SCHOOL OF ELECTRICAL ENGINEERING
AND TELECOMMUNICATIONS

Beamforming Design for Secrecy Rate Maximization in IRS-enabled Energy Harvesting Communication Systems

by

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Abstract

With the rapid growth of communication networks, wireless communication technology is gradually developing from 4G to 5G and 6G, and the requirements for wireless communication networks are becoming higher and higher. However, the coverage capacity of the 5G network is greatly reduced, so more base stations need to be introduced. In order to cope with the surge of equipment, increased energy consumption and increased cost caused by the 5G network. Intelligent reflection surface (IRS) has received more attention. It has a simple physical structure and low cost can be simply installed on the wall or building surface and provides better spectrum and energy efficiency. A secure network is the main research direction of information security communication. Self-sustainable intelligent reflection plane can better solve the problem of energy and power consumption in the network. However, these technologies need to be further optimized to be combined to further improve service quality and reduce energy consumption. Therefore, this paper proposes to apply the self-sustainable intelligent reflection plane to the wireless MISO communication system considering network security. In addition, the beamforming vector, artificial noise vector, phase shift scheduling of IRS and mode selection of IRS are jointly studied, forming a nonconvex optimization problem which is solved to maximize the system secrecy rate.

Acknowledgement

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Abbreviation

4G	Fourth Generation Communication Network
5G	Fifth Generation Communication Network
MIMO	Multiple-Input Multiple-Output
MISO	Multiple-Input Single-Output
MmWave	Millimeter wave
IRS	Intelligent Reflecting Surface
SWIPT	Simultaneous Wireless Information and Power Transfer
CA	Carrier Aggregation
BS	Base Station
AP	Access Point
AWGN	Additive White Gaussian Noise
CSI	Channel State Information
SINR	Signal-to-Interference-plus-Noise Ratio
QoS	Quality of Service
AO	Alternating Optimization
SCA	Successive Convex Approximation
SDR	Semi-Definite Relaxation

Contents

1. Introduction

With the development of communication technology, as people begin to demand faster network speed, more stable network quality and lower network delay, the 4G network is gradually developing towards 5G or even to 6G and beyond 5G [1]-[6]. Compared with 4G, the biggest change of this new communication network is that the frequency band used is greatly increased, resulting in the reduction of signal wavelength, the use of millimetre wave [7], and the use of massive MIMO, which increases the traffic bandwidth of 5G network by 100 to 1000 times compared with 4G, and the network delay is reduced to less than 1ms. However, the 5G network also has defects. The cost of high performance is the surge of 5G devices[8], the deployment of high-density base stations and the significant increase in energy consumption [9]. The energy of wireless network communication equipment powered by a battery is limited, which leads to the shortening of the service life of the communication network. If the network equipment somewhere fails due to power supply, it will cause a large-scale waste of energy. In order to solve these problems, the IRS intelligent reflection plane is proposed and tried to be applied to reduce power consumption to the greatest extent while ensuring that the number of devices remains unchanged and does not affect the system performance, so as to provide uninterrupted communication services for wirelessly connected devices and realize cost-effective solutions [10]-[12].

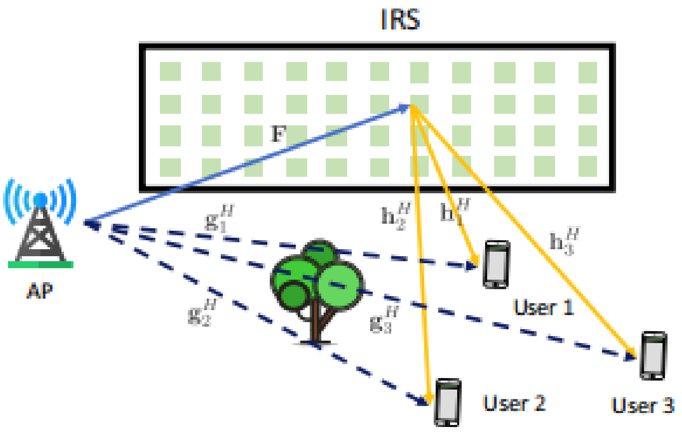

Fig.1 IRS-assisted MISO wireless communication system for multiuser
Cited from Xianghao Yu's work in 2020 [11]

IRS is a full duplex transparent relay. It can also solve the problem that the signal cannot propagate in a straight line due to the obstruction of trees or various buildings, so as to reduce the performance of the wireless network. Fig 1 shows the basic IRS-assisted MISO wireless network system. IRS consists of many passive reflection elements. By changing the phase shift by each element, the signal received from the transmit part can be changed in a specific direction, and the reflected signal can be transmitted to a specific user. These elements are just simple hardware that cost low energy in the IRS. Since the IRS nearly doesn't need a power supply, its component consumption is much smaller than other reflectors. The state of the system channel can be easily changed by using IRS controller to change the element's phase shift, which can make system performance better [13]. As shown above, the application of IRS can make communication systems have higher communication efficiency and lower multiple access interference, and IRS is the component, which can be easily embedded into the surface of any building [14], so as to improve the coverage of communication services.

However, for the past usual article, the consumption of IRS is ignored because it is less than the power for transmission and other power consumption in the communication network. However, although the power of IRS is less than the power for transmission, it still has power consumption. Most of its power consumption comes from the circuit and diode consumption of reflective elements which is related to phase shifter and their bit resolution [15],[16]. The total consumed energy of IRS panel is related to its elements’ number. Some elements need to be used as reflective elements to improve network performance, while others need to absorb energy to supply their own power consumption.

In recent years, to effectively improve wireless communication systems’ security problem, people try to concentrate on the security of the physical layer [17]. On the transmission side, configuring multiple antennas, using a beam forming algorithm and designing artificial noise, the quality of the eavesdropper's communication channel is greatly reduced. [18], [19] discussed the high-security technical requirements of IRS technology in the presence of eavesdroppers in order to obtain the solution of a secure IRS system.

The transmission method at the transmitter is also related to network performance. Therefore, the resource allocation algorithm is proposed to optimize the communication network system supported by IRS, so as to greatly improve the network performance.

In this report, we provide a MISO system equipped with the IRS which is self-sustainable, in a secure communication situation. Firstly, the artificial noise involved in ensuring security transmission in the case of eavesdroppers is discussed. Secondly, self-sustainable IRS is used in the system. Different from the traditional IRS version, the passive elements of the IRS are replaced with sustainable elements that can realize self-power supply so that additional power supply is not necessary for IRS. In addition to the change of hardware and the design of artificial noise, joint optimization is done to pursue more efficient system performance which combines the precoding and artificial noise at the transmitting side, and the phase scheduling and strategy collection scheduling at the IRS side, so as to maximize the difference between the security rate of effective users and the security rate of eavesdroppers. However, the formulation problem is nonconvex. Therefore, this report adopts a method to optimize the nonconvex problem and constraint to the convex by using semidefinite relaxation(SDR), successive convex approximation(SCA), alternating optimization(AO). It can be proved that our proposed algorithm actually achieve a MISO secure system assisted with the self-sustainable IRS. We can see from the simulation results that the good performance of average secrecy rate, and relationship between it and other elements like quantization bits, IRS elements, antenna numbers, users numbers and transmit power budget.

2. Background

A.The 5G Generation Communication System:

The 5G generation communication system is the most advanced wireless network technology, which received extensive attention and research, and has been applied in many regions and cities in recent years. With the further development of 4G technology, people have higher requirements and expectations for the 5G network, higher information transmission rate, lower transmission delay, lower energy loss and operation cost, higher system capacity and larger equipment connection capacity [20]. As far as the current situation is concerned, the 5G network has achieved a higher information transmission rate and lower transmission delay. Its information transmission rate can reach 10Gbits / s at most, which is about 100 times that of a 4G network, and can ensure that the transmission delay is 1ms, which is reduced to about one divide fifteen compared with a 4G network. With the increase of 5G frequency resources and the reduction of wavelength, its signal is seriously affected by obstacles. Therefore, large-scale equipment connection and high-density equipment network is needed to solve these problems, so that the energy loss and operation cost of the 5G network is not decreased, but greatly increased. However, it is the substantial increase and interconnection of equipment scale that enables the 5G network to interconnect all things, to enter the era in which things connect to each other to become the Internet. Therefore, the way to reduce the cost of the 5G network system is one of the main research problems [21].

The main different part between the 5G network and the 4G network lies in significant multiplication of frequency and channel. With the adoption of the 6GHz high-frequency band, its wavelength becomes shorter [22], so that the 5G network can realize many new technologies: millimetre wave, massive MIMO, LDPC / polar, as a layer, beam management, IRS, SWIPT, CA and so on, which has a good future development prospect.

B.Intelligent reflecting surface (IRS):

Although the traditional passive reflector technology has long appeared and applied in industrial fields, such as radar systems, communication between satellites, technology about remote sensing and so on. But they have a defect because these reflecting surfaces cannot realize dynamic phase shift, they can only reflect signals through the fixed phase reflecting surface set at the beginning, so they cannot be used in commercial fields. Compared with traditional reflector technology, IRS can dynamically change the phase to dynamically reflect the signal. IRS is a reflection plane that uses some passive antenna arrays to reflect radio signals transmitted from base stations. It can receive multiple input signals from the transmitter side and reflect required signal to the targeted receiver. Fig 2 shows a typical IRS system. The whole system includes the transmitter, receiver, IRS and IRS controller [7]. As shown in Fig 3, several meta-atoms composes the IRS panel [23], which can reflect the signal to the targeted user passively. Each atomic element can be used as an antenna to reflect the signal and connect to the IRS controller. In some situations, meta-atoms can be used to collect energy. With its characteristics of easy installation, energy-saving efficiency, the passive reflection of signals, easy adjustment and improving the security of the physical layer, IRS has gradually become one of the main technologies studied in communication networks and plays a vital role in the process of 5G commercialization.

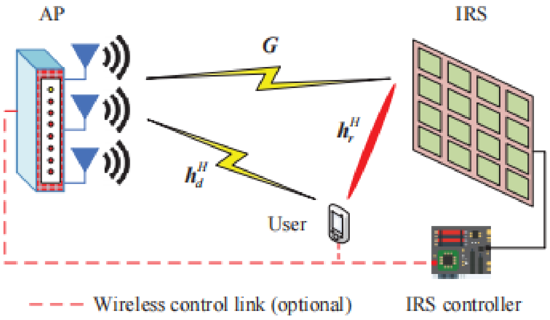

Fig.2 Basic IRS-assisted wireless system
Cited from Qingqing Wu’s work in 2018 [7]

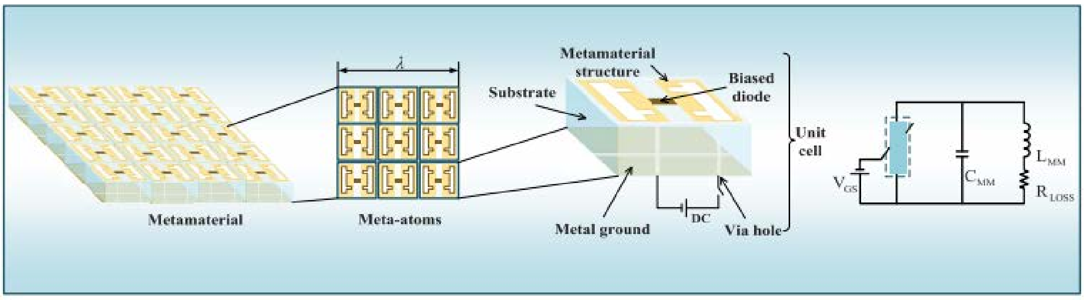

Fig.3 Physical structure of the IRS
Cited from Jinghe Wang’s work in 2021 [23]

C.Secure IRS-assisted system:

With the development of communication networks, the value of information and the emergence of hackers, network security technology has also become a major research technology. Ensuring physical layer security is one of the technologies to promote wireless secure communication [24] The signal will be concentrated to the receiving useful side and distorted on the unwanted side using the special configuration of multiple antennas on the transmission side and the beamforming for the transmit signal.

In [25], the author applied the beamforming algorithm to the conventional the MISO system and successfully realized the communication secure MISO wireless system. In [26], the author combined IRS with MISO wireless security system and jointly optimized the base's station's beamforming vector and IRS phase, to make system security rate better. In [27], the author studied the application of IRS in a multiuser MISO system and designed the resource allocation algorithm of the system to make the confidentiality rate of the system to the max value. In [28], the author talked about two ways in the MISO wireless system with IRS to make the secrecy rate in max value. In [29], the author combined intelligent reflecting surfaces in wireless communication to keep secrecy. Further, the concept of artificial noise (AN) is proposed and used in the security network system [30]-[32]. By designing artificial noise, it can concentrate on the eavesdropper and distort the receiving user, so that the signal at the eavesdropper can be further distorted without affecting the receiving user signal. In [19], as shown in Fig. 4, by adding a vector and jointly optimizing with IRS phase and the base station's beamforming vector , the author uses the algorithm of resource allocation to make the system performance of security rate to the max value.

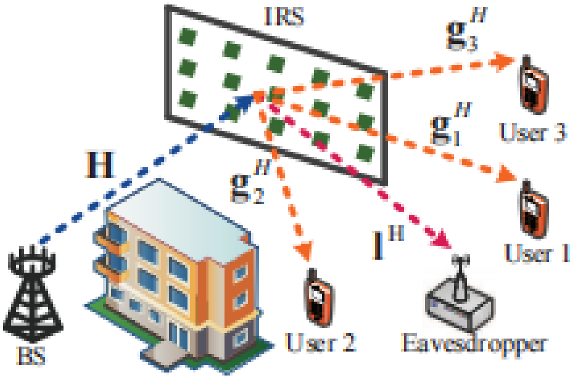

Fig.4 A wireless MISO communication system with the intelligent reflecting surface in secure situation
Cited from Dongfang Xu's work in 2019 [19]

D.Self-sustainable IRS:

IRS only contains passive components, without the characteristics of a power supply, so its own power consumption is very low. Most works ideally assume that the IRS's power consumption does not exist. However, although the IRS's power consumption is very low compared with conventional power supply equipment, it still exists and will still have an impact compared with transmission power. The power consumed by IRS mainly comes from the diode circuit of its reflective elements. the main factors affecting its power consumption are the bit resolution of each reflective element and the number of elements main factors affecting its power consumption [33].

So as to reduce the power impact of IRS itself, a special energy-saving IRS system need to be designed. In [31], the author designed a self-sustainable IRS with a WPT power supply [34]to provide the total rate of the system. However, due to the relevant hardware limitations and costs, it is difficult to apply in practice, and it only discusses the situation of the single antenna transmitting side, which is difficult to achieve when applied to the current mainstream transmitting system with a multi-antennae. In [35], as shown in Fig. 5, the author applied a IRS which can be self-sustainable in wireless MISO communication system. By equipping the IRS using discrete phase shifter and allocating the functions of the components of the IRS, some receive signals and reflect, and some receive energy to support IRS power consumption, so as to maximize the system comprehensive rate, then discussed the impact of resolution on the system performance.

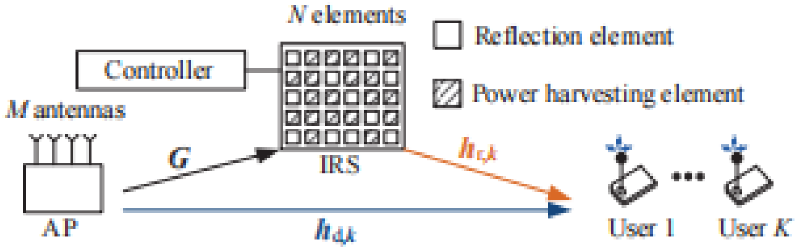

Fig.5 A self-sustainable IRS-assisted wireless communication system
Cited from Shaokang Hu’s work in 2020 [35]

3. Key Notation

In this part, we will talk about the key notation appears in this paper to make reading more clearly. The boldface lower letter, the lower case represent matrices and the boldface upper letters, denote vectors, scalars and matrices, respectively. H^N indicates the N × N complex Hermitian matrices. I^N represents an N × N identity matrix. $R^{N\times M}$ and $C^{N\times M}$ indicates the space of the N × M matrix which contains the real value and complex value, respectively. $(\,)^T, (\,)^H, (\,)^*$ show the transpose, the conjugate transpose and the conjugate of the vector, respectively. $|\cdot|$ and $||\cdot||$ indicate the absolute value of a complex scalar and the Euclidean norm of a vector, respectively. Rank(A), Tr(A) indicate the rank and trace of the matrix, respectively. diag(x) indicates the N×N diagonal matrix with diagonal elements x. $\nabla_x f(.)$ represents the gradient for the function f(x). $A \geq 0$ denotes A is the positive semi-definite diagonal matrix. E $\{\cdot\}$ indicatess statistical expectation. $CN(\mu, \sigma^2)$ represent that mean μ and variance σ^2 for the distribution of a circularly symmetric complex Gaussian random variable.

4. System Model

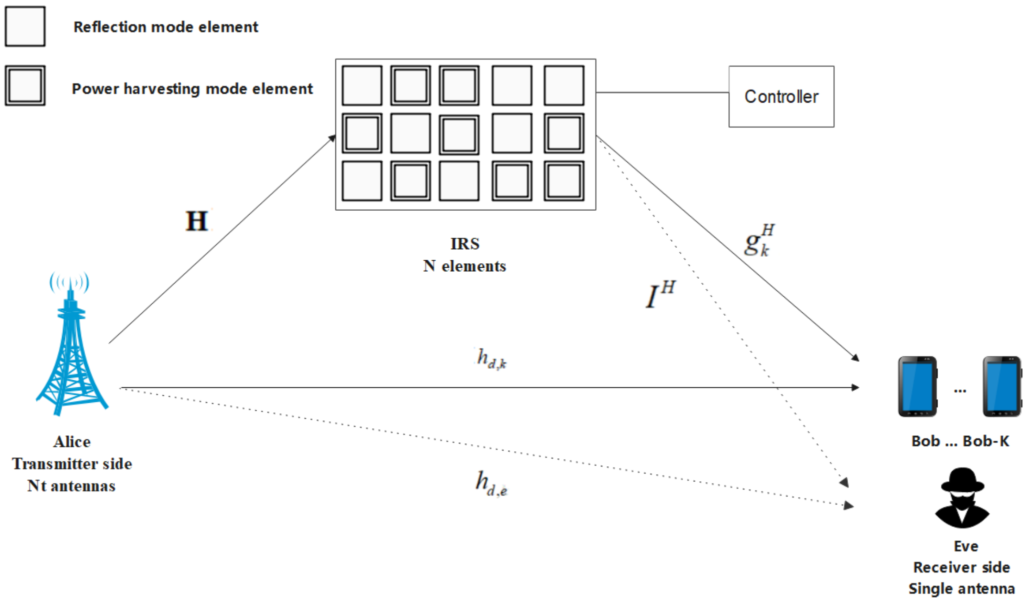

Fig.6 A MISO system in secure communication with a self-sustainable IRS

We can see from Fig 6, the system model of this article is mainly in the situation of a MISO system, which uses a self-sustainable IRS in a secure communication situation. We can see from Fig 1 that the transmitter has $N_T > 1$ antennas and transmits K signals to K users which are independent of each other. The K is the number of users that receive the signal selected from the set $\mathbf{K} = \{1,2,...,...,K\}$. Notice that there is an additional signal which transmits to the eavesdropper. All the users and eavesdropper only have one antenna. The RIS consists of N reflect elements, which also be selected from $\mathbf{N} = \{1,2,...,...,N\}$. And IRS reflected matrix is $\boldsymbol{\theta} = \mathbf{A\Phi}$, and $\boldsymbol{\Phi} = diag(\beta_1 e^{j\theta_1}, \beta_2 e^{j\theta_2}, ...,..., \beta_N e^{j\theta_N}) \in C^{N\times N}$ with amplitude coefficient restriction $\beta_n \in [0, 1] \quad \forall n \in \mathbf{N}$ and the phase shift restriction $\theta_n \in [0,2\pi)$. $\mathbf{A} = diag(\alpha_1, \alpha_2, ..., ..., \alpha_N) \in R^{N \times N}$ with the mode selection variable $\alpha_n \in \{0, 1\}$ The meaning of this variable is that

$$\alpha_n = \begin{cases} 1, \text{Refelction mode at IRS element n} \\ 0, \text{Power harvesting mode at IRS element n} \end{cases} . \quad (1)$$

To make the system easy to achieve, we assume that the reflection coefficient β_n is fixed to 1, and energy harvesting state or reflection state is determined by α_n. As for each IRS element phase, the phase shift interval is divided evenly for them, as shown in (2):

$$\theta_n \in S = \{0, ..., \Delta\theta, ..., \Delta\theta(B-1)\} \quad \forall n \in \mathbf{N} \quad (2)$$

S means the set of phase shifts and $\Delta\theta = \frac{2\pi}{B}$ which is divided into B parts and B is the phase shift levels determined by bit resolution b $B = 2^b$. All the elements in each model will consume the power P which is also related to b as shown like $P_{IRS}(b)$. For each model, when the element is in the reflection model, the only function of it is to reflect all the signal it received and send it to the receiver; when the element is in the power harvesting mode, the element only absorbs the power they receive and doesn’t reflect any signal.

For the further resource allocation design, CSI[23] of the whole system is assumed to be known at the transmitter side by applying the existing CSI estimation algorithm.

So we can get that the transmitter signal is

$$x = \sum_{k \in K} w_k x_k + z \quad (3)$$

Where $x_k \in C$ and $w_k \in C^{N_T}$ denotes the user K’s information signal and beamforming vector. The expectation of it is $\mathrm{E}\{|\mathrm{x_k}|^2\}=1，\forall \mathrm{k} \in \mathrm{K}$. Also, the artificial noise vector $z \in C^{N_T}$ used to make eavesdropper cannot receive the correct signal. The AN vector is a complex Gaussian random vector with zero means and covariance matrix $\mathbf{Z} \in（h_{d,k} + \mathbf{H})^{N_T}，\mathbf{Z} \geq 0$. What’s more, the sum energy of both beam forming vector and AN vector cannot exceed the total power budget.

The signal reflected by the IRS , then received by eavesdropper and user k are given by

$$y_k = (\mathbf{h}_{d,k}^H + \mathbf{HA\Phi} g_k^H)(\sum_{k \in K} w_k x_k + z) + n_k \tag{4}$$

$$y_e = (\mathbf{h}_{d,e}^H + \mathbf{HA\Phi} I^H)(\sum_{k \in K} w_k x_k + z) + n_k \tag{5}$$

Where $H \in C^{N_T \times N}$ and $h_{d,k（e）} \in C^{N_T \times 1}$ mean the channel matrix between IRS and transmitter, a direct path between receiver and transmitter, $g_k \in C^N$ and $I \in C^N$ denote channel vector between the IRS and receiver, between the eavesdropper and the IRS. Their additive white Gaussian noise for user K with a noise power σ_{nk}^2 and for eavesdropper with a noise power σ_{ne}^2 is $n_k \sim CN(0, \sigma_{nk}^2)$ and $n_e \sim CN(0, \sigma_{ne}^2)$.

Then user K’s received SINR is shown

$$SINR_k = \frac{|(\mathrm{h}_{d,k}^H + \mathbf{HA}\Phi g_k^H) w_k|^2}{\sum_{j \neq k} |(\mathrm{h}_{d,k}^H + \mathbf{HA}\Phi g_k^H) w_j|^2 + Tr[(\mathrm{h}_{d,k}^H + \mathbf{HA}\Phi g_k^H)^H (\mathrm{h}_{d,k}^H + \mathbf{HA}\Phi g_k^H) Z] + \sigma_{nk}^2} \tag{6}$$

Then user K’s rate is shown

$$R_k = \log_2(1 + SINR_k), \forall k \in K \tag{7}$$

The received SINR and its corresponding channel capacity for eavesdropping user K is given by the following formula:

$$SINR_e = \frac{|(\mathrm{h}_{d,e}^H + \mathbf{HA}\Phi I^H) w_k|^2}{\sum_{j \neq k} |(\mathrm{h}_{d,e}^H + \mathbf{HA}\Phi I^H) w_j|^2 + Tr[(\mathrm{h}_{d,e}^H + \mathbf{HA}\Phi I^H)^H (\mathrm{h}_{d,e}^H + \mathbf{HA}\Phi I^H) Z] + \sigma_{ne}^2} \tag{8}$$

$$R_e = \log_2(1 + SINR_e) \tag{9}$$

Thus, user K’s secrecy rate is shown

$$R_k^{\sec} = [R_k - R_e]^+ \tag{10}$$

In addition, the sum of energy harvest signals for the IRS is shown

$$y_{energy}(A, w_k) = A_{energy}(\mathbf{H}x + n_a) \tag{11}$$

Where $\mathbf{A}_{energy} = I_N - \mathbf{A}$ is the power harvesting matrix, and IRS’s thermal noise with a noise power σ_a^2 is $n_a \sim CN(0, \sigma_a^2 I_N)$.

The IRS’s total harvest power is shown

$$P_{energy} = \eta_h E(\| A_{energy}(\mathbf{H} \sum_{k \in K} w_k x_k + n_a) \|^2) \tag{12}$$

Where $0 \le \eta_h \le 1$ is the IRS elements’ power harvesting efficiency for getting energy from the received signal.

5. Problem Formulation

For our system, we need to keep a self sustainable IRS in the system and to make the secrecy rate in max value. So we design the transmit signal vector w_k , artificial noise vector z in the transmitter side; the mode selection α_n , phase shifter θ_n jointly. So the corresponding optimization problem can be formulated as

$$\underset{\mathrm{w_k}, z, \alpha_n, \theta_n}{\text{maximize}} \sum [R_k - C_k^E]^+ \tag{13}$$

$$
\begin{aligned}
s.t \quad & C1: \sum_{k \in K} \| w_k \|^2 + Tr(\mathbf{Z}) \le P_{\max} \\
& C2: \theta_n \in F, \forall n \in N \\
& C3: \sum_{n=1}^{N} \alpha_n P_{IRS}(b) \le P_{\text{energy}} \\
& C4: \alpha_n \in \{0, 1\} \ \forall \mathrm{n} \\
& C5: \mathbf{Z} \ge 0
\end{aligned}
$$

where constraint C1 limits BS transmit power including both signal and artificial noise part allowance to maximum transmit power budget $P_{\max}$. Constraint C2 shows that each IRS reflecting element’s phase shift is in the set F. Constraint C3 specifies that sum of power whole IRS used would not exceed harvested power which gets by harvesting mode IRS. Constraint C4 indicates that there are two modes: power harvesting mode and reflection mode for each IRS element. Constraint C5 says that the trace of the artificial noise must be positive.

We need to do the convexity analyses to operate the optimization. The problem formulates above is non-convex. The reason for that is the couple problem between variables w_k, z, about secrecy rate in constraint C1, the phase shift θ_n in constraint C2 and binary variable α_n in constraint C3.

To solve the optimization problem of (13), we can use the brute-force searching algorithm. However, this algorithm is too complex to achieve especially in a moderate size system. So, we will use algorithms including SCA,SDR and AO to solve the nonconvex constraint and formulated problem.[36]-[40]

6. Solution of the Optimization Problem

A.Problem Transformation

In this article, we talk about self-sustainable IRS and use the combination of $\boldsymbol{\theta} = \mathbf{A\Phi}$ as the reflection matrix of the IRS. We need to combine them into a whole factor to solve the coupling factor of these two parameters. We know that $\mathbf{\Phi} = diag(\beta_1 e^{j\theta_1}, \beta_2 e^{j\theta_2}, ..., ..., \beta_N e^{j\theta_N}) \in C^{N \times N}$ with amplitude coefficient restriction $\beta_n \in [0,\ 1] \quad \forall n \in \mathbf{N}$ and phase shift restriction $\theta_n \in [0, 2\pi)$ and $\mathbf{A} = diag(\alpha_1, \alpha_2, ..., ..., \alpha_N) \in R^{N \times N}$ with the mode selection variable $\alpha_n \in \{0,\ 1\}$.So we can redesign the mode selection matrix to make it also represent the performance of $\mathbf{\Phi}$ matrix $\tilde{\mathbf{A}} = diag(\tilde{\alpha}_1, \tilde{\alpha}_2, ..., ..., \tilde{\alpha}_N)$, where $\tilde{\alpha}_n \in \{\tilde{F}\} = \{0, \beta_1 e^{j\theta_1}, \beta_2 e^{j\theta_2}, ..., ..., \beta_N e^{j\theta_N}\}$. The angle $\theta_n \in [0, 2\pi)$ will be divided to the B parts by B+1 different models. When $\tilde{\alpha}_n = 0$, it means the IRS element n is selected to the power harvesting mode. While $\tilde{\alpha}_n \neq 0$, it means the IRS element n is selected to reflection mode. By doing this projection, we successfully to combine two matrices for selecting mode and angle to a whole matrix and solve the coupling problem. Then, we will change the problem of constraints 3 and 4 to that:

$$C3: \sum_{n=1}^{N} |\tilde{\alpha}_n| P_{IRS}(b) \leq P_{\text{energy}} \tag{14}$$

$$C4: \tilde{\alpha}_n \in \{\tilde{F}\} = \{0, \beta_1 e^{j\theta_1}, \beta_2 e^{j\theta_2}, ..., ..., \beta_N e^{j\theta_N}\} \ \forall n \tag{15}$$

Then, we will further optimize constraint 4 to simplify the discrete variable $\tilde{\alpha}_n$. In order to do that, we will introduce another variable to represent the selection of the B+1 mode $s_{\mathrm{i,\ n}}\ \forall i \in I = \{0,1,2,...,..., B+1\}$ $\mathrm{n} \in \mathrm{N}$ And these variables will combine as a matrix to show the situation of the mode selection $\mathbf{S} \in R^{(B+1)\times N},\ s_{i,n} \in \mathbf{S}$. When the value of $s_{\mathrm{i,\ n}}$ is 1, it means the n-th element select the i-th mode for it to operate and in this situation, the $s_{\mathrm{i,\ n}}$ value of the other mode for this n-th element is all zero. Then we can rewrite the constraint C4 as:

$$C4\mathrm{a}: \sum_{i\in I}^{N} s_{i,n} \le 1, \forall n \tag{16}$$

$$C4\mathrm{b}: s_{i,n} \in \{0,1\}\ \forall i, n \tag{17}$$

$$C4\mathrm{c}: \tilde{\alpha}_n = \sum_{\mathrm{i}\in\mathrm{I}} \mathrm{s}_{\mathrm{i,n}} f_i\ \forall n \tag{18}$$

f_i means element I for formal selection of mode from F related to (15).

After that, we can rewrite the power harvesting binary-valued matrix A_{energy} that

$$A_{\mathrm{energy}} = diag(s_1) \tag{19}$$

Since the first element of the mode represents the power harvesting mode, so the whole value for the mode selection matrix S 's first-row value can represents A_{EH} . Then we can optimize the constraint C3 as:

$$C3: (N - \sum_{n=1}^{N}(s_{1,n}))P_{IRS}(b) \le \eta_h(\sum_{k\in K} Tr(\mathbf{H}w_k w_k^H \mathbf{H}^H diag(s_1)) + n_a^2 \sum_{n=1}^{N} s_{1,n}) \tag{20}$$

After the transformation above, we can get the new form of the problem that:

$$\underset{\mathrm{w_k},z,\alpha_n,\theta_n}{\text{maximize}} \sum [R_k - C_k^E]^+ \tag{21}$$

$$s.t \quad C1, C3, C4a, C4b, C4c, C5$$

Although problem transformation has been made to change the nonconvex constraint to the convex constraint, however, the total problem is still nonconvex. In the following part, we will use the alternating optimization to change the problem to 2 sub-problem. The sub-problem is about $\{\mathbf{S}, \tilde{\alpha}_n, \forall \mathrm{n}\}$ and $\{\mathrm{w_k}, z, \forall \mathrm{k}\}$ respectively. Then we will solve them respectively by viewing one of them as a variable and the other of them as a fixed value.

B. Sub-problem 1: Optimization of transmit beamforming vector and artificial noise

AS we talk about in the last section, we will fix one of the variable values and talk about the other. In this section, we will do the optimization of transmit beamforming vector $\{\mathrm{w_k}, z, \forall \mathrm{k}\}$ with the condition that the mode selection binary and its corresponding element value $\{\mathbf{S}, \tilde{\alpha}_n, \forall \mathrm{n}\}$ is fixed. Then in order to simplify the following calculation, we will define several value. $W_k = w_k w_k^H$, $H_k = h_k h_k^H$, $h_k = \mathrm{h}_{d,k}^H + \mathbf{H}^H \tilde{\mathbf{A}}^H g_k^H$, $I_k = i_k i_k^H$, $i_k = \mathrm{h}_{d,k}^H + H^H \tilde{\mathbf{A}}^H I^H$. The received SINRs at the user and eavesdropper respectively can be rewritten as:

$$SINR_k = \frac{Tr(\mathrm{W_k} H_k)}{\sum_{j \neq k} Tr(\mathrm{W_j} H_k) + Tr(\mathrm{Z} H_k) + \sigma_{nk}^2} \tag{22}$$

$$SINR_e = \frac{Tr(\mathrm{W_k} I_k)}{\sum_{j\neq k} Tr(\mathrm{W_j} I_k) + Tr(\mathrm{Z} I_k) + \sigma_{ne}^2} \tag{23}$$

Then we can rewrite our problem that:

$$\underset{\mathrm{w_k},z}{\text{minimize}} \ -\sum [R_k - C_k^E]^+ \tag{24}$$

$$s.t \quad C1, C3, C5, C6: W_k \geq 0, \forall k, C7: Rank(W_k) \leq 1, \forall k,$$

Where added constraints C6, C7 and $W_k \in H^M$ can ensure that W_k still holds when optimization finished. Then, to deal with this nonconvex of the problem, the successive convex approximation(SCA) will be used iteratively.

Since we can learn that there are four main parts in the objective problem and we will change all of them to the form of convex for SCA calculation, the objective function after transformation is shown below:

$$\underset{\mathrm{w_k},z}{\text{minimize}} \ f = R_{k1} - R_{k2} + C_{k1} - C_{k2} \tag{25}$$

$$s.t \quad C1, C3, C5, C6: W_k \geq 0, \forall k, C7: Rank(W_k) \leq 1, \forall k,$$

$$R_{k1} = -\sum_{k\in K} \log_2 \left(\sum_{j\in K} Tr(\mathrm{W_j} H_k) + Tr(\mathrm{Z} H_k) + \sigma_{nk}^2\right)$$

$$R_{k2} = -\sum_{k\in K} \log_2 \left(\sum_{j\neq k} Tr(\mathrm{W_j} H_k) + Tr(\mathrm{Z} H_k) + \sigma_{nk}^2\right)$$

$$C_{k1} = -\sum_{k\in K} \log_2 \left(\sum_{j\neq k} Tr(\mathrm{W_j} I_k) + Tr(\mathrm{Z} I_k) + \sigma_{ne}^2\right)$$

$$C_{k2} = -\sum_{k\in K} \log_2 \left(\sum_{j\in K} Tr(\mathrm{W_j} I_k) + Tr(\mathrm{Z} I_k) + \sigma_{ne}^2\right)$$

After we construct them, especially for R_{k2} and C_{k2}, for any feasible point $W_k^{t_1}$ and Z^{t_1}, We can get the lower bound function of the differentiable convex function $R_{k2}(W, Z)$ and $C_{k2}(W, Z)$ respectively by using first-order Taylor expansion:

$$\begin{aligned} R_{k2}(W,Z) \geq R_{k2}(W^{t1},Z^{t1}) & \\ +Tr((\nabla_W R_{k2}(W^{t1},Z^{t1}))^H (W-W^{t1})) & \\ +Tr((\nabla_Z R_{k2}(W^{t1},Z^{t1}))^H (Z-Z^{t1})) & \end{aligned} \tag{26}$$

$$\begin{aligned} C_{k2}(W,Z) \geq C_{k2}(W^{t1},Z^{t1}) & \\ +Tr((\nabla_W C_{k2}(W^{t1},Z^{t1}))^H (W-W^{t1})) & \\ +Tr((\nabla_Z C_{k2}(W^{t1},Z^{t1}))^H (Z-Z^{t1})) & \end{aligned} \tag{27}$$

Where the first partial derivative of these two functions are

$$\nabla_W R_{k2}(W^{t1},Z^{t1}) = \frac{-1}{\ln 2}\sum_{j\neq k}\left(\frac{H_j}{\sum_{q\in K\setminus\{j\}} Tr(\mathrm{W}_{\mathrm{q}} H_j)+Tr(ZH_j)+\sigma_{nk}^2}\right) \tag{28}$$

$$\nabla_z R_{k2}(W^{t1},Z^{t1}) = \frac{-1}{\ln 2}\sum_{k\in K}\left(\frac{H_k}{\sum\limits_{j\neq k} Tr(\mathrm{W}_{\mathrm{j}} H_k)+Tr(ZH_k)+\sigma_{nk}^2}\right) \tag{29}$$

$$\nabla_W C_{k2}(W^{t1},Z^{t1}) = \frac{-1}{\ln 2}\sum_{k\in K}\left(\frac{I_k}{\sum\limits_{j\in k} Tr(\mathrm{W}_{\mathrm{j}} I_k)+Tr(ZI_k)+\sigma_{ne}^2}\right) \tag{30}$$

$$\nabla_z C_{k2}(W^{t1},Z^{t1}) = \frac{-1}{\ln 2}\sum_{k\in K}\left(\frac{I_k}{\sum\limits_{j\in k} Tr(\mathrm{W}_{\mathrm{j}} I_k)+Tr(ZI_k)+\sigma_{ne}^2}\right) \tag{31}$$

Then we can put these values in the problem so that we can use the semidefinite relaxation(SDR) technology to drop C7. After that, the optimization problem changes to a convex problem so it can be solved easily.

$$
\begin{aligned}
\underset{\mathrm{w_k},z}{\text{minimize}}\ f = {} & R_{k1}+C_{k1} \\
& - \sum_{\mathrm{k}\in\mathrm{K}} Tr((\nabla_W R_{k2}(W^{t1},Z^{t1}))^H (W-W^{t1})) \\
& - \sum_{\mathrm{k}\in\mathrm{K}} Tr((\nabla_Z R_{k2}(W^{t1},Z^{t1}))^H (Z-Z^{t1})) \\
& + \sum_{k\in K} \log_2 (\textstyle\sum_{j\neq k} Tr(\mathrm{W}_\mathrm{j}^{\mathrm{t1}} H_k) + Tr(Z^{t1} H_k) + \sigma_{nk}^2) \\
& - \sum_{k\in K} Tr((\nabla_W C_{k2}(W^{t1},Z^{t1}))^H (W-W^{t1})) \\
& - \sum_{k\in K} Tr((\nabla_Z C_{k2}(W^{t1},Z^{t1}))^H (Z-Z^{t1})) \\
& + \sum_{k\in K} \log_2 (\sum_{j\in K} Tr(\mathrm{W}_\mathrm{j}^{\mathrm{t1}} I_k) + Tr(Z^{t1} I_k) + \sigma_{ne}^2)
\end{aligned}
\tag{32}
$$

$s.t \quad C1, C3, C5, C6,$

We will use theorem 1 to show the tightness of SDR and prove it. The process of the prove below the theorem.

Theorem 1: If the question (32) is feasible with the constraint that $P_{\max} > 0$, the condition that $Rank(W_k) \leq 1$ is always guaranteed.

Proof: The process of the proof is at the end of this part.

We notice that when we use SCA to solve this problem, the result of (32) can be the upper bound of (25). By using algorithm 1, we can get the result of (32) to become closer to the upper bound through the iteration which means we can get the locally optimal solution of (25) after the end of the iteration.

Algorithm 1 iterative transmit beamforming and AN vector by SCA

```
1. Initialize the max iteration index $t_{1\max}$ and set the iteration index $t_1$ to 0.
2. Variable is $\{\mathrm{w_k}, z, \forall \mathrm{k}\}$ and given constant is $\{\mathbf{S},\ \tilde{\alpha}_n, \forall \mathrm{n}\}$.
3. Repeat.
```

```
4. Solve (32) for given $W_k^{t_1}$ and $Z^{t_1}$.
5. Refresh $W_k^{t_1}$ and $Z^{t_1}$ by using the result from step 4.
6. Make $t_1$ plus 1.
7. Until convergence or $t_1 = t_{1\max}$.
8. Get the result of $W_k^{t_1}$ and $Z^{t_1}$.
```

C.Sub-problem 2: IRS mode selection Optimization

Compared to the last section of sub-problem 1, in this section, we will do the optimization of the mode selection binary and its corresponding element value $\{\mathbf{S}, \tilde{\alpha}_n, \forall \mathrm{n}\}$ while the transmit beamforming vector $\{\mathrm{w}_{\mathrm{k}}, z, \forall \mathrm{k}\}$ is fixed. We notice that C4b is a selection that is difficult to talk about, so we change the form of it that:

$$C4b: s_{i,n} - s_{i,n}^2 \le 0, \forall i, n \tag{33}$$

$$C4d: 0 \le s_{i,n} \le 1, \forall i, n \tag{34}$$

Then in order to simplify the following calculation, we will define values like $R_k = diag(g_k^H)H$, $C_k = diag(I^H)H$ .Then we can get that $\mathbf{H}^H \tilde{\mathbf{A}}^H g_k^H = v^H R_k , \mathbf{H}^H \tilde{\mathbf{A}}^H I^H = v^H C_k$ where $v = [\tilde{\alpha}_1, ..., \tilde{\alpha}_N]^H$.

Then we can rewrite our problem that:

$$\underset{\mathbf{s}, \mathbf{v}, \omega_k, \xi_k, \psi_k, \zeta_k}{\text{minimize}} \sum_{k \in K} \text{-}\log_2(1 + \frac{\omega_k}{\xi_k + \sigma_{nk}^2}) + \log_2(1 + \frac{\psi_k}{\zeta_k + \sigma_{ne}^2}) \tag{35}$$

$s.t \quad C3, C4a, C4b, C4c, C4d,$

$C8\mathbf{:} \quad \omega_k \le | h_{d,k}^H w_k + v^H R_k w_k |^2, \forall k,$

$$C9\text{:}\quad \xi_k \geq \sum_{j\neq k} | h_{d,k}^H w_j + v^H R_k w_j |^2 + | h_{d,k}^H z + v^H R_k z |^2, \forall k,$$

$$C10\text{:}\quad \psi_k \geq | h_{d,k}^H w_k + v^H C_k w_k |^2, \forall k,$$

$$C11\text{:}\quad \zeta_k \leq \sum_{j\neq k} | h_{d,k}^H w_j + v^H C_k w_j |^2 + | h_{d,k}^H z + v^H C_k z |^2, \forall k,$$

Where $\omega_k, \xi_k, \psi_k, \zeta_k$ are all slack optimization variables and can reduce the complexity of the solution. We can see that when we add the inequality constraints C8, C9, C10 and C11. It still satisfies the optimal solution of (35).

And we can see that C4c, C8 and C11 are reverse convex functions that needs to use SCA to solve their non-convexity like in the last section. In this section, we define $t_{2\max}$ as the iteration index in Algorithm 2. Then we can transfer out the optimization problem that:

$$\begin{aligned}\underset{\mathbf{S},\mathbf{V},\omega_k,\xi_k,\psi_k,\zeta_k}{\text{minimize}}\ & f = R_{k3} + C_{k3} \\ & \text{-}\sum_{\mathrm{k}\in\mathrm{K}} \nabla_{\xi_k} R_{k4}(\xi_k^{t2})^H (\xi_k - \xi_k^{t2}) - R_{k4}(\xi_k^{t2}) \\ & \text{-}\sum_{\mathrm{k}\in\mathrm{K}} \nabla_{\psi_k} C_{k4}(\psi_k^{t2})^H (\psi_k - \psi_k^{t2}) - C_{k4}(\psi_k^{t2})\end{aligned} \tag{36}$$

$$s.t\quad C3, C4a, C4b, C4c, C4d, C8, C9, C10, C11$$

Where

$$R_{k3} = -\sum_{k\in K} \log_2(\sigma_{nk}^2 + \omega_k + \xi_k)$$

$$C_{k3} = -\sum_{k\in K} \log_2(\sigma_{ne}^2 + \zeta_k)$$

$$\nabla_{\xi_k} R_{k4}(\xi_k) = \frac{\text{-1}}{(\ln 2)(\xi_k + \sigma_{nk}^2)}$$

$$R_{k4}(\xi_k^{t2}) = \text{-}\sum_{k\in K} \log_2(\xi_k^{t2} + \sigma_{nk}^2)$$

$$\nabla_{\psi_k} C_{k4}(\psi_k) = \frac{-1}{(\ln 2)(\zeta_k + \sigma_{ne}^2 + \psi_k)}$$

$$C_{k4}(\psi_k^{t2}) = -\sum_{k \in K} \log_2(\zeta_k + \sigma_{ne}^2 + \psi_k^{t2})$$

$$C4c\text{：}\ s_{i,n} - (s_{i,n}^{t2})^2 - 2s_{i,n}^{t2}(s_{i,n} - s_{i,n}^{t2}) \leq 0, \forall i, n$$

$$C8\text{:}\ \ \omega_k - | h_{d,k}^H w_k + v^H R_k w_k |^2 - 2(h_{d,k}^H w_k + v^{t2H} R_k w_k) R_k w_k (v - v^{t2})) \leq 0, \forall k,$$

$$C11\text{:}\ \ \xi_k \leq \sum_{j \neq k} | h_{d,k}^H w_j + v^H C_k w_j |^2 + | h_{d,k}^H z + v^H C_k z |^2, \forall k,$$

$$C11\text{:}\ \ \xi_k - \sum_{j \neq k} | h_{d,k}^H w_j + v^H C_k w_j |^2 - | h_{d,k}^H z + v^H C_k z |^2 -$$
$$\sum_{\mathrm{j \neq k}} (2(h_{d,k}^H w_j + v^{t2H} C_k w_j) C_k w_j + 2(h_{d,k}^H z + v^{t2H} C_k z) C_k z)(v - v^{t2}) \leq 0, \forall k,$$

We notice that we use SCA to change C4c, C8 and C11 constraints to solve this problem, the result of (36) can be the upper bound of (35). By using algorithm 2, we can get the result of (36) to become closer to the upper bound through the iteration which means we can get the locally optimal solution of (35) after the end of the iteration. And Algorithm 3 is the combined algorithm for Algorithm 1 and Algorithm 2. And the convergence to a suboptimal solution of (13) is ensured by the monotonically non-increasing objective function after each iteration.

Algorithm 2 iterative IRS mode selection by SCA

```
1.Initialize the max iteration index $t_{2\max}$ and set the iteration index $t_2$ to 0.
2.Variable is $\{\mathbf{S}，\tilde{\alpha}_n, \forall \mathrm{n}\}$ and given constant is $\{\mathrm{w}_\mathrm{k}, z, \forall \mathrm{k}\}$.
3.Repeat.
4.Solve (32) for given $s_{i,n}^{t_2}$ , $v_n^{t_2}$ , $\omega_n^{t_2}$ , $\xi_n^{t_2}$ , $\psi_n^{t_2}$ and $\zeta_n^{t_2}$ .
5.Refresh $s_{i,n}^{t_2}$ , $v_n^{t_2}$ , $\omega_n^{t_2}$ , $\xi_n^{t_2}$ , $\psi_n^{t_2}$ and $\zeta_n^{t_2}$ by using the result from step 4.
6.Make $t_2$ plus 1.
7.Until convergence or $t_2 = t_{2\max}$.
8.Get the result of $s_{i,n}^{t_2}$ , $v_n^{t_2}$ , $\omega_n^{t_2}$ , $\xi_n^{t_2}$ , $\psi_n^{t_2}$ and $\zeta_n^{t_2}$ .
```

Algorithm 3 Total algorithm by Alternating Optimization

```
1.Initialize the max iteration index $t_{3\max}$ and set the iteration index $t_3$ to 0.
2.Variable are both $\{\mathrm{w}_\mathrm{k}, z, \forall \mathrm{k}\}$ and $\{\mathbf{S}，\tilde{\alpha}_n, \forall \mathrm{n}\}$.
3.Repeat .
4.Obtain $W_k^{t_3}$ and $Z^{t_3}$ with given $\{\mathbf{S}，\tilde{\alpha}_n, \forall \mathrm{n}\}$ by Algorithm 1.
5.Obtain $s_{i,n}^{t_3}$ and $v_n^{t_3}$ with given $\{\mathrm{w}_\mathrm{k}, z, \forall \mathrm{k}\}$ by Algorithm 2.
6.Refresh $\{\mathrm{w}_\mathrm{k}, z, \forall \mathrm{k}\}$ and $\{\mathbf{S}，\tilde{\alpha}_n, \forall \mathrm{n}\}$.
7.Make $t_3$ plus 1.
8.Until convergence or $t_3 = t_{3\max}$.
9.Get the result of $W_k^{t_3}$ , $Z^{t_3}$ , $s_{i,n}^{t_3}$ and $v_n^{t_3}$ .
```

7. Simulation Results

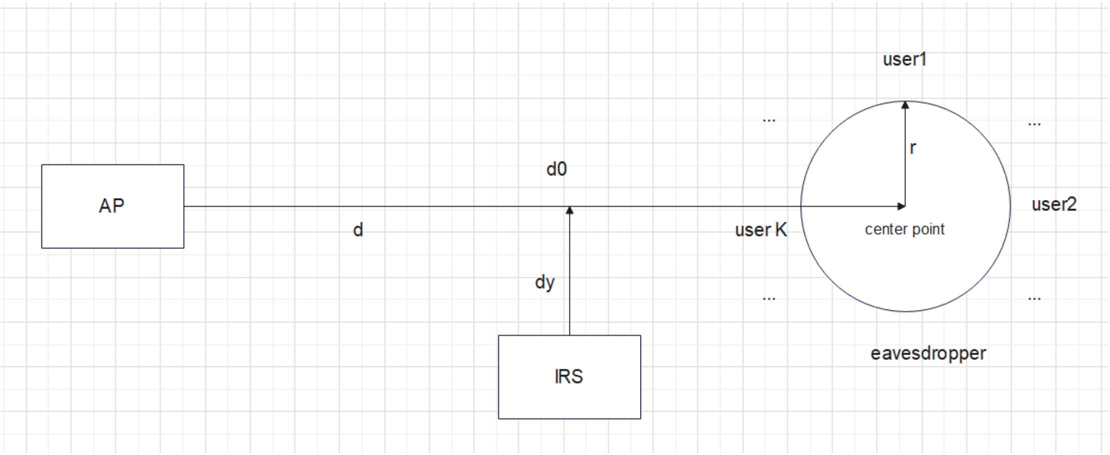

Fig.7 The system of simulation setup

In this part, we will test the proposed scheme in the last section, to talk about the system performance of this self-sustainable IRS-assisted secure system. Fig 7 shows us the system of simulation setup. From the picture, we can see that the users are distributed randomly as a circle with a radius (r=1m). Also, there is only one eavesdropper and it is also distributed in this circle. The distance between the centre point of the user and AP is ($d_0 = 60m$). The IRS locates between users and AP, the horizontal distance between AP is ($d = 30m$) and the vertical distance is ($d_y = 1m$). On AP transmitted side, it equips the linear array with ($N_T = 12$) antennas. On the reflection side, IRS equips the rectangular array with ($N = 40$) elements. On the received side, we suppose there are ($K = 2$) users.

For the transmission process, we assume it follows the distance

-dependent path loss model[41],[42], we set both antenna gain for transmitting and receiving side for IRS and AP is (10 dBi) while antenna gain for the received user is (0 dBi)[43]. The carrier frequency is (470 MHz)system and the bandwidth is (200 kHz) for the system[44]. The path loss model's reference distance is (10 meters). Since in a real transmitted environment, there is blocking and scattering which will attenuate the signal, we assume the AP-user link's path loss exponents is ($\alpha_{\mathrm{au}} = 3.6$). Since the IRS is normally used in a line-of-sight, we assume AP-IRS and IRS-user link's path loss exponents are ($\alpha_{\mathrm{ai}} = \alpha_{\mathrm{iu}} = 2.2$). Regarding small-scale fading coefficients, all links like the AP-user link, IRS-user link and AP-IRS link, are identically and independent generated and distributed (i.i.d.) Rican random variables, we use Rician factors to show the value related to it($\beta_{au=0}, \beta_{\mathrm{ai}} = \beta_{\mathrm{iu}} = 2$). We set the system noise containing quantization noise and thermal noise. Their power are (-47 dBm and -110 dBm)[45]. On the AP side, the maximum power budget is ($P_{\max} = 23dBm$), the IRS elements' power harvesting efficiency ($\eta_{\mathrm{h}} = 0.8$), the IRS element's phase shifter bit resolution is (b = 3 bits) and power consumption (PIRS(b)=1 dBm).

In fig 8, it shows the maximum transmit power budget versus the average secrecy rate in different numbers of antenna and quantization bits. We expected that the average secrecy rate will increase with the increase of the maximum transmit power budget. We set the value that there are 2 users, 1 eavesdropper and 40 IRS elements. We can see that with the development of the maximum transmit power budget, the average secrecy rate increases. While in the same maximum transmit budget, we can see that a large number of antennas and the number of quantization bits can improve system performance, to increase the average secrecy rate.

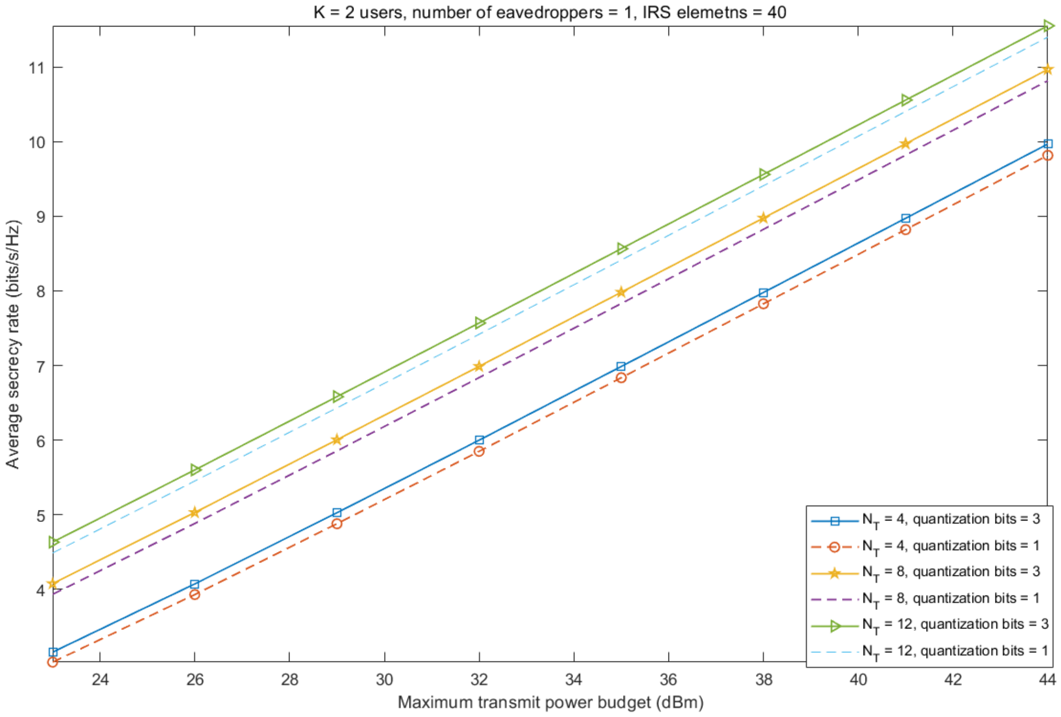

Fig.8 Maximum transmit power budget versus average secrecy rate in different numbers of antenna and quantization bits

In fig 9, it shows the number of users versus the average secrecy rate in different numbers of IRS elements. We expected that the average secrecy rate will increase with the increase of the number of users. We set value which there is 1 eavesdropper, 12 transmit antennas, 3-bit resolution and maximum transmit power is 23dBm. The plot shows that when the number of users increases, the average secrecy rate increases sharply at first from 2 users to 4 users. Then the increased range for each added user becomes slowly. While in the same number of users, the plot shows that a large number of IRS elements improve system performance, and also increase the average secrecy rate.

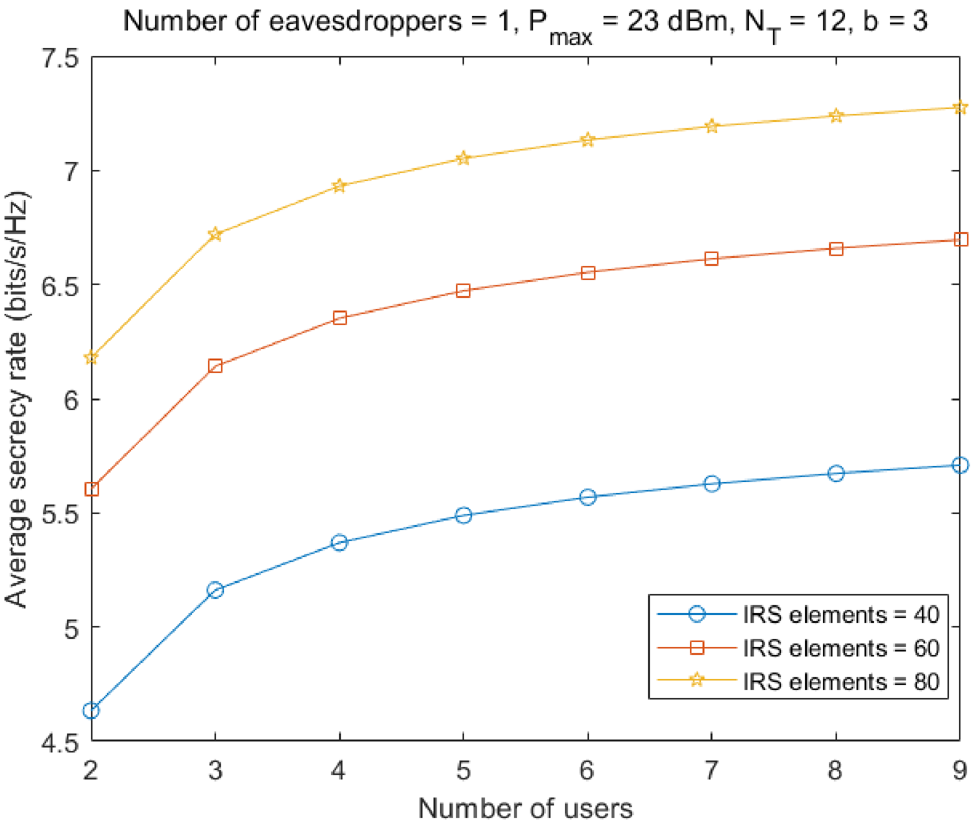

Fig.9 Numbers of users versus average secrecy rate in different numbers of IRS elements

8. Conclusion

In our thesis, we proposed the resource allocation algorithm in the security communication situation about AN applied with a IRS which is self-sustainable in a multi-user MISO communication system. The joint design of the beamforming vector and AN vector at AP, mode selection and phase shifts at IRS causes the formulated problem to be non-convex, so the AO, SCA and SDR are used to make the problem become a convex problem and guaranteed convergence.

We can see from the simulation results that our proposed scheme actually achieves a good system performance about average secrecy rate and improve the security of the IRS-assisted MISO system. It also shows that the number of antennas at AP, the bit resolution, IRS elements, numbers of users and maximum transmit power, the increase of all these values in a certain situations can further improve the system performance about average secrecy rate.

For future research, we may talk about the MIMO system rather than the MISO system in the same situation which is much more complicated. And also investigate the use of IRS in other areas like UAV, imperfect channel state information, or deep learning [46]-[52].

Appendix-The proof of theorem 1

By using the Karush-Kuhn-Tucker(KKT) to analyze the problem of (32), we can learn that a rank-one solution W_k^* and Z is necessary for solving a bounded dual problem and can get them by solving the dual variables of the dual problem of (32). Then we will talk about the detailed process of the proof by following a similar approach as in [53]-[57].

First, we will talk about the problem in both positive and negative situations. If $R_k - C_k^E \leq 0$, we can see that in this situation, the transmit information will be leaked and the transmission will be stopped which means $w_k = 0$ and $Rank(W_k) = 0$. So it fits constraint C7. While $R_k - C_k^E > 0$ and $P_{\max} > 0$,we will prove in the following that is still a rank-one matrix which also fits the constraint C7. To begin with, we transform the (25) into that:

$$\underset{\mathrm{w_k},z,\eta,\upsilon,\tau}{\text{minimize}}\ \eta \tag{37}$$

$$s.t \quad C1, C3, C5, C6: W_k \geq 0, \forall k,$$

$$C12\text{:}\ \ \overline{R}_{k1} \text{ - } \overline{R}_{k2} + \overline{C}_{k1} - \overline{C}_{k2} \leq \eta$$

$$C13\text{:}\ \ \upsilon_k \leq \sum_{j\in K} Tr(\mathrm{W_j} H_k) + Tr(\mathrm{Z} H_k)$$

$$C14\text{:}\ \ \tau_k \leq \sum_{j\in K} Tr(\mathrm{W_j} I_k) + Tr(\mathrm{Z} I_k)$$

Where $\overline{R}_{k1} = -\sum_{k\in K} \log_2(\sigma_{nk}^2 + \upsilon_k)$, and $\overline{C}_{k1} = -\sum_{k\in K} \log_2(\sigma_{ne}^2 + \tau_k)$.

Then the problem (37) is jointly convex to all variables. It fits the Slater's condition and holds a strong duality which means by solving this dual problem, we can get the optimal solution. So the Lagrangian function of (37) for the beamforming matrix W_k is

$$\begin{aligned} L &= \varepsilon \sum_{k\in K} Tr(W_k) - \sum_{k\in K} Tr(W_k Y_k) \\ &- \phi \mathrm{Tr}([\nabla_{\mathrm{W}} \overline{\mathrm{R}}_{\mathrm{k2}}(\mathrm{W}^{\mathrm{i}}, \mathrm{Z}^{\mathrm{i}}) + \nabla_{\mathrm{W}} \overline{\mathrm{C}}_{\mathrm{k2}}(\mathrm{W}^{\mathrm{i}}, \mathrm{Z}^{\mathrm{i}})]^{\mathrm{H}} (\mathrm{W} - \mathrm{W}^{\mathrm{i}})) \\ &- \sum_{\mathrm{k}\in\mathrm{K}} \varphi \sum_{j\in K} \mathrm{Tr}(W_j \mathrm{H}_{\mathrm{k}}) - \sum_{\mathrm{k}\in\mathrm{K}} \gamma \sum_{j\in K} \mathrm{Tr}(W_j \mathrm{I}_{\mathrm{k}}) + \delta \end{aligned} \tag{38}$$

Where δ represents the part in the Lagrangian function which is unrelated to the beamforming matrix W_k. $\varepsilon, Y_k, \phi, \varphi, \gamma$ is the scalar Lagrange multipliers related to C1, C4, C12, C13 and C14, respectively. Then the dual problem can be shown that

$$\underset{\varepsilon, Y_k, \phi, \varphi, \gamma \geq 0}{maximize} \quad \underset{\mathrm{w}_{\mathrm{k}}, z, \eta, \upsilon, \tau}{\text{minimize}} \ L(W_k, Z, \eta, \varepsilon, Y_k, \phi, \varphi, \gamma) \tag{39}$$

Then we will use Karush-Kuhn-Tucker(KKT) to get the optimal solution W_k^* and the KKT conditions are given by

$$K_1\text{:} \ \ \varepsilon^*, Y_k^*, \phi^*, \varphi^*, \gamma^* \geq 0 \quad K_2\text{:} \ \ Y_k^* W_k^* \quad K_3\text{:} \ \ \nabla_{W_k^*} * L = 0 \tag{40}$$

$\varepsilon^*, Y_k^*, \phi^*, \varphi^*, \gamma^*$ is the optimal Lagrange multipliers for the dual problem. Then we rewrite K_3 to do the further proof

$$Y_k^* = \varepsilon^* I_{N_T} - \Delta \tag{41}$$

Where Δ is given by

$$\begin{aligned} \Delta &= \phi^* (\nabla_{\mathrm{W}} \overline{\mathrm{R}}_{\mathrm{k2}}(\mathrm{W}^{\mathrm{i}}, \mathrm{Z}^{\mathrm{i}}) + \nabla_{\mathrm{W}} \overline{\mathrm{C}}_{\mathrm{k2}}(\mathrm{W}^{\mathrm{i}}, \mathrm{Z}^{\mathrm{i}})) \\ &+ \varphi^* \sum_{j\in K} \mathrm{Tr}(\mathrm{H}_{\mathrm{k}}) + \gamma^* \sum_{j\in K} \mathrm{Tr}(\mathrm{I}_{\mathrm{k}}) \end{aligned} \tag{42}$$

We will use the matrix Y_k^* to and optimal beamforming matrix W_k^* to verify that the optimal beamforming matrix should be a rank-one matrix. We know that $\Delta_{\max}$ is maximum eigenvalue of matrix Δ and constant since the matrix itself is negative semidefinite with zero probability since the channels are random. Then we will talk about the relationship between $\Delta_{\max}$ and ς^* in (41). When $\Delta_{\max} > \varsigma^*$, Y_k^* will not be the positive semidefinite matrix that doesn't fit K1. When $\Delta_{\max} < \varsigma^*$, Y_k^* will be a positive semidefinite matrix with the full rank which doesn't fit K2. If Y_k^* is the full rank, W_k^* will be forced to be zero and obviously not fit the condition. So there is the only situation $\Delta_{\max} = \varsigma^*$ is adopted, in this case, $Rank(Y_k^*) = \mathrm{N}_T - 1$ and $Rank(W_k) = 1$, it fits all the constraints and proves theorem 1.

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