Random Shifting Intelligent Reflecting Surface for OTP Encrypted Data Transmission

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Abstract—In this paper, we propose a novel encrypted data transmission scheme using an intelligent reflecting surface (IRS) to generate secret keys in wireless communication networks. We show that perfectly secure one-time pad (OTP) communications can be established by using a simple random phase shifting of the IRS elements. To maximize the secure transmission rate, we design an optimal time slot allocation algorithm for the IRS secret key generation and the encrypted data transmission phases. Moreover, a theoretical expression of the key generation rate is derived based on Poisson point process (PPP) for the practical scenario when eavesdroppers’ channel state information (CSI) is unavailable. Simulation results show that employing our IRS-based scheme can significantly improve the encrypted data transmission performance for a wide-range of wireless channel gains and system parameters.

Index Terms—Intelligent reflecting surface, physical layer security, reconfigurable intelligent surface, secret key generation.

I. INTRODUCTION

INTELLIGENT reflecting surface (IRS) is a promising candidate technology for future mobile communication systems due to its low-cost deployment and high spectral and energy efficiency [1]. By adaptively adjusting amplitudes and phase shifts of large-scale passive reflecting elements, IRS can reconfigure the electromagnetic propagation environment of wireless devices, thereby improving their communication performance [2], [3]. Recently, physical layer security in IRS assisted networks has also attracted extensive research attention [4]–[6]. However, most of these contributions focused on designing beamforming and artificial noise vectors, whilst IRS based secret key generation remains unexplored.

Physical layer secret key generation is an alternative security approach to computational complexity based encryption [7]. In this approach, secret keys are generated by legitimate transceivers using their reciprocal time-variant channels, while preventing eavesdroppers from inferring the generated keys through its own wireless channel observations due to spatial decorrelation. Notably, the key generation rate (KGR) is limited by the movement speed of the legitimate transceivers, which makes it impractical for stationary or slow-moving wireless devices. To achieve perfectly secure one-time pad (OTP) [8], artificial randomness can be introduced to boost the KGR. In [9], a method to induce randomness was proposed by selecting different local pilot constellations. In [10], private random precoding vectors were designed to induce randomness in multiple-input multiple-output (MIMO) systems. The authors in [11] utilized artificial noise to scramble eavesdropping channels and maximize the key generation capacity. We note that all the above contributions focused on increasing randomness at transceiver ends, rather than increasing the rate of channel randomness in the wireless environment.

In this letter, we consider the use of IRS to induce virtual fast fading channels, where artificial randomness is introduced into the propagation environment, thus no multiple-antenna configuration or high-order modulation is required. We propose a simple random IRS phase shifting scheme for physical layer key generation to support OTP encrypted data transmission. To provide detailed insights, we derive the secure transmission rate and KGR of our proposed scheme. Based on the maximum transmission rate, we develop an optimal time slot allocation algorithm for the key generation and data transmission phases. For randomly distributed eavesdroppers whose channel state information (CSI) is unknown, we further consider the use of a Poisson point process (PPP) model to derive the KGR that is only related to the distribution intensity of eavesdroppers. Finally, the advantages of our scheme and the validity of the analysis is verified through simulations. We show that the secure transmission rate is enhanced significantly by random phase shifted IRS compared with no IRS and IRS with fixed phase shifts. The impacts of important system design parameters including the length of coherence interval, the number of IRS elements, signal-to-noise ratio (SNR), the distribution intensity and distribution radius of eavesdroppers, are highlighted in the simulation results.

II. SYSTEM MODEL

Our proposed system model is shown in Fig. 1, which consists of a single-antenna base station (Alice) and a single-antenna user (Bob) wanting to exchange data securely over the public wireless channels, and $K$ single-antenna eavesdroppers.
(Eves) attempting to capture the transmitted information. To generate secret keys, Alice and Bob exploit their reciprocal channels in time-division duplex (TDD) mode, then encrypt and decrypt the transmitted messages using the OTP approach. We assume that Bob is a stationary or slow-moving wireless device which leads to a relative long coherence interval and thus a limited KGR. To significantly increase the KGR, we propose to use an $N$-element IRS (Rose) that can artificially adjust phase shifts and induce randomness in the wireless propagation environment. The best strategy for passive Eves is to be located close to either Alice or Bob so that their observed channels can be correlated with the legitimate ones, and similar keys can be obtained by Eves. Considering Bob is a mobile user, we assume all Eves are located around Alice.

III. RANDOM SHIFTING IRS FOR OTP ENCRYPTED DATA TRANSMISSION

Fig. 2 shows our proposed scheme which is composed of two phases: secret key generation and encrypted data transmission. In Phase 1, Alice and Bob exchange known pilot sequences during the first $2Q$ time slots, assisted by Rose which simply reflects the legitimate transmissions with a random set of phase shifts in each uplink and downlink round. During the odd time slots, Alice sends pilot signal $s_1 \sim \mathcal{CN}(0, I)$, and the received signal at Bob or the $k$th Eve can be expressed as

$$y_{i,1}^{(q)} = \sqrt{P}(h_{ai} + h_{bi}^H\Theta^{(q)}h_{ba})s_1 + z_i, \quad i \in \{a, e_k\},$$

where $h_{bi} \in \mathbb{C}^{1 \times 1}$, $h_{ba} \in \mathbb{C}^{N \times 1}$, and $h_{aj} \in \mathbb{C}^{N \times 1}$ denote the direct channel from Alice to node $i$, the incident channel from Alice to Rose, and the reflected channel from Rose to Bob or Eve, respectively. Let $\Theta^{(q)} = \text{diag}(e^{j\theta_{1,q}}, e^{j\theta_{2,q}}, \ldots, e^{j\theta_{Q,q}})$ denote the diagonal IRS phase shifting matrix in the $q$th round of channel training, where $q = 1, 2, \ldots, Q$. In the phase shifting matrix, $\theta_{n,q}$ represents the discrete phase shift induced by the $n$th reflecting element, which is generated based on an independent random variable (RV) uniformly distributed in a set with finite number of discrete values $\{0, \frac{2\pi}{2^B}, \ldots, \frac{(2^B-1)2\pi}{2^B}\}$, where $B$ is the number of quantization bits for phase shifts. In Fig. 2, $P$ is the transmit power, and $z_i \sim \mathcal{CN}(0, \sigma_z^2 I)$ is the independent and identically distributed (i.i.d.) complex additive white Gaussian noise vector.

Fig. 2. Time slot allocation for the IRS-assisted secret key generation phase and the OTP encrypted data transmission phase.

Similarly, during the even time slots, Bob transmits pilot signal $s_2 \sim \mathcal{CN}(0, I)$ with the same power $P$, and Alice or Eve receives

$$y_{i,2}^{(q)} = \sqrt{P}(h_{bi} + h_{bi}^H\Theta^{(q)}h_{ba})s_2 + z_i, \quad i \in \{a, e_k\},$$

where $h_{bi} \in \mathbb{C}^{1 \times 1}$ and $h_{ba} \in \mathbb{C}^{N \times 1}$ represent the channel from Bob to node $i$ and Rose, respectively. Here, we assume that all involved channels are quasi-static, i.e., they remain constant in each coherence interval and change independently between different coherence intervals. The IRS ensures that the equivalent channels change randomly in each round, which helps to significantly increase the KGR. The equivalent channels estimated at each node can be calculated from their observations as

$$\hat{h}_B^{(q)} = \frac{y_{i,1}^{(q)}h_{ai}^+}{\sqrt{\mathbb{E}[|s_1|^2]}},$$

$$\hat{h}_B^{(q)} = \frac{y_{i,2}^{(q)}h_{bi}^+}{\sqrt{\mathbb{E}[|s_2|^2]}},$$

and that between two phases: secret key generation and encrypted data transmission. Assuming that all Eves are located around Alice

$$\Delta T = \log_2 \left(1 + \frac{\rho_e B_2}{\rho_e B_2 - P_e} \right),$$

where $\rho_e = \mathbb{E}\{\tilde{h}_A^{(q)}\tilde{h}_B^{(q)*}\} = \mathbb{E}\{\tilde{h}_A^{(q)}\tilde{h}_B^{(q)*}\} = \mathbb{E}\{\tilde{h}_A^{(q)}\tilde{h}_B^{(q)*}\}$ denote the cross-correlations between $\tilde{h}_A^{(q)}$ and $\tilde{h}_B^{(q)}$, and that between $\tilde{h}_A^{(q)}$ and $\tilde{h}_B^{(q)}$, respectively. $\mathbb{E}\{\cdot\}$ represents the expectation with respect to (w.r.t.) the $Q$ samples.
Proof: The mutual information $I(\tilde{h}_A^{(q)}, \tilde{h}_B^{(q)} | \tilde{h}_{E_{1k}}^{r}, \tilde{h}_{E_{2k}}^{r})$ can be calculated as

$$I(\tilde{h}_A^{(q)}, \tilde{h}_B^{(q)} | \tilde{h}_{E_{1k}}^{r}, \tilde{h}_{E_{2k}}^{r}) = H(\tilde{h}_A^{(q)} | \tilde{h}_{E_{1k}}^{r}) - H(\tilde{h}_A^{(q)} | \tilde{h}_{E_{1k}}^{r}, \tilde{h}_B^{(q)})$$

where $H(\cdot)$ denotes the entropy function.

Similarly, the determinants of other matrices in (8) can be given as $\det(W_{AE_{1k}E_{2k}}) = 1 - \rho_{E_{1k}}$ and $\det(W_{E_{1k}E_{2k}}) = 1$. In addition, when there exists randomly distributed Eves, we focus on the performance analysis of our proposed scheme when the untrusted nodes are other users in the same network. However, we note that since the keys have been shared between Alice and Bob, this encrypted data transmission stage can be either uplink or downlink. Taking the downlink for an example, the transmission rate is given by

$$R_{MRT} = \frac{1}{\Delta T} \log_2 \left( 1 + \gamma_b |h_{ab} + h_B^H \Theta h_{ab}|^2 \right),$$

where $\gamma_b = P/\sigma_n^2$ is the reference SNR and $\Theta^*$ is the optimal IRS phase shift matrix defined in [1, 19]. Let $L$ denote the total number of symbols in each coherence interval, thus the remaining $(L - 2Q)$ time slots is used for encrypted data transmission. We observe that there exists a tradeoff between the two phases of generating keys and transmitting data: if $Q$ is too small, the generated keys will be insufficient to encrypt all the data to be transmitted; whereas if $Q$ is too large, the remaining time slots for data transmission will be insufficient and thus some generated keys will be wasted. Therefore, the secure transmission throughput in our proposed scheme depends on the minimum of the generated key bits and the transmitted data bits, where the secure transmission rate is derived as

$$Q_{\text{max}} = \frac{1}{\max \{ \alpha, Q_{\text{SKG}} \}}$$

Algorithm 1 Proposed Optimal Time Slot Allocation

1: Let Rose be in the receiving mode. Alice and Bob alternatively send pilot signals so that Rose can estimate $h_{ar}$ and $h_{ab}^H$. Alice estimates $h_{ab}$ and sends its phase to Rose, then $\Theta^*$ and $R_{MRT}$ can be calculated based on (10).

2: Initialize $Q^{(1)} = 1$.

3: repeat (Observation accumulation for $R_{SKG}^{(k)}$)

4: For given $Q^{(t)}$, let Rose be in the reflecting mode with randomly selected $\Theta^{(t)}$. Alice and Bob collect channel observations $h_{A}^{(q)}, h_{B}^{(q)}$, and $h_{E_{2k}}^{(q)}$ and normalize them. The corresponding $R_{SKG}^{(t)}$ can be computed according to (5).

5: Initialize $Q_{\min} = Q^{(t)}$ and $Q_{\max} = L$.

6: repeat (Bisection search for $Q^{(t)}$)

7: Set $Q = \frac{(Q_{\min} + Q_{\max})}{2}$, and calculate $\Delta R = \frac{Q R_{SKG}^{(t)} - (L - 2Q) R_{MRT}}{Q_{\max} - Q_{\min}}$. If $\Delta R \leq 0$, update $Q_{\min} = Q$; otherwise update $Q_{\max} = Q$.

8: until $(Q_{\max} - Q_{\min}) \leq 1$. Record this $Q$ as $Q_{t}^{(t)}$.

9: Update $Q^{(t+1)} = Q_{t}^{(t)} + 1$.

10: until $Q^{(t)} \geq Q^{(t-1)}$. Finally, we obtain $Q^* = Q^{(t-1)}$.

IV. PERFORMANCE ANALYSIS FOR RANDOMLY DISTRIBUTED EAVESDROPPERS

We find that $R_{SKG}$ in (7) depends on the minimum $R_{SKG}^{(k)}$, which is computed based on knowledge of $h_{A}^{(q)}, h_{B}^{(q)}$, and $h_{E_{2k}}^{(q)}$, where $h_{E_{2k}}^{(q)}$ is typically assumed to be known at Alice and Bob when the untrusted nodes are other users in the same network. However, we note that the CSI of passive and malicious Eves may be challenging to estimate and may not be perfectly known at Alice and Bob. To this end, in this section we focus on the performance analysis of our proposed scheme when there exists randomly distributed Eves.
Since the transmitted data has been XORed by OTP keys, Eves will not impact on the encrypted transmission stage. Only key generation can be compromised in the presence of Eves. From (9), we can derive that

\[
\frac{\partial R_{\text{SKG}}}{\partial \rho_{\text{E}}} = \frac{\ln(2(\rho_{\text{E}} - \rho_L)(1 - \rho_{\text{E}}^2))}{\Delta T(1 + \mu - 2\rho_{\text{E}}^2)} < 0, \\
\frac{\partial R_{\text{SKG}}}{\partial \rho_L} = \frac{\ln(2(\rho_L - \rho_{\text{E}}^2))}{\Delta T(1 - \mu)(1 + \mu - 2\rho_{\text{E}}^2)} > 0,
\]

when \(\rho_L > \rho_{\text{E}}^2\) holds. This condition is always satisfied because noise is the only factor that results in the decrease of \(\rho_L = \mathbb{E}\{\|g_{ab}(q)\|^2\}/(\mathbb{E}\{\|g_{ab}(q)\|^2\} + \sigma^2\)\). This is because of the high similarity between two observations \(\tilde{h}^{(q)}(q)\) and \(\tilde{h}^{(q)}(q)\) of the reciprocal channel \(g_{ab}(q)\), whereas \(\rho_{\text{E}}\) is weakened by the difference between the combined channels \(g^{(q)}_{\text{ab}}\) and \(g^{(q)}_{\text{bes}}\) in addition to noise. Therefore, \(R_{\text{SKG}}\) decreases as \(\rho_{\text{E}}\) increases or \(\rho_L\) decreases.

For a given SNR, \(\rho_L\) is fixed, while \(\rho_{\text{E}}\) is affected by the positions of Eves. Since Eves are passive, we assume that their exact locations are not known. Therefore, we consider a PPP to model the locations of randomly distributed Eves and analyze the impact on \(R_{\text{SKG}}\). Generally, a closer distance between Alice and Eve \(d_{\text{AE}}\), is associated with a stronger correlation \(\rho_{\text{E}}\), so we need to find the expectation of the closest distance \(d_{\text{min}}\), which corresponds to the largest \(\rho_{\text{E}}\) and \(R_{\text{SKG}}\). Specifically, we model the locations of Eves as a homogenous PPP in the plane denoted by \(\Phi_{\text{E}}\) with intensity \(\lambda_{\text{E}}\). The probability density function (PDF) of \(d_{\text{AE}}\) of the \(k\)th nearest Eve to Alice is expressed as

\[
f_{d_{\text{AE}}} (d_{\text{AE}}) = e^{-\lambda_{\text{E}} \pi d_{\text{AE}}^2} \frac{2\lambda_{\text{E}}^2 \pi^{k} d_{\text{AE}}^{2k-1}}{\Gamma(k)},
\]

where \(\Gamma(\cdot)\) is the gamma function. As such, the expectation of \(d_{\text{min}}\) (i.e., \(d_{\text{AE}}\)) can be calculated as

\[
E_{\Phi_{\text{E}}}(d_{\text{min}}) = \int_0^\infty 2\lambda_{\text{E}}^2 \pi d_{\text{min}}^2 e^{-\lambda_{\text{E}} \pi d_{\text{min}}^2} \, dd_{\text{min}} = \left( \int_0^\infty 2\lambda_{\text{E}} \pi d_{\text{min}}^2 e^{-\lambda_{\text{E}} \pi d_{\text{min}}^2} \, dd_{\text{min}} \right)^{\frac{1}{2}} = \frac{1}{\sqrt{4\lambda_{\text{E}}}},
\]

which indicates that when \(\lambda_{\text{E}}\) is high, \(d_{\text{min}}\) is expected to be small. Furthermore, the correlation between \(g_{ab}(q)\) and \(g_{\text{bes}}(q)\) can be characterized by

\[
\rho(d_{\text{AE}}) = |J_0(2\pi d_{\text{AE}}/\lambda)|^2,
\]

where \(J_0(\cdot)\) is the Bessel function of the first kind, and \(\lambda\) is the wavelength. Thus, the KGR in (7) can be simplified as

\[
R_{\text{SKG}} = \frac{1}{2\Delta T} \log_2 \left( \frac{(1 - \rho_{\text{E}}^2)^2}{1 + 2\rho_L \rho_{\text{E}} \max - 2\rho_{\text{E}}^2 \max - \rho_L^2} \right),
\]

where the maximum correlation among all \(\rho_{\text{E}}\) is

\[
\rho_{\text{E}} \max = \frac{\mathbb{E}\{\|g_{ab}(q)\|^2\} \rho(\Gamma(4/\lambda_{\text{E}})}{\sqrt{\mathbb{E}\{\|g_{\text{bes}}(q)\|^2\} + \sigma^2} \sqrt{\mathbb{E}\{\|g_{ab}(q)\|^2\} + \sigma^2}}.
\]

With this closed-form expression, we can investigate the influence of randomly distributed Eves on the security performance of our proposed scheme. Correspondingly, \(h_{\text{E2b}}^{(q)}\) in Step 4 of Algorithm 1 is no longer required, and Alice and Bob only need to determine a suitable \(\lambda_{\text{E}}\) according to their estimation of the surrounding network conditions.

V. SIMULATION RESULTS AND DISCUSSION

In this section, simulation results are presented to show the effectiveness of the proposed scheme by comparing with two benchmarks: (1) without IRS, (2) IRS with fixed optimal phases. We assume that the distance between Alice and Bob is \(d_{AB} = 100\) m. The central point of the IRS is located at a vertical distance of \(d_1 = 5\) m to the line that connects Alice and Bob, and the horizontal distance between the IRS and Bob is set as \(d_2 = 5\) m. Accordingly, the distance between Alice and Rose and that between Bob and Rose are given by \(d_{\text{ER}} = \sqrt{(d_{AB} - d_2)^2 + d_1^2}\) m and \(d_{\text{BR}} = \sqrt{d_2^2 + d_1^2}\) m, respectively. All Eves are randomly deployed within a circle of radius 1 m centered at Alice and their distances to Bob and Rose can be calculated correspondingly. The path loss is given by \(PL = (PL_0 + 10\log_{10}(d/d_0))\) dB, where \(PL_0 = 30\) dB is the path loss at reference distance \(d_0 = 1\) m, \(\zeta\) is the path loss exponent, and \(d\) is the distance between the transmitter and the receiver. The path loss exponents for the Alice-Rose link, Rose-Bob link, and Alice-Bob link (Eve-Bob link) are \(\zeta_{\text{AR}} = \zeta_{\text{ER}} = 2.2, \zeta_{\text{RB}} = 2.5,\) and \(\zeta_{\text{AB}} = \zeta_{\text{EB}} = 3.5,\) respectively. The small-scale fading of all involved channels follows a Rayleigh fading model, and the correlation between channel coefficients of legitimate channels and eavesdropping channels is characterized by (16). Other parameters are set as follows: the carrier frequency \(f_c = 1\) GHz, the transmit power \(P = 20\) dBm, the noise power \(\sigma^2 = -96\) dBm, \(\Delta T = 1\) ms, \(L = 30, N = 50, B = 3,\) and \(K = 4\) if not specified otherwise.

Fig. 3 shows the advantages of the proposed scheme over other benchmarks. IRS with fixed optimal phases yields higher \(R_{\text{SKG}}\) and \(R_{\text{EDT}}\) by improving the SNR compared with the case without IRS, but only one set of keys can be generated by using the existing channels. However, in our scheme, since the random IRS shifting is employed, the combined channels leads to \(Q^*\) times of key generation and therefore \(C_{\text{EDT}}\) is increased. In addition, we see that the performance is significantly improved when the transmit power \(P\) is increased since the corresponding high SNR benefits to both key generation and encrypted data transmission. The larger number of elements \(N\) also results in better performance, but the gain brought by the same number of IRS elements will gradually decrease as \(N\) increases. It can be observed that the number of quantization bits for phase shifts \(B\) basically does not affect \(C_{\text{EDT}}\), which indicates that our scheme can still provide good performance when equipping low-resolution hardware at the IRS.

Fig. 4 depicts the impact of time slot allocation on \(R_{\text{EDT}}\) as discussed in Section III. At first, as more keys are generated, \(R_{\text{EDT}}\) increases with \(Q\), then as \(Q\) further increases, \(R_{\text{EDT}}\) decreases due to insufficient time slots assigned for encrypted data transmission. The \(Q\) corresponding to each peak is \(Q^*\), which can be found by applying Algorithm 1 and the value of each peak pointed by the arrow is \(C_{\text{EDT}}\). Under the same \(P\), \(Q^*/L\) basically remains unchanged and the slight performance improvement comes from the increased accuracy of allocation proportion. This demonstrates that our scheme can be applied to various scenarios with a wide range of coherence intervals \(L\). When \(P\) decreases, the achievable \(R_{\text{EDT}}\) reduces as well, which is consistent with the analysis in Fig. 3. Meanwhile, we
The number of IRS elements

Fig. 4. The impact of time slot allocation $Q$ on encrypted transmission rate $R_{\text{EDT}}$ for different coherence interval $L$ and transmit power $P$.

Fig. 3. Encrypted transmission capacity $C_{\text{EDT}}$ versus transmit power $P$ for different schemes, number of quantization bits $B$ and number of elements $N$.

Fig. 5. The impact of randomly distributed Eves on secret key generation rate $R_{\text{SKG}}$ for different distribution radius $R$ and intensity $\lambda_E$.

note that $Q^*$ becomes larger because the SNR impacts more on secret key generation, which compromises reciprocity between legitimate channels and thereby decreases $\rho_5$ and $R_{\text{SKG}}$.

Fig. 4 investigates the impact of randomly distributed Eves and their distribution parameters. We can see that no matter how Eves are distributed, $R_{\text{SKG}}$ almost increases linearly with the number of IRS elements $N$. Moreover, when the radius of $\Phi_E$ is $R = 0.1 \text{ m}$, a lower $\lambda_E$ (less Eves) also improves $R_{\text{SKG}}$, which is consistent with our analysis in Section IV. However, this improvement becomes negligible when $R$ is increased to $1 \text{ m}$. This confirms the conclusion that Eves beyond several wavelengths can be ignored in secret key generation. Finally, simulation results given by [5] coincide well with theoretical results obtained from [6], which shows the correctness of our analysis.

VI. CONCLUSIONS

We investigated the confidential transmission in IRS assisted wireless networks with multiple passive eavesdroppers. A new encrypted data transmission scheme was designed, where the OTP secret keys were provided by random IRS phase shifting. The KGR was derived based on the assumption that all Eves were located near Alice, and an optimal time slot allocation algorithm was proposed to maximize the secure transmission rate. For practical implementations, we further analyzed the impact of randomly distributed Eves whose CSI is unavailable. The effectiveness of the proposed scheme and correctness of our analysis were validated by the simulation and theoretical results.

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