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Simultaneously transmitting and reflecting (STAR) RISs for 6G: fundamentals, recent advances, and future directions

Key words: Sixth-generation wireless communication (6G); Reconfigurable intelligent surface (RIS); Smart radio environment; Simultaneous transmission and reflection

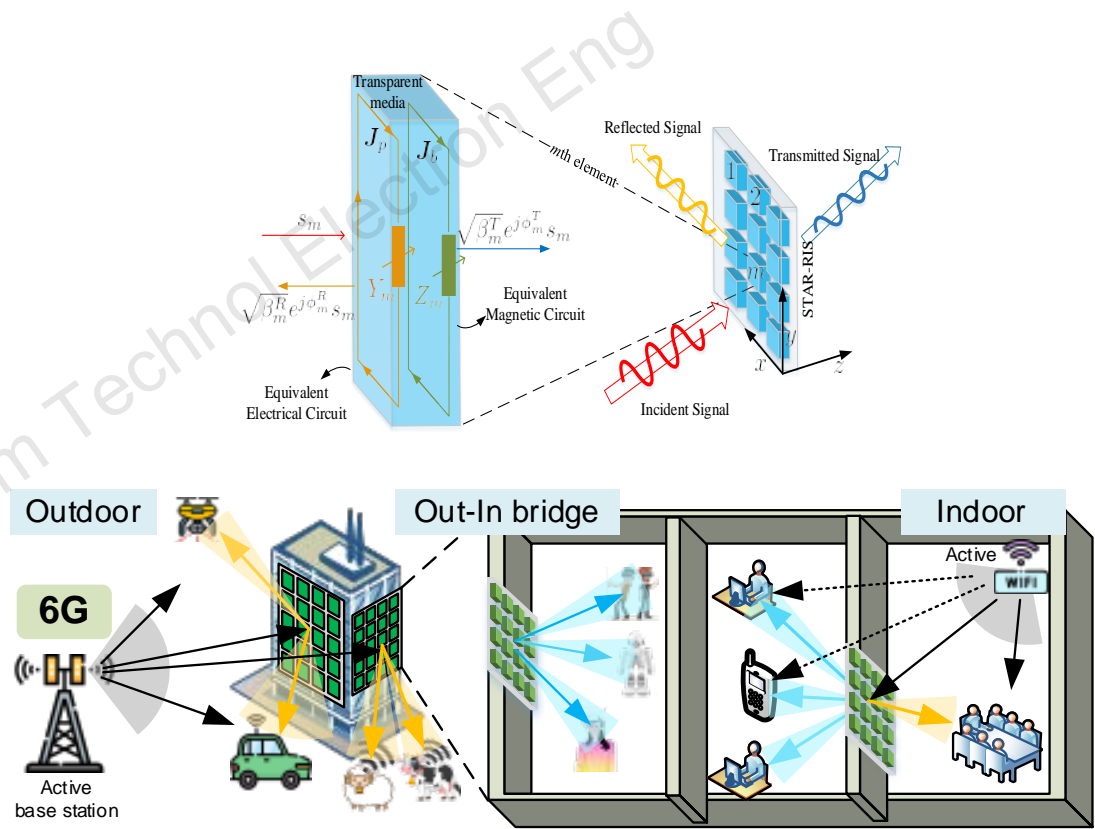
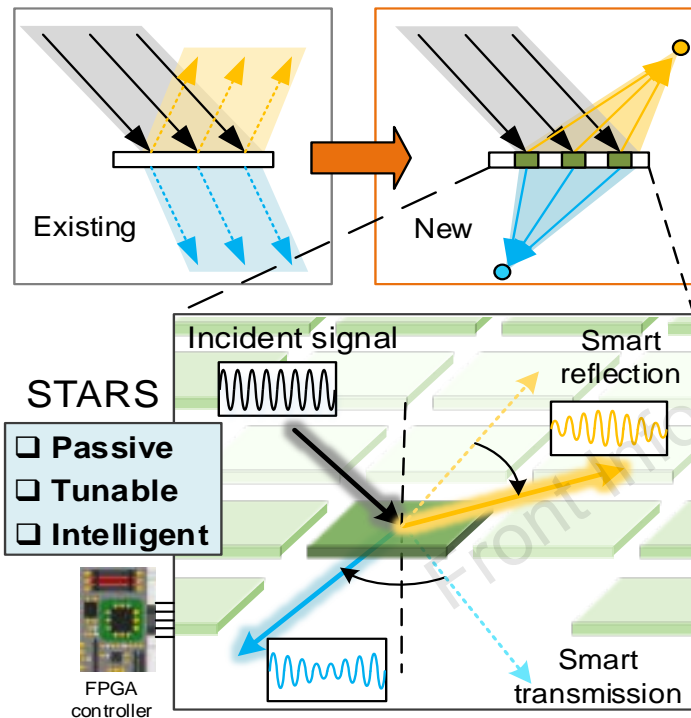
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Key advantages of STAR-RISs

- ❑ **360° coverage:** the coverage is extended to the entire space
- ❑ **Enhanced degrees-of-freedom:** generally independent transmission and reflection

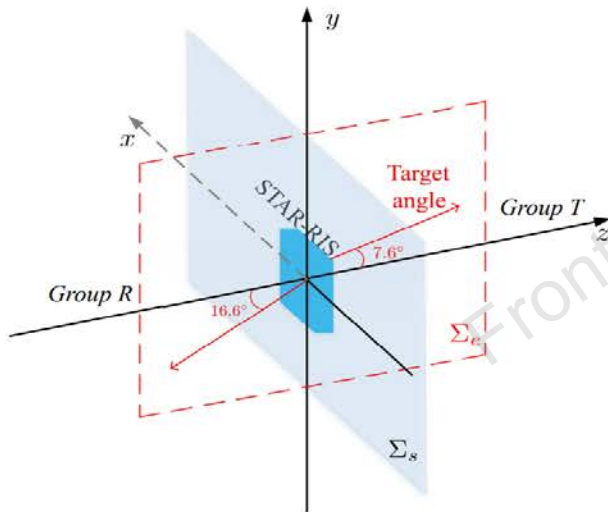


Comparison with conventional RISs

❑ Simulation setup

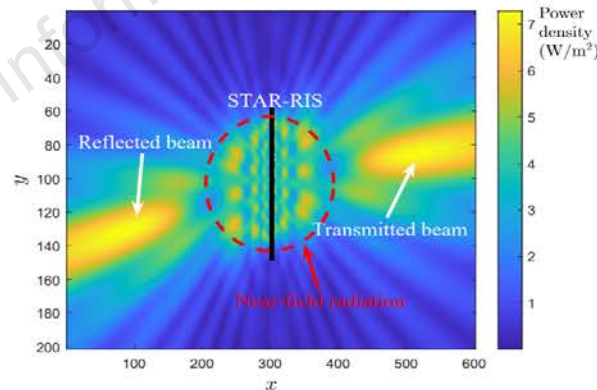
- STARS with 256 elements and equal amplitude control (i.e., $\beta_m^t = \beta_m^r$)
- Baseline: One reflecting-only RIS and one transmitting-only RIS, each of which has 128 elements.
- The target angles of the transmitted and reflected signals are 7.6° and 16.6° , respectively.

❑ Signal enhancement comparison

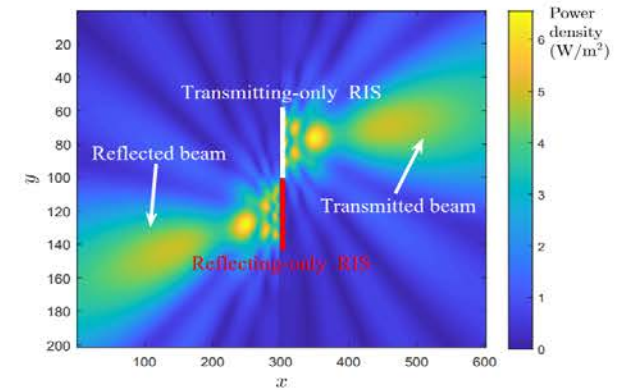


(a) Simulation setup

STARS achieves significant signal enhancement



(b) STAR-RIS

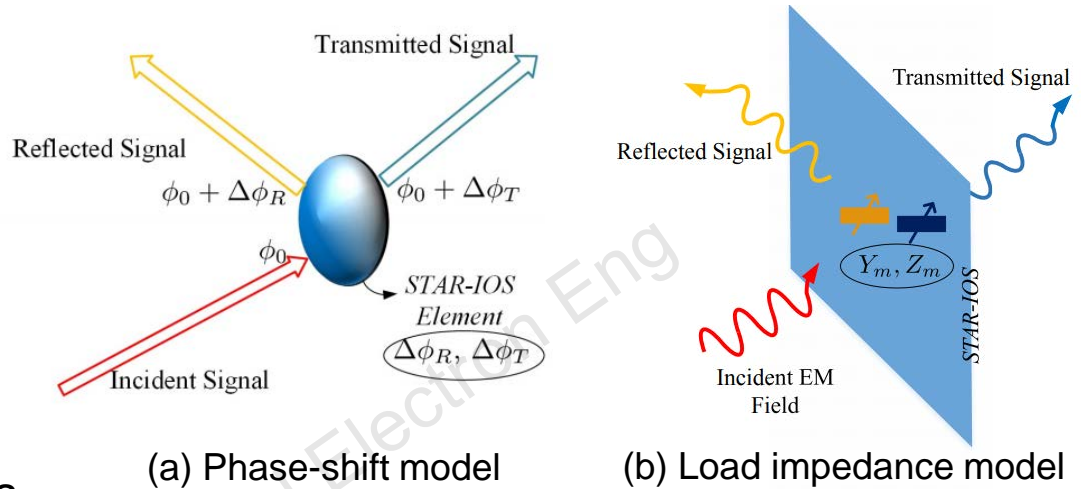


(c) Conventional RIS

Hardware models and channel models

❑ Hardware models:

- The phase-shift and load impedance models **best represent** the patch-array based STAR-RISs
- The generalized sheet transition conditions (GSTC) model **accurately mimics** the metasurface-based STAR-RISs



Hardware model	Properties used for modeling	STAR-RIS category	Pros.	Cons.
Phase-shift model	Phase shift (delay) values	Patch-array-based	Compact and easy to use	Oversimplified
Load impedance model	Surface averaged impedances	Patch-array-based	Compact and accurate	Not general
GSTC model	Electric and magnetic polarizability dyadic	Metasurface-based	General and accurate	Complicated

❑ Channel models:

- **Far-field models:** Ray-tracing based models
- **Near-field models:** Huygens-Fresnel principle based models
- **Other models:** angular spectrum, equivalent circuit, and Green's function method

Basic signal model for STAR-RISs

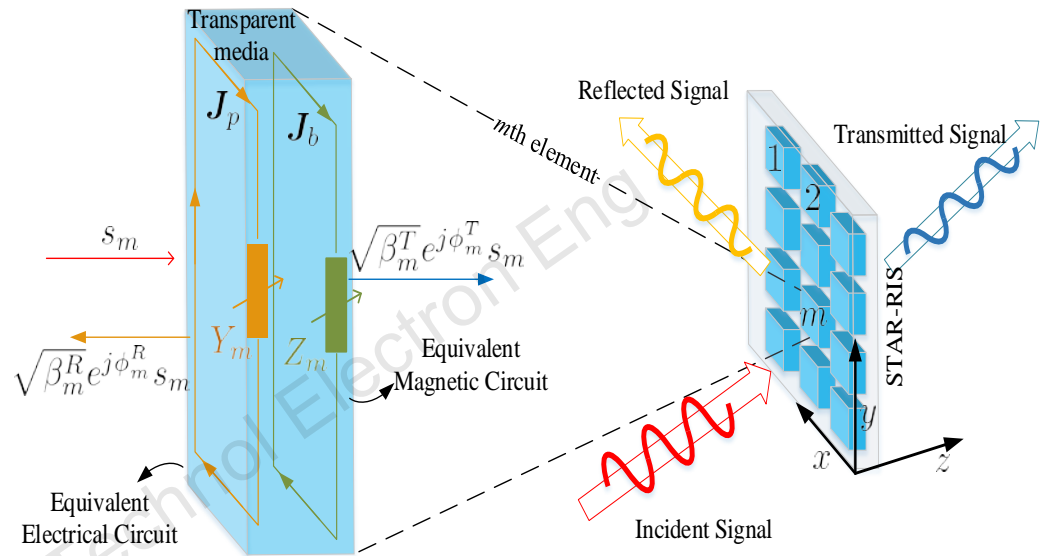
□ Incident signal on the m th element: s_m

□ The transmitted signal

$$t_m = \sqrt{\beta_m^t} e^{j\theta_m^t} s_m$$

□ The reflected signal

$$r_m = \sqrt{\beta_m^r} e^{j\theta_m^r} s_m$$

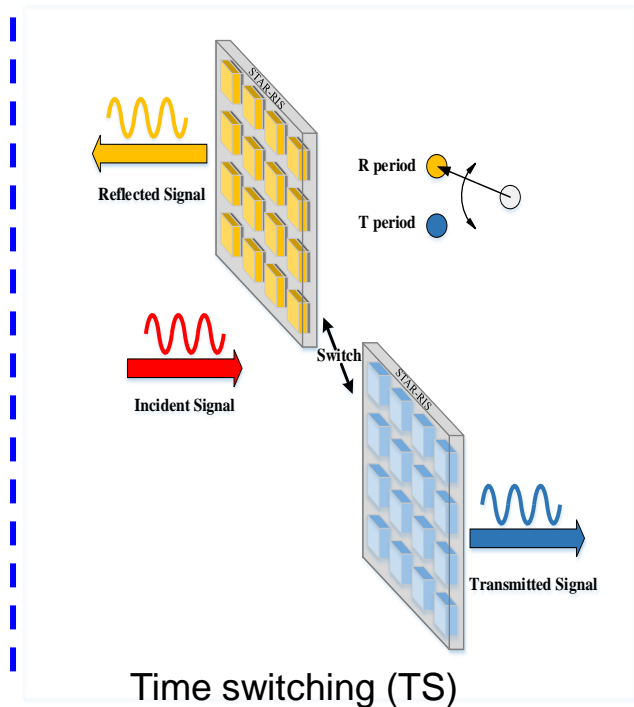
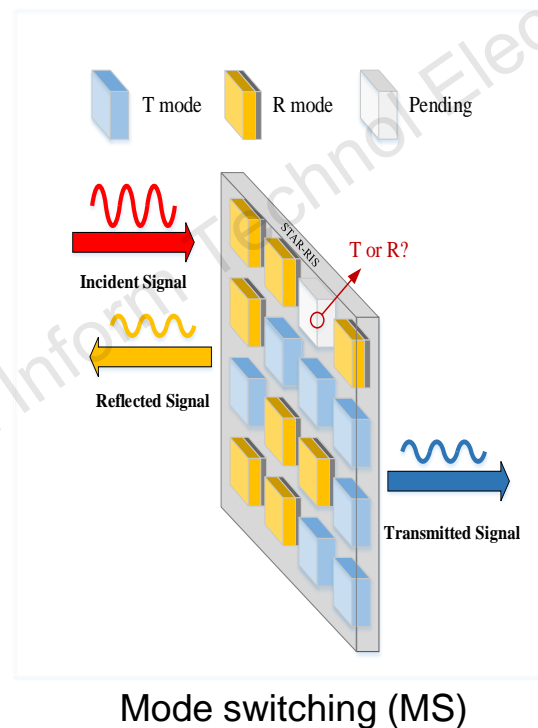
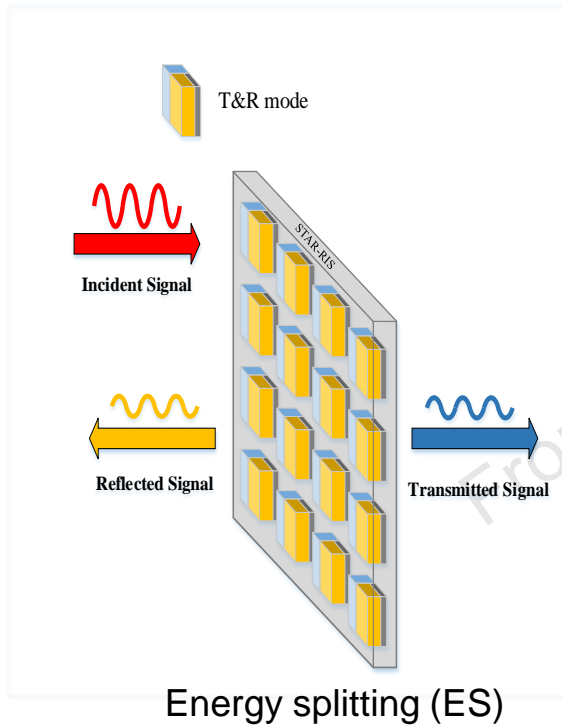


Here, $\beta_m^t, \beta_m^r \in [0,1]$ and $\theta_m^t, \theta_m^r \in [0, 2\pi)$ characterize the amplitude control and phase shift for transmission and reflection.

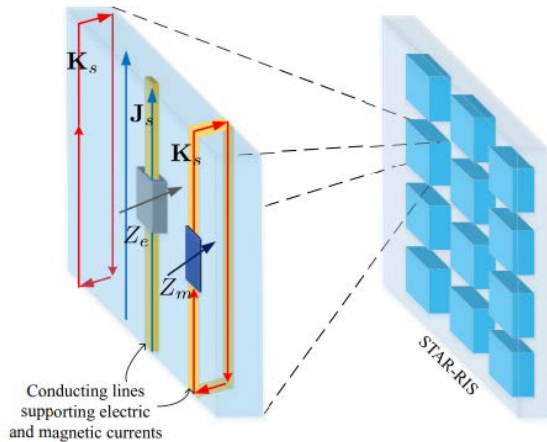
□ Law of energy conservation: $|t_m|^2 + |r_m|^2 = |s_m|^2$, i.e., $\beta_m^t + \beta_m^r = 1$

Operating protocols for STAR-RISs

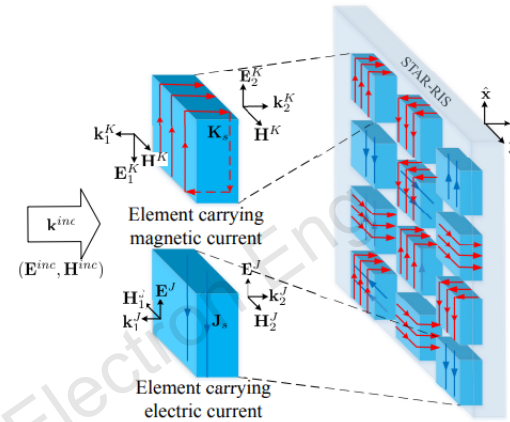
- Based on the signal model, each STAR element can be operated in
 - full transmission mode (T mode): $\beta_m^t = 1, \beta_m^r = 0$
 - full reflection mode (R mode): $\beta_m^t = 0, \beta_m^r = 1$
 - simultaneous transmission and reflection mode (T&R mode)
- **Practical operating protocols**



Coupled phase-shift STAR-RISs



(a) Surface equivalent currents of the STAR-RIS



(b) EM radiations of STAR-RIS elements carrying induced currents J_s and K_s

For **passive-lossless** STAR-RISs, the following physics principles should be met:

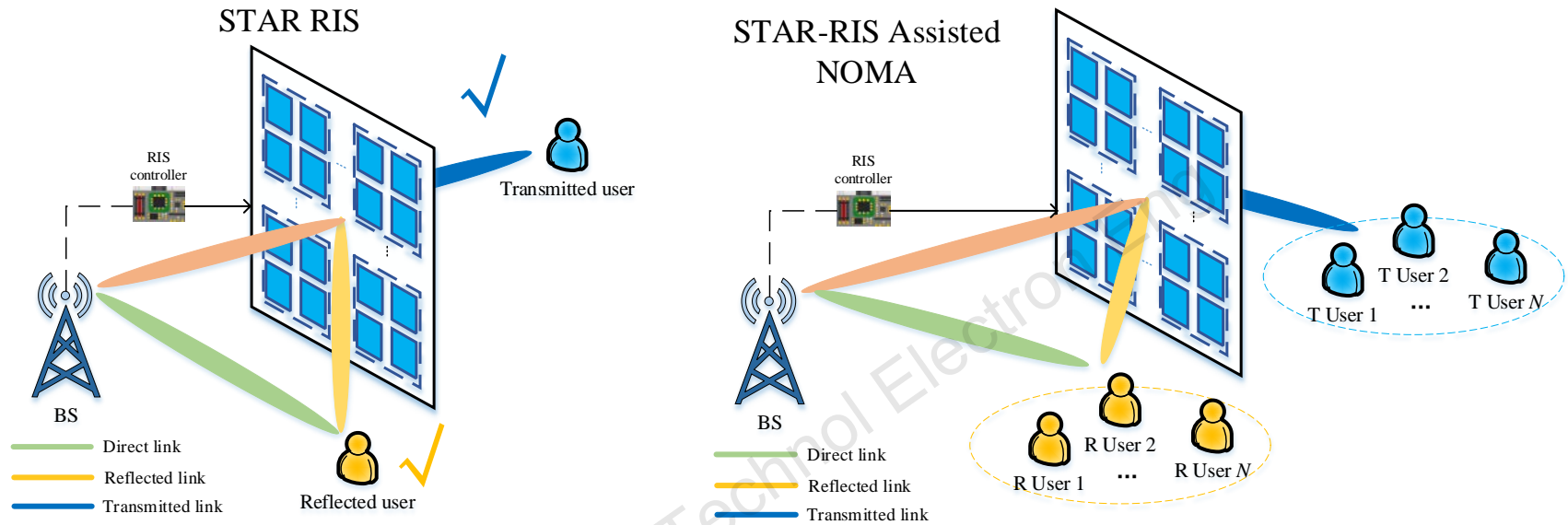
□ *Boundary conditions:* $\mathbf{n} \times (\mathbf{H}_1^J - \mathbf{H}_2^J) = \mathbf{J}_s$ and $\mathbf{n} \times (\mathbf{E}_1^K - \mathbf{E}_2^K) = \mathbf{K}_s$

□ *Energy conservation:* $\frac{dW}{dt} = \int (\mathbf{E} \times \mathbf{H}) d\Sigma - \int \mathbf{J} \cdot \mathbf{E} dV = 0$

These two principles lead to **the coupled phase-shift model:**

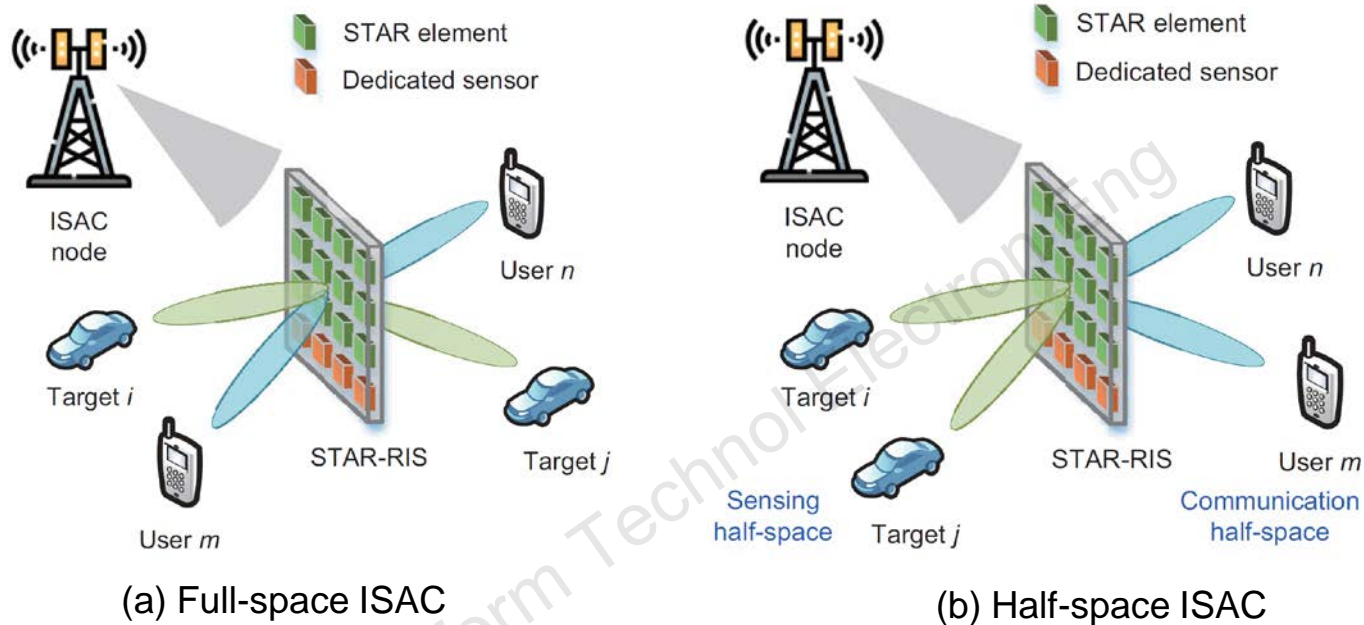
$$\theta_m^t - \theta_m^r = \frac{\pi}{2} + \nu_m \pi, \quad \nu_m = 0 \text{ or } 1$$

STAR-RIS for non-orthogonal multiple access



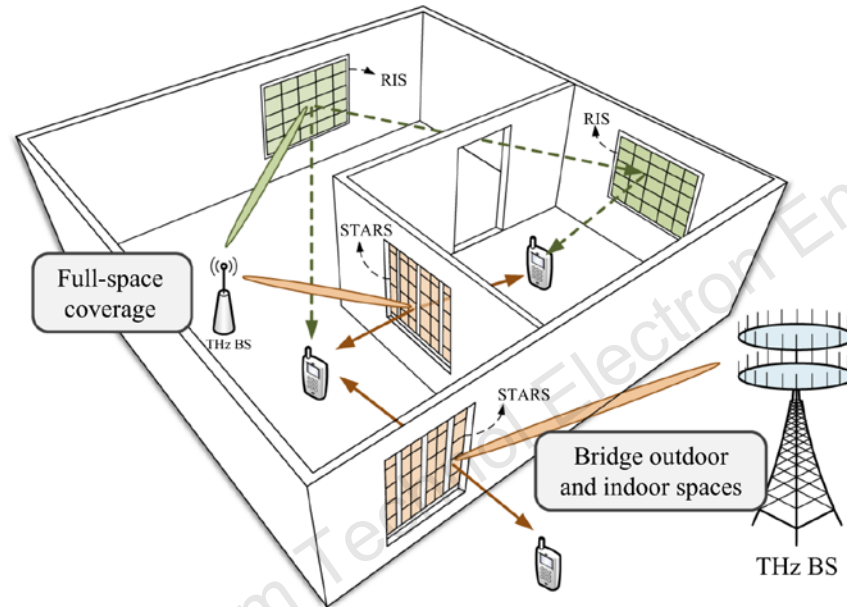
- ❑ A pair of users at the transmission and reflection sides can be grouped for NOMA.
- ❑ Asymmetric channel conditions among T and R users can be achieved by optimizing the transmission and reflection coefficients.
- ❑ Flexible resource allocation and high performance gain.

STAR-RIS for integrated sensing and communication



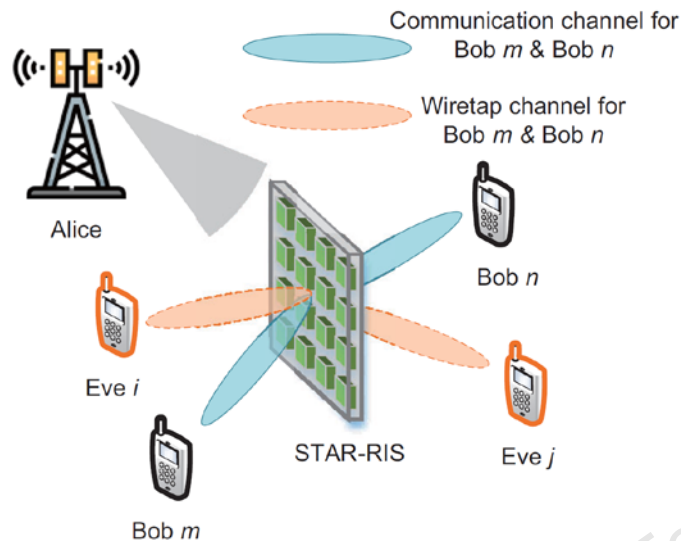
- ❑ STAR-RIS can enable full-space coverage for both sensing and communication.
- ❑ STAR-RIS can also facilitate sensing and communication separation.
- ❑ Installing low-cost active sensor at STAR-RISs can overcome significant multi-hop pathloss and avoid echo signal ambiguity.

STAR-RIS for terahertz communication

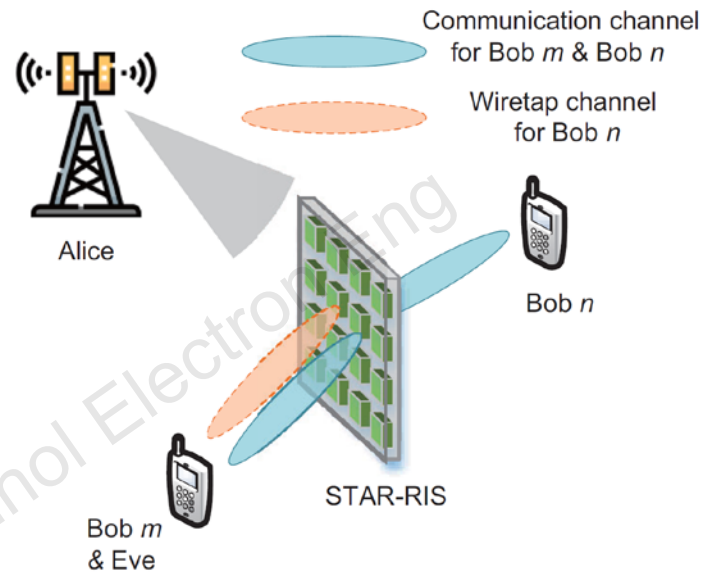


- ❑ STAR-RIS can overcome the high pathloss and obscuration issue in THz communication at a minimum cost.
- ❑ STAR-RIS can effectively bridge outdoor and indoor THz communication.
- ❑ Overcoming the beam squint or beam split issue in wideband THz communication requires additional analog devices, e.g., true-time delayer, in the hybrid beamforming architectures.

STAR-RIS for physical layer security



(a) PLS with external eavesdropper



(b) PLS with internal eavesdropper

- ❑ STAR-RIS can result in full-space wiretapping, requiring a revisit of PLS.
- ❑ How to address the full-space wiretapping issue and invoke artificial noise to further enhance the PLS for both external and internal eavesdropping cases still requires more research efforts.

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,” *IEEE Wirel Commun.*, vol. 28, no. 6, pp. 102–109, Dec. 2021
- [2] 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.
- [3] X. Mu, Y. Liu, L. Guo, J. Lin, and R. Schober, “Simultaneously transmitting and reflecting (STAR) RIS aided wireless communications,” *IEEE Trans. Wirel Commun.*, vol. 21, no. 5, pp. 3083–3098, May 2022
- [4] J. Xu, Y. Liu, X. Mu, J. T. Zhou, L. Song, H. V. Poor, and L. Hanzo, “Simultaneously transmitting and reflecting intelligent omni-surfaces: Modeling and implementation,” *IEEE Veh. Technol. Mag.*, vol. 17, no. 2, pp. 46–54, Jun. 2022.
- [5] 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,” *IEEE J. Sel. Topics Signal Process.*, vol. 16, no. 5, pp. 1097–1111, Aug. 2022.
- [6] Z. Wang, X. Mu, Y. Liu, and R. Schober, “Coupled phase-shift STAR-RISs: A general optimization framework,” *IEEE Wirel Commun. Lett.*, vol. 12, no. 2, pp. 207–211, Feb. 2023.
- [7] J. Zuo, Y. Liu, Z. Ding, L. Song, and H. V. Poor, “Joint design for simultaneously transmitting and reflecting (STAR) RIS assisted NOMA systems,” *IEEE Trans. Wirel Commun.*, vol. 22, no. 1, pp. 611–626, Jan. 2023.
- [8] Z. Wang, X. Mu, and Y. Liu, “STARS enabled integrated sensing and communications,” *IEEE Trans. Wirel Commun.*, vol. 22, no. 10, pp. 6750–6765, Oct. 2023.
- [9] Z. Wang, X. Mu, J. Xu, and Y. Liu, “Simultaneously transmitting and reflecting surface (STARS) for terahertz communications,” *IEEE J. Sel. Topics Signal Process.*, vol. 17, no. 4, pp. 861–877, Jul. 2023.
- [10] Z. Zhang, Z. Wang, Y. Liu, B. He, L. Lv, and J. Chen, “Security enhancement for coupled phase-shift STAR-RIS networks,” *IEEE Trans. Veh. Technol.*, vol. 72, no. 6, pp. 8210–8215, Jun. 2023.