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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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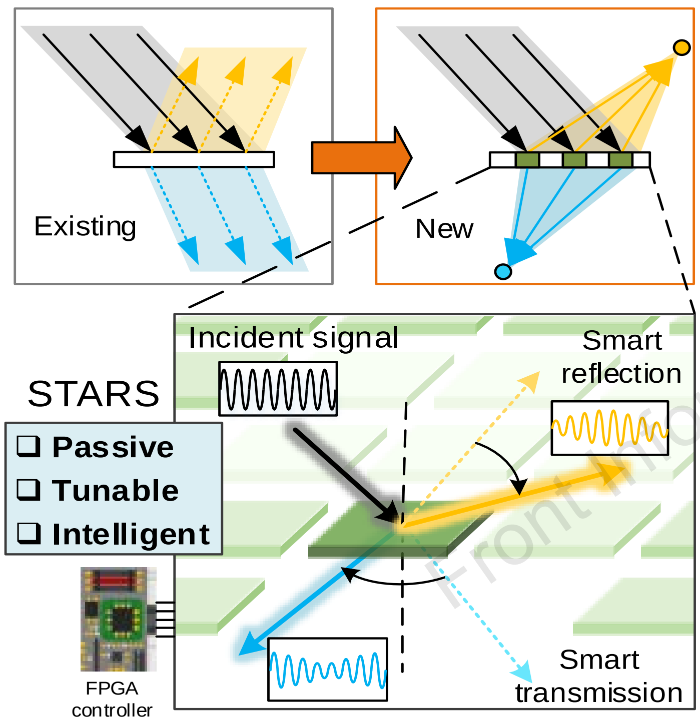
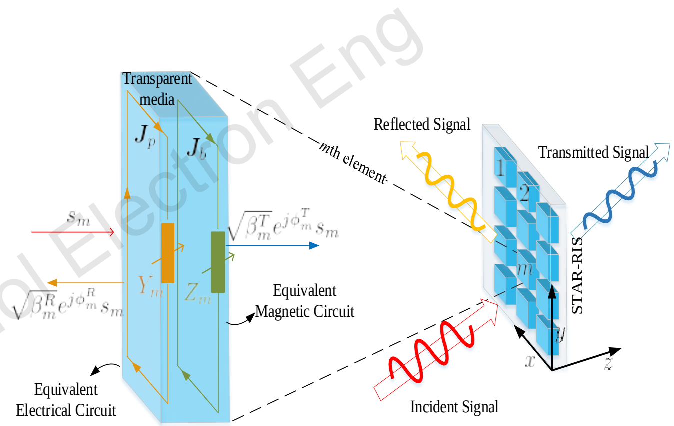
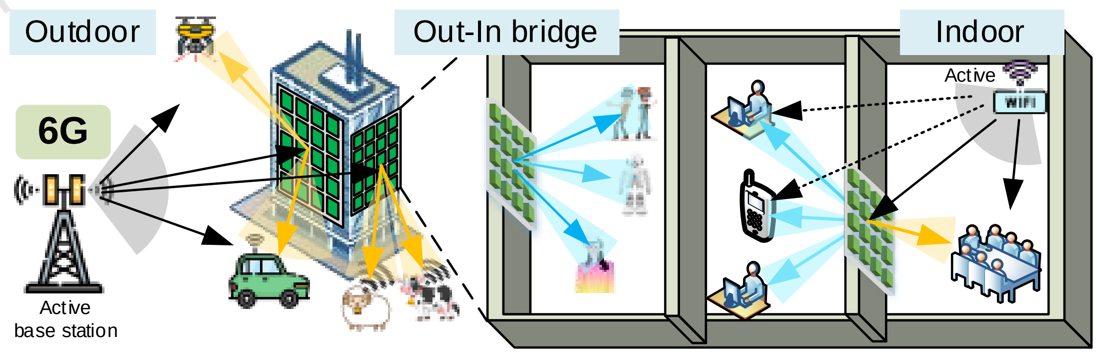
Key advantages of STAR-RISs

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







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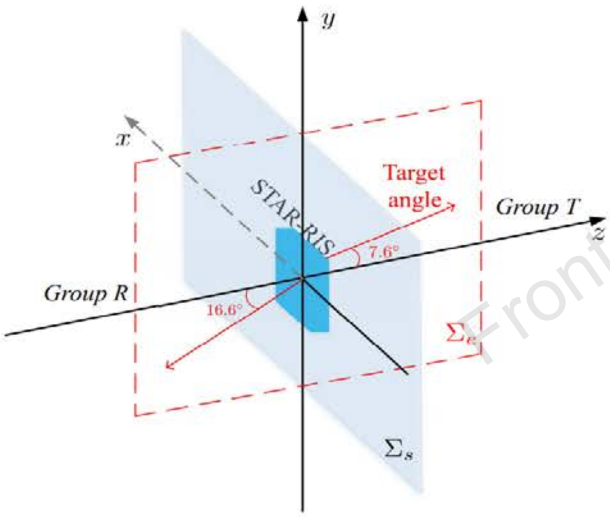
Comparison with conventional RISs

❑ Simulation setup

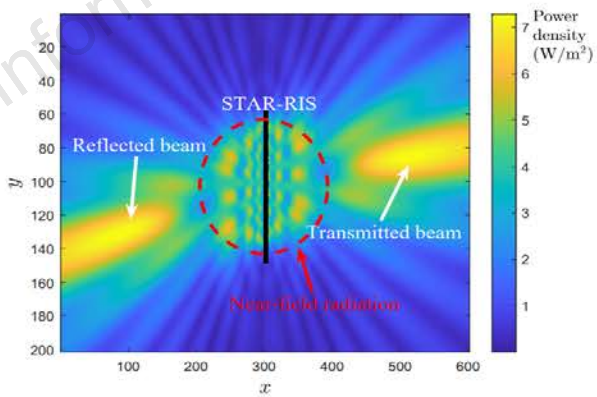
- STARS with 256 elements and equal amplitude control (i.e., $\beta_m^{\mathrm{t}} = \beta_m^{\mathrm{r}}$)
- Baseline: One reflecting-only RIS and one transmitting-only RIS, each of which has 128 elements.
- The target angles of the transmitted and reflected signals are 7.6° and 16.6°, respectively.

❑ Signal enhancement comparison

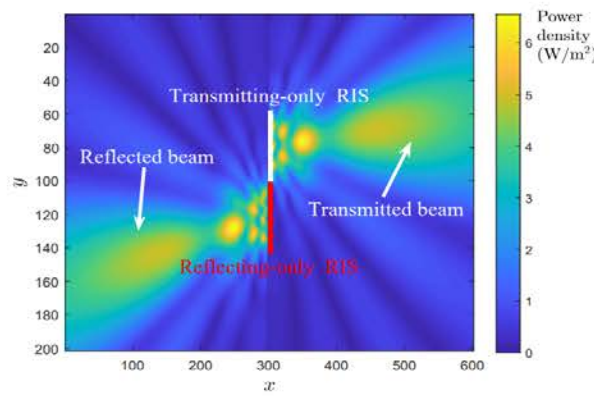
STARS achieves significant signal enhancement



(a) Simulation setup



(b) STAR-RIS

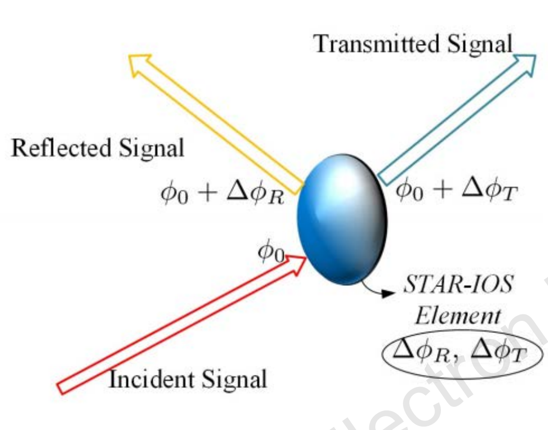


(c) Conventional RIS

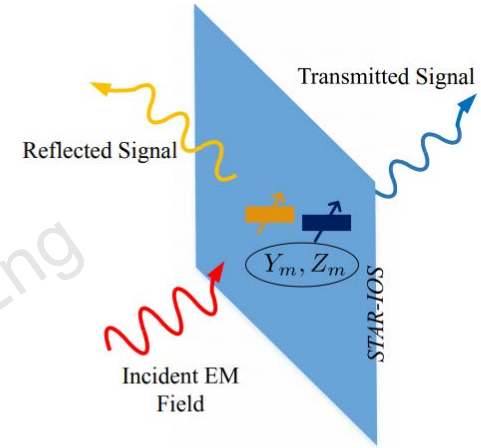
Hardware models and channel models

❑ 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



(a) Phase-shift model



(b) Load impedance model

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

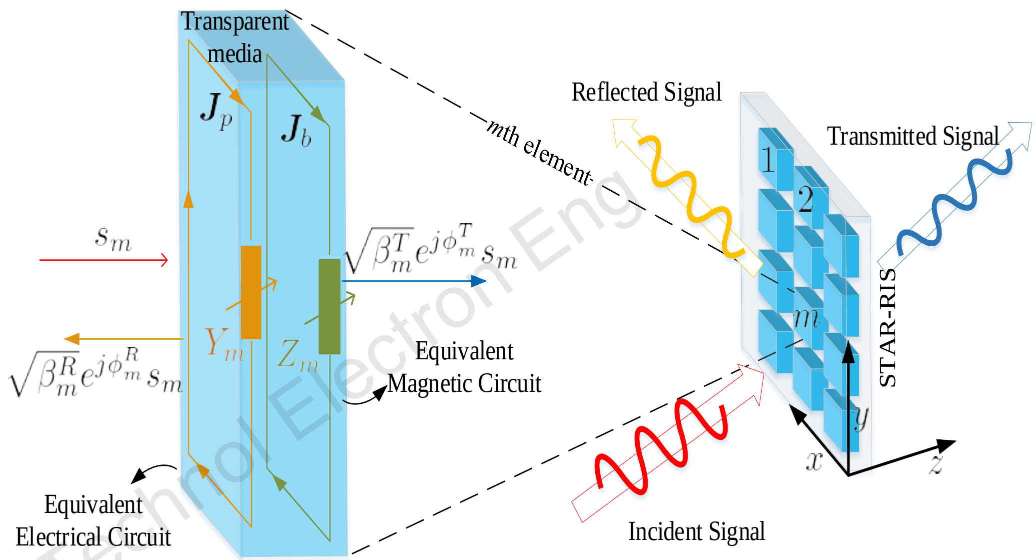
Basic signal model for STAR-RISs

- Incident signal on the mth element: s_m
- The transmitted signal

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

- The reflected signal

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

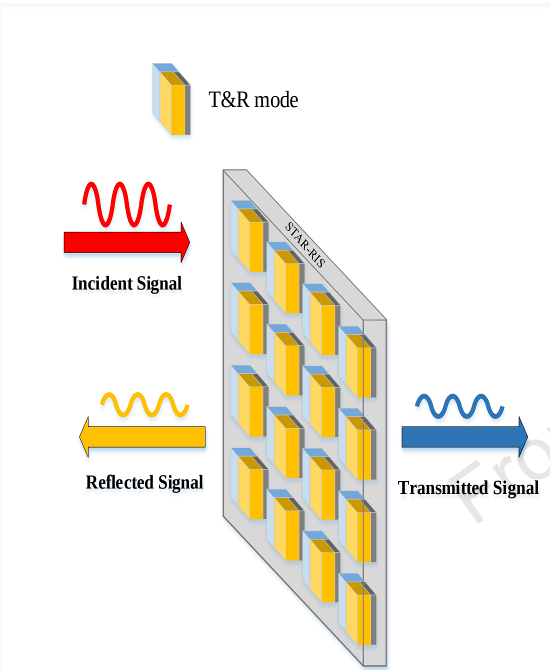


Here, $\beta_m^{\mathrm{t}}, \ \beta_m^{\mathrm{r}} \in [0,1]$ and $\theta_m^{\mathrm{t}}, \theta_m^{\mathrm{r}} \in [0, 2\pi)$ characterize the amplitude control and phase shift for transmission and reflection.

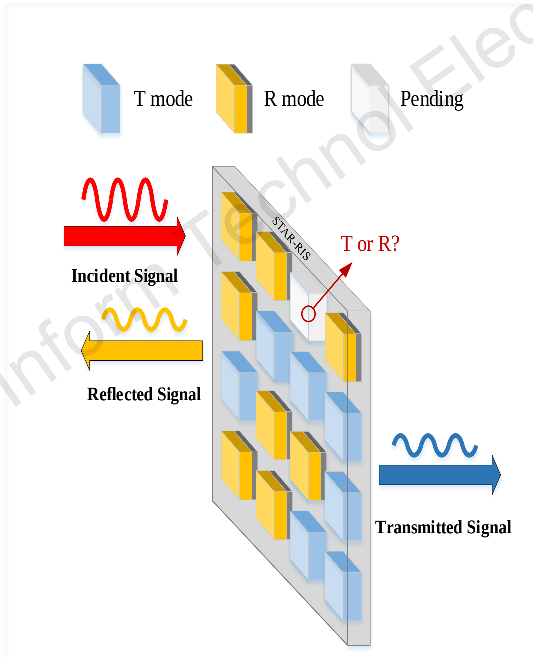
- **Law of energy conservation:** $|t_m|^2 + |r_m|^2 = |s_m|^2$, i.e., $\beta_m^{\mathrm{t}} + \beta_m^{\mathrm{r}} = 1$

Operating protocols for STAR-RISs

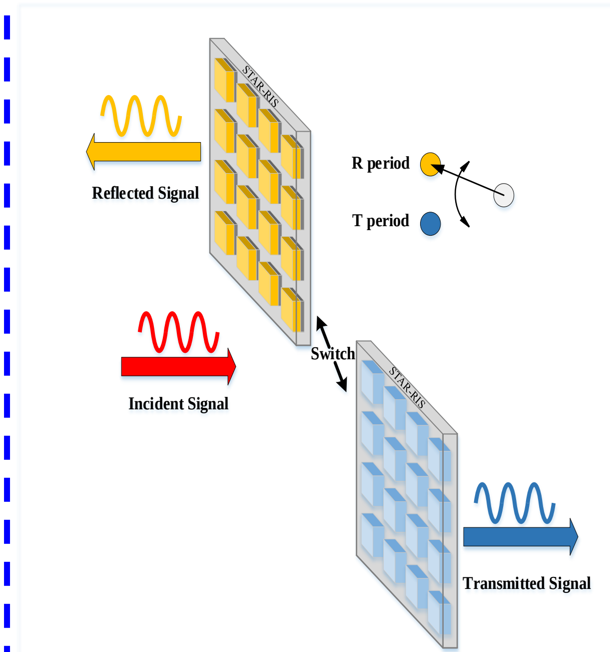
- Based on the signal model, each STAR element can be operated in
  - full transmission mode (T mode): $\beta_m^{\mathrm{t}} = 1,\ \beta_m^{\mathrm{r}} = 0$
  - full reflection mode (R mode): $\beta_m^{\mathrm{t}} = 0,\ \beta_m^{\mathrm{r}} = 1$
  - simultaneous transmission and reflection mode (T&R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



Energy splitting (ES)

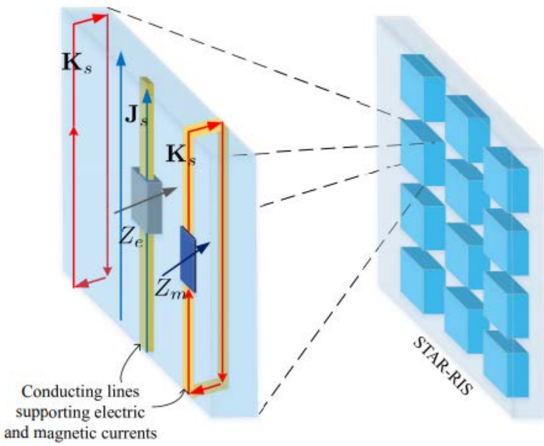


Mode switching (MS)

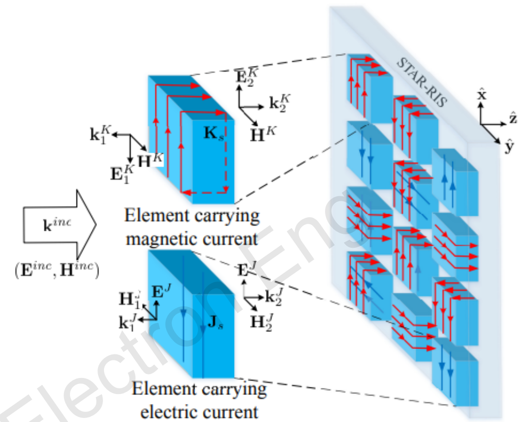


Time switching (TS)

Coupled phase-shift STAR-RISs



(a) Surface equivalent currents of the STAR-RIS



(b) EM radiations of STAR-RIS elements carrying induced currents $\boldsymbol{J}_s$ and $\boldsymbol{K}_s$

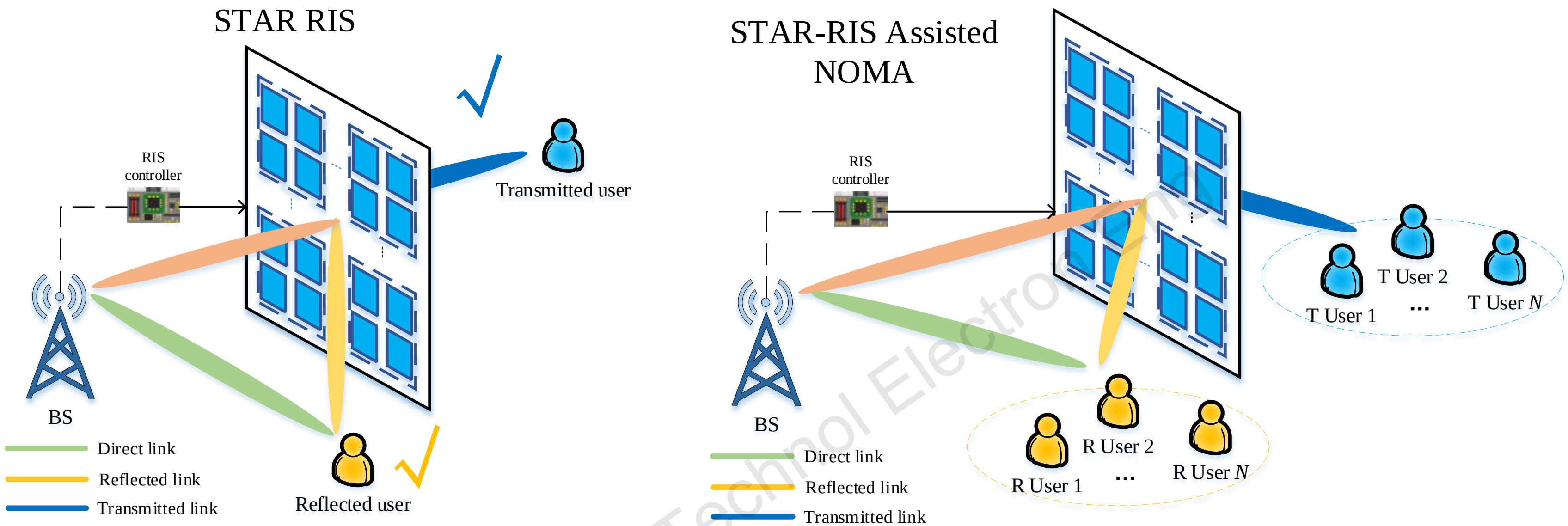
For **passive-lossless** STAR-RISs, the following physics principles should be met:

- *Boundary conditions:* $\boldsymbol{n} \times \left(\boldsymbol{H}_1^J - \boldsymbol{H}_2^J\right) = \boldsymbol{J}_s$ and $\boldsymbol{n} \times (\boldsymbol{E}_1^K - \boldsymbol{E}_2^K) = \boldsymbol{K}_s$
- *Energy conservation:* $\frac{\mathrm{d}W}{\mathrm{d}t} = \int (\boldsymbol{E} \times \boldsymbol{H})\, \mathrm{d}\Sigma - \int \boldsymbol{J} \cdot \boldsymbol{E}\, \mathrm{d}V = 0$

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

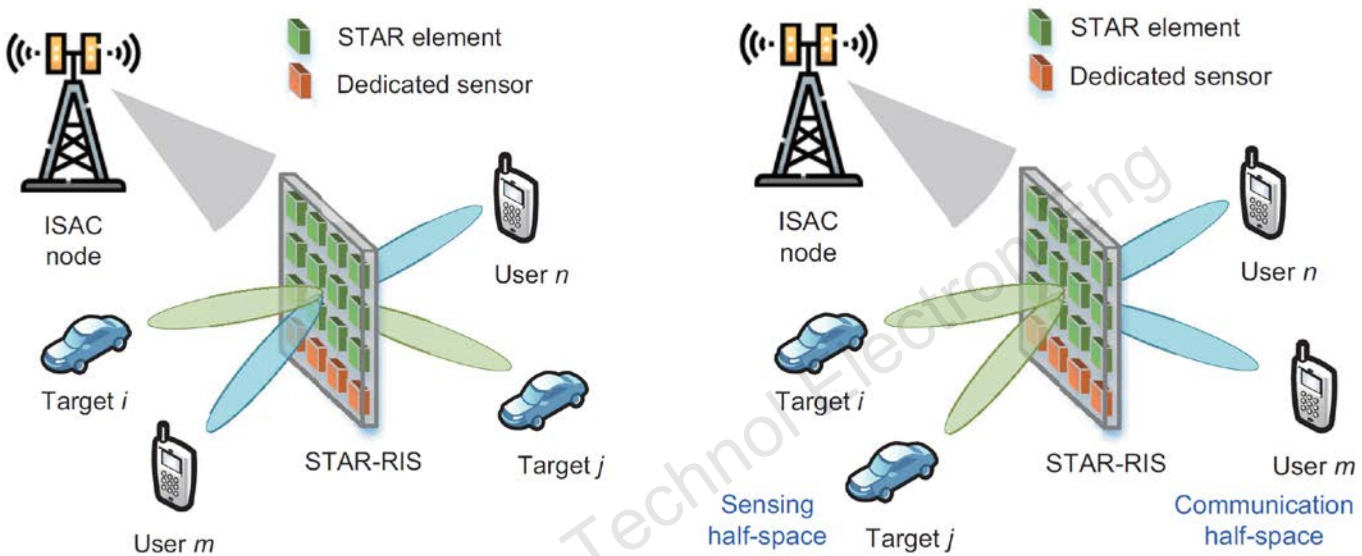
$$\boxed{\theta_m^{\mathrm{t}} - \theta_m^{\mathrm{r}} = \frac{\pi}{2} + \nu_m \pi,\ \ \nu_m = 0 \text{ or } 1}$$

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.

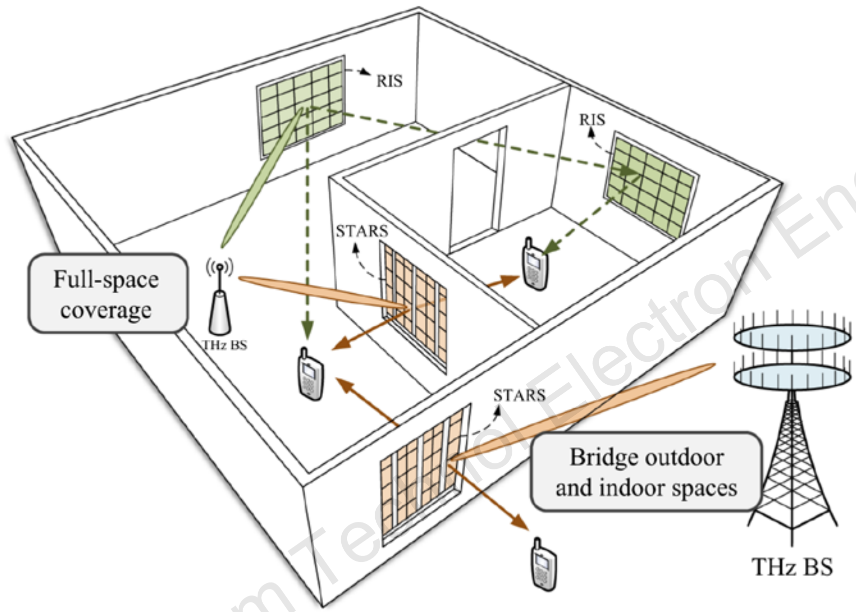
STAR-RIS for integrated sensing and communication



(a) Full-space ISAC (b) Half-space ISAC

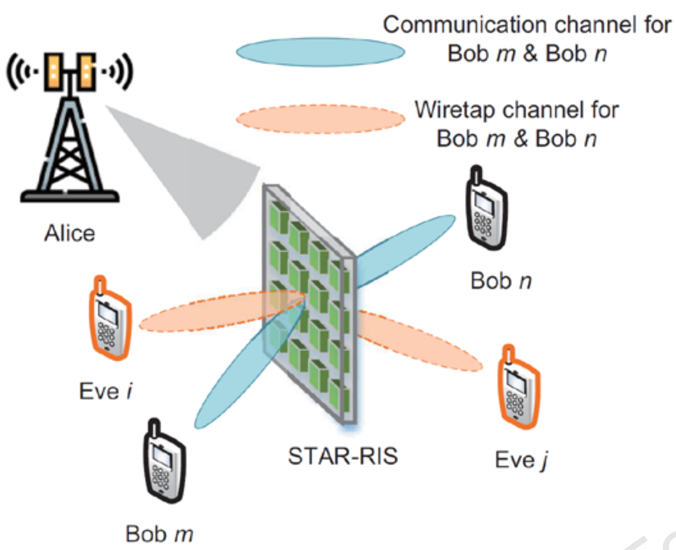
- ❑ STAR-RIS can enable full-space coverage for both sensing and communication.
- ❑ STAR-RIS can also facilitate sensing and communication separation.
- ❑ Installing low-cost active sensor at STAR-RISs can overcome significant multi-hop pathloss and avoid echo signal ambiguity.

STAR-RIS for terahertz communication

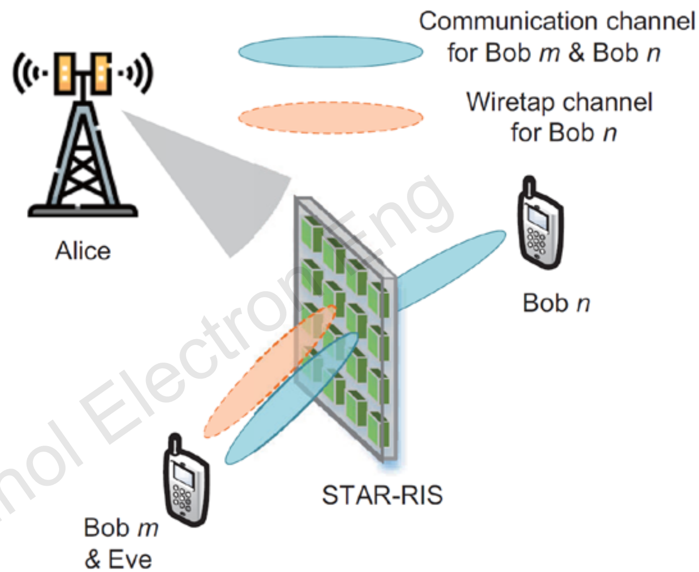


- STAR-RIS can overcome the high pathloss and obscuration issue in THz communication at a minimum cost.
- STAR-RIS can effectively bridge outdoor and indoor THz communication.
- Overcoming the beam squint or beam split issue in wideband THz communication requires additional analog devices, e.g., true-time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

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