IEEE Access
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SPECIAL SECTION ON RECENT ADVANCES ON RADIO ACCESS AND SECURITY METHODS IN 5G NETWORKS

Received January 28, 2018, accepted February 25, 2018, date of publication March 5, 2018, date of current version March 16, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2812180

GPI-Based Secrecy Rate Maximization Beamforming Scheme for Wireless Transmission With AN-Aided Directional Modulation

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This work was supported in part by the National Natural Science Foundation of China under Grant 61771244, Grant 61702258, Grant 61472190, Grant 61501238, and Grant 61602245, in part by the China Postdoctoral Science Foundation under Grant 2016M591852, in part by the Postdoctoral Research Funding Program of Jiangsu Province under Grant 1601257C, in part by the Natural Science Foundation of Jiangsu Province under Grant BK20150791, and in part by the Open Research Fund of National Mobile Communications Research Laboratory, Southeast University, China under Grant 2013D02.

ABSTRACT In a directional modulation network, a general power iterative (GPI) based beamforming scheme is proposed to maximize the secrecy rate (SR), where there are two optimization variables required to be optimized. The first one is the useful precoding vector of transmitting confidential messages to the desired user while the second one is the artificial noise (AN) projection matrix of forcing more AN to eavesdroppers. In such a secure network, the paramount problem is how to design or optimize the two optimization variables by different criteria. To maximize the SR (Max-SR), an alternatively iterative structure (AIS) is established between the AN projection matrix and the precoding vector for confidential messages. To choose a good initial value of iteration process of GPI, the proposed Max-SR method can readily double its convergence speed compared to the random choice of initial value. With only four iterations, it may rapidly converge to its rate ceil. From simulation results, it follows that the SR performance of the proposed AIS of GPI-based Max-SR is much better than those of conventional leakage-based and null-space projection methods in the medium and large signal-to-noise ratio (SNR) regions, and its achievable SR performance gain gradually increases as SNR increases.

INDEX TERMS Secrecy rate, artificial noise, directional modulation, general power iterative, alternatively iterative structure.

I. INTRODUCTION

In the recent decade, physical-layer security in wireless networks, as a new tool to provide an incremental safeguard of confidential message over conventional cryptography, has drawn tremendous research attention and interests from both academia and industry [1]–[11]. In [1], the author's seminal research work has established the channel model and found the tradeoff curve between the transmission rate and the data equivocation seen by the wire-tapper. More importantly, the author also proved that reliable transmission at rates up to C, is possible in approximately perfect secrecy. As a physical layer secure transmit technique suitable for line-of-propagation (LoP) scenario, directional modulation (DM) has made great progresses in many aspects with the aid of artificial noise (AN) and antenna array beamforming [12]–[19]. To enhance security, the symbol-level precoder in [13] was presented by using the concept of constructive interference in directional modulation with the goal of reducing the energy consumption at transmitter. In the presence of direction measurement error, Devaney [17] and Marengo and Gruber [18] designed three new robust DM synthesis methods for three different application scenarios: single-desired user, multi-desired user broadcasting, multi-desired user MIMO by fully making use of the property of direction measurement error. Compared with conventional non-robust methods, like null-space projection (NSP) [16], [20], the proposed robust methods actually harvests an appealing rate gain and almost an order-of-magnitude bit error rate (BER) performance improvement along desired directions. The works above only present an investigation on conventional DM with only direction-dependent property. However, if eavesdropper lies on the same direction from as the desired user, and its distance from the DM transmitter is different from the distance from the desired user to the DM transmitter, then it can still intercept the confidential messages successfully. This is the existing intrinsic secure problem for the conventional DM networks. To address the serious secure issue, recently, Colton and Kirsch [21] and Colton *et al* [22] proposed an original concept of secure and precise wireless transmission. In their works, the confidential messages are transmitted to the desired position precisely and securely. If eavesdropper is outside the small area around the desired position and locates in the same direction as the desired direction, it can not intercept the confidential messages successfully due to AN corruption and frequency random property. However, in this paper, we focus still on how to maximize the SR for conventional DM networks via GPI algorithm.

However, in a three-node directional modulation network, what is the maximum achievable secrecy rate in the absence of direction estimation error? This is an open NP-hard problem. In the following, we will solve the problem via a combination of general power iterative (GPI) method [23] and alternatively iterative structure (AIS). From simulation results, we find that the proposed GPI-based AIS can achieve an obvious secrecy rate (SR) performance gain compared to conventional NSP and leakage-based methods in the medium and large SNR regions. Our main contributions are summarized as follows:

1) In line-of-sight (LoS) scenarios, such as mmWave communications (massive MIMO), internet of things (IoT), unmanned aerial vehicle (UAV) and satellite communications, we propose a general power iterative (GPI) scheme in DM system to maximize secrecy rate (SR), which is shown to be much better than conventional NSP and leakage-based methods in terms of SR.
2) To accelerate the convergence rate of our proposed method, the leakage-based precoding vector and AN projection matrix are chosen to be the initial values instead of random generating. From simulation results, it follows that the new initial values can greatly reduce the number of iterations, and doubles the convergence rate compared to the random ones. This means that a good choice of initial values leads to a dramatic reduction in computational amount of the proposed method.

The remainder is organized as follows: Section II describes the system model. An AIS of maximizing secrecy rate (Max-SR) based on GPI with aided AN is proposed in Section III. Section IV presents the simulation results and complexity analysis. Finally, we draw conclusions in Section V.

Notations: Throughout the paper, matrices, vectors, and scalars are denoted by letters of bold upper case, bold lower case, and lower case, respectively. Signs $(\cdot)^T$, $(\cdot)^*$ and $(\cdot)^H$ denote transpose, conjugate, and conjugate transpose, respectively. Notation $\mathbb{E}\{\cdot\}$ stands for the expectation operation. Matrices $\mathbf{I}_N$ denotes the $N \times N$ identity matrix and $\mathbf{0}_{M\times N}$ denotes $M \times N$ matrix of all zeros. $\mathrm{tr}(\cdot)$ denotes matrix trace. Operation $\otimes$ denotes the Kronecker product of two matrices [24].

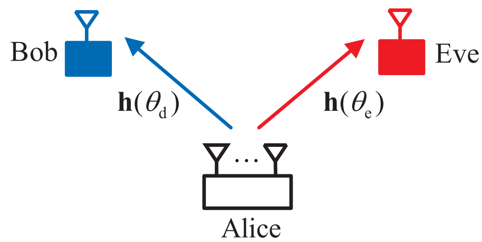

FIGURE 1. Directional modulation network.

II. SYSTEM MODEL

Fig. 1 sketches a diagram block of directional modulation (DM) network consisting of one base station (BS, Alice) equipped with N antennas, one desired node (Bob) and one eavesdropping node (Eve). Here, it is assumed that both desired node and eavesdropping node are employed with single antenna and BS employs an N-element uniformly spaced linear array. Due to its directional property, DM usually works in LoP channel. By introducing the precoding vector of confidential messages and AN projection matrix at transmitter, the transmit baseband signal from antenna array of BS is of the form

$$\mathbf{s} = \beta_1\sqrt{P_s}\mathbf{v}_d x + \alpha\beta_2\sqrt{P_s}\mathbf{P}_{AN}\mathbf{z}, \tag{1}$$

where x is the confidential message with $\mathbb{E}\left\{x^H x\right\} = 1$ and $\mathbf{z} \in \mathbb{C}^{N\times 1}$ denotes the AN vector of obeying complex Gaussian distribution $\mathcal{CN}(0, \mathbf{I}_{N-1})$. P_s denotes the total transmit power, β_1 and β_2 stand for the power allocation (PA) factors of confidential message and AN with $\beta_1^2 + \beta_2^2 = 1$. $\mathbf{v}_d \in \mathbb{C}^{N\times 1}$ denotes the transmit beamforming vector to align the confidential message to desired direction, $\mathbf{v}_d^H\mathbf{v}_d = 1$. $\mathbf{P}_{AN} \in \mathbb{C}^{N\times(N-1)}$ is the projection matrix, α normalizes $\mathbf{P}_{AN}\mathbf{z}$ such that $\alpha^2\mathbb{E}\{\mathrm{Tr}[\mathbf{P}_{AN}\mathbf{z}\mathbf{z}^H\mathbf{P}_{AN}^H]\} = 1$.

After experiencing the LoP channel, the received signal along direction θ is given by

$$\begin{aligned} y(\theta) &= \mathbf{h}^H(\theta)\mathbf{s} + n_r \\ &= \beta_1\sqrt{P_s}\mathbf{h}^H(\theta)\mathbf{v}_d x + \alpha\beta_2\sqrt{P_s}\mathbf{h}^H(\theta)\mathbf{P}_{AN}\mathbf{z} + n_r, \end{aligned} \tag{2}$$

where n_r is additive white Gaussian noise (AWGN) with $n_r \sim \mathcal{CN}(0, \sigma_r^2)$, $\mathbf{h}(\theta) \in \mathbb{C}^{N\times 1}$ is the normalized steering vector defined by $\mathbf{h}(\theta) = \sqrt{N^{-1}}[\exp(j2\pi\Psi_\theta(1)), \cdots, \exp(j2\pi\Psi_\theta(N))]^T$, and the phase function $\Psi_\theta(n)$ along direction θ is denoted as $\Psi_\theta(n) \triangleq -[n-(N+1)/2]d\cos\theta\lambda^{-1}$, $(n=1,2,\cdots,N)$, where n indexes the elements of transmit antenna array, d denotes the spacing of two adjacent antennas, and λ is the wavelength of the carrier. The receive signals at Bob and Eve are written as

$$y(\theta_d)=\beta_1\sqrt{P_s}\mathbf{h}^H(\theta_d)\mathbf{v}_d x+\alpha\beta_2\sqrt{P_s}\mathbf{h}^H(\theta_d)\mathbf{P}_{AN}\mathbf{z}+n_d, \tag{3}$$

and

$$y(\theta_e)=\beta_1\sqrt{P_s}\mathbf{h}^H(\theta_e)\mathbf{v}_d x+\alpha\beta_2\sqrt{P_s}\mathbf{h}^H(\theta_e)\mathbf{P}_{AN}\mathbf{z}+n_e, \tag{4}$$

where $n_d \sim \mathcal{CN}(0,\sigma_d^2)$ and $n_e \sim \mathcal{CN}(0,\sigma_e^2)$ represent the noise at Bob and Eve. With the help of some classic estimation algorithms such as Capon's method, MUSIC and ESPRIT, the DM transmitter in Fig. 1 can obtain the direction knowledge of eavesdroppers and desired users. Without loss of generality, it is assumed that the variances of σ_r^2, σ_d^2, and σ_r^e are equal, i.e., $\sigma_r^2=\sigma_d^2=\sigma_e^2=\sigma^2$.

To derive the SR, the achievable rates of Bob and Eve, $R(\theta_d)$ and $R(\theta_e)$ are defined as follows

$$R(\theta_d)=\log_2\left(1+\frac{\beta_1^2P_s\mathbf{h}^H(\theta_d)\mathbf{v}_d\mathbf{v}_d^H\mathbf{h}(\theta_d)}{\sigma_d^2+\alpha^2\beta_2^2P_s\mathbf{h}^H(\theta_d)\mathbf{P}_{AN}\mathbf{P}_{AN}^H\mathbf{h}(\theta_d)}\right), \tag{5}$$

and

$$R(\theta_e)=\log_2\left(1+\frac{\beta_1^2P_s\mathbf{h}^H(\theta_e)\mathbf{v}_d\mathbf{v}_d^H\mathbf{h}(\theta_e)}{\sigma_e^2+\alpha^2\beta_2^2P_s\mathbf{h}^H(\theta_e)\mathbf{P}_{AN}\mathbf{P}_{AN}^H\mathbf{h}(\theta_e)}\right), \tag{6}$$

Then, the SR $R_s(\mathbf{v}_d,\mathbf{P}_{AN})$ is defined as follows

$$\begin{aligned}R_s(\mathbf{v}_d,\mathbf{P}_{AN}) &= \max\{0, R(\theta_d)-R(\theta_e)\}\\ &= \max\{0,\log_2\left(\frac{\mathbf{v}_d^H(\mathbf{H}_d+A_d\mathbf{I}_N)\mathbf{v}_d}{\mathbf{v}_d^H(\mathbf{H}_e+A_e\mathbf{I}_N)\mathbf{v}_d}\times B\right)\},\end{aligned} \tag{7}$$

where $\mathbf{H}_d \triangleq \mathbf{h}_d\mathbf{h}_d^H$, $\mathbf{H}_e \triangleq \mathbf{h}_e\mathbf{h}_e^H$,

$$A_d=\alpha^2\beta_2^2\beta_1^{-2}\mathbf{h}^H(\theta_d)\mathbf{P}_{AN}\mathbf{P}_{AN}^H\mathbf{h}(\theta_d)+\sigma^2(\beta_1^2P_s)^{-1}, \tag{8}$$

$$A_e=\alpha^2\beta_2^2\beta_1^{-2}\mathbf{h}^H(\theta_e)\mathbf{P}_{AN}\mathbf{P}_{AN}^H\mathbf{h}(\theta_e)+\sigma^2(\beta_1^2P_s)^{-1}, \tag{9}$$

and

$$B=\frac{\mathbf{h}^H(\theta_e)\mathbf{P}_{AN}\mathbf{P}_{AN}^H\mathbf{h}(\theta_e)+\sigma^2(\alpha^2\beta_2^2P_s)^{-1}}{\mathbf{h}^H(\theta_d)\mathbf{P}_{AN}\mathbf{P}_{AN}^H\mathbf{h}(\theta_d)+\sigma^2(\alpha^2\beta_2^2P_s)^{-1}}. \tag{10}$$

The RS defined in (7) should be larger than or equal to zero. If it is less than zero, then the eavesdropper will get more mutual information than the desired user. This is not desired in a secure system. However, the second term on right hand side of (7) can be less than zero sometimes, i.e.,

$$\log_2\left(\frac{\mathbf{v}_d^H(\mathbf{H}_d+A_d\mathbf{I}_N)\mathbf{v}_d}{\mathbf{v}_d^H(\mathbf{H}_e+A_e\mathbf{I}_N)\mathbf{v}_d}\times B\right)<0 \tag{11}$$

if the eavesdropper is closer to the DM transmitter than the desired user. Thus, the operation max in RS given by (7) should be kept such that the SR is larger than or equal to zero. In what follows, we will maximize the SR by optimizing the beamforming vector $\mathbf{v}_d$ of confidential messages and the projection matrix $\mathbf{P}_{AN}$ of AN, which can be casted as

$$\begin{aligned}(\text{P1}):\ &\max_{\mathbf{v}_d,\mathbf{P}_{AN}}\ R_s(\mathbf{v}_d,\mathbf{P}_{AN})\\ &\text{subject to } \mathbf{v}_d^H\mathbf{v}_d=1,\quad \mathrm{Tr}[\mathbf{P}_{AN}\mathbf{P}_{AN}^H]=\alpha^{-2}.\end{aligned} \tag{12}$$

Obviously, the above optimization problem is NP-hard, and it is hard to be solved directly or find a closed-from solution to the above problem. The objective function in (12) as shown in (7) is divided into a sum of two non-convex functions of variables $\mathbf{v}_d$, and $\mathbf{P}_{AN}$. This means that it is still a non-convex function. Thus, we make a conclusion that the optimization problem in (12) is a nonlinear non-convex optimization.

III. PROPOSED ITERATIVE ALGORITHM TO DESIGN BEAMFORMING VECTOR $\mathbf{v}_d$ AND PROJECTION MATRIX $\mathbf{P}_{AN}$

Since the joint optimization $\mathbf{v}_d$ and $\mathbf{P}_{AN}$ in (12) is too complicated, we divided it into two mutual coupling subproblems and construct an iterative structure between them. By fixing the beamforming vector $\mathbf{v}_d$, the optimal $\mathbf{P}_{AN}$ is solved by utilizing the GPI algorithm [23]. For given projection matrix $\mathbf{P}_{AN}$, the optimal $\mathbf{v}_d$ is derived according to generalized Rayleigh-Ritz ratio in [24]. This forms an alternatively iterative structure. The Max-SR method outputs the beamforming vector $\mathbf{v}_d$ and projection matrix $\mathbf{P}_{AN}$ by repeatedly applying the GPI in [23].

A. OPTIMIZE $\mathbf{P}_{AN}$ FOR FIXED $\mathbf{v}_d$

If the beamforming vector $\mathbf{v}_d$ in (12) is fixed, then the optimization problem (12) can be reduced to

$$\begin{aligned}(\text{P1.1}):\ &\max_{\mathbf{P}_{AN}}\ R_s(\text{fixed } \mathbf{v}_d,\mathbf{P}_{AN})\\ &\text{subject to } \mathrm{Tr}[\mathbf{P}_{AN}\mathbf{P}_{AN}^H]=\alpha^{-2}.\end{aligned} \tag{13}$$

The cost function $R_s(\text{fixed } \mathbf{v}_d,\mathbf{P}_{AN})$ is rewritten as

$$\begin{aligned}R_s &= \log_2\left(\frac{\mathrm{Tr}(\mathbf{P}_{AN}^H\mathbf{B}_d\mathbf{P}_{AN})}{\mathrm{Tr}(\mathbf{P}_{AN}^H\mathbf{B}_e\mathbf{P}_{AN})}\times\frac{\mathrm{Tr}(\mathbf{P}_{AN}^H\mathbf{C}_e\mathbf{P}_{AN})}{\mathrm{Tr}(\mathbf{P}_{AN}^H\mathbf{C}_d\mathbf{P}_{AN})}\right)\\ &= \log_2\left(\frac{\mathbf{w}^H(\mathbf{I}_{N-1}\otimes\mathbf{B}_d)\mathbf{w}}{\mathbf{w}^H(\mathbf{I}_{N-1}\otimes\mathbf{B}_e)\mathbf{w}}\times\frac{\mathbf{w}^H(\mathbf{I}_{N-1}\otimes\mathbf{C}_e)\mathbf{w}}{\mathbf{w}^H(\mathbf{I}_{N-1}\otimes\mathbf{C}_d)\mathbf{w}}\right),\end{aligned} \tag{14}$$

where $\mathbf{w} \triangleq \mathrm{vec}(\mathbf{P}_{AN}) \in \mathbb{C}^{N(N-1)\times 1}$,

$$\mathbf{B}_d = \frac{\beta_2^2}{\beta_1^2}\mathbf{H}_d+\left(\frac{\sigma^2}{\beta_1^2P_s}+\mathbf{h}^H(\theta_d)\mathbf{v}_d\mathbf{v}_d^H\mathbf{h}(\theta_d)\right)\mathbf{I}_N, \tag{15}$$

$$\mathbf{B}_e = \frac{\beta_2^2}{\beta_1^2}\mathbf{H}_e+\left(\frac{\sigma^2}{\beta_1^2P_s}+\mathbf{h}^H(\theta_e)\mathbf{v}_d\mathbf{v}_d^H\mathbf{h}(\theta_e)\right)\mathbf{I}_N, \tag{16}$$

$\mathbf{C}_d=\mathbf{H}_d+\sigma^2(\beta_2^2P_s)^{-1}\mathbf{I}_N$, and $\mathbf{C}_e=\mathbf{H}_e+\sigma^2(\beta_2^2P_s)^{-1}\mathbf{I}_N$.

Consider that shrinking or stretching $\mathbf{P}_{AN}$ does not change the ratio value as shown in (14), the problem (P1.1) is equivalent to

$$(\text{P1.2}): \max_{\mathbf{w}} \frac{\mathbf{w}^H(\mathbf{I}_{N-1}\otimes\mathbf{B}_d)\mathbf{w}}{\mathbf{w}^H(\mathbf{I}_{N-1}\otimes\mathbf{B}_e)\mathbf{w}} \times \frac{\mathbf{w}^H(\mathbf{I}_{N-1}\otimes\mathbf{C}_e)\mathbf{w}}{\mathbf{w}^H(\mathbf{I}_{N-1}\otimes\mathbf{C}_d)\mathbf{w}}. \tag{17}$$

Since (17) is a non-convex quadratic fractional function, $(\mathbf{I}_{N-1}\otimes\mathbf{B}_d)$, $(\mathbf{I}_{N-1}\otimes\mathbf{B}_e)$, $(\mathbf{I}_{N-1}\otimes\mathbf{C}_d)$ and $(\mathbf{I}_{N-1}\otimes\mathbf{C}_d)$ are $N(N-1)\times N(N-1)$ positive semi-definite matrices. $\mathbf{w}$ can be solved by utilizing GPI algorithm in [23]. Then, $\mathbf{P}_{AN}$ is able to be reconstructed from $\mathbf{w}$.

B. OPTIMIZE $\mathbf{v}_d$ FOR FIXED $\mathbf{P}_{AN}$

If the AN projection matrix $\mathbf{P}_{AN}$ in (12) is fixed, the optimization problem (12) is simplified to

$$\begin{aligned}(\text{P1.3}):\quad &\max_{\mathbf{v}_d}\ R_s(\mathbf{v}_d,\ \text{fixed } \mathbf{P}_{AN})\\ &\text{subject to } \mathbf{v}_d^H\mathbf{v}_d=1\end{aligned} \tag{18}$$

Observing (7), we find that above optimization problem is equivalent to

$$\begin{aligned}(\text{P1.4}):\quad &\max_{\mathbf{v}_d}\ \frac{\mathbf{v}_d^H(\mathbf{H}_d+A_d\mathbf{I}_N)\mathbf{v}_d}{\mathbf{v}_d^H(\mathbf{H}_e+A_e\mathbf{I}_N)\mathbf{v}_d}\\ &\text{subject to } \mathbf{v}_d^H\mathbf{v}_d=1\end{aligned} \tag{19}$$

Actually, this is a generalized Rayleigh-Ritz ratio problem and the optimal $\mathbf{v}_d$ is the eigenvector corresponding to the largest eigenvalue of the matrix

$$(\mathbf{H}_e+A_e\mathbf{I}_N)^{-1}(\mathbf{H}_d+A_d\mathbf{I}_N). \tag{20}$$

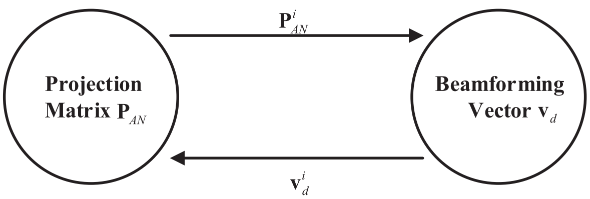

FIGURE 2. Schematic diagram of AIS.

C. INITIALIZATION OF $\mathbf{P}_{AN}$ AND $\mathbf{v}_d$

Based on the two previous subsections, we propose an AIS by alternatively solving $\mathbf{P}_{AN}$ and $\mathbf{v}_d$ to further improve secrecy rate R_s as shown in Fig. 2. The basic idea is to apply the two steps in Subsections A and B individually and repeatedly until the SR converges. The detailed process is as follows. Firstly, we take the initial values of $\mathbf{P}_{AN}$ and $\mathbf{v}_d$ being the associated eigen-vectors of the largest egienvalues of (23) and (25), respectively. Then, we compute $\mathbf{P}_{AN}$ by utilizing GPI algorithm in [23] for a given fixed $\mathbf{v}_d$. Subsequently, $\mathbf{v}_d$ is chosen to be the associated eigen-vectors of the largest egienvalues of matrix(20) under the condition $\mathbf{P}_{AN}$ is fixed. We repeat the process until the termination condition is satisfied.

Generally, the convergence rate of the iterative algorithm in Fig. 2 depends intimately on the the initial value. In what flows, we focus on the initialization of $\mathbf{P}_{AN}$ and $\mathbf{v}_d$ using the leakage concept in accordance with (3) and (4).

From the aspect of interfering the eavesdropper, the AN along direction θ_e should be viewed a useful component for eavesdropper, and the leakage of AN to the desired direction θ_d is regarded as interference. Hence, the AN-to-leakage-plus-noise ratio (ANLNR) corresponding to $\mathbf{P}_{AN}$ is defined as

$$\begin{aligned}ANLNR(\mathbf{P}_{AN}) &= \frac{\alpha^2\beta_2^2P_s\mathbf{h}^H(\theta_e)\mathbf{P}_{AN}\mathbf{P}_{AN}^H\mathbf{h}(\theta_e)}{\alpha^2\beta_2^2P_s\mathbf{h}^H(\theta_d)\mathbf{P}_{AN}\mathbf{P}_{AN}^H\mathbf{h}(\theta_d)+\sigma^2}\\ &= \frac{\mathrm{Tr}[\mathbf{P}_{AN}^H\mathbf{H}_e\mathbf{P}_{AN}]}{\mathrm{Tr}[\mathbf{P}_{AN}^H(\mathbf{H}_d+\frac{\sigma^2}{\beta_2^2P_s}\mathbf{I}_N)\mathbf{P}_{AN}]}.\end{aligned} \tag{21}$$

When maximizing the above cost function $ANLNR(\mathbf{P}_{AN})$, the optimization variable $\mathbf{P}_{AN}$ is a matrix. To solve this problem, we convert matrix $\mathbf{P}_{AN}$ into a column vector $\mathbf{w}$ using vec operation, and the associated cost function becomes

$$ANLNR(\mathbf{w}) = \frac{\mathbf{w}^H(\mathbf{I}_{N-1}\otimes\mathbf{H}_e)\mathbf{w}}{\mathbf{w}^H[\mathbf{I}_{N-1}\otimes(\mathbf{H}_d+\frac{\sigma^2}{\beta_2^2P_s}\mathbf{I}_N)]\mathbf{w}}. \tag{22}$$

Therefore, by maximizing the above objective function $ANLNR(\mathbf{w})$, we have the optimum $\mathbf{w}$ being the eigenvector corresponding to the largest eigenvalues of matrix

$$\left[\mathbf{I}_{N-1}\otimes(\mathbf{H}_d+\sigma^2(\beta_2^2P_s)^{-1}\mathbf{I}_N)\right]^{-1}(\mathbf{I}_{N-1}\otimes\mathbf{H}_e). \tag{23}$$

This completes the initialization of $\mathbf{P}_{AN}$.

Similarly, as the desired user hopes that the confidential message x should be leaked to the eavesdropper along the eavesdropper direction θ_e as little as possible, we define the confidential signal-to-leakage-plus-noise ratio (CSLNR) corresponding to $\mathbf{v}_d$ as

$$\begin{aligned}CSLNR(\mathbf{v}_d) &= \frac{\beta_1^2P_s\mathbf{v}_d^H\mathbf{h}(\theta_d)\mathbf{h}(\theta_d)^H\mathbf{v}_d}{\beta_1^2P_s\mathbf{v}_d^H\mathbf{h}(\theta_e)\mathbf{h}(\theta_e)^H\mathbf{v}_d+\sigma^2}\\ &= \frac{\mathbf{v}_d^H\mathbf{H}_d\mathbf{v}_d}{\mathbf{v}_d^H(\mathbf{H}_e+\frac{\sigma^2}{\beta_1^2P_s}\mathbf{I}_N)\mathbf{v}_d}.\end{aligned} \tag{24}$$

Maximizing (24) yields the initial value of $\mathbf{v}_d$ being the eigenvector corresponding to the largest eigenvalues of matrix

$$(\mathbf{H}_e+\sigma^2(\beta_1^2P_s)^{-1}\mathbf{I}_N)^{-1}\mathbf{H}_d. \tag{25}$$

Finally, the detailed implementation process of our proposed AIS scheme is summarized in Algorithm 1.

In Algorithm 1, parameter δ is the tolerance factor. To make the above algorithm more clear, the corresponding detailed flow graph is also presented in Fig. 3.

IV. SIMULATION, DISCUSSION, AND COMPLEXITY ANALYSIS

In this section, simulation results are presented to evaluate the performance of the proposed algorithm. The leakage-based method in [25] and NSP method in [20] are used For

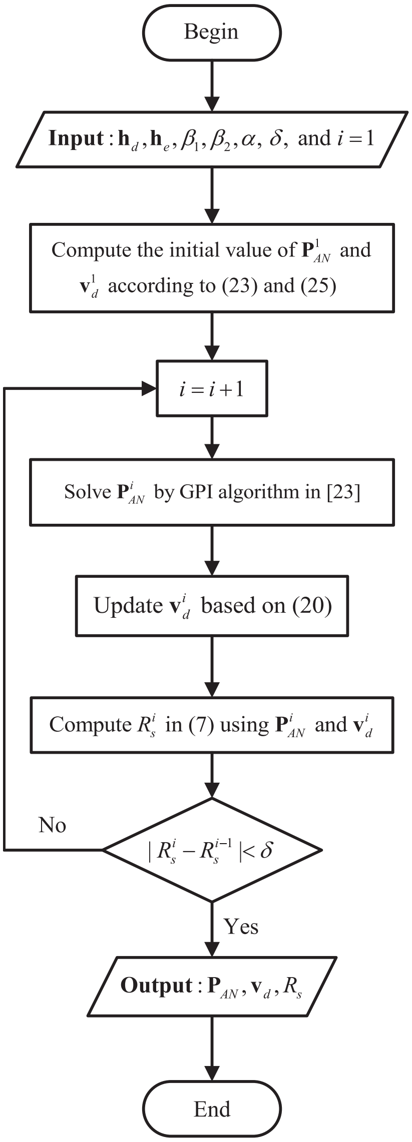

FIGURE 3. Flow graph of our proposed algorithm.

Algorithm 1 Proposed Iterative Algorithm to Solve $\mathbf{P}_{AN}$ and $\mathbf{v}_d$

Input: $\mathbf{h}_d$, $\mathbf{h}_e$, β_1, β_2, α and δ
Output: $\mathbf{P}_{AN}$, $\mathbf{v}_d$, R_s
Initialization: $i = 1$, and compute the initial value of $\mathbf{P}_{AN}^1$ and $\mathbf{v}_d^1$ by using (23) and (25).
repeat
1. $i = i + 1$.
2. Update $\mathbf{P}_{AN}^i$ utilizing GPI algorithm in [23];
3. Update $\mathbf{v}_d^i$ based on (20);
4. Compute R_s^i in (7) using updated $\mathbf{P}_{AN}^i$ and $\mathbf{v}_d^i$.

until $|R_s^i - R_s^{i-1}| < \delta$.
return $\mathbf{P}_{AN}$, $\mathbf{v}_d$ and R_s.

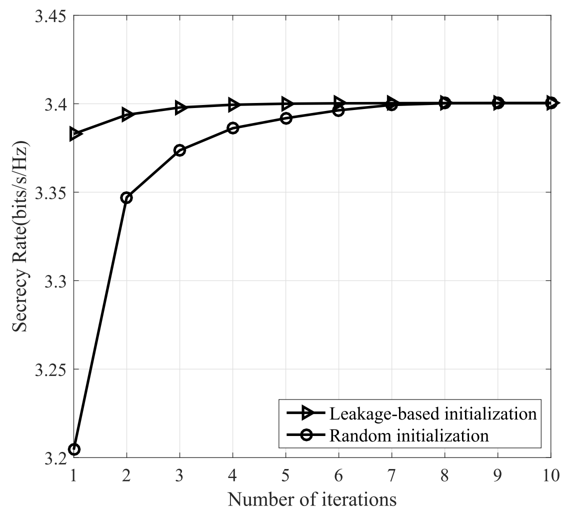

FIGURE 4. Curves of achievable secrecy rate versus the number of iterations (SNR=10dB).

comparison,. The system parameters are chosen as: $N = 8$, PA factors $\beta_1 = \sqrt{0.9}$ and $\beta_2 = \sqrt{0.1}$, $\theta_d = 45^\circ$ and $\theta_e = 70^\circ$, and QPSK.

A. SIMULATION RESULTS AND ANALYSIS

Fig. 4 shows the achievable SR versus the number of iterations between $\mathbf{P}_{AN}$ and $\mathbf{v}_d$ for leakage-based and random initial values, respectively. Here, SNR is chosen to be 10dB. It is seen that the iterative algorithm with leakage-based solution as initialization value converges more rapidly than that with random initialization. As shown in Fig. 4, the former converges to a constant rate after 4 iterations, while the latter requires 7 iterations to converge. And the two initialization methods finally converge to the same SR limit value. This implies that the SLNR initialization can provide a faster convergence speed than the random initialization.

Fig. 5 illustrates the achievable SR versus SNR of the proposed method, leakage-based method in [25] and NSP method in [20]. It can be seen that our proposed method performs better than the remaining two methods in almost all SNR regions. With the increase of SNR, the secrecy rate gain over them achieved by the proposed method show a gradual growth trend. For example, at SNR=15dB, the proposed method attains an approximate ten-percent and twenty-percent rate improvements over leakage and NSP methods, respectively.

Fig. 6 plots the bit error rate (BER) versus SNR of the proposed method, leakage-based method and NSP. All the three methods achieve their best BER performance along the desired direction $\theta_d = 45^\circ$, and a sharp BER performance degradation appears once the desired receiver deviates from the main beam of the desired direction 45°. Both NSP and our proposed method have approximately the same BER performance around the desired direction 45°. The main reason is that the proposed method reduces the effect of artificial noise on the desired direction by maximizing SR. The NSP

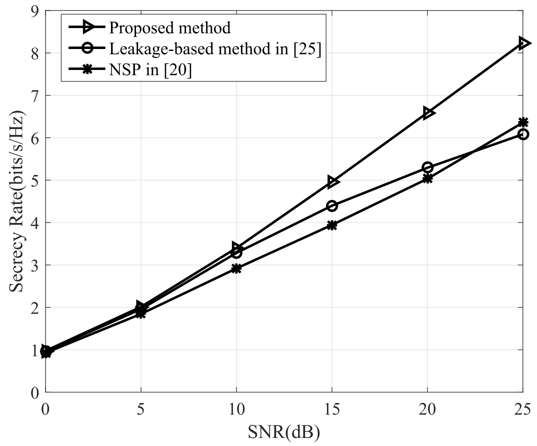

FIGURE 5. Achievable secrecy rate versus SNR of three different methods.

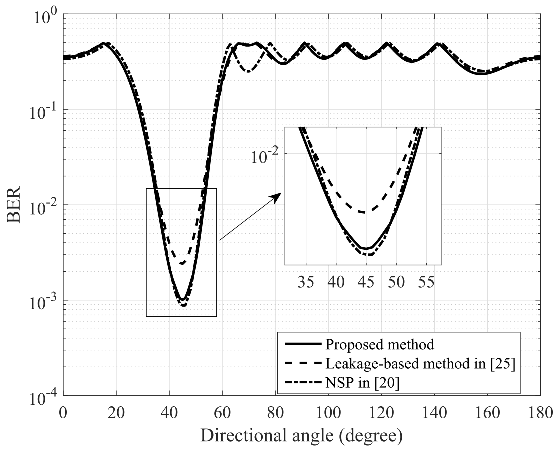

FIGURE 6. Curves of BER versus directional angles of three different methods.

even makes AN vanish in the desired direction. However, the conventional NSP one shows a better BER performance than the proposed method along the eavesdropper direction $\theta_e = 70°$, which means that the confidential messages can be easily intercepted along the direction.

B. COMPLEXITY COMPARISON AND CONVERGENCE ANALYSIS

The complexities of the proposed Max-SR, NSP, and leakage-based methods are $O(I(N^6))$, $O(N^3)$, and $O(N^3)$ floating-point operations (FLOPs), respectively, where I stands for the number of iterations. Our proposed method is due to the fact that the optimization variable $\mathbf{w} \triangleq \text{vec}(\mathbf{P}_{AN})$ in (13) is an $N(N-1)$-D column vector. Clearly, the proposed method has much higher complexity than NSP and leakage-based methods. Both NSP and leakage-based methods have the same order of complexity.

For the aspect of convergence, we propose two different choices of initial values in Section III: random and leakage-based. From Fig. 4, the former requires 7 iterations to converge the limit and the latter needs only 4 iterations. Clearly, the leakage-based initialization approximately doubles the convergence rate compared to the random initialization. This means a good initial choice accelerates the convergence of our proposed method.

V. CONCLUSION

In this paper, we have investigated three beamforming schemes including the proposed GPI-based Max-SR, leakage, and NSP. Compared to the last two methods based on NSP and leakage, the proposed GPI-based Max-SR method achieved a substantial SR improvement in the medium and large SNR regions. In particular, as SNR increases, the SR performance gain increases. Additionally, by an appropriate choice of initialization value, for example, with the leakage-based solution as initial value of GPI, the proposed method required only 4 iterations to converge to the limit value of SR. The random initialization requires 7 iterations. Thus, the leakage-based initialization saves about 40-percent computational amount over random one. In the coming future, the proposed scheme will be potentially applied to the following diverse applications such as mmWave communications (massive MIMO), IoT, UAV, satellite communications, and flying ad-hoc networks.

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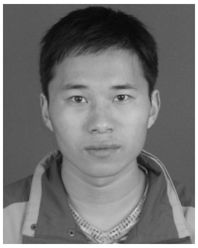

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