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Secure symbol level precoding for cell-free network based on band-region constraint of the eavesdropper's receiving signal①

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Abstract

A symbol level secure precoding scheme based on band-region constraint of the eavesdropper's receiving signal is proposed to enhance the energy efficiency of cell-free multiple-input multiple-output (MIMO) networks in the presence of an eavesdropper while guaranteeing the quality of service (QoS) of user and the security of system. Moreover, to lighten its high computational complexity, original problem is divided into several cascade sub-problems firstly, and then those sub-problems are handled by combining Lagrangian dual function and improved Hooke-Jeeves method together. Comparative experiment with other secure symbol-level precoding schemes demonstrate that proposed scheme can achieve the lower power consumption with almost same symbol error rate and QoS of user.

Key words: cell-free, symbol-level precoding (SLP), physical layer security (PLS), multiple-input multiple-output (MIMO), band-region constraint

0 Introduction

Cell-free multiple-input multiple-output (MIMO) system is considered to be a promising technology following 5G communication standards since it can effectively reduce inter-cell interference and improve the communication quality of users by introducing a large number of distributed base stations (BSs) working on collaboration pattern[1-2]. However, a large number of distributed BSs also mean more complex channel environment, which may induce higher security risks of the users in return[3]. Physical layer security (PLS) can be used to handle this problem since it has the merits such as being key-aided-free, easy implementation, high security and so on[4].

In MIMO systems, PLS can be achieved by using linear precoding techniques to exploit degrees of freedom (DoF) of massive antennas of MIMO, leading to signal-to-interference-plus-noise ratio (SINR) of eavesdropper (Eve) reducing[5-6]. For example, Zhang et al.[7] investigated the secure transmission in downlink cell-free MIMO systems in the presence of a multi-antenna Eve, moreover, by supposing additive quantization noise model, a closed-form expression of the achievable secrecy rate related to MIMO system is derived too. Choi et al.[8] combined linear precoding and artificial noise (AN) techniques together to minimize multi-user interference (MUI) of legitimate users while constraining the Eve's SINR below a certain threshold. Since it relies AN signal to suppress Eve, Jihoon's method suffers poor energy efficiency.

Recently proposed symbol-level precoding (SLP) technique seems to be another option which employs the energy of MUI to create constructive region and unconstructive regions related to legitimate user and Eve, respectively, thus not only energy efficient of system can be enhanced but also the SINR of Eve can be reduced[9]. Similar to Ref. [9], Refs [10,11] designed destructive interference for Eve to ensure the security in a multi-user synchronous wireless information and power transmission system. Since above work supposed that user and Eve employ the same symbol detector, their performance may deteriorate when Eve employs blind detector to decode symbols. Liu et al.[12] proposed an SLP method based on the Euclidean distance, i. e., region of Eve's receiving signal in the constellation diagram is constrained in an Euclidean ball, to improve the security of the system. However, overly strict constrains may tighten the feasible solution region, thus reducing energy efficiency of system.

To tackle above problems, a SLP is proposed to

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optimize the system energy efficiency with the quality of service (QoS) of user and the security of system guaranteed. The contributions are as follows.

(1) The optimal BS transmission scheme in which the Eve's receiving signal is constrained in a Band-region of constellation diagram is proposed to minimize the BS transmission power and to guarantee the QoS of legitimate user and security of system.

(2) Comparing with the method of Ref. [12], the proposed scheme relaxes the feasible solution region of the BS transmission power optimization and thus enhances the energy efficiency of the system.

(3) To address the computational burden induced by the solving above problem, original problem is decomposed into several cascade sub-problems firstly, and then those sub-problems are handled by combining Lagrangian dual function and improved Hooke-Jeeves method together.

The other sections of this paper are organized as follows. Section 1 describes the system model of cell-free network with one Eve and explains constructive/destructive interference. Section 2 details the proposed SLP based on Band-region constraint of Eve's receiving signal constellation diagram and the modified Hooke-Jeeves algorithm. Section 3 shows and analyzes the simulation results. Section 4 draws the conclusions.

1 System model and problem statement

1.1 System model

The cell-free network eavesdropping system model is described in Fig. 1, in which B BSs with M antennas transfer data to K legitimate users with N antennas, while one Eve with N antennas intends to intercept this data, in addition, the central processing unit (CPU) is connected to all BSs and is responsible for control, planning and so on. For simplicity, it is assumed that the Eve merely interests in the data of one user. $\boldsymbol{H}_{b,k}^{H} \in \boldsymbol{C}^{N\times M}$ and $\boldsymbol{H}_{b,e}^{H} \in \boldsymbol{C}^{N\times M}$ denote the channels between the b-th BS and the k-th user and between the b-th BS and the Eve, respectively.

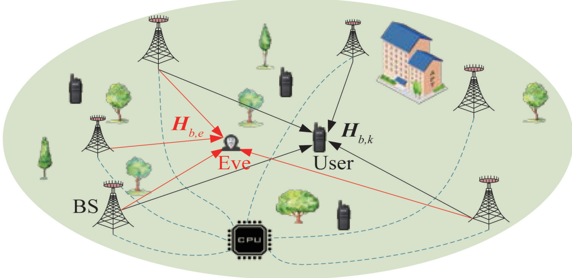

Fig. 1 The downlink channels in the cell-free network eavesdropping system

1.2 Symbol-level precoding constructive/destructive interference

Considering K independent transmission symbols, thus the transmission symbolic vector $\boldsymbol{s}$ generated by a Ω-PSK (phase shift keying) constellation will be Ω^K combinations. By defining each symbol vector and the corresponding precoding vector as $\boldsymbol{s}_m$ and $\boldsymbol{x}_m$ ($m = 1, 2, \cdots, \Omega^K$), respectively, the receiving signal at the k-th user and the Eve can be written as

$$\boldsymbol{Y}_{m,k} = \sum_{b=1}^{B} \boldsymbol{H}_{b,k}^{\mathrm{H}} \boldsymbol{x}_m + \boldsymbol{z}_k \tag{1a}$$

$$\boldsymbol{Y}_{m,e} = \sum_{b=1}^{B} \boldsymbol{H}_{b,e}^{\mathrm{H}} \boldsymbol{x}_m + \boldsymbol{z}_e \tag{1b}$$

where $\boldsymbol{z}_k \in \boldsymbol{C}^{N\times 1}$ and $\boldsymbol{z}_e \in \boldsymbol{C}^{N\times 1}$ are additive white Gaussian noise (AWGN) with zero mean $\boldsymbol{0}_N$ and covariance $\boldsymbol{\Xi}_k = \sigma_k^2 \boldsymbol{1}_N$ and $\boldsymbol{\Xi}_e = \sigma_e^2 \boldsymbol{1}_N$; $\boldsymbol{1}_N \in \boldsymbol{C}^{N\times 1}$ and all elements are 1. Defining the precoding matrix $\boldsymbol{X} \triangleq [\boldsymbol{x}_1, \cdots, \boldsymbol{x}_m, \cdots, \boldsymbol{x}_{\Omega^K}]$, the average transmission power of BS can be described as

$$P = \frac{\|\boldsymbol{X}\|_F^2}{\Omega^K} \tag{2}$$

where, $\|\boldsymbol{X}\|_F$ is the Frobenius norm of a matrix $\boldsymbol{X}$.

By supposing QPSK (quadrature phase shift keying) modulation to be employed, as described in Fig. 2, precoding vector $\boldsymbol{x}_m, m = 1, 2, \cdots, \Omega^K$, should to be designed to locate signals of legitimate users $\tilde{\boldsymbol{Y}}_{m,k} = \sum_{b=1}^{B} \boldsymbol{H}_{b,k}^{\mathrm{H}} \boldsymbol{x}_m$ in the constructive region while signals of Eve $\tilde{\boldsymbol{Y}}_{m,e} = \sum_{b=1}^{B} \boldsymbol{H}_{b,e}^{\mathrm{H}} \boldsymbol{x}_m$ in the corresponding neighboring destructive region[11]. Thus, Eqs (3) and (4) should be guaranteed.

$$\begin{aligned}&[\Re\{\tilde{\boldsymbol{Y}}_{m,k}\, e^{-j\angle s_{m,k}}\} - \sigma_k \boldsymbol{1}_N \sqrt{\Gamma_k}]\tan\Phi \\ &- |\Im\{\tilde{\boldsymbol{Y}}_{m,k}\, e^{-j\angle s_{m,k}}\}| \geqslant 0, \forall k, \forall m\end{aligned} \tag{3}$$

$$\begin{aligned}&[\Re\{\tilde{\boldsymbol{Y}}_{m,e}\, e^{-j(\angle s_{m,1}+\pi/2)}\} - \sigma_e \boldsymbol{1}_N \sqrt{\Gamma_e}]\tan\Phi \\ &- |\Im\{\tilde{\boldsymbol{Y}}_{m,e}\, e^{-j(\angle s_{m,1}+\pi/2)}\}| \geqslant 0, \forall m\end{aligned} \tag{4}$$

where $\Re\{\cdot\}$ and $\Im\{\cdot\}$ denote the real and imaginary part of a complex number, respectively; Γ_k and Γ_e are the signal-to-noise ratio (SNR) of the k-th user and the Eve, respectively.

1.3 Secure symbol-level precoding based on Euclidean distance

In the method of Ref. [12], all signals received by Eve simultaneously follow the constrains described in Eq. (5) to place them in the Euclidean distance region described in the Fig. 2, where triangles indicate the receiving signals of legitimate users and dots indicate the receiving signals of Eve. Different colors indicate different types of QPSK signals received.

$$\left|\sum_{b=1}^{B} \boldsymbol{H}_{b,e}^{\mathrm{H}} \boldsymbol{X}\boldsymbol{T}(:,j)\right| \leqslant \varepsilon, \forall j \quad (5)$$

where, $\boldsymbol{T} \in \{0, \pm 1\}^{\Omega^K \times Q}$ and $Q = \frac{\Omega(\Omega-1)}{2} \times \Omega^{2K-2}$ are the auxiliary matrix used to select any two symbols of the Eve; ε is the maximum distance threshold. From Fig. 2, it can be found that the receiving signals of Eve is constrained inside the Euclidean ball while many unconstructive regions of QPSK phase plane are unexploited, which means the constraint Eq. (5) may be overstrict, leading feasible set to small. Thus, its energy efficiency needs to be improved.

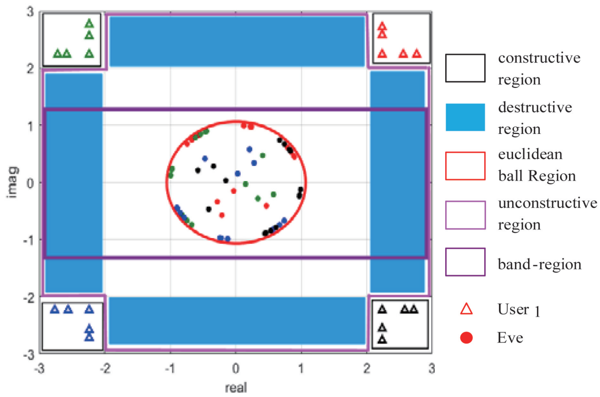

Fig. 2 Decision region for QPSK symbols

2 Secure symbol-level precoding based on band-region constraint

According to previous studies, to avoid the information of legitimate user leakage, the Eve's receiving signals should be placed in unconstructive regions of the constellation diagram with extremely disorder way and those unconstructive regions prefer to be fully exploited. While the method of Ref. [12] constrains the Eve's receiving signal in the Euclidean ball, many unconstructive regions of the constellation diagram is unexploited in this case, which may tighten feasible set related to BS transmission vector selecting, resulting in the energy efficiency reducing in return. To handle above problem, namely, to fully exploit unconstructive regions of the constellation diagram, Euclidean ball constraint of Eve's receiving signal is substituted by band-region constraint here. Specifically, the imaginary part of Eve's receiving signal following can be constrained by Eq. (6). It is of course to constrain the real part of Eve's receiving signal as well. The following simulation will demonstrate constraint on imaginary part or real part of Eve's receiving signal can achieve the same performance.

$$\left|\Im\left\{\sum_{b=1}^{B} \boldsymbol{H}_{b,e}^{\mathrm{H}} \boldsymbol{X}(:,m)\right\}\right| \leq \eta, m = 1,2,\cdots,\Omega^K \quad (6)$$

where η is the maximum range threshold. Thus, the problem is to minimize the transmit power while guaranteeing the QoS and security of the legitimate user can be described in Eq. (7).

$$\min_{X} \|\boldsymbol{X}\|_F^2 \quad (7a)$$

$$\text{s. t. } \left|\Im\left\{\sum_{b=1}^{B} \boldsymbol{H}_{b,e}^{\mathrm{H}} \boldsymbol{X}(:,m)\right\}\right| \leqslant \eta, \forall m \quad (7b)$$

$$[\Re\{\tilde{\boldsymbol{Y}}_{m,k} e^{-j\angle s_{m,k}}\} - \sigma_k \boldsymbol{1}_N \sqrt{\Gamma_k}]\tan\Phi - |\Im\{\tilde{\boldsymbol{Y}}_{m,k} e^{-j\angle s_{m,k}}\}| \geqslant 0, \forall k, \forall m \quad (7c)$$

By observing Eq. (7), It is noted that attempting a direct solution using the $M_1 \times 4^K (M_1 = M \times B)$ dimension optimized variable $\boldsymbol{X}$ and $2K_1 (K_1 = K \times N)$ linear matrix inequality (LMI) constraints might lead to elevated computational complexity, denoted as $O(\ln(1/\xi)\sqrt{2K_1 + 2 \times 4^K} M_1 4^K (2K_1 + 2K_1 M_1 4^K + 6 M_1^2 4^{4K-2} + M_1^2 4^{2K}))$, where ξ is the convergence threshold[13]. The modified Hooke-Jeeves method is utilized to solve Eq. (7) and thereby reduce computational complexity.

Since precoding vectors $\boldsymbol{x}_m, m = 1,2,\cdots,\Omega^K$, are independent of each other[11-12], the power minimization problem represented by Eq. (7) can be divided into cascade sub-problems to handle. Now, focus on solving the m-th sub-problem here and the others sub-problem can be handled similarly to it. Firstly, by employing Eq. (8), Eq. (7) can be rewritten as Eq. (9).

$$\begin{aligned}
&\bar{\boldsymbol{H}}_k \triangleq [\boldsymbol{H}_{1,k}, \cdots, \boldsymbol{H}_{b,k}, \cdots, \boldsymbol{H}_{B,k}]^{\mathrm{T}}\\
&\bar{\boldsymbol{H}}_e \triangleq [\boldsymbol{H}_{1,e}, \cdots, \boldsymbol{H}_{b,e}, \cdots, \boldsymbol{H}_{B,e}]^{\mathrm{T}}\\
&\tilde{\boldsymbol{H}}_k \triangleq \bar{\boldsymbol{H}}_k e^{\angle s_{m,k}}\\
&\widehat{\boldsymbol{H}}_k \triangleq [\Re\{\tilde{\boldsymbol{H}}_k\}^{\mathrm{T}}, \Im\{\tilde{\boldsymbol{H}}_k\}^{\mathrm{T}}]^{\mathrm{T}}\\
&\widehat{\boldsymbol{H}}_e \triangleq [\Re\{\bar{\boldsymbol{H}}_e\}^{\mathrm{T}}, \Im\{\bar{\boldsymbol{H}}_e\}^{\mathrm{T}}]^{\mathrm{T}}\\
&\bar{\boldsymbol{x}}_m \triangleq [\Re\{\boldsymbol{x}_m\}^{\mathrm{T}}, \Im\{\boldsymbol{x}_m\}^{\mathrm{T}}]^{\mathrm{T}}\\
&\triangle_1 \triangleq \begin{bmatrix} \boldsymbol{I}_{M_1\times M_1} & \boldsymbol{O}_{M_1\times M_1} \\ \boldsymbol{O}_{M_1\times M_1} & -\boldsymbol{I}_{M_1\times M_1} \end{bmatrix}\\
&\triangle_2 \triangleq \begin{bmatrix} \boldsymbol{O}_{M_1\times M_1} & \boldsymbol{I}_{M_1\times M_1} \\ \boldsymbol{I}_{M_1\times M_1} & \boldsymbol{O}_{M_1\times M_1} \end{bmatrix}
\end{aligned} \quad (8)$$

$$\min_{\bar{x}_m} \|\bar{\boldsymbol{x}}_m\|^2 \quad (9a)$$

$$\text{s. t. } \|\widehat{\boldsymbol{H}}_e^{\mathrm{T}} \Delta_2 \bar{\boldsymbol{x}}_m\|^2 \leq \eta^2 \quad (9b)$$

$$(\widehat{\boldsymbol{H}}_k^{\mathrm{T}} \Delta_1 \bar{\boldsymbol{x}}_m - \sigma_k \boldsymbol{1}_N \sqrt{\Gamma_k})\tan\Phi - \widehat{\boldsymbol{H}}_k^{\mathrm{T}} \Delta_2 \bar{\boldsymbol{x}}_m \geqslant 0, \forall k \quad (9c)$$

$$(\widehat{\boldsymbol{H}}_k^{\mathrm{T}} \Delta_1 \bar{\boldsymbol{x}}_m - \sigma_k \boldsymbol{1}_N \sqrt{\Gamma_k})\tan\Phi + \widehat{\boldsymbol{H}}_k^{\mathrm{T}} \Delta_2 \bar{\boldsymbol{x}}_m \geqslant 0, \forall k \quad (9d)$$

where Eq. (9b) is security constraint, and Eqs (9c) and (9d) are the QoS constraints related to the legitimate users. Next, defined as

$$\bar{\boldsymbol{H}} \triangleq [\widehat{\boldsymbol{H}}_1, \cdots \widehat{\boldsymbol{H}}_k,]^{\mathrm{T}}$$
$$\boldsymbol{A} \triangleq \begin{bmatrix} \bar{\boldsymbol{H}}(\Delta_1 \tan\Phi - \Delta_2) \\ \bar{\boldsymbol{H}}(\Delta_1 \tan\Phi + \Delta_2) \end{bmatrix}$$
$$\boldsymbol{B} \triangleq \Delta_2{}^{\mathrm{T}} \widehat{\boldsymbol{H}}_e^{\mathrm{T}} \widehat{\boldsymbol{H}}_e \Delta_2$$
$$\widehat{\boldsymbol{c}} \triangleq [\sigma_1 \mathbf{1}_N \sqrt{\Gamma_1}, \cdots, \sigma_k \mathbf{1}_N \sqrt{\Gamma_k}, \cdots, \sigma_K \mathbf{1}_N \sqrt{\Gamma_K}]$$
$$\boldsymbol{c} \triangleq [\widehat{\boldsymbol{c}}, \widehat{\boldsymbol{c}}]^{\mathrm{T}} \tag{10}$$

Eq. (9) is reformulated as

$$\min_{\bar{x}_m} \|\bar{\boldsymbol{x}}_m\|^2 \tag{11a}$$
$$\text{s.t. } \bar{\boldsymbol{x}}_m^{\mathrm{T}} \boldsymbol{B} \bar{\boldsymbol{x}}_m \leqslant \eta^2 \tag{11b}$$
$$\boldsymbol{A} \bar{\boldsymbol{x}}_m - \boldsymbol{c} \geqslant 0 \tag{11c}$$

Then, Lagrangian dual function of Eq. (9) is given by

$$\mathcal{L}(\bar{\boldsymbol{x}}_m, \boldsymbol{\lambda}, \mu) = \|\bar{\boldsymbol{x}}_m\|^2 + \boldsymbol{\lambda}(-\boldsymbol{A}\bar{\boldsymbol{x}}_m + \boldsymbol{c}) + \mu(\bar{\boldsymbol{x}}_m^{\mathrm{T}} \boldsymbol{B} \bar{\boldsymbol{x}}_m - \eta^2) \tag{12}$$

where $\boldsymbol{\lambda} \geqslant 0$ and $\mu \geqslant 0$ are the Lagrangian dual variables. By setting $\frac{\partial \mathcal{L}}{\partial \bar{x}_m} = 0_{2M_1 \times 1}$, one can achieve the optimal $\bar{\boldsymbol{x}}_m^* = (\boldsymbol{I} + \mu\boldsymbol{B})^{-1}\left(\frac{\boldsymbol{A}^{\mathrm{T}}\boldsymbol{\lambda}}{2}\right)$ and substitute it into Eq. (12), Lagrangian dual problem related to Eq. (11) is described in Eq. (13).

$$\min_{\boldsymbol{\lambda},\mu} f(\boldsymbol{\lambda}, \mu) = \left(\frac{\boldsymbol{\lambda}^{\mathrm{T}}\boldsymbol{A}}{2}\right)(\boldsymbol{I} + \mu\boldsymbol{B})^{-1} \left(\frac{\boldsymbol{A}^{\mathrm{T}}\boldsymbol{\lambda}}{2}\right) - \lambda^{\mathrm{T}}\boldsymbol{c} - \mu\eta^2 \tag{13a}$$
$$\text{s.t. } \boldsymbol{\lambda} \geqslant 0, \mu \geqslant 0 \tag{13b}$$

Now, modified Hooke-Jeeves algorithm listed in Algorithm 1 with $\bar{\boldsymbol{\lambda}} \triangleq [\boldsymbol{\lambda}^{\mathrm{T}}, \mu]^{\mathrm{T}}$ can be employed to tackle Eq. (13). After obtaining $\bar{\boldsymbol{\lambda}}^*$, the optimal $\bar{\boldsymbol{x}}_m^*$ can be achieved too. Then the optimal solution of the m-th sub-problem can be obtained by using Eq. (14).

$$\boldsymbol{x}_m = \bar{\boldsymbol{x}}_m^*(1:M_1) + j\bar{\boldsymbol{x}}_m^*(M_1 + 1:2M_1) \tag{14}$$

By observing Algorithm 1, its computational complexity Λ_m can be written as $O(2N_{\max}(2K_1+2)(4M_1^2 + 8M_1^3))$ [14], since tackling the original power minimization problem can be achieved by solving Ω^K cascade sub-problems each with Λ_m computational complexity, the total complexity related to solving Eq. (7) can be described as $O(2N_{\max}(2K_1+2)(4M_1^2+8M_1^3) \times \Omega^{\mathrm{K}})$. While computational complexity of SLP based on Euclidean distance is $O(2N_{\max}(J_m + 2K_1 + 1)(4M_1^2 J_m + 8M_1^3) \times \Omega^K)$, where $J_m = 6 \times \Omega^{2K-2}$ [12]. It is clearly the computational complexity of proposed method is much lower than that of method of Ref. [12].

Algorithm 1 The modified Hooke-Jeeves algorithm

1. Input: $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$, $N_{\max}$, δ_{th}, η
2. Initialize $\bar{\boldsymbol{\lambda}}^1 \geqslant 0$, $\bar{\boldsymbol{\lambda}}_{\mathrm{opt}} \leftarrow \bar{\boldsymbol{\lambda}}^1$, $iter \leftarrow 1$, $\delta \leftarrow 1$
3. while $iter \leqslant N_{\max}$ and $\delta \geqslant \delta_{th}$ do
4. Update the descent direction $\bar{\boldsymbol{\lambda}}_{\mathrm{opt}}$ using
5. if $f(\bar{\boldsymbol{\lambda}}_{\mathrm{opt}}) \geqslant \bar{\boldsymbol{\lambda}}^{\mathrm{iter}}$ then
6. Go to 11
7. else
8. $\bar{\boldsymbol{\lambda}}^{\mathrm{iter}+1} \leftarrow \bar{\boldsymbol{\lambda}}_{\mathrm{opt}}$
9. $\bar{\boldsymbol{\lambda}}_{\mathrm{opt}} \leftarrow \max\{0, \bar{\boldsymbol{\lambda}}^{iter+1} + \delta(\bar{\boldsymbol{\lambda}}^{iter+1} - \bar{\boldsymbol{\lambda}}^{iter})\}$
10. $iter \leftarrow iter + 1$, go back to 3
11. end if
12. if $\delta \geqslant \delta_{th}$ then
13. $\delta \leftarrow \delta/2$
14. $iter \leftarrow iter + 1$, go back to 3
15. end if
16. end while
17. $\bar{\boldsymbol{\lambda}}^* \leftarrow \bar{\boldsymbol{\lambda}}^{iter}$
18. Output: $\bar{\boldsymbol{\lambda}}^*$

3 Simulation results

3.1 System model

The simulation scenario is depicted in Fig. 1, unless otherwise noted, the simulation parameters are listed on Table 1, and the transmitted signals are QPSK. All simulation results are averaged over 10^5 independent channel realizations.

Table 1 The simulation parameters

Parameters	Notations	Typical values
B	Number of BS	5
M	Number of BS antennas	4
K	Number of User	3
N	Number of User antennas	2
σ^2	Noise power of User/Eve	−80 dBm
Γ_k	QoS of User	10
Γ_e	SNR of Eve	−5

Since secure SLP based on destructive regions employs Eve's SINR to evaluate security of system[10], while secure SLP based on Euclidean ball constraint[12] and the proposed secure SLP uses, the Euclidean distance between the different receiving symbols to evaluate security of system, to achieve a fair comparison, conversion relationship between Euclidean distance of Eve's different receiving signal and the SINR of Eve are needed. Destructive secure SLP scheme can be employed to obtain those conversion relationship here.

3.2 User requirements impact

In this subsection, performances of the proposed scheme are compared with some classical schemes such as secure SLP based on destructive regions (called DC)[10], secure SLP based on Euclidean ball (called ED)[12] and SLP of Eve unconsidered (called Const)[15]. To deeply exhibit the performances of proposed scheme, two cases are considered here, one is that constrain imaginary part (i. e., Proposed-Im) of the Eve's receiving signal lower than the threshold while the other is that constrain real part (i. e., Proposed-Re, details in the Appendix) of the Eve's receiving signal lower than the threshold.

Fig. 3 shows user's QoS requirements versus average transmission power of BS. It can be found that in all schemes, average transmission power of BS tend to increase with the user's QoS requirements, it is of obviously because more transmission power means better user's QoS. It is also clearly that Const shows the lowest transmission power at the same user's QoS requirement since security of system is uninvolved in this scheme which indicates its security cannot to be guaranteed. In addition, as expected, proposed scheme in two cases, namely Proposed-Re and Proposed-Im, shows the better performance than that of DC and ED, moreover, Proposed-Re and Proposed-Im show almost identical performance because constraints of the real part or the imaginary part related to Eve's receiving signal are symmetric in QPSK symbols plane.

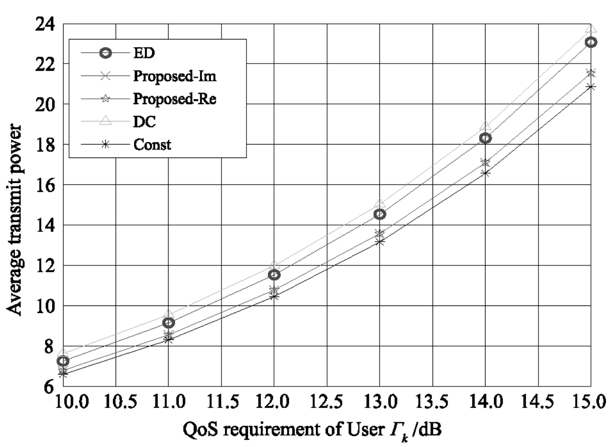

Fig. 3 Average transmit power versus QoS requirement of user

Fig. 4 shows user's QoS requirements versus user's symbol-error-rate (SER) or Eve's SER. It can be found that in all schemes, user's SER decreases while Eve's SER changes little with user's QoS requirement increasing. It is because of constraint related to Eve's receiving signal in those schemes remains unchanged with user's QoS requirements changing. In addition, similar to reasons described in Fig. 3, proposed scheme in two cases, namely Proposed-Re and Proposed-Im, shows the better performance than that of DC, moreover, Proposed-Re, Proposed-Im and ED show almost identical performance. Combining Fig. 3 and Fig. 4, it can be deduced that compared with ED scheme, proposed scheme achieves almost same SER with less transmission power in the same Γ_k.

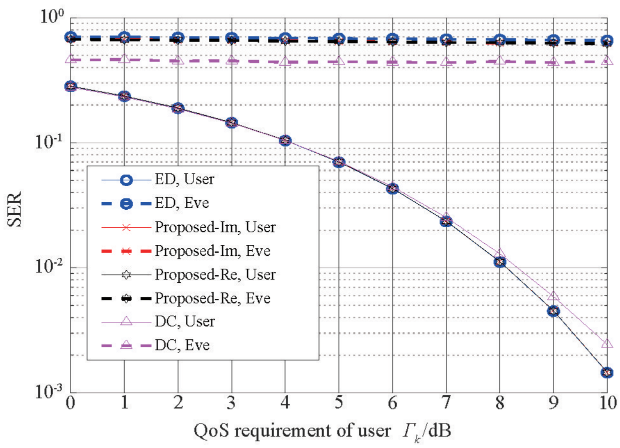

Fig. 4 SER versus QoS requirement of user

3.3 Eve requirements impact

Fig. 5 shows the average transmission power of BS versus Eve's SNR, namely Γ_e. In all schemes, similar to the reason described in Fig. 3, Const achieves the lowest transmission power with sacrificing security, while DC shows the poorest energy efficiency because it needs more energy to push Eve's signal far away from boundary of constructive region when the Γ_e increases. Since proposed scheme and ED employ average distance between the received symbols of Eve which can increase with Γ_e, this results in loosening constraint of optimization problem, which extends feasible set region and achieves energy efficiency enhancing in return.

Fig. 6 shows the SER versus Eve's SNR, namely Γ_e. It can be found that in all schemes, SER of legitimate user is apparently lower than Eve, and the proposed scheme in two aspects including SER of legitimate user and SER of Eve achieves almost same performance as ED scheme, apparently better than those of DC scheme. Combining Fig. 5 and Fig. 6, it can be deduced that compared with ED scheme, the proposed scheme achieves almost same SER with less transmission power in the same Γ_e.

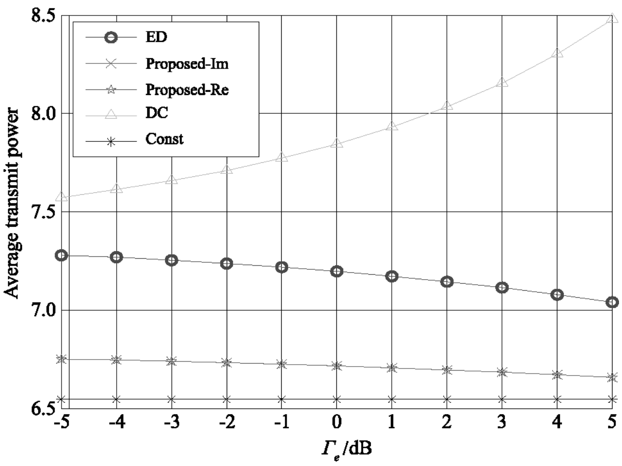

Fig. 5 Average transmit power versus Γ_e

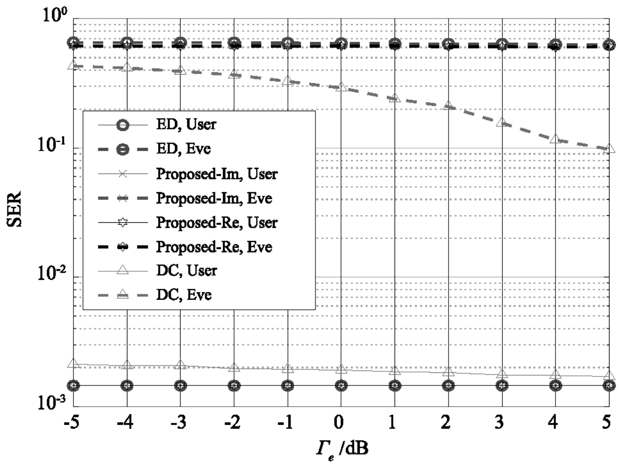

Fig. 6 SER versus Γ_e

4 Conclusion

A secure SLP scheme based on band-region constraint of the Eve's receiving signal is proposed to minimize BS transmission power while guaranteeing QoS and security of legitimate user in the cell-free network with one Eve. Moreover, a modified Hooke-Jeeves algorithm is also presented to reduce the computational burden induced by original optimization problem related to the proposed scheme. The simulation results show the advantages of the proposed secure symbol-level precoding scheme over other schemes in terms of energy efficiency and SER.

Appendix

For the case of the constrain real part of the Eve's received signal, similar to Eq. (6), the real part of Eve's receiving signal can be constrainted by

$$\left|\Re\left\{\sum_{b=1}^{B} \boldsymbol{H}_{b,e}^{H}\boldsymbol{X}(:,m)\right\}\right| \leqslant \eta, m = 1,2,\cdots,\Omega^{K} \quad (\text{A}.1)$$

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