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Subset Antenna Selection for Simultaneously Transmitting and Reflecting Surface Assisted Wireless Systems

Aadhya Agrawal, Tubati Vangmayi, Arfa Rubeen, and Rimalapudi Sarvendranath, *Senior Member, IEEE*

***Abstract*—Simultaneously transmitting and reflecting reconfigurable intelligent surfaces (STAR-RIS) enable full space coverage in a cost and energy-efficient manner. Subset antenna selection (AS), where the transmitter selects a subset of antennas based on channel conditions, harnesses diversity benefits at the cost of fewer radio frequency (RF) chains. To combine these benefits, we consider subset AS for a STAR-RIS-assisted system under independent and coupled phase shift models. We develop an algorithm that jointly optimizes the antenna subset, access point beamforming vectors, and the STAR-RIS transmission and reflection coefficients to maximize the rate achieved by the T-user subject to a minimum rate constraint for the R-user. It performs an exhaustive search over all possible subsets and uses alternating optimization to obtain beamforming vectors and STAR-RIS phase shifts. We also propose a low-complexity subset selection algorithm based on a metric derived from direct and cascaded link channel gains. We evaluate the impact of the STAR-RIS phase shift model on the achievable T-user rate and the R-user outage probability. We also show that the T-user rate increases with the number of STAR-RIS elements or RF chains.**

***Index Terms*—STAR-RIS, antenna selection, alternating optimization, exhaustive search, low complexity.**

I. Introduction

Simultaneously transmitting and reflecting reconfigurable intelligent surfaces (STAR-RIS) are envisioned to improve data rates, energy efficiency, and coverage for next-generation wireless communication systems. Unlike reconfigurable intelligent surfaces (RIS) which consist of a large number of low-power reflecting elements, the elements of STAR-RIS split the incident signal into transmitted and reflected components. STAR-RIS thus enables full 360° coverage compared to RIS that provides half-space coverage [1], [2]. Configuring the transmission and reflection coefficients of each STAR-RIS element enables these benefits while satisfying an energy conservation constraint. To further reduce hardware cost and power consumption, transmit antenna selection (AS) techniques limit the number of radio-frequency (RF) chains. Unlike conventional multiple-antenna systems that use dedicated RF chains for each antenna, AS at the transmitter uses fewer RF chains than the number of antennas. Several wireless standards adopt AS to harness diversity gains at lower cost [3].

STAR-RIS Beamforming [2], [4]–[7]: Researchers have extensively studied the joint design of active transmit beamforming at the access point (AP) and passive STAR-RIS transmission and reflection coefficients for various operating protocols, including energy splitting, mode switching, and time switching [2], [4]. For the independent phase shift model, where transmission and reflection phase shifts can be configured independently, a transmit power minimization problem is presented under quality of service (QoS) constraints in [2]. It proposes a penalty-based successive convex approximation (SCA) framework with alternating optimization to obtain the AP beamforming vectors and STAR-RIS coefficients. In addition, [4] jointly optimizes the AP transmit beamforming and STAR-RIS shifts to minimize the AP transmit power under minimum signal-to-inference-plus-noise ratio constraints for both users.

[5], [6] study a coupled phase shift model, where the difference between transmission and reflection phase shifts must be $\pm\pi/2$. Specifically, [5] minimizes the transmit power under minimum QoS rate constraints for both non-orthogonal multiple access and orthogonal multiple access via element-wise alternating optimization of STAR-RIS phase shifts and AP power allocation. For a weighted sum-rate maximization problem under discrete coupled-phase constraints, [6] employs a Lagrangian dual transformation-based element-wise optimization of the transmission and reflection coefficients. In [7], the authors consider antenna activation by allocating zero power to antennas with weak channel conditions, and jointly optimize the transmit beamforming at the AP and STAR-RIS coefficients to maximize energy efficiency. All the above works assume system models that require a dedicated RF chain for each transmit antenna, thus increasing hardware costs and power consumption.

RIS Assisted Antenna Selection [8]–[10]: Researchers have explored the integration of antenna selection with passive beamforming for RIS-assisted systems in [8]. For single-antenna selection, where the AP uses one RF chain, [8] derives the optimal antenna index and RIS phase shift in closed form. For subset selection, where the AP uses multiple RF chains, [8] develops manifold optimization-based algorithms. Similarly, [9] studies joint optimization of antenna selection, transmit beamforming, and RIS phase shifts to maximize the received signal-to-noise ratio (SNR). For low-complexity antenna selection, [9] proposes a discrete cuckoo search–based algorithm, followed by semidefinite relaxation for continuous variable optimization, assuming perfect channel state information (CSI). In [10], for a multi-user system, the authors

A. Agrawal (ee23b002@iittp.ac.in), T. Vangmayi (ee23b056@iittp.ac.in), A. Rubeen (ee23b071@iittp.ac.in), and R. Sarvendranath (sarvendranath@iittp.ac.in) are with IIT Tirupati. The work was supported by the DST INSPIRE research grant and SERB research grant SRG/2023/000070.

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consider energy efficiency maximization, defining it as the ratio of achievable rate to total power consumption. It employs a Dinkelbach-based approach for joint antenna selection and transmit beamforming, while using SCA to optimize the passive beamforming at the RIS. These algorithms, developed for reflecting-only surfaces, do not consider coupling constraints between transmission and reflection coefficients and cannot be directly extended to STAR-RIS.

STAR-RIS with Antenna Selection: In [11], the authors develop single AS rules for a STAR-RIS system to maximize the transmission space user (T-user) rate while ensuring that the reflection space user (R-user) achieves a minimum rate. The method aligns the phases of the direct and cascaded links and selects the antenna that maximizes the sum of absolute values of direct and cascaded links. To the best of our knowledge, existing works do not jointly optimize subset antenna selection, active beamforming at the AP, and the STAR-RIS phase coefficients.

A. Focus and Contributions

We focus on a downlink communication system assisted with STAR-RIS which operates in fixed energy splitting ratio mode. The AP performs subset antenna selection and serves users located in the transmission and reflection regions. Among all antenna subsets whose associated transmit beamforming vectors at the AP and STAR-RIS transmission and reflection phase coefficients ensure that the R-user rate exceeds a given threshold, our goal is to identify the subset that achieves the highest T-user rate.

Our model differs from existing works in the following aspects: First, we focus on subset antenna selection, which reduces hardware costs while harnessing the diversity benefits of multiple antennas. This differs from transmit beamforming approaches in [2], [4]–[6], which require the number of RF chains to be equal to the number of antennas. Second, unlike [7], where the AP has a dedicated RF chain for each antenna and transmits with non-zero power only from a subset of antennas, we consider an AP that switches the available limited number of RF chains to the selected antennas. This, in turn, reduces the hardware cost. Third, unlike [2], [4], we consider both independent and coupled phase shift models to study system performance. Fourth, unlike [6], which optimizes a weighted sum-rate-based objective function, and [7], we separate the users as primary and secondary and aim to maximize the achievable rate of the primary user, while satisfying a minimum QoS constraint for the secondary user.

Our specific contributions are as follows:

i) *Exhaustive Search (ES):* For QoS-constrained STAR-RIS-assisted subset antenna selection, we first develop an exhaustive search-based approach that finds the transmit beamforming and STAR-RIS phase coefficients over all possible antenna subsets. We derive closed-form expressions for the beamforming vectors and STAR-RIS phase shifts using an alternating optimization (AO) framework, which effectively handles the coupling between the optimization variables. The resulting complexity increases exponentially with the number of RF chains.

ii) *Low-Complexity (LC):* To reduce the complexity of the ES algorithm, we propose a low-complexity selection method based on a composite selection metric that is the sum of the absolute values of the direct link and cascaded reflected link channel gains. We sort these selection metrics in decreasing order of magnitude and select the antenna subset accordingly. For the selected subset, we employ AO to obtain the beamforming vector and STAR-RIS phase shifts. The resulting complexity is linear in terms of the number of RF chains.

iii) *Performance Comparison:* We evaluate the performance of our proposed methods using various system parameters such as varying transmit power at the AP, number of transmit antennas, RF chains, and STAR-RIS elements. Results show that all proposed AS algorithms outperform the benchmarks. We also show the impact of imperfect channel state information on the achievable rate.

II. System Model

We consider an N element STAR-RIS-assisted downlink communication system as shown in Fig. 1. The access point (AP) is equipped with N_t transmit antennas and N_{RF} RF chains. The AP performs subset antenna selection to communicate with two single antenna users over non-overlapping frequencies using orthogonal multiple access (OMA). We refer to the user in the transmission space as the T-user and the user in the reflection space as the R-user. The T-user acts as the primary user, while the R-user acts as the secondary user.

Let $\beta_{tn}e^{j\theta_{tn}}$ and $\beta_{rn}e^{j\theta_{rn}}$ denote the transmission and reflection coefficients of the n^{th} element, respectively, where $\theta_{tn}, \theta_{rn} \in [0, 2\pi)$ represent the phase shifts and $\beta_{tn}, \beta_{rn} \in [0, 1]$ denote the amplitude coefficients. Let $\boldsymbol{\theta}_t = [\beta_{t1}e^{j\theta_{t1}}, \ldots, \beta_{tN}e^{j\theta_{tN}}]^T$ and $\boldsymbol{\theta}_r = [\beta_{r1}e^{j\theta_{r1}}, \ldots, \beta_{rN}e^{j\theta_{rN}}]^T$ represent the transmission and reflection coefficient vectors. Let $\boldsymbol{\Theta}_t = \mathrm{diag}(\boldsymbol{\theta}_t)$ and $\boldsymbol{\Theta}_r = \mathrm{diag}(\boldsymbol{\theta}_r)$. The STAR-RIS, denoted by S, operates in fixed energy splitting ratio mode, i.e., $\beta_{tn}^2/\beta_{rn}^2 = E_r$. This combined with the energy conservation constraint, i.e., $\beta_{tn}^2 + \beta_{rn}^2 = 1, \quad \forall n$ yields $\beta_{tn}^2 = E_r/(1 + E_r)$ and $\beta_{rn}^2 = 1/(1 + E_r)$.

For STAR-RIS phase shifts we consider two models:

i) *Independent Phase Shift Model:* Here, θ_{tn} and θ_{rn} can be configured independently such that

$$0 \leq \theta_{tn}, \theta_{rn} < 2\pi, \quad \forall n. \tag{1}$$

ii) *Coupled Phase Shift Model:* For a passive lossless surface, the θ_{tn} and θ_{rn} are coupled. For energy-splitting mode they must satisfy $\cos(\theta_{tn} - \theta_{rn}) = 0$ [5], which is equivalent to

$$0 \leq \theta_{tn}, \theta_{rn} < 2\pi,\, \theta_{tn} - \theta_{rn} = \pm\pi/2, \quad \forall n. \tag{2}$$

Channel Model: Let $\mathbf{h}_t^d \in \mathbb{C}^{N_t \times 1}$ and $\mathbf{h}_r^d \in \mathbb{C}^{N_t \times 1}$ denote the direct-link channel vectors from the AP to the T-user

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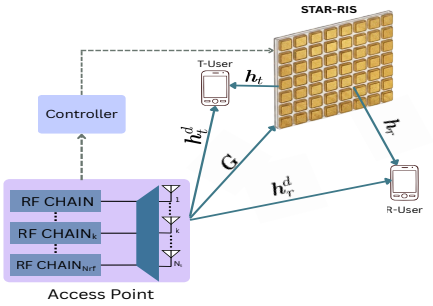


Fig. 1. System model for a simultaneously transmitting and reflecting reconfigurable intelligent surface (STAR-RIS) assisted system.

and R-user, respectively. Let $\mathbf{G} \in \mathbb{C}^{N \times N_t}$ denote the AP-S channel matrix. Let $\mathbf{h}_t \in \mathbb{C}^{N \times 1}$ and $\mathbf{h}_r \in \mathbb{C}^{N \times 1}$ denote the channel gain vectors from S to T-user and S to R-user, respectively. We consider independent and identically distributed (i.i.d.) rayleigh fading for the direct link channel gains and i.i.d. rician fading for the channel gains from AP to S, S to T-user, and S to R-user due to the presence of a strong line-of-sight (LoS) component.

Let $\mathcal{S} \subset \{1, 2, \ldots, N_t\}$ denote the subset corresponding to the N_{RF} number of antennas selected by the AP. Let $\mathcal{A}$ denote all possible subsets of $\{1, 2, \ldots, N_t\}$ with N_{RF} elements. For a given subset $\mathcal{S}$ and $u \in \{t, r\}$, let $\mathbf{G}_{\mathcal{S}} \in \mathbb{C}^{N \times N_{\mathrm{RF}}}$ and $\mathbf{h}^d_{u,\mathcal{S}} \in \mathbb{C}^{N_{\mathrm{RF}} \times 1}$ denote the corresponding AP to S channel gain matrix and AP to user channel gain vectors associated with the selected subset of antennas. Let $\mathbf{w}_t \in \mathbb{C}^{N_{\mathrm{RF}} \times 1}$ and $\mathbf{w}_r \in \mathbb{C}^{N_{\mathrm{RF}} \times 1}$ denote the beamforming vectors of T-user and R-user, respectively, such that $\|\mathbf{w}_t\|^2 = 1$ and $\|\mathbf{w}_r\|^2 = 1$. Power is split equally between the users. The signals received at the T-user and R-user are given by

$$y_t = \sqrt{P/2}(\mathbf{h}^{d\,T}_{t,\mathcal{S}} + \mathbf{h}_t^T \boldsymbol{\Theta}_t \mathbf{G}_{\mathcal{S}})\mathbf{w}_t\, d_t + z_t, \tag{3}$$

$$y_r = \sqrt{P/2}(\mathbf{h}^{d\,T}_{r,\mathcal{S}} + \mathbf{h}_r^T \boldsymbol{\Theta}_r \mathbf{G}_{\mathcal{S}})\mathbf{w}_r\, d_r + z_r, \tag{4}$$

where d_t and d_r denote the transmitted symbols, and $z_t, z_r \sim \mathcal{CN}(0, \sigma^2/2)$ represent additive white Gaussian noise (AWGN) of T-user and R-user, respectively.

A. Problem Statement

From (3) and (4), the signal to noise ratio (SNR) of the T-user and R-user is given as below:

$$\gamma_t(\mathcal{S}, \mathbf{w}_t, \boldsymbol{\theta}_t) = \frac{P}{\sigma^2}\left|\left(\mathbf{h}^{d\,T}_{t,\mathcal{S}} + \mathbf{h}_t^T \mathrm{diag}(\boldsymbol{\theta}_t)\mathbf{G}_{\mathcal{S}}\right)\mathbf{w}_t\right|^2, \tag{5}$$

$$\gamma_r(\mathcal{S}, \mathbf{w}_r, \boldsymbol{\theta}_r) = \frac{P}{\sigma^2}\left|\left(\mathbf{h}^{d\,T}_{r,\mathcal{S}} + \mathbf{h}_r^T \mathrm{diag}(\boldsymbol{\theta}_r)\mathbf{G}_{\mathcal{S}}\right)\mathbf{w}_r\right|^2. \tag{6}$$

The corresponding achievable rates are given as $R_t(\mathcal{S}, \mathbf{w}_t, \boldsymbol{\theta}_t) = 0.5\log_2\left(1 + \gamma_t(\mathcal{S}, \mathbf{w}_t, \boldsymbol{\theta}_t)\right)$ and $R_r(\mathcal{S}, \mathbf{w}_r, \boldsymbol{\theta}_r) = 0.5\log_2\left(1 + \gamma_r(\mathcal{S}, \mathbf{w}_r, \boldsymbol{\theta}_r)\right)$, where the pre-log factor of 0.5 arises as half of the bandwidth is allocated to each user.

QoS constraint: This constraint enforces that the rate achieved by the R-user is above the threshold R_{th}, i.e., $R_r(\mathcal{S}, \mathbf{w}_r, \boldsymbol{\theta}_r) \geq R_{\mathrm{th}}$.

Our goal is to optimize the antenna subset $\mathcal{S}$, transmit beamforming vectors $\mathbf{w}_t, \mathbf{w}_r$, and STAR-RIS coefficient vectors $\boldsymbol{\theta}_t, \boldsymbol{\theta}_r$ to maximize the achievable rate of the T-user subject to the QoS constraint of the R-user, unit norm constraint of $\mathbf{w}_t, \mathbf{w}_r$, subset size constraint $|\mathcal{S}| = N_{\mathrm{RF}}$, amplitude and phase constraints of the STAR-RIS coefficients. The optimization problem can be written as

$$\mathcal{P}: \max_{\mathcal{S}, \mathbf{w}_t, \mathbf{w}_r, \boldsymbol{\theta}_t, \boldsymbol{\theta}_r} \quad R_t(\mathcal{S}, \mathbf{w}_t, \boldsymbol{\theta}_t) \tag{7}$$

$$\text{s.t.} \quad R_r(\mathcal{S}, \mathbf{w}_r, \boldsymbol{\theta}_r) \geq R_{\mathrm{th}}, \tag{8}$$

$$\|\mathbf{w}_t\|^2 = 1, \|\mathbf{w}_r\|^2 = 1 \tag{9}$$

$$|\mathcal{S}| = N_{\mathrm{RF}}, \tag{10}$$

$$\text{Phase constraint (1) or (2)} \tag{11}$$

The optimization problem $\mathcal{P}$ is general and applies to both independent and coupled phase shift models. Obtaining a jointly optimal solution for $\mathcal{P}$ is challenging, as it is a mixed discrete–continuous non-convex optimization problem due to the combinatorial antenna subset selection and coupled variables.

III. Subset Antenna Selection With STAR-RIS

For the optimization problem $\mathcal{P}$, we will first develop an exhaustive search (ES) based subset antenna selection algorithm. Then, to reduce the number of computations, we propose a low complexity (LC) subset antenna selection algorithm.

A. Exhaustive Search Based Subset Selection

Since logarithm is a monotonically increasing function, maximizing $R_t(\mathcal{S}, \mathbf{w}_t, \boldsymbol{\theta}_t)$ is equivalent to maximizing $\gamma_t(S, \mathbf{w}_t, \boldsymbol{\theta}_t)$. We note that the optimal beamforming vectors $\mathbf{w}_t$ and $\mathbf{w}_r$ are dependent on the effective channel gains $\mathbf{h}^{d\,T}_{t,\mathcal{S}} + \mathbf{h}_t^T \mathrm{diag}(\boldsymbol{\theta}_t)\mathbf{G}_{\mathcal{S}}$ and $\mathbf{h}^{d\,T}_{r,\mathcal{S}} + \mathbf{h}_r^T \mathrm{diag}(\boldsymbol{\theta}_r)\mathbf{G}_{\mathcal{S}}$, respectively, which in turn are functions of the STAR-RIS coefficient vectors $\boldsymbol{\theta}_t$ and $\boldsymbol{\theta}_r$. To resolve this circular dependency, we employ an alternating optimization framework that iteratively update the STAR-RIS coefficients and the beamforming vectors until convergence.

Step 1: Optimal $\mathbf{w}_t$ and $\mathbf{w}_r$ for a given subset $\mathcal{S}$ and coefficient vectors $\boldsymbol{\theta}_t$ and $\boldsymbol{\theta}_r$: At the k^{th} iteration, for a fixed subset $\mathcal{S}$ and coefficient vectors $\boldsymbol{\theta}_t^k$ and $\boldsymbol{\theta}_r^k$, we obtain

$$\mathbf{w}_u^{k+1} = \arg\max_{\mathbf{w}_u} \gamma_u(\mathcal{S}, \mathbf{w}_u, \boldsymbol{\theta}_u^k), \text{for } u \in \{t, r\}. \tag{12}$$

Using Cauchy-Schwarz inequality, on (5) and (6), for a given $\mathcal{S}$, $\boldsymbol{\theta}_t^k$, and $\boldsymbol{\theta}_r^k$, the optimal beamforming vectors can be written as

$$\mathbf{w}_u = \frac{\left(\mathbf{h}^d_{u,\mathcal{S}} + \mathbf{G}^T_{\mathcal{S}}\mathrm{diag}(\boldsymbol{\theta}_u^k)\mathbf{h}_u\right)^*}{\left\|\mathbf{h}^d_{u,\mathcal{S}} + \mathbf{G}^T_{\mathcal{S}}\mathrm{diag}(\boldsymbol{\theta}_u^k)\mathbf{h}_u\right\|}, \text{for } u \in \{t, r\}. \tag{13}$$

The achievable rate corresponding to the above maximal ratio transmission (MRT) based beamforming vectors is equal to

$$0.5\log_2\left(1 + P\left\|\mathbf{h}^d_{u,\mathcal{S}} + \mathbf{G}^T_{\mathcal{S}}\boldsymbol{\Theta}^k_u\mathbf{h}_u\right\|^2/\sigma^2\right). \tag{14}$$

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Step 2: Optimize $\boldsymbol{\theta}_t$ and $\boldsymbol{\theta}_r$ for a given subset $\mathcal{S}$ and beamforming vectors $\mathbf{w}_t$ and $\mathbf{w}_r$:

At the k^{th} iteration, for a fixed subset $\mathcal{S}$ and beamforming vectors $\mathbf{w}_t^k$ and $\mathbf{w}_r^k$, we obtain

$$\boldsymbol{\theta}_u^{k+1} = \arg\max_{\boldsymbol{\theta}_u} \gamma_u(S, \mathbf{w}_u^k, \boldsymbol{\theta}_u). \tag{15}$$

Let $\mathbf{g}_{n,\mathcal{S}}^T \in \mathbb{C}^{1\times N_{\text{RF}}}$ be the n-th row of the subset channel matrix $\mathbf{G}_{\mathcal{S}}$ and $h_{t,n}, h_{r,n} \in \mathbb{C}^{1\times 1}$ denote the channel gain from the n-th STAR-RIS element to the T-user and R-user, respectively. We will now consider the two-phase shift models separately.

1) Independent Phase Shift Model: Here, the transmission and reflection coefficients can be configured independently. For a given antenna subset $\mathcal{S}$, set of beamforming vectors are $\mathbf{w}_t$ and $\mathbf{w}_r$, then the effective direct link channel gains of the T-user and R-user are given by $\mathbf{h}_{t,\mathcal{S}}^{dT}\mathbf{w_t}$ and $\mathbf{h}_{r,\mathcal{S}}^{dT}\mathbf{w_r}$. Similarly, $h_{t,n}\mathbf{g}_{n,\mathcal{S}}^T\mathbf{w_t}$ and $h_{r,n}\mathbf{g}_{n,\mathcal{S}}^T\mathbf{w_r}$ are the effective cascaded channel gains through the n^{th} element of the surface to the T-user and R-user, respectively. Therefore, the effective channel power gain of the T-user in (5), i.e., $\left|\left(\mathbf{h}_{t,\mathcal{S}}^{dT} + \mathbf{h}_t^T \text{diag}(\boldsymbol{\theta}_t)\mathbf{G}_{\mathcal{S}}\right)\mathbf{w}_t\right|^2$, can be written as

$$\mathbf{h}_{t,\mathcal{S}}^{dT}\mathbf{w}_t + \sum_{n=1}^{N} \beta_{tn} e^{j\theta_{tn}} h_{t,n}\mathbf{g}_{n,\mathcal{S}}^T\mathbf{w_t}. \tag{16}$$

Using the triangle inequality, the optimal phase shift θ_{tn} is given by

$$\theta_{t,n}^{\text{co}} = \angle(\mathbf{h}_{t,\mathcal{S}}^{dT}\mathbf{w_t}) - \angle(h_{t,n}\mathbf{g}_{n,\mathcal{S}}^T\mathbf{w_t}). \tag{17}$$

Similarly, optimal phase shift of the reflection coefficient, i.e., θ_{rn} is given by

$$\theta_{r,n}^{\text{co}} = \angle(\mathbf{h}_{r,\mathcal{S}}^{dT}\mathbf{w_r}) - \angle(h_{r,n}\mathbf{g}_{n,\mathcal{S}}^T\mathbf{w_r}). \tag{18}$$

These phase shifts that maximize the effective channel power gains and, in turn, maximize the achievable rate are referred as co-phases.

2) Coupled Phase Shift Model: Here, the phase shifts $\theta_{t,n}$ and $\theta_{r,n}$ must satisfy the condition (2). Since our objective is to maximize the T-user rate, we configure (17) for the transmission phase shifts. We know that the reflection phase shift $\theta_{r,n}^{\text{co}}$ in (18) is optimal for $\theta_{r,n}$. Therefore, among the two possibilities $\theta_{t,n} \pm \frac{\pi}{2}$ for the reflection phase shifts, we choose the one closest to the co-phase reflection phase shift in (18). It can be written as

$$\theta_{r,n} = \underset{\theta\in\{\theta_{t,n}+\frac{\pi}{2}, \theta_{t,n}-\frac{\pi}{2}\}}{\arg\min} \left|\theta - \theta_{r,n}^{\text{co}}\right|. \tag{19}$$

Subset Selection Algorithm: We now describe our exhaustive search-based subset selection algorithm in detail. For each subset in $\mathcal{A}$, we do the following

Initialization: To avoid the circular dependency between the beamforming vectors and the STAR RIS coefficients, for a given subset $\mathcal{S}$, we initialize the beamforming vectors to be MRT vectors corresponding to the direct links from the AP to the T-user and R-user, i.e., $\mathbf{w}_u = (\mathbf{h}_{u,\mathcal{S}}^d)^*/\|\mathbf{h}_{u,\mathcal{S}}^d\|$, for $u \in \{t, r\}$

Alternating Optimization : For each subset $\mathcal{S}$, we alternatively optimize the phase shifts and beamforming vectors. In each iteration, for a given beamforming vector $\mathbf{w_t}$, we update transmission phase shift using the cophase phase shifts in (17). For the independent phase shift model, for a given $\mathbf{w_r}$, we update the reflection phase shift using (18). For the coupled phase-shift model, we use (19) to update the reflection phase shift. We repeat this till the convergence of the T-user rate. We note that the updates are performed to maximize the T-user rate while the R-user rate constraint is checked during subset selection. Then the final phase shifts and beamforming vectors are stored in $\theta_{\mathbf{t},\mathbf{n},\mathcal{S}}$, $\theta_{\mathbf{r},\mathbf{n},\mathcal{S}}$, $\forall n$ and $\mathbf{w}_{\mathbf{t},\mathcal{S}}$, $\mathbf{w}_{\mathbf{r},\mathcal{S}}$, respectively. This subset $\mathcal{S}$ is added to the set of feasible subsets $\mathcal{F}$, if it satisfies the R-user rate constraint in (8).

Subset Selection: Finally, after repeating the above steps for the possible subsets, if the set of feasible subsets $\mathcal{F}$ is not empty, we select the subset $\mathcal{S}^* \in \mathcal{F}$ that yields maximum T-user rate. Else, if $\mathcal{F}$ is empty indicating no subset satisfies the QoS constraint of the R-user, we select the subset that maximizes the T-user rate among all possible subsets, i.e., we select $\mathcal{S}^* \in \mathcal{A}$, rather than refraining from transmission. Then we return the beamforming vectors $\mathbf{w}_{\mathbf{t},\mathcal{S}^*}$ $\mathbf{w}_{\mathbf{r},\mathcal{S}^*}$, and the phase shifts $\theta_{\mathbf{t},\mathbf{n},\mathcal{S}^*}$, $\theta_{\mathbf{r},\mathbf{n},\mathcal{S}^*}$, $\forall n$, corresponding to the selected subset $\mathcal{S}^*$. Algorithm 1 summarizes the complete procedure.

Convergence of T-user Rate: At iteration k, from (15), we know that $\gamma_t(\mathcal{S}, \mathbf{w}_t^k, \boldsymbol{\theta}_t^{k+1}) \geq \gamma_t(\mathcal{S}, \mathbf{w}_t^k, \boldsymbol{\theta}_t^k)$. Similarly, from (12), we know that $\gamma_t(\mathcal{S}, \mathbf{w}_t^{k+1}, \boldsymbol{\theta}_t^{k+1}) \geq \gamma_t(\mathcal{S}, \mathbf{w}_t^k, \boldsymbol{\theta}_t^{k+1})$. Therefore, we have a non-decreasing sequence of T-user achievable rates. This, combined with the fact that the T-user rate is bounded, implies that it converges to a stationary point.

Algorithm 1 Exhaustive Search Based Subset Selection

$\mathcal{F} \leftarrow \emptyset$
for $\mathcal{S} \in \mathcal{A}$ **do**
  $\mathbf{w_u}^{(0)} = \frac{(\mathbf{h}_{u,\mathcal{S}}^d)^*}{\|\mathbf{h}_{u,\mathcal{S}}^d\|}$, $k = 0$.
  repeat
    Update $\theta_{t,n}^{(k)} = \angle(\mathbf{h}_{t,\mathcal{S}}^{dT}\mathbf{w_t}^{(k)}) - \angle(h_{t,n}\mathbf{g}_{n,\mathcal{S}}^T\mathbf{w_t}^{(k)})\ \forall N$
    Compute $\theta_{r,n}^{\text{co}} = \angle(\mathbf{h}_{r,\mathcal{S}}^{dT}\mathbf{w_r}^{(k)}) - \angle(h_{r,n}\mathbf{g}_{n,\mathcal{S}}^T\mathbf{w_r}^{(k)})\ \forall N$
    if Independent phase model : $\theta_{r,n}^{(k)} = \theta_{r,n}^{\text{co}}$
    else if Coupled phase model
    $\theta_{r,n}^{(k)} = \arg\min_{\theta\in\{\theta_{t,n}^{(k)}+\frac{\pi}{2}, \theta_{t,n}^{(k)}-\frac{\pi}{2}\}} \left|\theta - \theta_{r,n}^{\text{co}}\right|$
    end if
    Update $\mathbf{w}_t^{(k+1)}$ and $\mathbf{w}_r^{(k+1)}$ using (13)
    $k = k + 1$
  until T-user rate converges
  $\mathbf{w}_{\mathbf{t},\mathcal{S}} = \mathbf{w}_t^{(k)}$, $\mathbf{w}_{\mathbf{r},\mathcal{S}} = \mathbf{w}_r^{(k)}$, $\theta_{\mathbf{t},\mathbf{n},\mathcal{S}} = \theta_{t,n}^{(k-1)}$, $\theta_{\mathbf{r},\mathbf{n},\mathcal{S}} = \theta_{r.n}^{(k-1)}$
  if $R_r(\mathcal{S}, \boldsymbol{\theta}_r) \geq R_{\text{th}}$ **then** $\mathcal{F} \leftarrow \mathcal{F} \cup \{\mathcal{S}\}$
end for
if $\mathcal{F} \neq \emptyset$ $\mathcal{S}^* = \arg\max_{\mathcal{S}\in\mathcal{F}} R_t(\mathcal{S}, \boldsymbol{\theta}_t)$
else $\mathcal{S}^* = \arg\max_{\mathcal{S}\in\mathcal{A}} R_t(\mathcal{S}, \boldsymbol{\theta}_t)$;
return $\mathcal{S}^*$, $\mathbf{w}_{\mathbf{t},\mathcal{S}^*}$, $\mathbf{w}_{\mathbf{r},\mathcal{S}^*}$, $\theta_{\mathbf{t},\mathbf{n},\mathcal{S}^*}$, $\theta_{\mathbf{r},\mathbf{n},\mathcal{S}^*}$

Computational Complexity: The algorithm searches exhaustively over $\binom{N_t}{N_{\text{RF}}}$ possible subsets in $\mathcal{A}$. For finding

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number of subsets we need $\mathcal{O}({N_t}^{N_{RF}})$ computations. For each subset, in each iteration, we need $\mathcal{O}(NN_{\mathrm{RF}})$ computations. Therefore, for I iterations, the overall computational complexity is $\mathcal{O}({N_t}^{N_{RF}} INN_{\mathrm{RF}})$. The complexity increases exponentially with N_{RF}.

B. Low-Complexity Subset Selection

From above, we see that the search over all possible subsets is computationally expensive. To reduce the computational complexity, we consider the selection metric of the single antenna selection. For antenna k at the AP, it is the sum of magnitudes of the direct link channel gain $h_{d,t,k}$, and the cascaded link channel gain $h_{t,n}g_{n,k}$, given by [12]

$$\Gamma_t(k) = |h_{d,t,k}| + \sum_{n=1}^{N} \beta_{t,n} \left|h_{t,n}g_{n,k}\right|, \text{ for } k \in \{1, 2, \ldots, N_t\}.$$

We then sort the metrics $\Gamma_t(1), \Gamma_t(2), \ldots, \Gamma_t(N_t)$ in the descending order. Then, from the sorted list, we select the first N_{RF} antennas as the subset $\mathcal{S}$. For the selected subset $\mathcal{S}$, we employ the AO framework described in the previous subsection to obtain the corresponding beamforming vectors $\mathbf{w}_{\mathbf{t},\mathcal{S}}$, $\mathbf{w}_{\mathbf{r},\mathcal{S}}$, and phase shifts $\theta_{\mathbf{t},\mathbf{n},\mathcal{S}}$, $\theta_{\mathbf{r},\mathbf{n},\mathcal{S}}$, $\forall n$. The obtained vectors and phase shifts are then used to compute the user rates. If the R-user rate is below the threshold, we declare outage. The number of computations required is $\mathcal{O}\big(N_t \log N_t + N_t N + INN_{\mathrm{RF}}\big)$ for I iterations. This is significantly lower than $\mathcal{O}\big({N_t}^{N_{RF}} INN_{\mathrm{RF}}\big)$ required by the exhaustive search.

IV. Numerical Results

In this section, we present numerical results to evaluate the performance of the proposed subset antenna selection algorithms. The considered STAR-RIS is configured as a uniform planar array (UPA) with inter-element spacing equal to a quarter wavelength, centered at $(0, 0, 0)$ and oriented along the yz-plane. The AP is located at $(50, -50, 0)$ and employs a uniform linear array (ULA) with half-wavelength inter-element spacing [2]. Based on the spatial configuration, the half-space $x \geq 0$ corresponds to the reflection region, while $x < 0$ defines the transmission region. Accordingly, the R-user and T-user are positioned at $(5, 5, -10)$ and $(-5, 5, -10)$, respectively. Large-scale fading is modeled using the logarithmic distance-based path-loss model $30{+}10\eta_p \log_{10}(d)$, where η_p represents the path-loss exponent and d is the link distance. The direct AP – user links follow rayleigh fading with $\eta_p = 3.6$, whereas the cascaded links involving the STAR-RIS (AP – STAR-RIS and STAR-RIS – user) are modeled using rician fading with a rician factor of $K = 10$ and a reduced path-loss exponent of $\eta_p = 2.2$ [5], [13]. The carrier frequency of the system is set to 2.4 GHz. The noise power at both users is fixed at $\sigma^2 = -104$ dBm. Each STAR-RIS element is assumed to equally split the incident signal energy between transmission and reflection, i.e., $\beta_{t,n} = \beta_{r,n} = 1/\sqrt{2}$, $\forall n$ [14].

All algorithms are evaluated over 10^5 Monte Carlo samples with a T-user rate convergence tolerance of $1e{-}5$. For most

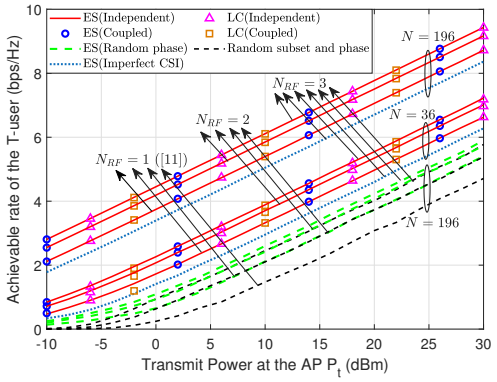


Fig. 2. Achievable rate of the T-user as a function of P_t for different N_{RF} and N ($N_t = 4$, $R_{\mathrm{th}} = 0.5$ bps/Hz and $\sigma_e = 3e{-}12$).

subsets, the alternating optimization procedure converges within 3 iterations. The average per-sample run time for $N = 196$, $N_t = 4$, $N_{RF} = 2$ is 0.767 ms and 0.279 ms for the ES and LC algorithms, respectively. We benchmark the performance of the proposed AS algorithms with the single AS rule in [11], random phase scheme, where STAR-RIS configures random phase shifts with exhaustive search for antenna subset, and random subset and random phase scheme where both antenna subset and phases are selected randomly.

Fig. 2 plots the achievable rate of the T-user as a function of transmit power P_t at the AP for different subset AS algorithms and number of STAR-RIS elements. All the proposed AS algorithms yield identical rates under perfect CSI. The proposed AS algorithms outperform the benchmarks as they align the phase shifts of direct and reflected links. For a given transmit power, the rate increases with the number of STAR-RIS elements. At $P_t = 6$ dBm and $N_{RF} = 2$, the rate increases by $1.71\times$ as N increases from 36 to 196 and by $1.68\times$ for $N_{RF} = 3$. The rate also increases monotonically with P_t for all configurations. For a fixed N, increasing N_{RF} improves the rate due to enhanced beamforming capability, while the incremental gain diminishes as N_{RF} increases. For imperfect CSI, modeled as $\hat{\mathbf{H}} = \sqrt{1-\sigma_e}\,\mathbf{H} + \sqrt{\sigma_e}\,\tilde{\mathbf{H}}$, where $\mathbf{H}$ denotes the true channel (direct or cascaded), $\tilde{\mathbf{H}} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$ and $\sigma_e \in [0, 1]$, at $N_{RF} = 3$, the rate drops by $1.2\times$ for $N = 196$ and $1.45\times$ for $N = 36$ compared to the perfect CSI case, for $\sigma_e = 3 \times 10^{-12}$. Results for other parameter combinations are omitted for visual clarity.

Fig. 3 illustrates the achievable rate of the T-user as a function of the number of STAR-RIS elements N for varying N_{RF} and transmit power levels P_t. The rate increases with N for all considered AS algorithms due to improved beamforming gain. However, the improvement decreases as N increases, indicating diminishing returns from additional STAR-RIS elements. Again, the proposed AS algorithms outperform the benchmarks, and the performance gap increases with N. Increasing P_t improves the rate by enhancing the received signal strength, resulting in an upward shift of curves. Similarly, increasing N_{RF} improves performance, as

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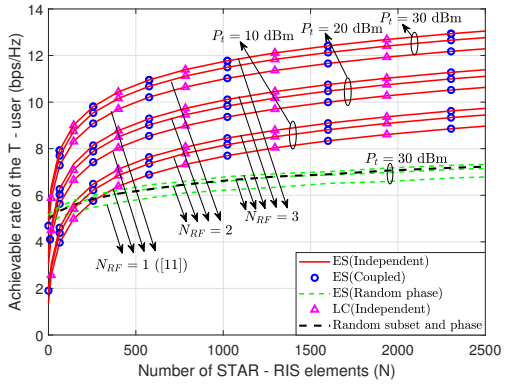
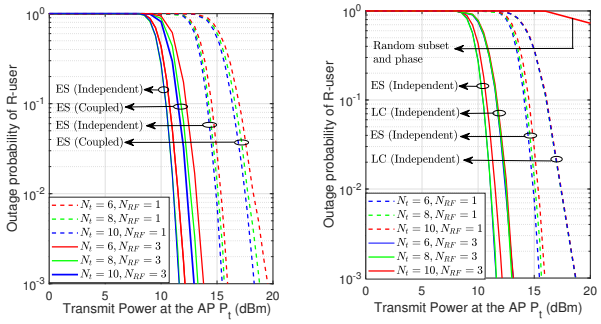


Fig. 3. Achievable rate of the T-user as a function of N for different N_{RF} and P_t ($N_t = 4$ and $R_{\text{th}} = 0.5$ bps/Hz).



(a) Independent vs. Coupled (b) ES vs. LC

Fig. 4. Outage probability of R-user as a function of P_t for different N_{RF} and N_t ($N = 36$ and $R_{\text{th}} = 0.5$ bps/Hz).

more number of transmit antennas are active.

Fig. 4 shows the outage probability of the R-user as a function of transmit power P_t at the AP for different AS algorithms, different number of transmit antennas N_t and RF chains N_{RF}. The outage probability decreases monotonically as P_t increases. At a lower P_t, the outage probability is one across all configurations, indicating that the R-user rate constraint is not met. The outage probability improves by two to three orders of magnitude when N_{RF} goes from 1 to 3. The ES-based independent phase shift AS algorithm achieves the lowest outage as it aligns the direct link and cascaded reflected links of the R-user. While, the coupled phase shift model as shown in Fig. 4a, performs worse due to its constrained phase adjustment and reduced beamforming gain. For a fixed N_{RF}, increasing N_t improves outage performance due to enhanced spatial diversity. For example, for $N_{RF} = 3$ at $P_t = 11$ dBm increasing N_t from 6 to 8, reduces the outage probability by $3.18\times$ for the independent phase shift model, compared to $2.08\times$ for the coupled model. Fig. 4b shows overlapping outage curves for the LC-based independent phase shift model for a fixed N_{RF} as N_t increases. This occurs because the LC-based independent phase shift model prioritizes subset selection to maximize T-user rate before satisfying the QoS constraint, leading to sub-optimal outage performance for the R-user.

V. Conclusions

We developed an ES algorithm to find optimal subset, the corresponding AP beamforming vectors to both T-user and R-user, along with the STAR-RIS phase coefficients, to maximize the T-user rate while satisfying the QoS constraint for the R-user rate. To reduce complexity, we proposed an LC algorithm that achieves a similar average rate as the ES algorithm with significantly lower computational cost. We also show that both the independent and the coupled phase shift models yield the same average rate for the T-user but the outage probability of the R-user is significantly higher in coupled phase shift model. All proposed AS algorithms outperform the chosen benchmarks. The T-user rate increases monotonically as the number of STAR-RIS elements or the number of RF chains increases. Increasing the number of transmit antennas significantly reduces the R-user outage probability due to enhanced spatial diversity.

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