-IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS) (pp. 1-6). IEEE.

[47] Zhang, X., Zhang, H., Du, W., Long, K. and Nallanathan, A., 2022. IRS Empowered UAV Wireless Communication with Resource Allocation, Reflecting Design and Trajectory Optimization. IEEE Transactions on Wireless Communications.

[48] Zhao, D., Lu, H., Wang, Y., Sun, H. and Gui, Y., 2021. Joint power allocation and user association optimization for IRS-assisted mmWave systems. IEEE Transactions on Wireless Communications, 21(1), pp.577-590.

[49] Wang, D., Rezaei, F. and Tellambura, C., 2020. Performance analysis and resource allocations for a WPCN with a new nonlinear energy harvester model. IEEE Open Journal of the Communications Society, 1, pp.1403-1424.

[50] Li, X., Zhang, C., He, C., Chen, G. and Chambers, J.A., 2021. Sum-rate maximization in IRS-assisted wireless power communication networks. IEEE Internet of Things Journal, 8(19), pp.14959-14970.

[51] Lin, Y., Jin, S., Matthaiou, M. and You, X., 2021. Tensor-based algebraic channel estimation for hybrid IRS-assisted MIMO-OFDM. IEEE Transactions on Wireless Communications, 20(6), pp.3770-3784.

[52] Kassem, M., Hassan, H.A.H., Nasser, A., Mansour, A. and Yao, K.C., 2021, October. Users Selection and Resource Allocation in Intelligent Reflecting Surfaces Assisted Cellular Networks. In 2021 17th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob) (pp. 121-126). IEEE.

[53] Abeywickrama, S., Zhang, R., Wu, Q. and Yuen, C., 2020. Intelligent reflecting surface: Practical phase shift model and beamforming optimization. IEEE Transactions on Communications, 68(9), pp.5849-5863.

[54] Pessoa, L.C.D.P., de Araújo, G.T., Gomes, P.R. and de Almeida, A.L., IRS-Assisted Communications Under Practical Channel Estimation and Hardware Model.

[55] Zargari, S., Farahmand, S., Abolhassani, B. and Tellambura, C., 2021. Robust active and

passive beamformer design for IRS-aided downlink MISO PS-SWIPT with a nonlinear energy harvesting model. IEEE Transactions on Green Communications and Networking, 5(4), pp.2027-2041.

[56] C. A. Floudas, Nonlinear and Mixed-Integer Optimization: Fundamentals and Applications, 1st ed. Oxford University Press, 1995.

[57] X. Li, X. Zhou, D. W. K. Ng and C. Sun, "Optimal Online Transmission Policy for Energy-Constrained Wireless-Powered Communication Networks," ICC 2019 - 2019 IEEE International Conference on Communications (ICC), Shanghai, China, 2019, pp. 1-7

[58] Liu, C., Liu, X., Ng, D.W.K. Ng and Yuan, J., 2021. Deep residual learning for channel estimation in intelligent reflecting surface-assisted multi-user communications. IEEE Transactions on Wireless Communications, 21(2), pp.898-912.

[59] Zhou, X., Yan, S., Wu, Q., Shu, F. and Ng, D.W.K., 2021. Intelligent reflecting surface (IRS)-aided covert wireless communications with delay constraint. IEEE Transactions on Wireless Communications, 21(1), pp.532-547.

[60] Chen, J., Chen, X., Gerstacker, W.H. and Ng, D.W.K., 2016. Resource allocation for a massive MIMO relay aided secure communication. Ieee transactions on information forensics and security, 11(8), pp.1700-1711.

[61] Wu, Q., Xu, J., Zeng, Y., Ng, D.W.K., Al-Dhahir, N., Schober, R. and Swindlehurst, A.L., 2020. 5G-and-beyond networks with UAVs: From communications to sensing and intelligence. arXiv preprint arXiv:2010.09317.

[62] Ng, D.W.K., Xiang, L. and Schober, R., 2013, September. Multi-objective beamforming for secure communication in systems with wireless information and power transfer. In 2013

IEEE 24th annual international symposium on personal, indoor, and mobile radio communications (PIMRC) (pp. 7-12). IEEE.

[63] Ng, D.W.K. and Schober, R., 2014, December. Resource allocation for coordinated multipoint networks with wireless information and power transfer. In 2014 IEEE Global Communications Conference (pp. 4281-4287). IEEE.

[64] Chen, G., Wu, Q., Chen, W., Ng, D.W.K. and Hanzo, L., 2021. IRS-aided wireless powered MEC systems: TDMA or NOMA for computation offloading?. arXiv preprint arXiv:2108.06120.

[65] Sun, Y., Ng, D.W.K., Xu, D., Dai, L. and Schober, R., 2018, June. Resource allocation for solar powered UAV communication systems. In 2018 IEEE 19th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC) (pp. 1-5). IEEE.