# Antenna Selection for a Simultaneously Transmitting and Reflecting Surface Assisted Communication System

Yalavarthi Narendra, Rimalapudi Sarvendranath, *Member, IEEE*, and Koppolu Sireesha

***Abstract*—Simultaneous transmitting and reflecting surface (STARS) can simultaneously transmit the signals to a user in the transmission space (T-user) and reflect the signals to a user in the reflection space (R-user) to improve diversity and extend coverage in all directions, unlike intelligent reflecting surfaces (IRS), which can only reflect the signals. Similarly, transmit antenna selection (AS) is a low hardware complexity technique in which the transmitter selects one antenna based on channel conditions and harnesses diversity benefits. We focus on less explored transmit AS for a STARS assisted communication system, which can improve the coverage, reduce the cost and power consumption. Considering both independent phase shift model and coupled phase shift model, we develop different AS rules that jointly optimize the antenna index at the access point and the transmission and reflection coefficients of the STARS to maximize the rate achieved by the T-user subject to the minimum rate achieved by the R-user. Different from the AS rules for the IRS assisted systems, these rules optimize both transmission and reflection phase shifts while ensuring coupled conditions are met. We show that the proposed AS rules increase the T-user rate significantly compared to random phase shift rules. Furthermore, we show that the T-user rate increases significantly as the number of elements at the STARS increase and the rate-outage of the R-user decreases by one to two orders of magnitude by increasing the number of antennas at the access point.**

***Index Terms*—STARS, antenna selection, independent phase shift model, coupled phase shift model.**

## I. Introduction

Simultaneously transmitting and reflecting surface (STARS) is made up of a large number of elements that can simultaneously transmit and reflect the incident signals and provide a $360^\circ$ smart radio environment [1]. It is different from the intelligent reflecting surface (IRS), which can only reflect the signals, and is being envisioned as a potential technology for 6G [1]–[3]. Compared to the IRS, STARS is shown to achieve a higher diversity order, lower outage probability, and higher data rates due to its ability to create multiple propagation paths [4], [5]. Part of the signal incident on a STARS element is reflected into the reflection space and remaining signal is transmitted into the transmission space. The amplitude gain and phase shift induced to the transmitted and reflected signals are controlled by the electric and magnetic impedances of each element [6]. In energy splitting (ES) mode, all the STARS elements will simultaneously transmit and reflect the signals based on the transmission and reflection coefficients programmed [1].

Similar to the STARS, transmit antenna selection (AS) harnesses the diversity benefits of multiple antennas in an energy and cost-efficient manner [7]. In it, a transmitter equipped with multiple antennas selects one antenna based on the channel conditions and connects it to the radio frequency (RF) chain. Due to its benefits, AS has become part of several cellular and WiFi standards [8]. We aim to combine the benefits of AS and STARS.

For a lossless STARS, by the law of conservation of energy the sum of the reflected and the transmitted signal powers equals the incident signal power. Therefore, the sum of squares of the reflection and transmission amplitude coefficients of each element is equal to one. For the relation between the transmission and reflection phase shifts, the following two models are considered. i) *Independent Phase Shift Model [2], [5]:* Here, the transmission and reflection phase shifts can be controlled independently. For this, we should be able to set arbitrary values to the electric and magnetic impedances of each element, which is difficult to realize in practice for a passive STARS. ii) *Coupled Phase-Shift Model [4], [6]:* Here, the transmission and reflection phase shifts are coupled. For a STARS made up of lossless passive elements, the coupled condition mandates that the difference between the transmission and reflection phase shifts should be either $\pi/2$ or $3\pi/2$.

*IRS Assisted Communication System [9]–[12]:* Conventional IRS systems with multiple antennas at the access point (AP) have been extensively studied in the literature. The joint AS at the AP and the passive beamforming at the IRS is studied in [9]–[12]. The joint optimization of the antenna index at the AP and the passive beamforming at the IRS that maximizes the received signal power is studied in [9]. Furthermore, low complexity AS rules that reduce the number of computations and the pilot transmissions are also proposed. AS rule that jointly selects the antenna index and a passive beamforming vector from a codebook with random phase shift configurations is studied for an orthogonal time frequency space (OTFS) system in [10]. A manifold optimization based AS rule that maximizes the sum rate of a multi user system is proposed in [11]. Beamforming algorithms to maximize the energy efficiency of an IRS-assisted system are proposed in [12].

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*STARS Assisted Communication System [2]–[5], [13]–[15]:* It is shown that an independent phase shift model based STARS assisted single-input-single-output (SISO) system can achieve full diversity [14]. Also, the outage-probability is analyzed when the direct link is blocked. Primary-secondary and diversity preserving phase shift configurations are proposed and their performance is studied in [4], for a SISO system. The joint optimization of transmit power and transmission and reflection phase shifts at the STARS is done to maximize the achievable sum rate of an orthogonal multiple access (OMA) system in [3]. For an AP with multiple antennas, the joint transmit beamforming at the AP and the passive beamforming at the STARS is studied in [2], [13], [15]. Minimization of the transmit power at the AP is considered in [2], [13] and is shown that the STARS can achieve significant reduction in the transmit power of the AP compared to the conventional IRS. On the other hand, [15] considered an AP with large number of antennas and performed subset AS to maximize the energy efficiency.

### A. Focus and Contributions

We focus on a STARS assisted downlink communication system where an AP with multiple antennas serves two single antenna users each one located in reflection space and transmission space of the STARS. The AP is equipped with one RF chain and performs AS. We jointly optimize the antenna index at the AP, transmission and reflection phase shifts at the STARS to maximize the rate achieved by the user in the transmission space (T-user) subject to the minimum rate constraint of the user in the reflection space (R-user). Our model is novel in the following aspects: i) Firstly, we study a less explored AS for a STARS assisted communication system. ii) We study both the independent and coupled phase shift models and compare their performances, unlike [2], [5], which focus on independent phase shift model only. iii) Unlike [14], we consider direct link as well as cascaded channels.

*Our Specific Contributions Are as Follows:*

*i) Independent Phase Shift Model:* For this model, we propose two AS rules. In independent phase shift AS rule first computes the reflection phase shifts that align the direct and the reflected links of the R-user, which we shall refer as cophase. Then among the antennas that satisfy the R-user rate constraint, it selects an antenna that yields maximum T-user rate when the T-user cophase is used as the transmission phase shifts. We also propose an independent random phase based AS rule, which uses randomly generated phases for the transmission and reflection phase shifts.

*ii) Coupled Phase Shift Model:* We propose T-user cophase, R-user cophase, and coupled random phase AS rules. For each STARS element, T-user cophase AS rule first computes the cophases for the T-user and for R-user it computes the phase shift that satisfies the coupled condition. Similarly, R-user cophase AS rule first computes the cophases for the R-user and for the T-user it computes the phase shift that satisfies the coupled condition. For each STARS element, coupled random phase AS rule configures a random phase to the R-user and for the T-user it randomly selects one phase shift from the set of phase shifts that satisfy coupled condition. For these phase shifts configured, the above AS rules selects an antenna that maximizes the T-user's rate among the antennas that satisfy the R-user's rate constraint. Then corresponding phases will be configured at the STARS.

*iii) Numerical Results:* We study the behavior of all the proposed AS rules as a function of the key system parameters such as the number of AP antennas, transmit power, and number of elements at the STARS. They show that the independent cophase rule yields the best performance both in terms of the T-user's rate and R-user's rate-outage. Among the AS rules developed for the coupled phase shift model, the T-user cophase rule performs well in terms of the T-user's rate and the R-user cophase rule performs well in terms of the R-user's rate-outage.

*Outline:* Section II presents our system model and problem statement. Our AS rules that are designed for the independent and coupled phase shift models are discussed in Section III. Numerical results are presented in Section IV and our conclusions are given in Section V.

*Notations:* Scalars are denoted by lower-case letters. Vectors and matrices are denoted by boldface lower-case and capital letters, respectively. $\mathbb{C}^{m\times 1}$ denotes the set of all complex-valued vectors of size $m\times 1$ and set of all complex-valued matrices of size $m\times n$ is denoted $\mathbb{C}^{m\times n}$ and $j=\sqrt{-1}$. A vector $\mathbf{x}$ with $n^{\text{th}}$ element as $x_n$ is denoted by $\mathbf{x}=[x_n]$ and $\mathbf{x}^T$ denotes its transpose. For a complex number $a$, $|a|$ and $\angle a$ denotes its absolute value and angle, respectively.

## II. System Model

Our downlink communication system model shown in Figure 1 consists of an AP with $N_t$ antennas and one RF chain, which performs AS to communicate to two single-antenna users with the help of a STARS equipped with $N$ elements. First user referred to as R-user is located in the reflection space of the STARS and the second user referred to as T-user is located in the transmission space of the STARS. Let $k\in\{1,2,\ldots,N_t\}$ and $n\in\{1,2,\ldots,N\}$ denote the indices of the $k^{\text{th}}$ antenna at the AP and the $n^{\text{th}}$ element at the STARS, respectively. We denote the reflection coefficient and transmission coefficient of $n^{\text{th}}$ STARS element by $R_n=\beta_{rn}e^{j\theta_{rn}}$ and $T_n=\beta_{tn}e^{j\theta_{tn}}$, respectively, where $\theta_{rn}$, $\theta_{tn}\in[0,2\pi)$ denote the reflection and the transmission phase shifts, respectively, and $\beta_{rn}$, $\beta_{tn}\in[0,1]$ denote the reflection and transmission amplitude coefficients, respectively [5]. By the law of conservation of energy, we know that $(\beta_{tn})^2+(\beta_{rn})^2=1$, $\forall n$, independent of $\theta_{rn}$ and $\theta_{tn}$ [2], [5], [6]. Let $\boldsymbol{\theta_r}=[\theta_{r1},\theta_{r2},\ldots,\theta_{rN}]^T$ and $\boldsymbol{\theta_t}=[\theta_{t1},\theta_{t2},\ldots,\theta_{tN}]^T$ denote the phase shift vectors corresponding to the R-user and the T-user, respectively. We consider STARS that operate in the ES mode. Therefore, the signal impinged on each STARS element is split into transmitted and reflected signals with an energy splitting ratio of $(\beta_{tn})^2/(\beta_{rn})^2$.

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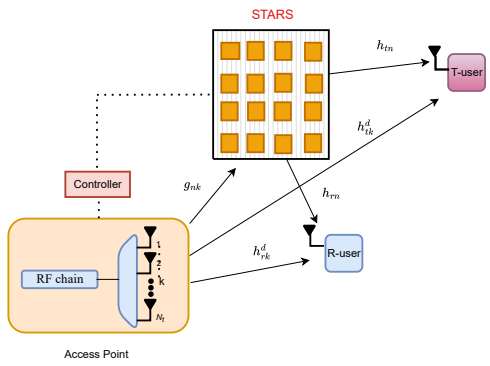



Fig. 1. System model that consists of the AP equipped with $N_t$ antennas and one RF chain communicating with T-user and R-user.

Let $\mathbf{g}_k = [g_{nk}] \in \mathbb{C}^{N\times 1}$ denote the complex baseband channel gain vector from the $k^{\text{th}}$ antenna at the AP to the STARS and $\mathbf{G} = [\mathbf{g}_1\ \mathbf{g}_2\ \dots\ \mathbf{g}_{N_t}] \in \mathbb{C}^{N\times N_t}$ denote the corresponding channel gain matrix. Let $\mathbf{h}_r = [h_{rn}] \in \mathbb{C}^{N\times 1}$ and $\mathbf{h}_t = [h_{tn}] \in \mathbb{C}^{N\times 1}$ denote the complex baseband channel gain vectors from the STARS to R-user and T-user, respectively. Let $\mathbf{h}_r^d = \left[h_{rk}^d\right] \in \mathbb{C}^{N_t\times 1}$ and $\mathbf{h}_t^d = \left[h_{tk}^d\right] \in \mathbb{C}^{N_t\times 1}$ denote the direct link complex baseband channel gain vectors from the AP to the R-user and the T-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 all the cascaded channel gains through STARS due to a strong line-of-sight (LoS) component.

*Channel State Information (CSI) Assumptions:* We assume that the AP knows the direct link channel gains, i.e., $h_{tk}^d$, $h_{rk}^d$, $\forall k$, and cascaded link channel gains through the STARS i.e., $h_{rn}g_{nk}$, $h_{tn}g_{nk}$, $\forall n$, $\forall k$. In the two-step method, first, the STARS is turned off and each user transmits an orthogonal pilot sequence to the AP simultaneously. This received signal is used to estimate direct link channel gains. In the second step, with STARS turned on, the users transmit the orthogonal pilot sequences and the AP obtains the estimates of the cascaded link channel gains after subtracting the direct link channel gains. Different channel estimation techniques proposed in [16] can be employed to obtain the CSI.

Let $s \in \{1, 2, \dots, N_t\}$ denote the index of the antenna selected at the AP. The AP splits the transmit power $P_t$ equally to transmit unit power data symbols $d_t$ and $d_r$ to the T-user and the R-user, respectively, over two adjacent narrowband orthogonal frequencies employing OMA. When the AP transmits with antenna $k$, the received signals at the T-user and R-user are given by

$$y_{tk} = \sqrt{\frac{P_t}{2}}\left(h_{tk}^d + \sum_{n=1}^{N} h_{tn}\beta_{tn}e^{j\theta_{tn}}g_{nk}\right)d_t + z_t, \quad (1)$$

$$y_{rk} = \sqrt{\frac{P_t}{2}}\left(h_{rk}^d + \sum_{n=1}^{N} h_{rn}\beta_{rn}e^{j\theta_{rn}}g_{nk}\right)d_r + z_r, \quad (2)$$

respectively, where $z_t$ and $z_r$ denote the circular symmetric complex additive white Gaussian noise with zero mean and variance $\sigma^2$ at the T-user and R-user, respectively. The AP to STARS channel gains are considered to be same for the T-user and R-user. Therefore, the achievable rate for the T-user and R-user are given by

$$R_t(\boldsymbol{\theta_t}, k) = \frac{1}{2}\log_2\left(1 + \frac{P_t}{\sigma^2}\left|h_{tk}^d + \sum_{n=1}^{N} h_{tn}T_n g_{nk}\right|^2\right), \quad (3)$$

$$R_r(\boldsymbol{\theta_r}, k) = \frac{1}{2}\log_2\left(1 + \frac{P_t}{\sigma^2}\left|h_{rk}^d + \sum_{n=1}^{N} h_{rn}R_n g_{nk}\right|^2\right), \quad (4)$$

respectively. The factor $\frac{1}{2}$ arises in the above equations as the T-user and R-user use half of the available bandwidth in orthogonal manner [6].

*Problem Statement:* We aim to jointly optimize the antenna index $s$ at the AP and the transmission and reflection coefficients, i.e., $\boldsymbol{\theta_t}, \boldsymbol{\theta_r}$, at the STARS to maximize the T-user data rate such that the rate achieved at the R-user is above a threshold $R_{\text{th}}$, i.e., $R_r(\boldsymbol{\theta_r}, s) \geq R_{\text{th}}$. It can be written as the following optimization problem:

$$\mathcal{P}: \quad \max_{s,\boldsymbol{\theta_t},\boldsymbol{\theta_r}} \quad R_t(\boldsymbol{\theta_t}, s), \quad (5)$$

$$\text{s.t} \quad R_r(\boldsymbol{\theta_r}, s) \geq R_{\text{th}}, \quad (6)$$

$$(\beta_{tn})^2 + (\beta_{rn})^2 = 1, \quad \beta_{tn}, \beta_{rn} \in [0, 1], \quad (7)$$

$$\theta_{tn}, \theta_{rn} \in [0, 2\pi), \quad n \in \{1, 2, \dots, N\}. \quad (8)$$

## III. Antenna Selection With STARS

In this section, we develop AS rules for independent and coupled phase-shift models separately.

### A. Independent Phase Shift Model

For a T-user or an R-user, we refer to a phase shift that aligns the direct link channel gain with the cascaded link channel gain through STARS as *cophase*. We first define $\mathcal{F}(\boldsymbol{\theta_r}) \subset \{1, 2, \dots, N_t\}$, which is the set of antennas at the AP that satisfy the constraint in (6), i.e.,

$$\mathcal{F}(\boldsymbol{\theta_r}) = \left\{k \middle| R_r(\boldsymbol{\theta_r}, k) \geq R_{\text{th}}\right\}. \quad (9)$$

*1) Independent Cophase AS Rule:* Firstly, for each antenna $k$, we compute the cophase $\theta_{rn}^c$ that aligns the AP to R-user (AP-R) direct link channel gain $h_{rk}^d$ with the AP to STARS to R-user (AP-SR-R) cascaded link channel gain $h_{rn}g_{nk}$. For the $n^{\text{th}}$ STARS element, it is given by

$$\theta_{rn}^c = \angle h_{rk}^d - \angle\left(h_{rn}g_{nk}\right), \quad n \in \{1, 2, \dots, N\}. \quad (10)$$

Upon substituting $\boldsymbol{\theta_r^c} = [\theta_{r1}^c, \theta_{r2}^c, \dots, \theta_{rN}^c]^T$ in (4), we get

$$R_r(\boldsymbol{\theta_r^c}, k) = \frac{1}{2}\log_2\left(1 + \frac{P_t}{\sigma^2}\left(\left|h_{rk}^d\right| + \sum_{n=1}^{N}\beta_{rn}\left|h_{rn}g_{nk}\right|\right)^2\right). \quad (11)$$

Then, we substitute $R_r(\boldsymbol{\theta_r^c}, k)$ in (9) to obtain the set of antennas that satisfy the rate constraint in (6). For these

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antennas, we compute the phase shift that aligns the AP to T-user (AP-T) direct link channel gain $h_{tn}g_{nk}$ with the AP to STARS to T-user (AP-SR-T) cascaded link channel gain $h_{tn}g_{nk}$. It is given by

$$\theta_{tn}^{c} = \angle h_{tk}^{d} - \angle\left(h_{tn}g_{nk}\right), \quad n \in \{1, 2, \ldots, N\}. \tag{12}$$

Upon substituting $\boldsymbol{\theta_t^c} = [\theta_{t1}^c, \theta_{t2}^c, \ldots, \theta_{tN}^c]^T$ in (3), we get

$$R_t(\boldsymbol{\theta_t^c}, k) = \frac{1}{2}\log_2\left(1 + \frac{P_t}{\sigma^2}\left(\left|h_{tk}^{d}\right| + \sum_{n=1}^{N}\beta_{tn}\left|h_{tn}g_{nk}\right|\right)^2\right). \tag{13}$$

Then, we select an antenna $s$ that maximizes the T-user achievable rate, i.e.,

$$s = \underset{k \in \mathcal{F}(\boldsymbol{\theta_r^c})}{\arg\max}\left\{R_t(\boldsymbol{\theta_t^c}, k)\right\}. \tag{14}$$

The corresponding transmission and reflection phase shifts will be configured at the STARS. From the above, we see that the independent cophase AS rule exploits the flexibility of configuring the two phase-shifts independently. It configures the cophases for both the users, which maximizes the corresponding rates, and selects an antenna that maximizes the T-user rate among the antennas that satisfy the R-user rate constraint.

*2) Independent Random Phase AS Rule:* Here, for all the STARS elements, we chose the phase shifts $\theta_{tn}, \theta_{rn}$ from a uniform distribution, i.e., $\theta_{tn}, \theta_{rn} \sim \mathcal{U}[0, 2\pi]$. We denote these random phase shifts by $\theta_{rn}^{ra}$ and $\theta_{tn}^{ra}$. Let $\boldsymbol{\theta_r^{ra}} = [\theta_{r1}^{ra}, \theta_{r2}^{ra}, \ldots, \theta_{rN}^{ra}]^T$ and $\boldsymbol{\theta_t^{ra}} = [\theta_{t1}^{ra}, \theta_{t2}^{ra}, \ldots, \theta_{tN}^{ra}]^T$ denote the random phase shift vectors of the R-user and T-user, respectively. Then, we obtain the set of antennas $\mathcal{F}\left(\boldsymbol{\theta_r^{ra}}\right)$ that satisfy the R-user rate constraint by substituting $\boldsymbol{\theta_r^{ra}}$ in (9). For each of these antennas, we use (3) to obtain the rate achieved by the T-user. Then an antenna that maximizes the T-user rate given by $s = \arg\max_{k \in \mathcal{F}(\boldsymbol{\theta_r^{ra}})}\left\{R_t(\boldsymbol{\theta_t^{ra}}, k)\right\}$, is selected and the corresponding random phases are configured at the STARS.

### *B. Coupled Phase Shift Model*

Here, the phase shifts of T-user and R-user, i.e., $\theta_{tn}$ and $\theta_{rn}$ are coupled with each other, which happens for the passive lossless STARS. The coupling condition is given by $\beta_{tn}\beta_{rn}\cos(\theta_{tn} - \theta_{rn}) = 0$ [6]. For the ES mode considered, we know that $\beta_{tn} \neq 0$ and $\beta_{rn} \neq 0$. Therefore, the coupling condition reduces to

$$\theta_{tn} - \theta_{rn} = \frac{\pi}{2} \quad \text{or} \quad \frac{3\pi}{2}, \quad n \in \{1, 2, \ldots, N\}. \tag{15}$$

*1) T-user Cophase AS Rule:* Here, we compute the T-user cophase $\theta_{tn}^c$ in (12) as the transmission phase shifts. For the reflection phase shifts of the R-user, we first compute the possible phase shifts $\theta_{tn}^c - \frac{\pi}{2}$ and $\theta_{tn}^c - \frac{3\pi}{2}$ that satisfy the coupled condition in (15) and select the one that is closer to the R-user cophase $\theta_{rn}^c$ in (10). Among these two possibilities, let $\theta_{rn}^u$ denote the reflection phase shift selected for the R-user at the $n^{\text{th}}$ STARS element and $\boldsymbol{\theta_r^u} = [\theta_{r1}^u, \theta_{r2}^u, \ldots, \theta_{rN}^u]^T$. Then, we substitute this in (9) to obtain the feasible set $\mathcal{F}\left(\boldsymbol{\theta_r^u}\right)$, the set of antennas that satisfy the R-user rate constraint. Then, we compute the T-user achievable rate by substituting $\boldsymbol{\theta_t^c}$ in (3), for each antenna $k$ in $\mathcal{F}\left(\boldsymbol{\theta_r^u}\right)$. Finally, from the set $\mathcal{F}\left(\boldsymbol{\theta_r^u}\right)$ an antenna that maximizes the T-user achievable rate, i.e.,

$$s = \underset{k \in \mathcal{F}(\boldsymbol{\theta_r^u})}{\arg\max}\left\{R_t(\boldsymbol{\theta_t^c}, k)\right\}. \tag{16}$$

is selected and corresponding phases are configured at the STARS. Therefore, for each antenna $k$, the T-user cophase AS rule computes the cophase for the T-user and a phase shift that satisfies the coupled condition for the R-user. Then, it selects an antenna that maximizes the T-user rate among the antennas that satisfy the R-user rate-constraint.

*2) R-User Cophase AS Rule:* In this rule, unlike the T-user cophase AS rule, we compute the cophases of the R-user $\theta_{rn}^c$ in (10) as the reflection phase shifts for all the STARS elements. Then, we substitute $\boldsymbol{\theta_r^c}$ in (9) to obtain the set of antennas $\mathcal{F}\left(\boldsymbol{\theta_r^c}\right)$ that satisfy the R-user's rate constraint. For each antenna $k \in \mathcal{F}\left(\boldsymbol{\theta_r^c}\right)$, similar to that of the T-user cophase rule, we compute the two possibilities for transmission phase shift of the T-user that satisfy the coupled condition in (15) and select the phase shift $\theta_{tn}^u$ that is close to the cophase of the T-user $\theta_{tn}^c$ given in (12). Then, we compute the T-user's achievable rate by substituting the transmission phase shift vector of the T-user $\boldsymbol{\theta_t^u} = [\theta_{t1}^u, \theta_{t2}^u, \ldots, \theta_{tN}^u]^T$ in (3). Finally, the antenna $s$ that maximizes the T-user's achievable rate is selected as

$$s = \underset{k \in \mathcal{F}(\boldsymbol{\theta_r^c})}{\arg\max}\left\{R_t(\boldsymbol{\theta_t^u}, k)\right\}. \tag{17}$$

So, the R-user cophase AS rule configures cophase for the R-user and for the T-user it configures a phase shift that satisfies the coupled condition.

*3) Coupled Random Phase AS Rule:* In this rule, we generate reflection phase shifts of the R-user $\theta_{rn}^{ra}$ randomly in the range 0 to $2\pi$ for all the STARS elements from uniform distribution. Then, we substitute these random phase shifts in (9) to obtain the set of antennas $\mathcal{F}\left(\boldsymbol{\theta_r^{ra}}\right)$ that satisfy R-user rate constraint. For each antenna $k$ in $\mathcal{F}\left(\boldsymbol{\theta_r^{ra}}\right)$, for all the STARS elements, we compute the two possible coupled phase shifts of the T-user, using coupled condition in (15) and select one of them randomly with equal probability. Let $\theta_{tn}^{ra}$ and $\boldsymbol{\theta_t^{ra}}$ denote the selected T-user phase shift of the $n^{\text{th}}$ STARS element and the corresponding phase shift vector. Then, for each antenna $k$ in $\mathcal{F}\left(\boldsymbol{\theta_r^{ra}}\right)$, we obtain the T-user rate by substituting $\boldsymbol{\theta_t^{ra}}$ in (3). An antenna $s$ that maximizes the T-user's rate given by

$$s = \underset{k \in \mathcal{F}(\boldsymbol{\theta_r^{ra}})}{\arg\max}\left\{R_t(\boldsymbol{\theta_t^{ra}}, k)\right\}, \tag{18}$$

is selected. Here, R-user phase shifts are chosen randomly from uniform distribution and T-user phase shifts are chosen randomly from the two possibilities that satisfy the coupled condition.

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## IV. Numerical Results

In this section, we present the numerical results that study the performance of the proposed AS rules. The STARS made up of a uniform planar array (UPA) with element size of quarter wavelength is placed at $(0, 0, 0)$ along the $yz$ plane. The AP located at $(50, -50, 0)$ is equipped with a uniform linear array (ULA) with half wavelength spacing between the antennas [2]. As AP is located on the positive half space of the $x$-axis, i.e., $x \geq 0$, all the locations with positive $x$-coordinates form the reflection space and all the locations with the negative $x$-coordinates will form the transmission space. The R-user is positioned at $(5, 5, -10)$ and the T-user is positioned at $(-5, 5, -10)$. The path-loss of all the links are computed using $30 + 10\eta_p \log_{10}(d)$, where $\eta_p$ denotes the path-loss exponent and $d$ denotes the distance. We set $\eta_p = 3.6$ for the AP-T and AP-R direct links, which are modeled as Rayleigh fading, and $\eta_p = 2.2$ for remaining links (AP-SR, SR-T, and SR-R), which are modeled as Rician fading with strong LoS component ($K = 10$) [3], [6]. The carrier frequency is set to 2.4 GHz and the noise power for both users is set to $\sigma^2 = -104$ dBm. We consider equal energy splitting with $\beta_{tn} = \beta_{rn} = 1/\sqrt{2}, \forall n$, where all STARS elements transmit and reflect the incident signal simultaneously [4].

*Independent Phase Shift Model:* Figure 2 plots the achievable rate of the T-user as a function of the total transmit power at the AP for different number of STARS elements $N$. It compares the performance of the proposed independent cophase and random phase based AS rules. For both AS rules, we see that the rate increases as $P_t$ increases. Cophase based AS rule achieves higher rate as it chooses the phase shifts to align the direct link and the reflected links instead of choosing phase shifts randomly. For example, when $P_t = 26$ dBm, it achieves $1.39\times$, $1.56\times$, and $1.65\times$ higher rates for $N = 36, 100$, and 196, respectively. We see that the rate increases as $N$ increases for both AS rules. Furthermore, the increase is high for the cophase rule compared to that of the random phase rule. For example, as $N$ increases from 36 to 196, the rate of the cophase rule increase by $1.35\times$ and the rate of the random phase rule increases only by $1.14\times$.

*Coupled Phase Shift Model:* Figure 3 compares the performance of the AS rules proposed for the coupled phase shift model, i.e., T-user cophase AS rule, R-user cophase AS rule, and coupled random phase AS rule, with the independent cophase AS rule. It plots the T-user rate as a function of $P_t$ for different values of $N$. As expected, the rate increases as $P_t$ increases for all the AS rules. It also increases as $N$ increases. Among the coupled phase shift rules, T-user cophase rule achieves the highest rate as it chooses the transmission phase shift to align the direct link and the cascaded STARS link corresponding to the T-user. Its performance also matches with that of the independent cophase AS rule. We see that the gap between the T-user cophase and R-user cophase AS rules decreases as $N$ increases. For example, at $P_t = 10$ dBm, rate of the T-user cophase AS rule is $1.11\times$, $1.06\times$, and $1.03\times$ higher than the rate of the R-user cophase AS rule for $N = 36$, $N = 100$, and $N = 196$, respectively.

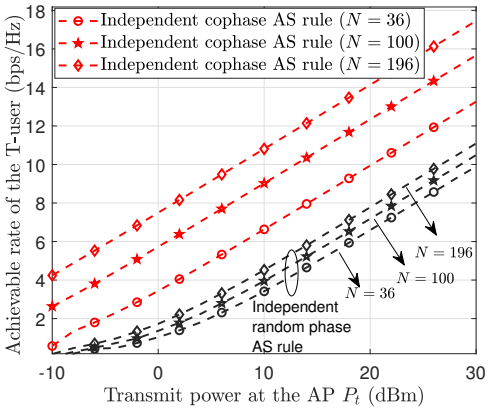



Fig. 2. The rate achieved by the T-user as a function of $P_t$ for different number of the STARS elements ($N_t = 4$ and $R_{\text{th}} = 0.5$ bps/Hz).

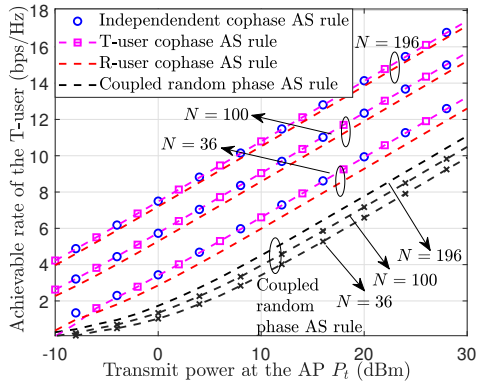



Fig. 3. The rate achieved by the T-user as a function of $P_t$ for different number of the STARS elements ($N_t = 4$ and $R_{\text{th}} = 0.5$ bps/Hz).

Figure 4 plots the T-user rate as a function of $N$ for different values of $P_t$. It compares the performance of all the proposed coupled phase shift model and independent phase-shift model AS rules. For all the AS rules, the rate increases as $N$ increases. We see that the slope is higher for small values of $N$ and it is small for larger values of $N$. Furthermore, the gap between the T-user cophase AS rule and R-user cophase AS rule decreases as $N$ increases. For example, with $P_t = 10$ dBm, rate achieved by the T-user cophase AS rule is $1.14\times$, $1.08\times$, and $1.03\times$ compared to R-user cophase AS rule for $N = 25$, $N = 64$, and $N = 196$, respectively. As $P_t$ increases, the gap further reduces. For example, with $P_t = 15$ dBm rate achieved by the T-user cophase AS rule is $1.12\times$, $1.06\times$, and $1.02\times$ the rate achieved by the R-user cophase AS rule for $N = 25$, $N = 64$, and $N = 196$, respectively.

Figure 5 plots the rate-outage probability of the R-user as a function of $P_t$ for different AS rules. Among all the AS rules, the rate-outage is lowest for the R-user cophase rule as it configures the reflection phase shifts that aligns the direct link

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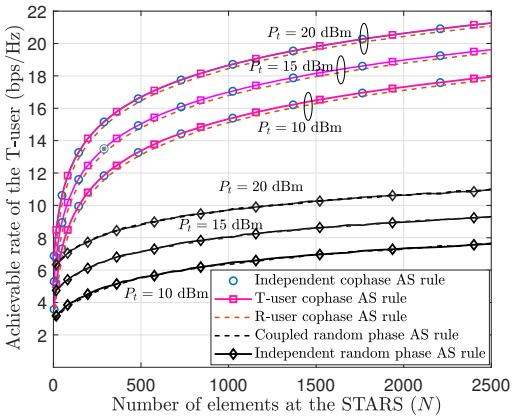



Fig. 4. The rate achieved by the T-user as a function of number of elements at the STARS ($N_t = 4$ and $R_{\text{th}} = 0.5$ bps/Hz).

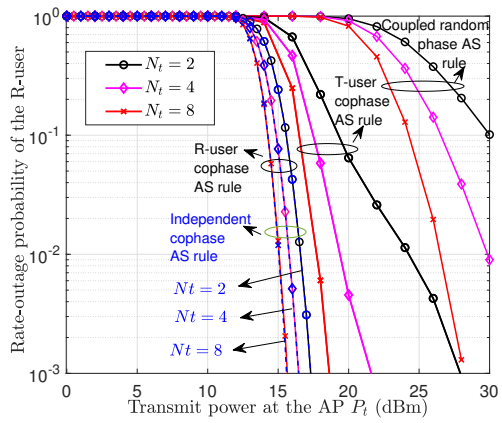



Fig. 5. The rate-outage probability of R-user as a function of $P_t$ for different number of antennas at the AP ($N = 36$ and $R_{\text{th}} = 4$ bps/Hz).

and the reflected links corresponding to the R-user. For small values of $P_t$, the rate-outage probability of all the AS rules is one as none of the antennas satisfy the R-user rate constraint. For large values of $P_t$, we see that the rate-outage decreases significantly as $P_t$ increases. For R-user cophase rule, the rate-outage probability at $P_t = 16$ dBm is $864\times$, $90\times$, and $14\times$ lower compared to the rate-outage probability at $P_t = 14$ dBm for $N_t = 8$, $N_t = 4$, and $N_t = 2$, respectively. Furthermore, the rate-outage decreases significantly as $N_t$ increases. At $P_t = 16$ dBm, the rate-outage is $10\times$ and $202\times$ lower for $N_t = 4$ and $N_t = 8$ when compared to $N_t = 2$.

## V. Conclusions

We considered both independent and coupled phase shift models and proposed AS rules that jointly selects an antenna at the AP and transmission and reflection phase shifts at the STARS to maximize the T-user rate subject to a minimum rate constraint at the R-user. Independent cophase rule exploited the flexibility and configured cophases for the transmission and the reflection phase shifts where as coupled phase shift rules had to adhere to the coupled condition. T-user cophase rule aligned the direct and cascaded links of the T-user and achieved highest rate among AS rules developed for the coupled phase shift model. On the other hand R-user cophase rule has shown lowest rate-outage probability as it aligned the direct and cascaded links of the R-user. Furthermore, we showed that the T-user cophase rule achieved a similar rate as that of the independent cophase rule in spite of the coupled condition. We showed that the gap between the performance of the R-user cophase rule and the T-user cophase rule reduced as the number of STARS elements increased. We saw that the increase in the number of STARS elements increased T-user rate significantly and increase in the number of antennas at the AP yielded a significant reduction in the rate-outage probability of the R-user.

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