Simultaneous Transmission and Reflection
Reconfigurable Intelligent Surface Assisted
Full-Duplex Communications

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Abstract—This work demonstrates the effectiveness of a novel simultaneous transmission and reflection reconfigurable intelligent surface (STAR-RIS) in Full-Duplex (FD) aided communication system. The objective is to minimize the total transmit power by jointly designing the transmit power and the transmitting and reflecting (T&R) coefficients of the STAR-RIS. To solve the non-convex problem, an efficient algorithm is proposed by utilizing the alternating optimization framework to iteratively optimize variables. Specifically, in each iteration, we drive the closed-form expression for the optimal power design. The successive convex approximation (SCA) method and semidefinite program (SDP) are used to solve the passive beamforming optimization problem. Numerical results verify the convergence and effectiveness of the proposed algorithm, and further reveal in which scenarios STAR-RIS are used to solve the passive beamforming optimization problem.

Index Terms—Reconfigurable intelligent surface, full-duplex, beamforming design, alternating 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 large number of passive reflecting elements, which can dynamically change the wireless channels by adjusting the phase shifts and/or amplitude[2].

However, since conventional RIS can either reflect or transmit signals, it highly constrains the locations of the transmitter and the receiver. To improve the convenience of communication, a novel technique called simultaneous transmission and reflection reconfigurable intelligent surface (STAR-RIS) was proposed in [3] and [4]. By altering the electromagnetic properties of the STAR-RIS elements with a smart controller, it can split the incident signal into transmission (T) region and the reflection (R) region, achieving 360° coverage. The STAR-RIS assisted non-orthogonal multiple access (NOMA) networks was studied in [5] and outperformed the conventional cooperative communication system. To solve the energy efficiency (EE) maximization problem for NOMA assisted STAR-RIS downlink network, a deep reinforcement learning method was proposed in [6].

The author in [6] also investigated the weighted sum secrecy rate (WSSR) in a STAR-RIS aided MISO network.

Besides, the full-duplex (FD) communication has been studied to boost the spectral efficiency of wireless systems[7, 8]. 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, communications in FD mode would suffer from strong self-interference (SI) signal. Fortunately, a number of SI cancellation methods can suppress the SI power to the noise floor, which promotes the FD-based applications[9].

Motivated by above, this work exploits the potential of the STAR-RIS aided FD communication system, where an uplink (UL) user and a downlink (DL) user locate on the opposite side of the STAR-RIS. To the best of our knowledge, this is the first work that studies the combination of STAR-RIS and FD. The main contributions are summarized as follows:

• We establish a 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 at the STAR-RIS.
• We decouple the non-convex problem into power optimization and passive beamforming subproblems and use the alternative optimization (AO) framework to solve them iteratively, where the closed-form optimal power design scheme is derived in every iteration.
• To make the initial solution feasible for subsequent iterative optimization, we proposed an orthogonal interference transmission method (OITM) to initialize the transmitting coefficients of the STAR-RIS.
• The performance of STAR-RIS assisted FD system is compared with STAR-RIS assisted HD system and conventional-RIS assisted FD system. Simulation results verify the convergence and effectiveness of the proposed algorithm.

Notation: |x| and ||x||_2 denote the absolute value of a scalar x and Euclidean norm of a column vector x. Tr(X), X^T, X^H, λ(X), and rank(X) denote the trace, transpose, conjugate transpose, maximum eigenvalue, and rank of the matrix X, respectively. X ≥ 0 denotes that matrix X is positive semidefinite. [X]_{m,n} is the (m,n)-th element of matrix X and [x]_m is the (m)-th element of vector x. diag(x) is a diagonal matrix with the entries of x on its main diagonal while diag(X) is a vector whose elements are the corresponding ones on the main diagonal of X. Re(x) represents the real part of the complex number x. C^{m×n} denotes the space of m × n complex matrices. I represents an identity matrix and 1 denotes an all-ones vector.
II. SYSTEM MODEL AND PROBLEM FORMULATION

A. STAR-RIS

We let $\mathbf{\beta} = [\beta_1, ..., \beta_M]^T$ and $\mathbf{\beta}_r = [\beta_1', ..., \beta_M']^T$ be the power of STAR-IRS T&R elements response.

Assuming the total number of STAR-IRS T&R elements is $M$. Let $s_m$ denote the signal incident on the $m$-th element of the STAR-RIS, where $m \in \{1, 2, ..., M\}$. The transmitted signal and the reflected signal can be denoted as $t_m = \sqrt{\beta_m} e^{j\phi_m} s_m$ and $r_m = \sqrt{\beta_m'} e^{j\phi_m'} s_m$, where $\sqrt{\beta_m} \in [0, 1]$ and $\sqrt{\beta_m'} \in [0, 1]$ denote the amplitude response of the $m$th element’s transmission and reflection coefficients.

To obey the law of energy conservation, we restrict that $\beta_m + \beta_m' = 1$. $\phi_m \in [0, 2\pi)$ and $\phi_m' \in [0, 2\pi)$ are the phase response of the $m$th element’s transmission and reflection coefficients. We assume an ideal STAR-RIS with adjustable surface electric and magnetic impedance is deployed in the system, thus $\phi_m'$ and $\phi_m$ can be tuned independently.

Therefore, the whole T&R coefficient vectors can be modelled as

$$\mathbf{q}_r = (\sqrt{\beta_1} e^{j\phi_1}, ..., \sqrt{\beta_M} e^{j\phi_M})^T,$$

(1)

and

$$\mathbf{q}_r = (\sqrt{\beta_1'} e^{j\phi_1'}, ..., \sqrt{\beta_M'} e^{j\phi_M'})^T,$$

(2)

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. 1. We assume that there is no direct link between the users and the BS because of deep fading or heavy shadowing, so their communication must rely on the STAR-RIS. The BS is equipped with a single transmit antenna and a 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. We assume the STAR-RIS adopt the energy splitting (ES) protocol, where all elements can simultaneously transmit and reflect signals.

Denote $\mathbf{h}_{UL} \in \mathbb{C}^{M \times 1}$, $\mathbf{h}_{UL}' \in \mathbb{C}^{1 \times M}$, $\mathbf{h}_{BI} \in \mathbb{C}^{1 \times M}$, $\mathbf{h}_{ID} \in \mathbb{C}^{1 \times M}$, $\mathbf{h}_{BB} \in \mathbb{C}$ as the channel between the uplink 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 downlink user and SI channel of the BS respectively. In addition, we assume perfect channel state information (CSI) can be obtained, thus the optimized system performance can serve as a lower bound. According to [10], [11], the reflecting SI from the STAR-RIS can be reasonably neglected or cancelled.

Let us denote $\sqrt{p_U} x_U$ as the signal transmitted from the UL user to the BS, where $p_U$ is the transmit power. Meanwhile, the BS transmits $\sqrt{p_D} x_D$ to the DL user with given power $p_D$. Thus, the UL signal received at the BS can be expressed as

$$y_U = h_{ID}^H \mathbf{\Phi}_r \mathbf{h}_{UL} \sqrt{p_U} x_U + h_{BB} \sqrt{p_U} x_D + n_U,$$

(3)

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

$$y_D = h_{ID}^H \mathbf{\Phi}_r \mathbf{h}_{BI} \sqrt{p_D} x_D + h_{ID}^H \mathbf{\Phi}_r \mathbf{h}_{UL} \sqrt{p_U} x_U + n_D,$$

(4)

where $n_D \sim \mathcal{C}\mathcal{N}(0, \sigma_D^2)$ is the AWGN at the downlink user and $\mathbf{\Phi}_r = \text{Diag}(\mathbf{q}_r)$. Therefore, the achievable rate in bits second per Hertz (bps/Hz) of the UL and the DL can be formulated as

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

(5)

and

$$R_D = \log_2 \left( 1 + \frac{p_D |h_{ID}^H \mathbf{\Phi}_r \mathbf{h}_{UL}|^2}{p_U |h_{ID}^H \mathbf{\Phi}_r \mathbf{h}_{UL}|^2 + \sigma_D^2} \right).$$

(6)

C. Problem Formulation

In this letter, 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 T&R elements feasible set.

Mathematically, the optimization problem is derived as

$$\mathcal{P}1 : \min_{p_U, p_D, \mathbf{q}_r} p_U + p_D$$

s.t. $R_U \geq R_U^l$, $R_D \geq R_D^l$, $\mathbf{q}_r \in F_k, \forall k \in \{t, r\},$

(7a)

(7b)

(7c)

where $R_U^l$ and $R_D^l$ denote the minimum data rate of the uplink and the downlink and $F_k$ denotes the feasible set for the T&R coefficient vectors.

The optimization problem $\mathcal{P}1$ is non-trivial considering the non-convex data rate requirements. In addition, the power optimization and passive beamforming vector are also 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 passive beamforming design subproblems and adopt the AO method to solve them iteratively.

A. Active Beamforming Optimization With Given $\Theta$

We define $\mathbf{h}_1 = \text{Diag}(\mathbf{h}^U_1)\mathbf{u}_1$, $\mathbf{h}_2 = \text{Diag}(\mathbf{h}^U_2)\mathbf{u}_1$, $\mathbf{h}_3 = \text{Diag}(\mathbf{h}^R)\mathbf{u}_1$ and $H_1 = \mathbf{h}_1^*\mathbf{h}^H_1$, $H_2 = \mathbf{h}_2^*\mathbf{h}^H_2$, $H_3 = \mathbf{h}_3^*\mathbf{h}^H_3$. With given $\mathbf{q}_t$ and $\mathbf{q}_r$, we define $Q_t = \mathbf{q}_t\mathbf{h}^H_1$ and $Q_r = \mathbf{q}_r\mathbf{h}^H_2$.

Therefore, the original problem $\mathcal{P}1$ can be transformed into power optimization subproblem as follows

$$\mathcal{P}2 : \min_{P_U, P_D} P_U + P_D \quad \text{s.t.} \quad P_U \text{Tr}(Q_tH_1) \geq \rho U^H \left( P_D |\mathbf{h}BB|^2 + \sigma^2_U \right), \quad \text{(8a)}$$

$$P_D \text{Tr}(Q_rH_2) \geq \rho D^H \left( P_U \text{Tr}(Q_rH_3) + \sigma^2_D \right), \quad \text{(8b)}$$

where $R_U^H = 2R_U^U - 1, \quad R_D^H = 2R_D^U - 1.

Proposition 1: Minimal transmit power can be obtained if and only if the UL and DL transmit signals at the minimal requiring rate.

Proof: Suppose the uplink and downlink transmit signals at the minimal requiring rate. Thus, according to (8b) and (8c), the DL transmit power can be expressed as

$$\bar{P}_D = \frac{R_U^H \left( R_U^U \sigma^2_U \text{Tr}(Q_tH_1) + \text{Tr}(Q_rH_1) \sigma^2_D \right)}{\text{Tr}(Q_rH_2) \text{Tr}(Q_rH_1) - R_D^H R_U^H |\mathbf{h}BB|^2 \text{Tr}(Q_rH_3)}. \quad \text{(9)}$$

Then $\bar{P}_U$ can further be expressed as

$$\bar{P}_U = \frac{R_U^H |\mathbf{h}BB|^2 + \sigma^2_U}{\text{Tr}(Q_rH_1)}. \quad \text{(10)}$$

We then assume that the uplink user transmits signals to the BS at higher data rate $\bar{R}_D$. By substituting $R_D^H$ with $\bar{R}_D$ in (10), we obtain the required power $\bar{P}_D$ which is larger than $\bar{P}_D$ considering the denominator is decreased while the numerator is increased. Meanwhile, the $\bar{P}_U$ is also augmented. Therefore, the total transmitting power is increased. Similar conclusion can also be obtained if uplink data rate is higher than $R_U^H$.

B. Passive Beamforming Optimization With Given $p_D$ and $p_U$

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

$$\mathcal{P}3 : \text{find} \ \ Q_t, Q_r \quad \text{s.t.} \ Rank(Q_t) = 1, Rank(Q_r) = 1, \quad \text{(11a)}$$

$$\text{Rank}(Q_t) = 1, \text{Rank}(Q_r) = 1, \quad \text{(11b)}$$

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. The Gaussian randomization approach can be applied to obtain $\mathbf{q}_t^*$ ($\mathbf{q}_r^*$) if we get the optimal solution $Q_t^*$ ($Q_r^*$). 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 SCA method.

Based on the Proposition 3 in [12], the rank-one constraint (11b) is satisfied when $Q_t^*$ ($Q_r^*$) has only one non-zero eigenvalue. Thus, the rank-one constraint can be transformed as

$$\text{Rank}(Q_t) = 1 \leftrightarrow \text{Tr}(Q_t) - \lambda(Q_t) = 0. \quad \text{(12)}$$

where $l \in \{t, r\}$ represents any of the transmit or reflect mode. We define $f(Q_t) = \text{Tr}(Q_t) - \lambda(Q_t)$. Therefore, we can rewrite problem $\mathcal{P}3$ as

$$\mathcal{P}4 : \min_{Q_t, Q_r} f(Q_t) + f(Q_r) \quad \text{s.t.} \ (7b)-(7c) \quad \text{(13a)}$$

In order to ensure the convergence of SCA algorithm, we further rewrite $f(Q_t)$ as $f(Q_t) = \text{Tr}(Q_t) + \frac{\rho}{2} \|Q_t\|_F^2 - \left( \lambda(Q_t) + \frac{\rho}{2} \|Q_t\|_F^2 \right)$. The quadratic term which makes the objective function $f(Q_t)$ to be the difference of two $\beta$-strongly convex functions. We define $g(Q_t) = \left( \lambda(Q_t) + \frac{\rho}{2} \|Q_t\|_F^2 \right)$, thus its first-order approximation at the feasible point $Q_t^{(k-1)}$ can be given by

$$g(Q_t) \geq g\left(Q_t^{(k-1)}\right) + \text{Tr}\left( \partial_h g(Q_t)|_{Q_t = Q_t^{(k-1)}} Q_t - Q_t^{(k-1)} \right) \quad \text{(14)}$$

where $Q_t^{(k-1)}$ is the solution at the $k$-th iteration.

The subgradient of $g(Q_t)$ can be expressed as

$$\partial_{Q_t} g(Q_t) = \alpha \left( Q_t^{(k-1)} \right)\alpha \left( Q_t^{(k-1)} \right)^H + \rho Q_t^{(k-1)},$$

in which the $\alpha \left( Q_t^{(k-1)} \right)$ is the corresponding eigenvector of the largest eigenvalue.

Hence, by adopting SCA method, the solution $Q_t$ and $Q_r$ at the $k$-th iteration can be obtained by solving the following problem

$$\mathcal{P}4' : \min_{Q_t, Q_r} \sum_{l} \text{Tr}(Q_l) + \frac{\rho}{2} \|Q_l\|_F^2 - \text{Tr}\left( \partial_h g(Q_l)|_{Q_l = Q_l^{(k-1)}} Q_l \right) \quad \text{(15a)}$$

$$\text{s.t.} \ (7b)-(7c), \quad \text{(15b)}$$

Problem $\mathcal{P}4'$ is a standard SDP that can be solved by CVX. If the object function iteratively decreases and is eventually below a given threshold $\epsilon$, 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. OITM Initiation

In general, the solution of $p_U$ and $p_D$ needs to be non-negative. However, if we adopt the common-used random phase initiation for STAR-RIS, it would probably lead to
negative value. To sidestep this failure, we propose an OITM
for phase initiation.

**Proposition 2:** One initialization of \( q_t \) subject to T&R
element amplitude requirement can be expressed as

\[
q_{b0} = \frac{\left( I_M - h_3 h_3^H / \| h_3 \|_2^2 \right) x}{\max_m \left[ \left( I_M - h_3 h_3^H / \| h_3 \|_2^2 \right) x \right]_m},
\]

where \( m \in \{1, \ldots, M \} \) and \( x \in \mathbb{C}^{M \times 1} \) is a randomly generated unit-modulus vector.

**Proof:** When \( \text{Tr}(Q_0 H_3) = 0 \), we can eliminate the
negative occurrence of \( P_D \) and \( P_U \). Therefore, the phase
shift of transmitting elements \( q_t \) should be orthogonal to
the interference channel \( h_3 \). The orthogonal compliment projector
of \( h_3 \) can be given as

\[
P_A^k = I_M - h_3 h_3^H / \| h_3 \|_2^2.
\]

Hence, by generating one unit-modulus vector \( x \in \mathbb{C}^{M \times 1} \)
we can obtain the transmitting coefficient vector \( y \in \mathbb{C}^{M \times 1} \)
orthogonal to \( h_3 \) as

\[
q_{b0} = \frac{y}{\max_m y_m} = \frac{\left( I_M - h_3 h_3^H / \| h_3 \|_2^2 \right) x}{\max_m \left[ \left( I_M - h_3 h_3^H / \| h_3 \|_2^2 \right) x \right]_m},
\]

Hence, the phase shift of \( q_t \) can be initialized randomly and
its element amplitude can be expressed as

\[
\| q_{b0} \|_m = 1 - \| q_{b0} \|_m.
\]

D. Overall Algorithm

Our proposed algorithm is summarized in Algorithm 1. \( \varepsilon_1 \)
and \( \varepsilon_2 \) are small thresholds, while \( N \) and \( K \) represent
the maximum numbers of iterations.

**Algorithm 1 Alternating Optimization Algorithm for \( \mathcal{P}_1 \)**

1: **Initialization:** set \( n = 1 \), initialize \( q_t \) based on (16)
2: repeat
3:  Solve problem \( \mathcal{P}2 \) to get \( p_{U}^{(n)} \) and \( p_{D}^{(n)} \) with
4:  given \( q_t^{(n-1)} \) and \( q_t^{(n-1)} \);
5:  Set \( k = 0 \);
6:  while \( \text{Tr}(Q_k^U) - \lambda(Q_k^U) + \text{Tr}(Q_k^D) - \lambda(Q_k^D) \geq \varepsilon_1 \)
7:  and \( k \leq K \) do
8:  Solve \( \mathcal{P}4' \) to update \( Q_t^{(k+1)} \) and \( Q_t^{(k+1)} \) with
9:  given \( p_{U}^{(n)} \) and \( p_{D}^{(n)} \);
10:  Update \( k = k + 1 \);
11: end while
12: Update \( n = n + 1 \);
13: until \( (p_n^{(n-1)} - p_n^{(n)}) / p_n^{(n-1)} \leq \varepsilon_2 \) or \( n \geq N \).
14: **Output:** power design and passive beamforming vectors.

IV. SIMULATION RESULTS

This section provides simulation results to verify the perfor-
mance of our proposed algorithm. We assume that the
location of STAR-RIS, uplink user, BS and downlink user are
(0m,50m), (0m,35m), (5m,45m) and (0m,100m). We set
\( \sigma_U^2 = \sigma_D^2 = -80 \text{dBm} \). The large-scale fading is modelled by
\( PL(d) = PL_0(d/d_0)^{-\sigma} \), where \( PL_0 = -30 \text{dB} \) is the path loss
at the reference distance \( d_0 = 1 \text{m} \), \( d \) is the link distance, and
\( \sigma \) is the path-loss exponent. The path-loss exponent is set to
2.2. For small-scale fading, the Rician fading model with 3dB
Rician factor and the Rayleigh fading model are assumed for
all channels[10].

Fig. 2 investigates the convergence of the proposed algo-
rithm, where \( M \) is set to 40, \( R_D \) is set to 4 bps/Hz, \( R_U \) is set
to 1 bps/Hz and the path loss of SI channel at the BS is set to
-100dB. Considering the STAR-RIS-HD scheme can achieve
the optimal power design with closed-form expression of T&R
elements, it obtains the optimal solution at the first iteration.
It can be seen from the figure that as the number of iterations
continues to increase, the power consumption of STAR-RIS-
FD and CON-RIS-FD schemes decreases to convergence.

Fig. 3 shows the minimal transmit power versus the number
of STAR-RIS(CON-RIS) elements, where \( R_D \) is set to 4
bps/Hz, \( R_U \) is set to 1 bps/Hz and the path loss of SI channel
at the BS is set to -100dB. The minimal transmit power of all three schemes decreases with the increase of STAR-RIS(CON-FRIS) elements. Compared to conventional 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. Thus, the STAR-RIS outperforms the conventional RIS. Besides, 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 system working in HD mode consumes more transmit power compared with FD.

Fig. 3 shows the minimal power consumption versus different minimum downlink data rate requirement, $M$ is set to 40, $R_U$ is set to 1 bps/Hz and the path loss of SI is set to -100dB. When the minimal downlink data rate demand is lower than 3 bps/Hz, the interference from the UL has 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 larger than the interference. Thus, in order to minimize the transmit power, 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 conventional RIS working at FD mode, requires lower transmit power with higher downlink rate demand.

Fig. 4 shows the minimal transmit power versus the intensity of SI at the BS, where $M$ is set to 40, $R_D$ is set to 4 bps/Hz, $R_U$ is set to 1 bps/Hz. The SI intensity has no impact on the STAR-RIS system operating in HD. However, for STAR-RIS and conventional RIS working in the FD mode, the total power consumption decreases with SI intensity.

V. CONCLUSION

In this letter, we studied the STAR-RIS aided system which operates in FD mode. We formulated the power consumption minimization problem, subject to the minimum data rate demand of the UL and DL, as well as the T&R elements constraint at the STAR-RIS. We divided the optimization problem into power design and passive beamforming design subproblems, and adopted the AO framework to solve them, where the closed-form optimal power design scheme is derived in every iteration. An OITM was also proposed to initialize the transmitting coefficients of the STAR-RIS, avoiding negative power value. Simulation results demonstrated the performance of the proposed algorithm and further revealed in which scenarios STAR-RIS assisted FD communication defeats the HD and conventional RIS.

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