SCHOOL OF ELECTRICAL ENGINEERING AND TELECOMMUNICATIONS

Secure Communication in Multifunctional Active Intelligent Reflection Surface-assisted MISO Systems

By

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Abstract

In the sixth-generation mobile communication systems, the intelligent reflective surfaces are expected to replace the massive MIMO technology in the fifth-generation mobile communication systems to reduce system energy consumption and implementational cost. In this thesis, we adopt the use of active intelligent reflective surface to improve the system performance, to jointly optimize the beamforming vector (Phase and Amplitude) at the IRS and the beamforming vector of the antenna array at the base station through the design of optimization algorithm. In particular, we aim to find the best beamforming vector, to maximize the minimal individual user's data rate in the system for fairness provisioning. Our design also takes into account the existence of eavesdroppers, to achieve secure communication. Besides, artificial noise is designed and injected to the communication channels deliberately to strike a balance between interference mitigation and communication secrecy.

Index Terms-Intelligent Reflecting surface (IRS), secure communication, beamforming, convex optimization.

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Sincere wishes to you, may everything be pleasant to you.

Abbreviations

5G	Fifth-Generation
6G	Sixth-Generation
mm-Wave Communication	Millimetre - Wave Communication
Massive MIMO	Massive Multiple-Input Multiple-Output
LDPC	Low-Density Parity Check
NOMA	Non-Orthogonal Multiple Access
SDN	Software-Defined Networking
THz Communication	Terahertz Communication
SM-MIMO	Spatial Modulation Multiple-Input Multiple-Output
IRS	Intelligent Reflecting Surface
OAM	Operations, Administration, and Maintenance
VLC	Visible Light Communication
FeMMB	Further enhanced Mobile Broadband
eRLLC	enhanced Ultra-Reliable, Low − Latency Communication
unMTC	ultra massive Machine Type Communication
LDHMC	Long-Distance and High-Mobility Communications
ELPC	Extremely Low-Power Communications
eMBB	enhanced Mobile Broadband

URLLC	Ultra-Reliable Low Latency Communication
mMtc	massive Machine type communication
LoS	Line-of-Sight
DoF	Degree of Freedom

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Chapter 1

Introduction

Since 2020, 5G communication technology has been deployed and used globally. Industry and academia have been promoting advance research on B5G and 6G communication system. Meanwhile, with the purpose of satisfying the more stringent requirements of 6G and addressing some of the limitations and difficulties in 5G. For example, in 6G communication systems we expect higher energy efficiency, more reliable connectivity, wider coverage, higher data rates, lower latency. These problems are challenging to solve through the key technologies of 5G and will introducing higher costs. For example, in 5G mobile communication system, MIMO rely on AP or use a huge number of multiple-input multiple-output antenna technologies to has been proposed. Precise beamforming, which requires huge hardware costs and cannot meet growing performance requirements [1].

Table 1.1: Comparison of 5G,6G Cellular System [8][9]

	5G	6G
Capacity	10-20 Gbps	100Gbps-1Tbps
Frequency (Max)	100GHz	10THz
Mobile Support Rate	500km/hr	1000km/hr
Delay	1-10ms	<1ms
Bandwidth	1GHz	100GHz
Main-Tech	mm-Wave Communication Massive MIMO LDPC/Polar Code NOMA/SDN Ultradense Network Flexible Frame Structure	THz communication SM-MIMO IRS/HBP/OAM Laser/VLC Quantum Communication AI/Machine Learning
Main Sensoria	eMBB/URLLC mMtc	FeMMB/eRLLC/unMTC/LDHMC ELPC

To break through the limitations of 5G communications, it is necessary to introduce low-cost, low-complexity, and sustainable new technologies into 6G. It has been advocated that the introduction of IRS in 6G offer a viable solution to address the upcoming challenges posed by 6G [2], The initial IRS was a passive metric plane containing a large number of low-cost passive reflective elements. Each element could independently adopt the phase of the incident wave and assist in three-dimensional beamforming. Subsequently, transmissive IRS and active IRS were introduced. In particular, ones we can apply advanced signal processing algorithm to obtain the optimal beamforming vector of each element of active IRS, thereby accurately adjusting the phase and amplitude of each unit. After adjustment, the system can obtain better beamforming performance and obtain more Accurate beamforming results significantly improve the signal rate of the communication system and the signal-to-noise ratio at legitimate users [3][4]. This advantage will be discussed and verified in this thesis.

In addition, the security of the physical layer can also be improved by deploying IRS. As one of the hot spots in the 6G communication system, concerning on secure communication should be taken for granted. Wireless communication systems are very vulnerable to attacks by eavesdroppers. The 6G system emphasizes the intelligent connection of all things. For example, autonomous driving technology and government and military networks are very demanding for secure and confidential communications [5]. In many thesis, the number of eavesdropper antennas is assumed to be smaller than the number of legitimate users, which is not necessarily reasonable in actual communication systems [6][7]. In this thesis, we assume that the eavesdropper is mature and knows our communication codebook and channel status. We included artificial noise to fight against the eavesdropper. At the same time, combined with active IRS, the impact signal can be reflected to Required legitimate users and promptly shut down active IRS in extreme cases. Assuredly, while resisting eavesdroppers, the introduction of artificial noise will also be introduced into the SINR of legitimate users as unavoidable noise, which will reduce the SINR of legitimate users to a certain extent.

To solving with complex non-convex optimization problems, we will use a suboptimal method of alternating optimization to find effective and reasonable suboptimal solutions. We will alternately adjust the beamforming matrix to find the optimal combination of phase and amplitude to achieve more accurate beamforming and use optimization algorithms to find the beamforming vector of the legal user with the smallest amount of energy in the communication to achieve the maximum capacity. Meanwhile, artificially introduced noise to resist multi-antenna eavesdropper attacks to achieve secure communication.

1.1 Overview of 6G networks challenges and Technologies

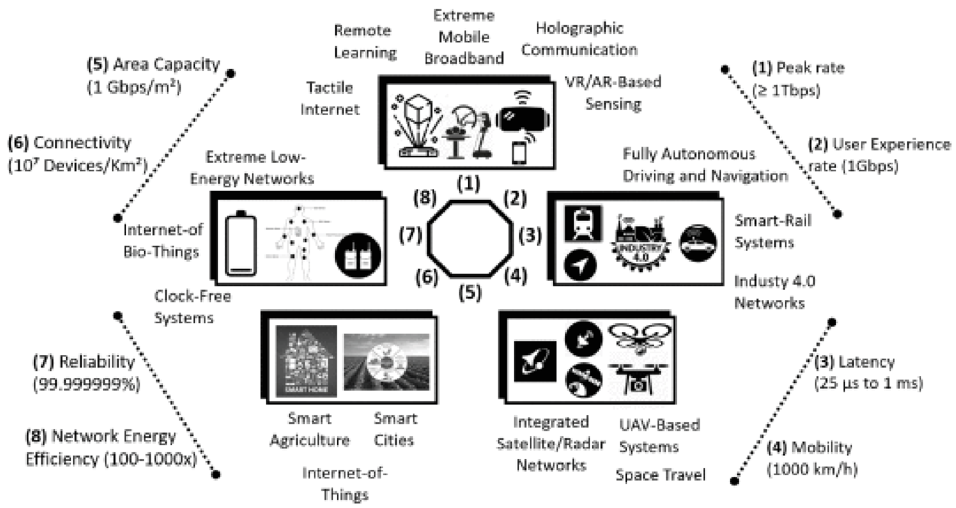

Figure 1.1: Vision for 6G systems and its underlaying use cases [10].

While the fifth-generation system has become commercial reality [10] from 2020, to a certain extent, 5G has initially met the needs of the Internet of Things (IoT). However, effectively controlling its deployment costs and continuously improving energy efficiency are still bottlenecks that are difficult to break through. A more cost-effective system with higher data rates, more reliability and greater capacity need to be researched and explored. It can be described that the emergence of the sixth-generation mobile communication system is the inevitable result of changes in modern lifestyles and social development. Article [10] summarizes the key social needs of 6G systems and focuses on how to solve various challenges encountered in the development of 6G from the physical layer (PHY). In addition, more thesis that delve into the physical layer have also been published. For example, the research contribution in [11] focuses on exploring how the waveforms in the high-frequency band are different from the past, and how to make these waveforms overcome the hardware impairment of the physical layer and perform their best performance. [12] describes the wireless power supply solution required to implement 6g physical network architecture, as well as the key technologies and challenges required. [13] discusses various radio frequency link hardware challenges faced when using the THz band in 6G systems.

Furthermore, the challenges of the physical layer are only part of the 6G system. Improvements in the data link layer and network layer are also the key points to solve the challenges in the 6g communication system. For instance, the existing TCP/IP protocol cannot guarantee the service quality of 6G applications [10].

In the following content, this thesis will discuss the key challenges facing by 6G from six directions, they are: data rate requirements, low latency requirements, synchronization requirements, security requirements, computing volume requirements, and reliability requirements. For each direction, here are some briefly descried corresponding to the actual usage scenario:

1. Data rate requirements: In holographic communication, system aim to provide users with immersive three-dimensional images. Different from the number and size of previous images, future system needs a very high data rate. In addition, unlike conventional data compression technologies, traditional technical solutions will reduce the required transmission rate but also destroy the user experience [14].
2. Low latency requirements: In scenarios related to vision and touch, ultra-low latency requirements are particularly important [10]. The industry 4.0 era emphasizes the interaction between humans and IoT systems, that is, the interaction between humans and machines. This requires suppressing the delay in the communication link to between 100 microseconds and 1 millisecond. Only in this way can provide user with a better operating experience. For example, in the future medical system, doctors want to achieve remote surgery. During the COVID-19 process, human have already experienced the convenience and importance of telemedicine. No matter where the doctor and patient are, with the help of ultra-low latency surgical robots, users can operate high-precision surgeries with real-time tactile and visual feedback, which is crucial for humans [15][16].
3. Synchronization requirements: In the future transportation system, autonomous driving technology is crucial, ranging from the driving system of private cars to the autonomous driving systems of airplanes and rockets. Through interactive systems that can be synchronized in real time, the driver can understand the implementation of the entire transportation system. Also, relying on mature autonomous driving systems to assist human driving and free up the driver's hands reduce the probability of traffic jams and traffic accidents. Meanwhile, in an autonomous driving system, information from different locations must be strictly synchronized.

4. Security requirements: Based on the above discussion of surgical robots and autonomous driving technology, it is no doubt that security must be guaranteed. Malicious disruption or malicious eavesdropping of the communication system may have catastrophic consequences. Furthermore, 6G communications will also provide services for national defence systems and government agencies, it is even more important to have a secure communications system that is not vulnerable to attack.
5. Computational requirements: As we all know, the more sophisticated the system, the greater the amount of information that needs to be processed, which means that the computational complexity is very high, and the computational complexity will bring greater time delays. This is something unexpected. For example, when engineers want to perform more accurate beamforming, they may use a convex optimization algorithm to find the global optimal solution, that is, calculate the best beamforming vector. If the system aims to find a strict global optimal solution, the computational complexity will be very high, and the computing requirements of the system will also be massive. On the one hand, how to bring more powerful computing power to the system is significant, and on the other hand, how to effectively reduce the computational complexity of the communication algorithm is also a problem that needs to be concerned [17].
6. Reliability requirements: For the entire communication system, how to reduce packet loss? How to control delays within an acceptable range? How to ensure stable service quality? How to promptly recover from system failures? All those questions are crucial to maintaining reliable communication requirements. In the 6G communication scenario described above, whether it is the autonomous driving system of a private car or the national defence information system of the entire country, the industrial IoT system need to maintain as high reliability rate, such as 99.99999% [18].

1.2 IRS Technology

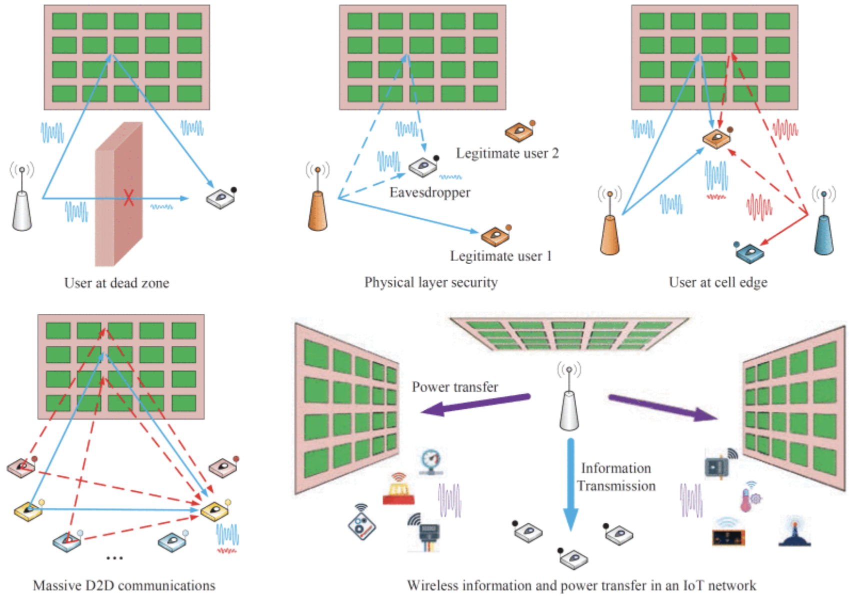

Figure 1.2: Typical IRS applications in wireless network [2].

Intelligent reconfigurable surfaces have become one of the significant technologies in 6G communications. Compared with 5G's large-scale antenna arrays, IRS has the advantages of low cost, low power consumption, high plasticity, and easy deployment. With the improvement of raw material production technology, Intelligent reconfigurable surfaces have attracted more people’s interest. By comparing the first generation of passive IRS to a mirror. The beam is emitted from the transmitting end and is reflected by the IRS. Obtain electromagnetic signals with new propagation characteristics [19]. Using IRS to replace traditional radio frequency links can achieve low energy consumption and low-cost deployment scenarios. IRS can be manufactured in various sizes and installed at any position and on any shape of object surface [21], meeting the requirements of most communication scenarios [2]. For example, when there isn’t exist straight path between the transmitter and the receiver, allocate an IRS at a suitable location between them is a good solution. By artificially creating a virtual line of sight link Los, communication scenarios with blind spots can be effectively assisted.

In addition, for millimetre wave communication scenarios with many indoor obstructions, installing passive IRS is particularly useful [2]. In view of the rapid development of electromagnetic EM technology, researchers have launched a new generation of STAR-IRS with both transmission and reflection functions [20]. Existing research shows that STAR-IRS has benefits in increasing the gain of systems, but it's combining the difficulties of hardware implementation, [20] describes the hardware challenges faced in its implementation and proposes multiple implementation solutions, such as STAR-IOS based on single-layer graphene material and STAR-IOS based on silicon material.

Table1.2: Difference Between Reflecting-Only IRS and STAR-IRS [22]

Components	Reflecting-Only IRS	STAR-IRS
Substrates	Opaque	Transparent at Radio Frequency
Elements	Only Passive reflect electric	Both Magnetic currents and electric
Coefficients	Reflection Coefficients	Transmission and Reflection Coefficients

It is well known that multiple fading effects occur in communication systems. If system only use passive IRS, only limited energy gain can be obtained. To mining more energy gain, the active IRS has been introduced. Different from the passive IRS, active IRS can achieve the effect of amplifying the reflected signal, which brings huge energy gain to wireless communication systems. The verification in [20] shows that in a typical wireless communication system, adding active IRS to the communication system can achieve a gain up to 130%, which is much higher than the gain brought by passive IRS. In addition to actively amplifying reflected signals, beamforming and coding technologies can be combined to further tap more potential in the limited resources of the communication system.

As we well know, IRS will also introduce additional noise when amplifying the signal, including IRS own noise and the inevitable amplified noise in the base station signal. It is worth mentioning that each element in the active IRS is adjustable. System can obtain the optimal beamforming vector of each unit through an algorithm, and independently adjust the beamforming vector of each unit to obtain the best SINR. This also results in higher data rates.

In addition to using passive IRS alone or active IRS indecently, by combining active and passive IRS, or even combing traditional AP and IRS will achieve better performance. [23] proposed multi-active multi-passive MAMP-IRS and modelled an efficient optimization algorithm based on graph theory. [24] considered a communication system with multiple passive IRs cooperating, maximizing the user acceptance power by finding the best reflection path, and proved that obvious gains can be obtained after multiple IRS reflections, but at the same time introduced multiplicative interference causes path loss. [25] analysed network design for hybrid passive/active beamforming, also considered how to obtain the maximum system capacity by adjusting the ratio of IRS and BS.

IRS will contribute to improving channel capacity, expanding coverage, and saving power consumption in the 6G communication system. However, it is obviously that after manually adjusted the ratio of active IRS to passive IRS, or adjust the ratio of base stations to IRS, the obtained system capacity value does not increase infinitely, which means that after reaching a certain threshold, the system capacity is infinitely. In conclusion, when deploying IRS, engineers also need to consider how to define the deployment cost of IRS, and where to deploy IRS? How to achieve sustainable development?

1.3 Secure communication

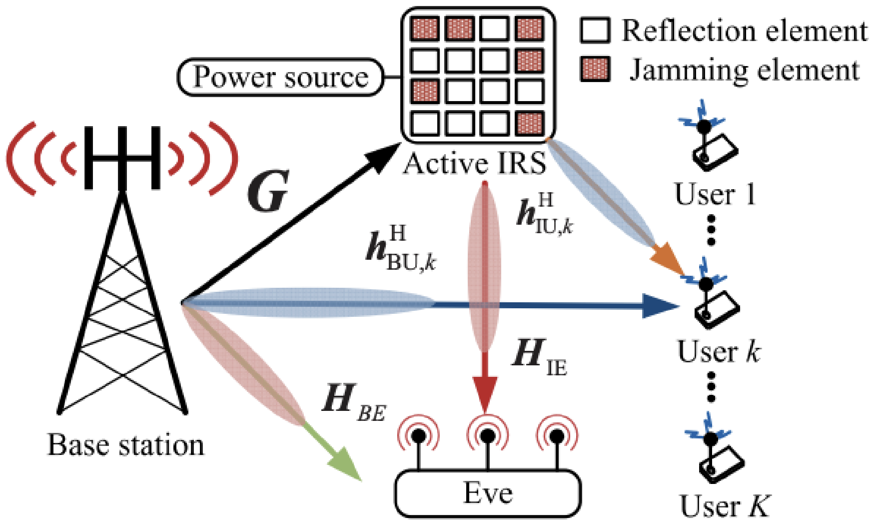

Figure 1.3: A secure wireless communication system with a multifunctional active IRS, a multi-antenna eavesdropper (Eve), and K users [29].

Conventionally, compared with unicast and broadcast communications, multicast is a more efficient way to send large amounts of public content to multiple receivers simultaneously and will be widely used in future content-centric wireless networks. However, multi-user broadcast systems are more vulnerable to eavesdropper attacks. The security issue of the physical layer is a challenging issue for 6G. In thesis [27], the maximum-security capacity of a large-scale multi-output multi-receiver communication system is found by optimizing the transmission matrix of the transmitted signal. In [26], an IRS-assisted secure multicast communication system is considered, and an equivalent channel that can maximize the security rate is formulated after trying to obtain the user channel status and the eavesdropper channel status. [2] shows the solution of how to use IRS to improve the security of the physical layer. It deploys IRS at a reasonable physical location and uses the characteristic that the reflected signal of IRS can be coordinated to offset the signal from the BS at the eavesdropper. Reduce the risk of information leakage.

However, in real communication systems, it is difficult to obtain the exact location of the eavesdropper in time, not to mention that the eavesdropper has real-time mobility. In the literature [28], artificial noise is introduced. By controlling the beamforming vector of artificial noise, the probability of leakage of signals sent by the base station is effectively reduced. At the same time, the signal quality obtained by eavesdroppers in the system is reduced. Meanwhile, the system performance and confidentiality rate are effectively improved. However, this technology has shortcomings. Researchers point out that this technology can effectively ensure information security only when the total number of eavesdropper antennas is smaller than the total number of transmitter antennas.

In the literature [29], to overcome the above difficulties, a new active IRS-assisted secure communication system is designed, allowing active IRS to act as an independent interference source to combat the illegal activities of eavesdroppers. At the same time, the optimization algorithm is used to effectively select the working mode of the IRS and adjust the amplitude and phase of each independent element in the active IRS board to reflect the impact signal to the legitimate user to achieve the goal of safe communication.

1.4 Beamforming Concept

Beamforming technology came into people's vision with the fifth generation of mobile communication systems and was widely used. During the beamforming process, the transmitting antenna maximizes the gain of the entire antenna in the direction of the mobile terminal by forming a beam. To achieve the goal of increasing signal power in a positive proportion to the number of transmitting antennas, beamforming technology is indispensable.

Generally, beamforming relies on antenna arrays consisting of 8 or more antennas. Beamforming is performed by applying different complex gains, or so-called weighting coefficients, to different elements of the antenna array. All propagation beams can be pointed in different directions, and this process is completed by phase shifting of different signals on different antennas.

The biggest difference between massive MIMO and traditional MIMO antenna systems is their beamforming technology. The conventional communication method mainly uses one or more antennas of a certain base station to realize the electromagnetic wave transmission task between the user antennas. And the principle of beamforming technology is a certain base station has many antennas, which can realize the transmission of electromagnetic waves from different sources. The directional of signal is adjusted to achieve an overlapping crossover pattern at the user end to enhance the signal. The technology that uses large-scale antenna beamforming related algorithms generally uses matrix inversion operations.

However, with the widespread use of big data and the increasing application requirements of various terminal devices. The existing 5G LTE communication system faces severe challenges. Therefore, major standardization organizations and telecommunications manufacturers around the world have carried out research and construction of the sixth-generation mobile communications system. The 6G system is committed to improving technology and adding innovations to meet the continuous development needs of future expansion of data services and growth in the number of connections, and to further enhance user experience. It can simultaneously achieve 100 times the capacity and exceed data rate at 10Gbit/s [8][9]. Beamforming technology is one of the outstanding technologies in 5G and 6G wireless communication technology and has attracted much attention in the communications field.

There are still some key issues need to be considered:

(1) For the 5G communication systems, due to the continuous increase in the number of antennas and array elements, the size of the antennas has been continuously enlarged. Under the existing technology, the antenna size exceeds the engineering construction range.
(2) The method of using 2D beam propagation channel does not meet the requirements of large-scale antennas beamforming.
(3) How can large-scale antenna systems quickly and accurately collect different terminal signals? How to combine user information accurately transmitted to each antenna? How to reduce the feedback cost generated by collecting terminal signals? How to design pilot design and channel estimation suitable for FDD systems to achieve the purpose of reciprocity between upstream and downstream channels?
(4) When using large-scale antenna beamforming related algorithms, how to choose the appropriate algorithm to reduce the computational complexity of the system and achieve real-time beam forming?

To summarize, the three most crucial issues in current technology research are:
(1) Solve the information acquisition and analysis technology about the system.
(2) Select the channel information transmission scheme of the system.
(3) Integrate the resource allocation of the system [30].

It is worth mentioning that the IRS technology proposed in the 6G communication system is a revolutionary technology because it is composed of a large number of low-cost passive elements, and each element is highly controllable. By designing software, we can control the phase and power amplification coefficient of each element and independently reflect the incident signal through IRS. This technology allows us to achieve 3D passive beamforming without removing the traditional RF link. [31] proves that by deploying IRS to assist MISO communication, the SINR at the user is significantly improved, and explains how to use the alternating optimization algorithm to find the best beamforming solution.

1.5 Challenges in 6G IRS communication

For the IRS used in 6G communication systems, its efficiency is valuable, such as, low manufacturing cost, easy deployment on any object surface, low installation cost, energy saving and low maintenance cost. While most of the above advantages are based on passive IRS, which can be regarded as a mirror, but its function is only to reflect electromagnetic waves, it is unknown that whether the reflection direction is perfectly aimed at the user or not.

Driven by the requirement for obtain better communication quality, one of the solutions is to intelligently reconfigure the wireless channel by dynamically adjusting IRS elements [23]. Some trade-offs need to be considered, such as adding FPGA circuits to IRS. To ensure that each element is independently controllable, corresponding software need to be developed to drive the hardware and seek the best control solution through optimization algorithms. In this way, more accurate CSI is obtainable to perform precise beamforming, but system may also encounter more complex manufacturing process challenges, higher economic costs, and higher energy consumption.

When many engineers model communication systems, they assume that the communication system model has a perfect channel state and that the sender and receiver know CSI, which is not consistent with actual application scenarios. Firstly, there must be very complex channels in the communication system because electromagnetic waves must undergo multiple refraction and reflection when propagating in the air [33]. The channel conditions in actual communication systems must be very complex, and there is a high probability that there is no non-blocking reflection link between the base station and the user. Secondly, the channel status is updated dynamically in real time, especially in the 6G mobile communication system. Within a limited times unit, there will be multiple information transmissions in a communication system. How to obtain it timely and correctly in the IRS-assisted communication system?

Obtaining CSI always is a big challenge [34]. It is generally difficult to estimate the completely passive IRS independently. It can only be inferred through the signal received by the user in the BS-IRS-user channel. For active IRS, sensors can be installing on the IRS board [34].[35] mentioned that channel estimation could be performing based on AOA and path gain. In addition, there are different signal processing tools based on deep learning and compressed sensing. To carry out channel estimation and other solutions [36].

Last but not least, more attention should be paid on the hardware impairment of IRS. There is no doubt that each IRS has multiple elements, and engineers need to consider the coupling characteristics between each unit. Furthermore, by using active IRS, in addition to the corresponding cost increase, the noise signal will be inevitably amplified at the same time when performing power amplification and introduce more interference to the system, which will directly affect the SINR of the communication system.

1.6 Prior Works & Improvement

Low latency requirements, high data rate requirements, synchronization requirements, security requirements, computational requirements and reliability requirements have brought many challenges to 6G, even far exceeding the processing capabilities of existing communication systems. Therefore, there is a large amount of research pay attention on designing solutions to the above challenges. Now, promising solutions can be divided into two aspects. One is a solution that focuses on performance improvement at the expense of economy and energy consumption, and the other is a solution that focuses on economy and energy consumption at the expense of performance. Obviously, any solution that sacrifices either side is not perfect. Engineers need to find the optimal solution that can achieve a balance between energy efficiency and economy.

The IRS-assisted 6G communication system has received widespread attention as a very promising research direction. Many engineers and scientists have highly recognized its existing advantages and achieved many valuable research results. Of course, the IRS-assisted 6G Communication systems still have unlimited potential waiting for us to explore. Literature [23] [32] summarizes existing research results and unsolved technical challenges. Literature [37] [38] [39] respectively discussed the software, hardware implementation, and performance analysis required for IRS-assisted communication.

[31] used passive IRS, considered the scenario where jointly optimizes AP transmission/coding and IRS adjustment phase, and proposed effective optimization solutions in single-user and multi-user scenarios, proving that compared with traditional communication systems, the use of IRs-assisted communication The performance of wireless networks has been significantly improved in terms of energy consumption and coverage. However, its research has shortcomings. Because IRS cannot directly perform channel estimation, furthermore, papers [40][41] proposed a scheme to assist single-user systems in channel estimation through double-IRS. The research shows that using two cooperative IRS for passive beamforming is significantly better than using only one IRS, but its research is limited to using double IRS.

[24] introduced a hybrid active/passive multi-IRS-assisted communication system, and jointly optimized multi-path beam beamforming to find the optimal split path and maximize the received power of the user end. However, the research in [24] still has flaws, because as

the number of IRS increases, the path loss increases. How to effectively reduce the path loss is a problem waiting to be solved. In addition, when all signals are at the same frequency, how to avoid path overlapping when entering the path world? Literature [42] proposes an effective solution based on graph theory. The author of [42] mentioned in his subsequent paper about avoiding channel estimation difficulties! Estimate channel training can be performed, that is, the IRS send pilots to each other offline when idle, and the optimal reflection path of each component can be remembered and fed back to the bs for channel estimation and beamforming.

When attempting to use the active IRS system to tap larger communication resources, the first thing should be considered is how to achieve more precise beamforming through each element in the active IRS. This goal can be achieved by adjusting not only the amplitude but also the phase of each element. But there still exists a trade -off between passive beamforming and computational complexity. To implement precise beam control, some FPGA circuits may be added to the IRS, at the same time there brings the needs to design corresponding software to control the circuit, which will inevitably increase the existing manufacturing cost and complexity. A mitigation plan was proposed in the lecture [43], that is, not all elements are in an active state, but a partitioning plan is used, and the optimal solution of how to partition and how many elements to activate is based on the water filling principal algorithm. The lecturer of [43] pointed out that when system using IRS, it is not that the IRS with more sub-blocks is better, and the more gain is obtained. As the number of sub-blocks increases, the impact of user multiplexing cannot be ignored. At the same time, [43] pointed out that most of the modelling of communication systems in the past was far-field modelling, and engineers should more carefully consider near-field modelling in future work. Also, the impact caused by field effects.

If the channel status information is already known, how to obtain fast beamforming? [44] proposed a fast IRS reflected beam training method under IRS-assisted communication system. The elements of IRS are divided into multiple groups, and the optimal beam direction is obtained based on snr through the user end. The problem of [44] is that when receiving several high-energy beams, it is difficult to determine which beam caused the high-energy due to multi-beam interference. The corresponding solution is to train multiple beams at the same time and use the dichotomy method to find and determine the best beam.

Previously many thesis attempted to find the optimal beamforming vector by jointly optimizing the amplitude and phase of each independently adjustable element of the active IRS. But most of them are limited to local optimal solutions rather than global optimal solutions [4], [45]. In future optimization algorithms, how to find the global optimal solution will be a major challenge.

1.7 Organization of the Thesis

Inspired by previous works, this thesis considers IRS-aided wireless networks. An overview of the remainder of the work for this thesis: In Chapter2, the system model has been defined. In Chapter3 the problem formulation has been carried out. Chapter4 record the simulation result. Chapter5 summarizes the work in this thesis and carry out the proposal for future work.

Chapter 2

System Model and Problem Formulation

2.1 System Signal Model

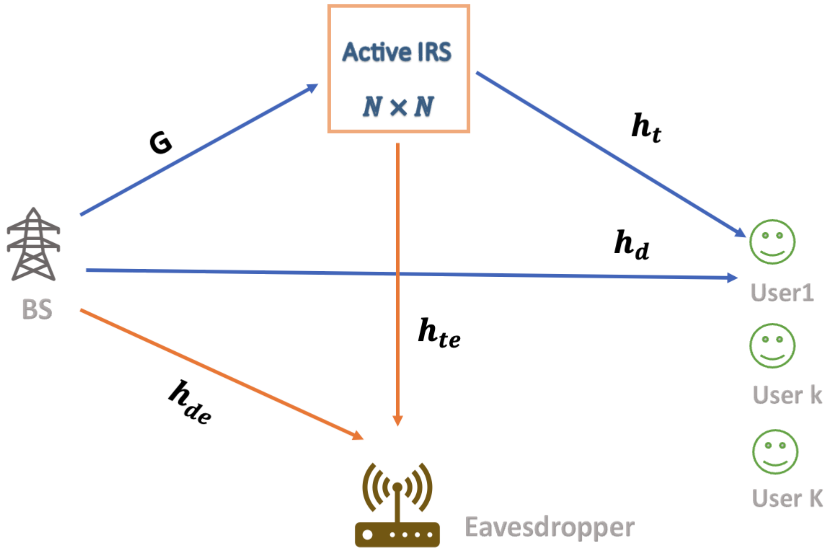

Figure 2.1: An IRS-assisted MISO wireless communication system with a multi-antenna Eavesdropper.

To considered secure transmission system, in the thesis, we consider an IRS-assisted MISO wireless communication system which exist a BS with M antennas. K wireless legal users equipped with single antenna receiving the transmitted signal. There is an $N \times N$ reflecting elements IRS which is known as active IRS participants the communication between BS and K users. It's obviously that the system is a Multiple-input and single output system modelling. In particular, the eavesdropper is equipped with L antennas.

The system model is depicted in Figure2.1. What's more, we assume that the channel state information (CSI) of all the channels is always well known. The equivalent baseband channel from BS to active IRS($BS - IRS$), the channel from active-IRS to user k ($IRS - user_k$),the directly channel from BS to User k ($BS - user_k$) ,the channel from active-IRS to the eavesdropper ($IRS - EAV$), the directly channel from BS to the eavesdropper ($BS - EAV$) are denoted by $G \in \mathbb{C}^{N \times M}$, $h_{t,k} \in \mathbb{C}^{N \times 1}$, $h_{d,k} \in \mathbb{C}^{M \times 1}$, $h_{te,l} \in \mathbb{C}^{N \times L}$,and $h_{de,l} \in \mathbb{C}^{M \times L}$ respectively.

A. System Signal Model

(i) Transmitted Signal at the BS: During each transaction, the transmitted signal vector from the BS is given by:

$$T_x = \vec{x} = \vec{s} + \vec{a}, \qquad (2.1.1)$$

For multiple users1~K:

$$\vec{x} = \sum_{k=1}^{K} \overrightarrow{w_k}\, s_k + \overrightarrow{w_N} a\,, \qquad (2.1.2)$$

where $\overrightarrow{w_k} \in \mathbb{C}^{M\times 1}, \forall k \in \{1, \ldots, K\}$,refers to the beamforming vector for user k and $s_k \sim \mathcal{CN}(0,1)$ is the data transmitting to user k. a is the artificial noise which is intending generated by BS to defence and combat the eavesdropper, while $\overrightarrow{w_N} \in \mathbb{C}^{M\times 1}$, determine the beamforming vector for artificial noise. In total we have $K+1$signals to be transmitted.

(ii) Reflected Signal at the active-IRS:

The reflection Matrix of the active IRS is given as $\Theta = \mathrm{A}\Phi$,the Φ is a matrix written as $\Phi = diag(\emptyset) \in \mathbb{C}^{N\times N}$,where $\emptyset = [\emptyset_1, \ldots, \emptyset_n, \ldots \emptyset_{N\times N}]^T \in \mathbb{C}^{N\times N}$, $\emptyset_n = \mathrm{P}_n e^{j\theta n} \forall n \in [1, \ldots, N\times N]$, $\theta \in [0,2\pi)$, $\mathrm{P}_n \geq 0$, $\mathrm{A} = \mathrm{diag}(\alpha) \in \mathbb{C}^{N\times N}$.We also define the device noise of the active-IRS as $n_I \in \mathbb{C}^{N^2\times 1}, n_I \sim \mathcal{CN}(0, \sigma_I^2)$.

(iii) Signal Model of Users: The received signal by user $k, \forall k$, can be modelling as:

$$y_k = h_{t,k}^H \Theta G \vec{x} + h_{d,k}^H \vec{x} + \mathrm{A}\Phi n_I + n_{BS}, \qquad (2.3.1)$$

the thermal noise at user k go through by the equivalent baseband channel from BS to active IRS($BS - IRS$) plus the channel from active-IRS to user k ($IRS - user_k$) is represented by $\mathrm{A}\Phi n_I$,while the noise from the directly channel from BS to User k ($BS - user_k$) is represented by n_{BS} . $\mathrm{A}\Phi n_I \sim \mathcal{CN}(0, \sigma_I^2)$, $n_{BS} \sim \mathcal{CN}(0, \sigma_n^2)$ .Therefore,the signal-to-interference-to-noise ratio (SINR) at user $k, \forall k$ and the achievable data rate are:

$$R_{U,k} = \log_2(1 + SINR_k), \qquad (2.3.2)$$

$$SINR_k = \frac{\left|\left(h_{t,k}^H \Theta G + h_{d,k}^H\right) \overrightarrow{w_k}\right|^2}{\sum_{j\neq k}\left|\left(h_{t,k}^H \Theta G + h_{d,k}^H\right)\overrightarrow{w_J}\right|^2 + \left|\left(h_{t,k}^H \Theta G + h_{d,k}^H\right)\overrightarrow{w_N}\right|^2 + \mathrm{A}\Phi\sigma_I^2 + \sigma_n^2}, \qquad (2.3.3)$$

(iv) Eavesdropper's Signal Model: The received signal at the eavesdropper is model as:

$$\overrightarrow{y_E} = h_{te,k}^H \Theta G \vec{x} + h_{de,k}^H \vec{x} + n_E, \qquad (2.4.1)$$

where $\left|F_{eq}w_N w_N^H F_{eq}^H\right|^2$ represent the artificial noise as an interference, $\sigma_I^2 \mathrm{Ah}_{te,k}\Phi\Phi^H h_{te,k}^H$is the thermal noise thought active-IRS, the last part $\sum_{K-1}\left|F_{eq}w_k w_k^H F_{eq}^H\right|^2$represent the inter-symbol interference.

$$F_{eq} = \left(h_{te,k}^H \Theta G + h_{de,k}^H\right), \qquad (2.4.2)$$

$$Q = \left(\left|F_{eq}w_N w_N^H F_{eq}^H\right|^2 + \sigma_I^2\left|\mathrm{Ah}_{te,k}\Phi\Phi^H h_{te,k}^H\right| + \sum_{K-1}\left|F_{eq}w_k w_k^H F_{eq}^H\right|^2\right), \qquad (2.4.3)$$

$$R_{E,k} = \log_2\left(det\left(I_k + Q^{-1}F_{eq}w_k w_k^H F_{eq}^H\right)\right) \ \ ,\forall k, \qquad (2.4.4)$$

Finally, the system's achievable secrecy rate between the BS and legal user k can be written as:

$$R_k = \left[R_{U,k} - R_{E,k}\right]^+ \qquad (2.4.5)$$

2.2 Problem Formulation

In this work, we propose to maximize the minimal received signal for user cofinally we can maximize the system achievable data rate by jointly designing: $\overrightarrow{w_k}, \overrightarrow{w_N}, \mathrm{A}$, Φ ,which can be formulated as optimization problem $\mathcal{P}1$:

$$\mathcal{P}1: Maximize \left\{\min_k R_k\right\} = Maximize \left\{\min_k\{R_{U,k} - R_{E,k}\}\right\} \qquad (2.5.1)$$

$$s.t. \qquad C1: \qquad \sum_K \|\overrightarrow{w_k}\|^2 + \|\overrightarrow{w_N}\|^2 \le \mathrm{P}_{BS\,Budget},$$

$$C2: \|\mathrm{A}\Phi\mathrm{G}\|^2 + \sigma_I^2\|\mathrm{A}\Phi\|^2 \le \mathrm{P}_{IRS\,Budget},$$

$$C3: R_{E,k} \le C_{K\,max} \rightarrow \log_2\left(det\left(I_k + Q^{-1}F_{eq}w_k w_k^H F_{eq}^H\right)\right) \le C_{K\,max}\ ,\forall k,$$

$$C4: \qquad \Phi = \mathrm{diag}\left(e^{j\theta_1}, \dots, e^{j\theta_n}\right), \theta \in \{0, \pi\},$$

Here, constrains C1 ensure that the max power of system is under the Transmission power from BS. Constrains C2, the power that active-IRS can amplify the signal is limited by the maximum power of IRS itself. In constrains C3, the maximum tolerable information leakage to the eavesdropper for wiretapping the signals transmitted to user k is limited to $C_{K\,max}$. constrains C4 defines the maximum adjustable range of the angle.

Chapter 3

Solution of the Optimization Problem

3.1 Algorithm Design

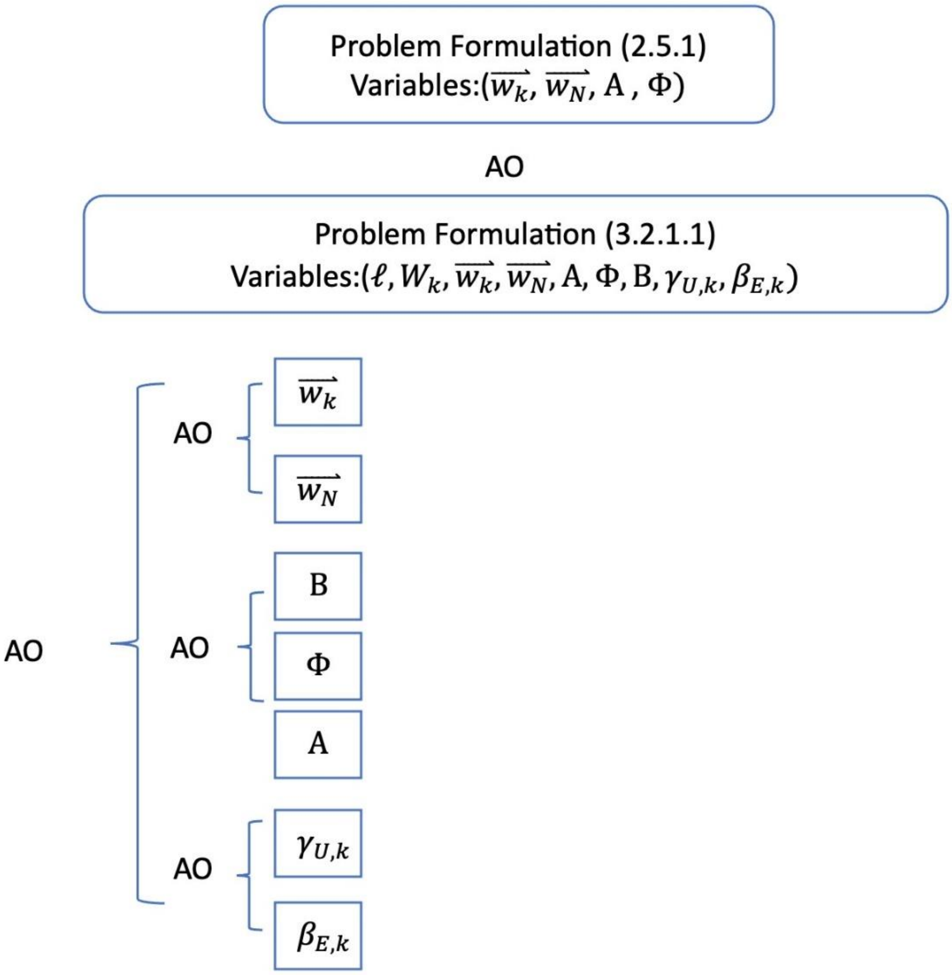

Figure 3.1: Flow chart of the proposed algorithm for solving the non-convex problem.

In this following chapter, we aiming to find the solution of the aforementioned problem in (2.5.1). It can be observed that optimization problem (2.5.1) is non-convex due to the constrains C1, C2 and C3. Normally, it takes a lot of resources to obtain the global optimization solution of $\mathcal{P}1$,it not only requires an exhaustive search but also include exceeding high computation and cost. Therefore, we obtain a sub-optimal solution to the problem $\mathcal{P}1$ by adopting AO algorithm alternatively. We implement alternate optimization in terms of

$\{\overrightarrow{w_k}, \overrightarrow{w_N}\}$ and $\{\mathrm{A}\ , \Phi\}$ respectively. We split the optimization variables via AO method [51], the problem in (2.5.1) transfer to two separate subproblems, where each separate subproblem may only has one grouped variable, and other grouped variable is at a feasible value. Which means that for the first subproblem with variables $\{\overrightarrow{w_k}, \overrightarrow{w_N}\}$,we adopt SDR algorithm to solving the problem. Finally, we will obtain the final optimize solution by updating these two grouped optimization variables alternatively. Figure3.1 shows the proposed algorithm.

3.2 Alternating Optimization

In this section, we rewrite the objection function $\mathcal{P}1$ as its equivalent function $\mathcal{P}2$, aiming to handle the non-convexity of $\mathcal{P}1$. To start with, we introduce the following proposition to handle the problem.

To start with, let $B = A\Phi$, $\mathrm{B} = (\alpha_1, \dots, \alpha_N), \alpha_N \in \{0, \pi\}$,then, let $R_{U,k} = \gamma_{U,k}$, $R_{E,k} = \beta_{E,k}$.Therefore $\mathcal{P}1$can be rewritten as following:

$$\mathcal{P}2: Maximize_{\substack{\overrightarrow{w_k}, \overrightarrow{w_N}, \mathrm{A}, \Phi, \mathrm{B}, \\ \gamma_{U,k}, \beta_{E,k}}} \left\{\min_k R_k\right\} = Maximize \left\{\min_k \{\gamma_{U,k} - \beta_{E,k}\}\right\} \quad (3.2.1)$$

$$s.t.$$

$$C1: \quad \sum_K \|\overrightarrow{w_k}\|^2 + \|\overrightarrow{w_N}\|^2 \leq \mathrm{P}_{BS\,Budget},$$

$$C2: \|\mathrm{BG}(w_k + w_N)\|^2 + \sigma_I^2 \|\mathrm{B}(w_k + w_N)\|^2 \leq \mathrm{P}_{IRS\,Budget},$$

$$C3: R_{E,k} \leq C_{K\,max} \;, \forall k,$$

$$\Leftrightarrow C3: \log_2\left(det\left(I_k + Q^{-1} F_{eq} w_k w_k^H F_{eq}^H\right)\right) \leq C_{K\,max} \;, \forall k,$$

$$\overline{C4}: \quad \mathrm{B} = \mathrm{diag}(\alpha_1, \dots, \alpha_N), \alpha \in \{0, \pi\},$$

$$C5: \gamma_{U,k} \leq R_{U,k} \; \forall k,$$

$$C6: \beta_{E,k} \geq R_{E,k} \; \forall k,$$

Consequently, let the maximum achievable security rate can be express as $\ell = \gamma_{U,k} - \beta_{E,k}$,then we get $\mathcal{P}3$ as following [60]:

$$\mathcal{P}3: Maximize_{\substack{\overrightarrow{w_k}, \overrightarrow{w_N}, \mathrm{A}, \Phi, \mathrm{B} \\ \alpha_N, \gamma_{U,k}, \beta_{E,k} \\ \ell}} \left\{\min_k R_k\right\} = Maximize \; \ell \quad (3.2.2)$$

$$s.t.$$

$$C1, C2, C3, \overline{C4}, C5, C6$$

$$C7: \ell \leq R_{U,k} \; \forall k$$

Then, we introduce the following step to simplifying the considered constraint for the optimization problem. Handle $R_{U,k}$ $\forall k$ as following:

$$R_{U,k} = \log_2(1 + SINR_k), \quad (3.2.3)$$

$$SINR_k = \frac{\left|\left(h_{t,k}^H \mathrm{B}G + h_{d,k}^H\right) \overrightarrow{w_k}\right|^2}{\sum_{j \neq k}\left|\left(h_{t,k}^H \mathrm{B}G + h_{d,k}^H\right)\overrightarrow{w_j}\right|^2 + \left|\left(h_{t,k}^H \mathrm{B}G + h_{d,k}^H\right)\overrightarrow{w_N}\right|^2 + \mathrm{B}\sigma_I^2 + \sigma_n^2}, \quad (3.2.4)$$

$$R_{U,k} = \log_2\left(1 + \frac{\left|\left(h_{t,k}^H \mathrm{B}G + h_{d,k}^H\right) \overrightarrow{w_k}\right|^2}{\sum_{j \neq k}\left|\left(h_{t,k}^H \mathrm{B}G + h_{d,k}^H\right)\overrightarrow{w_j}\right|^2 + \left|\left(h_{t,k}^H \mathrm{B}G + h_{d,k}^H\right)\overrightarrow{w_N}\right|^2 + \mathrm{B}\sigma_I^2 + \sigma_n^2}\right), \quad (3.2.5)$$

Firstly tackling $C5$: Rewrite the numerator of (3.2.4) as $\Delta\mathcal{N}_{U,k}$,also rewrite the denominator of (3.2.4) as $\Delta\mathcal{D}_{U,k}$:

$$\overline{C5}: \gamma_{U,k} \leq \; R_{U,k} = \log_2\left(1 + \frac{\Delta\mathcal{N}_{U,k}}{\Delta\mathcal{D}_{U,k}}\right), \forall k,$$

$$\Leftrightarrow \overline{C5}: (2^{\gamma_{U,k}} - 1) \leq \frac{\Delta\mathcal{N}_{U,k}}{\Delta\mathcal{D}_{U,k}} \;, \forall k,$$

$$\Leftrightarrow \overline{C5}: (2^{\gamma_{U,k}} - 1)\Delta\mathcal{D}_{U,k} \leq \; \Delta\mathcal{N}_{U,k} \,, \forall k,$$

Now, handling $R_{E,k}$

$$R_{E,k} = \log_2\left(det\left(I_k + Q^{-1}F_{eq}w_k w_k^H F_{eq}^H\right)\right) \;, \forall k, \tag{3.2.6}$$

Then tackling $C6$ and $C3$:

$$C3: R_{E,k} \leq C_{K\,max} \,,$$

$$\Leftrightarrow$$

$$\overline{C3}: \log_2\left(det\left(I_k + Q^{-1}F_{eq}w_k w_k^H F_{eq}^H\right)\right) \leq C_{K\,max} \;, \forall k,$$

Proposition 1. Since $Q^{-\frac{1}{2}}F_{eq}w_k w_k^H F_{eq}^H Q^{-\frac{1}{2}}$ is a rank-one matrix, C3 in $\mathcal{P}1$ can be transformed as its equivalent function as:

$$\overline{C3}: C_{E,k}^{\,Tol}\left(F_{eq}w_k w_k^H F_{eq}^H + \mathrm{h}_{te,k}(\mathrm{I} - \mathrm{A})\Phi\Phi^H h_{te,k}^H + \sigma_I^2 \mathrm{h}_{te,k}\Phi\Phi^H h_{te,k}^H\right) - F_{eq}w_k w_k^H F_{eq}^H \succcurlyeq 0,$$

Proof reference Appendix I.

$$where \;\; C_{E,k}^{\,Tol} = 2^{C_{K\,max}} - 1.$$

Proof. reference Appendix A.

$$C6: \beta_{E,k} \;\geq\; R_{E,k} \;\; \forall k,$$

$$\Leftrightarrow C6: \beta_{E,k} \;\geq\; \log_2\left(det\left(I_k + Q^{-1}F_{eq}w_k w_k^H F_{eq}^H\right)\right) \;, \forall k$$

$$\Leftrightarrow C6: \beta_{E,k} \;\geq\; \log_2\left(1 + (F_{eq}w_k Q^{-1} w_k^H F_{eq}^H)\right) \;, \forall k$$

$$\Leftrightarrow C6: 2^{\beta_{E,k}} - 1 \;\geq\; F_{eq}w_k Q^{-1} w_k^H F_{eq}^H \,, \forall k$$

$$\Leftrightarrow \overline{C6}: \left(2^{\beta_{E,k}} - 1\right)(Q) - F_{eq}w_k w_k^H F_{eq}^H \;\succcurlyeq 0 \,, \forall k$$

Therefore, the $\mathcal{P}3$ can be rewritten as following:

$$\mathcal{P}4: Maximize_{\substack{\overrightarrow{w_k}, \overrightarrow{w_N}, \mathrm{A}, \Phi, \mathrm{B}, \\ \gamma_{U,k}, \beta_{E,k}, \\ \ell}} \left\{\min_k R_k\right\} = Maximize \left\{\min_k \{\ell\}\right\} \tag{3.2.7}$$

$$s.t.$$

$$C1, C2, \overline{C3}, \overline{C4}, C5, \overline{C6}, C7$$

Furthermore, we use AO algorithm to obtain a sub-optimal solution to the problem $\mathcal{P}4$.We implement alternate optimization in terms of $\{\overrightarrow{w_k}, \overrightarrow{w_N}\}$ and $\{\gamma_{U,k}, \beta_{E,k}, \ell\}$ and $\{\mathrm{B}\}$ via fixing the other variables, respectively.

Algorithm 1 The alternating Optimization Algorithm

1: Let $B = A\Phi$

2: Replace $R_{U,k}$ by $\gamma_{U,k}$; $R_{E,k}$

3: Equivalent the original optimize problem as $\ell = \gamma_{U,k} - \beta_{E,k}$ with constrains 7

4: Handling $R_{U,k}$,tackling constrains 5

5: Handling $R_{E,k}$ tackling constrains 3 and 6

6: Adopt AO algorithm to obtain a sub-optimal solution to the problem $\mathcal{P}4$

3.2.1 Sub-problem 1: Optimization of Artificial Noise and Precoder Vector at the Base Station

Sub-problem 1 optimizes the beamforming vector w_k of precoder for user k, w_N, the beamforming vector of artificial noise. By defining $W_k = w_k w_k^H$[29][49], problem $\mathcal{P}4$ can be equivalent rewritten as:

$$\mathcal{P}5: Maximize_{\substack{\overrightarrow{w_k},\overrightarrow{w_N},\mathrm{A},\Phi,\mathrm{B},\\ \gamma_{U,k},\beta_{E,k},\\ \ell,W_k}} \left\{\min_k R_k\right\} = Maximize_{\substack{\overrightarrow{w_k},\overrightarrow{w_N},\mathrm{A},\Phi,\mathrm{B},\\ \gamma_{U,k},\beta_{E,k},\\ \ell,W_k}} \{\ell\} \quad (3.2.1.1)$$

$$s.t.$$

$$C1: \quad \sum_K \|\overrightarrow{w_k}\|^2 + \|\overrightarrow{w_N}\|^2 \le \mathrm{P}_{BS\,Budget},$$

$$C2: \|\mathrm{BG}(w_k + w_N)\|^2 + \sigma_I^2 \|\mathrm{B}(w_k + w_N)\|^2 \le \mathrm{P}_{IRS\,Budget},$$

$$\overline{C3}: C_{E,k}^{Tol}\left(F_{eq} w_N w_N^H F_{eq}^H + \mathrm{h}_{te,k}(\mathrm{I}-\mathrm{A})\Phi\Phi^H h_{te,k}^H + \sigma_I^2 \mathrm{h}_{te,k}\Phi\Phi^H h_{te,k}^H\right) - F_{eq} W_k F_{eq}^H \succcurlyeq 0, \forall k,$$

$$\overline{C4}: \quad \mathrm{B} = \mathrm{diag}(\alpha_1, \dots, \alpha_N), \alpha \in \{0, \pi\},$$

$$\overline{C5}: \quad (2^{\gamma_{U,k}} - 1)\Delta\mathcal{D}_{U,k} \le \Delta\mathcal{N}_{U,k}, \forall k,$$

$$\overline{C6}: \left(2^{\beta_{E,k}} - 1\right)\left(\left|F_{eq} w_N w_N^H F_{eq}^H\right|^2 + \sigma_I^2 \mathrm{A}\mathrm{h}_{te,k}\Phi\Phi^H h_{te,k}^H + \sum_{K-1}\left|F_{eq} W_k F_{eq}^H\right|^2\right) - F_{eq} W_k F_{eq}^H \succcurlyeq 0, \forall k,$$

$$C7: \quad \ell \le R_{U,k}, \forall k,$$

$$C8: \quad W_k \succcurlyeq 0, \forall k,$$

$$C9: \quad Rank(W_k) \le 1, \forall k,$$

Now, we adopt SDR by removing the rank=1 constraint in $C9$ such that the result problem in convex.

Algorithm 2 SDR-based Active IRS Optimization Algorithm
1: Present the beamforming matrix of transmitter signal as $W_k = w_k w_k^H$
2: Rewrite the alternating function as $\mathcal{P}5$,at the same time rewrite all the constrains
3: Adopt SDR to remove rank constraint
4: Repeat
5: Until convergence

In the following theorem we show that the adopted SDR is tight.

Theorem 1. If $\mathcal{P}5$ is feasible, a rank equal one solution of W_k in (3.2.1.1) can always be constructed. By exploiting the Karush-Kuhn-Tucker (KKT) conditions of $\mathcal{P}5$,it can be proved that there always exists a rank equal one solution of W_k to ensure a bounded solution of $\mathcal{P}5$[50].

Then, adopt Karush-Kuhn-Tucker (KKT) conditions by introducing the corresponding Lagrangian and the dual problem [48][54], the Lagrangian of (3.2.1.1) can be expressed as [58]:

$$\mathcal{L}\big(\ell, W_k, \overrightarrow{w_k}, \overrightarrow{w_N}, \mathrm{A}, \Phi, \mathrm{B}, \gamma_{U,k}, \beta_{E,k}, \mathcal{X}_k, \mathcal{Y}_k, \mathcal{Z}_k, \mu_k, \nu_k\big) \qquad (3.2.1.2)$$

$$\begin{aligned}
&= \sum_{k=1}^{K} \ell + \sum_{k=1}^{K} Tr\{\mathcal{X}_k\big[F_{eq} W_k F_{eq}^H \\
&\qquad - C_{E,k}^{Tol}\big(F_{eq} w_N w_N^H F_{eq}^H + \mathrm{h}_{te,k}(\mathrm{I}-\mathrm{A})\Phi\Phi^H h_{te,k}^H + \sigma_I^2 \mathrm{h}_{te,k}\Phi\Phi^H h_{te,k}^H\big)\big]\} \\
&\qquad + \sum_{k=1}^{K} Tr\Bigg\{\mathcal{Z}_k\Bigg[F_{eq} W_k F_{eq}^H \\
&\qquad - \big(2^{\beta_{E,k}}-1\big)\Bigg(\big|F_{eq} w_N w_N^H F_{eq}^H\big|^2 + \sigma_I^2 \mathrm{A}\mathrm{h}_{te,k}\Phi\Phi^H h_{te,k}^H + \sum_{K-1}\big|F_{eq} W_k F_{eq}^H\big|^2\Bigg)\Bigg]\Bigg\} \\
&\qquad - \sum_{k=1}^{K} Tr\{\mathcal{V}_k W_k\} + \mu[Tr\sum_{k=1}^{K}(W_k) + \sum_{k=1}^{K}(w_N w_N^H)] - \mathrm{P}_{BS\,Budget}] \\
&\qquad + \nu[Tr\sum_{k=1}^{K}(\mathrm{B}^H \mathrm{G}^H W_k \mathrm{BG} + \mathrm{B}^H \mathrm{G}^H w_N w_N^H \mathrm{BG}) \\
&\qquad + \sigma_I^2 Tr\sum_{k=1}^{K}(\mathrm{B}^H W_k \mathrm{B} + \mathrm{B}^H w_N w_N^H \mathrm{B}) - \mathrm{P}_{IRS\,Budget}] \\
&\qquad + \sum_{k=1}^{K}\{\rho_k[(2^{\gamma_{U,k}}-1)\Delta\mathcal{D}_{U,k} - \Delta\mathcal{N}_{U,k}]\} + \sum_{k=1}^{K}\{\eta_k[(\ell - R_{U,k})]\}
\end{aligned}$$

Where $\mathcal{X}_k, \mathcal{Z}_k$ and $\mathcal{V}_k$ are the dual variable matrices of the constraints $\overline{C3}, \overline{C6}$ and $C8$,respectively. μ, ν, ρ_k and η_k are the scalar dual variables of constrains $C1, C2, \overline{C5}$ and $C7$ respectively [56].

On the other hands, constrains $\overline{C4}$ and $C9$ will be illustrated in the later part.

Then, the dual problem of SDR optimization problem in (3.2.1.1) is given by:

$$\underset{\substack{\mathcal{X}_k,\mathcal{Z}_k,\mathcal{V}_k,\\ \mu,\nu,\\ \rho_k}}{maximize}\ \underset{\substack{\overrightarrow{w_k},\overrightarrow{w_N},\mathrm{A},\Phi,\mathrm{B},\\ \gamma_{U,k},\beta_{E,k},\\ \ell,W_k}}{minimize} \mathcal{L}\big(\ell, W_k, \overrightarrow{w_k}, \overrightarrow{w_N}, \mathrm{A}, \Phi, \mathrm{B}, \gamma_{U,k}, \beta_{E,k}, \mathcal{X}_k, \mathcal{Z}_k, \mathcal{V}_k, \mu, \nu, \rho_k\big)$$

$$(3.2.1.3)$$

Since the SDR optimization problem in (3.2.1.1) satisfied constraint qualification and is jointly convex with respect to the optimization variables [47], solving (3.2.1.3) is equivalent to solving (3.2.1.1) [59].

By defining $\{\ell, W_k, \overrightarrow{w_k}, \overrightarrow{w_N}, \mathrm{A}, \Phi, \mathrm{B}, \gamma_{U,k}, \beta_{E,k}\}$ and $\{\mathcal{X}_k, \mathcal{Z}_k, \mathcal{V}_k, \mu, \nu, \rho_k\}$ as the optimal primal solution and the optimal dual solution of (3.2.1.1),now we operating the KKT conditions[53]. The KKT conditions:

1) Gradient of the Lagrangian

$$\mathcal{L}\big(\ell, W_k, \overrightarrow{w_k}, \overrightarrow{w_N}, \mathrm{A}, \Phi, \mathrm{B}, \gamma_{U,k}, \beta_{E,k}, \mathcal{X}_k, \mathcal{Y}_k, \mathcal{V}_k, \mu, \nu, \rho_k\big) = 0 \,, \forall k \quad (3.2.1.4)$$

2) Let all constrains in terms of

$$h(x) = 0(equality\ constrians)$$
$$g(x) \le 0(inequality\ constrains)$$

After adopting KKT conditions we obtain

$$\frac{\partial \mathcal{L}}{\partial W_k} = \mathcal{X}_k F_{eq} F_{eq}^H + \mathcal{Z}_k F_{eq} F_{eq}^H - \left(2^{\beta_{E,k}} - 1\right)\mathcal{Z}_k F_{eq} F_{eq}^H - \mathcal{V}_k + \mu \mathrm{I} + \nu \mathrm{B}^H \mathrm{G}^H \mathrm{BG} + \nu \sigma_I^2 \mathrm{B}^H B, \forall k, \quad (3.2.1.5)$$

Then [52],

$$\mathcal{X}_k F_{eq} F_{eq}^H + \mathcal{Z}_k F_{eq} F_{eq}^H - \left(2^{\beta_{E,k}} - 1\right)\mathcal{Z}_k F_{eq} F_{eq}^H - \mathcal{V}_k + \mu \mathrm{I}_k + \nu \mathrm{B}^H \mathrm{G}^H \mathrm{BG} + \nu \sigma_I^2 \mathrm{B}^H B = 0, \quad (3.2.1.6)$$

Then,

$$\mathcal{V}_k = \mu \mathrm{I}_k + \mathcal{X}_k F_{eq} F_{eq}^H + \mathcal{Z}_k F_{eq} F_{eq}^H - \left(2^{\beta_{E,k}} - 1\right)\mathcal{Z}_k F_{eq} F_{eq}^H + \nu \mathrm{B}^H \mathrm{G}^H \mathrm{BG} + \nu \sigma_I^2 \mathrm{B}^H B, \quad (3.2.1.7)$$

It can be observed from (3.2.1.7) that the structure of W_k depends on the space spanned by $\mathcal{V}_k$,without loss generality, we denote $r_{V,k} = Rank(\mathcal{V}_k)$,$r_{W,k} = Rank(W_k)$.In this case, we investigate the structure of W_k when $\mathcal{V}_k$ is a full-rank matrix, i.e., $r_{V,k} = N$.By exploiting (3.2.1.7) and a basic inequality for the rank of matrices, we have:

1) $\mu > 0$,
2) $Rank(\mathcal{V}_k) = N - 1 \Leftrightarrow Rank(W_k) = 1$.

Proof. Please refer to the Appendix B.

Chapter 4

Simulation Results

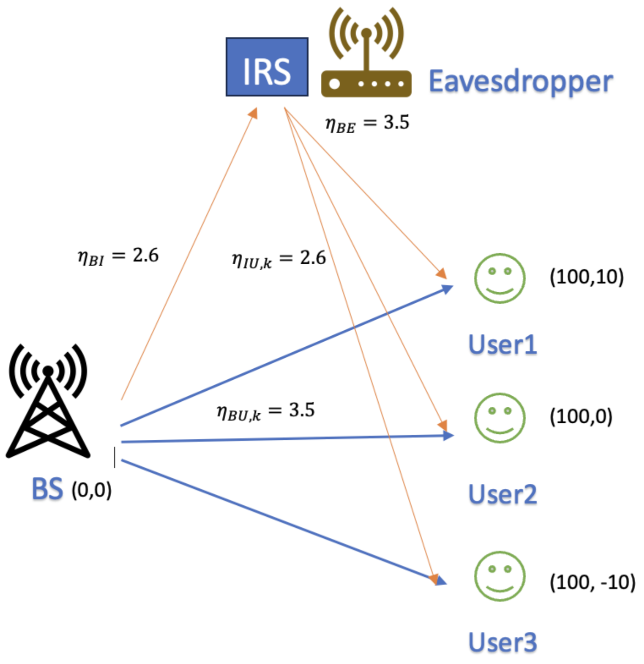

Figure 4.1: System setup for the simulation.

In this paragraph, we simulated to get the result of the proposed algorithm based on the active IRS-assisted network. As shown in figure 4.1[55], we proposed this system has K=3 users which receive transmit signal from the BS, a single active IRS board with 30 independent elements allocated between the BS and the users. The location of BS, active IRS, K users and the eavesdropper are set in (0,0), (60.20), {(100,10), (100, -10), (100,0)}, and (80,20) respectively in Cartesian coordinate system. In addition, we use the path loss model in [31], set the reference distance as 1m.

The path loss exponents of the BS to active IRS $(BS - IRS)$, the active-IRS to user $k(IRS - user_k)$,the BS to User $k(BS - user_k)$,the active-IRS to the eavesdropper $(IRS - EAV)$, the directly channel from BS to the eavesdropper $(BS - EAV)$ are $\eta_{BI} = 2.6$, $\eta_{IU,k} = 2.6$, $\eta_{BU,k} = 3.5$, $\eta_{IE} = 2.6$, $\eta_{BE} = 3.5$ respectively. Setting the centre frequency as 2. 4GHz.The number of the active IRS elements, the BS's antennas and the eavesdropper's antennas are 30, $N_T = 3/6/9$ and $N_E = 2$,respectively. The Rician factors of the BS to active IRS$(BS - IRS)$, the active-IRS to user $k(IRS - user_k)$,the BS to User $k(BS - user_k)$,the active-IRS to the eavesdropper $(IRS - EAV)$, the directly channel from BS to the eavesdropper $(BS - EAV)$ are $\beta_{BI} = 3$, $\beta_{IU,k} = 3$, $\beta_{BU,k} = 0$, $\beta_{IE} = 3$, $\beta_{BE} = 0$ respectively.

The maximum tolerable information leakage to the eavesdropper for wiretapping the signals transmitted to user k is limited to $C_{K\,max} = 1.6\ bit/s/Hz$ for all users. The power that active-IRS can amplify the signal is limited by the maximum power of IRS itself as $P_{IRS\,max} = 10dBm$.

Simulation related parameters are listed in table 4.1.

Table 4.1: System Parameters

Noise power at user k	$\sigma_{U,k}^2 = -100dBm$
Noise power at active IRS	$\sigma_I^2 = -100\ dBm$
Power budget at BS	$P_{BS,Budget} = 30\ dBm$
Active IRS elements num	M=30
User num	K=3
IRS maximum power	$P_{IRS\,max} = 10dBm$
Rician factors$(BS - IRS)$	$\beta_{BI} = 3$
Rician factors $(IRS - user_k)$	$\beta_{IU,k} = 3$
Rician factors$(BS - user_k)$	$\beta_{BU,k} = 0$
Rician factors$(IRS - EAV)$	$\beta_{IE} = 3$
Rician factors$(BS - EAV)$	$\beta_{BE} = 0$
The path loss exponents$(BS - IRS)$	$\eta_{BI} = 2.6$
The path loss exponents$(IRS - user_k)$	$\eta_{IU,k} = 2.6$
The path loss exponents$(BS - user_k)$	$\eta_{BU,k} = 3.5$
The path loss exponents$(IRS - EAV)$	$\eta_{IE} = 2.6$
The path loss exponents$(BS - EAV)$	$\eta_{BE} = 3.5$

4.1 Average minimum secrecy rate with different number of active IRS elements under certain BS Power budget

In this part, we simulated the average minimum secrecy rate in a system which exist 3 users and one eavesdropper equipped with muti-antennas. The system has certain BS station power budget which equal 30 dBm. We simulated in 3 different scenarios which the BS equipped with different antennas numbers to obtain their average minimum secrecy rate. At the same time, we increase the number of active IRS elements to get the trend of average minimum secrecy rate.

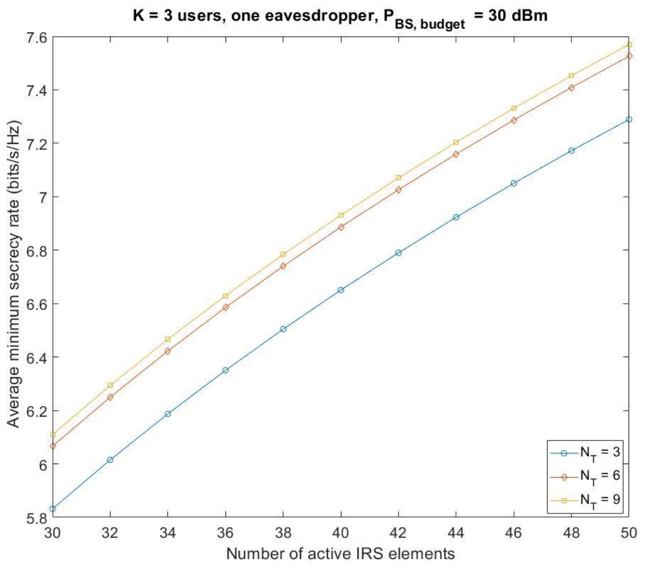

Figure 4.2: Average minimum secrecy rate when users K=3,$P_{BS,Budget} = 30\ dBm$.

Figure 4.2 demonstrate the average minimum secrecy rate versus the number of active IRS elements, as shown in the figure, the average minimum secrecy rate keeps increasing when the active IRS equipped with more elements. Moreover, when we fix the number of active IRS elements, we will obtain higher average minimum secrecy rate when the BS equipped with more antennas.

In contract, due to limited DoF and insufficient flexibility to optimize system resources, when the antennas number of eavesdropper lager than BS, especially with the increase of eavesdropper's number, eavesdroppers can enjoy more spatial freedom to achieve more effective eavesdropping which means the system will get lower average minimum secrecy rate.

Therefore, in an actual communication system, higher power is allocated both at the antennas of BS and the active IRS to offset the eavesdropper's decoding ability, but this solution will increase the total power consumption in the system. To improve this scenario, we can increase the number of active IRS elements to reduce average system power consumption. In fact, the additional spatial DoF provided by the additional IRS elements provides greater flexibility to enhance the signal quality between the BS and the user while effectively reducing information leakage to eavesdroppers.

4.2 Average minimum secrecy rate with certain number of active IRS elements under different power budget

In this section, we fixed the number of IRS elements as 30. The system exists 3 users and one muti-antennas eavesdropper, we calculated the average minimum secrecy rate under different BS power budget. Then we changed the BS equipped antennas number to explore the average minimum secrecy rate under different scenario.

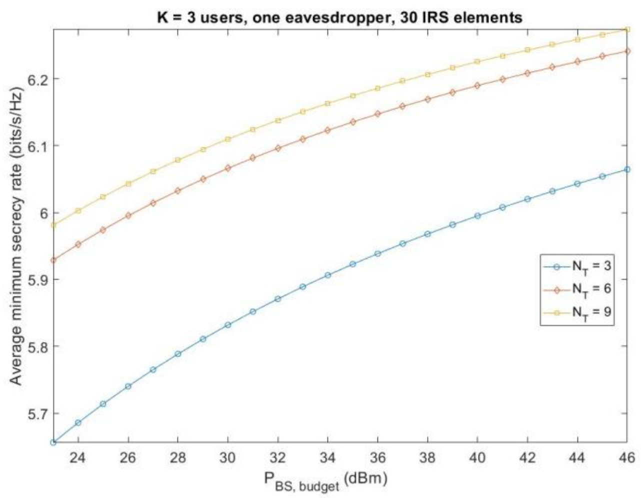

Figure 4.3: Average minimum secrecy rate when users K=3,$IRS\ elments = 30$.

Figure 4.3 illustrates the average minimum secrecy rate versus the different power consumption budget at BS. As shown in this figure, under certain BS power budget, system will obtain higher average minimum secrecy rate when we increase the number of antennas at BS. It is obviously that the system gets better performance when the BS power budget increase. While in actual system the BS power budget cannot be increased continuously.

Chapter 5

Conclusion

5.1 Summary of Simulation Results

In this thesis, we simulated a communication system equipped active IRS board in the MISO system which exist multi-antennas eavesdropper [61][62]. We investigated that both the active IRS board and the base station can launch the artificial noise to increase the security communication rate when multi antennas eavesdropper exist in downlink communication. A maximize security rate problem was defined as a non-convex problem while guaranteeing the limited power budget. Our design optimized the beamforming matrix at transmitter side and the amplitude, phase of each active IRS board elements at the same time [63], [64], [65].

We adopted the AO algorithm and SDR techniques to design a suboptimal solution [57], simulation results unveiled that under certain BS power budget we can obtain higher average minimum secrecy rate by increasing active IRS elements number or equipped more antennas at the BS.

Furthermore, with fixed active IRS elements number, we obtain higher average minimum secrecy rate when we keep increasing the BS power budget, but it obviously that the BS power budget is a limited resource and cannot be increased infinitely.

5.2 Future work

In this thesis, from the first part of simulation we can get the conclusion of that with more adjustable active IRS elements we can achieve higher average minimum secrecy rates. Moreover, we haven't investigated that with a large number of elements include [66], [67], more interference also included in the system, there must exist an optimal number of elements for the system to achieve optimal average minimum secrecy rate. Therefore, future work can be considered to continue in the following two directions. First, this thesis only explores limited number of active IRS elements. Then, future work can focus on illustrate system achievable rate with more active IRS elements, until find the optimal value. Second, we should consider the interference between each element, especially when there are a large number of elements.

From the second part of simulation, we fixed the number of active IRS elements and tried to keep increasing both the BS power budget and the BS equipped antennas number to investigate whether we can get higher average minimum secrecy rate. Furthermore, we should consider that when the number of eavesdropper antennas exceeds that of the BS, what kind of situation the system will meet and what the proposed scheme can still provide secure communication.

On the other hand, we can apply active IRS to various emerging wireless applications, e.g., integrated and sensing communication (ISAC) [68]-[71], movable antenna systems [72], [73], near-field communication [74]-[77], and distributed communication networks [78].

Appendix A

According to [46] Weinstein-Aronszajn identity:

$$det(\mathrm{I} + \mathrm{AB}) = det(\mathrm{I} + \mathrm{AB})$$

And thus $Rate_{E,k}$ in constraint $C3$ of $\mathcal{P}1$ is equivalent as:

$$\log_2\left(det\left(I_k + Q^{-1}F_{eq}w_k w_k^H F_{eq}^H\right)\right) \leq C_{K\,max} \;\;,\forall k, \qquad (A.1)$$

$$\Leftrightarrow \log_2\left(det\left(1 + Tr(\mathrm{w}_k^H F_{eq}^H Q^{-1} F_{eq} w_k)\right)\right) \leq C_{K\,max} \;\;,\forall k, \qquad (A.2)$$

$$\Leftrightarrow w_k^H F_{eq}^H Q^{-1} F_{eq} w_k \leq C\,_{E,k}^{Tol}, \qquad (A.3)$$

$$\Leftrightarrow Tr(Q^{-1} F_{eq} w_k w_k^H F_{eq}^H) \leq C\,_{E,k}^{Tol}, \qquad (A.4)$$

$$\Leftrightarrow_a \;\lambda_{max}\left\{Q^{-\frac{1}{2}} F_{eq} w_k w_k^H F_{eq}^H Q^{-\frac{1}{2}}\right\} \leq C\,_{E,k}^{Tol}, \qquad (A.5)$$

$$\Leftrightarrow C\,_{E,k}^{Tol} Q - F_{eq} w_k w_k^H F_{eq}^H \succcurlyeq 0, \qquad (A.6)$$

Appendix B

To exploit the rank of the matrix ,we denote $r_{V,k} = Rank(\mathcal{V}_k)$,$r_{W,k} = Rank(W_k)$ .In this case, we first focus on matrix $\mathcal{V}_k$ is a full-rank matrix with $r_{V,k} = N$.

Regarding to the equation:

$$\mathcal{V}_k = \mu \mathrm{I}_k + \mathcal{X}_k F_{eq} F_{eq}^H + \nu \mathrm{B}^H \mathrm{G}^H \mathrm{BG} + \nu \sigma_I^2 \mathrm{B}^H B - 2^{\beta_{E,k}} \mathcal{Z}_k F_{eq} F_{eq}^H, \qquad (B.1)$$

We define $\mathcal{M}_k$, the expression is given as:

$$\mathcal{M}_k = \mu \mathrm{I}_k + \mathcal{X}_k F_{eq} F_{eq}^H + \nu \mathrm{B}^H \mathrm{G}^H \mathrm{BG} + \nu \sigma_I^2 \mathrm{B}^H B, \qquad (B.2)$$

Then, we rewrite the first equation as:

$$\mathcal{V}_k = \mathcal{M}_k - 2^{\beta_{E,k}} \mathcal{Z}_k F_{eq} F_{eq}^H, \qquad (B.3)$$

For full rank scenario: When Matrix $\mathcal{M}_k$ is a full rank matrix. Since I_k is a full rank matrix:

$$\mathcal{V}_k W_k = 0, \forall k,$$

Cause $W_k = 0$ means we transform nothing, as a result:

$$W_k \neq 0, \forall k,$$

Based on the property of rank, we could rewrite a as follows:

$$Rank(\mathcal{V}_k) \geq Rank(\mathcal{M}_k) - Rank(\mathcal{Z}_k) = N - 1, \qquad (B.4)$$

We assume $Rank(\mathcal{V}_k) = N - 1$, considering the condition $\mathcal{V}_k W_k = 0$,their rank relationship following:

$$Rank(\mathcal{V}_k) = N - Rank(W_k),$$
$$\Rightarrow Rank(W_k) = N - (N - 1) = 1, \qquad (B.5)$$

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