RIS-Assisted Cooperative NOMA With SWIPT
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Abstract—This letter proposes a two-stage reconfigurable intelligent surface (RIS)-assisted transmission scheme for cooperative non-orthogonal multiple access (C-NOMA) networks with simultaneous wireless information and power transfer (SWIPT). To alleviate the energy constraint, the application of simultaneous wireless information and power transfer (SWIPT) to the C-NOMA system has been studied in some prior works, such as [11] and [12]. C-NOMA was first proposed in [7] and investigated the application of RIS in the SWIPT-C-NOMA network [15], the RIS was only utilized in the direct transmission stage to assist the link between the base station and the strong user. To take full advantage of RIS, this letter considers that the RIS is applied to assist both the direct transmission and the cooperative transmission. Specifically, an RIS-assisted two-stage transmission scheme is designed and an optimization problem is formulated, which maximizes the achievable rate of strong users while guaranteeing the quality-of-service (QoS) of weak users. The simulation results in [12] showed that a high network throughput could be achieved only when the transmit power of the base station is large enough.

The combination of RIS and NOMA has received great attention in recent years [13], [14], [15]. In [13], the power minimization problem was formulated and solved for RIS-assisted networks with coordinated multi-point reception. The sum rate maximization problem was investigated in [14] for a two-cell downlink RIS-assisted NOMA cellular network. However, few papers have devoted to the study of the RIS-assisted C-NOMA networks with SWIPT. Although a recent study investigated the application of RIS in the SWIPT-C-NOMA network [15], the RIS was only utilized in the direct transmission stage to assist the link between the base station and the strong user. To take full advantage of RIS, this letter considers that the RIS is applied to assist both the direct transmission and the cooperative transmission. Specifically, an RIS-assisted two-stage transmission scheme is designed and an optimization problem is formulated, which maximizes the achievable rate of strong users while guaranteeing the quality-of-service (QoS) of weak users. The simulation results in [12] showed that a high network throughput could be achieved only when the transmit power of the base station is large enough.

In order to enhance the reliability of the cell-edge users, cooperative non-orthogonal multiple access (C-NOMA) has been studied in [7], [8], [9], [10]. The C-NOMA strategy was first proposed in [7], in which the strong user was employed to help the weak user. The achievable rate maximization problem in C-NOMA system with MIMO channels was studied in [8].

I. INTRODUCTION

RECENTLY, reconfigurable intelligent surface (RIS) has been widely studied as an emerging technology [1], [2], [3], [4]. RIS can reconfigure the wireless propagation channel between transceivers by adjusting the phase of each passive element on the surface. In particular, compared with the conventional relay and multiple-input multiple-output (MIMO) techniques, RIS can achieve signal enhancement and interference suppression in a cost-effective and energy-efficient manner [3]. Besides, RISs can be flexibly deployed in existing communication systems. The above-mentioned benefits of RIS have motivated an upsurge of interest in the integration of RISs in various scenarios [5], [6].

In order to enhance the reliability of the cell-edge users, cooperative non-orthogonal multiple access (C-NOMA) has been studied in [7], [8], [9], [10]. The C-NOMA strategy was first proposed in [7], in which the strong user was employed to help the weak user. The achievable rate maximization problem in C-NOMA system with MIMO channels was studied in [8].

To alleviate the energy constraint, the application of simultaneous wireless information and power transfer (SWIPT) to the C-NOMA system has been studied in some prior works, such as [11] and [12]. By jointly optimizing the beamforming vectors and the power splitting factor, a problem of maximizing the achievable rate of strong users while guaranteeing the quality-of-service (QoS) of weak users was studied in [12]. The simulation results in [12] showed that a high network throughput could be achieved only when the transmit power of the base station is large enough.

The combination of RIS and NOMA has received great attention in recent years [13], [14], [15]. In [13], the power minimization problem was formulated and solved for RIS-assisted networks with coordinated multi-point reception. The sum rate maximization problem was investigated in [14] for a two-cell downlink RIS-assisted NOMA cellular network. However, few papers have devoted to the study of the RIS-assisted C-NOMA networks with SWIPT. Although a recent study investigated the application of RIS in the SWIPT-C-NOMA network [15], the RIS was only utilized in the direct transmission stage to assist the link between the base station and the strong user. To take full advantage of RIS, this letter considers that the RIS is applied to assist both the direct transmission and the cooperative transmission. Specifically, an RIS-assisted two-stage transmission scheme is designed and an optimization problem is formulated, which maximizes the rate of the strong user with better channel quality while satisfying the weak user’s QoS requirement. This problem is a multivariate coupling problem with complex constraints about the sum of fractional and linear functions with respect to the RIS phase shift, which was never studied in the published literature. Accordingly, we propose an iterative algorithm based on the alternate optimization (AO) framework, penalty-based arithmetic-geometric mean approximation (PBAGM), and successive convex approximation (SCA)-based method.

II. SYSTEM MODEL

As shown in Fig. 1, we consider a RIS-assisted C-NOMA network with SWIPT, which consists of one access point (AP) equipped with K antennas, a RIS with M reflection elements, and two single-antenna users (U1 and U2). U1 (strong user) is assumed to have a better channel condition than U2 (weak user), and U1 can assist the AP to transmit the signal to U2. Moreover, U1 is energy constrained, and needs to harvest radio-frequency (RF) energy from the AP to power its relaying operations, and the power splitting (PS) scheme is employed to perform SWIPT.

We assume that the AP and all the other devices operate over the same frequency band, i.e., channel reciprocity holds for all channels. Moreover, it is assumed that the AP can acquire perfect channel state information [1]. The channel coefficients

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from the AP to $U_1$ ($i \in \{1, 2\}$, from the AP to the RIS, and from the RIS to $U_i$ are denoted by $h_{d,i} \in \mathbb{C}^{K \times 1}$, $G \in \mathbb{C}^{M \times K}$, and $h_{r,i} \in \mathbb{C}^{M \times 1}$, respectively. Moreover, the channel coefficients from $U_1$ to $U_2$, from $U_1$ to the RIS, and from the RIS to $U_2$ are denoted by $g_{d} \in \mathbb{C}$, $g \in \mathbb{C}^{M \times 1}$, and $g_{r} \in \mathbb{C}^{M \times 1}$, respectively.

A. Transmission Scheme

For the above described network, a two-stage RIS-assisted transmission scheme is proposed. In stage 1, the AP transmits the superimposed signal to $U_1$ and $U_2$ by applying superposition coding with the assistance of RIS. The received signal at $U_1$ is divided into two parts, one for energy harvesting (EH) and the other one for information decoding. In stage 2, $U_1$ forwards the information to $U_2$ by using the harvested energy with the help of RIS. Moreover, it is assumed that the two stages have the same transmission duration $\tau$.\footnote{The transmission duration could be also incorporated in the optimization problem. However, for making the problem more focused on the RIS related designs, we assume the same duration for the two transmission stages.} The details of the proposed scheme are described as follows:

Stage 1 (RIS-Assisted Direct Transmission): During this stage, the AP transmits the superimposed signal $x = w_{1,1} + w_{2,2}$ to both users, where $w_{i} \in \mathbb{C}^{K \times 1}$ ($i \in \{1, 2\}$) stands for the corresponding transmit beamforming vectors and $x_{i} \in \mathbb{C}$ ($i \in \{1, 2\}$) is the transmitted symbol intended for $U_i$, with $\mathbb{E}\{|x_{i}|^2\} = 1$. The received signal at $U_1$ is:

$$y^{(1)}_{1} = (h_{r,1}^H \Theta_1 G + h_{d,1}^H) x + n_{1},$$  \hspace*{1cm} (1)

where $n_{1} \sim \mathcal{C}\mathcal{N}(0, \sigma^2_{1})$ is the additive white Gaussian noise (AWGN) and $\sigma^2_{1}$ stands for the noise variance at $U_1$. Moreover, the diagonal matrix $\Theta_1 = \text{diag}(\theta_{1,1}, \theta_{1,2}, \ldots, \theta_{1,M}) \in \mathbb{C}^{M \times M}$ represents the reflection phase-shift matrix in stage 1 and $\theta_{1,m} = e^{j\Phi_{1,m}}$ ($\Phi_{1,m} \in [0, 2\pi]$), $m \in \{1, 2, \ldots, M\}$. Let $\alpha \in [0, 1]$ denote the power splitting factor of $U_1$ used for EH. Combined with the assumption that the transmission duration $\tau = 1/2$, the harvested energy at $U_1$ can be given as

$$E = \frac{1}{2} \alpha \eta (\|h_{r,1}^H \Theta_1 G + h_{d,1}^H\|_2^2 + \|h_{r,1}^H \Theta_1 G + h_{d,1}^H\|_2^2),$$  \hspace*{1cm} (2)

where $\eta \in (0, 1]$ is the energy conversion efficiency. According to the successive interference cancellation (SIC) principle of NOMA, $U_1$ first decodes the information of $U_2$, and the corresponding signal to interference-plus-noise-ratio (SINR) for $U_1$ to decode the information of $U_2$ is

$$\text{SINR}_{1 \rightarrow 2}^{(1)} = \frac{(1 - \alpha) (\|h_{r,1}^H \Theta_1 G + h_{d,1}^H\|_2^2)}{(1 - \alpha) (\|h_{r,1}^H \Theta_1 G + h_{d,1}^H\|_2^2 + \sigma^2_{1})}.$$

$U_1$ subtracts the information of $U_2$ from the superimposed signal. Thus, the signal-to-noise ratio (SNR) of $U_1$ for decoding its own information can be written as

$$\text{SNR}_{1}^{(1)} = \frac{(1 - \alpha) (\|h_{r,1}^H \Theta_1 G + h_{d,1}^H\|_2^2)}{\sigma^2_{1}}.$$

The SINR of $U_2$ can be described as

$$\text{SINR}_{2}^{(1)} = \frac{(1 - \alpha) (\|h_{r,2}^H \Theta_1 G + h_{d,2}^H\|_2^2)}{\|h_{r,2}^H \Theta_1 G + h_{d,2}^H\|_2^2 + \sigma^2_{2}}.$$

Stage 2 (RIS-Assisted Cooperative Transmission): During this stage, $U_1$ transmits the signal $x_2$ to $U_2$ with the assistance of RIS by using the harvested energy in the first stage. The received signal of $U_2$ can be written as

$$y^{(2)}_{2} = \sqrt{P_t^{\text{CT}} (g_{d}^H + g_{r}^H \Theta_2 G)} x_2 + n_2,$$

where the diagonal matrix $\Theta_2 = \text{diag}(\theta_{2,1}, \theta_{2,2}, \ldots, \theta_{2,M}) \in \mathbb{C}^{M \times M}$ is the reflection phase-shift matrix in this stage and $\theta_{2,m} = e^{j\Phi_{2,m}}$ with $\Phi_{2,m} \in [0, 2\pi]$. Moreover, $P_t^{\text{CT}}$ stands for the transmit power of $U_1$ and it can be expressed as

$$P_t^{\text{CT}} = E/(1/2) = \alpha \eta \left(\|h_{r,1}^H \Theta_1 G + h_{d,1}^H\|_2^2 + \|h_{r,1}^H \Theta_1 G + h_{d,1}^H\|_2^2\right).$$

Thus, the received SNR of $U_2$ in this stage is given by

$$\text{SNR}_{2}^{(2)} = \alpha \eta |g_{d}^H + g_{r}^H \Theta_2 G|_2^2 \left(\|h_{r,1}^H \Theta_1 G + h_{d,1}^H\|_2^2 + \|h_{r,1}^H \Theta_1 G + h_{d,1}^H\|_2^2\right) \bigg/ \sigma^2_{2}.$$

$U_2$ combines its received signals in both stages to decode $x_2$ by applying the maximal-ratio combining [12], i.e., the corresponding SINR can be expressed as

$$\text{SINR}_{2} = \text{SINR}_{2}^{(1)} + \text{SINR}_{2}^{(2)} = \frac{(h_{r,2}^H \Theta_1 G + h_{d,2}^H w_2^2)^2}{\|h_{r,2}^H \Theta_1 G + h_{d,2}^H w_2^2\|_2^2 + \sigma^2_{2}}$$

$$+ \alpha \eta |g_{d}^H + g_{r}^H \Theta_2 G|_2^2 \left(\|h_{r,1}^H \Theta_1 G + h_{d,1}^H\|_2^2 + \|h_{r,1}^H \Theta_1 G + h_{d,1}^H\|_2^2\right) \bigg/ \sigma^2_{2}.$$

B. Problem Formulation

The joint design of the PS factor at $U_1$, the transmit beamforming at the AP, as well as the RIS reflection coefficients in both stages can be mathematically formulated as

$$\text{P1: } \max_{\alpha, w_1, w_2, \Theta_1 \geq 0, \Theta_2 \geq 0} \frac{1}{2} \log_2 \left(1 + \text{SNR}_{1}^{(1)} \right) \text{ s.t. } C_1 : \frac{1}{2} \log_2 (1 + \text{SNR}_{1 \rightarrow 2}) \geq \gamma_2;$$

$$C_2 : \frac{1}{2} \log_2 (1 + \text{SNR}_2) \geq \gamma_2,$$
where $\gamma_2$ is the target rate of $U_2$. The objective function is the achievable rate of $U_1$. The constraint $C_1$ guarantees that $U_1$ can successfully decode $\tilde{x}_2$. The constraint $C_2$ is imposed to ensure the QoS requirement of $U_2$. Moreover, the constraints of the power budget at the AP and the power splitting factor are characterized by $C_3$ and $C_4$, respectively. Furthermore, $C_5$ represents the passive RIS phase shift constraints in stage 1 and stage 2. Next, in order to make the problem more concise, let $\sigma_1^2 = \sigma_2^2 = \sigma^2$, $\tilde{w}_i = \frac{w_i}{\sigma^2}$, $\rho = \frac{P_2}{\sigma^2}$ and $\Gamma_2 = 2^{2\gamma_2} - 1$, then Problem 2 can be transformed as

$$
P2 : \max_{\theta_1, \tilde{w}_1, \tilde{w}_2} \quad (1 - \alpha) \left| \sqrt{\rho} \left( h_{r,1}^H \theta_1 G + h_{d,2}^H \right) \tilde{w}_1 \right|^2 \\
\text{s.t.} \quad C_1 : \left| \sqrt{\rho} \left( h_{r,1}^H \theta_1 G + h_{d,2}^H \right) \tilde{w}_1 \right|^2 \geq \Gamma_2, \\
C_2 : \left| \sqrt{\rho} \left( h_{r,1}^H \theta_1 G + h_{d,2}^H \tilde{w}_2 \right) \right|^2 + \alpha \eta \times \left| g_d^H + \theta_2 g \right|^2 \geq \left| \sqrt{\rho} \left( h_{r,1}^H \theta_1 G + h_{d,1}^H \tilde{w}_2 \right) \right|^2, \\
C_3 : \left| \tilde{w}_1 \right|^2 + \left| \tilde{w}_2 \right|^2 \leq 1, \\
C_4 : 0 \leq \alpha \leq 1, \\
C_5 : 0 \leq \Phi_{i,m} \leq 2\pi, \forall m, i \in \{1, 2\}. \tag{11}$$

C. The Proposed Algorithm

The main challenges to solve P2 can be summarized as follows: i) the PS factor, beamforming coefficients, and RIS reflection matrix are coupled; ii) the non-convex unit-modulus constraints $C_5$; iii) the left-hand side of the non-convex QoS constraint $C_2$ is the sum of a fraction and a linear function. In general, it is difficult to directly solve this problem. Accordingly, we first apply the AO method to decouple P2 into three sub-problems and then tackle each sub-problem separately.

Firstly, optimize $\tilde{w}_1$, $\tilde{w}_2$, and $\alpha$ with given $\Theta_1$ and $\Theta_2$. For ease of representation, let $\tilde{\theta}_1 = \left[ \tilde{\theta}_{1,1}, \tilde{\theta}_{1,2}, \ldots, \tilde{\theta}_{1,M} \right] \in \mathbb{C}^{M \times 1}$ and $\tilde{G}_{r,i} = \text{diag}(h_{r,i}^H) \tilde{G}$. Then, we have

$$\begin{align*}
\left| \sqrt{\rho} (h_{r,1}^H \tilde{\theta}_1 G + h_{d,2}^H) \tilde{w}_1 \right|^2 &= \left| \sqrt{\rho} (\tilde{\theta}_1^H \tilde{G}_{r,i} + h_{d,2}^H) \tilde{w}_1 \right|^2 \\
&= \left| h_{r,1}^H \tilde{w}_1 \right|^2 \frac{\tilde{G}_{r,i} \tilde{w}_1}{h_{r,1}^H \tilde{w}_1} \text{Tr}(H_2 \tilde{W}_1).
\end{align*} \tag{12}$$

Now, the constraint $C_1$ in P2 can be transformed into

$$\frac{(1 - \alpha) \text{Tr}(H_1 W_2)}{(1 - \alpha) \text{Tr}(H_1 W_1) + 1} \geq \Gamma_2. \tag{13}$$

In addition, by letting $g_d^H + \theta_2 g = \tilde{g}$, the constraint $C_2$ in P2 can be equivalently written as

$$\frac{\text{Tr}(H_2 W_2)}{\text{Tr}(H_2 W_1) + 1} + \alpha \eta |\tilde{g}|^2 \text{Tr}(H_1 (W_1 + W_2)) \geq \Gamma_2. \tag{14}$$

Based on the above analysis, we can obtain the following subproblem

$$\text{P3} : \max_{\alpha, W_1 \geq 0, W_2 \geq 0} (1 - \alpha) \text{Tr}(H_1 W_1) \tag{15}$$

$$\text{s.t.} \quad C_1 : 0 \leq \text{Tr}(W_1) + \text{Tr}(W_2) \leq 1, \\
C_2 : 0 \leq \alpha \leq 1, \\
C_3 : \text{rank}(W_i) \leq 1, i \in \{1, 2\}, \tag{16}$$

Problem P3 jointly optimizes the beamforming coefficients and the PS factor, which can be solved by using the Algorithm 1 in [12].

Secondly, optimize $\tilde{\theta}_1$ with given $\alpha$, $W_1$, $W_2$ and $\Theta_2$. Let $\sqrt{\rho} G_{r,1} \tilde{w}_1 = a_1, \sqrt{\rho} h_{d,1}^H \tilde{w}_1 = b_1$, and introducing auxiliary variable $\tilde{\theta}_1 = \left[ \tilde{\theta}_1 \right]$, one can get

$$\begin{align*}
\left| \sqrt{\rho} (h_{r,1}^H \theta_1 G + h_{d,1}^H) \tilde{w}_1 \right|^2 &= \left| \sqrt{\rho} (\tilde{\theta}_1^H \tilde{G}_{r,i} + h_{d,1}^H) \tilde{w}_1 \right|^2 \\
&= \theta_1^H a_1 a_1^H \tilde{\theta}_1 + \theta_1^H b_1 a_1^H \tilde{\theta}_1 + |b_1|^2 \\
&= f(\tilde{\theta}_1, a_1, b_1), \tag{17}
\end{align*}$$

where $f(\tilde{\theta}_1, a_1, b_1)$ can be rewritten as

$$f(\tilde{\theta}_1, a_1, b_1) = \left[ \begin{array}{c} \theta_1^H \\ \tilde{\theta}_1 \end{array} \right] \left[ \begin{array}{ccc} a_1 a_1^H & 0 \\ b_1 a_1^H & 0 \end{array} \right] \left[ \begin{array}{c} \theta_1 \\ \tilde{\theta}_1 \end{array} \right]. \tag{18}$$

and $\tilde{\theta}_1$ satisfies

$$\left( \tilde{\theta}_1 \right)_{m,m} = 1, m = 1, 2, \ldots, M + 1, \quad \text{rank} \left( \tilde{\theta}_1 \right) = 1. \tag{19}$$

Similarly, by letting $\sqrt{\rho} G_{r,2} \tilde{w}_2 = a_2$, $\sqrt{\rho} h_{d,2}^H \tilde{w}_2 = b_2$, $\sqrt{\rho} G_{r,2} \tilde{w}_2 = a_3$, $\sqrt{\rho} h_{d,2}^H \tilde{w}_2 = a_4$, $\sqrt{\rho} h_{d,2}^H \tilde{w}_2 = b_4$, $g = \text{diag}(g_r^H) g = a_5$, $g_d^H = b_5$, and defining

$$R_j = \left[ \begin{array}{cc} a_j a_j^H & a_j b_j^H \\ b_j a_j^H & 0 \end{array} \right], \quad j \in \{1, 2, 3, 4, 5\}, \tag{20}$$

the constraints $C_1$ and $C_2$ in P2 are respectively equivalent to

$$1 - \alpha \left( \text{Tr} \left( R_1 \tilde{\theta}_1 \right) + |b_2|^2 \right) \geq \Gamma_2 (1 - \alpha) \left( \text{Tr} \left( R_1 \tilde{\theta}_1 \right) + |b_1|^2 \right) + 1, \tag{21}$$

and

$$\begin{align*}
\frac{\text{Tr}(R_1 \tilde{\theta}_1) + |b_4|^2}{\text{Tr}(R_3 \tilde{\theta}_1) + |b_3|^2 + 1} + \alpha \eta \left( \text{Tr}(R_5 \tilde{\theta}_2) + |b_5|^2 \right) \\
\times \left( \text{Tr}(R_1 + R_2) \tilde{\theta}_1 \right) + |b_1|^2 + |b_2|^2 \geq \Gamma_2. \tag{22}
\end{align*}$$

The corresponding optimization subproblem with respect to $\tilde{\theta}_1$ is

$$\text{P4} : \max_{\tilde{\theta}_1 \geq 0} (1 - \alpha) \left( \text{Tr} \left( R_1 \tilde{\theta}_1 \right) + |b_1|^2 \right) \tag{23}$$

$$\text{s.t.} \quad (18), (19), (21), (22).$$
Note that (22) is the sum of fraction and linear functions with respect to $\Theta_1$. We introduce an auxiliary variable $\mathcal{X}$ to replace the fractional function term. Then, (22) can be equivalently transformed into

$$\frac{\text{Tr}(R_2\tilde{\Theta}_1) + |b_4|^2}{\text{Tr}(R_3\tilde{\Theta}_1) + |b_3|^2} + 1 \geq \mathcal{X}, \quad (24)$$

and

$$\mathcal{X} + \alpha \eta \left(\text{Tr}(R_2\tilde{\Theta}_2) + |b_5|^2\right) \times \left(\text{Tr}\left[(R_1 + R_2)\tilde{\Theta}_1\right] + |b_1|^2 + |b_2|^2\right) \geq \Gamma_2. \quad (25)$$

Then, $P_4$ can be reformulated as

$$P_5 : \max_{\tilde{\Theta}_1 \succeq 0, \mathcal{X}} \left(1 - \alpha\right) \left(\text{Tr}(R_1\tilde{\Theta}_1) + |b_1|^2\right)$$

s.t. (18), (19), (21), (24), (25). \quad (26)

According to the arithmetic-geometric mean inequality, (24) can be approximated as

$$\left(y(n)\mathcal{X}\right)^2 + \left(\frac{\text{Tr}(R_3\tilde{\Theta}_1) + |b_3|^2}{y(n)}\right)^2 \leq 2 \left(\text{Tr}(R_2\tilde{\Theta}_1) + |b_4|^2\right) + \mathcal{X}, \quad \left(y(n)\right)^2 = \frac{\text{Tr}(R_2\tilde{\Theta}_1) + |b_4|^2}{\text{Tr}(R_3\tilde{\Theta}_1) + |b_3|^2} - \mathcal{X}.$$

where $y(n) = \sqrt{\frac{\text{Tr}(R_2\tilde{\Theta}_1) + |b_4|^2}{\text{Tr}(R_3\tilde{\Theta}_1) + |b_3|^2} - \mathcal{X}}$. For constraint (19), we first use the semidefinite relaxation to deal with it, i.e., in the $n^{th}$ iteration, one only needs to solve

$$P_6 : \max_{\tilde{\Theta}_1 \succeq 0, \mathcal{X}} \left(1 - \alpha\right) \left(\text{Tr}(R_1\tilde{\Theta}_1) + |b_1|^2\right)$$

s.t. (18), (21), (25), (27). \quad (28)

If $\text{rank}(\tilde{\Theta}_1) \neq 1$, we use $\text{Tr}(\tilde{\Theta}_1) - ||\tilde{\Theta}_1||_2 = 2$ to replace $\text{rank}(\tilde{\Theta}_1) = 1$, and linearize $||\tilde{\Theta}_1||_2$ as $\partial||\tilde{\Theta}_1||_2$. Then the penalty-based method is used to deal with it, i.e., in the $n^{th}$ iteration, we need to solve the optimization problem

$$P_7 : \max_{\tilde{\Theta}_1 \succeq 0, \mathcal{X}} \left(1 - \alpha\right) \left(\text{Tr}(R_1\tilde{\Theta}_1) + |b_1|^2\right)$$

$$- c \left(\text{Tr}(\tilde{\Theta}_1) - \langle\partial||\tilde{\Theta}_1||_2, \tilde{\Theta}_1\rangle\right)$$

s.t. (18), (21), (25), (27). \quad (29)

The detailed procedure for solving $\Theta_1$ is summarized in Algorithm 1, and $\theta_1$ can be obtained by extracting the first $M$ rows of the last column of $\tilde{\Theta}_1$.

Finally, given $\alpha$, $W_1$, $W_2$, and $\tilde{\Theta}_1$, $\theta_2$ can be obtained by solving the following feasibility-check problem,

$$P_8 : \text{Find } \tilde{\Theta}_2$$

s.t. $C_1 : \text{rank}(\tilde{\Theta}_2) = 1$,

$$C_2 : \left(\tilde{\Theta}_2\right)_{m,m} = 1, m = 1, 2, \ldots, M + 1,$$

$$C_3 : \left(\tilde{\Theta}_2\right)_{m,m} = 0, m = 1, 2, \ldots, M + 1.$$ \quad (30)

The challenge of this subproblem is the non-convex rank-one constraint, which can be transformed into the equivalent form $\text{Tr}(\tilde{\Theta}_2) - ||\tilde{\Theta}_2||_2 = 0$. Then, one can solve $P_8$ by using the SCA-based method, i.e., at each iteration, one only needs to replace the objective function in $P_8$ with minimizing $\text{Tr}(\tilde{\Theta}_2) - \langle\partial||\tilde{\Theta}_2||_2, \tilde{\Theta}_2\rangle$, and then solve it by CVX.

Based on the above analysis, we summarize the overall algorithm for both stages in Algorithm 2. The computational complexity of each iteration mainly comes from steps 3, 4, and 5. Specifically, the complexity of step 3 is determined by SDP, and the complexity of steps 4 and 5 is jointly determined by the convex approximation and SDP. Thus, the complexity of Algorithm 2 is roughly $O\left(\log\left(\frac{1}{\rho}\right)(L_W K^3 + (L_{\Theta_1} + L_{\Theta_2})(M + 1)^{3.5})\right)$, where $\rho$ is the convergence tolerance of the interior point method. Moreover, $L_W$, $L_{\Theta_1}$, and $L_{\Theta_2}$ stand for the iteration number of the corresponding subproblems, respectively.

### III. Numerical Results

This section provides some representative numerical results to verify the effectiveness of the proposed scheme. We assume that the AP has $K = 4$ transmit antennas and the number of the RIS reflection elements is $M = 40$. We consider a three-dimensional (3D) coordinate system, where the AP and RIS are located at $(0, 2, 0)$ meter (m) and $(11, 2, 0)$ m, respectively. The locations of $U_1$ and $U_2$ are $(8, 0, 0)$ m and $(12, 2, 0)$ m. The large-scale path loss is set as $PL = -30 - 10 \alpha \log_{10}(d)$ dB, where $d$ is the link length. Moreover, the path loss exponents for both AP-$U_1$ and $U_1$-$U_2$ channels are set to $\alpha_1 = 3.5$, the AP-$U_2$ channel is set to $\alpha_2 = 4$, and the RIS-assisted links are set to $\alpha_3 = 2$. The small-scale fading of all RIS-assisted links follows a Rician distribution with the Ricean factor 2, and all direct links follow Rayleigh fading. The noise variance for both users is set to $-50$ dBm and the target rate is $\gamma_2 = 0.5$ bit/s/Hz, $c = 15$.

We consider two baseline schemes: i) Random phase: the initial values of $\theta_1$ and $\theta_2$ are randomly generated, and the other variables are optimized by using the algorithm in [12]; ii) Without RIS: let $M = 0$, and then P1 is solved by the algorithm in [12]. Fig. 2 and Fig. 3 show the feasible probability and the achievable rate of $U_1$ for different schemes with
IV. Conclusion

In this letter, we have introduced a two-stage RIS-assisted scheme and designed the corresponding performance optimization algorithms for improving the achievable rate of the C-NOMA network with SWIPT. The AO-based technique has been applied to decompose the original problem and the complex phase shift constraints in the two stages have been addressed by using the PBAGM-based algorithm and SCA-based algorithm. The performance of the system could be significantly degraded by the imperfect CSI and SIC in practical scenarios. The investigation of imperfect CSI and SIC cases can be extended by our model and will be left for our future research.

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