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Fast Beam Splitting Technique for STAR-RISs with Coupled T&R Phase Shifts

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Abstract

A simultaneously transmitting and reflecting reconfigurable intelligent surface (STAR-RIS) aided communication system is investigated, where an access point sends information to multiple users located on both sides of the STAR-RIS. Different from prior works which assume that the phase-shift coefficients for transmission and reflection signals can be independently adjusted, a coupled transmission and reflection phase-shift model is considered. Based on this model, a fast beam splitting (FBS) technique is proposed for STAR-RISs to split signals into a multiple beams. Exploiting the FBS technique, the number of split beams can be controlled by using STAR-RIS with one-bit phase shifters and by reconfiguring only a small portion of its elements.

1 Introduction

Recently, the novel concept of simultaneously transmitting and reflecting reconfigurable intelligent surfaces (STAR-RISs) [1] has been proposed. In contrast to conventional reflecting-only RISs [2], the wireless signal incident on STAR-RISs is divided into the transmitted and reflected signals propagating into each side of the surface, thus achieving a full-space reconfigurable wireless environment. Therefore, by deploying STAR-RISs, transmitters and receivers do not have to be located on the same side of the surface assumed for the case of conventional reflecting-only RISs, thus enhancing flexibility. Motivated by this promising characteristic, growing research efforts have been devoted to investigating the benefits of deploying STAR-RISs in wireless networks. For example, the authors of [3] investigated the general hardware model and channel model for STAR-RISs, where the diversity gain achieved by STAR-RISs was analyzed. In [4], the authors proposed three practical operating protocols for STAR-RISs and studied the corresponding joint beamforming design problems in both unicast and multicast scenarios. In [5], different categories of STAR-RIS hardware implementations, hardware models, and channel models were discussed and compared.

Despite these advantages of the STAR-RIS, most existing research contributions [3, 4] assume that the phase-shift of transmission and reflection (T&R) coefficients can be independently adjusted, which requires that the corresponding electric and magnetic impedances can assume arbitrary values. This, however, may be impossible for passive lossless STAR-RISs whose electric and magnetic impedances are limited to purely imaginary numbers [6]. Following this line of research, the authors of [7] considered the correlation between T&R coefficients of each STAR-RIS element. In this case, the phase-shift coefficients for transmission and reflection are coupled with each other, which makes the transmission and reflection coefficient/beamforming design much more complicated than in existing works. Motivated by this, in this paper, we investigate how T&R coefficients are coupled for lossless STAR-RIS elements. Based on the coupled phase-shift model, we propose a fast beam splitting (FBS) technique for dividing the transmitted or reflected signal into multiple beams. This technique enables the STAR-RIS to split beams on one side of while maintaining a specular reflection/transmission on the other side. For the proposed FBS technique, we further reveal the configuration parameter that determines the number of split beams and use Monte Carlo method to simulate the resultant radiation pattern on both sides of the STAR-RIS.

2 A Coupled Phase Shift Model for Passive Lossless STAR-RISs

The T&R coefficients are the ratio between the complex amplitudes of the transmitted / reflected signals and the incident signal, which can be expressed in terms of the following forms:

$$T_m = \beta_m^T \cdot e^{j\phi_m^T}, \ \ R_m = \beta_m^R \cdot e^{j\phi_m^R}, \tag{1}$$

where β_m^T and $\beta_m^R \in [0,1]$ are the real-valued transmission and reflection amplitudes, respectively, and ϕ_m^T and $\phi_m^R \in [0,2\pi)$ are the corresponding phase-shift values for transmission and reflection.

In the following, let us inspect the constraints imposed on the T&R coefficients of STAR-RIS elements due to the law of energy conservation. We illustrate these constraints using the following diagram. In Fig 1, the circle is centered at point C with diameter OQ of length equals to one. If point P is in *Region I* (within the circle), $\vec{QP}$ and $\vec{OP}$ represent legitimate T&R coefficients for a passive lossy STAR-RIS. If point P is in *Region II* (outside of the circle), the corresponding T&R coefficients can only be achieved by an active element. If point P is on the circle, the corresponding

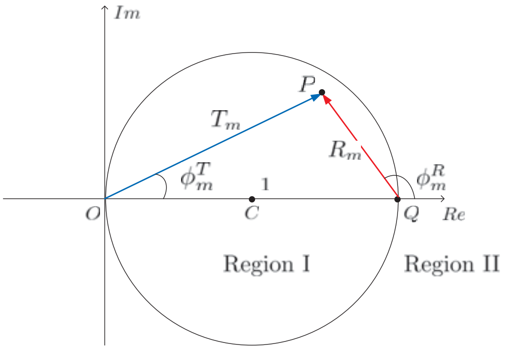

Figure 1. Illustration of T_m and R_m on the complex plane.

vectors represent the T&R coefficients for a lossless element, where the T&R coefficients follows:

$$|R_m|^2 + |T_m|^2 = 1, \tag{2}$$

or equivalently,

$$(\beta_m^R)^2 + (\beta_m^T)^2 = 1. \tag{3}$$

For a closer inspection, for the passive lossless STAR-RIS elements, we have $|R_m \pm T_m| = 1$ [6]. This is equivalent to the following correlation between the phase of T&R coefficients:

$$\phi_m^R - \phi_m^T = \frac{\pi}{2} + \nu_m \pi, \ \nu_m = 0 \text{ or } 1, \ \forall m = 1, 2, \cdots, M, \tag{4}$$

where M denotes the total number of STAR-RIS elements. ν_m is referred to as the *auxiliary bit*[1] for the lossless STAR-RIS in the following and provides an additional degree of freedom which links the possible phase shift values between the transmission and reflection coefficients.

3 The Fast Beam-Splitting Technique

In this section, we present the proposed FBS technique. Due to the new constraint introduced in (4), it is more challenging to optimize both the T&R phase shifts, especially for the case of multi-user broadcasting networks. As a remedy, the proposed FBS technique enables a passive lossless STAR-RIS with only one-bit phase-shift control to maintain specular reflection/transmission on one side[2] while achieving beam-splitting on the other side. In addition, the number of beams can be conveniently changed by only adjusting the phase shifts of a small portion of the elements. This can largely reduce the overhead and energy consumption of configuring the STAR-RIS before the beginning of each transmission. Without loss of generality, we investigate the case of carrying out beam-splitting on the transmitted signal in the rest of this paper. Consider the system illustrated in Fig. 2, a base station (BS) is communicating with multiple users on both sides. The line-of-sight links exist between BS and users on the reflecting side (Rrxs). However, line-of-sight links are blocked between the BS and the users on the opposite side of the wall (Rt1-RtN). A STAR-RIS is deployed on the wall to recover services for these users. Suppose that the users are spread out within the far-field region of the STAR-RIS on the y-z plane. The STAR-RIS need to split the transmitted signal into a number of N beams, which coincides with the number of transmitted users (Rtxs).

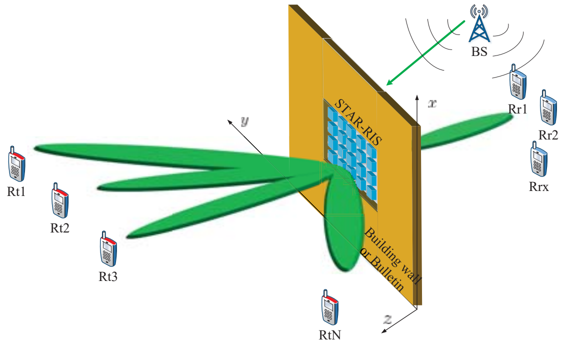

Figure 2. STAR-RIS for transmitted beam splitting.

According to (4), for the considered STAR-RIS implementation, the phase difference between the reflection and transmission coefficients can be either $\pi/2$ or $3\pi/2$. Thus, we assign one control bit, namely ν_m in (4), to each element to determine this phase difference. Since all users are located on the $x = 0$ plane, the STAR-RIS only needs to split the beams in the horizontal (azimuth) directions. Thus, all elements in the same column can be configured to the same phase shift. We denote the T&R phase shift coefficient of the mth element column by ϕ_m^T and ϕ_m^R. The FBS technique only requires the STAR-RIS configuring the phase shifts imposing on the transmitted signal of the mth element column as follows:

$$\phi_m^T = \begin{cases} (\phi_m^R - \frac{\pi}{2}) - \pi & \text{if } m \pmod p < q, \\ \phi_m^R - \frac{\pi}{2} & \text{otherwise,} \end{cases} \tag{5}$$

where ϕ_m^R is configured according to the cophase condition[3] to support specular reflection [2], p and q are integer parameters which control the number and relative strengths of beams produced by the FBS technique. In Table. 1, we give the number of split beams for some exemplary cases. As can be seen from the table, for $p > 3$, the number of transmitted beam generated by the proposed FBS technique is equal to $2 * (p - 3) + 1$. Moreover, only $1/p$ of the total number of element need to be reconfigured to have trans-

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[1] ν_m can only take on two values, 0 or 1. Thus, its value represents the two possible phase difference between ϕ_m^R and ϕ_m^T, i.e., the phase difference is either $\pi/2$ or $3\pi/2$.

[2] Here, *specular* reflection/transmission means the smart surface maintain the specular component of the incident beam.

[3] According to the cophase condition, the reflection coefficient can be determined as $\phi_m^R = \angle h_d^R - \angle h_{cas,m}^R$, where $\angle h_d^R$ is the phase of the direct BS-Rrx link, and $h_{cas,m}^R$ is the cascaded channel from BS to Rrx through the mth element.

p	3	4	5	6	7
Number of beams	3	3	5	7	9
Percentage of elements need to be configured	33%	25%	20%	16.7%	14.3%

Table 1. Number of split beams and the percentage of elements need to be reconfigured for different values of p, $q = 1$.

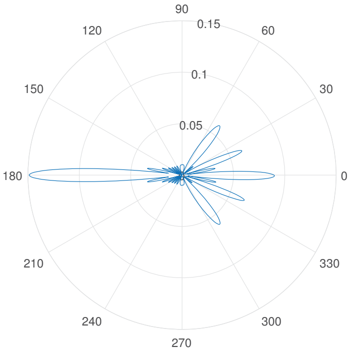

Figure 3. Radiation pattern for $p = 5$.

mission coefficient different from the remaining ones. In the following section, we numerically verify this result.

4 Numerical Results

In this section, simulation results are provided to demonstrate the proposed FBS technique for STAR-RISs. For our simulations, we assume that the STAR-RIS is a uniform planar array consisting of $M = 18 \times 18$ elements. The spacing between adjacent elements is half of the carrier wavelength. We plot the radiation patterns generated by the STAR-RIS employing the proposed FBS technique with $q = 1$. For each figure, the left half of the sphere (angle range from 90° to 270°) is the reflection side while the right half is the transmission side. The STAR-RIS is placed alongside the 90°-270° direction. As shown in Fig. 3, for the case of $p = 5$, there are five distinct beams generated on the transmission side while specular reflection is maintained on the reflection side. It can be observed that all split beams have relatively the same power levels and are evenly spread on the transmission side. In Fig. 4, for the case of $p = 6$, there are nine beams on the transmission side. According to the simulation, there are two beams point in the direction of 90° and 270°. In reality, however, signal power in these directions are especially weak due to the effect of reduced receiving cross-section and the leaning factor [3]. As a result, these two beams are not counted in Table. 1.

5 Conclusion and Outlook

In this paper, a coupled T&R phase-shift model for STAR-RISs was proposed. Based on the model, we presented a FBS technique for STAR-RIS to split incident signal into multiple beams using only one-bit phase shift and a small portion of elements. Future directions for the study of STAR-RISs include optimizing the amplitude of the T&R phase-shift coefficients, designing network with multiple STAR-RISs, and considering the frequency respond of STAR-RIS for wideband communications.

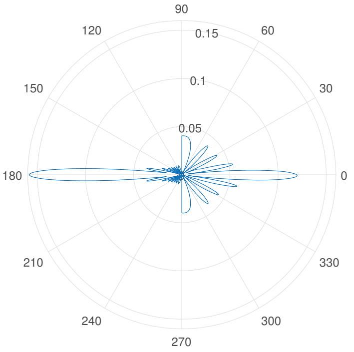

Figure 4. Radiation pattern for $p = 6$.

References

[1] Y. Liu, X. Mu, J. Xu, R. Schober, Y. Hao, H. V. Poor, and L. Hanzo, "STAR: Simultaneous transmission and reflection for 360° coverage by intelligent surfaces," *accepted for publication in IEEE Wireless Commun., Available: arXiv:2103.09104*, 2021.

[2] Y. Liu, X. Liu, X. Mu, T. Hou, J. Xu, M. Di Renzo, and N. Al-Dhahir, "Reconfigurable intelligent surfaces: Principles and opportunities," *IEEE Commun. Surv. Tutor.*, vol. 23, no. 3, pp. 1546–1577, 2021.

[3] J. Xu, Y. Liu, X. Mu, and O. A. Dobre, "STAR-RISs: Simultaneous transmitting and reflecting reconfigurable intelligent surfaces," *IEEE Commun. Lett.*, vol. 25, no. 9, pp. 3134–3138, May, 2021.

[4] X. Mu, Y. Liu, L. Guo, J. Lin, and R. Schober, "Simultaneously transmitting and reflecting (STAR) RIS aided wireless communications," *IEEE Trans. Wireless Commun.*, Early Access, 2021, doi: 10.1109/TWC.2021.3118225.

[5] J. Xu, Y. Liu, X. Mu, J. T. Zhou, L. Song, H. V. Poor, and L. Hanzo, "Simultaneously transmitting and reflecting (STAR) intelligent omni-surfaces, their modeling and implementation," *arXiv preprint arXiv:2108.06233*, 2021.

[6] B. O. Zhu, K. Chen, N. Jia, L. Sun, J. Zhao, T. Jiang, and Y. Feng, "Dynamic control of electromagnetic wave propagation with the equivalent principle inspired tunable metasurface," *Sci. rep.*, vol. 4, no. 1, pp. 1–7, 2014.

[7] J. Xu, Y. Liu, X. Mu, R. Schober, and H. V. Poor, "STAR-RISs: A correlated t&r phase-shift model and practical phase-shift configuration strategies," *arXiv preprint arXiv:2112.00299*, 2021.