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Transmit Power Optimization of Simultaneous Transmission and Reflection RIS Assisted Full-Duplex Communications

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ABSTRACT Reconfigurable intelligent surface (RIS) has been proven to be a promising technology for improving the performance of future wireless systems. However, since conventional RIS can only reflect or transmit (i.e., refract) incident signals, it limits the applications of RISs. Fortunately, a novel simultaneous transmission and reflection reconfigurable intelligent surface (STAR-RIS) is proposed to improve the convenience of communication. By altering the electromagnetic properties of the STAR-RIS elements with a smart controller, it can split the incident signal into transmission and reflection signals, achieving 360° coverage. This work demonstrates the effectiveness of STAR-RIS aided full-duplex (FD) communication system, where a FD base station (BS) communicates with an uplink (UL) user and a downlink (DL) user simultaneously over the same time-frequency dimension assisted by a STAR-RIS. The objective is to minimize the total transmit power subject to the given minimal data rate requirement. We decouple the original problem into power optimization and STAR-RIS passive beamforming subproblems and adopt the alternating optimization (AO) framework to solve them iteratively. Specifically, in each iteration, we derive the closed-form expression for the optimal power design, then use the successive convex approximation (SCA) method and semidefinite program (SDP) to solve the passive beamforming optimization subproblem. Simulation results verify the convergence and effectiveness of the proposed algorithm and further reveal the performance gain compared with the half-duplex (HD) and conventional RIS.

INDEX TERMS Simultaneously transmission and reflection reconfigurable intelligent surface, full-duplex, beamforming design, power optimization.

I. INTRODUCTION

Recently, reconfigurable intelligent surface (RIS) has gained in popularity because of its potential to improve the wireless network performance [1]. RIS is equipped with a large number of passive reflecting elements, which can dynamically change the wireless channels by adjusting the phase shifts and/or amplitude [2]. There have been extensive industrial and academic investigations of RIS. The RIS has been studied to promote data rate [3], [4], save transmit power [5], [6], improve energy efficiency [7], [8], and enhance energy detection [9]–[11]. The RIS-assisted mmWave and Terahertz wireless communication systems were analyzed in [12]–[14]. The robust beamforming schemes under the imperfect channel state information were investigated in [15]–[17]. Some AI-empowered methods for optimizing the phase shifts of RIS were also proposed in [18], [19].

Considering the conventional RIS can either reflect or transmit (i.e., refract) signals, to improve the adaptability of various communication scenarios, some new types of RIS have been investigated. For one thing, an intelligent omni-surface was proposed in [20], [21], which engineers its reflective and refractive properties to achieve full-dimensional communications. For another, equipping RIS with extra magnetization currents, a novel technique called simultaneous transmission and reflection reconfigurable intelligent surface (STAR-RIS) was also proposed in [22], [23].

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By altering the electromagnetic properties of the STAR-RIS elements with a smart controller, it can split the incident signal into the transmission (T) region and the reflection (R) region, achieving 360° coverage. The main advantages of STAR-RIS can be summarized as follows:

- It has the capability of simultaneously transmitting and reflecting the incident signals. Therefore, the coverage of STAR-RISs is extended to the entire space.
- The power ratio of the reflected and transmitted signals of every element in the STAR-RIS can be designed dynamically. Unlike simply integrating the reflecting-only and transmitting-only RISs, each element of STAR-RIS has another degree of freedom to be optimized.
- Since STAR-RISs are generally designed to be optically transparent, they are aesthetically pleasing and readily compatible with existing building structures, such as windows [24].

Some literatures have studied the effectiveness of STAR-RIS. A channel estimation method was proposed in STAR-RIS aided wireless communication system in [25]. The STAR-RIS-assisted non-orthogonal multiple access networks were studied in [26]–[28]. To maximize the energy efficiency problem for STAR-RIS assisted network, a deep reinforcement learning method was proposed in [29]. The author in [30] investigated the weighted sum secrecy rate in a STAR-RIS aided network.

On the other hand, full-duplex (FD) communication has been studied to boost the spectral efficiency of wireless systems [31], [32]. FD technology enables signal transmission and reception over the same time-frequency dimension and thus doubles the spectral efficiency theoretically compared with half-duplex (HD). Nevertheless, FD systems would suffer from strong self-interference (SI) signals. Fortunately, a number of SI cancellation methods can suppress the SI power to the noise floor, which promote the FD-based applications [33].

The effectiveness of combining FD and conventional RIS has been demonstrated in some literature [34]–[37], thus the combination of FD and STAR-RIS is also advantageous considering it can boost the spectral efficiency and broaden the communication range at the same time. However, the STAR-RIS aided FD system faces extra challenges, considering the uplink (UL) signals can be transmitted through the STAR-RIS and causes interference to downlink (DL) user on the other side. Thus, the transmission and reflection (T&R) coefficients of the STAR-RIS should be properly designed to aid the UL and DL communications while suppressing the interference at the same time, which is still challenging.

This work is motivated by the aforementioned issue and study the transmit power optimization problem of the STAR-RIS aided FD communication system, where an UL user and a DL user locate on the opposite sides of the STAR-RIS. The main contributions are summarized as follows:

- We formulate the transmit power minimization problem, subject to the minimum data rate demands of the UL and the DL, together with the transmission and reflection (T&R) coefficients constraint of the STAR-RIS. To the best of our knowledge, this is the first work that investigates the transmit power minimization problem in the STAR-RIS aided FD communication system.
- We decouple the non-convex problem into power optimization and passive beamforming subproblems and use the alternative optimization (AO) framework to solve them iteratively. To reduce the computational complexity, we derive the closed-form optimal power solution for the power optimization subproblem in every iteration.
- Due to the particularity of the combination of STAR-RIS and FD communication, conventional random-phase initialization would not be applicable. Therefore, we propose an orthogonal interference transmission method (OITM) to set the initial T&R coefficients for the STAR-RIS.
- To reveal the effectiveness of our proposed method in STAR-RIS aided FD communication system, we compare the system performance with conventional RIS scenario and HD communication scenario. Simulation results show that STAR-RIS aided FD system outperforms STAR-RIS aided HD system and conventional RIS aided FD system in terms of transmit power.

The rest of this paper is organized as follows. Section II introduces the mechanism of STAR-RIS and establishes the system model, then formulates the objective problem. In Section III, we decouple the problem into power optimization and STAR-RIS passive beamforming design subproblems and adopt the AO method to solve them iteratively. We also propose an orthogonal interference transmission method (OITM) to initialize the T&R coefficients of the STAR-RIS. In Section IV we summarize our proposed algorithm and prove the convergence, then we analyze the algorithm complexity. Section V demonstrates the simulation results. Finally, Section VI concludes the paper.

Notation: $|x|$ and $\|x\|_2$ denote the absolution value of a scalar x and Euclidean norm of a column vector x. $\mathrm{Tr}(\mathbf{X})$, $\mathbf{X}^T$, $\mathbf{X}^H$, $\lambda(\mathbf{X})$, and $\mathrm{rank}(\mathbf{X})$ denote the trace, transpose, conjugate transpose, maximum eigenvalue, and rank of matrix $\mathbf{X}$, respectively. $[\mathbf{x}]_m$ is the (m)-th element of vector $\mathbf{x}$. $\mathrm{Diag}(\mathbf{x})$ is a diagonal matrix with the entries of $\mathbf{x}$ on its main diagonal. $\mathrm{diag}(\mathbf{X})$ denotes a vector whose elements are the corresponding ones on the main diagonal of $\mathbf{X}$. $\mathbf{X} \succeq 0$ denotes that matrix $\mathbf{X}$ is positive semidefinite. $\mathbb{C}^{m\times n}$ denotes the space of $m \times n$ complex matrices. $\mathrm{Re}\,(x)$ represents the real part of the complex number x. The letter j is used to represent $\sqrt{-1}$ when there is no ambiguity.

II. SYSTEM MODEL

A. STAR-RIS DESCRIPTION

The mechanism of STAR-RIS is depicted in Fig. 1. The STAR-RIS is a new type of RIS which is transparent for wireless signals at their operating frequency [23]. The STAR-RIS support both electric polarization currents and magnetization

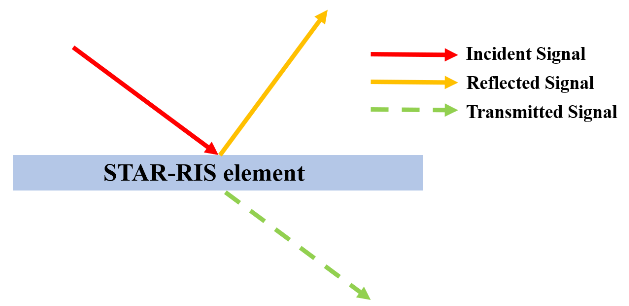

FIGURE 1. STAR-RIS operating mechanism.

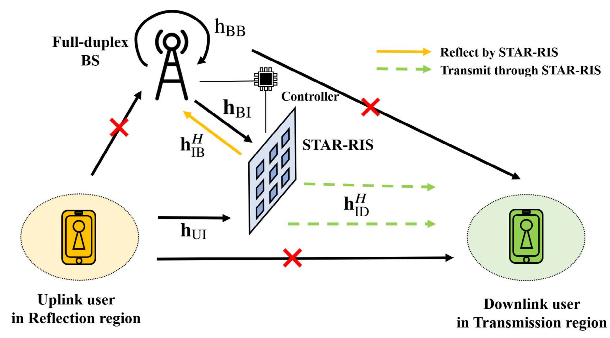

FIGURE 2. A STAR-RIS assisted FD communication system.

currents. When the signals impinge on the elements of STAR-RIS, the electric polarization currents shift the phase of the signals and produce the reflected signals, while the magnetization currents produce the transmitted signals. Therefore, the incident signals can be reflected and transmitted simultaneously by STAR-RIS, which makes STAR-RIS distinct from conventional RIS. We assume the STAR-RIS adopts the energy splitting (ES) protocol [22], where all elements can simultaneously transmit and reflect signals.

Assuming the total number of STAR-RIS transmission and reflection (T&R) elements is M. Let s_m denote the signal incident on the m-th element, where $m \in \{1, 2, \ldots, M\}$. The transmitted signal through the STAR-RIS can be denoted as

$$t_m = \sqrt{\beta_m^t} e^{j\phi_m^t} s_m, \tag{1}$$

and the signal reflected by the STAR-RIS and be expressed as

$$r_m = \sqrt{\beta_m^r} e^{j\phi_m^r} s_m, \tag{2}$$

where $\phi_m^t \in [0, 2\pi)$ and $\phi_m^r \in [0, 2\pi)$ are the phase responses of the m-th element's T&R coefficients. We assume an ideal STAR-RIS with adjustable surface electric and magnetic impedance is deployed in the system, thus ϕ_m^t and ϕ_m^r can be tuned independently [26]. $\sqrt{\beta_m^t} \in [0, 1]$ and $\sqrt{\beta_m^r} \in [0, 1]$ denote the amplitude responses of the m-th element's T&R coefficients. To obey the law of energy conservation [26], we restrict that

$$\beta_m^t + \beta_m^r = 1. \tag{3}$$

The transmitting coefficient vectors of the whole STAR-RIS can be expressed as

$$\mathbf{q}_t = (\sqrt{\beta_1^t} e^{j\phi_1^t}, \ldots, \sqrt{\beta_M^t} e^{j\phi_M^t})^H, \tag{4}$$

and the reflecting coefficient vectors can be expressed as

$$\mathbf{q}_r = (\sqrt{\beta_1^r} e^{j\phi_1^r}, \ldots, \sqrt{\beta_M^r} e^{j\phi_M^r})^H. \tag{5}$$

B. SYSTEM MODEL DESCRIPTION

Consider a FD system consisting of a BS, a STAR-RIS, an UL user and a DL user, as depicted in Fig. 2. For the purpose of showing the coverage extension advantage of STAR-RIS, we assume that there is no direct link between the users and the BS and the link between the two users is blocked because of deep fading or heavy shadowing [38]–[40]. The BS is equipped with a single transmit antenna and a single receive antenna, which operates in the FD mode. The UL and DL users are both equipped with a single antenna and operate in the HD mode.[1]

Denote $\mathbf{h}_{\mathrm{UI}} \in \mathbb{C}^{M\times 1}$, $\mathbf{h}_{\mathrm{IB}}^H \in \mathbb{C}^{1\times M}$, $\mathbf{h}_{\mathrm{BI}} \in \mathbb{C}^{M\times 1}$, $\mathbf{h}_{\mathrm{ID}}^H \in \mathbb{C}^{1\times M}$, $h_{\mathrm{BB}} \in \mathbb{C}$ as the channel between the UL user and the STAR-RIS, between the STAR-RIS and the BS, between the BS and the STAR-RIS, between the STAR-RIS and the DL user and SI channel of the BS respectively. In addition, we assume that the channel state information (CSI) of each link as well as the T&R coefficients of STAR-RIS is perfectly known by each source (CSI estimation methods have been proposed in [41]–[43]), then the reflect SI from STAR-RIS to BS can be reasonably canceled [44], thus it is ignored in the following formulations.

Let us denote x_U and x_D as the independent data symbol with normalized power of UL and DL. $\sqrt{p_U}$ and $\sqrt{p_D}$ are transmit power of UL user and BS. Thus, the signal received at the BS can be expressed as

$$y_U = \mathbf{h}_{\mathrm{IB}}^H \mathbf{\Phi}_r \mathbf{h}_{\mathrm{UI}} \sqrt{p_U} x_U + \underbrace{h_{\mathrm{BB}} \sqrt{p_D} x_D}_{\text{SI at the BS}} + n_U, \tag{6}$$

where $\Phi_r = \mathrm{Diag}(\mathbf{q}_r^H)$, and $n_U \sim \mathcal{CN}(0, \sigma_U^2)$ is the additive white Gaussian noise (AWGN) at the BS. The received signal at the DL user can be expressed as

$$y_D = \mathbf{h}_{\mathrm{ID}}^H \mathbf{\Phi}_t \mathbf{h}_{\mathrm{BI}} \sqrt{p_D} x_D + \underbrace{\mathbf{h}_{\mathrm{ID}}^H \mathbf{\Phi}_t \mathbf{h}_{\mathrm{UI}} \sqrt{p_U} x_U}_{\text{interference from the UL user}} + n_D, \tag{7}$$

where $\Phi_t = \mathrm{Diag}(\mathbf{q}_t^H)$, and $n_D \sim \mathcal{CN}(0, \sigma_U^2)$ is the AWGN at the DL user.

Therefore, the achievable data rate in bits second per Hertz (bps/Hz) of the UL and the DL can be formulated as

$$R_U = \log_2\left(1 + \frac{p_U \left|\mathbf{h}_{\mathrm{IB}}^H \mathbf{\Phi}_r \mathbf{h}_{\mathrm{UI}}\right|^2}{p_D |h_{\mathrm{BB}}|^2 + \sigma_U^2}\right), \tag{8}$$

[1] Similar to [34]–[36], to focus on our study, we consider a typical single-antenna two-user FD system; while the results in this paper can be extended to the general setup of multi-antenna and/or multi-user FD systems, which are left for future work.

and

$$R_D = \log_2\left(1 + \frac{p_D\left|\mathbf{h}_{\mathrm{ID}}^H \boldsymbol{\Phi}_t \mathbf{h}_{\mathrm{BI}}\right|^2}{p_U\left|\mathbf{h}_{\mathrm{ID}}^H \boldsymbol{\Phi}_t \mathbf{h}_{\mathrm{UI}}\right|^2 + \sigma_D^2}\right). \tag{9}$$

C. PROBLEM FORMULATION

In this paper, we target to minimize the total transmit power by jointly designing the transmit power of the UL and the DL, together with optimizing the passive beamforming at the STAR-RIS. Besides, our design is within the constraints of the minimum data rate demands and STAR-IRS's T&R elements feasible set.

Mathematically, the optimization problem is derived as

$$\mathcal{P}1: \min_{p_U, p_D, \mathbf{q}_t, \mathbf{q}_r} p_U + p_D \tag{10a}$$
$$\text{s.t. } R_U \geqslant R_U^{\text{th}}, \tag{10b}$$
$$R_D \geqslant R_D^{\text{th}}, \tag{10c}$$
$$\left[\mathbf{q}_t^H\right]_m = \sqrt{\beta_m^t} e^{j\phi_m^t}, \phi_m^t \in [0, 2\pi), \quad \forall m \in \mathcal{M}, \tag{10d}$$
$$\left[\mathbf{q}_r^H\right]_m = \sqrt{\beta_m^r} e^{j\phi_m^r}, \phi_m^r \in [0, 2\pi), \quad \forall m \in \mathcal{M}, \tag{10e}$$
$$\left[\boldsymbol{\beta}^t\right]_m \in [0, 1], \quad \forall m \in \mathcal{M}, \tag{10f}$$
$$\left[\boldsymbol{\beta}^r\right]_m \in [0, 1], \quad \forall m \in \mathcal{M}, \tag{10g}$$
$$\left[\boldsymbol{\beta}^t\right]_m + \left[\boldsymbol{\beta}^r\right]_m = 1, \quad \forall m \in \mathcal{M}, \tag{10h}$$

where R_U^{th} and R_D^{th} denote the minimum data rate requirements of the UL and the DL. (10d)-(10h) are the coefficients constraints of STAR-RIS.

The optimization problem $\mathcal{P}1$ is non-trivial considering the non-convex data rate requirements. In addition, the transmit power and STAR-RIS's passive beamforming vectors are highly coupled, which also makes the optimization intractable.

III. TRANSMIT POWER MINIMIZATION ALGORITHM DESIGN

In this section, we decouple the problem $\mathcal{P}1$ into power optimization and STAR-RIS passive beamforming design subproblems and adopt the AO method to solve them iteratively.

A. POWER OPTIMIZATION WITH GIVEN T&R COEFFICIENT VECTORS

We define $\mathbf{h}_1 = \mathrm{Diag}(\mathbf{h}_{\mathrm{IB}}^H)\mathbf{h}_{\mathrm{UI}}$, $\mathbf{h}_2 = \mathrm{Diag}(\mathbf{h}_{\mathrm{ID}}^H)\mathbf{h}_{\mathrm{BI}}$, $\mathbf{h}_3 = \mathrm{Diag}(\mathbf{h}_{\mathrm{ID}}^H)\mathbf{h}_{\mathrm{UI}}$ and $\mathbf{H}_1 = \mathbf{h}_1\mathbf{h}_1^H$, $\mathbf{H}_2 = \mathbf{h}_2\mathbf{h}_2^H$, $\mathbf{H}_3 = \mathbf{h}_3\mathbf{h}_3^H$. To facilitate formulation, we define $\mathbf{Q}_t = \mathbf{q}_t\mathbf{q}_t^H$ and $\mathbf{Q}_r = \mathbf{q}_r\mathbf{q}_r^H$.

Therefore, with given $\mathbf{q}_t$ and $\mathbf{q}_r$, the original problem $\mathcal{P}1$ can be transformed into a power optimization subproblem as follows

$$\mathcal{P}2: \min_{p_U, p_D} p_U + p_D \tag{11a}$$
$$\text{s.t. } p_U \mathrm{Tr}\left(\mathbf{Q}_r\mathbf{H}_1\right) \geqslant R_U^{\text{TH}}\left(p_D|h_{\mathrm{BB}}|^2 + \sigma_U^2\right), \tag{11b}$$
$$p_D \mathrm{Tr}\left(\mathbf{Q}_t\mathbf{H}_2\right) \geqslant R_D^{\text{TH}}\left(p_U \mathrm{Tr}\left(\mathbf{Q}_t\mathbf{H}_3\right) + \sigma_D^2\right), \tag{11c}$$

where $R_U^{\text{TH}} = 2^{R_U^{\text{th}}} - 1$ and $R_D^{\text{TH}} = 2^{R_D^{\text{th}}} - 1$.

Since the objective function (11a) is convex w.r.t. p_U and p_D, and the constraints (11b) − (11c) are convex, problem $\mathcal{P}2$ constitutes a convex optimization problem, which can be solved by standard convex solver packages, such as CVX [45]. However, the resultant computational complexity is high. In the following proposition, we derive the closed-form expression for the optimal power design.

Theorem 1: Minimal transmit power can be obtained if and only if the UL and DL transmit signals at the minimal data rate requirement.

Proof: If the UL and DL transmit signals at the minimal rate requirement, then according to (11b) and (11c), the DL transmit power can be expressed as

$$\bar{p}_D = \frac{R_D^{\text{TH}}\left[R_U^{\text{TH}}\sigma_U^2 \mathrm{Tr}\left(\mathbf{Q}_t\mathbf{H}_3\right) + \mathrm{Tr}\left(\mathbf{Q}_r\mathbf{H}_1\right)\sigma_D^2\right]}{\mathrm{Tr}\left(\mathbf{Q}_t\mathbf{H}_2\right)\mathrm{Tr}\left(\mathbf{Q}_r\mathbf{H}_1\right) - R_D^{\text{TH}}R_U^{\text{TH}}|h_{\mathrm{BB}}|^2\mathrm{Tr}\left(\mathbf{Q}_t\mathbf{H}_3\right)}, \tag{12}$$

and $\bar{p}_U$ can further be expressed as

$$\bar{p}_U = \frac{R_U^{\text{TH}}\left[\bar{p}_D|h_{\mathrm{BB}}|^2 + \sigma_U^2\right]}{\mathrm{Tr}\left(\mathbf{Q}_r\mathbf{H}_1\right)}. \tag{13}$$

According to the proof by contradiction, we assume that the minimal power is obtained under the condition that the transmit data rate is higher than the threshold, which can be expressed as $\tilde{R}_U > R_U^{\text{TH}}$ and $\tilde{R}_D > R_D^{\text{TH}}$. Thus, according to (11b) and (11c), we can get the following conclusions:

$$\tilde{p}_U > \bar{p}_U, \tag{14}$$
$$\tilde{p}_D > \bar{p}_D, \tag{15}$$

which are contradictory to the minimal power assumption. Thus, we conclude that minimal transmit power can be obtained if and only if the UL and DL transmit signals at the minimal data rate demands. ■

B. PASSIVE BEAMFORMING OPTIMIZATION WITH GIVEN POWER DESIGN

With given power design p_D and p_U, the STAR-RIS passive beamforming design subproblem is a feasibility check problem, which can be written as follows

$$\mathcal{P}3: \min_{\mathbf{Q}_t, \mathbf{Q}_r, \boldsymbol{\beta}_t, \boldsymbol{\beta}_r} C_0 \tag{16a}$$
$$\text{s.t. } \mathrm{Rank}\left(\mathbf{Q}_t\right) = 1, \tag{16b}$$
$$\mathrm{Rank}\left(\mathbf{Q}_r\right) = 1, \tag{16c}$$
$$\mathrm{diag}(\mathbf{Q}_t) = \boldsymbol{\beta}_t, \tag{16d}$$
$$\mathrm{diag}(\mathbf{Q}_r) = \boldsymbol{\beta}_r, \tag{16e}$$
$$\mathbf{Q}_t \succeq 0, \tag{16f}$$
$$\mathbf{Q}_r \succeq 0, \tag{16g}$$
$$(10f) - (10h), (11b) - (11c), \tag{16h}$$

where C_0 denotes any constant number. $\boldsymbol{\beta}_t = [\beta_1^t, \ldots, \beta_M^t]^T$ and $\boldsymbol{\beta}_r = [\beta_1^r, \ldots, \beta_M^r]^T$.

Problem $\mathcal{P}3$ is non-convex because of the rank-one constraint. Conventionally, we can use the semidefinite relaxation (SDR) method to drop the rank-one constraint and adopt gaussian randomization approach to obtain $\mathbf{q}_t^*$ ($\mathbf{q}_r^*$). However, after relaxing the rank-one constraint, the solutions are not guaranteed to meet the data rate constraints. Hence, we develop a more efficient algorithm to find an optimal rank-one solution based on the SCA method.

Based on Proposition 3 in [46], the rank-one constraints (16b) and (16c) are satisfied when neither $\mathbf{Q}_t^*$ nor $\mathbf{Q}_r^*$ has more than one non-zero eigenvalue. Thus, the rank-one constraint can be transformed as

$$\mathrm{Tr}\left(\mathbf{Q}_l\right) - \lambda\left(\mathbf{Q}_l\right) = 0, \tag{17}$$

where $l \in \{t, r\}$ represents any of the transmitting or reflecting modes. We define $f\left(\mathbf{Q}_l\right) = \mathrm{Tr}\left(\mathbf{Q}_l\right) - \lambda\left(\mathbf{Q}_l\right)$. Therefore, we can rewrite problem $\mathcal{P}3$ as

$$\mathcal{P}4: \min_{\mathbf{Q}_t,\mathbf{Q}_r,\boldsymbol{\beta}_t,\boldsymbol{\beta}_r} f\left(\mathbf{Q}_t\right) + f\left(\mathbf{Q}_r\right) \tag{18a}$$

$$\text{s.t. } (16\text{d}) - (16\text{h}). \tag{18b}$$

In order to ensure the convergence of the SCA algorithm, we further rewrite $f\left(\mathbf{Q}_l\right)$ as

$$f\left(\mathbf{Q}_l\right) = \mathrm{Tr}\left(\mathbf{Q}_l\right) + \frac{\rho}{2}\left\|\mathbf{Q}_l\right\|_F^2 - \left(\lambda\left(\mathbf{Q}_l\right) + \frac{\rho}{2}\left\|\mathbf{Q}_l\right\|_F^2\right), \tag{19}$$

where $\frac{\rho}{2}\left\|\mathbf{Q}_l\right\|_F^2$ is the quadratic term which makes the objective function $f\left(\mathbf{Q}_l\right)$ to be the difference of two ρ-strongly convex functions.

We define $g\left(\mathbf{Q}_l\right) = \left(\lambda\left(\mathbf{Q}_l\right) + \frac{\rho}{2}\left\|\mathbf{Q}_l\right\|_F^2\right)$, thus its first-order approximation at the feasible point $\mathbf{Q}_l^{(k-1)}$ can be given by

$$g\left(\mathbf{Q}_l\right) \geqslant g\left(\mathbf{Q}_l^{(k-1)}\right) + \mathrm{Tr}\left\{\mathrm{Re}\left[\partial_{\mathbf{Q}_l^{(k-1)}}^H g\left(\mathbf{Q}_l\right)\left(\mathbf{Q}_l - \mathbf{Q}_l^{(k-1)}\right)\right]\right\}, \tag{20}$$

where $\partial_{\mathbf{Q}_l^{(k-1)}} g\left(\mathbf{Q}_l\right)$ is the subgradient of $g\left(\mathbf{Q}_l\right)$ at $\mathbf{Q}_l^{(k-1)}$, which can be expressed as

$$\partial_{\mathbf{Q}_l^{(k-1)}} g\left(\mathbf{Q}_l\right) = \boldsymbol{\alpha}\left(\mathbf{Q}_l^{(k-1)}\right)\boldsymbol{\alpha}\left(\mathbf{Q}_l^{(k-1)}\right)^H + \rho\mathbf{Q}_l^{(k-1)}, \tag{21}$$

where the $\boldsymbol{\alpha}\left(\mathrm{Q}_l^{(k-1)}\right)$ is the corresponding eigenvector of the largest eigenvalue.

Hence, by adopting SCA method, the solution $\mathbf{Q}_t$ and $\mathbf{Q}_r$ at the k-th iteration can be obtained by solving the following problem

$$\mathcal{P}4': \min_{\mathbf{Q}_t,\mathbf{Q}_r,\boldsymbol{\beta}_t,\boldsymbol{\beta}_r} \sum_l \mathrm{Tr}\left(\mathbf{Q}_l\right) + \frac{\rho}{2}\left\|\mathbf{Q}_l\right\|_F^2 - \mathrm{Tr}\left\{\mathrm{Re}\left[\partial_{\mathbf{Q}_l^{(k-1)}}^H g\left(\mathbf{Q}_l\right)\mathbf{Q}_l\right]\right\} \tag{22a}$$

$$\text{s.t. } (16\text{d}) - (16\text{h}). \tag{22b}$$

Problem $\mathcal{P}4'$ is a standard SDP that can be solved by CVX [45]. If the object function iteratively decreases and is eventually below a given threshold ε, then we consider our proposed method succeeds in finding an optimal rank-one solution. Finally, we can get the optimal $\mathbf{q}_t^*$ and $\mathbf{q}_r^*$ by eigenvalue decomposition.

C. ORTHOGONAL INTERFERENCE TRANSMISSION METHOD (OITM)

Due to the particularity of the combination of STAR-RIS and FD communication, conventional random-phase initialization would not be applicable. Therefore, we propose an OITM to set the initial T&R coefficients for the STAR-RIS.

We observe that when $\mathrm{Tr}\left(\mathbf{Q}_t\mathbf{H}_3\right) = 0$, we can set proper initial values for p_D and p_U according to (12) and (13). Therefore, the phase shifts of transmitting elements $\mathbf{q}_t$ should be orthogonal to the interference channel $\mathbf{h}_3$. The orthogonal complement projector of $\mathbf{h}_3$ can be given as

$$\mathbf{P}_A^{\perp} = \mathbf{I}_M - \mathbf{h}_3\mathbf{h}_3^H / \left\|\mathbf{h}_3\right\|_2^2, \tag{23}$$

where $\mathbf{I}$ represents the identity matrix.

Therefore, by generating one unit-modulus vector $\mathbf{x} \in \mathbb{C}^{M\times 1}$, we can obtain the transmitting coefficient vector as

$$\mathbf{q}_t^{(0)} = \frac{\mathbf{y}}{\max\limits_m \mathbf{y}_m} = \frac{\left(\mathbf{I}_M - \mathbf{h}_3\mathbf{h}_3^H / \left\|\mathbf{h}_3\right\|_2^2\right)\mathbf{x}}{\max\limits_m \left[\left(\mathbf{I}_M - \mathbf{h}_3\mathbf{h}_3^H / \left\|\mathbf{h}_3\right\|_2^2\right)\mathbf{x}\right]_m}, \tag{24}$$

where $m \in \{1, \ldots, M\}$.

Hence, the phase shift of $\mathbf{q}_r$ can be initialized randomly and its element amplitude can be set as

$$\left|\left[\mathbf{q}_r^{(0)}\right]_m\right| = 1 - \left|\left[\mathbf{q}_t^{(0)}\right]_m\right|. \tag{25}$$

In this way, we get the initial T&R coefficient vectors.

IV. OVERALL ALGORITHM AND ANALYSIS

Our proposed algorithm is summarized in Algorithm 1. ε_1 and ε_2 are small thresholds, while N and K represent the maximum numbers of iterations.

A. CONVERGENCE ANALYSIS

Theorem 2: Algorithm 1 yields a convergent solution.

Proof: Without loss of generality, we suppose that $P(p^{(n)}, \mathbf{q}^{(n)})$ is the total transmit power with given power design $p^{(n)} = \left(p_U^{(n)}, p_D^{(n)}\right)$ and passive STAR-RIS beamforming vectors $\mathbf{q}^{(n)} = \left(\mathbf{q}_t^{(n)}, \mathbf{q}_r^{(n)}\right)$ at the n-th iteration. Thus, we have the following formulation

$$P(p^{(n)}, \mathbf{q}^{(n)}) \overset{(a)}{\geqslant} P(p^{(n+1)}, \mathbf{q}^{(n)}) \overset{(b)}{=} P(p^{(n+1)}, \mathbf{q}^{(n+1)}), \tag{26}$$

where (a) holds because problem $\mathcal{P}2$ is convex and the power design $P^{(n+1)} = p_U^{(n+1)} + p_D^{(n+1)}$ is optimal, which is updated at $(n+1)$-th iteration with the passive beamforming $\mathbf{q}^{(n)}$. However, the updated passive beamforming $\mathbf{q}^{(n+1)}$ does not change the power design of $p^{(n+1)}$ at $(n+1)$-th iteration, thus (b) also holds.

Algorithm 1 Alternating Optimization Algorithm for $\mathcal{P}1$

1: **Initialization:** Set iteration index $n = 1$, initialize $\mathbf{q}_t^{(0)}$ based on (24) and $\mathbf{q}_r^{(0)}$ based on (25).
2: **repeat**
3: Solve problem $\mathcal{P}2$ to get $p_U^{(n)}$ and $p_D^{(n)}$ with given $\mathbf{q}_t^{(n-1)}$ and $\mathbf{q}_r^{(n-1)}$ according to (12) and (13);
4: Set $k = 0$;
5: **while** $\mathrm{Tr}\left(\mathbf{Q}_t^k\right) - \lambda\left(\mathbf{Q}_t^k\right) + \mathrm{Tr}\left(\mathbf{Q}_r^k\right) - \lambda\left(\mathbf{Q}_r^k\right) \geq \varepsilon_1$ and $k \leq K$ **do**
6: Solve $\mathcal{P}4'$ to update $\mathbf{Q}_t^{(k+1)}$ and $\mathbf{Q}_r^{(k+1)}$ with given $p_U^{(n)}$ and $p_D^{(n)}$;
7: Update $k = k + 1$;
8: **end while**
9: Update $\mathbf{q}_t^{(n)}$ and $\mathbf{q}_t^{(n)}$ by eigenvalue decomposition;
10: Calculate $P^{(n)} = p_U^{(n)} + p_D^{(n)}$;
11: Update $n = n + 1$;
12: **until** $(P^{(n-1)} - P^{(n)})/P^{(n-1)} \leq \varepsilon_2$ or $n \geq N$.
13: **Output:** power design and passive beamforming vectors.

Because of the limited resource in the system and minimal data rate requirement, we suppose that the objective function of the original problem $\mathcal{P}1$ must be lower bounded by a finite value. Thus, our proposed Algorithm 1 is proven to converge to a feasible solution. ■

B. COMPLEXITY ANALYSIS

The complexity of the proposed algorithm is dominated by solving SDP $\mathcal{P}4'$, for which the complexity is $O\left(M^4\right)$. According to [47], the overall complexity is $O\left(I_1 I_2 M^4\right)$, where I_1 and I_2 are the iteration numbers of AO algorithm and SCA algorithm, respectively.

V. SIMULATION RESULTS

This section provides simulation results to verify the performance of our proposed algorithm. We assume that the locations of BS, STAR-RIS, UL user and DL user are (5m, 45m), (0m,50m), (0m, 35m) and (0m, 100m). We set $\sigma_U^2 = \sigma_D^2 = -80$dBm. The large-scale fading is modelled by $PL\left(d\right) = PL_0(d/d_0)^{-\varpi}$, where $PL_0 = -30$dB is the path loss at the reference distance $d_0 = 1$m, d is the distance, and ϖ is the path-loss exponent which is set to 2.2 [22]. We adopt the Rician model for all channels, where the Rician factor is 5dB in SI channel [48] and 3dB for others [22]. The path loss of SI channel is much lower due to SI cancellation, which is set to -100dB by default. We assume R_U^{th} is 1 bps/Hz for all scenarios.

The proposed optimization scheme for the STAR-RIS aided FD system, namely STAR-RIS-FD, is compared to the following benchmark schemes:

- STAR-RIS aided FD system with fixed phase (FIXED-PHASE): In this method, the T&R coefficients are fixed at the solutions obtained by the proposed OITM method. Therefore, this benchmark scheme can be realized by using the proposed Algorithm 1 but removing Step 4-9, in which the phase shifts are not optimized.
- STAR-RIS aided HD system (STAR-RIS-HD): We assume that the UL and DL communication is assigned with an equal time slot. Then the T&R coefficients in different slots are optimized separately.
- Conventional-RIS aided FD system (CON-RIS-FD): We assume one transmitting-only RIS and one reflecting-only RIS are adjacent to each other and deployed at the same coordinate as the STAR-RIS. The operation choice of each element in the conventional RIS is fixed, which is reflecting or transmitting. On the contrary, the element of STAR-RIS can split the incident signal into partially reflected and partially transmitted signal. However, the STAR-RIS operating mechanism is still under energy conservation (3). To some extent, the conventional RIS serves as a special case of STAR-RIS. Thus, for fair comparison in the energy perspective, the total elements number of conventional RIS and STAR-RIS should be set to be equal. We assume there are $M/2$ elements for each transmitting-only and reflecting-only RIS [22]. The UL communication is facilitated by the reflecting-only RIS, while the DL communication depends on the transmitting-only RIS. The system operates in FD mode.

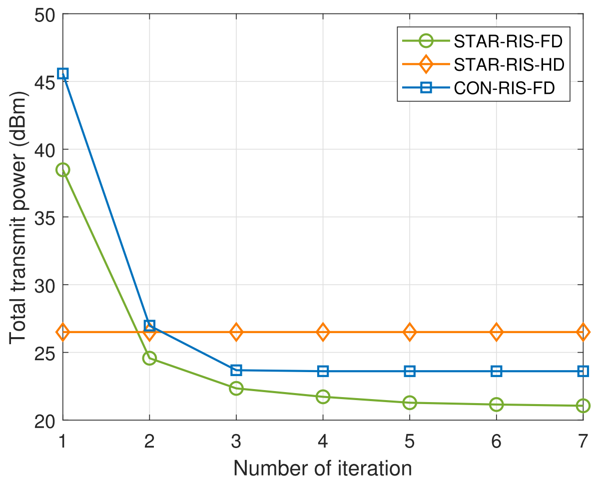

FIGURE 3. Performance of the proposed method versus the number of iterations.

Fig. 3 investigates the convergence of the proposed algorithm, where M is set to 40, R_D^{th} is set to 4 bps/Hz and the path loss of the SI channel at the BS is set to -100dB. Considering the optimal power design of the STAR-RIS-HD scheme can be expressed in closed-form expression, it converges at the first iteration. It can be seen that as the number of iterations continues to increase, the transmit power of STAR-RIS-FD and CON-RIS-FD schemes decreases to convergence.

Fig. 4 shows the transmit power versus the number of STAR-RIS (CON-RIS) elements, where R_D^{th} is set to 4 bps/Hz and the path loss of SI channel at the BS is set to -100dB. The minimal transmit power of all four schemes decreases

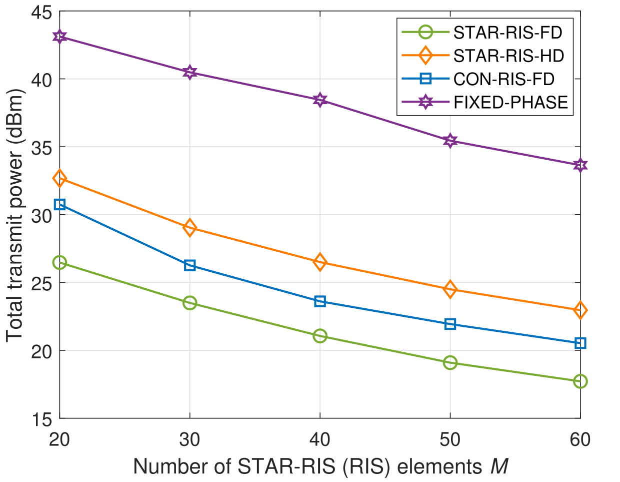

FIGURE 4. **Total transmit power versus the number of STAR-RIS (CON-RIS) elements.**

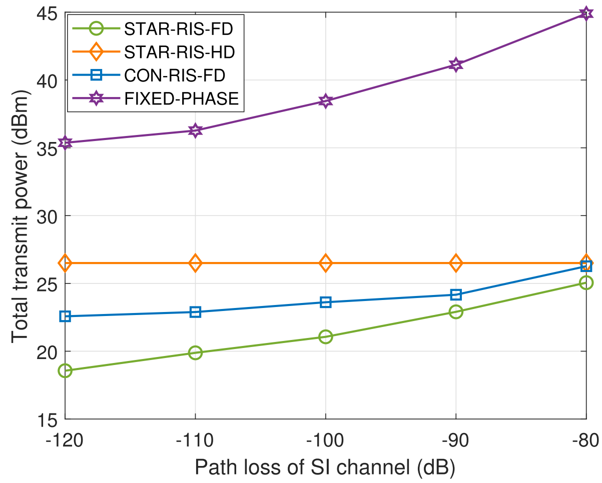

FIGURE 6. **Total transmit power versus the path loss of SI channel.**

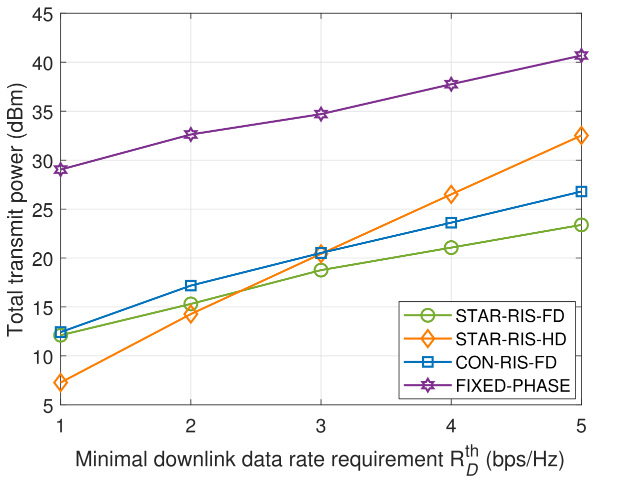

FIGURE 5. **Total transmit power versus DL data rate requirement.**

with the increase of STAR-RIS (CON-RIS) elements. It can be shown from the figure that by carefully optimizing the phase shifts for minimizing the transmit power, our proposed STAR-RIS-FD method significantly outperforms the FIXED-PHASE scheme. We observe that the STAR-RIS-FD scheme also outperforms other benchmarks, the reasons can be explained as follows. Compared to CON-RIS with fixed numbers of T&R elements, STAR-RIS can exploit all degrees-of-freedom (DoFs) to enhance the desired signal strength and mitigate interference. Besides, the element of STAR-RIS can split the incident signal into partially reflected and partially transmitted signal, providing another degree to be optimized. Thus, the STAR-RIS outperforms the CON-RIS. On the other hand, the achievable rate is penalized due to the half communication time in the HD mode. Therefore, under the same data rate requirement in this scenario, the HD system consumes more transmit power compared with FD.

Fig. 5 shows the transmit power versus different DL data rate requirement, where M is set to 40 and the path loss of SI is set to -100dB. It is observed again that the AO algorithm performs better than the FIXED-PHASE scheme. When the DL data rate demand is lower than 3 bps/Hz, the interference from the UL has a greater influence on the DL user than DL transmission from the BS. Therefore, the STAR-RIS uses its full capacity to restrain the DL interference. Interference causes much more deterioration to the FD mode compared with the penalty because of half communication time to the HD mode. However, as the DL data rate demand augments, the signal strength from the BS is much stronger than the interference. Thus, aiding the DL transmission is the STAR-RIS's working priority, which is the same as DL transmission in HD mode. Besides, the half-time penalty to the HD mode increases rapidly with rate demand. Hence, the STAR-RIS in FD mode, even the CON-RIS working at FD mode, requires lower transmit power with higher DL rate demand.

Fig. 6 shows the transmit power versus the path loss of SI at the BS, where M is set to 40, R_D^{th} is set to 4 bps/Hz. The SI intensity has no impact on the STAR-RIS system operating in HD. However, for STAR-RIS and CON-RIS working in the FD mode, the transmit power increases with SI intensity. It can be verified by the mathematical formulation in Proposition 1, where the decrease of $|h_{\text{BB}}|^2$ would cause smaller value of p_D and p_U. The results show the effectiveness of STAR-RIS compared with conventional RIS and further reveal that STAR-RIS assisted FD scheme would outperform HD mode in lower SI scenarios.

VI. CONCLUSION

In this paper, we studied the STAR-RIS aided FD system. We formulated the transmit power minimization problem, subject to the minimum data rate demand of the UL and DL, as well as the constraints of the STAR-RIS coefficient vectors. We divided the optimization problem into power design and passive beamforming design subproblems, and adopted the AO framework to solve them iteratively. The closed-form optimal power design scheme was derived in every iteration.

The SCA method and SDP were used to solve the passive beamforming optimization subproblem. An OITM scheme was also proposed to initialize the transmitting and reflecting coefficients of the STAR-RIS. Simulation results demonstrated the effectiveness of STAR-RIS compared with conventional RIS and further revealed that STAR-RIS assisted FD scheme would outperform HD mode in higher data rate and lower SI scenarios.

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