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Transceiver Design for Downlink SWIPT NOMA Systems With Cooperative Full-Duplex Relaying

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ABSTRACT This paper studies the application of simultaneous wireless information and power transfer (SWIPT) to downlink non-orthogonal multiple access (NOMA) system. A novel cooperative NOMA protocol for high communication reliability and user fairness is proposed, where a near NOMA user acts as a full-duplex (FD) energy-harvesting relay to help transmission from the source node S to the far NOMA user. The power splitting (PS) architecture is adopted at the relay to perform the SWIPT. The aim is to maximize the data rate of the near NOMA user while satisfying the QoS requirement of the far NOMA user and the energy causality condition of the near NOMA user. The formulated problem is a non-convex fractional programming. By jointly optimizing the power allocation factor, the PS ratio, the receiver filter, and the transmit beamforming, we propose alternative optimization (AO)-based algorithm to obtain an optimal solution. In addition, a low-complexity suboptimal scheme is proposed and the semi-closed form solution is derived to characterize the performance of our proposed design. The simulation results verify the correctness of theoretical analysis and show performance gain of our proposed protocol over the existing transmission protocols.

INDEX TERMS Non-orthogonal multiple access (NOMA), simultaneous wireless information and power transfer (SWIPT), power splitting, full-duplex relaying, alternative optimization (AO), suboptimal scheme.

I. INTRODUCTION

Currently, the rapid development of mobile communication causes the insufficiency of limited spectrum resource, which is extremely urgent to enhance the spectrum utilization under the requirement of the QoS in wireless communication networks [1], [2]. Based on this background, non-orthogonal multiple access (NOMA) is proposed and is expected to be a candidate technology in fifth-generation (5G) wireless networks [3], [4]. In contrast to conventional orthogonal multiple access (OMA), the key idea of NOMA is to realize multiple access in power domain, i.e., multiple users are permitted to receive the superposition signal from transmitter at the same time/frequency/code with different levels of power. Then, these users extract the intended elements from the superposition signal by employing successive interference cancelation (SIC) technique [5].

To achieve higher diversity gain, cooperative NOMA has recently attracted attention in academia. To our knowledge, cooperative NOMA is mainly divided into two cases: outband relaying cooperative NOMA and inband relaying cooperative NOMA. The former has dedicated relays for assisting communication between the transmitter and users [6]–[8], and the latter lets the near users with strong channel conditions act as relays to improve the performance of the far users with poor channel conditions [9], [10]. However, The cooperative NOMA relay mostly operates in half-duplex (HD) mode in the early works [7]–[11]. There is no doubt that higher transmission reliability brought by cooperative NOMA is accompanied by a reduction of spectral efficiency resulting

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from cooperative delay. Reference [6] integrated full-duplex (FD) relay into cooperative NOMA to reduce delay caused by the dedicated relay and enhance end to end transmission quality. With regard to the in-band relay, [12] utilized FD relay user instead, which proved the advantage of the FD mode in enhancing performance gain. Reference [13] maximized energy efficiency for full-duplex cooperative NOMA with power allocation. In [14], an energy-efficient scheduling scheme for FD-NOMA-based in-band self-backhauling heterogeneous networks was proposed. In addition, both [15] and [16] considered FD cooperative NOMA scheme and HD cooperative NOMA scheme from different aspects, and proposed a novel scheme, which can dynamically switch between two schemes. According to [17]–[20], FD relay technique is mainly divided into two categories, namely FD amplify-and-forward (AF) relaying and FD decode-and-forward (DF) relaying.

Taking into account that the primary objective of 5G network is to maximize energy efficiency possibly while improving spectral efficiency, simultaneous wireless information and power transfer (SWIPT) has drawn wide attention, especially in energy constrained relay systems [22]–[24]. To perform SWIPT, there are two practical receiver architectures, i.e., time switching (TS) or power splitting (PS). Reference [23] proposed two-phase protocol for simultaneous energy harvesting and information forwarding, which showed the superiority of the proposed scheme over the TS-based scheme in throughput gain of the relay. Liu *et al.* [23] and Zhao *et al.* [24] studied the application of PS-based SWIPT to FD relaying systems in terms of outage probability and end-to-end transmission rate, respectively. Reference [23] also pointed out that utilization of TS-based SWIPT at FD relay would lead to degradation of spectral efficiency. Motivated by this, some researchers began to integrate PS-based SWIPT into the NOMA systems [10], [11], [21], where the half-duplex relay user can harvest the energy from the received radio frequency (RF) signals and use it for cooperative transmission rather than consuming itself, which prolongs the lifetime of the energy-restricted relay user. In addition, [30] adopts a practical non-linear EH model to perform SWIPT in cognitive radio inspired NOMA system. The total transmission power of the network is minimized by the joint optimization of The transmission beamforming vectors and artificial noise-aided covariance matrix.

A. CONTRIBUTION

Motivated by the above discussion, we can know that the combination of FD, SWIPT and cooperative NOMA not only improves spectral efficiency but also prolongs the lifetime of battery at relay node to guarantee the communication reliability. Therefore, we consider the application of PS-based SWIPT and FD mode to cooperative NOMA system, where the near user acts as the full-duplex relay to forward messages and harvest energy from the received signals by using power splitting structure to support the relay behavior. The main contributions of this work are summarized as follows:

- We study the maximization of data rate at the near user in PS-based SWIPT cooperative NOMA system, where both power splitting structure and FD mode are employed at the near NOMA user. The near NOMA user serves as a cooperative relay powered by harvested energy from received signals, which further guarantees communication reliability as well as prolongs the lifetime of its battery.
- Under QoS requirement of the far NOMA user and power constraints at S and the near NOMA user, we formulate the joint optimization problem of power splitting ratio, power allocation coefficient as well as receive and transmit beamforming vectors. The problem appears to be a non-convex and multivariate, which is hard to be solved. To tackle it, we propose alternative optimization (AO) based scheme to generate optimal solution by iteration. Meanwhile, a suboptimal strategy is proposed with semi-closed form solution, which reduce significantly complexity.
- By making a comprehensive comparison of some schemes, numerical results show that the superiority of the proposed scheme in performance gain and communication reliability. Moreover, it is also verified that the proposed strategy outperforms ZF-based suboptimal scheme.

B. ORGANIZATION & NOTATIONS

The remainder of this paper is organized as follows. Section II introduces the system model of full-duplex cooperative NOMA with SWIPT assisted, and then presented the formulated optimization problem. In section III, we propose optimal and suboptimal schemes for problem solution, respectively. We present the simulation results and conclusions are in Section IV and Section V, respectively.

Notations: In this paper, scalars, vectors and matrices are respectively denoted by lower case, boldface lower case and boldface upper case letters. I represents an identity matrix and 0 denotes an all-zero vector. $\|\bullet\|$ denotes the Euclidean norm. $(\bullet)^T$ and $(\bullet)^H$ denote transpose and the Hermitian operations of a vector or matrix respectively. $|\bullet|$ denotes the absolute value of a complex scalar. $x \sim \mathcal{CN}(n, \Theta)$ represents the distribution of a circularly symmetric complex Gaussian (CSCG) random vector with mean n and covariance matrix Θ. $\mathbb{C}^{p\times q}$ stands for the space of $p \times q$ complex matrices.

II. SYSTEM MODELS

Consider a two-user downlink NOMA system, where the source node S transmits a superposed signal $x(t)$ to two users, i.e., the near NOMA user U1 and the far NOMA user U2. Assume that S and U2 are single-antenna devices, and U1 adopts FD mode by using M_r receive antennas and M_t transmit antennas, which can efficiently eliminate self-interference in spatial domain [27], [19]. It is common to see such scenarios that the direct link from S to U2 is hard to meet the QoS requirement of the far NOMA user U2 when

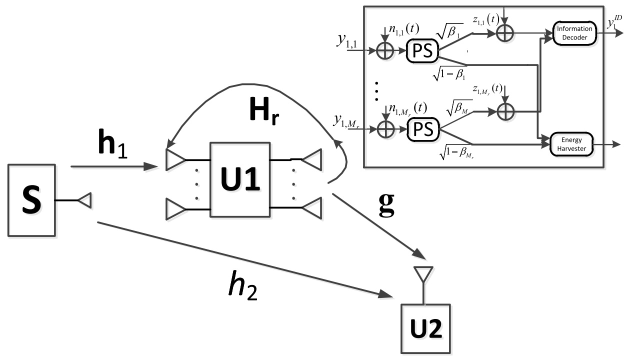

FIGURE 1. Full-duplex SWIPT-aided cooperative NOMA system.

suffering from deep fading or the target rate is too high. To ensure QoS target of the far NOMA user, the near NOMA user U1 acts a cooperative relay and adopts DF protocol [28] to decode and forward the message to U2, which can be regarded as device-to-device (D2D) communication [29].

Note that U1 is assumed to decode and forward the signal x_2 to U2 successfully. For making U1 perform relaying positively, the PS architecture is employed at it to perform SWIPT. Hence, the direct transmission phase and the cooperative transmission phase can be implemented concurrently and the near NOMA user U1 will no longer worry about the shortage of its battery life.

A. SIGNAL MODEL

Let $\mathbf{h}_1 \in \mathbb{C}^{M_r \times 1}$, $h_2 \in \mathbb{C}$ and $\mathbf{g} \in \mathbb{C}^{1 \times M_t}$ denote the S − U1, S − U2 and U1 − U2 channels, respectively. Let $\mathbf{H}_r \in \mathbb{C}^{M_r \times M_t}$ denote the loop channel from the M_t transmitting antennas of U1 to its M_r receiving antennas. Assume that all channel state information (CSI) is perfectly known [30]. Based on the concept of NOMA [12], the transmitted signal at node S can be written as

$$x(t) = \sqrt{\alpha P_s} x_1(t) + \sqrt{(1-\alpha) P_s} x_2(t), \tag{1}$$

where P_s is the transmit power of S, $\alpha\ (0 \le \alpha \le 1)$ and $(1-\alpha)$ are the power allocation coefficient. In general, α can be further limited to $\left(0, \frac{1}{2}\right]$ to stipulate better fairness between the users. $x_1(t)$ and $x_2(t)$ $\left(\mathbb{E}|x_i(t)|^2 = 1,\ i = 1, 2\right)$ are the messages for U1 and U2, respectively.

The received signal at the FD near NOMA user, U1, can be given as

$$\mathbf{y}_1(t) = \mathbf{h}_1 x(t) + \mathbf{H}_r \mathbf{w} s(t) + \mathbf{n}_1(t), \tag{2}$$

where $\mathbf{w} \in \mathbb{C}^{M_t \times 1}$ is transmit beamforming of U1, $s(t) = \hat{x}_2(t-\tau)$ is the decoded version of message $x_2(t)$ and τ represents the processing delay at U1, $\mathbf{n}_1 \sim \mathcal{CN}\left(\mathbf{0}, \sigma_1^2 \mathbf{I}\right)$ is the additive white Gaussian noise (AWGN) vector at the receiver antennas of U1. Note that the PS architecture is introduced in U1, then, the signal for information decoding and energy harvesting can be respectively expressed as

$$\mathbf{y}_1^{\mathrm{ID}}(t) = \sqrt{\beta}\left[\mathbf{h}_1 x(t) + \sqrt{\rho}\mathbf{H}_r \mathbf{w} s(t) + \mathbf{n}_1(t)\right] + \mathbf{z}_1(t) \tag{3}$$

and

$$\mathbf{y}_1^{\mathrm{EH}}(t) = \sqrt{1-\beta}\left[\mathbf{h}_1 x(t) + \mathbf{H}_r \mathbf{w} s(t) + \mathbf{n}_1(t)\right] \tag{4}$$

where $\beta \in [0, 1]$ is the PS ratio to be optimized and $\mathbf{z}_1 \sim \mathcal{CN}\left(\mathbf{0}, \delta_1^2 \mathbf{I}\right)$ is the AWGN. $0 \le \rho \le 1$ denotes the loop-interference (LI) cancellation factor [31], whose value can refer to [32]. Here, for simplicity, we assume that the same power splitting factor β is used at each receive antenna of U1 [33], [34]. U1 adopts a linear receiver, $\mathbf{r} \in \mathbb{C}^{M_r \times 1}$ and satisfies $\|\mathbf{r}\| = 1$, on the received signal $\mathbf{y}_1^{\mathrm{ID}}$, to obtain the data estimate

$$\tilde{x}(t) = \mathbf{r}^H \left\{\sqrt{\beta}\left[\mathbf{h}_1 x(t) + \sqrt{\rho}\mathbf{H}_r \mathbf{w} s(t) + \mathbf{n}_1(t)\right] + \mathbf{z}_1(t)\right\} \tag{5}$$

Then, the received signal at the far NOMA user, U2, is

$$y_2(t) = h_2 x(t) + \mathbf{g}\mathbf{w}\hat{x}(t-\tau) + n_2(t), \tag{6}$$

where $n_2 \sim \mathcal{CN}\left(0, \sigma_2^2\right)$ is the complex Gaussian noise at U2.

B. IMPLEMENTATION OF COOPERATIVE SWIPT NOMA

In NOMA, successive interference cancelation (SIC) is generally carried out at the near NOMA user U1. Particularly, U1 first decodes the far NOMA user U2's data, i.e., x_2, and then subtracts this component from the received signal. After that, U1 will detect its own data x_1. Therefore, the received SINR at U1 to detect x_2 of U2 is given by

$$\gamma_{\mathrm{U1}}^{x_2} = \frac{\beta(1-\alpha)P_s\left|\mathbf{r}^H\mathbf{h}_1\right|^2}{\beta\left(\alpha P_s\left|\mathbf{r}^H\mathbf{h}_1\right|^2 + \rho\left|\mathbf{r}^H\mathbf{H}_r\mathbf{w}\right|^2 + \sigma_1^2\right) + \delta_1^2} \tag{7}$$

And the received SINR at U1 to detect its own signal x_1 can be written as

$$\gamma_{\mathrm{U1}}^{x_1} = \frac{\alpha\beta P_s\left|\mathbf{r}^H\mathbf{h}_1\right|^2}{\beta\left(\rho\left|\mathbf{r}^H\mathbf{H}_r\mathbf{w}\right|^2 + \sigma_1^2\right) + \delta_1^2} \tag{8}$$

Based on (4), ignoring the negligible energy harvested from the receiver noise n_1, the total harvested energy at U1 can be given as

$$E = \zeta(1-\beta)\left(P_s\|\mathbf{h}_1\|^2 + \|\mathbf{H}_r\mathbf{w}\|^2\right)T \tag{9}$$

where $0 \le \zeta \le 1$ denotes the energy harvesting efficiency at U1, T is the total block duration including the direct transmission and the relaying transmission. Particularly, we assume that the harvested energy is only stored for forwarding and the circuit power consumed by U1 is supplied by its own battery which could be charged by renewable resources [24], [25]. For briefness, T is set by 1.

Then, the received SINRs at U2 to detect x_2 from S and U1 are respectively expressed as

$$\gamma_{\mathrm{U2,S}}^{x_2} = \frac{(1-\alpha)P_s|h_2|^2}{\alpha P_s|h_2|^2 + \sigma_2{}^2} \tag{10}$$

and

$$\gamma_{\mathrm{U2,U1}}^{x_2} = \frac{|\mathbf{g}\mathbf{w}|^2}{\sigma_2{}^2}. \tag{11}$$

Assuming the signals from S and U1 are fully resolvable at U2 [12], they can be appropriately cophased and merged by maximal-ratio combining (MRC). Therefore, the overall SINR at U2 is equal to two received SINR from S and U1, which can be written as

$$\gamma_{\text{U2,MRC}}^{x_2} = \gamma_{\text{U2,S}}^{x_2} + \gamma_{\text{U2,U1}}^{x_2} = \frac{(1-\alpha)P_s|h_2|^2}{\alpha P_s|h_2|^2 + \sigma_2^2} + \frac{|\mathbf{g}\mathbf{w}|^2}{\sigma_2^2} \tag{12}$$

C. PROBLEM FORMULATION

Our design goal is to maximize the data rate of the near NOMA user while fulfilling the QoS requirement of the far NOMA user and the power constraints at S and the near user. Obviously, rate maximization of U1 means maximizing its SINR. Mathematically, the corresponding optimal problem $\mathcal{P}1$ can be formulated as

$$\max_{\alpha,\beta,\mathbf{w},\|\mathbf{r}\|^2=1} \gamma_{\text{U1}}^{x_1} \tag{13a}$$

$$s.t.\ \min\left\{\gamma_{\text{U1}}^{x_2}, \gamma_{\text{U2,MRC}}^{x_2}\right\} \geq \gamma_0, \tag{13b}$$

$$\|\mathbf{w}\|^2 \leq \frac{E}{T-\tau}, \tag{13c}$$

$$0 < \alpha \leq 1/2, \tag{13d}$$

$$0 \leq \beta \leq 1, \tag{13e}$$

where constraints (13b) indicates that the received SINR at U2 and U1 to detect x_2 must be above the target SINR, γ_0. Constraint (13c) means that the transmission power consumed at U1 would not exceed that harvested in the long term. Meanwhile, we assume that the initial energy stored at the battery of U1 is sufficiently large to support the initial operation of FD U1 [22], [35]. Finally, the fairness among two users is guaranteed by constraint (13d), and the range of the PS ratio is given in constraint (13e).

III. QoS GUARANTEED TRANSCEIVER DESIGN

The aforementioned problem is highly non-convex and is hard to be tackled directly. Clearly, the nonconvexity is related to four variables including two scalars α, β, and two vectors $\mathbf{r}$, $\mathbf{w}$. In the following, we first propose optimal AO-based strategy for problem solution. The outer of proposed optimal scheme is to two-dimension search over two scalars and the inner of proposed scheme is to obtain two vectors by using AO protocol. Then, a zero forcing(ZF) based algorithm with low complexity is presented.

A. OPTIMAL DESIGN

By analysing the structure of optimization problem, two scalars can first be fixed and then two vectors can be handled by using AO algorithm. The core of AO algorithm is to cope with one variable when others are fixed. Thus, we need to handle two subproblems respectively.

1) OPTIMIZATION OF w WITH FIXED r

When $\mathbf{r}$ is fixed, the problem is still nonconvex due to its nonlinear objective and nonconvex constraints (13b)-(13c). Using semidefinite relaxation (SDR) technique, i.e., let $\mathbf{W} = \mathbf{w}\mathbf{w}^H$, then the subproblem with respect to $\mathbf{w}$ can be written as

$$\max_{\mathbf{W}\succeq\mathbf{0}} \frac{\alpha P_s \text{Tr}\left(\mathbf{H}_1\mathbf{R}\right)}{\rho \text{Tr}\left(\mathbf{V}\mathbf{W}\right) + \sigma_1^2 + \frac{\delta_1^2}{\beta}} \tag{14a}$$

$$s.t.\ \frac{(1-\alpha)\left|h_2\right|^2 P_s}{\alpha|h_2|^2 P_s + \sigma_2^2} + \frac{\text{Tr}\left(\mathbf{G}\mathbf{W}\right)}{\sigma_2^2} \geqslant \gamma_0, \tag{14b}$$

$$\frac{(1-\alpha)P_s \text{Tr}\left(\mathbf{H}_1\mathbf{R}\right)}{\alpha P_s \text{Tr}\left(\mathbf{H}_1\mathbf{R}\right) + \rho\text{Tr}\left(\mathbf{V}\mathbf{W}\right) + \sigma_1^2 + \frac{\delta_1^2}{\beta}} \geqslant \gamma_0, \tag{14c}$$

$$\text{Tr}\left(\mathbf{W}\right) \leqslant \frac{\zeta(1-\beta)\left(P_s\|\mathbf{h}_1\|^2 + \text{Tr}\left(\mathbf{H}_r\mathbf{W}\right)\right)}{1-\tau}, \tag{14d}$$

$$\text{rank}\left(\mathbf{W}\right) = 1, \tag{14e}$$

where $\mathbf{R} = \mathbf{r}\mathbf{r}^H$. Next, we discuss two cases.

(i) If $\frac{(1-\alpha)|h_2|^2P_s}{\alpha|h_2|^2P_s+\sigma_2^2} = \gamma_0$, i.e., the received SINR from S has satisfied QoS requirement of U2, then U1 is unnecessary to serve U2, i.e., $\mathbf{w} = \mathbf{0}$. After substituting it into subproblem of $\mathbf{r}$, we can obtain optimal $\mathbf{r}^*$ by CVX.

(ii) If $\frac{(1-\alpha)|h_2|^2P_s}{\alpha|h_2|^2P_s+\sigma_2^2} < \gamma_0$, i.e., the received SINR from S can't satisfy QoS requirement of U2, then U1 have to act as relay for helping U2, i.e., $\mathbf{W} \succ \mathbf{0}$.

In second case, assume that problem (13) is feasible and is also dual feasible. Inspired by [37, Th. 4.2], we can verify that optimal $\mathbf{W}^*$ always satisfies

$$\text{rank}^2\left(\mathbf{W}^*\right) \leqslant 3 \tag{15}$$

From $\mathbf{W} \succ \mathbf{0}$, thus $\text{rank}\left(\mathbf{W}^*\right) \geqslant 1$. Combining (15), we can conclude that $\text{rank}\left(\mathbf{W}^*\right) = 1$. Hence, (14e) should be omitted. Then, we adopt Dinkelbach method for the fractional programming. By introducing auxiliary variable λ^*, the problem can be equivalent to

$$\max_{\mathbf{W}\succ\mathbf{0}} \alpha P_s \text{Tr}\left(\mathbf{H}_1\mathbf{R}\right) - \lambda^*\left(\rho\text{Tr}\left(\mathbf{V}\mathbf{W}\right) + \sigma_1^2 + \frac{\delta_1^2}{\beta}\right) \tag{16a}$$

$$s.t.\ \frac{(1-\alpha)\left|h_2\right|^2 P_s}{\alpha|h_2|^2 P_s + \sigma_2^2} + \frac{\text{Tr}\left(\mathbf{G}\mathbf{W}\right)}{\sigma_2^2} \geqslant \gamma_0, \tag{16b}$$

$$(1-\alpha)P_s\text{Tr}\left(\mathbf{H}_1\mathbf{R}\right) \geqslant \gamma_0\left[\alpha P_s\text{Tr}\left(\mathbf{H}_1\mathbf{R}\right) + \rho\text{Tr}\left(\mathbf{V}\mathbf{W}\right) + \sigma_1^2 + \frac{\delta_1^2}{\beta}\right], \tag{16c}$$

$$\text{Tr}\left(\mathbf{W}\right) \leqslant \frac{\zeta(1-\beta)\left(P_s\|\mathbf{h}_1\|^2 + \text{Tr}\left(\mathbf{H}_r\mathbf{W}\right)\right)}{1-\tau}, \tag{16d}$$

Algorithm 1 Dinkelbach Method for Problem (16)

1: **Initilization**: Set $n = 0$, given auxiliary variable λ^* and maximum tolerance ε_1
2: **While**
3: Solve (15) and obtain the optimal solution $\mathbf{W}^*$ with λ_n
4: Set $n = n + 1$
5: Update $\lambda_n = \frac{\alpha P_s \mathrm{Tr}(\mathbf{H}_1\mathbf{R})}{\rho \mathrm{Tr}(\mathbf{VW}^*)+\sigma_1^2+\frac{\delta_1^2}{\beta}}$
6: **Until** $\left|\alpha P_s \mathrm{Tr}\left(\mathbf{H}_1\mathbf{R}\right) - \lambda_n\left(\rho \mathrm{Tr}\left(\mathbf{VW}^*\right) + \sigma_1^2 + \frac{\delta_1^2}{\beta}\right)\right| \leqslant \varepsilon_1$
7: End while
8: **Output:** $\mathbf{W}^*$

Theorem 1: The optimal data rate of U1 $\lambda^* = \frac{\alpha P_s \mathrm{Tr}(\mathbf{H}_1\mathbf{R})}{\rho \mathrm{Tr}(\mathbf{VW}^*)+\sigma_1^2+\frac{\delta_1^2}{\beta}}$ if and only if λ^* satisfies

$$\begin{aligned}\max_{\mathbf{W}}\ &\alpha P_s \mathrm{Tr}\left(\mathbf{H}_1\mathbf{R}\right) - \lambda^*\left(\rho \mathrm{Tr}\left(\mathbf{VW}\right) + \sigma_1^2 + \frac{\delta_1^2}{\beta}\right)\\ &= \alpha P_s \mathrm{Tr}\left(\mathbf{H}_1\mathbf{R}\right) - \lambda^*\left(\rho \mathrm{Tr}\left(\mathbf{VW}^*\right) + \sigma_1^2 + \frac{\delta_1^2}{\beta}\right)\\ &= 0. \end{aligned} \tag{17}$$

The detailed proof of Theorem 1 can refer to [37]. Theorem 1 shows the relationship between the transformed problem and original problem, i.e., the optimal objective value of (16) is equal to the root of the equation $\max_{\mathbf{W}\succ\mathbf{0}} \alpha P_s \mathrm{Tr}\left(\mathbf{H}_1\mathbf{R}\right) - \lambda^*\left(\rho \mathrm{Tr}\left(\mathbf{VW}\right) + \sigma_1^2 + \frac{\delta_1^2}{\beta}\right) = 0$. For given λ^*, the parametric problem (16) is convex and can be directly solved by CVX. The optimal beamforming vector $\mathbf{w}^*$ can be further obtained from $\mathbf{W}^*$ by eigen-decomposition. The algorithm is presented as follows.

In the parametric problem, the convergence of the optimum λ^* is guaranteed and the objective function is non-decreasing during the iteration, whose proof is similar to [38].

2) OPTIMIZATION OF r WITH FIXED w

Substitute the optimal $\mathbf{w}^*$ in the first step into (13), we can further convert the problem into the following subproblem of $\mathbf{R}$ by employing SDR, i.e., set $\mathbf{R} = \mathbf{rr}^H$.

$$\max_{\mathbf{R}\succ\mathbf{0}} \frac{\alpha P_s \mathrm{Tr}\left(\mathbf{H}_1\mathbf{R}\right)}{\rho \mathrm{Tr}\left(\mathbf{VW}\right) + \sigma_1^2 + \frac{\delta_1^2}{\beta}} \tag{18a}$$

$$s.t.\ (1-\alpha)P_s \mathrm{Tr}\left(\mathbf{H}_1\mathbf{R}\right) \geqslant \gamma_0\left[\alpha P_s \mathrm{Tr}\left(\mathbf{H}_1\mathbf{R}\right) + \rho \mathrm{Tr}\left(\mathbf{VW}\right) + \sigma_1^2 + \frac{\delta_1^2}{\beta}\right], \tag{18b}$$

$$\mathrm{rank}\left(\mathbf{R}\right) = 1, \tag{18c}$$

where $\mathbf{W} = \mathbf{ww}^H$. Similarly, we can know that rank $(\mathbf{R}) \leqslant 1$ and $\mathbf{R}$ is non-zero matrix. Thus, rank $(\mathbf{R}) = 1$. The constraint (18c) can be neglected. Finally, with the help of CVX, we can obtain optimal $\mathbf{R}^*$. Then, we can get $\mathbf{r}^*$ by eigen-decomposition and normalization.

Algorithm 2 The Inner AO Algorithm for Problem (13)

1: **Initilization**: Set $n = 0$, given $\mathbf{r}_0$, α, β and maximum tolerance ε_2,
2: **While**
3: For fixed $\mathbf{r}_n$, solve (16) to obtain the optimal solution $\mathbf{w}^*$
4: Update $\mathbf{w}_n = \mathbf{w}^*$
5: For fixed $\mathbf{w}_n$, solve (18) to obtain the optimal solution $\mathbf{r}^*$
6: Update $\mathbf{r}_{n+1} = \mathbf{r}^*$
7: $G_n = \frac{\alpha P_s \mathrm{Tr}(\mathbf{H}_1\mathbf{R}_n)}{\rho \mathrm{Tr}(\mathbf{VW}_n)+\sigma_1^2+\frac{\delta_1^2}{\beta}}$
8: Set $n = n + 1$
9: **Until** $|G_n - G_{n-1}| \leqslant \varepsilon_2$
10: End while
11: **Output:** $\mathbf{w}^*$, $\mathbf{r}^*$

Finally, we can attain optimal $\mathbf{r}^*$ and $\mathbf{w}^*$ of the original problem (13) based on AO algorithm when α and β are fixed, whose detailed flow is proposed in algorithm 2. The outer of the algorithm is to two-dimension search about α and β.

Notably, it is easily proved that the objective of (13) is non-decreasing function. Thus, the AO algorithm can converge at some point, whose proof can refer to [39].

B. SUBOPTIMAL DESIGN

The complexity of optimal scheme in the above subsection is high. Thus, we propose a low complexity suboptimal scheme. In this scheme, semi-closed solutions for characterizing system performance are derived, which reduces computational complexity greatly. By invoking ZF scheme [40], i.e., $\mathbf{H}_r\mathbf{w} = \mathbf{0}$, we can derive the semi-closed solution, which reduce computing complexity greatly. Then, the corresponding optimal problem $\mathcal{P}2$ can be expressed as

$$\max_{\alpha,\beta,\mathbf{r},\mathbf{w}} \frac{\alpha P_s \left|\mathbf{r}^H\mathbf{h}_1\right|^2}{\sigma_1^2 + \frac{\delta_1^2}{\beta}} \tag{19a}$$

$$s.t.\ \frac{(1-\alpha)\,|h_2|^2 P_s}{\alpha|h_2|^2 P_s + \sigma_2^2} + \frac{|\mathbf{gw}|^2}{\sigma_2^2} \geqslant \gamma_0, \tag{19b}$$

$$\frac{(1-\alpha)\left|\mathbf{r}^H\mathbf{h}_1\right|^2 P_s}{\alpha\left|\mathbf{r}^H\mathbf{h}_1\right|^2 P_s + \sigma_1^2 + \frac{\delta_1^2}{\beta}} \geqslant \gamma_0, \tag{19c}$$

$$\|\mathbf{w}\|^2 \leqslant \frac{\varsigma\,(1-\beta)\left|\mathbf{r}^H\mathbf{h}_1\right|^2 P_s}{1-\tau}, \tag{19d}$$

$$\mathbf{H}_r\mathbf{w} = \mathbf{0},\quad 0 < \alpha \leqslant 0.5,\ 0 \leqslant \beta \leqslant 1, \tag{19e}$$

Clearly, the nonconvexity is related to four variables including two scalars α, β, and two vectors $\mathbf{r}$, $\mathbf{w}$. In the following, the stepwise optimization method will be adopted to optimize the scalar variables and the vector variables separately.

1) JOINT OPTIMIZATION OF r AND w WITH GIVEN α AND β

For given α and β, (19a) is equivalent to $\max_{\mathbf{w},\|\mathbf{r}\|^2=1} \left|\mathbf{r}^H\mathbf{h}_1\right|^2$. Note that constraints (19b) and (19c) are more likely to be satisfied with the increasing of $\left|\mathbf{r}^H\mathbf{h}_1\right|^2$. Therefore, we can conclude that, given α and β, the optimal objective value of problem (19) can be obtained with $\mathbf{r}^* = \frac{\mathbf{h}_1}{\|\mathbf{h}_1\|}$.

Next, let's pay attention to variable $\mathbf{w}$. It is easy to learn that the optimal objective value in (19a) requires the value of α as large as possible. However, this will decrease the value of $\frac{(1-\alpha)|h_2|^2P_s}{\alpha|h_2|^2P_s+\sigma_2{}^2}$ in (19b), i.e., weaken the direct transmission between S and U2. Hence, in this case, we need to make full use of the cooperative transmission by U1 to fulfill the QoS requirement of U2, which leads to the following sub-problem

$$\max_{\mathbf{w}} \ |\mathbf{g}\mathbf{w}|^2 \tag{20a}$$
$$s.t.\ \mathbf{H}_r\mathbf{w} = 0, \tag{20b}$$
$$\|\mathbf{w}\|^2 \leqslant \frac{\zeta\,(1-\beta)\,\|\mathbf{h}_1\|^2P_s}{1-\tau} \tag{20c}$$

Based on (20), the closed-form optimal solution of $\mathbf{w}$ can be given as

$$\mathbf{w}^* = \sqrt{P}\frac{\mathbf{U}\mathbf{U}^H\mathbf{g}^H}{\left\|\mathbf{U}\mathbf{U}^H\mathbf{g}^H\right\|}, \tag{21}$$

where $P = \frac{\zeta(1-\beta)\left|\mathbf{r}^{*H}\mathbf{h}_1\right|^2P_s}{1-\tau}$ and $\mathbf{U}$ is defined as the orthogonal basis of the null space of H_r. Thus, the optimal value of $|\mathbf{g}\mathbf{w}|^2$ is equal to $\frac{(1-\beta)}{v}$, where $\upsilon = \frac{\sigma_2^2(1-\tau)}{\zeta u\|\mathbf{h}_1\|^2P_s}$ and $u = \frac{|\mathbf{g}\mathbf{U}\mathbf{U}^H\mathbf{g}^H|^2}{\|\mathbf{U}\mathbf{U}^H\mathbf{g}^H\|^2}$.

2) OPTIMIZATION OF α AND β

So far, we have completed joint optimization of $\mathbf{r}$ and $\mathbf{w}$. Substituting $\mathbf{r}^*$ and $\mathbf{w}^*$ into problem (19) and doing some simple transformations, we formulate the problem as below,

$$\max_{\alpha,\beta} \ \frac{\alpha P_s\|\mathbf{h}_1\|^2}{\sigma_1^2+\frac{\delta_1^2}{\beta}} \tag{22a}$$
$$s.t.\ \beta \leqslant 1 + \frac{\nu\,(1-\alpha)\,|h_2|^2P_s}{\alpha|h_2|^2P_s+\sigma_2^2} - \gamma_0\upsilon, \tag{22b}$$
$$\beta \geqslant \frac{\delta_1^2\gamma_0}{[1-(1+\gamma_0)\,\alpha]\,\|\mathbf{h}_1\|^2P_s - \gamma_0\sigma_1^2} \tag{22c}$$
$$0<\alpha\leqslant 0.5, \quad 0\leqslant\beta\leqslant 1, \tag{22d}$$

Note that the design goal of maximizing data rate of U1 implies that the data rate of U2 only peaks at the target value, i.e., $\gamma_{U2,MRC}^{x_2}$ and $\gamma_{U1}^{x_2}$ should be no greater than γ_0, i.e., the term $\frac{\upsilon(1-\alpha)|h_2|^2P_s}{\alpha|h_2|^2P_s+\sigma_2{}^2} - \gamma_0\upsilon$ (in constraint (22b)) must be less than or equal to zero and $1-\upsilon\gamma_0 \leqslant \beta \leqslant 1$. $0<\alpha<\min\left\{\frac{1}{2}, \frac{c}{1+\gamma_0}\right\}$, where $c = 1-\frac{\gamma_0\sigma_1^2}{\|\mathbf{h}_1\|^2P_s}$, ensures a positive value of $(1-(1+\gamma_0)\,\alpha)\,\|\mathbf{h}_1\|^2P_s - \gamma_0\sigma_1^2$ (the denominator in constraint (22c)) so that the feasibility is guaranteed. Obviously, the feasible regions $1-\upsilon\gamma_0 \leqslant \beta \leqslant 1$ and $0 < \alpha < \min\left\{\frac{1}{2}, \frac{c}{1+\gamma_0}\right\}$ become smaller than the initial feasible regions in (19e), which will ease the derivation of the jointly optimal α and β in the following.

As seen from the objective in (22), β is expected to be larger and larger for the fixed α. Thus, for any given α, the optimal β^* can be obtained when constraint (22b) is satisfied with equality, which can be written as

$$\beta^* = 1 + \frac{\upsilon\,(1-\alpha)\,|h_2|^2P_s}{\alpha|h_2|^2P_s+\sigma_2{}^2} - \gamma_0\upsilon. \tag{23}$$

According to (23), we can observe that β^* decreases with $|h_2|$ with the given α, i.e., the larger channel gain of channel S-U2, the more power the relay user U1 needs to split for energy harvesting to meet the QoS requirement of U2, which indicates the importance of cooperative transmission in guaranteeing the reception reliability of the far user, U2, especially when the channel gain of S-U2 is particularly small.

Finally, by substituting β^* into objective value, optimal α^* can be obtained by solving the following problem

$$\max_{0<\alpha<\min\left\{\frac{1}{2},\frac{c}{1+\gamma_0}\right\}} \ \psi\,(\alpha), \tag{24}$$

with $\psi\,(\alpha) \triangleq \frac{\rho_1\alpha^2+\rho_2\alpha}{\rho_3\alpha+\rho_4}$, $\rho_1 = (1-(1+\gamma_0)\,\upsilon)\,|h_2|^2P_s$, $\rho_2 = \sigma_2^2+\upsilon\left(|h_2|^2P_s-\gamma_0\sigma_2^2\right)$, $\rho_3 = \sigma_2^2\delta_1^2-\rho_1\sigma_1^2$ and $\rho_4 = \rho_2\sigma_1^2+\delta_1^2|h_2|^2P_s$. Obviously, the optimum can be obtained by one-dimension search.

IV. NUMERICAL RESULTS

Without loss of generality, the noise power is set to be $\sigma_1^2 = \sigma_2^2 = \delta_1^2 = -80$ dBm and the system bandwidth is assumed to be 1MHz. The energy conversion efficiency at U1 is set as $\zeta = 0.8$. All allowable tolerances are set as $\varepsilon_1 = \varepsilon_2 = 10^{-3}$ and the processing delay is $\tau = 0.5$. Moreover, we assume that U1 is equipped with $M_r = 2$ received antennas and $M_t = 4$ transmitted antennas. All channels are assumed to undergo path loss for line of sight (LoS) [27], which are modeled by $\mathbf{h}_1 = \sqrt{10^{-\sigma_{LoS}/10}}\hat{\mathbf{h}}_1$, $h_2 = \sqrt{10^{-\sigma_{LoS}/10}}\hat{h}_2$ and $\mathbf{g} = \sqrt{10^{-\sigma_{LoS}/10}}\hat{\mathbf{g}}$ respectively. $\hat{\mathbf{h}}_1$, $\hat{h}_2$ and $\hat{\mathbf{g}}$ are independent circularly symmetric complex Gaussian (CSCG) random variables with zero means and unit variances and $10^{-\sigma_{LoS}/10}$ represents path loss, where $\sigma_{LoS} = 30.18 + 26\log(d)$. The distances from S-U1, S-U2 and U1-U2 are 10m, 16m and 9m respectively. In the optimal scheme, the SI cancellation level $\rho = -40$ dB, Besides, loop-interference channel follows the free-space path loss model [34]. All simulation results are achieved over 2000 random channel realizations.

For comparison, we provide another three transmission strategies, i.e., HD cooperative NOMA with SWIPT [21], FD cooperative NOMA without SWIPT [12] and conventional OMA with SWIPT; In HD cooperative NOMA with SWIPT scheme, the relay user operates in HD mode and employs energy harvesting technique for relaying. The only difference between FD cooperative NOMA without SWIPT

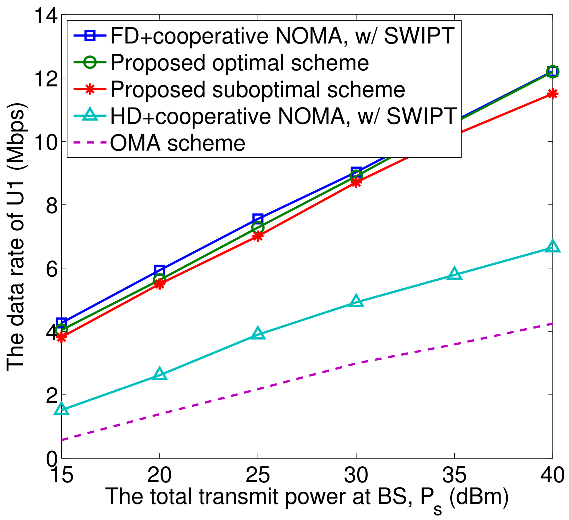

FIGURE 2. Data rate of U1 versus the total transmission power with $\gamma_0 = 1$.

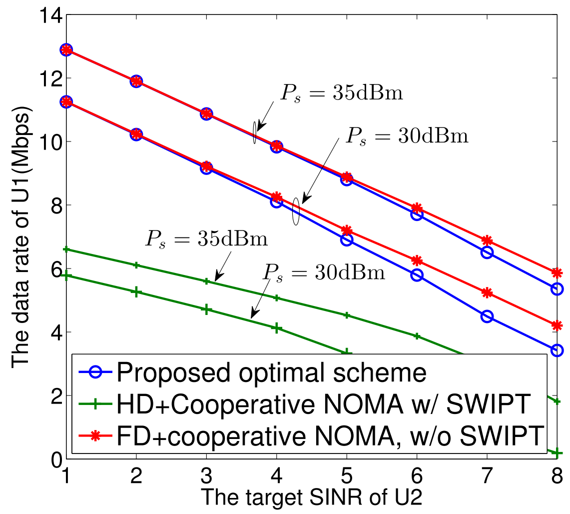

FIGURE 3. Data rate of U1 versus the target SINR of U2 with different total transmit power.

scheme and the proposed schme is that the FD relay consumes its own battery to help forward message instead of adopting energy harvesting technique in FD cooperative NOMA without SWIPT scheme. Note that both HD cooperative NOMA with SWIPT scheme and FD cooperative NOMA without SWIPT scheme adopt the same optimal method.

Fig. 2 illustrates the data rate of U1 in terms of total transmit power for different transmission strategies. It is observed that the data rate of U1 increases with the total transmit power for all strategies. Apparently, the FD NOMA schemes outperform the HD NOMA scheme. Meanwhile, the proposed optimal strategy obtains more performance gain than the proposed suboptimal scheme, which indicate optimal $\mathbf{w}$ doesn't locate on the null space of channel $\mathbf{H}_r$. Besides, performance of the proposed strategy is inferior to the FD cooperative NOMA without SWIPT scheme in the low power regime while the performance of two schemes begin to converge in the high power region. This is because the U1 uses harvested energy for cooperative forwarding in proposed optimal strategy instead of consuming its own power and the QoS requirement of U2 can be satisfied by the direct link form S to U2 with increase of transmit power so that U2 avoids resorting to U1. Finally, the OMA with SWIPT strategy yields the worst performance among all the considered transmission strategies. It proves the advantage of NOMA in improving system spectrum efficiency.

Fig.3 compares the data rate of U1 with respect to target SINR of U2 for some transmission strategies with P_s = 30 dBm and P_s = 35 dBm respectively. As displayed, the curves of all transmission strategies decreases with the target SINR of U2.The reason is that S distributes more power to U2 so as to meet the requirement of U2, which directly results in decrease of power allocated to U1. Note that the performance gap between the proposed design and the FD cooperative NOMA without SWIPT scheme becomes wider in two different total transmission power cases. This is

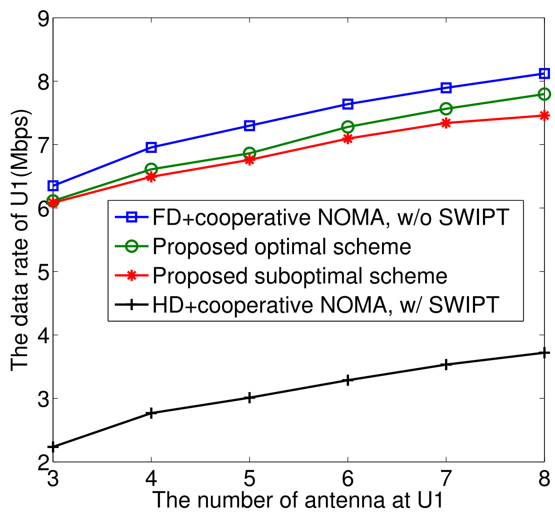

FIGURE 4. Data rate of U1 versus the number of transmit antennas at U1 with $P_s = 30$ dBm and $\gamma_0 = 1$.

because U1 allocates more received signals for energy harvesting to help U2, which indicates cooperative transmission of U1 is essential in reception reliability of U2.

Fig.4 presents the impact of the number of U1's received antennas on the data rate of U1 for three transmission schemes with $P_s = 30$ dBm and $\gamma_0 = 1$. In Fig.4, the data rate of U1 for all strategies substantially increases with number of U1's receive antennas, which demonstrates the significant benefit by applying large antenna arrays at U1. In addition, the performance gap gets bigger and bigger with increasing of the number of transmit antenna at U1, which demonstrates the suboptimal scheme prefers small antenna array system.

We show in Fig.5 the feasible probability of transmission algorithms versus the target SINR of U2 with $P_s = 30$ dBm. Herein, the feasibility probability is defined as probability of existing optimal solution among 2000 times simulation. It is observed that the feasible probabilities of the proposed

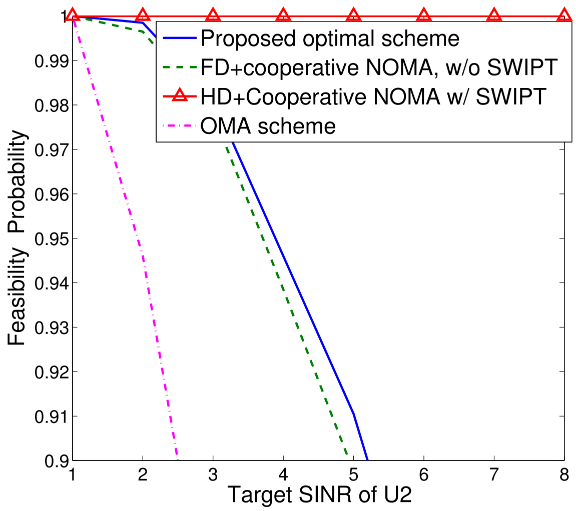

FIGURE 5. Feasible probability versus the target SINR of U2 with $P_s = 30$ dBm.

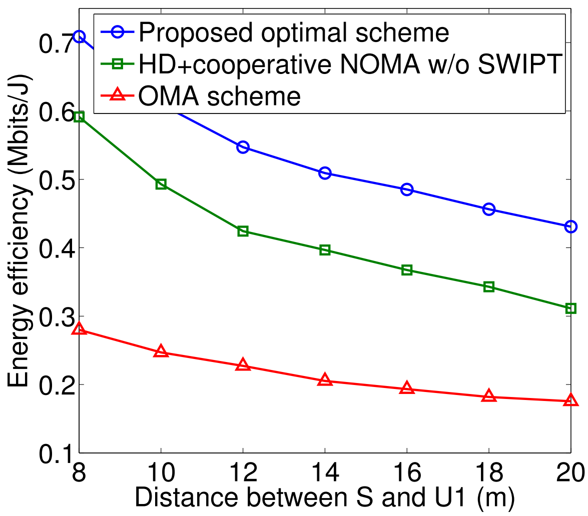

FIGURE 6. The system energy efficiency versus distance between S and U1 with $P_s = 30$ dBm.

scheme at least reaches 90 %, even is 100% when target SINR of U2 is less than 1.5. Besides, as shown in this figure, when the feasible probability is fixed, the proposed scheme supports larger target SINR of U2.

At last, Fig.6 presents the impact of distance between S and U1 on the system energy efficiency. Assume that the distances of S-U2 and U1-U2 is fixed and the constant power consumption is set by 45 dBm. As shown, the system energy efficiency of all schemes decrease with distance between S and U1. Moreover, the proposed optimal scheme is superior to other strategies towards energy efficiency. Due to that FD mode avoids delay, thus the proposed FD NOMA scheme outperforms the HD one.

V. CONCLUSION

In this paper, we have proposed a novel protocol for a SWIPT-aided cooperative NOMA system where power splitter and FD technique are employed at the near NOMA user. To maximize data rate of relay user, we formulated the joint optimization of the power allocation factor, the PS ratio, the receiver filter and the transmit beamforming. We have proposed AO-based scheme to solve the optimal solutions. In addition, we also proposed a low complexity suboptimal scheme. Simulation results indicated the performance gain of the proposed scheme.

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