Abstract—We propose a new secure transmission scheme which uses directional modulation (DM) with artificial noise and is aided by the intelligent reflecting surface (IRS). Specifically, the direct path and IRS-enabled reflect path carry the same confidential signal and thus can be coherently added at the desired position to maximize the total received power, while the received signals at other positions are distorted. We derive a closed-form expression for the secrecy rate achieved by the proposed scheme. Using simulation results, we show that the proposed scheme can achieve two-dimensional secure transmission at a specific position. Also, its performance advantage over the conventional DM scheme becomes more pronounced as the number of reflecting elements at the IRS increases.

Index Terms—Intelligent reflecting surface, directional modulation, artificial noise, physical layer security.

I. INTRODUCTION

Intelligent reflecting surface (IRS) has recently emerged as a promising and cutting-edge technology for the fifth generation (5G) and beyond wireless networks, which aims to improve signal coverage and quality by controlling the low-cost passive reflecting elements integrated on a surface [1]–[4]. Specifically, an IRS comprises a huge number of low-cost passive reflecting elements, which can adjust the phase shift of the incident wave, provide favourable wireless communication channels, and reduce the radio waves emission at the transmitter. It is noted that 5G networks may operate at high frequencies (e.g., 4.5–6 GHz). This would incur transmission outage since signals can be easily blocked by moving humans and static obstacles in an enclosed room. This blockage problem can be addressed by using the IRS to control the propagation environment, since the blocked signal can be reflected by the IRS to the desired user. Thus, IRS is a compelling wireless technology, particularly for indoor applications with the high density of users (e.g., stadium, shopping mall, and exhibition center).

In wireless communication systems, physical layer security is a fundamental but formerly untapped solution to secrecy problems, which aims to guarantee the confidentiality of transmitted information [5]. Comparing to the techniques using higher-layer encryption, physical layer security explores the characteristics of the communications medium to reduce the signal error of the eavesdropper. Among various techniques, directional modulation (DM) is one of the effective schemes to enhance physical layer security [6]–[9]. Specifically, DM can distort the constellation of the signals received at potential eavesdroppers while retaining the original shape of the signals received at the legitimate user. As indicated in [6], [7], the signal transmission in the DM scheme depends delicately on the line-of-sight (LoS) path, since the unwanted artificial noise (AN) is introduced towards the desired user in the multipath environment. Motivated by this, we apply the IRS to DM with AN to reinforce the control of the wireless propagation environment and utilize the multipath environment to enhance the physical layer security.

In this work, we propose a novel transmission scheme to enhance the physical layer secrecy performance of the system where a transmitter communicates with its legitimate receiver in the presence of an eavesdropper. The main contributions of this work are summarized as follows.

• The scheme uses DM with AN and is aided by the IRS, which reinforces the control of the propagation environment and utilizes the static multipath environment to enhance the physical layer security.
• A closed-form expression is derived for the secrecy rate achieved by the proposed scheme. We also compare the signal-to-noise ratio (SNR) of the proposed scheme with the conventional scheme.
• Using simulation results, we find that the proposed scheme can achieve two-dimensional (2D) secure transmission. We also find that the proposed scheme outperforms the conventional DM scheme, specifically when more reflecting elements are integrated at the IRS.

The remainder of this paper is organized as follows. Section II details our system model and assumptions. A thorough performance analysis of the proposed scheme is provided in Section III. Section IV provides simulation results to validate our analysis and provide useful insights into the impact of system parameters. Section V draws the conclusions.

Notations: Scalar variables are denoted by italic symbols. Vectors and matrices are denoted by lower-case and upper-case boldface symbols, respectively. Given a complex number, $|\cdot|$ denotes the modulus. Given a complex vector or matrix, $(\cdot)^*$, $(\cdot)^T$, $(\cdot)^H$, and $\|\cdot\|$ denote the conjugate, transpose, conjugate transpose, and norm, respectively. $\mathbb{C}^{p \times q}$ denotes the space of $p \times q$ complex-valued matrices. The $N \times N$ identity matrix is referred to as $I_N$ and $\mathbb{E}[\cdot]$ denotes expectation operation. $\mathcal{CN}(\mu, \sigma^2)$ denotes the distribution of a circularly symmetric complex Gaussian (CSCG) random variable with mean $\mu$ and
where $g_t$ is the transmit spatial steering vector given by
\[
g_t = \frac{1}{\sqrt{N_a}} \left[ e^{j2\pi \Phi_0(\phi_{ar})}, \ldots, e^{j2\pi \Phi_{N_a-1}(\phi_{ar})} \right]^H, \tag{4}
\]
and $g_r \in \mathbb{C}^{N_r \times 1}$ is the receiving steering vector with all-one elements. The IRS can be treated as a reflector with a large number of low-cost passive elements. Thus, it can reflect the electromagnetic waves by adding an additional phase to the received signal. The steering vector from the IRS to Bob and Eve are denoted by $h_{ab}^H \in \mathbb{C}^{1 \times N_r}$ and $h_{re}^H \in \mathbb{C}^{1 \times N_r}$, respectively, with all-one elements. The diagonal phase shifting matrix of the IRS is given by
\[
\Theta(\theta) = \text{diag} \left( e^{-j2\pi \Phi_{\theta_b}}, \ldots, e^{-j2\pi \Phi_{\theta_e}} \right), \tag{5}
\]
where $\theta \in \{\theta_b, \theta_e\}$ is the deflection angle for the signal of Bob or Eve at the IRS.

The signal received at Bob from both the Alice-Bob and the Alice-IRS-Bob paths can be expressed as
\[
y_b = \sqrt{P_t} h_{ab}^H x + n_b, \tag{6}
\]
where $n_b \sim \mathcal{C}\mathcal{N}(0, \sigma_b^2)$ is the additive white Gaussian noise (AWGN) at Bob, $P_t$ is the transmit power. The complex baseband transmitted signal at Alice is given by
\[
x = [x_a, x_r]^T. \tag{7}
\]
Moreover, $H_b$ denotes the two paths from Alice to Bob, given by
\[
H_b = \left[ \sqrt{L_{ab}} h_{ab}^H \sqrt{L_{arb}} h_{re}^H \Theta(\theta_b) G \right]. \tag{8}
\]
Due to the time difference between the two paths, we assume that the confidential signals are carefully designed to transmit at different time slots, allowing Bob to receive the signals from two paths at the same time. Hence, we have $x_a = \sqrt{\alpha} w_a + \sqrt{1 - \alpha} P_a z$ and $x_r = \sqrt{\alpha} w_r$, where $z$ is the confidential data for Bob with the average power $\mathbb{E} \|z\|^2 = 1$, $w_a$ and $w_r$ denote the precoding vectors of the Alice-Bob path and the Alice-IRS-Bob path, respectively. Moreover, we have $P_a \triangleq \|I_{N_a} - h_{ab} h_{ab}^H\|/\|I_{N_a} - h_{ab} h_{ab}^H\|$ as the vector to transmit AN signals towards Eve [7], where $z$ consists of $N_a$ i.i.d. circularly-symmetric complex Gaussian random variables with zero-mean and unit-variance, i.e., $z \sim \mathcal{C}\mathcal{N}(0, I_{N_a})$, and $\alpha$ denotes the power allocation factor between useful signals and AN signals. We next adopt $L_{xy} = (d_{xy}/d_0)^{-2}$ as the free-space path loss model, where $d_0$ is the reference distance and $d_{xy}$ is the distance between $x$ and $y$. Accordingly, $L_{ab}$ denotes the Alice-Bob distance and $L_{arb}$ denotes the Alice-IRS-Bob distance. In order to maximize the SNR at Bob, we set $w_a$ and $w_r$ as $w_a = h_{ab}$ and $w_r = g_r$, respectively.

The received signal at Eve is expressed
\[
y_e = \sqrt{P_t} h_e^H x + n_e, \tag{9}
\]
where $n_e \sim \mathcal{C}\mathcal{N}(0, \sigma^2)$ is the AWGN at Eve and $H_e$ denotes the two paths from Alice to Eve, given by
\[
H_e = \left[ \sqrt{L_{ae}} h_{ae}^H \sqrt{L_{are}} h_{re}^H \Theta(\theta_e) G \right]. \tag{10}
\]
Therefore, the SNR at Bob is given by
\[
\text{SNR}_{\text{Bob}} = \frac{P_\text{t} |h_{\text{ab}}|^2}{N_\text{f} \sigma_n^2}
\]
where \(\gamma\) is the SNR or the signal-to-interference-plus-noise ratio (SINR) at receiver, and the \(Q\)-function is defined as
\[
Q(u) = \frac{1}{\sqrt{2\pi}} \int_u^\infty e^{-\frac{t^2}{2}} \, dt.
\]
In this work, we consider the use of quadrature phase shift keying (QPSK) such that the BER is given by \(\text{BER} = Q(\sqrt{\gamma})\).

### III. Secrecy Performance Analysis

In this section, we analyze the secrecy performance of the proposed scheme. By using the expressions for \(x_n\) and \(x_c\) and noting that \(h_{\text{ab}}^H w_a = 1\), the received signal at Bob is rewritten as
\[
y_b = \sqrt{P_\text{t} L_{\text{arb}} h_{\text{ab}}^H} \left( \sqrt{\alpha P_a s} + \sqrt{1-\alpha P_a z} \right) + \sqrt{P_\text{t} L_{\text{arb}} h_{\text{rb}}^H} \Theta(\theta_b) G \left( \sqrt{\alpha P_a z} \right) + n_b
\]
\[
= \sqrt{P_\text{t} L_{\text{arb}} h_{\text{ab}}^H} \left( \alpha P_a s + \alpha P_a z \right) + \sqrt{P_\text{t} L_{\text{arb}} h_{\text{rb}}^H} \Theta(\theta_b) G \left( \sqrt{\alpha P_a z} \right) + n_b,
\]
where \(P_a z\) is orthogonal to \(h_{\text{ab}}^H\), implying \(h_{\text{ab}}^H P_a z = 0\). As per (4) and (5), we obtain
\[
h_{\text{rb}}^H \Theta(\theta_b) G w_r = \frac{1}{N_a} \sum_{k=0}^{N_a-1} \sum_{l=0}^{N_a-1} e^{j 2 \pi (\psi_1 + \psi_2)}
\]
\[
= N_r,
\]
where \(\psi_1 = \Phi_k(\phi_{ar}) - \Phi_k(\phi_{ar})\) and \(\psi_2 = \Phi_l(\theta_b) - \Phi_l(\theta_b)\). Therefore, the SNR at Bob is given by
\[
\gamma_b = \frac{P_\text{t} \sqrt{L_{\text{arb}}} + \sqrt{L_{\text{arb}}} N_r}{\sigma^2},
\]
Similarly, the received signal at Eve is rewritten as
\[
y_e = \sqrt{P_\text{t} L_{\text{arb}} h_{\text{ae}}^H} \left( \sqrt{\alpha P_a s} + \sqrt{1-\alpha P_a z} \right) + \sqrt{P_\text{t} L_{\text{arb}} h_{\text{re}}^H} \Theta(\theta_c) G \left( \sqrt{\alpha P_a z} \right) + n_e
\]
\[
= \sqrt{P_\text{t} L_{\text{arb}} h_{\text{ae}}^H} \left( \alpha P_a s + \alpha P_a z \right) + \sqrt{P_\text{t} L_{\text{arb}} h_{\text{re}}^H} \Theta(\theta_c) G \left( \sqrt{\alpha P_a z} \right) + n_e.
\]
Accordingly, the signal-to-interference-plus-noise ratio (SINR) at Eve can be given by
\[
\gamma_e = \frac{P_\text{t} \sqrt{L_{\text{arb}}} h_{\text{ae}}^H w_a + \sqrt{L_{\text{arb}}} h_{\text{re}}^H \Theta(\theta_c) G w_r}{(1-\alpha) P_\text{t} \sqrt{L_{\text{arb}}} h_{\text{ae}}^H P_a z + \sigma^2},
\]
where
\[
\gamma_e = \frac{\left( \sum_{k=0}^{N_a-1} \sum_{l=0}^{N_a-1} e^{j 2 \pi (\psi_1 + \psi_2)} \right)}{\sigma^2}
\]
\[
= \sum_{k=0}^{N_a-1} \sum_{l=0}^{N_a-1} e^{j 2 \pi (\psi_1 + \psi_2)}
\]
\[
= \sin \left( \frac{\pi N_a}{2} \cos \theta_e - \cos \theta_b \right)
\]
\[
\leq N_r.
\]

Following (18) and noting that \(h_{\text{ae}}^H w_a \leq 1\) and \(h_{\text{ae}}^H P_a z \geq 0\), we find that \(\gamma_e\) is lower than \(\gamma_b\).

In the considered system, the rate at Bob and Eve are given by \(R_b = \log_2 (1 + \gamma_b)\) and \(R_e = \log_2 (1 + \gamma_e)\), respectively. Thus, as per the rules of physical layer security, the secrecy rate of the proposed scheme is calculated as
\[
R_s = [R_b - R_e]^{+} = \log_2 \left( \frac{1 + \gamma_b}{1 + \gamma_e} \right),
\]
where \([x]^{+} = \max\{0, x\}\). Since we find \(\gamma_e < \gamma_b\), \(R_s\) is always a positive value.

### IV. Simulation Results and Discussion

In this section, we use simulations to evaluate the secrecy performance of the proposed scheme. Unless stated otherwise, we consider the number of antenna at Alice is set as \(N_a = 16\) and the number of elements of IRS is set as \(N_r = 50\). The noise power is set as \(\sigma^2 = -20\) dBm and transmit power \(P_t = 25\) dBm. The reference distance is \(d_0 = 1\) m and power allocation factor between useful signals and AN signals is \(\alpha = 0.6\). The spacing between antennas or reflecting elements is half of the wavelength. The locations of Alice, Bob, and IRS are set as Alice \((0, 0)\), Bob \((20, 0)\), and IRS \((20, -15)\), respectively.

Fig. 2 shows the BER of our considered system versus \(\phi_{ar}\) and \(\theta\). We observe from this figure that there are two lines achieving the lower BER than other lines. Specifically, one line is the Alice-Bob path and the other line is the Alice-IRS-Bob path. Interestingly, the intersection of these two paths, which achieves the minimum BER by our proposed scheme, is the location of Bob, which is our desired direction. We also observe that the BER rapidly becomes worse in undesired directions, e.g. the BER hovers around 0.5. This is due to the fact that the signal along the desired direction

![Fig. 2. The BER of our considered system versus \(\phi_{ar}\) and \(\theta\).](image-url)
is enhanced by the Alice-IRS-Bob path but not impacted by AN signals, while the signals along the undesired directions are severely impacted by AN signals. This indicates that our proposed scheme achieves 2D secure transmission by taking the advantage of the additional path enabled by the IRS.

In Fig. 4 we compare the secrecy performance of our proposed scheme, referred to as “DM, IRS”, with that of the benchmark scheme where DM is applied without the IRS, referred to as “DM, No-IRS”. The secrecy rate, $R_s$, achieved by the two schemes are plotted versus $N_r$ for $P_t = 10$ dBm and $P_t = 15$ dBm. We observe that for our proposed scheme, $R_s$ increases when $N_r$ increases, while for the benchmark scheme, $R_s$ remains unchanged. We then observe that the secrecy performance advantage of our proposed scheme over the benchmark scheme becomes more profound when $N_r$ increases. These observations indicate that using the IRS can effectively enhance the security performance of a wireless communication system with low power consumption.

Fig. 4 shows the secrecy rate $R_s$ versus the distance between Alice and Bob, $d_{ab}$, for $P_t = 10$ dBm and $P_t = 15$ dBm. We first observe that our proposed scheme always outperform the benchmark scheme, by achieving a higher secrecy rate, when $d_{ab}$ increases. Second, we observe that the secrecy rate achieved by both schemes decreases when $d_{ab}$ increases. Third, we observe that when $d_{ab}$ is sufficient large (e.g., $d_{ab} = 50$ m), the secrecy performance advantage of our proposed scheme over the benchmark scheme for $P_t = 15$ dBm is more significant than that for $P_t = 10$ dBm. This is mainly due to the fact that the transmit power constraint at Alice is a main contributor to the secure transmission aided by the passive IRS.

V. CONCLUSION

A new IRS-aided DM with AN scheme was proposed in this work to utilize the multipath propagation environment for enhancing the physical layer security. In order to examine the secrecy performance of the proposed scheme, we derived a closed-form expression for the secrecy rate. Simulation results showed that 2D secure transmission can be achieved by our proposed scheme. We found that our proposed scheme outperforms the conventional DM scheme which does not use IRS, and this performance advantage increases when there are more reflecting elements at the IRS. Additionally, we found that the transmit power constraint at the transmitter plays a key role in governing the secrecy rate improvement of our proposed scheme when the distance between the transmitter and the legitimate receiver is sufficiently large.

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