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IRS-Assisted MC-NOMA System Communication Security Scheme

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ABSTRACT

To address the communication security of the Intelligent Reflecting Surface (IRS)-assisted Multicarrier Non-Orthogonal Multiple Access (MC-NOMA) system, a problem of maximizing the secure sum rate is formulated under the constraints of subcarrier allocation schemes, base station transmission power, and IRS phase shifts. The security performance of the communication system is enhanced by jointly alternating optimizing beamforming vectors and IRS phase shifts. Simulation results demonstrate that the proposed scheme exhibits significant advantages in improving the security and efficiency of communication systems.

KEYWORDS

Intelligent Reflecting Surface (IRS); Multicarrier Non-Orthogonal Multiple Access (MC-NOMA); Communication Security; Beamforming Vectors; Alternating Optimization

1. INTRODUCTION

Non-Orthogonal Multiple Access (NOMA) technology offers advantages of improved spectrum efficiency and support for massive connections. [1, 2]. Multicarrier NOMA (MC-NOMA) technology combines traditional multicarrier schemes with NOMA, further enhancing the overall system performance. Compared with Single-Carrier NOMA (SC-NOMA) systems, resource allocation in MC-NOMA systems involves more complex user fairness issues [3, 4]. IRS has attracted significant attention due to its critical role in enabling an intelligently controllable wireless propagation environment [5]; its integration into communication systems can further improve communication quality [6-8]. By adaptively adjusting the amplitude and phase shifts of its reflecting elements, IRS can manipulate the propagation paths of incident signals, thereby constructing a favorable intelligent radio environment [9]. This not only effectively enhances the strength of received signals at legitimate users but also imposes destructive jamming at potential eavesdroppers, reducing the risk of information leakage [10-13] proposes using IRS to enhance wireless communication security, with a focus on minimizing the Signal-to-Noise Ratio (SNR) at eavesdroppers and maximizing the SNR at legitimate users by jointly optimizing the active beamforming at the base station and passive beamforming at the IRS. Reference [14] investigates the physical layer security of NOMA systems, analyzing performance metrics such as security outage probability, strictly positive secrecy capacity, and eavesdropping probability. Reference [15, 16] addresses the communication security of users with high secrecy requirements in cooperative NOMA systems, analyzes threats from multiple non-cooperative eavesdroppers, and proposes a secure communication solution for cooperative NOMA systems, effectively reducing eavesdropping risks.

2. SYSTEM MODEL

An IRS-assisted MC-NOMA system is considered, as illustrated in Figure 1. It is assumed that the base station has perfect Channel State Information (CSI), and the channels between the base station, users, and IRS follow Rician fading. The system consists of a base station with K antennas, M single-antenna legitimate users, N eavesdroppers, and an IRS with L reflecting elements; the system bandwidth B is divided into S subcarriers. Define the following channel gains: $h_{m,s} \in \mathbb{C}^{1\times K}$: Channel gain between the base station and the m user on the s subcarrier; $h_{b,e} \in \mathbb{C}^{K\times 1}$: Channel gain between the base station and the eavesdropper $f_{b,i} \in \mathbb{C}^{L\times K}$: Channel gain between the base station and the IRS on the $g_{m,s} \in \mathbb{C}^{L\times 1}$: Channel gain between the IRS and the m user on the s subcarrier; $h_{i,e} \in \mathbb{C}^{L\times 1}$: Channel gain between the IRS and eavesdropper. $\Theta = \text{diag}(e^{j\theta_1}, e^{j\theta_2} \cdots, e^{j\theta_L})$ denotes the diagonal phase shift matrix of the IRS, where $\theta_l \in 0,2\pi), l \in (1,2 \cdots, L)$ is the phase shift of the reflecting element.

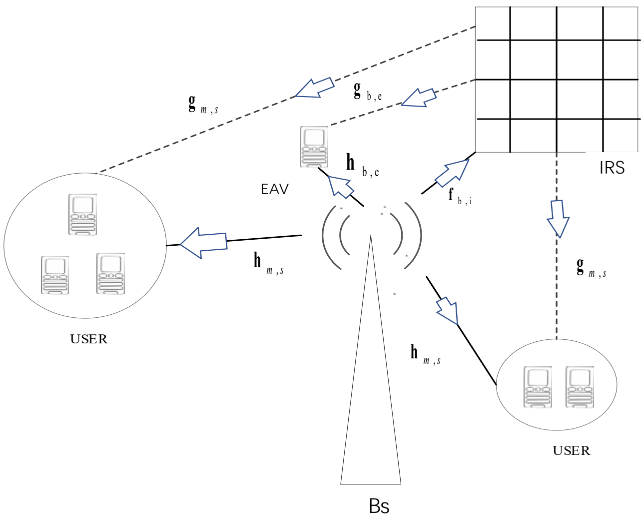

Figure 1. System Model

Without loss of generality, assume there are Z users on any subcarrier. The superimposed signal transmitted by the base station to users on the s subcarrier is $x_s = \sum_{m=1}^{Z} w_{m,s} x_{m,s} p_{m,s}$, where $w_{m,s} \in \mathbb{C}^{K\times 1}$: Beamforming vector for the m user on the s subcarrier; $x_{m,s}$: Information signal of the user; $p_{m,s}$: Power allocated.

In the downlink communication of the IRS-assisted MC-NOMA system, users adopt SIC at the receiver to eliminate interference. The received signal of the m user on the s subcarrier is: $y_{m,s} = (g_{m,s}^H \Theta f_{b,i} + h_{m,s}) w_{m,s} x_{m,s} p_{m,s} + \sum_{c\in C_m} (g_{m,s}^H \Theta f_{b,i} + h_{m,s}) w_{c,s} x_{c,s} p_{c,s} + n_{m,s}$, m is the first term represents the desired signal of the user; The second term represents interference from other un-decoded users; $n_{m,s} \sim CN(0,\sigma^2)$ denotes Additive White Gaussian Noise (AWGN); C_m denotes the set of users decoded after the m user. The transmission rate of the m user decoding its own signal is:

$$R_{m,s} = log_2\left(1 + \frac{\left|(g_{m,s}^H \Theta f_{b,i} + h_{m,s}) w_{m,s}\right|^2 p_{m,s}}{\sum_{c\in C_m} \left|(g_{c,s}^H \Theta f_{b,i} + h_{c,s}) w_{c,s}\right|^2 p_{c,s} + \sigma^2}\right)$$

In physical layer security analysis, a worst-case assumption is adopted: eavesdroppers fully grasp the decoding order of legitimate users and precoding vector information. Using this information, eavesdroppers can apply SIC to decode the same target signal as legitimate users. Thus, the eavesdropping rate of any n-th eavesdropper when decoding the m-th user's signal is:

$$R_{n,m} = log_2\left(1 + \frac{\left|\left(g_{n,s}^H \Theta f_{b,i} + h_{n,s}\right) w_{m,s}\right|^2 p_{m,s}}{\sum_{c \in C_m}\left|\left(g_{n,s}^H \Theta f_{b,i} + h_{n,s}\right) w_{c,s}\right|^2 p_{c,s} + \sigma^2}\right)$$

The total secure rate of the system is:

$$R_t = \sum_{s=1}^{S}\sum_{m=1}^{M}\left[R_{m,s} - \max_{n \in \{1,\cdots,N\}} R_{n,m}\right]^+$$

Based on the above analysis, an optimization problem for maximizing the secure sum rate is formulated for the IRS-assisted MC-NOMA security system. The security performance of the communication system is improved by optimizing subcarrier allocation, beamforming vectors, the IRS phase shift matrix, and user power allocation. To facilitate the description of resource allocation, define a subcarrier allocation indicator $\chi_{m,s}$: if the m user occupies the s subcarrier $\chi_{m,s} = 1$, and $\chi_{m,s} = 0$ otherwise. The optimization problem is expressed as:

$$\max_{w_{m,s},\Theta} \sum_{s=1}^{S}\sum_{m=1}^{M} R_t \tag{4}$$

$$\text{s.t.} \sum_{s=1}^{S}\sum_{m=1}^{M} p_{m,s} \leq P_{max} \tag{4a}$$

$$R_{m,s} \geq R\{1,2\cdots,S\}\{1,2\cdots,M\}_{min} \tag{4b}$$

$$\sum_{m=1}^{M} \chi_{m,s} \leq Q, s \in \{1,2\cdots,S\} \tag{4c}$$

$$\chi_{m,s} \in \{0,1\}, \forall s \in \{1,2\cdots,S\}, \forall m \in \{1,2\cdots,M\} \tag{4d}$$

$$p_{m,s} > 0, \forall s \in \{1,2\cdots,S\}, \forall m \in \{1,2\cdots,M\} \tag{4e}$$

$$\left|\Theta_{l,l}\right| = 1, \forall l \in \{1,2\cdots,L\} \tag{4f}$$

Constraint (4a): Total transmission power of the base station does not exceed; (4b): Secrecy rate of each user meets the minimum rate requirement; (4c): Maximum number of users per subcarrier; (4d): Each user occupies exactly one subcarrier; (4e): Non-negativity of power allocation; (4f): Amplitude constraint of IRS reflecting elements.

3. SOLUTION TO THE SECURE RATE PROBLEM

3.1. Beamforming Vector Optimization

Under the condition of assigning subcarriers and decoding order, fixed user power allocation and intelligent reflection plane shift matrix are used to optimize the beamforming vector through Weighted Minimum Mean Square Error (WMMSE) method. The rate maximization problem is transformed into a Mean Square Error (MSE) minimization problem. By introducing auxiliary variables (weight matrix and equalizer), the beamforming vector is updated through alternating optimization to maximize the safety and rate of all users. The optimization problem is as follows:

$$\max_{w} \chi_{m,s} R_t$$

$$s.t. \sum_{s=1}^{S} \sum_{m=1}^{M} p_{m,s} \leq P_{max}$$

$$R_{m,s} \geq R\{1,2 \cdots, S\}\{1,2 \cdots, M\}_{min}$$

The received signals of the known legitimate users mentioned above are: $y_{m,s} = \left(g_{m,s}^{H} \Theta f_{b,i} + h_{m,s}\right) w_{m,s} x_{m,s} p_{m,s} + \sum_{c \in C_m} \left(g_{m,s}^{H} \Theta f_{b,i} + h_{m,s}\right) w_{c,s} x_{c,s} p_{c,s} + n_{m,s}$, Among them, $x_{m,s}$ is the receiving symbol of the user, Satisfied $E\left[\left|x_{m,s}\right|^2\right] = 1$. If the user uses equalizer $u_{m,s}$ to estimate the signal, there will be $\hat{x}_{m,s} = u_{m,s} y_{m,s}$, and at this time, there will be a minimum estimation error of $E\left[\left|x_{m,s} - \hat{x}_{m,s}\right|^2\right]$, which is $u_{m,s}^{opt} = arg \min_{u_{m,s}} E\left[\left|x_{m,s} - \hat{x}_{m,s}\right|^2\right]$. Let $g_{m,s}^{H} \Theta f_{b,i} + h_{m,s} = H_{m,s}$, then $y_{m,s} = H_{m,s} w_{m,s} x_{m,s} p_{m,s} + \sum_{c \in C_m} H_{m,s} w_{c,s} x_{c,s} p_{c,s} + n_{m,s}$. At this point, the mean square error expression is:

$$\mathrm{MES}_{m,s} = E\left[\left|x_{m,s} - u_{m,s} y_{m,s}\right|^2\right]$$

Derive $\mathrm{MES}_{m,s}$ from $u_{m,s}$ and make the derivative zero, resulting in the optimal equalizer $u_{m,s}^{opt}$ as follows:

$$u_{m,s}^{opt} = \frac{H_{m,s}^{*} w_{m,s} p_{m,s}}{\left|H_{m,s} w_{m,s} p_{m,s}\right|^2 + \sum_{c \in C_m} \left|H_{m,s} w_{c,s} p_{c,s}\right|^2 + \sigma^2}$$

To ensure that minimizing weighted MSE is equivalent to maximizing rate, weight $\varpi_{m,s}$ should be defined as $\varpi_{m,s} = \frac{1}{MSE_{m,s}}$:, and substituting $u_{m,s}^{opt}$ into $\mathrm{MES}_{m,s}$ yields optimal weights $\varpi_{m,s}^{opt}$ and $\mathrm{MES}_{m,s}^{opt}$:

$$\varpi_{m,s}^{opt} = \frac{\left|H_{m,s} w_{m,s} p_{m,s}\right|^2 + \sum_{c \in C_m} \left|H_{m,s} w_{c,s} p_{c,s}\right|^2 + \sigma^2}{\sum_{c \in C_m} \left|H_{m,s} w_{c,s} p_{c,s}\right|^2 + \sigma^2}$$

According to reference [17], the original safety rate maximization problem can be equivalently transformed into a weighted MSE minimization problem:

$$\min_{w,u,\varpi} \sum_{s=1}^{S} \sum_{m=1}^{M} \chi_{m,s} \left(\varpi_{m,s} \mathrm{MSE}_{m,s} - log_2 \varpi_{m,s}\right) - \sum_{n} \phi_n \sum_{m} \left(\varpi_{n,m} \mathrm{MSE}_{n,m} - log_2 \varpi_{n,m}\right)$$

Among them, ϕ_n satisfy the following conditions:

$$\phi_n = \begin{cases} 1, n = n^{*} = argmax \sum_{m} R_{n,m}, \forall n \in \{1,2 \cdots, N\} \\ 0, other \end{cases}$$

Next, perform alternating optimization by fixing the beamforming vector, optimizing the equalizer and weights, using $u_{m,s}^{opt}$ for the equalizer and $\varpi_{m,s}^{opt}$ for the weights. Next, fix the equalizer and weights, optimize the beamforming vector, and the problem is as follows:

$$\min_{w} \sum_{s=1}^{S} \sum_{m=1}^{M} \chi_{m,s} \left(\varpi_{m,s} \mathrm{MSE}_{m,s}\right) - \sum_{m=1}^{M} \varpi_{n^*,m} \mathrm{MSE}_{n^*,m}$$

$$s.t. \sum_{s=1}^{S} \sum_{m=1}^{M} p_{m,s} \le P_{max}$$

Let $W_s = \left[w_{1,s}, w_{2,s}, \cdots w_{Z,s}\right]$, H_s and H_n are the channel matrices for legitimate users and eavesdroppers, respectively. The weight equalizer matrix for legitimate users is $\Omega_s = \mathrm{diag}\left(\chi_{1,s}\omega_{1,s}\left|u_{1,s}\right|^2, \cdots, \chi_{Z,s}\omega_{Z,s}\left|u_{Z,s}\right|^2\right)$, and the equalizer matrix for eavesdroppers is $\Omega_{n^*} = \mathrm{diag}\left(\omega_{n^*,1}\left|u_{n^*,1}\right|^2, \cdots, \omega_{n^*,m}\left|u_{n^*,Z}\right|^2\right)$. The objective function has the following matrix form:

$$F(\boldsymbol{w}) = \sum_{s=1}^{S}\left(\mathrm{Tr}\left(\boldsymbol{W}_s^{\mathrm{H}}\boldsymbol{H}_s^{\mathrm{H}}\boldsymbol{\Omega}_s\boldsymbol{H}_s\boldsymbol{W}_s\right) - 2\mathrm{Re}\left\{\mathrm{Tr}\left(\boldsymbol{B}_s^{\mathrm{H}}\boldsymbol{W}_s\right)\right\}\right)$$
$$-\left(\mathrm{Tr}\left(\boldsymbol{W}_s^{\mathrm{H}}\boldsymbol{H}_n^{\mathrm{H}}\boldsymbol{\Omega}_n\boldsymbol{H}_n\boldsymbol{W}_s\right) - 2\mathrm{Re}\left\{\mathrm{Tr}\left(\boldsymbol{D}_n^{\mathrm{H}}\boldsymbol{W}_s\right)\right\}\right)$$

In the formula $B_s = \Omega_s U_s H_s$, $D_n = \Omega_n U_n H_n$, $U_s = \mathrm{diag}\left(u_{1,s}, \cdots, u_{Z,s}\right)$, $U_n = \mathrm{diag}\left(u_{n^*,1}, \cdots, u_{n^*,Z}\right)$ To solve the objective function, a Lagrange function is constructed as follows:

$$L(w, \lambda) = F(w) + \lambda\left(\sum_{s=1}^{S} \sum_{m=1}^{M} p_{m,s} - P_{max}\right)$$

Among them, λ is the Lagrange coefficient, which $\sum_{s=1}^{S} \sum_{m=1}^{M} p_{m,s} = P_{max}$ is adjusted by binary method to make the Lagrange function deviate from the beamforming vector W_s and make it equal to zero:

$$\frac{\partial L}{\partial \boldsymbol{W}_s} = 2\left(\boldsymbol{H}_s^{\mathrm{H}}\boldsymbol{\Omega}_S\boldsymbol{H}_s\boldsymbol{W}_s - \boldsymbol{G}_n^{\mathrm{H}}\boldsymbol{\Omega}_n\boldsymbol{G}_n\boldsymbol{W}_s\right)$$
$$-2\left(\boldsymbol{B}_s - \boldsymbol{D}_n\right) + 2\lambda\boldsymbol{W}_s$$

The closed form solution can be obtained as follows:

$$W_s = \left(H_s^H \Omega_S H_s - G_n^H \Omega_n G_n + \lambda I\right)^{-1}\left(B_s - D_n\right)$$

3.2. IRS Phase Shift Matrix Optimization

Next, under the allocation of subcarriers, beamforming vectors, and user power, the intelligent reflection surface shift matrix is optimized. The optimization problem is constructed as follows:

$$\max_{\Theta} \sum_{s=1}^{S} \sum_{m=1}^{M} R_t$$

$$s.t. \left|\Theta_{l,l}\right| = 1, l \in \{1,2 \cdots, L\}$$

$$\theta_l \in 0,2\pi), l \in \{1,2 \cdots, L\}$$

The reflection surface Θ can be shifted to affect the channel gain of subcarriers, indirectly affecting safety speed. Therefore, the optimization objective can be changed to maximize the total channel gain of all subcarriers minus the maximum eavesdropper's channel gain:

$$\max_{\Theta} \sum_{s=1}^{S} \sum_{m=1}^{M} \left|g_{m,s}^{H} \Theta f_{b,i} + h_{m,s}\right|^2 - \left|g_{n,s}^{H} \Theta f_{b,i} + h_{n,s}\right|^2$$

$\varphi = \left(e^{j\theta_1}, e^{j\theta_2} \cdots, e^{j\theta_L}\right)^H$, $G_{m,s} = f_{\mathrm{b,i}} \mathrm{diag}\left(g_{m,s}^{H}\right)$, $G_{n,s} = f_{\mathrm{b,i}} \mathrm{diag}\left(g_{n,s}^{H}\right)$ The objective function is as follows:

$$T(\varphi) = \sum_{s=1}^{S} \sum_{m=1}^{M} \left\|G_{m,s} \varphi + h_{m,s}\right\|^2 - \left\|G_{n,s} \varphi + h_{n,s}\right\|^2$$

Derive φ to obtain gradient

$$\begin{aligned} \nabla T = & 2\sum_{s=1}^{S}\sum_{m=1}^{M} \boldsymbol{G}_{m,s}^{\mathrm{H}} \left(\boldsymbol{G}_{m,s}\boldsymbol{\varphi} + \boldsymbol{h}_{m,s}\right) \\ & -2\boldsymbol{G}_{n,s}^{\mathrm{H}} \left(\boldsymbol{G}_{n,s}\boldsymbol{\varphi} + \boldsymbol{h}_{n,s}\right) \end{aligned}$$

Project the Euclidean gradient onto the tangent space of the unit circular manifold:

$$\mathrm{grad}\mathrm{T} = \nabla \mathrm{T} - \mathrm{Re}(\nabla T \odot \varphi^*) \odot \varphi$$

Update along the negative Riemann gradient direction and project the reflux shape:

$$\varphi^{(t+1)} = \mathrm{Proj}(\boldsymbol{\varphi}^t - \eta \mathrm{grad}\mathrm{T})$$

Among them, η is the step size. If the safety and rate changes are less than the threshold, the iteration will be stopped. The Riemann gradient descent method avoids the sub optimality of traditional projection methods by constraining the optimization variables on a complex circular manifold. Its core lies in the adaptation of gradient projection to manifold structure.

4. SIMULATION RESULTS

This section verifies the performance of the proposed method through simulation, with some parameters shown in Table 1. To verify the performance of the proposed scheme, comparisons were made with traditional NOMA systems, IRS assisted NOMA systems, and MC-NOMA systems without IRS assistance. The traditional NOMA system only optimizes beamforming vectors and power allocation, while the IRS assisted NOMA system optimizes beamforming vectors, power allocation, and IRS phase shift. The MC-NOMA system without IRS assistance optimizes beamforming vectors, power allocation, and subcarrier allocation.

Table 1. Simulation Parameters

Parameters	value
Path Loss Exponent	2
Noise Power	-80dBm
Maximum Base Station Transmission Power	40
Maximum Number of Iterations	20
Number of Legitimate Users/Eavesdroppers	M=10, N=2
Number of Antennas/Reflecting Elements ()	K=4, L=4

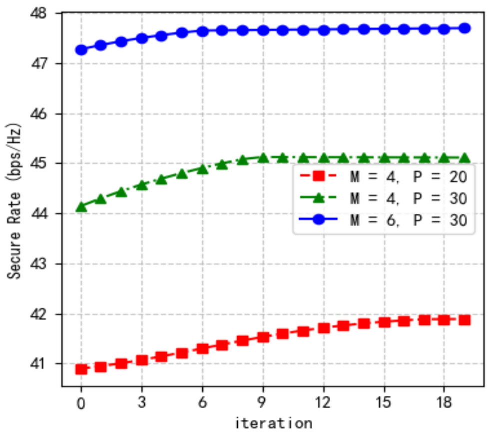

Figure 2. Secure Rate Number of Iterations

Figure 2 shows the variation trend of system safety rate under different numbers of antenna configurations and maximum transmission power conditions. The observation results indicate that as the number of iterations increases, the safety rate of the system shows an upward trend and reaches a stable convergence value within a limited number of iterations. Based on this, it can be concluded that increasing the maximum transmission power or increasing the number of antennas can effectively improve the safety rate of the system.

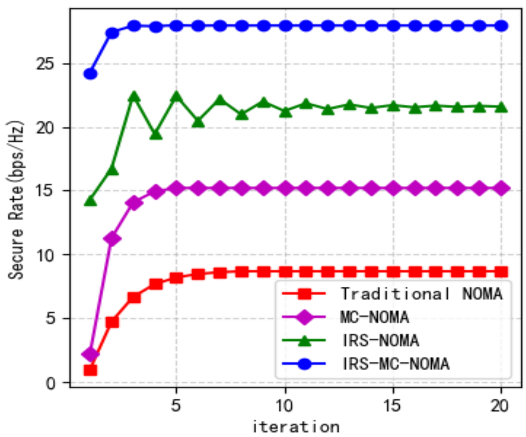

Figure 3. Secure Rate of Four NOMA Systems

Figure 3 compares the variation of safety rate with iteration times for four NOMA systems. It is evident from the graph that as the number of iterations increases. Among them, the scheme proposed in this article relies on the collaborative optimization of intelligent reflective surfaces and multiple carriers, achieving the highest safety rate and a relatively high safety rate with fewer iterations

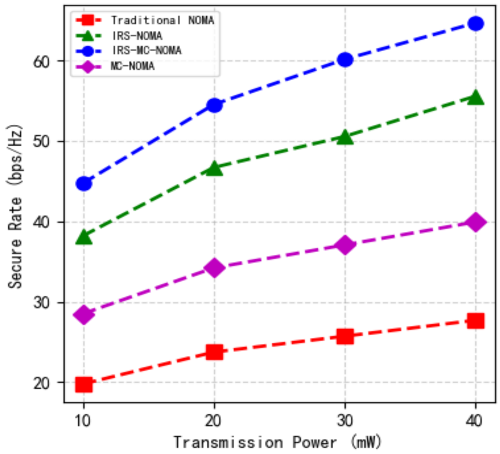

Figure 4. Secure Rate of Four NOMA Systems with Transmission Power

The results in Figure 4 show that as the maximum transmission power increases, the system safety rate of each scheme shows an upward trend In addition, under the condition of=40, compared with the IRS-NOMA scheme, the system's safety rate has increased by 16.1%. Therefore, the proposed scheme in this paper performs more outstandingly in terms of safety rate.

5. CONCLUSION

This article proposes a joint optimization scheme for the communication security of IRS assisted MC-NOMA system, which constructs a secure rate maximization problem under the constraints of subcarrier allocation scheme, base station transmission power, and IRS phase shift. Alternating optimization was performed to solve the non convex optimization problem, achieving maximum safety and speed. The simulation experiment results show that increasing the maximum transmission power or the number of antennas can effectively improve the safety rate of the system. The proposed scheme in this article achieves a higher safety rate with fewer iterations through the collaborative optimization of intelligent reflective surfaces and multiple carriers. Compared with other schemes, the safety rate is significantly improved. Meanwhile, as the number of reflective elements increases, the system's safety rate shows an upward trend, but the growth rate gradually slows down. Overall, the proposed solution in this article has significant advantages in improving the security and efficiency of communication systems.

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