STAR: Simultaneous Transmission and Reflection for 360° Coverage by Intelligent Surfaces

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Abstract
A novel simultaneous transmitting and reflecting (STAR) system design relying on reconfigurable intelligent surfaces (RISs) is conceived. First, an existing prototype is reviewed, and the potential benefits of STAR-RISs are discussed. Then the key differences between conventional reflecting-only RISs and STAR-RISs are identified from the perspectives of hardware design, physical principles, and communication system design. Furthermore, the basic signal model of STAR-RISs is introduced, and three practical protocols are proposed for their operation, namely energy splitting, mode switching, and time switching. Based on the proposed protocols, a range of promising application scenarios are put forward for integrating STAR-RISs into next-generation wireless networks. By considering the downlink of a typical RIS-aided multiple-input single-output system, numerical case studies are provided for revealing the superiority of STAR-RISs over other baselines when employing the proposed protocols. Finally, several open research problems are discussed.

Introduction
With the rapid development of metasurfaces and the corresponding fabrication technologies, reconfigurable intelligent surfaces (RISs) and their diverse variants have emerged as promising techniques for sixth-generation (6G) wireless networks. Generally speaking, RISs are 2D structures comprising a large number of low-cost reconfigurable elements. By employing a smart controller (e.g., a field-programmable gate array, FPGA) attached to the RIS, both the phase and the amplitude of these reconfigurable elements can be beneficially controlled, thus reconfiguring the propagation of the incident wireless signals and realizing a “smart radio environment” (SRE) [1].

Although some recent studies have considered both transmissive and reflective metasurfaces for wireless communications (as discussed below), the existing contributions mainly focus on RISs whose only function is to reflect an incident signal; hence, both the source and the destination have to be on the same side of the RIS (i.e., within the same half-space of the SRE). This topological constraint limits the flexibility of employing conventional RISs, and to address this issue, we propose the concept of simultaneous transmitting and reflecting RISs (STAR-RISs) [6], where the incident wireless signals can be reflected within the half-space of the SRE at the same side of the RIS, but they can also be transmitted into the other side of the RIS. As a result, a full-space SRE can be created by STAR-RISs.

From Conventional Reflecting-Only RISs to STAR-RISs: A Prototype
We commence by providing a brief introduction to three types of signal propagation, namely full reflection, full transmission, as well as simultaneous transmission and reflection, based on a prototype developed by researchers from NTT DOCOMO, Japan [7]. Figure 1a depicts NTT DOCOMO’s prototype, where a metasurface is covered by a transparent substrate made of glass. By modifying the distance between the entire metasurface and the transparent substrate, the aforementioned three types of signal propagation can be achieved [7], as shown in Figs. 1b-1d. For the full reflection scenario of Fig. 1b, the incident signals are completely reflected and cannot penetrate the surface. This type of wireless signal manipulation is widely investigated for conventional reflecting-only RISs. In contrast, for the full transmission scenario of Fig. 1c, all incident signals pass through the surface into the transmission space, while no signal is reflected. Finally, for the simultaneous transmission and reflection scenario of Fig. 1d, the incident signals are divided into two parts by the surface. Part of the signal is reflected to the reflection space, while the remaining part is radiated into the transmission space, thus facilitating the full-space manipulation of signal propagation.

1 From a physical perspective, transmission and reflection refer to the two fundamental physical processes of electromagnetic wave propagation through the surface. In this article, we use the term “transmission” to describe the passive signal refraction process instead of the process of actively producing a signal.
**Key Advantages and Motivations for Employing STAR-RISs in Wireless Communication Systems**

Considering the above unique features, the employment of STAR-RISs has the following advantages in wireless communication systems:

1. Thanks to their capability of simultaneously transmitting and reflecting the incident signals, the coverage of STAR-RISs is extended to the entire space, thus serving both half-spaces using a single RIS, which is not possible for conventional reflecting-only RISs.

2. STAR-RISs provide enhanced degrees of freedom (DoFs) for signal propagation manipulation, which significantly increases the design flexibility in satisfying stringent communication requirements.

3. Since STAR-RISs are generally designed to be optically transparent [7], they are aesthetically pleasing and readily compatible with existing building structures such as windows. Therefore, STAR-RISs will have no undesired aesthetic effect, which is of vital importance for practical implementations.

As noted above, the joint manipulation of transmission and reflection is not a new idea, especially from the perspectives of the physical and meta-surface technology. Apart from the above NTT DOCOMO prototype [7], the authors of [8–10] also proposed concepts similar to STAR [6]. In [8], the authors reported frequency-selective reflection and transmission of signals by using a dual-band bi-functional metasurface structure. The authors of [9] proposed an intelligent omni-surface (IOS), where the signals transmitted and reflected by an IOS element are adjusted via a common phase shift. For the STAR-RISs in this work, the transmitted and reflected signals can be simultaneously reconfigured by each element via two generally independent coefficients, namely the transmission and reflection coefficients [6]. This distinct characteristic facilitates the flexible design of STAR-RIS-aided wireless networks. However, the wireless communication design of STAR-RISs is still in its infancy. This motivates us to provide a systematic introduction to STAR-RISs, including the fundamental differences from conventional reflecting-only RISs, the basic signal model, and practical operating protocols for STAR-RISs, complemented by their promising application scenarios and performance evaluation.

The main contributions of this article can be summarized as follows:

- The differences between conventional reflecting-only RISs and STAR-RISs are identified from the perspectives of hardware design, physical principles, and communication system design. In particular, the importance of exploiting both the electric and magnetic properties for achieving STAR is highlighted.
- A basic signal model for incorporating STAR-RISs in wireless communications is introduced, and three practical protocols for operating STAR-RISs, namely energy splitting (ES), mode switching (MS), and time switching (TS), are presented along with their benefits and drawbacks.
- A range of promising application scenarios of STAR-RISs in wireless networks are proposed in both outdoor and indoor environments.
- The performance of STAR-RISs for different operating protocols is studied and compared with those of other baselines in a downlink multiple-input single-output (MISO) system for both unicast and multicast scenarios.

**Key Differences between Reflecting-Only RISs and STAR-RISs**

In this section, we discuss the key differences between conventional reflecting-only RISs and the proposed STAR-RISs from their hardware design, physical principles, and communication system design perspectives, respectively. We highlight that STAR-RISs rely on substrates, which are transparent at RF and have elements that support magnetic currents. These structural properties allow STAR-RISs to achieve simultaneous and independent control of their transmission and reflection coefficients.

**Hardware Design Differences**

Reflecting-only RISs and STAR-RISs are different in terms of both their equipped elements and substrates. The following analogy illustrates the structural differences between reflecting-only RISs and STAR-RISs. For reflecting-only RISs, the reconfigurable elements on the substrate are like *biscuits placed on a metal plate*, as illustrated in Fig. 2a, while for STAR-RISs, the reconfigurable elements are like *ice cubes in a glass of water*, as illustrated in Fig. 2b. To elaborate, the substrates of reflecting-only RISs are opaque for wireless signals at their operating frequency. The opaque substrate serves as a bed on which the tunable elements are integrated. It also prevents the wireless signals from penetrating the RIS so that no energy is leaked into the space behind the RIS. In contrast, the substrates of STAR-RISs have to be transparent for wireless signals at their operating frequency. Naturally, for facilitating simultaneous transmission and reflection, STAR-RISs rely on a more complex design, since...
their elements have to support both electric and magnetic currents. A beneficial practical hardware design is to employ an equivalent principle inspired tunable metasurfaces [11, 12], where each element is composed of a parallel resonant LC tank and small metallic loops to provide the required electric and magnetic surface reactance. Moreover, the electric and magnetic reactance of each element can be adjusted by applying different bias voltages to the integrated varactors, thus achieving independent control of transmission and reflection.

**Physical Principles Differences**

Again, compared to conventional reflecting-only RISs, STAR-RISs must have elements that support both electric polarization currents $J_e$ and magnetization currents $J_m$ [12, 13]. The physical principles behind STAR-RISs can be summarized in three steps, namely induction, production, and radiation, as illustrated in Fig. 2.

- First, the elements are polarized by the incident field. The patch elements of pure reflecting RISs only respond to the electric component of the incident field, and a polarization density $P$ is induced. In contrast, the elements of STAR-RISs respond to both the electric and magnetic components of the incident field. Hence, both a polarization density $P$ and a magnetization density $M$ are induced. The strengths of the polarization and magnetization densities depend on the electric susceptibility $\chi_e$ and magnetic susceptibility $\chi_m$, respectively. The tunable parameters of the elements can be used to adjust the values of these susceptibilities within a certain quantization error.

- Second, the oscillating polarization and magnetization densities produce time-varying electric polarization and magnetization currents on the surface, respectively.

- Last, these time-varying currents radiate both the transmitted and reflected fields back into free-space, producing phase differences between the incident field and the transmitted or reflected fields.

As illustrated in Fig. 2a, reflecting-only RISs with non-magnetic elements can only support surface electric polarization currents. If the elements consist of only single-layered metallic scatters (not considering the substrate), the radiated fields on both sides of the RIS are identical [14]. Thus, this symmetry limitation of non-magnetic RISs does not facilitate independent control of the transmitted and reflected signals. On the contrary, by also supporting magnetic currents, STAR-RISs break this symmetry limitation and can achieve simultaneous control of both the transmitted and reflected signals [13]. As illustrated in Fig. 2b, assuming the electric and magnetic susceptibilities of each element are constant, the magnetization density $M$ introduces extra DoFs by enabling the independent adjustment of the phase shift for transmission.

**Communication System Design Differences**

From the perspective of communication system design, the benefits of supporting surface magnetic currents in STAR-RISs can be exploited as follows:

- **Adjustable energy ratio:** The amplitudes of the transmitted and reflected waves of each STAR-RIS element can be dynamically adjusted. Since the overall energies of the transmitted and reflected signals are determined by the magnitudes of the respective complex-valued sums of the contributions of all elements, the energy ratio between the transmitted and reflected signals can be conveniently controlled.

- **Independent beamforming:** Again, the introduction of surface magnetic currents enables independent phase shift control for the transmitted and reflected signals. As a result, STAR-RISs allow independent beamforming for both the transmitted and reflected signals within two half-spaces. The ability of independent beamforming implies that the STAR-RIS is capable of steering both the transmitted and reflected beam in the desired direction, thus improving the flexibility of communication system design.

**Basic Signal Model and Practical Operating Protocols**

In this section, we introduce the basic signal model for STAR-RISs and then propose three practical operating protocols for integrating STAR-RISs into wireless communication systems, while identifying their respective advantages and disadvantages.

**Basic Signal Model**

As discussed in the previous section, STAR-RISs are capable of independently controlling the transmitted and reflected signals, which introduces additional DoFs that can be exploited. To characterize this unique feature, for a STAR-RIS having $M$ elements, let $s_m$ denote the signal incident upon the $m$th element. After being reconfigured by the corresponding transmission and reflection coefficients, the signals transmitted and reflected by the $m$th element are given by

$$\left(\sqrt{\beta_m} e^{j\theta_m}\right) s_m$$

and

$$\left(\sqrt{\beta'_m} e^{j\theta'_m}\right) s_m,$$

respectively. In particular, $\sqrt{\beta_m}, \sqrt{\beta'_m} \in [0, 1]$ and $\theta_m, \theta'_m \in [0, 2\pi]$ characterize the amplitude and phase shift adjustments imposed on the incident signal facilitated by the $m$th element during transmission and reflection, respectively. The
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Promising Applications of STAR-RISs in 6G

Having presented practical protocols for operating STAR-RISs, in this section, we discuss several attractive applications of STAR-RISs in next-generation networks for both outdoor and indoor environments, as illustrated in Fig. 4.

| Protocols | Optimization variables | Advantages | Disadvantages |
|-----------|------------------------|------------|---------------|
| ES        | • Amplitude and phase shift coefficients of each element for transmission and reflection | High flexibility | Large number of design variables |
| MS        | • Mode selection of each element | Easy to implement | Reduced transmission and reflection gain |
| TS        | • Time allocation | Independent T and R design | High hardware implementation complexity |

The adjustments of the phase shifts for transmission and reflection can generally be chosen independent of each other [6]. However, the transmission and reflection amplitude coefficients must obey the law of energy conservation: the sum of the energies of the transmitted and reflected signals has to be equal to the incident signal’s energy. Hence, the sum of $\beta_{\text{tm}}$ and $\beta_{\text{rm}}$ should be equal to one [6]. Accordingly, by adjusting the amplitude coefficients used for both transmission and reflection, each STAR-RIS element can be operated in full transmission mode (referred to as T mode), full reflection mode (referred to as R mode), or simultaneous transmission and reflection mode (referred to as T&R mode). Based on the above basic signal model of STAR-RISs, in the following, we propose three practical protocols for operating STAR-RISs in wireless networks, namely energy splitting (ES), mode switching (MS), and time switching (TS), as illustrated in Fig. 3.

**Energy Splitting**

For ES, all elements of the STAR-RIS are assumed to operate in T&R mode, as shown in Fig. 3a. For given transmission and reflection amplitude coefficients, the signals incident upon each element are split into transmitted and reflected signals having different energy. In a practical implementation, the amplitude and phase shift coefficients of each element for transmission and reflection can be optimized jointly for achieving diverse design objectives in wireless networks.

**Mode Switching**

In MS, all elements of the STAR-RIS are partitioned into two groups. Specifically, one group contains the elements that operate in T mode, while the other group contains the elements operating in R mode. As shown in Fig. 3b, an MS STAR-RIS can be viewed as being composed of a conventional reflecting-only RIS and a transmitting-only RIS of reduced sizes. For this protocol, the element-wise mode selection and the corresponding transmission and reflection phase shift coefficients can be optimized jointly. The resulting “on-off” type of protocol (i.e., transmission or reflection) makes MS easy to implement. However, the drawback is that MS generally cannot match the transmission and reflection gain of ES, since only a subset of the elements are selected for transmission and reflection, respectively.

**Time Switching**

In contrast, the STAR-RIS employing the TS protocol periodically switches all elements between T mode and R mode in orthogonal time slots (referred to as T period and R period), as illustrated in Fig. 3c. This is like switching “venetian blinds” in different time slots. The fraction of time allocated to fully transmitting and fully reflecting signals can be optimized to strike a balance between the communication qualities of the front and back sides. Compared to ES and MS, the advantage of TS is that, for a given time allocation, the transmission and reflection coefficients are not coupled; hence, they can be optimized independently. Nevertheless, periodically switching the elements imposes stringent time synchronization requirements, thus increasing the implementation complexity compared to the ES and MS.

In Table 1, we summarize the unique ES, MS, and TS optimization variables, and identify their respective advantages and disadvantages.

![FIGURE 3](image_url) Illustration of three practical protocols for operating STAR-RISs: a) energy splitting (ES); b) mode switching (MS); c) time switching (TS).
One of the most promising applications of STAR-RISs is to improve the coverage area/quality of wireless networks, especially when the links between the base stations (BSs) or access points (APs) and users are severely blocked by obstacles (e.g., trees along roads, buildings, and metallic shells of vehicles). As shown at the top right of Fig. 4, STAR-RIS-aided coverage extension can be loosely divided into three scenarios, namely outdoor, outdoor-to-indoor, and indoor.

In outdoor communications, similar to conventional reflecting-only RISs, STAR-RISs can be mounted on building facades and roadside billboards to create an additional communication link. More innovatively, STAR-RISs can also be accommodated by the windows of vehicles (e.g., cars, aircraft, and cruise ships) to enhance the signal strength received inside by exploiting their transmission capability, thus extending the coverage area/quality of BSs and satellites. For outdoor-to-indoor communications, the severe penetration loss caused by building walls gravely restricts the coverage provided by outdoor BSs, especially in mmWave and THz communications. In fact, STAR-RISs constitute an efficient technique for creating an outdoor-to-indoor bridge as illustrated in Fig. 4. For indoor communications, STAR-RISs are more appealing than conventional reflecting-only RISs. As conventional reflecting-only RISs merely achieve half-space coverage, the signals emerging from the AP may require multihop bounces for reaching the target user. However, by exploiting both transmission and reflection, the resultant full-space coverage may reduce the propagation distance, thus increasing the received signal power.

An example where conventional reflecting-only RISs require two hops, whereas the STAR-RIS needs only a single hop, is illustrated at the middle right of Fig. 4. In a nutshell, STAR-RISs substantially outperform conventional reflecting-only RISs, since they not only possess the same capabilities as conventional reflecting-only RISs but also support additional design options due to their transmission capability.

Non-orthogonal multiple access (NOMA) is a promising next-generation candidate facilitating flexible resource allocation, high spectrum efficiency, and support for massive connectivity. For NOMA to achieve a high performance gain over orthogonal multiple access (OMA), it is important to pair users having different channel conditions. However, for conventional reflecting-only RISs, the benefits of NOMA may not be fully reaped since the channel conditions of users in the local reflected space are generally similar. Exploiting STAR-RISs facilitates a more beneficial communication framework, namely transmission-reflection NOMA, where a pair of users at the transmission- and reflection-oriented side can be grouped together for supporting NOMA, as shown at the bottom left of Fig. 4. By optimizing the transmission and reflection coefficients of the proposed ES or MS protocol, sufficiently different transmitted and reflected channel conditions can be achieved, thus enhancing the NOMA gain.

CoMP Communication via Transmission and Reflection
For realistic multi-cell communication networks, the performance of cell edge users cannot be guaranteed due to the strong inter-cell interference. Coordinated multipoint (CoMP) communication...
efficiently mitigates the inter-cell interference. In the middle left of Fig. 4, a beneficial STAR-RIS-aided CoMP scenario is presented. In particular, several multiple-antenna BSs are employed for cooperatively supporting a cell edge user, referred to as CoMP-user. Additionally, each BS serves an additional cell center user, referred to as non-CoMP-user. A STAR-RIS is deployed in each cell where the CoMP-user is located in the transmission half-space, while the non-CoMP-user is located in the reflection half-space. The advantages of this implementation are that on one hand, the received signal-to-interference-plus-noise ratio (SINR) of the CoMP-user can be enhanced through the design of the cooperative transmission coefficients of all STAR-RISs, while on the other hand, the reflection coefficients of each STAR-RIS can be optimized for mitigating the intra-cell interference received from the cell edge user by each non-CoMP-user.

**Full-Space Physical Layer Security**

RISs are also capable of improving the physical layer security (PLS), where the channel conditions of eavesdroppers can be degraded by degrading their signal propagation. However, for conventional reflecting-only RIS-aided secure communication, the legitimate users and eavesdroppers are assumed to be located at the same side of the RISs, even though this idealized simplifying assumption may not hold in practice. Fortunately, STAR-RISs come to the rescue. Observe at the top left of Fig. 4 that with the assistance of full-space STAR-RIS propagation, PLS can be enhanced regardless of the eavesdropper location.

**Indoor Localization and Sensing**

By overcoming signal blockages and providing full-space coverage, STAR-RISs are capable of improving both the localization and sensing capability of wireless networks, especially in indoor environments. As illustrated at the bottom right of Fig. 4, the employment of STAR-RISs in smart factories improves the positioning of mobile robots and the data rate of control links.

There are also other promising application scenarios for STAR-RISs in 6G networks, such as STAR-RIS-aided simultaneous wireless information and power transfer (SWIPT), STAR-RIS-assisted visible light communications (VLC), STAR-RIS-aided mmWave/THz communications, and STAR-RIS-augmented robotic communications. These applications constitute interesting future research directions.

**Numerical Case Studies**

In this section, we present numerical examples to characterize the performance of STAR-RISs employing the proposed operating protocols and to compare them with other baselines. More specifically, we consider the case where a two-antenna AP communicates with two single-antenna users with the aid of a STAR-RIS having $M$ elements. One user is located in the STAR-RIS’s transmission half-space, referred to as T user, and the other user is located in the reflection half-space, referred to as R user. The geographical setup is shown in Fig. 5a. The direct AP-user links are assumed to be blocked, and only the STAR-RIS transmission/reflection-side AP-user links are available.

For the setup considered, we investigate both unicast and multicast scenarios. In particular, the AP sends different messages to different users in the unicast scenario, while conveying a common message to both users in the multicast scenario. For each scenario, the active beamforming at the AP and the transmission and reflection coefficients of the STAR-RIS employing different protocols are jointly optimized for minimizing the transmit power required to satisfy the target user rates [15]. For comparison, two baselines are considered. For baseline 1, the full-space coverage is achieved by employing one conventional reflecting-only RIS and one transmitting-only RIS, each of which has $M/2$ elements. For baseline 2, the full-space coverage is achieved by an omni-surface proposed in [9], where each element is assumed to have identical transmission and reflection coefficients.

Figures 5b and 5c show that for STAR-RISs with different operating protocols and those baseline schemes in both scenarios, the minimum required transmit power decreases upon increasing $M$, since a higher transmission/reflection gain can be achieved. Regarding the performance of STAR-RISs, it is interesting to observe that TS achieves the best performance in the unicast scenario, whereas ES is preferable in the multicast scenario. This is because TS achieves interference-free communication for each user in the unicast scenario. In contrast, since the multicast scenario does not introduce inter-user interference, ES exploits...
The unique differences between the proposed STAR-RISs and conventional reflecting-only RISs have been discussed from the perspectives of the hardware design, physical principles, and communication system design. Furthermore, three practical operating protocols have been proposed for STAR-RISs, and their benefits and drawbacks have been highlighted.

The proposed STAR concept introduces new research challenges for the spatial analysis of RIS-aided large-scale networks, since transmission and reflection are determined by both the spatial locations and orientations of the involved nodes. To facilitate the application of the powerful stochastic geometry tools for performance analysis, new point processes that can capture the randomness of the angle-related spatial distributions have to be developed for the APs, STAR-RISs, and users.

- **Spatial analysis of STAR-RIS-aided networks using stochastic geometry:** The proposed STAR concept introduces new research challenges for the spatial analysis of RIS-aided large-scale networks, since transmission and reflection are determined by both the spatial locations and orientations of the involved nodes. To facilitate the application of the powerful stochastic geometry tools for performance analysis, new point processes that can capture the randomness of the angle-related spatial distributions have to be developed for the APs, STAR-RISs, and users.

- **Channel estimation for STAR-RISs:** Due to the near-passive nature of RISs, the acquisition of accurate channel state information is a nontrivial task in the face of having both transmission and reflection links. On one hand, based on the TS protocol, the transmission and reflection links can be consecutively estimated, thus achieving high accuracy, but at the cost of considerable pilot-overhead. On the other hand, the channels for the two links can also be simultaneously estimated based on the ES protocol, hence reducing the pilot-overhead. The development of efficient channel estimation methods for striking an attractive trade-off between the performance and overhead requires further research.

- **Deployment strategies for STAR-RISs:** Since STAR-RISs provide full-space 360° coverage, the corresponding deployment design problem raises a lot of challenging questions, especially for realistic multi-user scenarios. The deployment locations of STAR-RISs have to be carefully chosen to balance the number of users in the transmission and reflection half-spaces. This constitutes an interesting but challenging new research problem.

**Concluding Remarks and Future Research**

The unique differences between the proposed STAR-RISs and conventional reflecting-only RISs have been discussed from the perspectives of hardware design, physical principles, and communication system design. Furthermore, three practical operating protocols have been proposed for STAR-RISs, and their benefits and drawbacks have been highlighted. Moreover, several promising application scenarios for STAR-RISs in wireless networks have been identified for both outdoor and indoor environments. Through numerical case studies, the performance of STAR-RISs has been evaluated and compared to other baseline schemes in both unicast and multicast scenarios. However, the investigation of STAR-RISs is still at a very early stage, and there are numerous open research problems, some of which are exemplified below:

- **Spatial analysis of STAR-RIS-aided networks using stochastic geometry:**
- **Channel estimation for STAR-RISs:**
- **Deployment strategies for STAR-RISs:**

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