Two Low-complexity Efficient Beamformers for IRS-aided Directional Modulation Networks

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Abstract—As an excellent tool for aiding communication, intelligent reflecting surface (IRS) can extend the coverage area, remove blind area, and achieve a dramatic rate improvement. In this paper, we improve the secret rate (SR) performance at directional modulation (DM) networks using IRS. To fully explore the benefits of IRS, two efficient methods are proposed to enhance SR performance. The first approach computes the confidential message (CM) beamforming vector by maximizing the SR, and the signal-to-leakage-noise ratio (SLNR) method is used to optimize the IRS phase shift matrix, which is called Max-SR-SLNR. Here, Eve is maximally interfered by transmitting artificial noise (AN) along the direct path and null-space projection (NSP) on the remaining two channels. To reduce the computational complexity, the CM, AN beamforming and IRS phase shift design are independently designed in the following methods. The CM beamforming vector is constructed based on maximum ratio transmission (MRT) criteria along the channel from Alice-to-IRS, and phase shift matrix of IRS is directly given by phase alignment (PA) method. This method is called MRT-NSP-PA. Simulation results show that the SR performance of the Max-SR-SLNR method outperforms the MRT-NSP-PA method in the cases of small-scale and medium-scale IRSs, and the latter approaches the former in performance as IRS tends to lager-scale.

Index Terms—Intelligent reflecting surface, directional modulation, confidential message, artificial noise, secrecy rate.

I. INTRODUCTION

Wireless network and mobile communication play extremely important roles in one’s daily life and have a significant impact on the development of society. However, the broadcast nature of wireless communications makes information vulnerable to interception or eavesdropping by unauthorized users [1]–[5]. Therefore, in the recent years, the physical layer security (PLS) of wireless communication has attracted extensive attention. Moreover, PLS will potentially become one of the key techniques of future sixth generation (6G) mobile communications. The main solution to the traditional PLS problem is to prevent illegal users with a computational NP-complete difficulty from breaking the confidential message (CM) by using the encryption mechanism in the upper-layer protocol stack [6].

Nevertheless, encryption technology that relies on encryption algorithms has security risks due to its conditional security. Therefore, a keyless PLS security eavesdropping channel wire-tap model was proposed by Wyner [7]. secure communication can be achieved without relying on encryption technology. In [8], [9], the authors proposed to use the artificial noise (AN) to effectively enhance the legitimate channels and weaken the eavesdropping channels in order to realize the wireless network security. In [10], the authors made an investigation of PLS with multiple single-antenna eavesdroppers in millimeter wave channel. Here, two transmission schemes, maximum ratio transmission (MRT) and maximizing the security throughput under the constraint of security interruption probability, were proposed by utilizing the specific propagation characteristics of mmWave. In [11], the authors discussed a single-antenna system and proposed a cooperative power allocation method of minimizing the Eve’s signal-to-interference-noise ratio, thereby enabling secure communication. In [12], the authors established a multi-antenna cooperative jammer-aided secure communication problem, derived its closed-form expressions for various secrecy performance metrics such as traversal secrecy rate (SR), and secrecy interception capacity.

As an effective physical layer transmission technology suitable for the line-of-sight propagation channels, directional modulation (DM) attracts increasingly research attentions from both industry and academic world in [13]–[16]. DM technology mainly addresses the problem of CM leakage in the process of transmitting information in the desired direction by designing CM beamforming, and at the same time distorts the signal constellation in the undesired direction using AN projection, such that undesired users cannot recover original signal correctly [14]. When there existed a direction measurement error, a robust DM synthesis method was designed in [15], which used the statistical properties of the direction measurement error to design the beamforming vector by using the conditional minimum mean squared error (MMSE) method.

Adding AN to the DM network is an extraordinary effective way [17]. In [16], the DM and AN synthesis scheme based on frequency-diverse arrays was proposed to achieve an improved SR performance for multiple legitimate users (LUs) where frequency offsets were optimized by maximizing signal-to-leakage-noise ratio (Max-SLNR). In [18], the Lagrange multiplier method was adopted to derive the optimal power
allocation of maximizing SR, and the AN beamforming was designed by using the NSP method. In [19], a truncated Gaussian distribution for multi-beam broadcast systems was proposed, and the robust beamforming vectors based on the SLNR and conditional expectations took DOA measurement into account to robust and secure information transmission. In [20], phase alignment (PA), AN, and random subcarrier selection based on orthogonal frequency division multiplexing were combined to achieve a precise secure wireless communications.

Compared to relay [21], intelligent reflecting surface (IRS) has the following main advantages: low-power consumption, low-cost and easy to realize large-scale or even ultra-large-scale. Thus, IRS is becoming an extremely hot research topic. By adjusting its phase shift matrix, IRS may intelligently control and change wireless environment to improve system spectral efficiency and energy efficiency [22]–[26]. IRS can be applied to a diverse variety of communication areas, such as multiple input multiple output (MIMO) [27], [28], relay [29], secure wireless information and power transmission (SWIPT) [30], spatial modulation networks [31] and unmanned aerial vehicle (UAV) network [32]. In [28], adjusting the phase of IRS was to mitigate the interference at cell-edge, and the performance of cell-edge user was improved. In an IRS-assisted multi-antenna relay network [29], an alternating iterative structure was presented to jointly optimize the beamforming and the phase shift of the IRS to harvest a substantial rate performance gain. To maximize the received power at energy harvesting receivers in IRS-assisted SWIPT system, secure transmit beamforming and phase shift matrix of IRS were jointly optimized [30]. In [31], the IRS-assisted spatial modulation was presented with the aim of maximizing SR by adjusting the switching state of the IRS and power control. In IRS-assisted unmanned aerial vehicle (UAVs) network, the average SR was improved by jointly optimizing the design of beamforming, joint trajectory and phase shift of IRS [32].

In [33], to address the problem that only an IRS cannot deal with increasing the number of eavesdroppers effectively due to the lack of sufficient spatial degrees of freedom, AN was shown to be an effective way to improve SR. In IRS-aided covert communication [34], penalty successive convex approximation algorithm and a low-complexity two-stage algorithm to jointly design the reflection coefficient of IRS and the transmission power of Alice was proposed. More importantly, the authors proved the existence of perfect covertness under perfect channel state information (CSI). The authors considered a practical scenario without Eve’s CSI, where the minimum transmit power was presented to meet Bob’s quality of service and to interfere with Eve, and was solved by using the oblique manifold and minorization-maximization algorithms [35]. In an IRS-assisted multiple-input single-output system [36], a joint optimization of transmit-side beamforming, IRS phase shift, IRS orientation and position were proposed to improve the rate performance at Bob. In [37], the authors presented a performance analysis for the IRS-aided networks with the joint impacts of the co-channel interference and noise under the assumption of non-identically distributed interferers, the exact expressions for outage probability and average bit error rate (BER) were derived.

Combining IRS and DM can make a dramatic rate performance improvement [38]–[40]. In [38], using multipath channel, a single CM signal was transmitted from Alice to Bob using two symbolic time slots, where the IRS phase matrix was aligned with the direct and cascade paths, respectively. This scheme implemented a substantial performance gain. In traditional DM networks, only one bitstream can be transmitted between base station and user, even with multiple antennas. With the help of IRS, it is possible to achieve a multiple stream transmission via controlled multipath in the line-of-sight channel. In [39], with the aid of IRS, the DM can achieve two independent CM streams from Alice to Bob under a multipath channel. To investigate the impact of optimizing the receive beamforming (RBF) vector on the performance of IRS-aided DM system, two alternately optimizing methods of jointly designing RBF vectors and IRS phase shift matrix were proposed to maximize the receive power sum in [40].

However, the proposed two methods in [39] are of high computational complexity with a high-rate-performance, and the proposed scheme is of a low spectral-efficiency with a large rate performance loss due to the fact two-symbol-period only transmits one symbol [38]. In this paper, we will propose two beamforming methods, which will strike a good balance between performance and complexity. The main contributions of the paper are as follows:

1) The IRS-assisted DM network is established to transmit a single CM stream by making full use of the advantages of DM and IRS to improve SR performance. To obtain a high performance SR, the CM beamforming vector is given by the rule of maximizing the SR (Max-SR), and the method of maximizing the signal-to-leakage-noise ratio (SLNR) in [41] is used to design the phase shift matrix of the IRS. An alternately iterative process is introduced between the CM beamforming vector and the IRS phase shift matrices to further improve the SR performance. AN is independently projected on the null-space of Alice-IRS and Alice-Bob channels, maximizing interference with Eve through direct channel. The iterative process is related to the initial value. Therefore, the method has high computational Complexity.

2) To reduce the computational complexity of the first method, a maximum ratio transmission (MRT)-based method is proposed. Here, the CM and AN beamforming vectors are constructed by using MRT and MRT-NSP, respectively whereas the IRS phase shift matrix is designed by using phase alignment (PA). It is particularly noted that the three optimization variables (OVs) are designed independently and the method is called MRT-NSP-PA. In addition, CM beamforming only is aligned to the Alice-to-IRS channel, ignoring the direct channel, etc. Therefore, the relationship between the direction of CM beamforming and the number of IRS elements is observed by simulation. By designing different MRT methods at different IRS scales, the SR performance of the MRT-NSP-PA method is improved at small-scale and medium-scale IRSs.
The remainder is organized as follows. Section II shows the system model and SR problem, two methods and one inquiry are proposed in Section III. In Section IV, numerical simulations and related analysis are presented. In the end, section V draws our conclusions.

Notations: In this paper, bold lowercase and uppercase letters represent vectors and matrices, respectively. Signs $(\cdot)^H$, $(\cdot)^{-1}$, $(\cdot)^\dagger$ and $\| \cdot \|$ denote the conjugate transpose operation, inverse operation, pseudo-inverse and 2-norm operation, respectively. The notation $I_N$ indicates the $N \times N$ identity matrix. The sign $E\{ \cdot \}$ expresses the expectation operation, and diag$(\cdot)$ denotes the diagonal operator.

II. SYSTEM MODEL

As shown in Fig. 1, an IRS-assisted DM network is sketched. Alice is a transmitter equipped with $N_a$ antennas, both Bob and Eve are the legal and illegal receivers equipped with single antenna, respectively, and IRS has $N_s$ passive reflecting elements.

The baseband signal sent from Alice is given by

$$x = \sqrt{\beta_1 P} v_{CM} s + \sqrt{\beta_2 P} v_{AN} z,$$

where $\beta_1$ and $\beta_2$ denote the power allocation (PA) factors for CM and AN with $\beta_1 + \beta_2 = 1$, $P_t$ stands for the transmit power, $v_{CM}$ represents the precoding vector of the CM with $v_{CM} \in \mathbb{C}^{N_a \times 1}$, $v_{AN}$ represents the precoding vector of the AN with $v_{AN} \in \mathbb{C}^{N_a \times 1}$, $s$ represents the CM and with a constraint $\mathbb{E}\{ |s|^2 \} = 1$, and $z$ is the AN with a constraint $\mathbb{E}\{ |z|^2 \} = 1$.

The signal received at Bob is represented as

$$y_b = (\sqrt{g_{ab}} h_{ab}^H + \sqrt{g_{ib}} h_{ib}^H \Theta_{ai} ) x + n_b,$$

where $\beta_1$ and $\beta_2$ denote the power allocation (PA) factors for CM and AN with $\beta_1 + \beta_2 = 1$, $P_t$ stands for the transmit power, $v_{AN}$ represents the precoding vector of the AN with $v_{AN} \in \mathbb{C}^{N_a \times 1}$, $s$ represents the CM and with a constraint $\mathbb{E}\{ |s|^2 \} = 1$, and $z$ is the AN with a constraint $\mathbb{E}\{ |z|^2 \} = 1$.

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III. PROPOSED BEAMFORMING METHODS

In this section, two beamforming methods, called Max-SR-SLNR and MRT-NSP-PA, are proposed in IRS-assisted DM networks. The SR performance of the two proposed methods improves by about 30% over the existing method [38], and the complexity of the latter is two orders of magnitude lower than the former under the large-scale IRS. To further improve the SR performance of the MRT-NSP-PA, the relationship between the direction of CM beamforming and the number of IRS elements is explored.

A. Proposed Max-SR-SLNR

First, we optimize the AN beamforming vector, which is independent of $\theta$ and $v_{CM}$. Alice projects the $v_{AN}$ on the null space of Alice-to-Bob channel and Alice-to-IRS channel, and maximize the received AN power along Alice-to-Eve direct channel at Eve. The optimization problem of $v_{AN}$ is given by

$$\max_{v_{AN}} \quad v_{AN}^H h_{ae} h_{ae}^H v_{AN} \quad (13a)$$

s.t. \quad $$(h_{ab} \quad H_{ai})^H v_{AN} = 0, \quad v_{AN}^H v_{AN} = 1. \quad (13b)$$

Let us define

$$P = (h_{ab} \quad H_{ai})^H. \quad (14)$$

According to the first constraint of (13), $v_{AN}$ can be rewritten as

$$v_{AN} = \left[I_{Na} - P H (P P^H)^\dagger P \right] u_{AN}, \quad (15)$$

where $u_{AN}$ is a new optimization variable with $u_{AN}^H u_{AN} = 1$. Let us define

$$T = \left[I_{N} - P H (P P^H)^\dagger P \right]. \quad (16)$$

Therefore, (13) can be simplified as

$$\max_{u_{AN}} \quad u_{AN}^T h_{ae} h_{ae}^T u_{AN} \quad (17a)$$

s.t. \quad $u_{AN}^H u_{AN} = 1. \quad (17b)$$

Since the matrix $T$ is a matrix of rank-one, $v_{AN}$ can be expressed as

$$v_{AN} = \frac{T-a e h_{ae}}{\|T-a e h_{ae}\|} \quad (18)$$

Next, we design the alternating iterative optimization problem with two variables, $v_{CM}$ and $\theta$. The optimization problem with the criterion of maximizing the SR can be expressed as

$$\max_{v_{CM}, \theta} \quad R_s (v_{CM}, \theta) \quad (19a)$$

s.t. \quad $v_{CM}^H v_{CM} = 1, \quad \theta^H \theta = N_s. \quad (19b)$$

The SINR of Bob can be re-expressed as follows

$$\gamma_b = \frac{v_{CM}^H h_{b1} h_{b1}^H v_{CM}}{v_{AN}^H h_{ae} h_{ae}^T v_{AN} + \sigma_6^2}, \quad (20)$$

where

$$h_{b1}^H = \left[\sqrt{\beta_1} P_{gb} h_{ae}^H h_{ae} + \sqrt{\beta_1} P_{gb} h_{ae}^H h_{ae} \Theta h_{ai} \right],$$

$$h_{b2}^H = \left[\sqrt{\beta_2} P_{gb} h_{ae}^H h_{ae} + \sqrt{\beta_2} P_{gb} h_{ae}^H h_{ae} \Theta h_{ai} \right]. \quad (21)$$

Accordingly, the rate of Bob can be rewritten as

$$R_b = \log_2 \left(1 + \frac{v_{CM}^H h_{b1} h_{b1}^H v_{CM}}{v_{AN}^H h_{ae} h_{ae}^T v_{AN} + \sigma_6^2} \right). \quad (22)$$

Similarly, the SINR of Eve can be rewritten as

$$\gamma_e = \frac{v_{CM}^H h_{e1} h_{e1}^H v_{CM}}{v_{AN}^H h_{ae} h_{ae}^T v_{AN} + \sigma_6^2}, \quad (23)$$

where

$$h_{e1}^H = \left[\sqrt{\beta_1} P_{ge} h_{ae}^H h_{ae} + \sqrt{\beta_1} P_{ge} h_{ae}^H h_{ae} \Theta h_{ai} \right],$$

$$h_{e2}^H = \left[\sqrt{\beta_2} P_{ge} h_{ae}^H h_{ae} + \sqrt{\beta_2} P_{ge} h_{ae}^H h_{ae} \Theta h_{ai} \right]. \quad (24)$$

Therefore, the rate of Eve can be expressed as follows

$$R_e = \log_2 \left(1 + \frac{v_{CM}^H h_{e1} h_{e1}^H v_{CM}}{v_{AN}^H h_{ae} h_{ae}^T v_{AN} + \sigma_6^2} \right). \quad (25)$$

According to (22) and (25), given $\Theta$ and $v_{AN}$, the optimization problem of (19) can be converted into

$$\max_{v_{CM}, \theta} \quad v_{CM}^H \left((a + \sigma_6^2) I_{Na} + h_{b1} h_{b1}^H \right) v_{CM} \quad (26a)$$

s.t. \quad $v_{CM}^H v_{CM} = 1, \quad (26b)$$

where $a = v_{AN}^H h_{ae} h_{ae}^T v_{AN}$, and $b = v_{AN}^H h_{ae} h_{ae}^T v_{AN}$ due to the fact that the logarithm function is a monotonically increasing function.

Accordingly, the Rayleigh-Ritz ratio theorem can be used, and $v_{CM}$ is the eigenvector corresponding to the largest eigenvalue of the following formula

$$((a + \sigma_6^2) I_{Na} + h_{e1} h_{e1}^H)^{-1} ((a + \sigma_6^2) I_{Na} + h_{b1} h_{b1}^H). \quad (27)$$

The signal-to-leakage-noise ratio (SLNR) method is used to design the phase shift of IRS [41] as follows

$$\max_{\theta} \quad \text{SLNR}(\theta) \quad (28a)$$

s.t. \quad $\theta^H \theta = N_s, \quad (28b)$$

where the objective function of (28) is

$$\text{SLNR}(\theta) = \frac{h_{eb}^H \Theta h_{ai} v_{CM} v_{CM}^H h_{e1}^H \Theta h_{eb}}{h_{eb}^H \Theta h_{ai} v_{CM} v_{CM}^H h_{e1}^H \Theta h_{eb} + \sigma_6^2}. \quad (29)$$

Onces obtain

$$\text{diag}(a) b = \text{diag}(b) a, \quad (30)$$

where $a \in \mathbb{C}^{N_s \times 1}$ and $b \in \mathbb{C}^{N_s \times 1}$. Therefore, the objective function of (28) can be expressed as

$$\frac{\theta^H A \theta}{\theta^H B \theta}. \quad (31)$$

where $A = \text{diag}(H_{ai} v_{CM}) h_{ai} h_{ai}^H \text{diag}(H_{ai} v_{CM})$, and $B = \text{diag}(H_{ai} v_{CM}) h_{ae} h_{ae}^H \text{diag}(H_{ai} v_{CM}) + \sigma_6^2 I_{Na}$. Accordingly, the Rayleigh-Ritz ratio theorem can be used, and $\theta$ can be expressed as the eigenvector corresponding to the largest eigenvalue of the following formula

$$B^{-1} A. \quad (32)$$
Let us define the eigenvector corresponding to the largest eigenvalue of (32) as u. Since $\theta$ has a constant mode constraint, $\theta$ can be expressed as

$$\theta = e^{j \text{arg } u}. \quad (33)$$

Up to now, the CM beamforming vector, AN beamforming vector and IRS phase shift matrix have been designed. It is particularly noted that the AN beamforming is independent of the CM beamforming and the IRS phase shift matrix, while the CM beamforming and the IRS phase shift matrix are mutually coupled. Therefore, it is necessary to alternately optimize $v_{CM}$ and $\theta$ until $R_s^{(p)} - R_s^{(p-1)} \leq \epsilon$, where $p$ represents the number of iterations, and the optimal $v_{CM}$ and $\theta$ can be iterated. The whole iterative process is listed in the following table.

**Algorithm 1 Proposed Max-SR-SLNR method**

1: Set initial solution $\Theta^{(0)}$, $v_{CM}^{(0)}$ and $v_{AN}$. Random multiple phases of $\theta$, and calculate the initial $R_s^{(0)}$.
2: Set $p=0$, threshold $\epsilon$.
3: repeat
4: Given $(\Theta^{(p)}, v_{AN})$, according to (27) to get $v_{CM}^{(p+1)}$.
5: Given $(v_{CM}^{(p+1)}, v_{AN})$, according to (32) to get $\Theta^{(p+1)}$.
6: Compute $R_s^{(p+1)}$ using $v_{CM}^{(p+1)}$, $v_{AN}$ and $\Theta^{(p+1)}$.
7: $p=p+1$;
8: until $R_s^{p} - R_s^{p-1} \leq \epsilon$, and record the maximum SR value.

The computational complexity of the proposed Max-SR-SLNR method is

$$O(D_1(D_2(N_s^3 + 7N_s^2 + 8N_aN_s - 2N_s - 2 + 2N_a^3 + 4N_a^2 + 2N_a + N_a - 1))) \quad (34)$$

float-point operations (FLOPs), where $D_1$ and $D_2$ represent the iterative numbers of optimization variables $v_{CM}$ and $\theta$.

**B. Proposed MRT-NSP-PA**

In the above subsection, the iterative optimization process between variables $v_{CM}$ and $\theta$ led to a high computational complexity. In order to reduce the complexity, a low-complexity MRT-NSP-PA method is proposed in which the three variables $v_{CM}$, $v_{AN}$ and $\theta$ are designed independently in the following.

Let us define

$$h_{ai} = h^H(\theta_{AI}^e). \quad (35)$$

First, the MRT method is used to design $v_{CM}$. Taking the transmit power limit into account, the final CM beamforming vector can be directly given by

$$v_{CM} = \frac{h_{ai}}{\|h_{ai}\|}. \quad (36)$$

In the same manner, the AN beamforming method based on MRT and NSP is

$$v_{AN} = \frac{T_{\text{ac}}h_{ac}}{\|T_{\text{ac}}h_{ac}\|}. \quad (37)$$

Now, we design the IRS phase matrix $\theta$, which is fully different from the former two vectors. The receive CM power via the cascaded path at Bob is equal to

$$P_b = \beta_1P_t g_{ai} v_{CM}^H \Theta H h_{ai}^H h_{ib} \Theta H v_{CM}. \quad (38)$$

(38) can be rewritten as

$$P_b = \beta_1P_t g_{ai} \theta_{HI} \text{diag}(H_{ai}v_{CM}) h_{ib}, \quad (39)$$

$$h_{ib}^H \text{diag}(H_{ai}v_{CM}) \theta. \quad (40)$$

To maximize the receive CM power along the cascaded path from Alice to Bob via IRS at Bob, the PA method directly gives the value of $\theta$ as follows

$$\theta = e^{-j \text{arg}(h_{ib}^H \text{diag}(H_{ai}v_{CM}))^H}. \quad (41)$$

The complexity of this algorithm is

$$O(2N_s^2 + 2N_aN_s - 2N_a + 4N_a^2 + 2N_a^2 - 2) \quad (42)$$

FLOPs.

In the above, the CM beamforming is only phase-aligned the Alice-to-IRS channel, ignoring the direct path in the desired user Bob, etc. In order to evaluate the impact of the CM beamforming direction on SR performance, we explore the relationship between the number of IRS elements and the direction of CM beamforming. Thus, the CM beamforming is allowed to rotate in the angle range during $[0, \pi]$. In this case, the direction of CM beamforming $\theta_{CM}$ is written as

$$\theta_{CM} \in [0, \pi]. \quad (43)$$

In what follows, we adopt three methods to design $v_{CM}$ as follows

$$v_{CM} = \frac{h_{ai}}{\|h_{ai}\|}. \quad (44)$$

$$v_{CM} = \frac{(h_{ai} + h_{ab})}{\|h_{ai} + h_{ab}\|}. \quad (45)$$

and

$$v_{CM} = \frac{h_{ai}}{\|h_{ai}\|}. \quad (46)$$

**IV. SIMULATION AND DISCUSSION**

In this section, the numeral results to examine the performance of our proposed algorithms are provided. Simulation parameters are set as follows: $P_s = 30 \text{ dBm}$, $\sigma_b^2 = \sigma_a^2 = -40 \text{ dBm}$, $N_a = 16$, the PA factor is set as $\beta_1 = 0.8$, and the distances are set as $d_{ai} = 20 \text{ m}, d_{ab} = 40 \text{ m}$, and $d_{ac} = 50 \text{ m}$, respectively. The angles of departure of each channel are set as $\theta_{ai} = 17\pi/36, \theta_{ab} = 1\pi/2$ and $\theta_{ac} = 53\pi/90$, respectively. The terminal parameter $\epsilon$ of the Max-SR-SLNR method is $10^{-3}$.

In the following, our two proposed methods are compared with the two benchmark schemes below:

1) **No-IRS**: All IRS phase shift values are set to 0, i.e., $\Theta = 0_{N_s \times N_s}$.
2) **Random Phase**: The IRS phase shift value takes on a random value, and each IRS phase shift value is randomly distributed within $[0, 2\pi]$.

Fig.2 shows that the SR versus the number of IRS elements for our proposed two methods with no IRS and random phase
as performance benchmarks. The SR performance of the two proposed methods is much better than the cases of no IRS, random phase and existing method, and gradually grows with \(N_s\). The SR performance of the Max-SR-SLNR method is much better than that of the MRT-NSP-PA method when the IRS is small to medium scale. For the case of large-scale, the latter approaches the Max-SR-SLNR in terms of SR. Therefore, optimizing the phase shift matrix of the IRS is very important.

![Fig. 2. Secrecy rate versus the number of IRS elements](image)

![Fig. 3. Secrecy rate versus the SNR](image)

![Fig. 4. Secrecy rate versus distance between Alice and Bob](image)

![Fig. 5.-Fig. 7. illustrate the SR versus directional angle of CM beamforming with different number of IRS elements as follows: 16, 128 and 512. With the increase of the number of IRS elements, the directional angle of CM beamforming is constantly changing from 0 to \(\pi\). When \(N_s=16\), the SR is the highest when the CM beamforming is transferred to the direct channel from Alice-to-Bob. When \(N_s=128\), CM beamforming is directed to the middle of Alice-to-IRS channel and Alice-to-Bob channel. When \(N_s=512\), the SR is the highest when the CM beamforming is aimed at Alice-to-IRS channel. These results are mainly due to the fact that the Alice-to-Bob direct channel dominates in the case of small-scale IRS whereas the cascaded channel via Alice, IRS and Bob dominates for the large-scale scenario. Based on the inspiration of Figs. 5.-7., three different MRT methods for designing CM beamforming vectors are proposed. In Fig. 8., SR versus the number of IRS elements is plotted for different MRT methods. It can be seen from the figure that the three methods have different advantages under different numbers of IRS elements. When \(N_s\) ranges from 8 to 32, \(v_{CM}\) is aligned with the channel \(h_{ab}\) to achieve the best SR performance. When \(N_s\) varies from 32 to 256, \(v_{CM}\) is aligned with the channel between \(h_{ab}\) and \(h_{ai}\) to achieve the best SR performance. And when \(N_s\) changes from 256 to 1024 (i.e. under hyperscale), \(v_{CM}\) is aligned with the channel \(h_{ai}\) to achieve the best SR performance.

![Fig. 9. plots the computational complexity versus the number](image)
of magnitude lower than the Max-SR-SLNR for small-scale and large-scale IRS, respectively. Moreover, as the number of IRS elements increases, the complexity gradually and linearly increases.

V. Conclusions

In this paper, we have designed the beamforming of IRS-aided DM networks in order to fully exploit the SR performance benefit from IRS. Two beamforming methods, called Max-SR-SLNR and MRT-NSP-PA, were proposed. Simulation results showed that the two proposed methods can achieve an obvious SR performance gains over no-IRS, random phase, and existing methods, especially in large-scale IRS. Moreover, the SR gains harvested by the proposed two methods grows gradually with the number of IRS elements increases. In the small-scale and medium-scale IRSs, the proposed Max-SR-SLNR method is better than the MRT-NSP-PA method in terms of SR and the latter approaches the former as the number of IRS elements goes to large-scale. However, the latter is at least one to two orders of magnitude lower than the former when the IRS size ranges from small to large.

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