Uplink Secure Communication via Intelligent Reflecting Surface and Energy-Harvesting Jammer

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***Abstract*—In this paper, we investigate the uplink secure communication by combining intelligent reflecting surface (IRS) and energy-harvesting (EH) jammer. Specifically, we propose an IRS-aided secure scheme for the uplink transmission via an EH jammer, to fight against the malicious eavesdropper. An energy transfer (ET) phase and an information transmission (IT) phase are proposed in this scheme. In the ET phase, we optimize the phase-shift matrix of IRS to maximize the harvested energy of jammer. In the IT phase, the phase-shift matrix of IRS and time switching factor are jointly optimized to maximize the secrecy rate. To tackle the non-convex problem, we first decompose it into two subproblems to solve by capitalizing on semi-definite relaxation (SDR) and Lagrange duality. Then, the solutions to the original problem can be obtained by alternately optimizing the two subproblems. Simulation results show that the proposed Jammer-IRS assisted secure transmission scheme can significantly enhance the uplink security.**

***Index Terms*—Energy harvesting, intelligent reflecting surface, jamming, physical layer security, time switching.**

I. Introduction

Physical layer security (PLS), as a promising technique to improve the security of wireless communications, has been widely studied recently in many directions, e.g., beamforming design, artificial jamming (AJ), cooperative relaying, *etc*. The principle of PLS is to take the advantage of wireless channels, such as fading, noise and interference, to fight against the malicious eavesdropping and achieve security enhancement [1]. In particular, AJ is often used in the downlink to ensure the secure transmission. However, in the uplink, due to the physical structure and power constraint of devices, there is not enough spatial freedom or power to transmit AJ, which motives the emerging of cooperative jamming [2]. Cooperative jamming can be achieved by deploying a friendly jammer to confuse the eavesdropper. In practical networks, devices are usually energy-limited or selfish. To tackle this challenge, energy harvesting (EH) is adopted to scavenge energy from the environment for continuous energy supply [3].

Recently, intelligent reflecting surface (IRS) has been proposed to create a smart and reconfigurable wireless environment [4]. IRS, a plane consisting of a number of low-cost passive reflecting elements, can be used to enhance or attenuate the channels by individually altering the amplitude and phase of the incident signals [5]. Compared to traditional related approaches like conventional reflecting surface, amplify-and-forward relaying and backscattering, IRS has the advantages of reconfigurable reflecting coefficients, low energy consumption, low cost and easy deployment [6]. Due to these merits, IRS has been utilized in various scenarios to improve the capacity, energy efficiency, PLS, *etc*. In particular, IRS has provided appealing solutions to improving PLS by enhancing the strength of legitimate links while attenuating the eavesdropping via passive beamforming [4].

Based on the aforementioned background, both IRS and EH jammer can contribute to PLS. However, little attention has been focused on secrecy rate maximization aided by both the IRS and the friendly EH jammer for the uplink in existing works. As a result, we propose an uplink Jammer-IRS scheme, in which the transmission process can be divided into an energy transfer (ET) phase and an information transmission (IT) phase. In the ET phase, the jammer harvests energy from the BS. The harvested energy of jammer is maximized by deriving the optimal phase-shift matrix of IRS in closed form. In the IT phase, aided by IRS, the user transmits confidential information to the BS in the presence of eavesdropper, and the jammer uses the energy harvested in the previous phase to confuse the eavesdropper without affecting the legitimate transmission. The secrecy rate is finally maximized by jointly optimizing the phase-shift matrix of IRS and the time switching factor.

II. System Model and Problem Formulation

A. System Model

As shown in Fig. 1, we consider an uplink wireless communication system consisting of one BS, one legitimate user and one malicious eavesdropper (Eve). To effectively fight against the Eve, a friendly EH jammer (Jam) and an IRS with *N* reflecting elements are introduced. Assume that the BS, the user and the Eve are all equipped with a single antenna, while the number of antennas at the Jam is *M*. Since the Jam harvests energy before transmitting AJ, the whole transmission process can be divided into an ET phase with αT and an IT phase with $(1-\alpha)T$. $0<\alpha<1$ denotes the time switching factor between ET and IT while T represents the duration of a frame. The quasi-static flat-fading is assumed for all channels. $\mathbf{h}_{bj} \in \mathbb{C}^{M\times 1}$, $\mathbf{h}_{je} \in \mathbb{C}^{1\times M}$ and $h_{uf}(f \in \{b,e\})$ denote the channel coefficients of direct links for BS $\rightarrow$ Jammer, Jammer $\rightarrow$ Eve, User $\rightarrow$ BS and User $\rightarrow$ Eve, respectively,

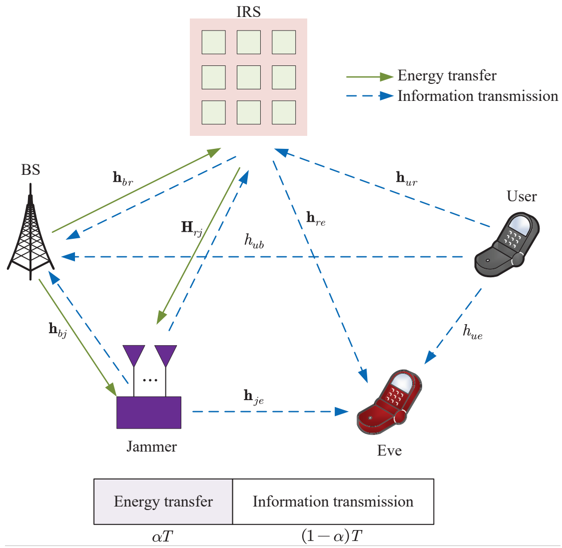

Fig. 1. Uplink system model with the help of IRS and jammer.

while the channel coefficient vectors of IRS-assisted links for BS → IRS, User → IRS, IRS → Eve and IRS → Jammer are denoted as $\mathbf{h}_g(g \in \{br, ur, re\}) \in \mathbb{C}^{N\times 1}$ and $\mathbf{H}_{rj} \in \mathbb{C}^{N\times M}$, respectively. In this work, we assume that IRS is a square array with a number of $\sqrt{N}$ elements in both the horizontal and vertical directions. Let $\boldsymbol{\theta} = [\theta_1, \ldots, \theta_n, \ldots, \theta_N]^T$ and $v_n = \beta_n e^{j\theta_n}$, where $\theta_n \in [0, 2\pi)$ and $\beta_n \in [0, 1]$ denotes the phase shift and amplitude reflection coefficient of the IRS's n-th element. $\mathbf{\Phi} = \mathrm{diag}(v_1, \cdots, v_n, \cdots, v_N)$ denotes the phase-shift matrix of IRS. $\beta_n = 1$ is set to maximize the signal reflection in the following analysis. In addition, we denote the complex additive white Gaussian noise (AWGN) at the Jam, the BS and the Eve as $n_l \sim \mathcal{CN}(0, \sigma^2), l \in \{j, b, e\}$, respectively.

B. First Phase: Energy Transfer

During the first phase, the BS transmits with the fixed power P_b. We denote the transmitted signal as x_b with $E[|x_b|^2] = 1$. $\mathbf{u}_J$ is the combining vector with the dimension of $M \times 1$. To maximize the harvested energy at the Jam, $\mathbf{u}_J$ is derived as $\mathbf{u}_J = \frac{\mathbf{H}_{rj}^\dagger \mathbf{\Phi}_1 \mathbf{h}_{br} + \mathbf{h}_{bj}}{\left\|\mathbf{H}_{rj}^\dagger \mathbf{\Phi}_1 \mathbf{h}_{br} + \mathbf{h}_{bj}\right\|}$ using the maximal ratio combining (MRC). The signal received at the Jam can be expressed as

$$y_j = \mathbf{u}_J^\dagger (\mathbf{H}_{rj}^\dagger \mathbf{\Phi}_1 \mathbf{h}_{br} + \mathbf{h}_{bj}) \sqrt{P_b} x_b + n_j, \tag{1}$$

where $\mathbf{\Phi}_1 = \mathrm{diag}(v_{1,1}, \cdots, v_{1,n}, \cdots, v_{1,N})$ denotes the phase-shift matrix of IRS with $|v_{1,n}| = 1, n = 1, \ldots, N$. The energy harvested by the Jam can be expressed as

$$E_J = \alpha T \eta P_b \left| \mathbf{u}_J^\dagger (\mathbf{H}_{rj}^\dagger \mathbf{\Phi}_1 \mathbf{h}_{br} + \mathbf{h}_{bj}) \right|^2, \tag{2}$$

where $0 < \eta < 1$ denotes the EH efficiency. Within the remaining $(1 - \alpha)T$, the Jam will use the harvested energy to transmit the jamming signal. Therefore, the transmit power of Jam can be expressed as

$$P_J = \frac{E_J}{(1-\alpha)T} = \frac{\alpha \eta P_b \left\| \mathbf{H}_{rj}^\dagger \mathbf{\Phi}_1 \mathbf{h}_{br} + \mathbf{h}_{bj} \right\|^2}{1 - \alpha}. \tag{3}$$

To make jammer work better in the IT phase, we optimize the phase-shift matrix of IRS to maximize the harvested energy at the Jam. To achieve this goal, let $\mathbf{v}_1 = [v_{1,1}, \ldots, v_{1,n}, \ldots, v_{1,N}]$, and we have $\left\| \mathbf{H}_{rj}^\dagger \mathbf{\Phi}_1 \mathbf{h}_{br} + \mathbf{h}_{bj} \right\| = \left\| \mathbf{H}_{rj}^\dagger \mathrm{diag}\left(\mathbf{h}_{br}\right) \mathbf{v}_1^{\mathrm{T}} + \mathbf{h}_{bj} \right\|$. During this phase, IRS is deployed to maximize the harvested power at the Jam, according to

$$(\mathrm{P1}): \max_{\mathbf{v}_1} \quad \left\| \mathbf{H}_{rj}^\dagger \mathrm{diag}\left(\mathbf{h}_{br}\right) \mathbf{v}_1^{\mathrm{T}} + \mathbf{h}_{bj} \right\|^2 \tag{4a}$$

$$s.t. \quad |v_{1,n}| = 1, n = 1, \ldots, N. \tag{4b}$$

With the optimal solution to (P1), the transmit power P_J can be maximized to degrade the eavesdropping channel in the IT phase as much as possible.

C. Second Phase: Information Transmission

In the second phase, the transmit power of user is P_u. We denote the transmitted signal as $x_r, r \in \{u, j\}$ with $E[|x_r|^2] = 1$. The signal received at the BS and Eve can be expressed as

$$y_b = \left(\mathbf{h}_{br}^\dagger \mathbf{\Phi}_2 \mathbf{h}_{ur} + h_{ub}\right) \sqrt{P_u} x_u + \left(\mathbf{h}_{br}^\dagger \mathbf{\Phi}_2 \mathbf{H}_{rj} + \mathbf{h}_{bj}^\dagger\right) \mathbf{w}_J \sqrt{P_J} x_j + n_b, \tag{5}$$

$$y_e = \left(\mathbf{h}_{re}^\dagger \mathbf{\Phi}_2 \mathbf{h}_{ur} + h_{ue}\right) \sqrt{P_u} x_u + \left(\mathbf{h}_{re}^\dagger \mathbf{\Phi}_2 \mathbf{H}_{rj} + \mathbf{h}_{je}\right) \mathbf{w}_J \sqrt{P_J} x_j + n_e, \tag{6}$$

where $\mathbf{\Phi}_2 = \mathrm{diag}(v_{2,1}, \cdots, v_{2,n}, \cdots, v_{2,N})$ with $|v_{2,n}| = 1, n = 1, \cdots, N$. To prevent the impact of jamming on the BS, we should perform zero-forcing, and the precoding vector $\mathbf{w}_J$ should satisfy $\left(\mathbf{h}_{br}^\dagger \mathbf{\Phi}_2 \mathbf{H}_{rj} + \mathbf{h}_{bj}^\dagger\right) \mathbf{w}_J = 0$. As a result, $\mathbf{w}_J$ can be derived as $\mathbf{w}_J = \left(\mathbf{I}_M - \left(\bar{\mathbf{h}}_{jb}^\dagger \left(\bar{\mathbf{h}}_{jb} \bar{\mathbf{h}}_{jb}^\dagger\right)^{-1} \bar{\mathbf{h}}_{jb}\right)\right) \mathbf{w}_0$, where $\mathbf{I}_M$ is the M dimensional identity matrix, $\bar{\mathbf{h}}_{jb} = \mathbf{h}_{br}^\dagger \mathbf{\Phi}_2 \mathbf{H}_{rj} + \mathbf{h}_{bj}^\dagger$ and $\mathbf{w}_0$ is the arbitrary vector with the dimension of M. Let $\mathbf{v}_2 = [v_{2,1}, \ldots, v_{1,n}, \ldots v_{2,N}]$, the corresponding received signal-to-interference-plus-noise ratio (SINR) can be denoted as

$$\gamma_B = \rho_u \left| \tilde{\mathbf{v}}_2^\dagger \mathbf{a}_B \right|^2, \tag{7}$$

$$\gamma_E = \frac{\rho_u \left| \tilde{\mathbf{v}}_2^\dagger \mathbf{a}_E \right|^2}{1 + \rho_j \left| \tilde{\mathbf{v}}_2^\dagger \mathbf{A}_{JE} \mathbf{w}_J \right|^2}, \tag{8}$$

where $\rho_u = \frac{P_u}{\sigma^2}$, $\rho_j = \frac{P_J}{\sigma^2}$, and $\tilde{\mathbf{v}}_2 = \begin{bmatrix} \mathbf{v}_2^\dagger \\ 1 \end{bmatrix}$. $\mathbf{a}_B = \begin{bmatrix} \mathrm{diag}(\mathbf{h}_{br}^\dagger) \mathbf{h}_{ur} \\ h_{ub} \end{bmatrix}$, $\mathbf{a}_E = \begin{bmatrix} \mathrm{diag}(\mathbf{h}_{re}^\dagger) \mathbf{h}_{ur} \\ h_{ue} \end{bmatrix}$ and $\mathbf{A}_{JE} = \begin{bmatrix} \mathrm{diag}(\mathbf{h}_{re}^\dagger) \mathbf{H}_{rj} \\ \mathbf{h}_{je} \end{bmatrix}$. In addition, $\bar{\mathbf{h}}_{jb} = \tilde{\mathbf{v}}_2^\dagger \mathbf{A}_{BJ}$ can be obtained with $\mathbf{A}_{BJ} = \begin{bmatrix} \mathrm{diag}(\mathbf{h}_{br}^\dagger) \mathbf{H}_{rj} \\ \mathbf{h}_{bj}^\dagger \end{bmatrix}$ to update $\mathbf{w}_J$.

With the help of the jammer and IRS, we aim at maximizing the uplink secrecy rate through optimizing the phase-

$$\varphi(\tilde{\mathbf{V}},t_e)=\ln\left(1+\rho_u\mathrm{tr}\left(\tilde{\mathbf{V}}\boldsymbol{\psi}_B\right)\right)+\ln\left(1+\rho_j\mathrm{tr}\left(\tilde{\mathbf{V}}\mathbf{A}_{JE}\mathbf{w}_J\mathbf{w}_J^\dagger\mathbf{A}_{JE}^\dagger\right)\right)-t_e\left(1+\rho_u\mathrm{tr}\left(\tilde{\mathbf{V}}\boldsymbol{\psi}_E\right)+\rho_j\mathrm{tr}\left(\tilde{\mathbf{V}}\mathbf{A}_{JE}\mathbf{w}_J\mathbf{w}_J^\dagger\mathbf{A}_{JE}^\dagger\right)\right)+\ln t_e+1. \quad (18)$$

shift matrix of IRS and the time switching factor. Hence, the optimization problem can be modeled as

$$(\mathrm{P2}): \max_{\mathbf{\Phi}_2,\alpha} \quad C_s \quad (9a)$$
$$s.t. \quad |v_{2,n}|=1, n=1,\cdots,N, \quad (9b)$$
$$0\le\alpha\le1. \quad (9c)$$

C_s is the achievable secrecy rate, which can be expressed as

$$C_s=(1-\alpha)[\log_2(1+\gamma_B)-\log_2(1+\gamma_E)]^+, \quad (10)$$

where $[x]^+=\max(x,0)$. (9b) represents the unit modulus constraints of the phase of IRS in the IT phase, and (9c) is the constraint of the time switching factor. (P2) is non-convex due to multi-variable coupling and unit modulus constraints.

III. Optimization for Beamforming and Time Allocation

To obtain the effective solutions to the proposed scheme, we first derive the closed-form solution to the problem (P1). Then, the problem (P2) is divided into two subproblems and solved with the alternating algorithm.

A. Optimizing Phase-Shift Matrix in the First Phase

Since the Euclidean norm is satisfied with the triangle inequality, (4a) should satisfy

$$\left\|\mathbf{H}_{rj}^\dagger\mathrm{diag}(\mathbf{h}_{br})\mathbf{v}_1^{\mathrm{T}}+\mathbf{h}_{bj}\right\|\le\left\|\mathbf{H}_{rj}^\dagger\mathrm{diag}\left(\mathbf{h}_{br}\right)\mathbf{v}_1^{\mathrm{T}}\right\|+\|\mathbf{h}_{bj}\|$$
$$=\left|\underbrace{\sum_{m=1}^{M}\left[\mathbf{H}_{rj}^\dagger\mathrm{diag}\left(\mathbf{h}_{br}\right)\right]_m}_{\mathbf{d}}\mathbf{v}_1^{\mathrm{T}}\right|+\left|\underbrace{\sum_{m=1}^{M}[\mathbf{h}_{bj}]_m}_{d_0}\right|. \quad (11)$$

For (11), the equality holds if and only if $\angle(\mathbf{d}\mathbf{v}_1^{\mathrm{T}})=\angle(d_0)$, where $\angle(x)$ denotes the phase of x [7]. Thus, the problem (P1) can be converted as

$$(\mathrm{P3}): \max_{\mathbf{v}_1} \quad \left|\mathbf{d}\mathbf{v}_1^{\mathrm{T}}\right|^2 \quad (12)$$
$$s.t. \quad |v_{1,n}|=1, n=1,\ldots,N, \quad (13)$$
$$\angle(\mathbf{d}\mathbf{v}_1^{\mathrm{T}})=\angle(d_0). \quad (14)$$

We can verify that the optimal solution to the problem (P3) can be obtained by $\mathbf{v}_1^\star=e^{j(\angle(d_0)-\angle(\mathbf{d}))}$. Then, $\mathbf{\Phi}_1^\star=\mathrm{diag}(\mathbf{v}_1^\star)$ can be obtained accordingly.

B. Optimizing Phase-Shift Matrix and Time Switching Factor in the Second Phase

For the second phase, the problem (P2) is non-convex because of the coupling of $\mathbf{\Phi}_2$ and α. Therefore, the problem is divided into two sub-problems to be optimized alternately as follows.

1) Optimizing $\mathbf{\Phi}_2$ for Given α:

For a fixed time switching factor α, let $\tilde{\mathbf{V}}=\tilde{\mathbf{v}}_2\tilde{\mathbf{v}}_2^\dagger$ and $\boldsymbol{\psi}_q=\mathbf{a}_q\mathbf{a}_q^\dagger$ $(q\in\{B,E\})$, and we have $|\tilde{\mathbf{v}}_2^\dagger\mathbf{a}_q|^2=\mathrm{tr}\left(\tilde{\mathbf{V}}\boldsymbol{\psi}_q\right)$. Meanwhile, $\tilde{\mathbf{V}}\succeq0$ and rank($\tilde{\mathbf{V}}$)=1 should also hold. By using SDR to relax the rank-1 constraint, the problem (P2) can be transformed as

$$(\mathrm{P4}): \max_{\tilde{\mathbf{v}}_2} \quad (1-\alpha)\left[\log_2\left(1+\rho_u\mathrm{tr}\left(\tilde{\mathbf{V}}\boldsymbol{\psi}_B\right)\right)-\log_2\left(1+\frac{\rho_u\mathrm{tr}\left(\tilde{\mathbf{V}}\boldsymbol{\psi}_E\right)}{1+\rho_j\mathrm{tr}\left(\tilde{\mathbf{V}}\mathbf{A}_{JE}\mathbf{w}_J\mathbf{w}_J^\dagger\mathbf{A}_{JE}^\dagger\right)}\right)\right] \quad (15)$$
$$s.t. \quad \tilde{\mathbf{V}}\succeq0,\tilde{\mathbf{V}}_{n,n}=1,n=1,\ldots,N. \quad (16)$$

Since the problem (P4) is still non-convex, the non-convex terms of (15) can be transformed according to the following lemma [8].

Lemma 1: For the function $\varphi(t)=-tx+lnt+1,\forall x>0$, $-\ln x=\max_{t>0}\varphi(t)$ is satisfied when $t=\frac{1}{x}$. ■

By applying Lemma 1 and setting $x=1+\rho_u\mathrm{tr}\left(\tilde{\mathbf{V}}\boldsymbol{\psi}_E\right)+\rho_j\mathrm{tr}\left(\tilde{\mathbf{V}}\mathbf{A}_{JE}\mathbf{w}_J\mathbf{w}_J^\dagger\mathbf{A}_{JE}^\dagger\right)$, $t=t_e$, C_s can be changed into

$$\frac{C_s\ln2}{1-\alpha}=\max_{t_e>0}\varphi(\tilde{\mathbf{V}},t_e), \quad (17)$$

where $\varphi(\tilde{\mathbf{V}},t_e)$ is shown in (18).

We can omit "$\ln 2$" and "$1-\alpha$" since they are constant. Therefore, the optimization problem (P4) for a given α can be rewritten as

$$(\mathrm{P5}): \max_{\tilde{\mathbf{V}},t_e} \quad \varphi(\tilde{\mathbf{V}},t_e) \quad (19)$$
$$s.t. \quad \tilde{\mathbf{V}}\succeq0, \quad (20)$$
$$\tilde{\mathbf{V}}_{n,n}=1,n=1,\ldots,N+1, \quad (21)$$
$$t_e>0. \quad (22)$$

It is obvious that (P5) is convex with respect to either $\tilde{\mathbf{V}}$ or t_e. Hence, it can be solved through alternately optimizing $\tilde{\mathbf{V}}$ and t_e. According to Lemma 1, the optimal solution to t_e in each iteration can be derived as

$$t_e^*=\left(1+\rho_u\mathrm{tr}\left(\tilde{\mathbf{V}}\boldsymbol{\psi}_E\right)+\rho_j\mathrm{tr}\left(\tilde{\mathbf{V}}\mathbf{A}_{JE}\mathbf{w}_J\mathbf{w}_J^\dagger\mathbf{A}_{JE}^\dagger\right)\right)^{-1}. \quad (23)$$

While for the fixed t_e^*, the optimal $\tilde{\mathbf{V}}$ can be obtained by using convex optimization solvers, e.g., CVX, which can be expressed as

$$\tilde{\mathbf{V}}^*=\arg\max_{\tilde{\mathbf{V}}_{n,n}=1}\varphi(\tilde{\mathbf{V}},t_e^*). \quad (24)$$

Since the rank-1 constraint in the problem (P4) is relaxed by applying SDR, $\tilde{\mathbf{v}}_2^*$ can be obtained from $\tilde{\mathbf{V}}=\tilde{\mathbf{v}}_2\tilde{\mathbf{v}}_2^\dagger$

Algorithm 1 Proposed algorithm to solve the problem (P4).

Input: α, ρ_u, ρ_j, $\boldsymbol{\psi}_B$, $\boldsymbol{\psi}_E$, $\mathbf{A}_{JE}$ and $\mathbf{A}_{BJ}$.
Output: $\mathbf{v}_2^{\star}$.
Initialize $\mathbf{v}_2$ and $\tilde{\mathbf{v}}_2$ in the constraint (16).
Set $s=1$ as the index of iteration, and $\tilde{\mathbf{V}}^{(0)}=\tilde{\mathbf{v}}_2\tilde{\mathbf{v}}_2^{\dagger}$.
repeat
  Obtain the optimal $t_e^{(s)}$ by (23) for the given $\tilde{\mathbf{V}}^{(s-1)}$.
  Obtain the optimal $\tilde{\mathbf{V}}^{(s)}$ by (24) for the given $t_e^{(s)}$.
  Update $s=s+1$.
until The objective value of the problem (P5) converges.
Recover $\tilde{\mathbf{v}}_2$ from $\tilde{\mathbf{V}}$ and obtain $\mathbf{v}_2$ from (25).

through using the eigenvalue decomposition if $\tilde{\mathbf{V}}$ is a rank-1 matrix, otherwise $\tilde{\mathbf{v}}_2^*$ can be obtained roughly by the Gaussian randomization. After extracting $\tilde{\mathbf{v}}_2^*$ from $\tilde{\mathbf{V}}^*$, the reflection coefficients can be obtained as

$$v_{2,n}^{*}=e^{j\angle\frac{\tilde{v_n}}{\tilde{v}_{N+1}}},n=1.\ldots,N. \tag{25}$$

By alternately updating $\tilde{\mathbf{V}}$ and t_e, the objective function of the problem (P5) tends to converge. Thus, the optimal solution $\mathbf{\Phi}_2^{\star}$ can be derived by $v_{2,n}^{\star}$ accordingly. The details are summarized as Algorithm 1.

2) Optimizing α for Given $\mathbf{\Phi}_2$:

For a given $\mathbf{\Phi}_2$, we first set C, D and E as

$$C=\frac{\eta P_b\left\|\mathbf{H}_{rj}^{\dagger}\mathbf{\Phi}_1\mathbf{h}_{br}+\mathbf{h}_{bj}\right\|^2\mathrm{tr}\left(\tilde{\mathbf{V}}\mathbf{A}_{JE}\mathbf{w}_J\mathbf{w}_J^{\dagger}\mathbf{A}_{JE}^{\dagger}\right)}{\sigma^2}, \tag{26}$$

$$D=1+\rho_u\mathrm{tr}\left(\tilde{\mathbf{V}}\boldsymbol{\psi}_E\right),E=\log_2\left(1+\rho_u\mathrm{tr}\left(\tilde{\mathbf{V}}\boldsymbol{\psi}_B\right)\right). \tag{27}$$

After introducing $t_1=\alpha$ and $t_2=1-\alpha$, C_s can be rewritten as a function of $\mathbf{t}=[t_1,t_2]$ as

$$C_s=t_2E+t_2\log_2\left(1+\frac{t_1}{t_2}C\right)-t_2\log_2\left(D+\frac{t_1}{t_2}C\right). \tag{28}$$

Accordingly, the problem (P2) can be transformed as

$$\text{(P6)}:\max_{t_1,t_2}\quad C_s \tag{29}$$

$$s.t.\quad t_1+t_2\leq 1, \tag{30}$$

$$0\leq t_1,t_2\leq 1. \tag{31}$$

We can observe that the objective function of the problem (P6) is non-convex. We should first convert the non-convex item of the problem (P6) to make it solvable. Define a function $f(x_1,x_2)$ with variables $x_1\geq 0$ and $x_2\geq 0$ as

$$f\left(x_1,x_2\right)=\begin{cases}x_1\log\left(1+\frac{x_2}{x_1}\mu\right), & x_1>0,\\ 0, & x_1=0.\end{cases} \tag{32}$$

According to [9], it is known that $f(x_1,x_2)$ is a jointly concave function with respect to x_1 and x_2. Therefore, define the non-convex item in the problem (P6) as $f(t_1,t_2)=-t_2\log_2\left(D+\frac{t_1}{t_2}C\right)$. It needs to be converted to convex using its linear approximation form, i.e., the first-order Taylor series expansion at the fixed point $(\bar{t}_1,\bar{t}_2)$ as

$$\begin{aligned}f(t_1,t_2|\bar{t}_1,\bar{t}_2)=&-\left[\log_2\left(\frac{\bar{t}_1C}{\bar{t}_2}+D\right)+\frac{1}{\ln 2}\left(\frac{D}{\frac{\bar{t}_1C}{\bar{t}_2}+D}-1\right)\right]t_2\\&-\left[\frac{1}{\ln 2}\left(\frac{C}{\frac{\bar{t}_1C}{\bar{t}_2}+D}\right)\right]t_1\\=&-Ft_2-Gt_1.\end{aligned} \tag{33}$$

Since $f(t_1,t_2)\geq f(t_1,t_2|\bar{t}_1,\bar{t}_2)$, the equality holds when $t_1=\bar{t}_1$ and $t_2=\bar{t}_2$. Thus, C_s can be changed as

$$C_s=t_2\log_2\left(1+\frac{t_1}{t_2}C\right)+(E-F)t_2-Gt_1. \tag{34}$$

It can be observed that (34) is a concave function of $\mathbf{t}$ and the constraint in (30) is affine. Thus, the optimization problem (P6) is convex and satisfies the Slater's condition [10], and thus the Lagrange duality method can be used to solve it. Based on (29)-(31), the Lagrangian function of the problem (P6) can be expressed as

$$\begin{aligned}\mathcal{L}(t_1,t_2,\lambda)=&C_s-\lambda\left(t_1+t_2-1\right)\\=&t_2\log_2\left(1+\frac{t_1}{t_2}C\right)+(E-F-\lambda)t_2-(G+\lambda)t_1+\lambda,\end{aligned} \tag{35}$$

where λ denotes the Lagrange multiplier related to the constraint in (30). Therefore, we can denote the dual problem of (P6) as $\min_{\lambda>0}\max_{t_1\geq 0,t_2\geq 0}\mathcal{L}\left(t_1,t_2,\lambda\right)$. The optimal solution $\mathbf{t}^*$ can be easily found by solving the dual problem.

Proposition 1: The optimal solution to $\mathbf{t}^*=[t_1^*,t_2^*]$ can be calculated as

$$t_1^*=\left(\frac{t_2^*}{(G+\lambda^*)\ln 2}-\frac{t_2^*}{C}\right)^+, \tag{36}$$

$$t_2^*=\frac{t_1^*C}{z^*}, \tag{37}$$

where $\lambda^*>0$ denotes the optimal dual solution and z^* denotes the solution to the following equation.

$$f(z)=\ln(1+z)-\frac{z}{1+z}=(F-E+\lambda)\ln 2. \tag{38}$$

Proof: To solve the optimization problem (P6), the Karush-Kuhn-Tucker (KKT) conditions need to be satisfied as follows.

$$\frac{\partial\mathcal{L}}{\partial t_1^*}=\frac{C}{\left(1+\frac{t_1^*}{t_2^*}C\right)\ln 2}-(G+\lambda^*)=0, \tag{39}$$

$$\frac{\partial\mathcal{L}}{\partial t_2^*}=\ln\left(1+\frac{t_1^*}{t_2^*}C\right)-\frac{\frac{t_1^*}{t_2^*}C}{\left(1+\frac{t_1^*}{t_2^*}C\right)}+(E-F-\lambda^*)\ln 2=0, \tag{40}$$

$$\lambda^*\left(t_1^*+t_2^*-1\right)=0. \tag{41}$$

Since $t_1^*+t_2^*=1$ should hold for the problem (P6), $\lambda^*>0$ is assumed without loss of generality. From (39), we have t_1^* in (36) with the given t_2^* and λ^*. Let $z^*=\frac{t_1^*C}{t_2^*}$, and thus (40) can be transformed as $f(z)=(F-E+\lambda^*)\ln 2$, where $f(z)$ is given in (38). It should be noticed that $f(z)$ is monotonically

Algorithm 2 Proposed algorithm to solve the problem (P6).

Input: C, D and E.

Output: $\alpha^{\star}$.

1: Initialize $t_1^{(0)}$, $t_2^{(0)}$, $\bar{t}_1^{(0)}$, $\bar{t}_2^{(0)}$, $F^{(0)}$ and $G^{(0)}$.
2: Set k=0 as the index of iteration.
3: **repeat**
4: Update $k = k + 1$.
5: Obtain the optimal $\lambda^{(k)}$ by solving the problem (P7) for given $t_1^{(k-1)}$ and $t_2^{(k-1)}$.
6: Obtain the optimal $t_1^{(k)}$ by (36) for given $\bar{t}_2^{(k-1)}$ and $\lambda^{(k)}$.
7: Obtain the optimal $t_2^{(k)}$ by (37) for given $t_1^{(k)}$ and $\lambda^{(k)}$.
8: Update $\bar{t}_1^{(k)} = t_1^{(k)}$, $\bar{t}_2^{(k)} = t_2^{(k)}$, $F^{(k)}$ and $G^{(k)}$.
9: **until** The objective value of the problem (P6) converges.
10: The optimal solution $\alpha^{\star} = t_1$.

increasing of $z \geq 0$ with $f(0)=0$. In order to obtain a unique solution z^* to (38), $\lambda^* \geq E - F$ has to be satisfied. After solving the equation (38), t_2^* can be obtained as per (37). ■

From Proposition 1, we can obtain the optimal solutions t_1^* and t_2^* by fixing one of them to optimize another in turn with a given λ. With $\mathbf{t}^*$ obtained for each given λ, the optimal λ^* can be found within the range as

$$(\text{P7}): find \quad \lambda^* \tag{42}$$

$$s.t. \quad \lambda \leq \frac{C}{\ln 2} - G, \tag{43}$$

$$\lambda \geq (E - F)^+, \tag{44}$$

$$t_1^*(\lambda) + t_2^*(\lambda) = 1. \tag{45}$$

For the non-negative t_1 and t_2, (43) and (44) can be developed. t_1^* and t_2^* are the functions of λ and thus (45) can be obtained. It can be seen that $g(\lambda) = t_1^*(\lambda) + t_2^*(\lambda) - 1$ increases as λ decreases until $g(\lambda^*) = 0$, where λ^* can be obtained by the bisection method. In addition, $t_1^* = 0$ and $t_2^* = 1$ are set when λ is not within the feasible range. Finally, the optimal λ^* and $\mathbf{t}^{\star}$ can be obtained by an iterative algorithm showed in Algorithm 2. Then, the optimal time switching factor $\alpha^{\star}$ can be determined by $\alpha^{\star} = t_1^{\star}$.

C. Overall Algorithm

The overall algorithm to solve the proposed scheme can be concluded as follows. The optimal closed-form solution to IRS's phase-shift matrix in ET phase can be given first. Then, to tackle the non-convex problem (P2), we divide it into two subproblems by fixing one variable and solving the other one. The optimal solutions $\mathbf{\Phi}_2^{\star}$ and $\alpha^{\star}$ are obtained by alternately running Algorithm 1 and Algorithm 2 until convergence. As a result, the phase-shifting matrix and the time allocation factor can be optimally achieved to significantly improve the secrecy performance for the proposed secure scheme.

IV. Simulation Results and Discussion

In this section, we demonstrate the performance of the proposed Jammer-IRS scheme through simulations. Set the situation $d_{ue} < d_{ub}$ and $d_{ue} > d_{ub}$ as Case 1 and Case 2, respectively. The locations of Case 1 are set as BS (5,0,0), IRS (4,0,5), User (15,10,0), Eve (5,15,0) and Jam (5,5,0) in meters, unless otherwise specified. User (0,10,0) and Eve (15,5,0) in Case 2 are different from Case 1. Let $M = 2$, $\eta = 0.5$, $P_b = 40$ dBm, $P_u = 20$ dBm and $\sigma^2 = -110$ dB. Rayleigh fading and Rician fading are assumed for direct links and reflecting links respectively, while BS-Jammer is regarded as a LoS link. Their corresponding channel coefficients can be generated as

$$h_{uf} = \sqrt{L_0 d_{uf}^{-a_d}} \mathrm{g}_{uf}^{\mathrm{NLoS}}, f \in \{b, e\}, \tag{46}$$

$$\mathbf{h}_{bj} = \sqrt{L_0 d_{bj}^{-a_{bj}}} \mathbf{g}_{bj}^{\mathrm{LoS}}, \tag{47}$$

$$\mathbf{h}_g = \sqrt{L_0 d_g^{-a_r}} \left(\sqrt{\frac{K}{K+1}} \mathbf{g}_g^{\mathrm{LoS}} + \sqrt{\frac{1}{K+1}} \mathbf{g}_g^{\mathrm{NLoS}} \right), g \in \{br, ur, re\}, \tag{48}$$

where $K = 3$ dB is the Rician factor, $\mathbf{g}_{bj}^{\mathrm{LoS}}$ and $\mathbf{g}_g^{\mathrm{LoS}}$ denote the deterministic LoS components, while $\mathrm{g}_{uf}^{\mathrm{NLoS}}$ and $\mathbf{g}_g^{\mathrm{NLoS}}$ denote the Rayleigh fading components. $L_0 = -30$ dB denotes the path loss at 1 m. Set the exponents of direct and reflecting path loss as $a_d = 3.6$ and $a_r = 2.2$, respectively. $a_{bj} = 2$ is assumed for the direct link of BS-Jammer. d_{AB} denote the distance from A to B where A and B are the specific nodes of the system. $\mathbf{h}_{je}$ and $\mathbf{H}_{rj}$ adopt the channels as shown in (46) and (48), respectively.

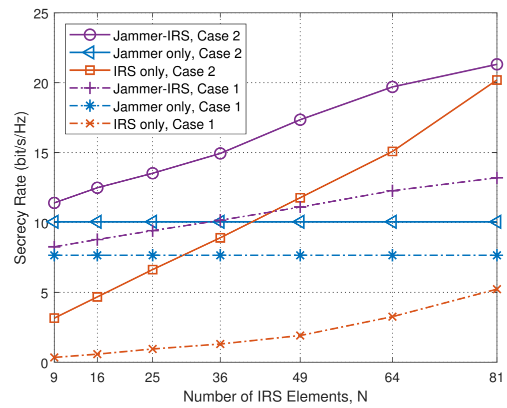

Fig. 2. Secrecy rate comparison between the proposed scheme and benchmarks with different N.

The secrecy rate of the proposed Jammer-IRS scheme in Case 1 and Case 2 is compared in Fig. 2 with the benchmarks including IRS only in Case 1 and 2, and Jammer only in Case 1 and 2, with different N. Notice that the secrecy rate of both the schemes "Jammer-IRS" and "IRS only" increases with N, while the "Jammer only" scheme remains constant. It is also shown that the proposed scheme outperforms the benchmarks. Specifically, in Case 2, with a small N, both the proposed scheme and the "Jammer only" benchmark perform better than "IRS only" when the Jam contributes more to the improvement of secrecy performance. With the

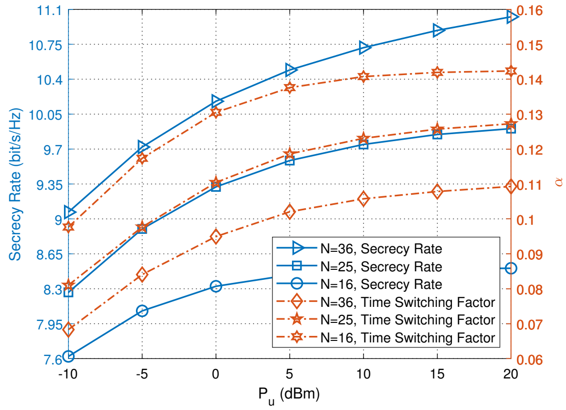

Fig. 3. Performance comparison of secrecy rate and time switching factor α with different user transmit power. N = 16, 25 and 36.

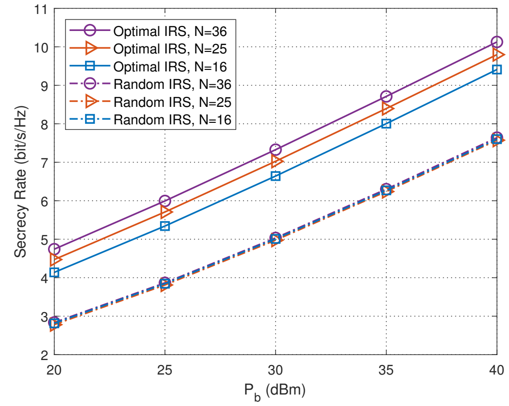

Fig. 4. Secrecy performance comparison between the optimal IRS scheme and the random IRS benchmark with different P_b and N.

increase of N, the performance of "Jammer-IRS" is gradually close to that of "IRS only", indicating that the IRS plays a greater role in the security enhancement. However, even in Case 1 where the eavesdropper is a threat, the "Jammer-IRS" always outperforms the "IRS only", which shows that the combination of jammer and IRS can significantly enhance the security.

Both the secrecy rate and the time switching factor are compared in Fig. 3 under different user transmit power, with N = 16, 25 and 36. As P_u increases, what can be clearly seen in this figure is the growth of both the secrecy rate and time switching factor α. An explanation for this is that the risk of confidential information leakage increases influenced by the increasing transmit power of user, and thus more time is allocated to the ET phase for EH to enhance the security of information transmission. The secrecy rate also increases thanks to the well-protected transmission of confidential information. With different N = 16, 25 and 36, it can be seen that IRS with a higher number of elements N has stronger reflecting ability, which can help jammer to harvest energy faster in the ET phase, and then enhance legal information transmission and weaken eavesdropping information simultaneously in the IT phase. Therefore, α is smaller while the secrecy rate is higher with a larger N.

With different P_b and N, the secrecy rate between the proposed scheme and the random IRS benchmark is compared in Fig. 4. The secrecy rate increases with P_b in both optimal IRS scheme and random IRS benchmark. This is because the increase of P_b can lead to α decrease, and thus more time will be allocated for the IT phase to improve the secrecy rate. Affected by increasing number of IRS elements, the secrecy performance of the proposed scheme can be enhanced whereas the secrecy rate of the random IRS benchmark remains almost unchanged. Furthermore, it is obvious that the proposed scheme can significantly improve the secrecy rate compared to the benchmark of random IRS, which verifies the effectiveness of the proposed scheme in security enhancement.

V. Conclusions

In this paper, we have proposed a secure uplink transmission scheme assisted by both the IRS and EH jammer. In the first phase, the harvested energy at the Jam is maximized by designing the phase-shift matrix of IRS. In the second phase, the secrecy rate is maximized by jointly optimizing the phase-shift matrix of IRS and the time switching factor. Compared with the benchmarks via simulations, it is shown that the proposed scheme can effectively improve the security performance of the uplink wireless communications.

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