Simultaneously Transmitting And Reflecting Surface (STARS) for 360° Coverage

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STAR LAB | SMART COMMUNICATIONS RESEARCH

Outline

- **STARS Basis**
  - Signal Modelling: Performance Evaluation (What)
  - Coverage/Capacity Characterization (Why)
  - Operating Protocols and Joint Beamforming (How)
  - Varieties of STARS: Coupled, Dual-Side
  - Channel Estimation
- **STARS Platform**
  - Sensing-at-STARS
  - Amplifying-at-STARS
  - Caching-at-STARS
- **Case Studies of STARS**
  - STARS Aided Transmission-Reflection NOMA
  - STARS for THz Communications
  - Spatial Analysis for STARS via Stochastic Geometry
  - Integrating NOMA and Air Federated Learning via STARS
- **Prototype, Standardization, and Commercial Progress of STARS**
- **Research Opportunities and Open-Source Codes for STARS**

❖ Codes available: https://github.com/STAR-Yuanwei-Liu

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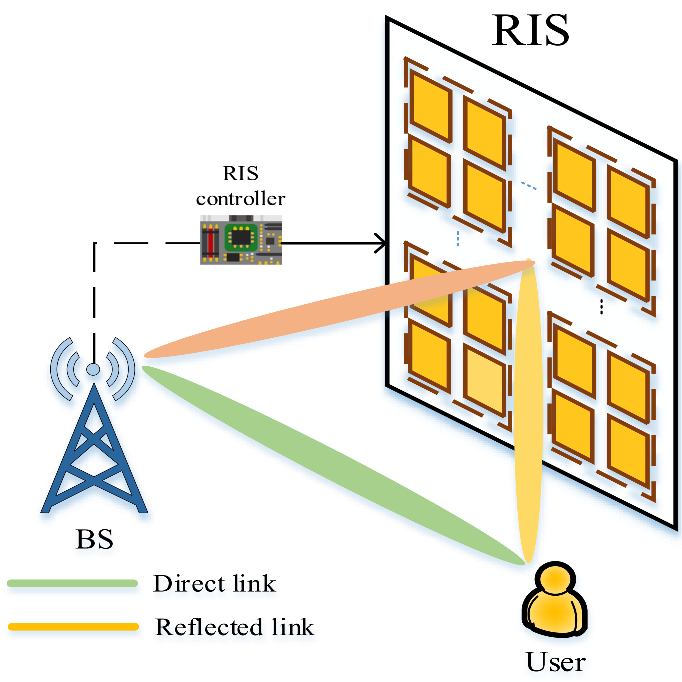
Overview of RIS

❑ Reconfigurable Intelligent Surface (RIS)

- A planar surface consists of massive reconfigurable elements
- Adjusting the propagation of incident signal (via phase and amplitude)
- Smart Radio Environment (SRE)



❑ Advantages

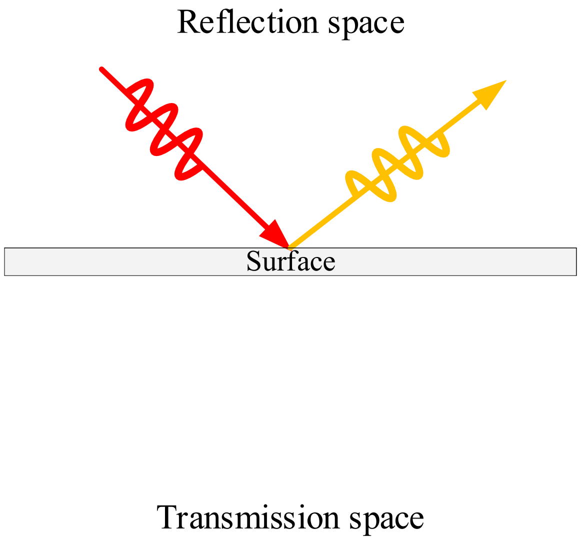
- Easy to deploy
- Low cost
- Low energy consumption
- …

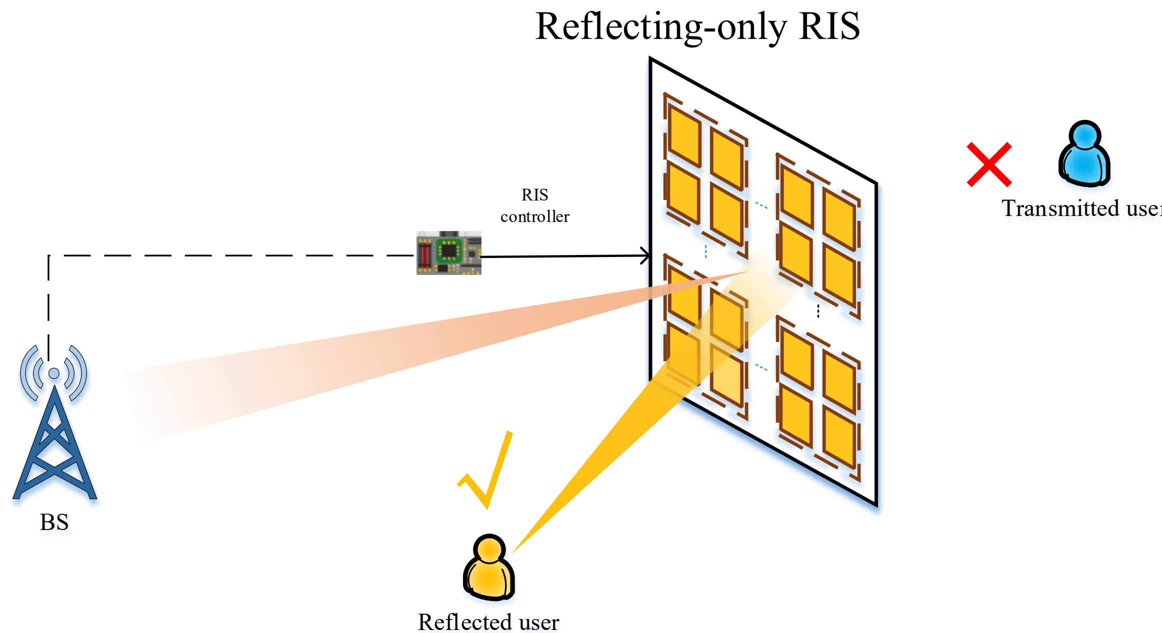
[1] **Y. Liu,** *et al*., "Reconfigurable Intelligent Surfaces: Principles and Opportunities", *IEEE Commun. Surv. Tut.,* vol. 23, no. 3, pp. 1546-1577, thirdquarter 2021, http://arxiv.org/abs/2007.03435. (ESI Highly Cite Paper)
[2] **Y. Liu**, *et. al* "Reconfigurable Intelligent Surface (RIS) Aided Multi-User Networks: Interplay Between NOMA and RIS", *IEEE Wireless Commun.,* vol. 29, no. 2, pp. 169-176, Apr. 2022, *https://arxiv.org/abs/2011.13336*.

From Reflecting-only RIS to STARS

❑ Reflecting-only RIS

- ➢ Both the source and the destination have to be at the same side of the RISs, i.e., *half-space/180° SRE*
- ➢ Limits the flexibility





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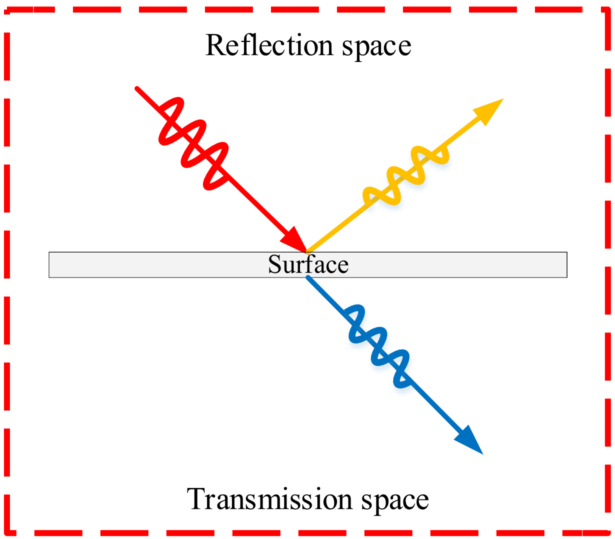
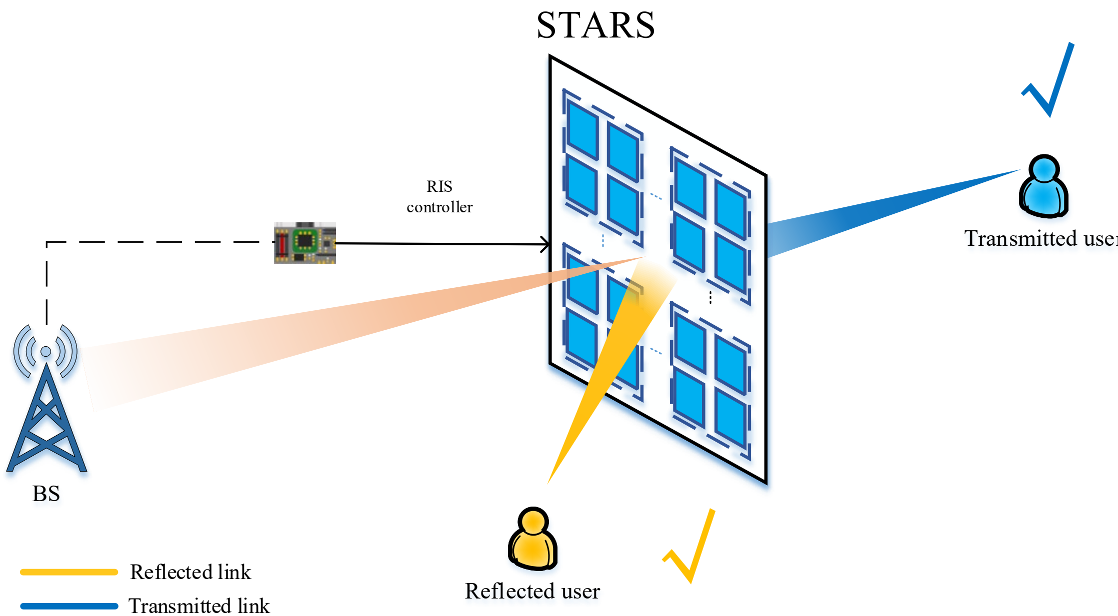
From Reflecting-only RIS to STARS

❑ Simultaneously Transmitting And Reflecting Surface (STARS)

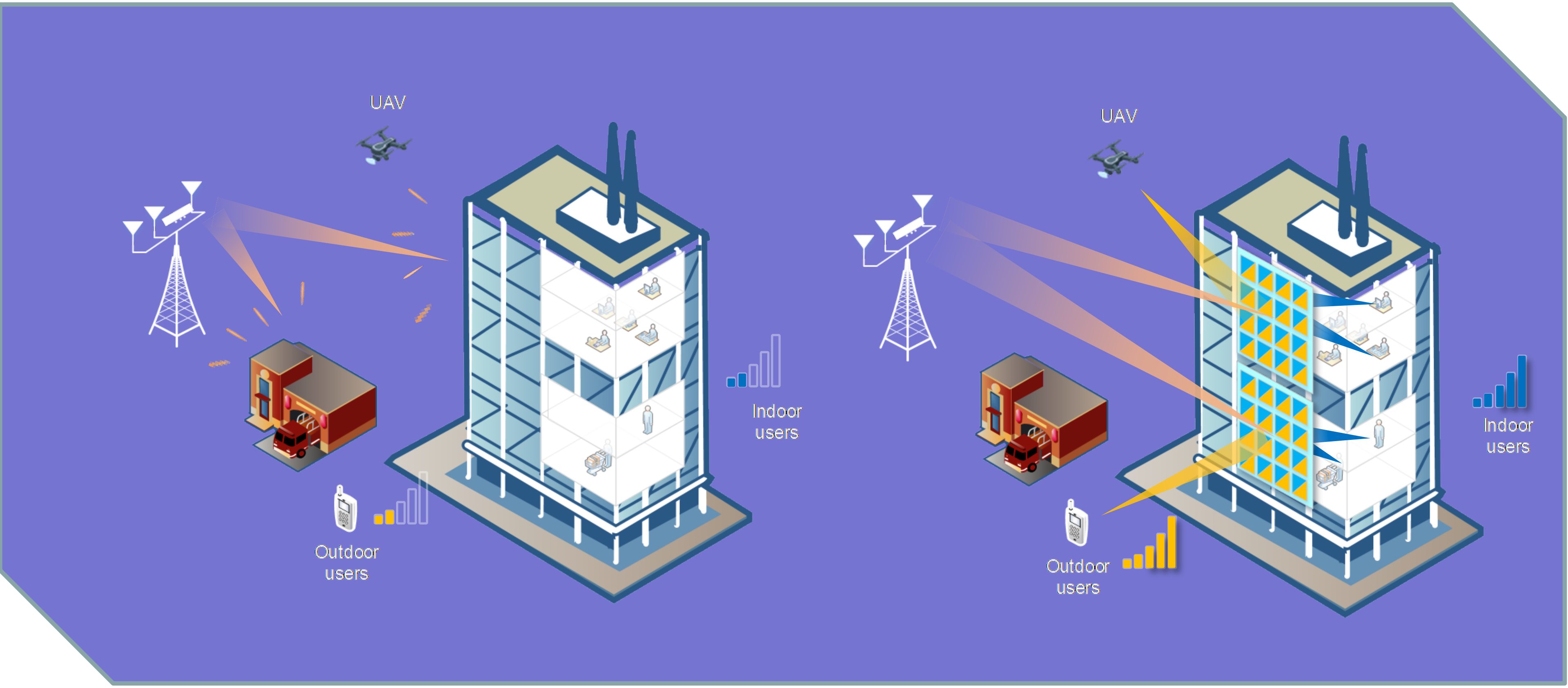
➢ The incident wireless signals can be reflected and transmitted into the both sides of the RIS, i.e., *full-space/360° SRE*





[1] **Y. Liu**, *et al.*, "STAR: Simultaneous Transmission And Reflection for 360° Coverage by Intelligent Surfaces", *IEEE Wireless Commun.*, vol. 28, no. 6, pp. 102-109, Dec. 2021, https://arxiv.org/abs/2103.09104. (ESI Highly Cited Paper)

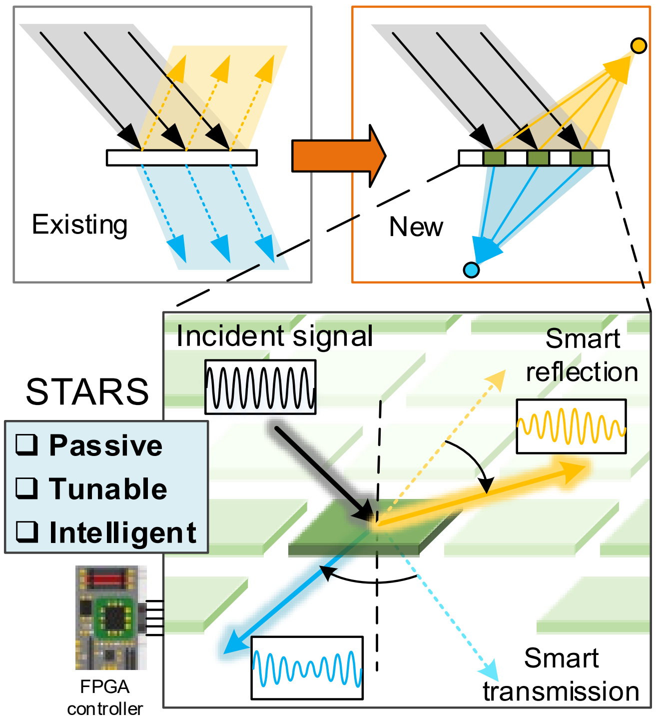
Comparing STARS with Existing Surfaces

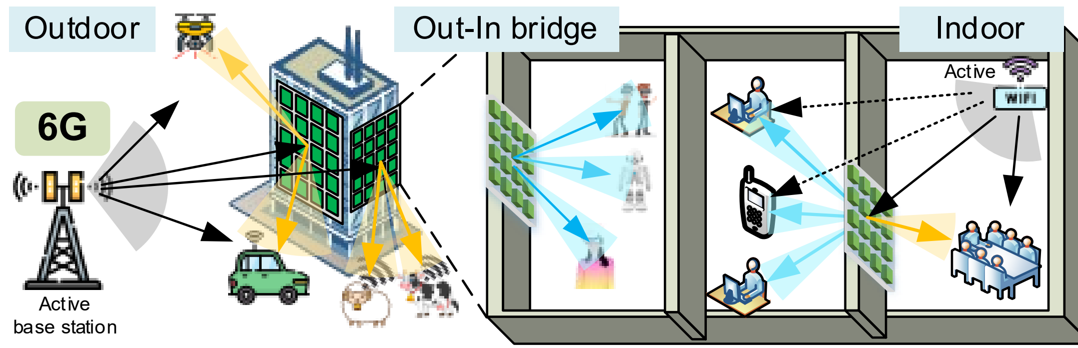


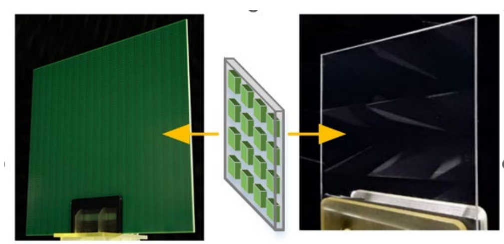
[1] **Y. Liu**, *et al.*, “STAR: Simultaneous Transmission And Reflection for 360° Coverage by Intelligent Surfaces”, *IEEE Wireless Commun.*, vol. 28, no. 6, pp. 102-109, Dec. 2021, https://arxiv.org/abs/2103.09104. (ESI Highly Cited Paper)
[2] **35 Innovators Under 35 China in 2022 by MIT Technology Review**, https://www.innovatorsunder35.com/the-list/yuanwei-liu/
[3] **IEEE Young Professionals Blog**. “*STARS” shine in the “6G Sky*”, August 2022 https://yp.comsoc.org/stars-shine-in-the-6g-sky/

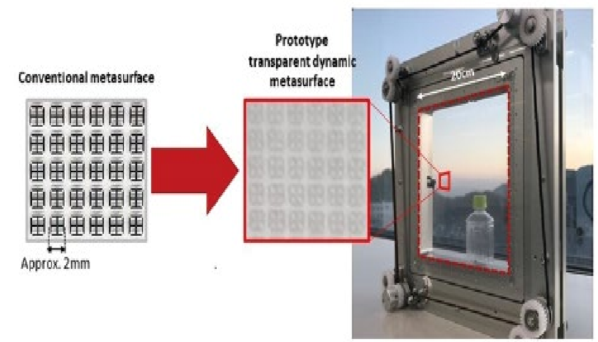
Key Advantages of STARS

- ❑ 360° coverage: Thanks to the STAR capability, the coverage is extended to the entire space
- ❑ Enhanced degrees-of-freedom (DoFs): Generally independent transmission and reflection coefficients









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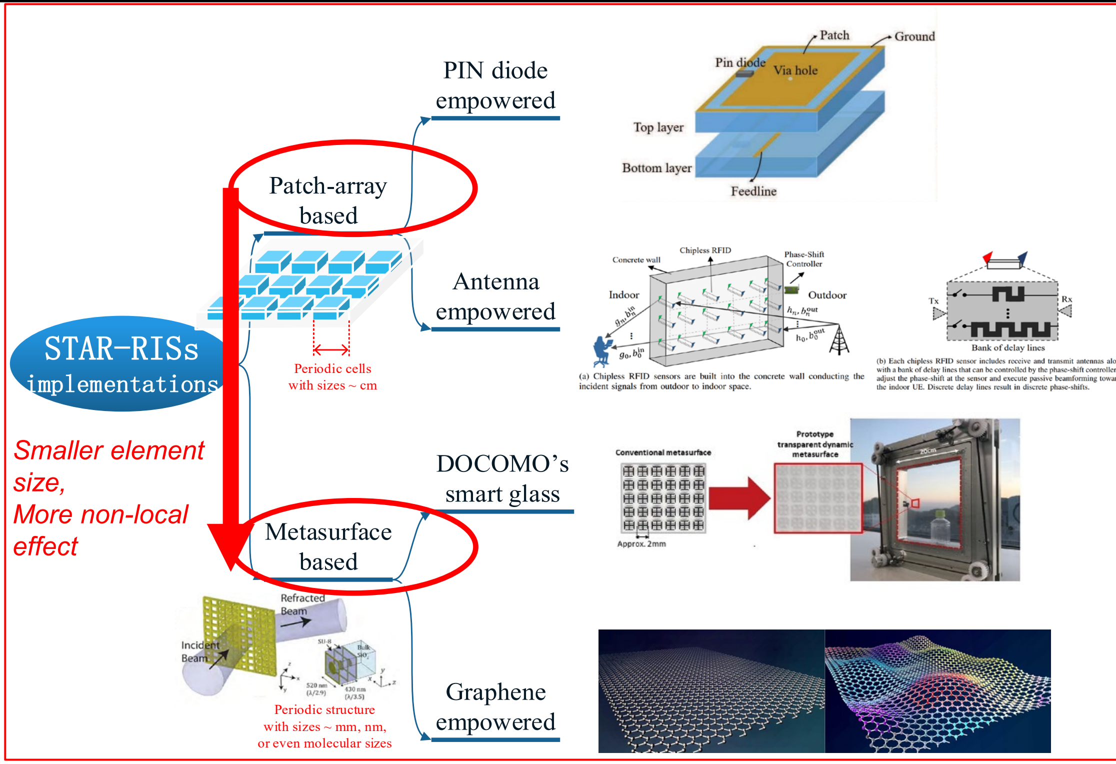
[D1] **NTT DOCOMO,** "DOCOMO conducts world's first successful trial of transparent dynamic metasurface,"

How STARS Can Be Implemented?

- ❑ Patch-array based (PIN diode, antenna)
  Periodic cells with sizes about several cms

- ❑ Metasurface based (smart glass, graphene)
  Periodic structure with sizes ~ mm, nm, or even molecular sizes



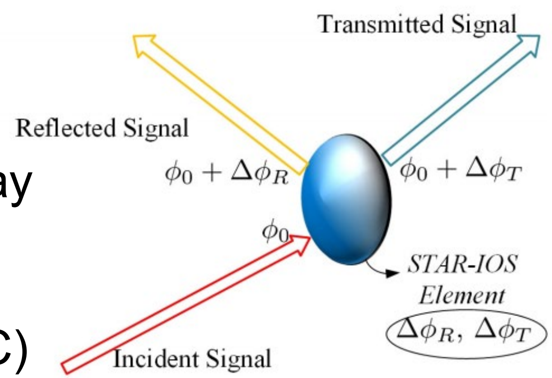
Implementations	Operating frequency	STAR prototype	Tuning mechanism	Independent T&R control
Patch-array based	Sub 6GHz	PIN diodes empowered	Bias voltages	Difficult
		Antenna empowered	Delay lines	Can
Metasurface based	mmWave, THz, visible light	DOCOMO's smart glass	Substrate distance	Theoretically achievable
		Graphene empowered	Conductivity	Can

[1] J. Xu, **Y. Liu**, *et al.,* "Simultaneously Transmitting and Reflecting (STAR) Intelligent Omni-Surfaces, Their Modeling and Implementation," *IEEE VT Magazine*, vol. 17, no. 2, pp. 46-54, Jun. 2022, https://arxiv.org/pdf/2108.06233 (IEEE VTM Popular Article)

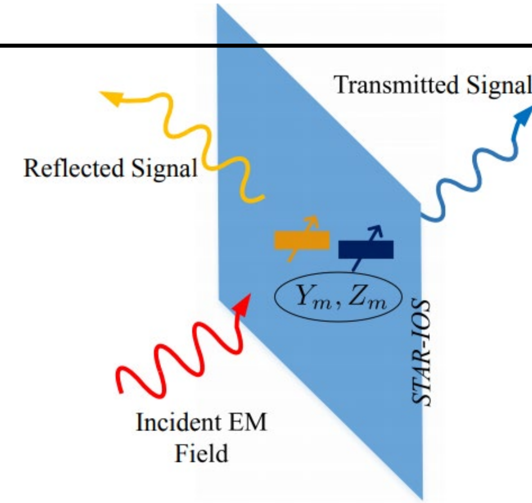
Hardware Models and Channel Models

❑ Hardware models:

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



The phase-shift model



The load impedance model

Hardware models	Properties used for modeling	Apply to	Advantages	Disadvantages
Phase-shift model	Phase shift (delay) values	Patch-array based STAR-IOSs	Compact and easy to use	Oversimplified
Load impedance model	Surface averaged impedances	Patch-array based STAR-IOSs	Compact and accurate	Not general
GSTC model	Electric and magnetic polarizability dyadics	Metasurface based STAR-IOSs	General and accurate	Complicated

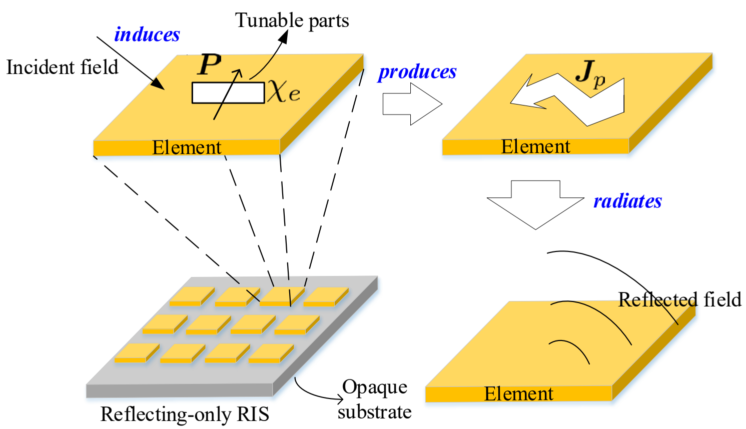
❑ Channel models:

- ➢ Near-field channel models: Ray-tracing based models
- ➢ Far-field channel models: Huygens-Fresnel principle based models
- ➢ Other channel models: Angular spectrum, Equivalent circuit, Green's function models

[1] J. Xu, **Y. Liu**, et al., "Simultaneously Transmitting and Reflecting (STAR) Intelligent Omni-Surfaces, Their Modeling and Implementation," *IEEE VT Magazine*, vol. 17, no. 2, pp. 46-54, Jun. 2022, https://arxiv.org/pdf/2108.06233 (IEEE VTM Popular Article)
[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, Sept. 2021. [Code] (IEEE Featured Article, IEEE CL Top 1 Popular Article, ESI Highly Cited Paper)
[3] J. Xu and **Y. Liu**, "A Near-Field Channel Model for Metasurface-Based STAR-RISs", IEEE ICCT 2023, pp. 1538-1543. (Best Paper Award).

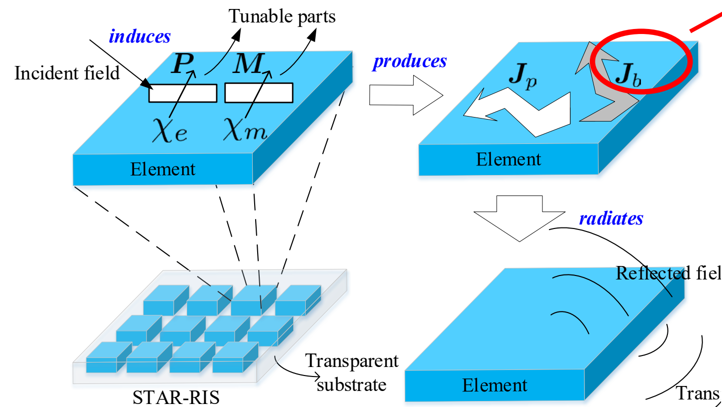
Difference Between Reflecting-Only RIS and STARS

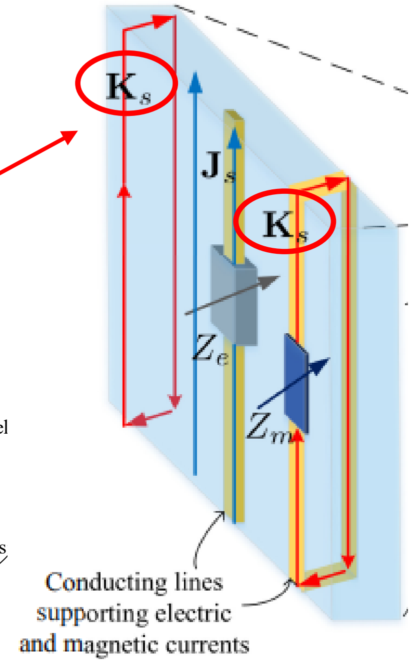
❑ Reflecting-Only RIS



(Biscuits placed on a metal plate)

❑ STARS





(transparent at radio frequency)

(Ice cubes in a glass of water)

Components	Reflecting-Only RIS	STARS
Substrates	Opaque	Transparent at radio frequency
Elements	Only support electric currents	Support both electric and *equivalent* magnetic currents
Coefficients	Reflection coefficients	Transmission and reflection coefficients

[Note]:Magnetic currents are vortex (circular) currents

[1] **Y. Liu**, *et al.*, “STAR: Simultaneous Transmission And Reflection for 360° Coverage by Intelligent Surfaces”, *IEEE Wireless Commun.*, vol. 28, no. 6, pp. 102-109, Dec. 2021, https://arxiv.org/abs/2103.09104. (ESI Highly Cited Paper)

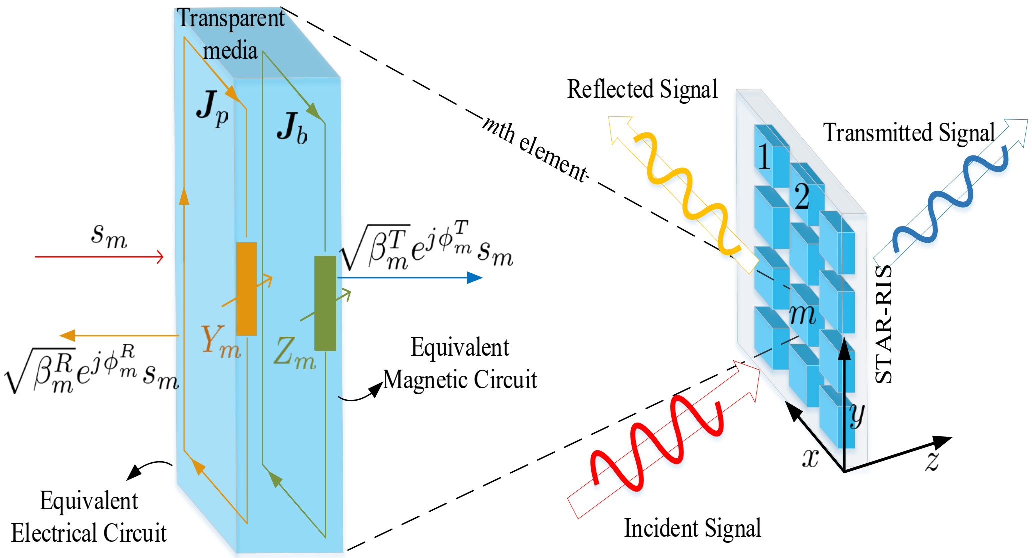
Basic Signal Model for STARS

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

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

- The reflected signal

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



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., $\beta_m^t + \beta_m^r = 1$

[1] 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, Sept. 2021. [Code] (IEEE Featured Article, IEEE CL Top 1 Popular Article, ESI Highly Cited Paper)

Communication Design Difference

Reflecting-Only RIS

- Reflection-coefficient matrix

$$\mathbf{\Theta} = \mathrm{diag}\left(\sqrt{\beta_1}e^{j\theta_1}, \sqrt{\beta_2}e^{j\theta_2}, \ldots, \sqrt{\beta_M}e^{j\theta_M}\right)$$

where $\beta_m \in [0,1]$ and $\theta_m \in [0,2\pi)$.

STARS

- Transmission-coefficient matrix

$$\mathbf{\Theta} = \mathrm{diag}\left(\sqrt{\beta_1}e^{j\theta_1}, \sqrt{\beta_2}e^{j\theta_2}, \ldots, \sqrt{\beta_M}e^{j\theta_M}\right)$$

- Reflection-coefficient matrix

$$\mathbf{\Theta} = \mathrm{diag}\left(\sqrt{\beta_1}e^{j\theta_1}, \sqrt{\beta_2}e^{j\theta_2}, \ldots, \sqrt{\beta_M}e^{j\theta_M}\right)$$

where $\beta_m^t,\ \beta_m^r \in [0,1]$, $\beta_m^t + \beta_m^r = 1$, and $\theta_m^t, \theta_m^r \in [0,2\pi)$.

- For each STAR element, the phase shifts for transmission and reflection can be chosen generally independently from each other.
- For each STAR element, the amplitude control for transmission and reflection are coupled by the law of energy conservation.

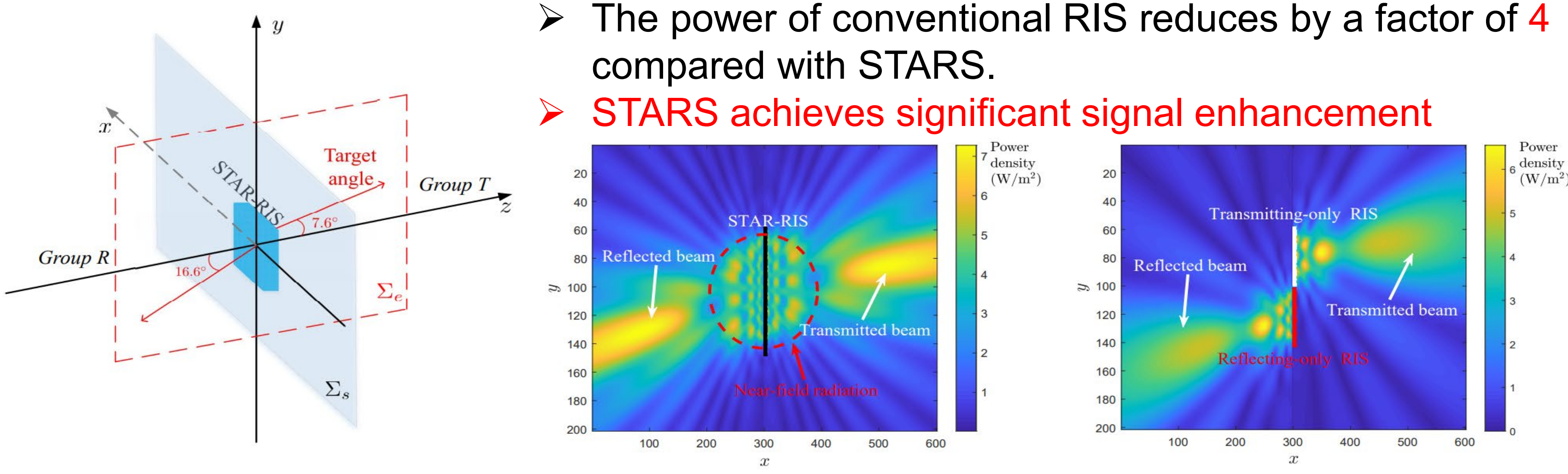
Comparison with Conventional RISs

❑ Performance Gains of STARS

- Conventional RISs: one reflecting RIS and one transmitting RIS, each of which has M elements
- STARS: $2M$ elements

	Conventional RISs	STARS
Diversity orders	$d_C^T + d_C^R = M + 2$	$d_S^T + d_S^R = 2M + 2$
Power scaling laws	$(M/2)^2$ for each side	M^2 for both sides

- The power of conventional RIS reduces by a factor of 4 compared with STARS.
- STARS achieves significant signal enhancement



(a) Simulation setup (b) STAR-RIS (c) Conventional RIS

[1] 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, Sept. 2021. [Code] (IEEE Featured Article, IEEE CL Top 1 Popular Article, ESI Highly Cited Paper)

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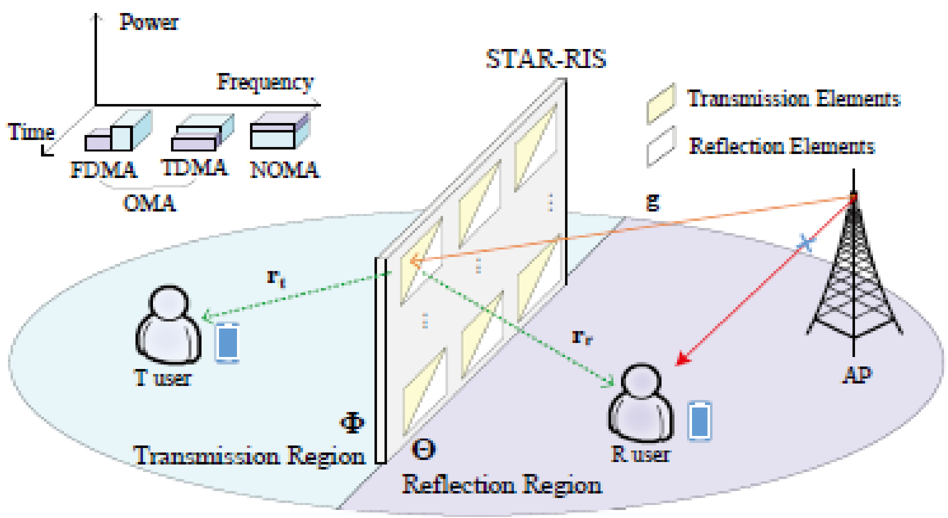
Coverage Characterization for STARS

❑ System Model

- AP communicates with one T user and one R user employing both NOMA and OMA with the aid of a STARS.
- **Objective:** to maximize the total coverage of the STARS, subject to the QoS constraints of T and R users



[1] C. Wu, **Y. Liu**, X. Mu, X. Gu, and O. A. Dobre, "Coverage Characterization of STAR-RIS Networks: NOMA and OMA," *IEEE Commun. Lett.*. vol. 25, no. 9, pp. 3036-3040, Sep. 2021, **[Code]** , https://arxiv.org/abs/2104.10006 (IEEE CL Popular Article)

Coverage Characterization for STARS

❑ Problem Formulation for NOMA

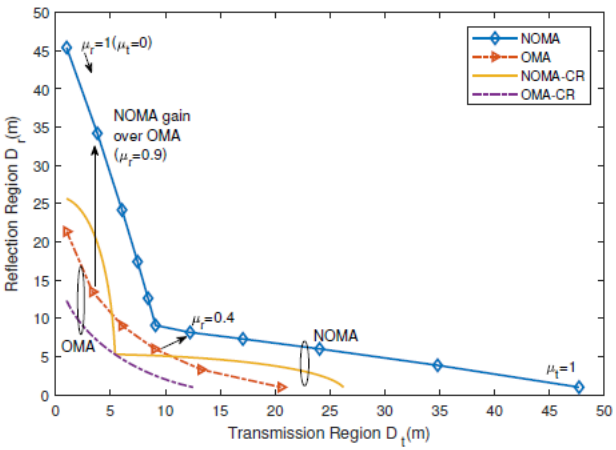
$$
\begin{aligned}
\max_{\{p_k,\beta_k,D_k,\lambda(k),\mathbf{v}_k,D_0\}} \quad & D_0 \\
\text{s.t.} \quad & D_k \geq u_k D_0, \forall k \in \mathcal{K}, \\
& D_k \geq 1, \forall k \in \mathcal{K}, \\
& r_k^N \geq \gamma_k, \forall k \in \mathcal{K}, \\
& \sum_k p_k \leq P_{\max}, \\
& \theta_m^k \in [0, 2\pi], \forall m \in \mathcal{M}, k \in \mathcal{K}, \\
& \beta_r + \beta_t = 1, \\
& \lambda(k) \in \{0,1\}, \lambda(t) + \lambda(r) = 1, \\
& \begin{cases} |h_t|^2 \geq |h_r|^2, \text{if } \lambda(t) = 1 \\ |h_t|^2 \leq |h_r|^2, \text{otherwise} \end{cases},
\end{aligned}
$$

- D_0: total coverage
- D_t, D_r: transmission and reflection coverage
- β_t, β_r: amplitude control
- $\mathbf{v}_t$, $\mathbf{v}_r$: phase shift
- p_t, p_r: power allocation
- $\lambda(t)$, $\lambda(r)$: NOMA decoding order

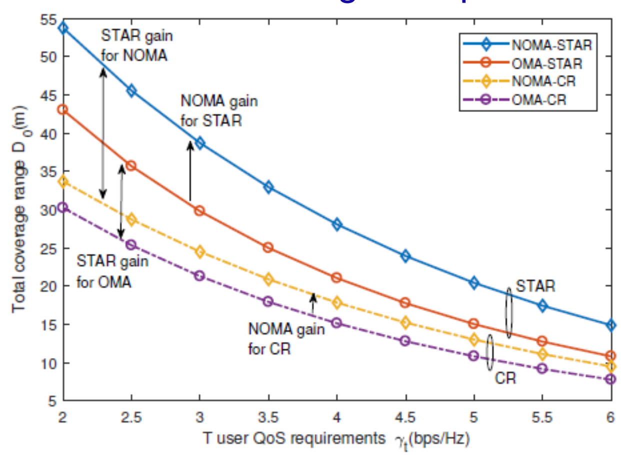
❑ Problem Formulation for OMA

$$
\begin{aligned}
\max_{\{p_k,\beta_k,\omega_k,D_k,\mathbf{v}_k,D_0\}} \quad & D_0 \\
\text{s.t.} \quad & r_k^O \geq \gamma_k, \forall k \in \mathcal{K}, \\
& \sum_k \omega_k \leq 1, \\
& \text{(7b), (7c), (7e)} - \text{(7g)}.
\end{aligned}
$$

➢ Coverage tradeoff



➢ Total coverage comparison



- ✓ STARS outperforms conventional RIS for both NOMA and OMA
- ✓ STARS improve the NOMA gain over OMA than conventional RIS
- ✓ STARS gain is more pronounced in NOMA than that in OMA
- ✓ STARS+NOMA is a win-win combination

[1] C. Wu, **Y. Liu**, X. Mu, X. Gu, and O. A. Dobre, "Coverage Characterization of STAR-RIS Networks: NOMA and OMA," *IEEE Commun. Lett.*. vol. 25, no. 9, pp. 3036-3040, Sep. 2021, [Code] , https://arxiv.org/abs/2104.10006 (IEEE CL Popular Article)

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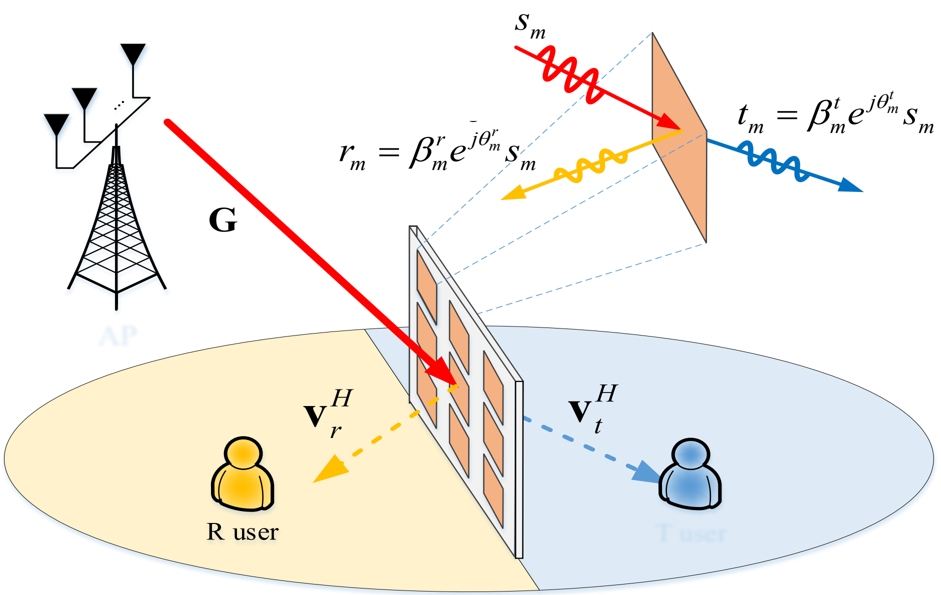
Joint Beamforming Design for STARS



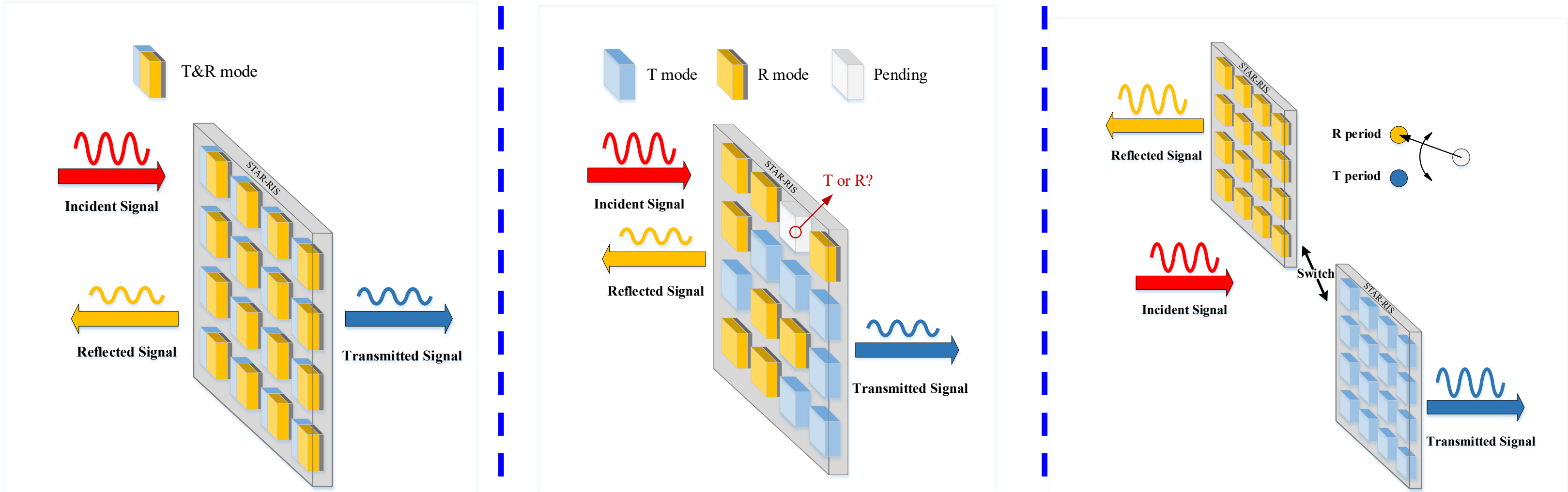
STAR-RIS

- ❑ Multiple-antenna AP: Active beamforming
- ❑ STARS: Passive transmission and reflection beamforming
- ❑ **Joint Beamforming Design**: to minimize the power consumption for satisfying the QoS requirements of each user for each proposed operating protocol

[1] X. Mu, **Y. Liu,** L. Guo, J. Lin, R. Schober, "Simultaneously Transmitting And Reflecting (STAR) RIS Aided Wireless Communications", *IEEE Trans. Wireless Commun.*, vol. 21, no. 5, pp. 3083-3098, May 2022, **[Code]** , https://arxiv.org/abs/2104.01421. (ESI Highly Cited Paper)

Operating Protocols for STARS

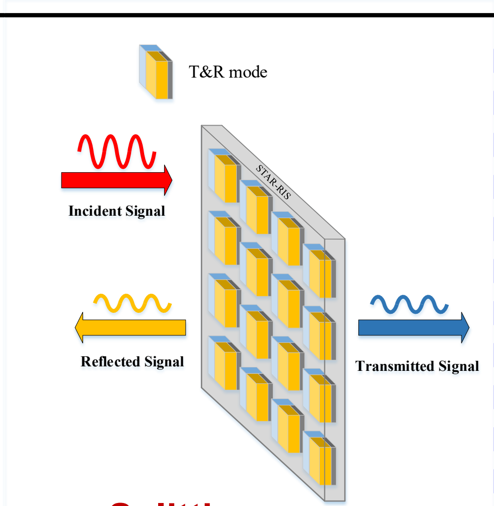
- Based on the signal model, each STAR element can be operated in
  - Full transmission mode (T mode): $\beta_m^t = 1,\ \beta_m^r = 0$
  - Full reflection mode (R mode): $\beta_m^t = 0,\ \beta_m^r = 1$
  - Simultaneous transmission and reflection mode (T&R mode)
- Practical operating protocols

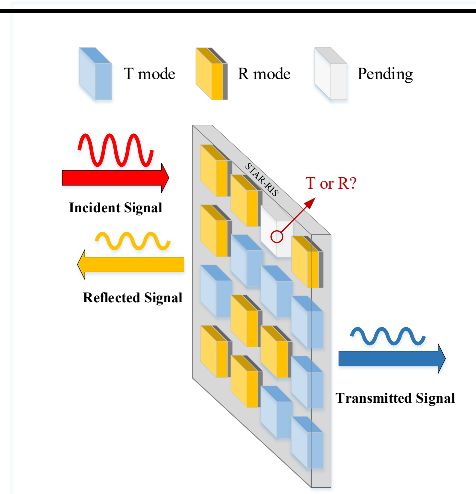


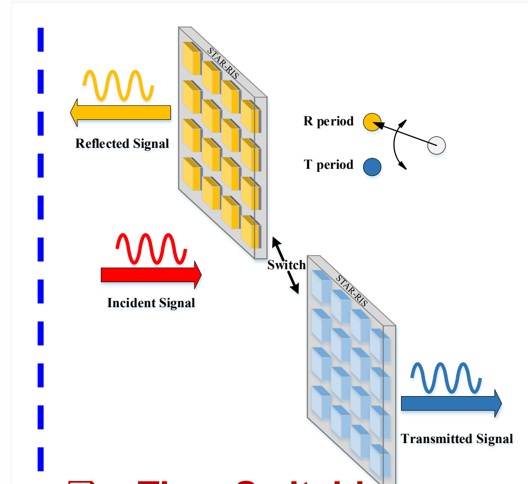
Energy Splitting (ES) | Mode Switching (MS) | Time Switching (TS)

[1] X. Mu, **Y. Liu,** L. Guo, J. Lin, R. Schober, "Simultaneously Transmitting And Reflecting (STAR) RIS Aided Wireless Communications", *IEEE Trans. Wireless Commun.*, vol. 21, no. 5, pp. 3083-3098, May 2022, [Code] , https://arxiv.org/abs/2104.01421. (ESI Highly Cited Paper)

Operating Protocols for STARS







❑ Energy Splitting

➢ All elements are operated in T&R mode

$$\mathbf{\Theta}_t^{\mathrm{ES}} = \mathrm{diag}\left(\sqrt{\beta_1^t}e^{j\theta_1^t}, \sqrt{\beta_2^t}e^{j\theta_2^t}, \ldots, \sqrt{\beta_M^t}e^{j\theta_M^t}\right)$$

$$\mathbf{\Theta}_r^{\mathrm{ES}} = \mathrm{diag}\left(\sqrt{\beta_1^r}e^{j\theta_1^r}, \sqrt{\beta_2^r}e^{j\theta_2^r}, \ldots, \sqrt{\beta_M^r}e^{j\theta_M^r}\right)$$

$$s.t.\ \beta_m^t, \beta_m^r \in [0,1], \beta_m^t + \beta_m^r = 1, \theta_m^t, \theta_m^r \in [0, 2\pi)$$

❑ Mode Switching

➢ All elements are operated in either T mode or R mode

$$\mathbf{\Theta}_t^{\mathrm{MS}} = \mathrm{diag}\left(\sqrt{\beta_1^t}e^{j\theta_1^t}, \sqrt{\beta_2^t}e^{j\theta_2^t}, \ldots, \sqrt{\beta_M^t}e^{j\theta_M^t}\right)$$

$$\mathbf{\Theta}_r^{\mathrm{MS}} = \mathrm{diag}\left(\sqrt{\beta_1^r}e^{j\theta_1^r}, \sqrt{\beta_2^r}e^{j\theta_2^r}, \ldots, \sqrt{\beta_M^r}e^{j\theta_M^r}\right)$$

$$s.t.\ \beta_m^t, \beta_m^r \in \{0,1\}, \beta_m^t + \beta_m^r = 1, \theta_m^t, \theta_m^r \in [0, 2\pi)$$

❑ Time Switching

➢ All elements are periodically operated in T mode and R mode

$$\mathbf{\Theta}_t^{\mathrm{TS}} = \mathrm{diag}\left(e^{j\theta_1^t}, e^{j\theta_2^t}, \ldots, e^{j\theta_M^t}\right), 0 \le t \le \lambda^t T$$

$$\mathbf{\Theta}_r^{\mathrm{TS}} = \mathrm{diag}\left(e^{j\theta_1^r}, e^{j\theta_2^r}, \ldots, e^{j\theta_M^r}\right), \lambda^t T < t \le T$$

$$s.t.\ \lambda^t, \lambda^r \in [0,1], \lambda^t + \lambda^r = 1, \theta_m^t, \theta_m^r \in [0, 2\pi)$$

Protocols	Advantages	Disadvantages
ES	High flexibility	Large number of design variables
MS	Easy to implement	Reduced transmission and reflection gain
TS	Independent T and R design	High hardware implementation complexity

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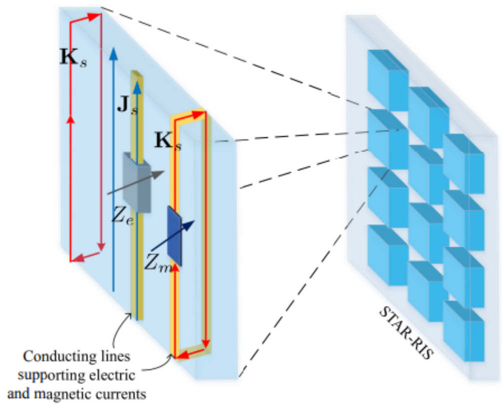
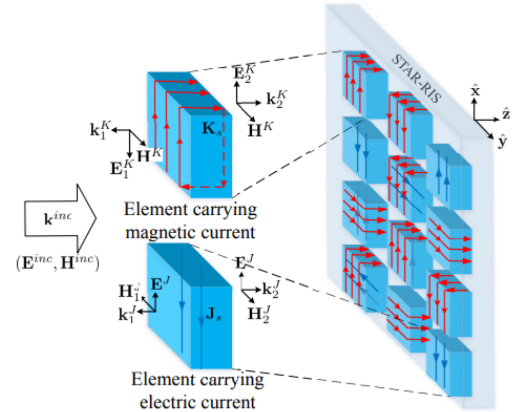
A Correlated/Coupled T&R Phase-Shift Model



(a) Surface equivalent currents of the STAR-RIS.



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

For **passive-lossless** STARS, 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: $\frac{dW}{dt} = -\int_{(\Sigma)} (\mathbf{E} \times \mathbf{H})\, d\Sigma - \int_{(V)} \mathbf{J} \cdot \mathbf{E}\, dV$ *=0*

$$T = \beta^T \cdot e^{j\phi^T} = (E^J + E_2^K + E^{inc})/E^{inc},$$ -> the transmission coefficient

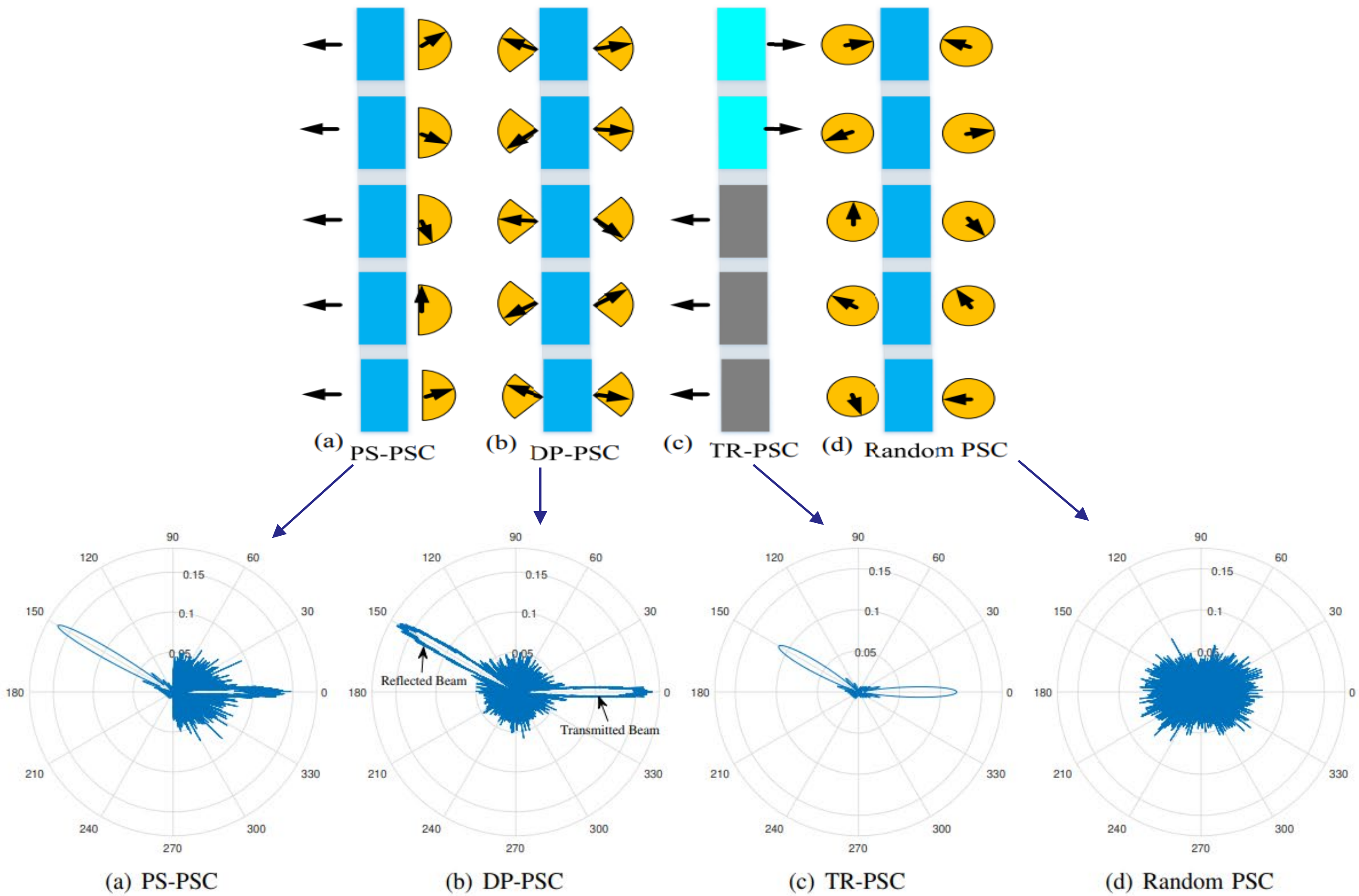
$$R = \beta^R \cdot e^{j\phi^R} = (E^J + E_1^K)/E^{inc},$$ -> the reflection coefficient

This leads to **the Correlated Model:** $\beta_m^T = \sqrt{1 - (\beta_m^R)^2}$, amplitude correlation

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

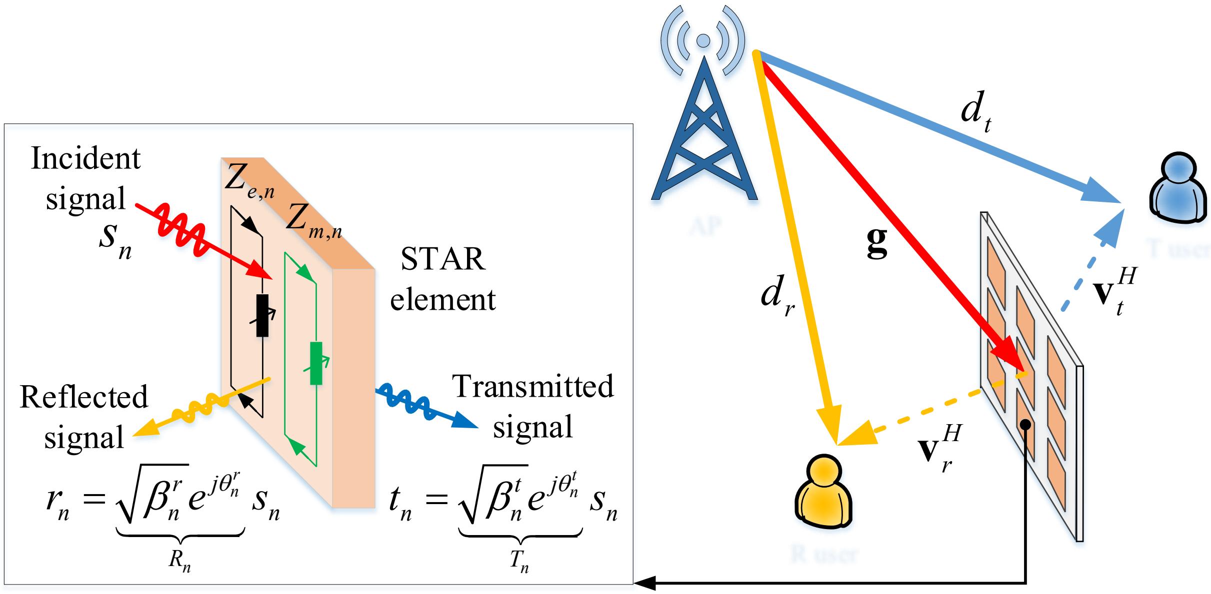
[1] J. Xu, **Y. Liu,** X. Mu, R. Schober, H. V. Poor, “STAR-RISs: A Correlated T&R Phase-Shift Model and Practical Phase-Shift Configuration Strategies”, *IEEE JSTSP,* vol. 16, no. 5, pp. 1097-1111, Aug. 2022, **[Code]** , https://arxiv.org/abs/2112.00299 (IEEE JSTSP Popular Article)

Practical Phase-Shift Configuration (PSC)



(1) Primary-Secondary (2) Diversity-Preserving (3) T&R-Group

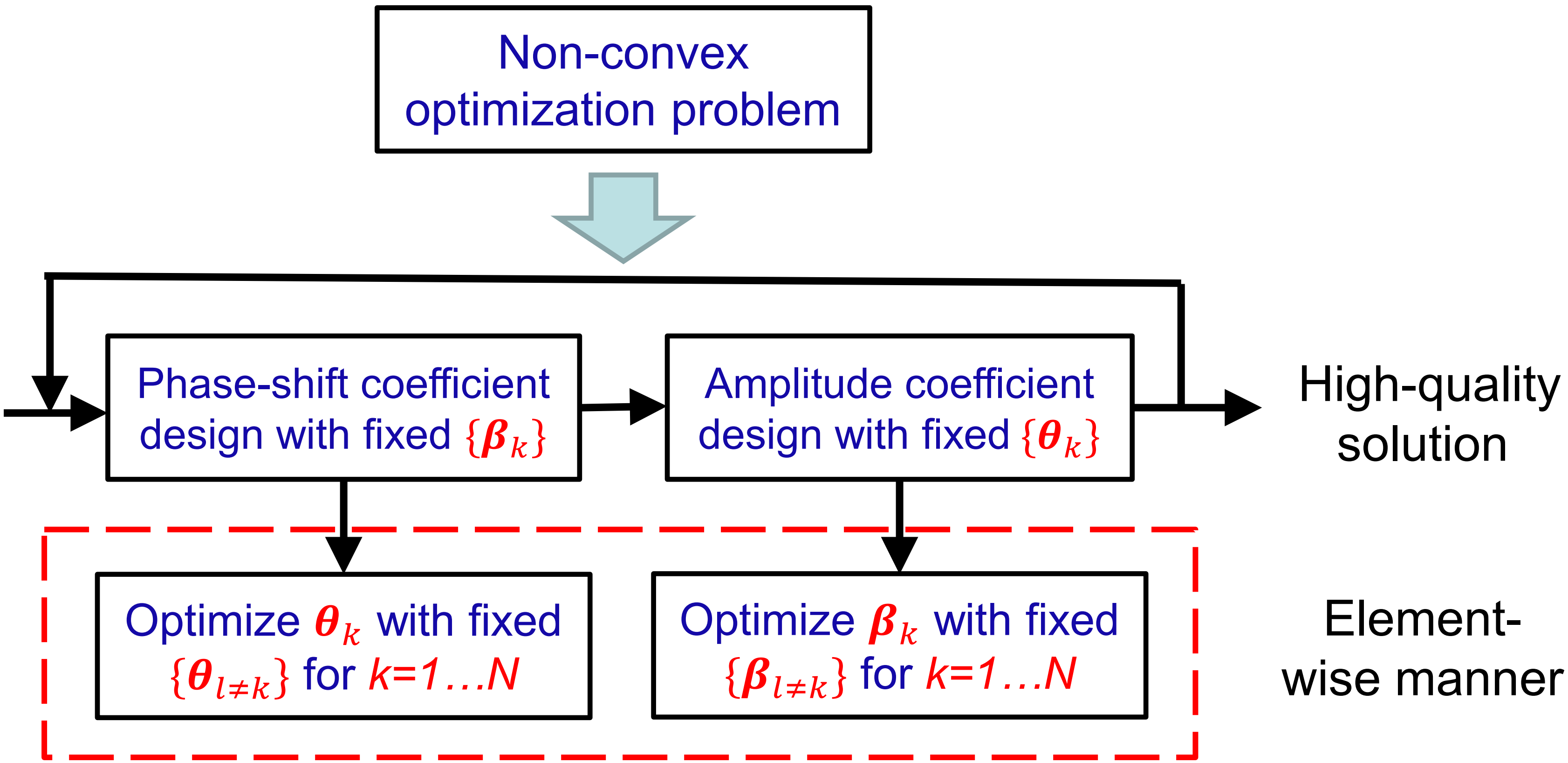
STARS Coefficient Design with Coupled Phase Shifts



- ❑ A coupling phase-shift model for STARS: $\left|\theta_n^t - \theta_n^r\right| = \frac{\pi}{2}, \frac{3\pi}{2}$
- ❑ Challenge: The design of phase-shift coefficients for transmission and reflection is highly-coupled.
- ❑ **Solutions**: An element-wise alternating optimization algorithm.

[1] **Y. Liu**, X. Mu, R. Schober, H. V. Poor, "Simultaneously Transmitting and Reflecting (STAR)-RISs: A Coupled Phase-Shift Model", *IEEE ICC 2022*, pp. 2840-2845, **[Code]**, https://arxiv.org/abs/2110.02374. (IEEE SPCC-TC Best Paper Award)

Element-wise alternating optimization



✓ The complexity of the proposed element-wise AO algorithm increases only linearly with the number of STARS elements.

[1] **Y. Liu**, X. Mu, R. Schober, H. V. Poor, "Simultaneously Transmitting and Reflecting (STAR)-RISs: A Coupled Phase-Shift Model", *IEEE ICC 2022*, pp. 2840-2845, **[Code]** , https://arxiv.org/abs/2110.02374. (IEEE SPCC-TC Best Paper Award)

A General Optimization Framework

- Although the complexity of the element-wise algorithm is low, it has the following problems.
  - *Limited application scenario*: single-antenna BS, two communication users
  - *No optimality.*

- *Shall we design an optimization framework that is applicable to **various scenarios** (e.g., NOMA, SWIPT, ISAC, PLS, UAV) and has the **provable optimality**?*

A General Optimization Framework

- A *general* optimization framework with *provable optimality* and *low complexity*
- Consider the following optimization problem:

$$\min_{\mathbf{x}\in\mathcal{X},\boldsymbol{\theta}_t,\boldsymbol{\theta}_r} F(\mathbf{x},\boldsymbol{\theta}_t,\boldsymbol{\theta}_r)$$

$$\text{s.t.} \quad \beta_{t,n}^2+\beta_{r,n}^2=1, \forall n\in\mathcal{N},$$

$$\cos(\phi_{t,n}-\phi_{r,n})=0, \forall n\in\mathcal{N}, \longrightarrow |\phi_{t,n}-\phi_{r,n}|=\frac{\pi}{2} \text{ or } \frac{3\pi}{2}$$

- $\boldsymbol{\theta}_i=[\beta_{i,1}e^{j\phi_{i,1}},\ldots,\beta_{i,N}e^{j\phi_{i,N}}]^T$
- $F(\mathbf{x},\boldsymbol{\theta}_t,\boldsymbol{\theta}_r)$: *objective function* such as utility functions of communication, e.g., weighted sum-rate and max-min fairness
- $\mathcal{X}$: feasible set of variable $\mathbf{x}$

[1] Z. Wang, X. Mu, **Y. Liu**, R. Schober, "Coupled Phase-Shift STAR-RISs: A General Optimization Framework", *IEEE Wireless Commun. Lett.*, vol. 12, no. 2, pp. 207-211, Feb. 2023. [Code], https://arxiv.org/abs/2208.01942 (IEEE WCL Popular Article)

Remarks

Remarks

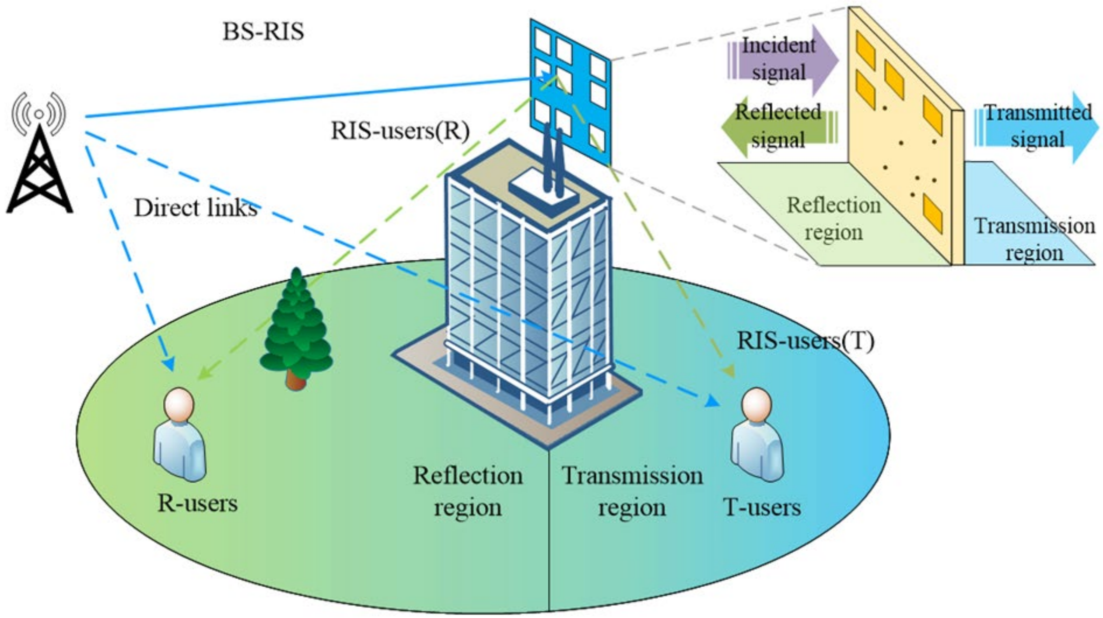
- **From Independent to Coupled:**
  Algorithm A for independent → *Algorithm A + Proposed framework* for coupled

- **Low Complexity:**
  Amplitude and phase shifts are updated in *closed-form.*

- **Convergence & Optimality:**
  If *Robinson's condition* or *MFCQ condition* is satisfied → KKT optimal solution
  If not → at least convergence is guaranteed

[1] Z. Wang, X. Mu, **Y. Liu**, R. Schober, "Coupled Phase-Shift STAR-RISs: A General Optimization Framework", *IEEE Wireless Commun. Lett.*, vol. 12, no. 2, pp. 207-211, Feb. 2023. [Code], https://arxiv.org/abs/2208.01942 (IEEE WCL Popular Article)

AI enabled Coupled STARS Beamforming



- Energy splitting (ES) protocol: simultaneously operate transmitting and reflecting modes with coupled splitting coefficients.
- STARS for MISO: Passive transmission and reflection beamforming
- **Optimization objective**: Minimize the long-term power consumption by joint optimize the active & passive beamforming

[1] R. Zhong, **Y. Liu**, X. Mu, Y. Chen, X. Wang, and L. Hanzo, "Hybrid Reinforcement Learning for STAR-RISs: A Coupled Phase-Shift Model Based Beamformer", *IEEE J. Sel. Areas Commun*, vol. 40, no. 9, pp. 2556-2569, Sept. 2022, **[Code]** https://arxiv.org/abs/2205.05029

Hybrid Continuous and Discrete Action (Why do we need AI?)

❑ STARS Model

- ❖ Reflection coefficient $v_{\mathcal{R}} = \beta_{\mathcal{R},n} e^{j\theta_{\mathcal{R},n}}$,
- ❖ Transmission coefficien $v_{\mathcal{T}} = \sqrt{1-\beta_n^2} e^{j\theta_{\mathcal{T},n}}$.
- ❖ Relationship:

$$\beta_n \sqrt{1-\beta_n^2} \cos(\theta_{\mathcal{R},n} - \theta_{\mathcal{T},n}) = 0,$$

- ❖ Reflection/transmission matrix

$$\mathbf{\Theta}_{\mathcal{R}}[t] = \mathrm{diag}\left(\beta_1 e^{j\theta_{\mathcal{R},1}[t]}, \beta_2 e^{j\theta_{\mathcal{R},1}[t]}, \cdots, \beta_N e^{j\theta_{\mathcal{R},N}[t]}\right),$$

$$\mathbf{\Theta}_{\mathcal{T}}[t] = \mathrm{diag}\left(\sqrt{1-\beta_1^2} e^{j\theta_{\mathcal{T},1}[t]}, \sqrt{1-\beta_2^2} e^{j\theta_{\mathcal{T},1}[t]}, \cdots, \sqrt{1-\beta_N^2} e^{j\theta_{\mathcal{T},N}[t]}\right).$$

❑ Problem Formulation

$$\min_{\mathbf{w},\mathbf{\Theta}_{\mathcal{T}},\mathbf{\Theta}_{\mathcal{R}},\boldsymbol{\beta}} \sum_{t=1}^{T} \sum_{k=1}^{K} \| \mathbf{w}_{k,t}^2 \|,$$

$$\begin{aligned}
\text{s.t.} \quad & -\pi \le \theta_{\mathcal{T},n,t} \le \pi, \forall n, \forall t, \\
& -\pi \le \theta_{\mathcal{R},n,t} \le \pi, \forall n, \forall t, \\
& R_{k,t} \ge R_{\mathrm{QoS}}, \forall k, \forall t, \\
& 0 < \beta_{n,t} \le 1, \forall n, \forall t, \\
& \beta_{n,t} \sqrt{1-\beta_{n,t}^2} \cos(\theta_{\mathcal{R},n,t} - \theta_{\mathcal{T},n,t}) = 0, \\
& P_{b,t} \le P_{\max},
\end{aligned}$$

✓ The motivation of AI

- ❖ The **coupled phase shift model** leads to **hybrid actions**
- ❖ **Long term time varying** problem
- ❖ Massive STARS elements (**from SISO to MISO**): high action dimension

[1] R. Zhong, **Y. Liu**, X. Mu, Y. Chen, X. Wang, and L. Hanzo, "Hybrid Reinforcement Learning for STAR-RISs: A Coupled Phase-Shift Model Based Beamformer", *IEEE J. Sel. Areas Commun*, vol. 40, no. 9, pp. 2556-2569, Sept. 2022, [Code] https://arxiv.org/abs/2205.05029

Conventional Optimization vs. AI-based Method

- ❑ Our proposed general optimization framework in [1] can also be exploited to solve the problem in [2].

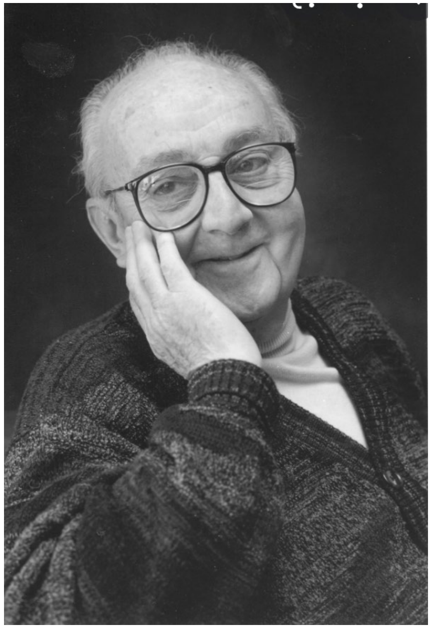
- ❑ ***Tradeoff*** in choosing the method in [1] and [2]
  - ❖ The conventional optimization method in [1] can guarantee the ***optimality*** of solutions but need ***many iterations*** to obtain a solution.
  - ❖ The AI-based method in [2] can obtain a solution ***in milliseconds*** but ***cannot guarantee the optimality*** of the solutions.

- ❑ ***Complexity vs. Optimality***

[1] Z. Wang, X. Mu, **Y. Liu**, R. Schober, "Coupled Phase-Shift STAR-RISs: A General Optimization Framework", *IEEE Wireless Commun. Lett.*, vol. 12, no. 2, pp. 207-211, Feb. 2023. **[Code]**, https://arxiv.org/abs/2208.01942
[2] R. Zhong, **Y. Liu**, X. Mu, Y. Chen, X. Wang, and L. Hanzo, "Hybrid Reinforcement Learning for STAR-RISs: A Coupled Phase-Shift Model Based Beamformer", *IEEE J. Sel. Areas Commun*, vol. 40, no. 9, pp. 2556-2569, Sept. 2022, **[Code]** https://arxiv.org/abs/2205.05029

Which model is better?

"Essentially, all models are wrong, but some are useful."



----George E. P. Box

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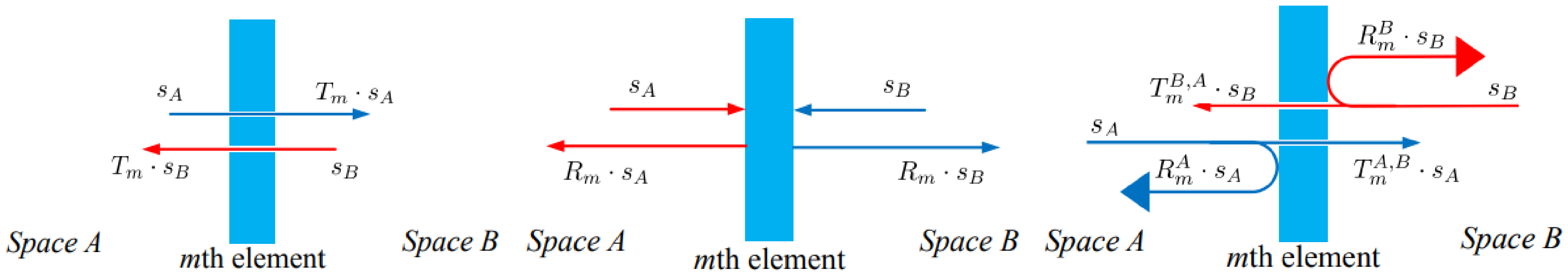
❖ Codes available: https://github.com/STAR-Yuanwei-Liu

Dual-Sided STARS: When Signals Incident on Both Sides

- In this case (e.g., uplink communication), we have different scenarios:



(A) Purely dual transmission **(B) Purely dual reflection** **(C) Dual-sided "STAR"**

- A dual-sided STARS is able to perform all the above three functions. It has following signal model:

$$s'_A = R_m \cdot s_A + T_m \cdot s_B,$$

$$s'_B = T_m \cdot s_A + R_m \cdot s_B,$$

$$T_m = \frac{2Z_e}{2Z_e + \eta} - \frac{Z_m}{Z_m + 2\eta},$$

$$R_m = \frac{Z_m}{Z_m + 2\eta} - \frac{\eta}{2Z_e + \eta}$$

✓ Note that in this model, $T_m^{A,B} = T_m^{B,A}$ and $R_m^A = R_m^B$, indicating the dual-sided STARS has ***symmetrical*** EM response on the two sides.

✓ Z_e and Z_m are the scalar electric and magnetic impedance of STARS element.

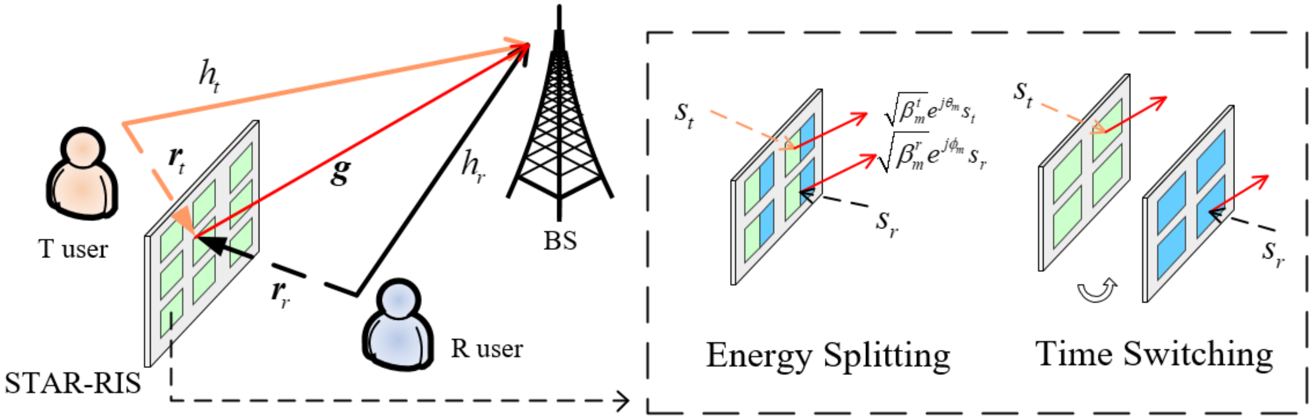
[1] J. Xu, X. Mu, J. T. Zhou and **Y. Liu**, "Simultaneously Transmitting and Reflecting (STAR)-RISs: Are They Applicable to Dual-Sided Incidence?," in *IEEE Wireless Commun. Lett.*, vol. 12, no. 1, pp. 129-133, Jan. 2023. https://arxiv.org/abs/2209.05317

Channel Estimation for STARS

❑ System Model

- **Time Switching**: Estimate the channels separately.
- **Energy Splitting**: Estimate the concatenated channels of the two users simultaneously. $p_t = p_r = \frac{p}{2}$ for a fair comparison.
- **Objective:** To minimize the sum mean square error under least square estimator.

✓ **STARS in uplink**



[1] C. Wu, C. You, **Y. Liu**, X. Gu, and Y. Cai, "Channel Estimation for STAR-RIS aided Wireless Communication," *IEEE Commun. Lett.*, vol. 26, no. 3, pp. 652-656, Mar. 2022 **[Code]** https://arxiv.org/abs/2112.01413 (IEEE CL Popular Article)

[2] J. Xu, X. Mu, J. T. Zhou and **Y. Liu**, "Simultaneously Transmitting and Reflecting (STAR)-RISs: Are They Applicable to Dual-Sided Incidence?," in *IEEE Wireless Commun. Lett.*, vol. 12, no. 1, pp. 129-133, Jan. 2023..

Channel Estimation for STARS

❑ Problem Formulation for TS

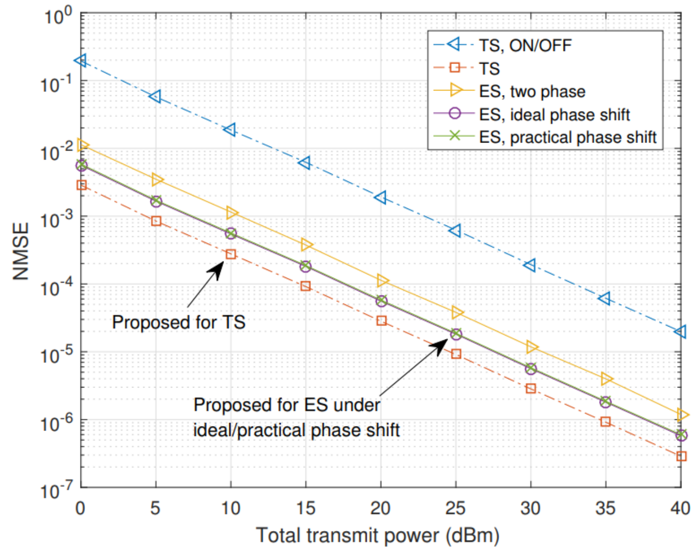
$$\min_{\boldsymbol{\Theta}} \ \frac{\sigma^2}{p}\mathrm{Tr}[(\boldsymbol{\Theta}^H\boldsymbol{\Theta})^{-1}]$$
$$\text{s.t.} \ \ \theta_{m,i}, \phi_{m,i} \in [0, 2\pi), m \in \mathcal{M}, i = 1, ..., \tau_t,$$
$$\mathrm{rank}(\boldsymbol{\Theta}) = M + 1.$$

❑ Problem Formulation for ES

$$\min_{\{\mathbf{s}_k, \beta_m^k, \bar{\boldsymbol{\Theta}}, \bar{\boldsymbol{\Phi}}\}} \ \frac{2\sigma^2}{p}\mathrm{Tr}[(\mathbf{V}^H\mathbf{V})^{-1}] \quad (12a)$$
$$\text{s.t.} \ \ \theta_{m,i}, \phi_{m,i} \in [0, 2\pi), m \in \mathcal{M}, i = 1, ..., \tau, \quad (12b)$$
$$\mathrm{rank}(\mathbf{V}) = 2M + 2, \quad (12c)$$
$$\beta_m^t + \beta_m^r \leq 1, \quad (12d)$$
$$\beta_m^k > 0, k \in \mathcal{K}, \quad (12e)$$
$$\cos(\theta_{m,i} - \phi_{m,i}) = 0. \quad (12f)$$

- ❑ Baseline 1: ON/OFF scheme
- ❑ Baseline 2: Two-phase scheme: Estimate direct link and cascaded link separately.

➢ NMSE comparison under different transmit power



- ✓ The overhead is the same for TS and ES and can be reduced by element-grouping.
- ✓ TS protocol achieves a smaller channel estimation error since ES leads to power leakage during uplink transmission.
- ✓ Robust beamforming is an interesting topic in the future.

[1] C. Wu, C. You, **Y. Liu**, X. Gu, and Y. Cai, "Channel Estimation for STAR-RIS aided Wireless Communication," *IEEE Commun. Lett.*, vol. 26, no. 3, pp. 652-656, Mar. 2022 [Code] https://arxiv.org/abs/2112.01413 (IEEE CL Popular Article)

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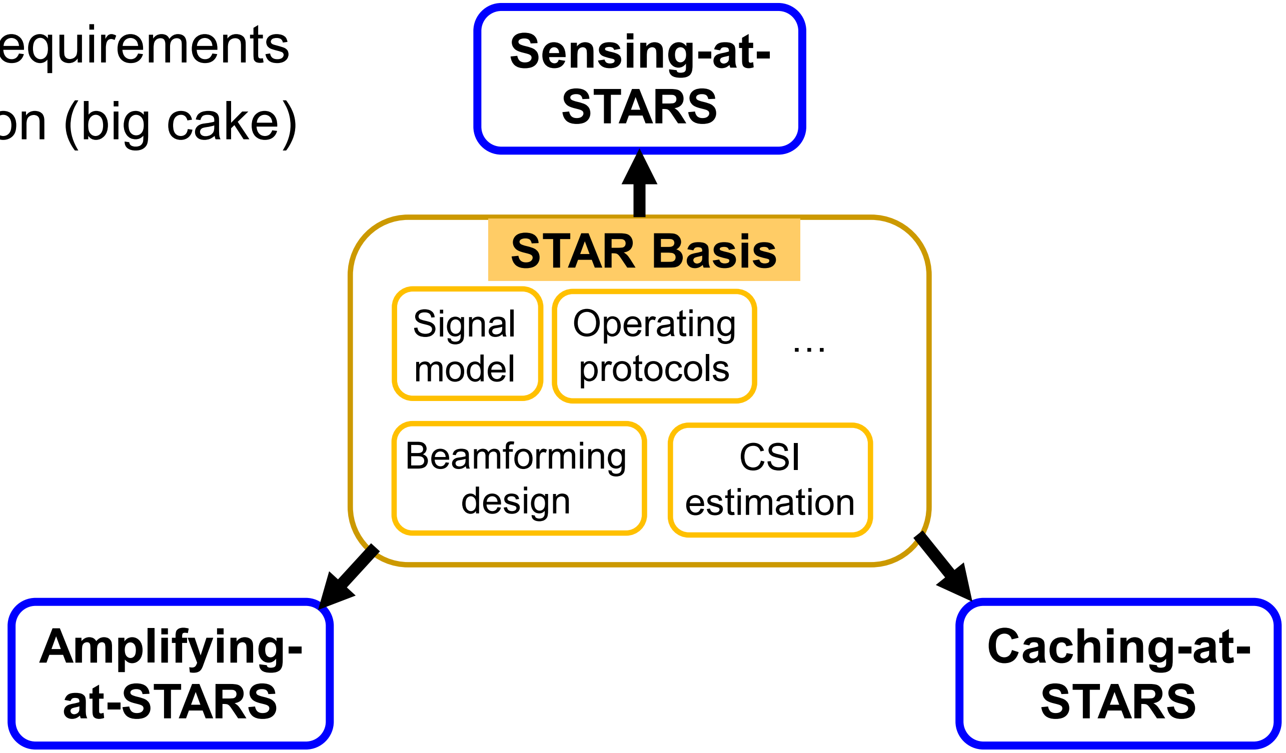
The Idea of STARS Platform

- Fundamental issues with STARS (Almost resolved)
  - *What Next Story Is* (Still far from happy ending)

- **STARS Platform** for 6G and Beyond
  - Upgrade existing STARS with new functions
  - Well support 6G requirements
  - Open for innovation (big cake)
  - …



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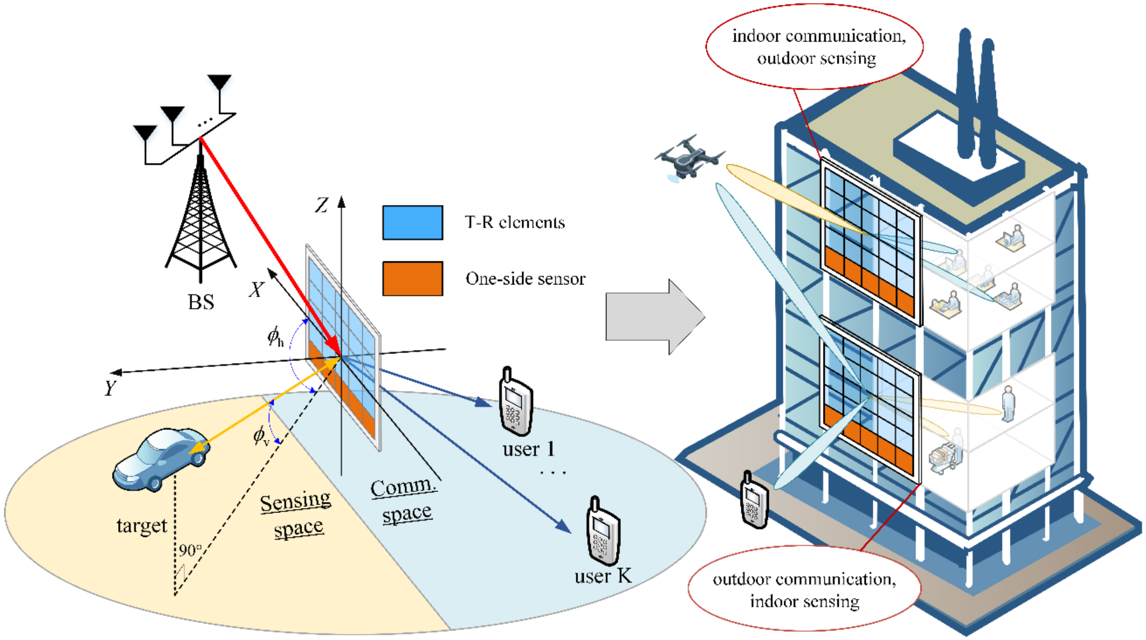
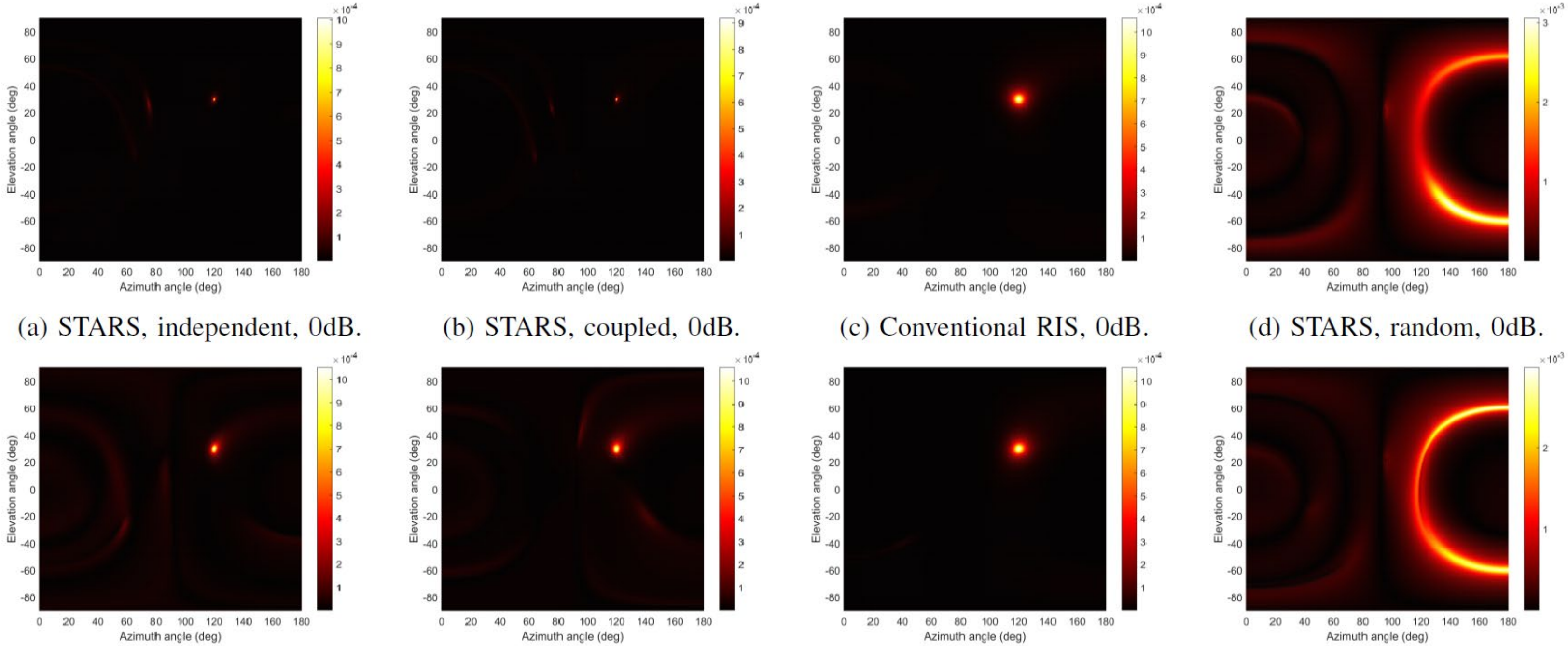
Sensing-at-STARS



- STARS splits the space into two subspace: *sensing space* and *communication space*
- ***Sensing-at-STARS***: install low-cost *active sensor* at the STARS.
  - Overcome significant path loss through multi-hops, BS→STARS→target→STARS→BS.
  - Avoid echo signal ambiguity at the BS (from transmission side? or from reflection side?)
- ***2D Sensing***: Estimating both *azimuth and elevation Directions-of-Arrival (DOAs).*

[1] Z. Wang, X. Mu, **Y. Liu**, "STARS Enabled Integrated Sensing and Communications: A CRB Optimization Perspective", *IEEE VTC2022-Fall*, (Best student paper award)
[2] Z. Wang, X. Mu, **Y. Liu**, "STARS Enabled Integrated Sensing and Communications", *IEEE Trans. Wireless Commun, vol. 22, no. 10, pp. 6750-6765, Oct. 2023,* https://arxiv.org/abs/2207.10748. (IEEE TWC Popular Article)

STARS Enabled ISAC



(a) STARS, independent, 0dB. (b) STARS, coupled, 0dB. (c) Conventional RIS, 0dB. (d) STARS, random, 0dB.

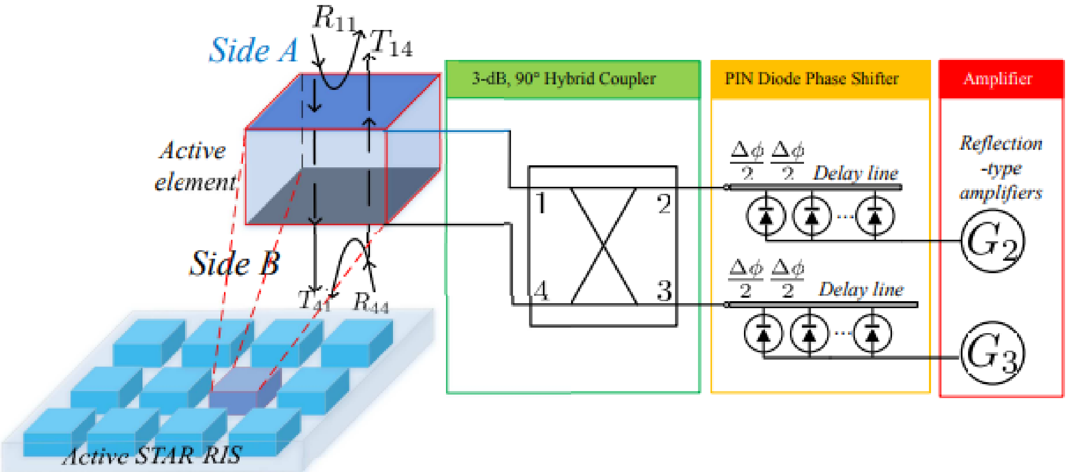
(e) STARS, independent, 20dB. (f) STARS, coupled, 20dB. (g) Conventional RIS, 20dB. (h) STARS, random, 20dB.

- ❑ Consider different *communication SINR thresholds*: 0dB and 20dB
- ❑ DOA estimation results obtained by *Maximum Likelihood Estimation (MLE)* for a target at the angle of (120^{o}, 30^{o}).
- ❑ STARS can achieve *point-like estimation results*, but conventions RIS cannot.
- ❑ Without optimizing CRB, the DOAs cannot be estimated through MLE.

[1] Z. Wang, X. Mu, **Y. Liu**, “STARS Enabled Integrated Sensing and Communications”, *IEEE Trans. Wireless Commun, vol. 22, no. 10, pp. 6750-6765, Oct. 2023,* https://arxiv.org/abs/2207.10748. (IEEE TWC Popular Article)

Amplifying-at-STARS

- Amplifying-at-STARS (active STARS): using amplifiers to achieve higher gain
  - We propose the following hardware model for active STARS:



By using two amplifiers: G2 and G3, the T&R coefficients can be ***independently configured****.*

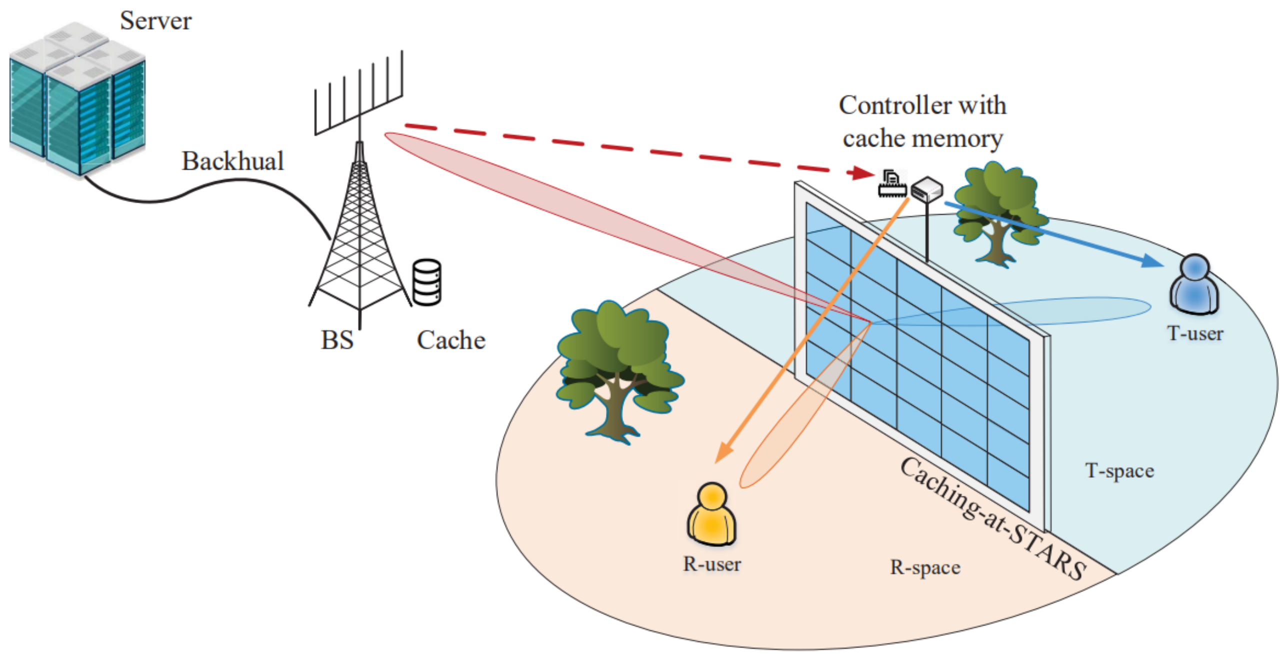
  - Based on the proposed hardware, signal model is given by:

Recall the signal model for dual-sided STARS

$$\begin{pmatrix} y_m^A \\ y_m^B \end{pmatrix} = \begin{pmatrix} \tilde{R}_m^A & \tilde{T}_m^{AB} \\ \tilde{T}_m^{BA} & \tilde{R}_m^B \end{pmatrix} \begin{pmatrix} s_m^A \\ s_m^B \end{pmatrix} \Rightarrow \begin{aligned} R_m^A &= -R_m^B = (\tilde{G}_3 - \tilde{G}_2)/2 \\ T_m^{AB} &= T_m^{BA} = j(\tilde{G}_2 + \tilde{G}_3)/2. \end{aligned}$$

[1] J. Xu, J. Zuo, J. T. Zhou and **Y. Liu**, "Active Simultaneously Transmitting and Reflecting (STAR)-RISs: Modelling and Analysis," *IEEE Commun. Lett.*, vol. 27, no. 9, pp. 2466-2470, Sept. 2023. https://arxiv.org/abs/2302.04432 (IEEE CL Popular Article)

Caching-at-STARS



- ***Caching-at-STARS***: install *cache memory and smart controller* at the STARS.
  - Satisfy user demands with fewer hops and desired channel conditions.
- Joint optimization of caching replacement and ***Information-centric hybrid beamforming*** (Design beamforming based on caching information):
  - BS → STARS' elements → users (requests are fetched at BS, hybrid beamforming).
  - STARS' smart controller → users (requests are fetched at Caching-at-STARS, active beamforming).
  - Hybrid mode (some requests are fetched at BS, others at Caching-at-STARS, hybrid beamforming).

[1] Z. Hu, R. Zhong, C. Fang, **Y. Liu**, "Caching-at-STARS: the Next Generation Edge Caching", *IEEE Trans. Wireless Commun., early access,* doi: 10.1109/TWC.2023.3349230. https://arxiv.org/abs/2308.00562.

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- ❑ **STARS Basis**
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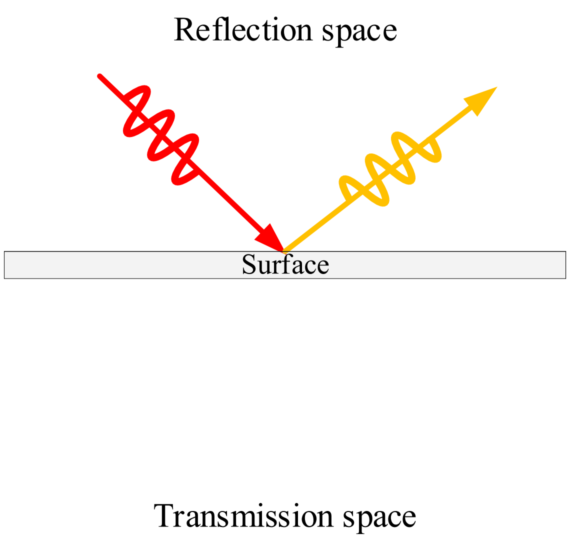
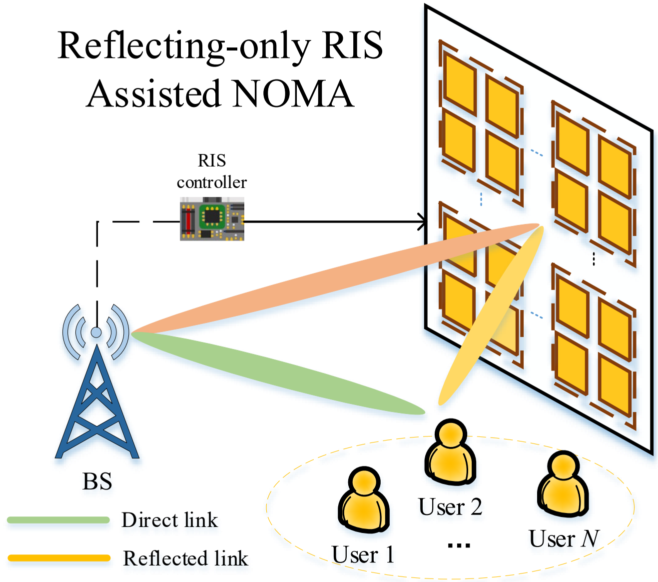
❖ Codes available: https://github.com/STAR-Yuanwei-Liu

❑ Conventional Reflecting-only RIS aided NOMA



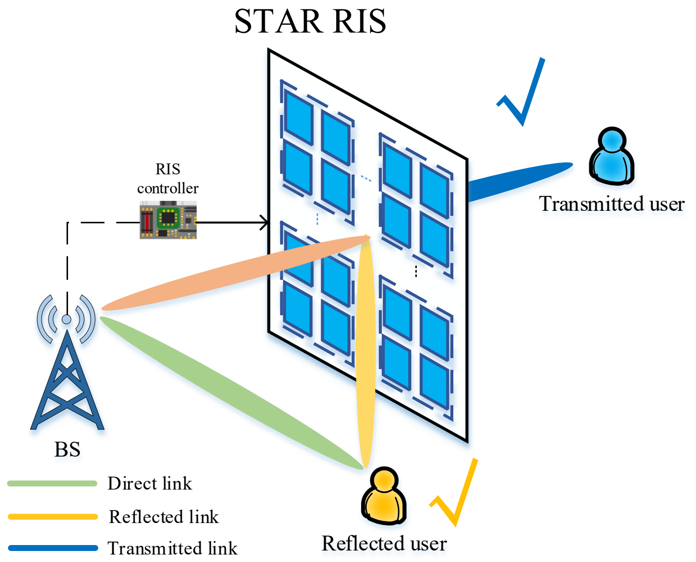


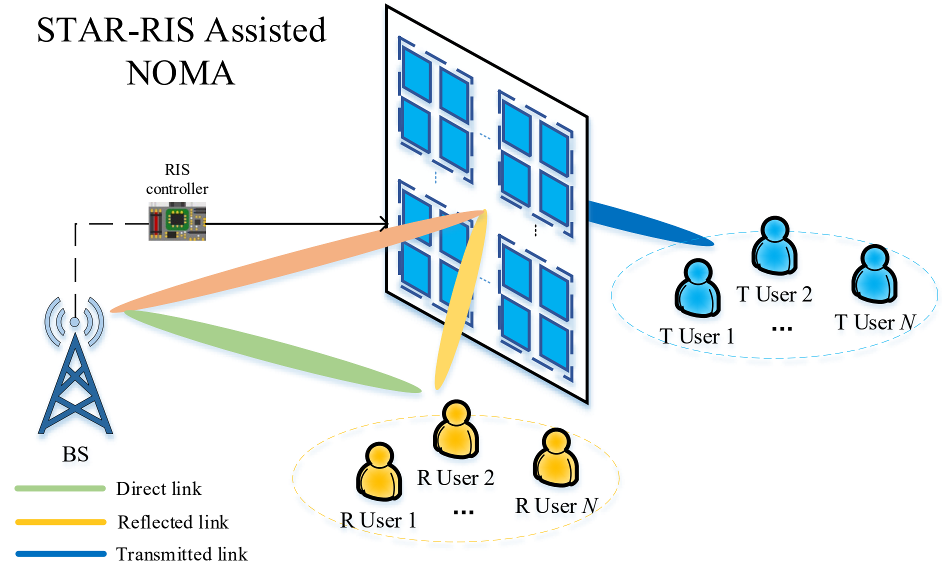
- ❑ For NOMA to achieve a large performance gain over OMA, it is important to pair users having different channel conditions [1,2].
- ❑ **Limitations:** channel conditions of users in reflected space are generally similar, which may be not easy to fully exploit the benefits of NOMA

[1] **Y. Liu**, *et. al*, "Evolution of NOMA Toward Next Generation Multiple Access (NGMA) for 6G," *IEEE J. Sel. Areas Commun*, vol. 40, no. 4, pp. 1037-1071, April 2022. https://arxiv.org/abs/2108.04561 (ESI Highly Cited Paper)
[2] **Y. Liu**, *et. al*, "The Road to Next-Generation Multiple Access: A 50-Year Tutorial Review," *Proceedings of the IEEE*, under review. https://arxiv.org/abs/2403.00189 (Invited Paper)
[3] X. Mu, **Y. Liu,** L. Guo, J. Lin, N. Al-Dhahir, "Exploiting Intelligent Reflecting Surfaces in NOMA Networks: Joint Beamforming Optimization", *IEEE Trans. Wireless Commun.*, vol. 19, no. 10, pp. 6884-6898, Oct. 2020, https://arxiv.org/abs/1910.13636 (ESI Highly Cited Paper)

STARS Aided Transmission-Reflection NOMA

❑ STARS aided Transmission-Reflection NOMA





- ❑ A pair of users at the transmission- and reflection-oriented side can be grouped together for facilitating 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.

[1] X. Yue, J. Xie, **Y. Liu**, *et al.*, "Simultaneously Transmitting and Reflecting Reconfigurable Intelligent Surface Assisted NOMA Networks", *IEEE Trans. Wireless Commun.*, vol. 22, no. 1, pp. 189-204, Jan. 2023, https://arxiv.org/abs/2112.01336 (ESI Highly Cited Paper)

Joint Design for STARS Aided NOMA

❑ Problem formulation

$$\max_{\mathcal{D}_c,\rho_{c,\mathcal{D}_c(k)},\mathbf{w}_c,\mathbf{u}_p} \sum_{c\in\mathbb{C}}\sum_{k\in\mathbb{K}_c} R^c_{\mathcal{D}_c(k)\to\mathcal{D}_c(k)},$$

$$s.t.\ R^c_{\mathcal{D}_c(k)\to\mathcal{D}_c(k)} \geqslant R^{\min}_{c,\mathcal{D}_c(k)}, \forall k\in\mathbb{K}_c, \forall c\in\mathbb{C},$$

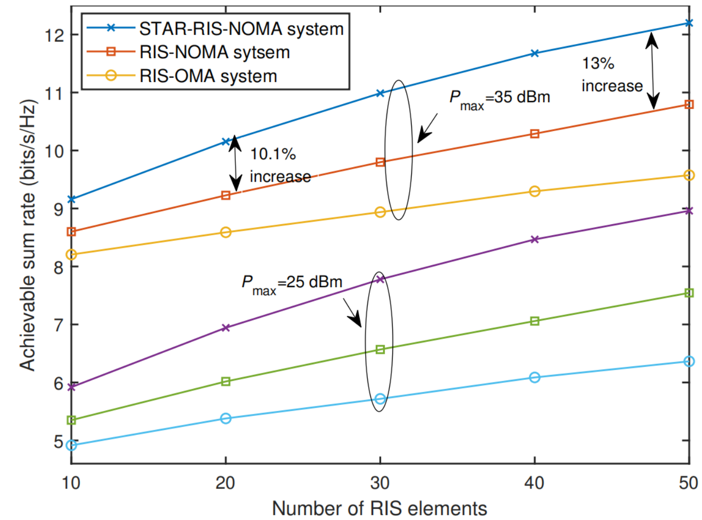
$$R^c_{\mathcal{D}_c(j)\to\mathcal{D}_c(k)} \geqslant R^c_{\mathcal{D}_c(k)\to\mathcal{D}_c(k)}, j\geqslant k, \forall j,k\in\mathbb{K}_c, \forall c\in\mathbb{C},$$

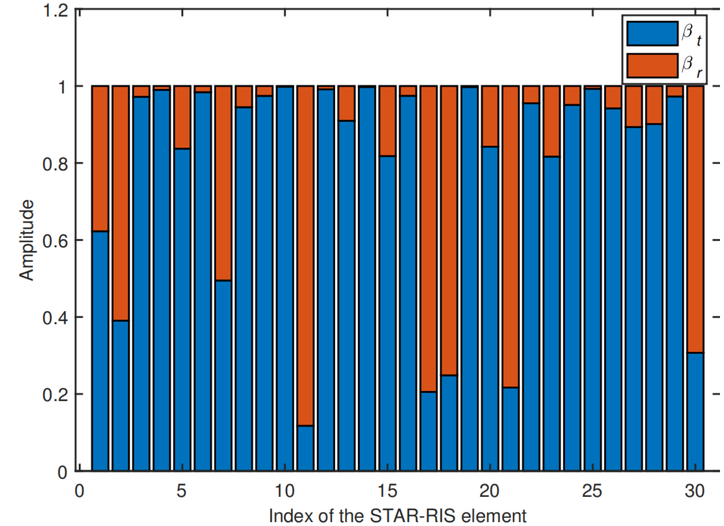
$$\sum_{c\in\mathbb{C}} \|\mathbf{w}_c\|_2^2 \leqslant P_{\max},$$

$$\sum_{k\in\mathbb{K}_c} \rho_{c,\mathcal{D}_c(k)} = 1, \forall c\in\mathbb{C},$$

$$\beta^p_m, \theta^p_m \in \mathbb{R}_{\beta,\theta}, \forall m\in\mathbb{M}, \forall p\in\{t,r\},$$

$$\mathcal{D}_c\in\mathbb{D}, c\in\mathbb{C},$$



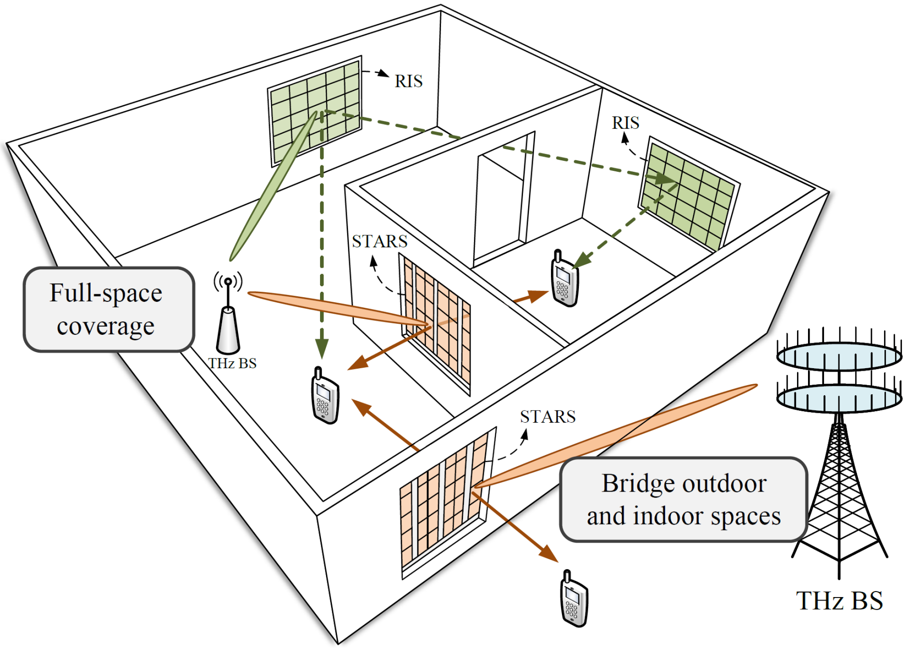


- ❑ Baseline 1: Conventional RIS aided NOMA
- ❑ Baseline 2: Conventional RIS aided OMA

- ✓ STARS aided NOMA outperforms conventional RIS based systems
- ✓ If there are more users in the transmission space, then STARS will allocate more energy to the transmission amplitudes

[1] J. Zuo, **Y. Liu**, Z. Ding, L. Song, and H. Poor, "Joint design for simultaneously transmitting and reflecting (STAR) RIS assisted NOMA systems", *IEEE Trans. Wireless Commun.*, vol. 22, no. 1, pp. 611-626, Jan. 2023, https://arxiv.org/abs/2106.03001 (ESI Highly Cited Paper).

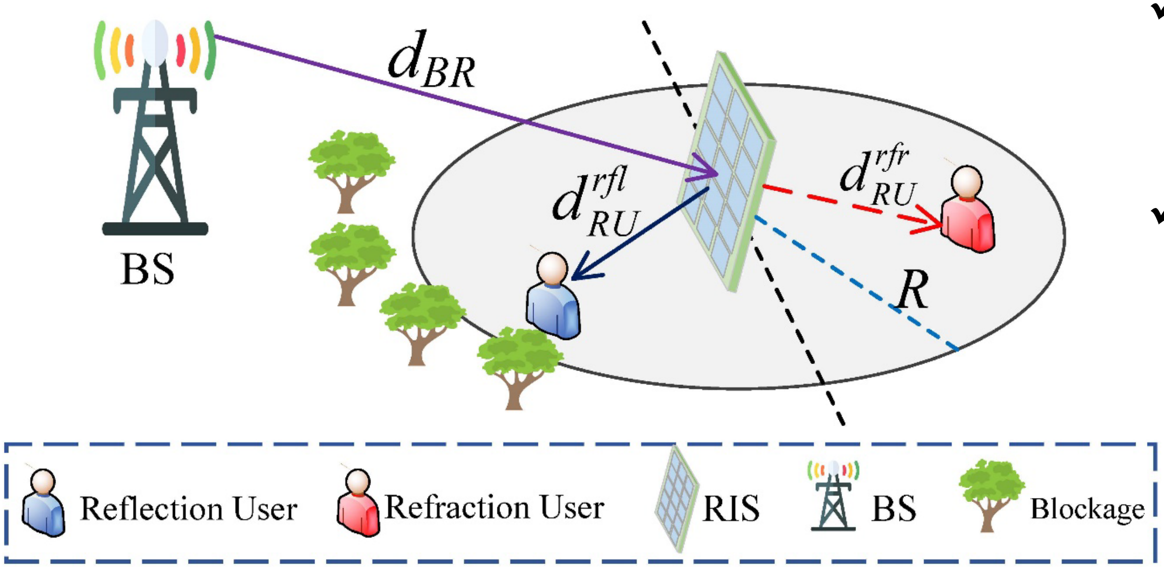
STARS aided THz Communications



- ❑ THz bands (0.1~10 THz) provide a broad communication bandwidth in the order of tens of gigahertz (GHz).
- ❑ THz communications is very sensitive to the blockage.
- ❑ STARS is more flexible than RIS to address the blockage issue.
- ❑ Based on different spectrum allocation schemes, the system bandwidth of THz communications can be either reasonably small or extremely large.

[1] Z. Wang, X. Mu, J. Xu, and **Y. Liu**, "Simultaneously Transmitting and Reflecting Surface (STARS) for Terahertz Communications", *IEEE JSTSP*, vol. 17, no. 4, pp. 861-877, July 2023, *https://arxiv.org/abs/2212.00497* (IEEE JSTSP Popular Article)

Spatial Analysis of STARS

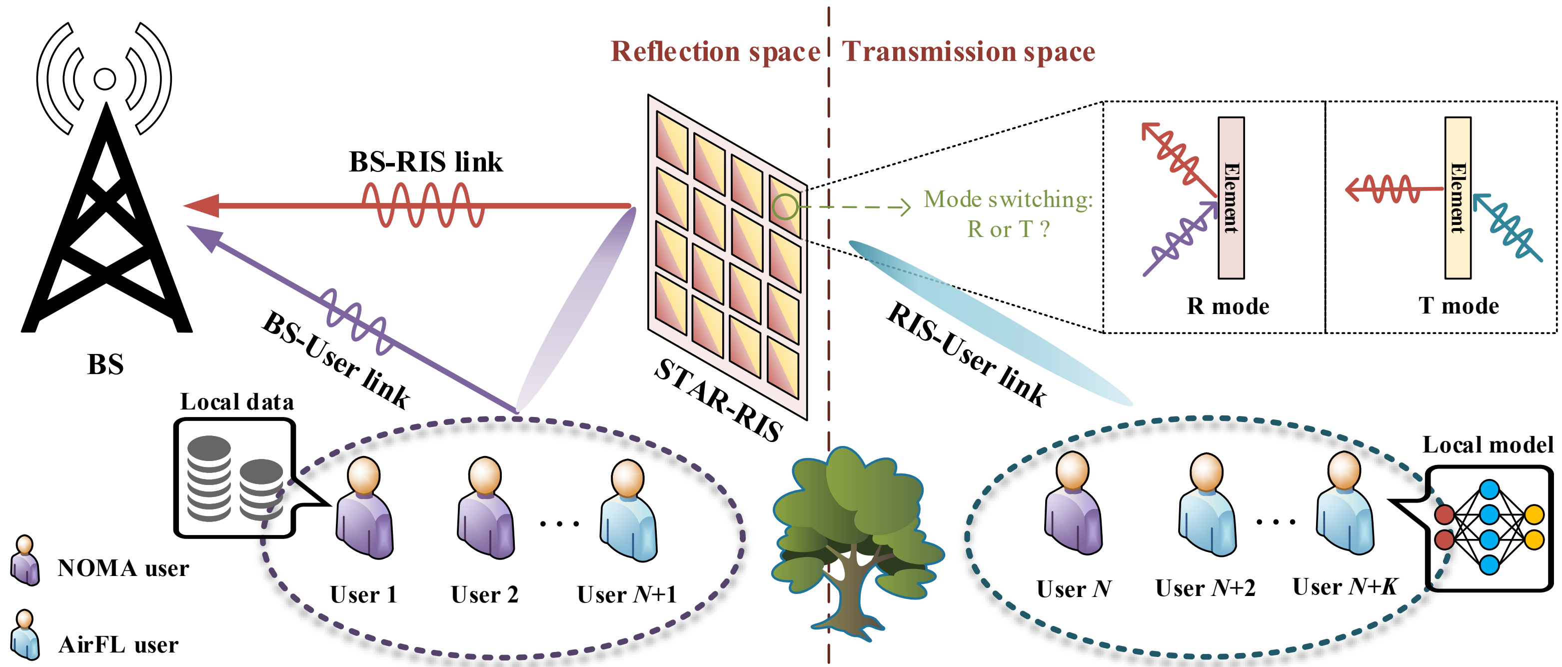


- ✓ A STARS-aided downlink NOMA network
- ✓ Deployment: 1) a fixed BS and a fixed RIS; 2) randomly deployed users in a circle area.

- ❑ Channel links: 1) the reflecting user is blocked by obstacles and receive signals by reflection; 2) the transmitting user receive signals by transmission
- ❑ ES protocol: simultaneously operate transmitting and reflecting modes with different splitting coefficients.
- ❑ Other protocols: MS protocol & TS protocol

[1] C. Zhang, W. Yi, **Y. Liu**, Z. Ding and L Song, "STAR-IOS Aided NOMA Networks: Channel Model Approximation and Performance Analysis", *IEEE Trans. Wireless Commun.*, vol. 21, no. 9, pp. 6861-6876, Sep. 2022, **[Code]** , https://arxiv.org/abs/2107.01543.

Integrating NOMA and AirFL via STARS



- Heterogeneous network: co-existence of NOMA users and AirFL users
- STARS protocol: Mode switching for **uplink communication**
- **Joint Beamforming Design**: to minimize the optimality gap of AirFL users while satisfying the QoS requirements of NOMA users

[1] W. Ni, **Y. Liu,** Y. C. Eldar, Z. Yang, H. Tian, "STAR-RIS Integrated Non-Orthogonal Multiple Access and Over-the-Air Federated Learning: Framework, Analysis, and Optimization", *IEEE Internet of Things*, vol. 9, no. 18, pp. 17136-17156, Sep. 2022, https://arxiv.org/abs/2106.08592.

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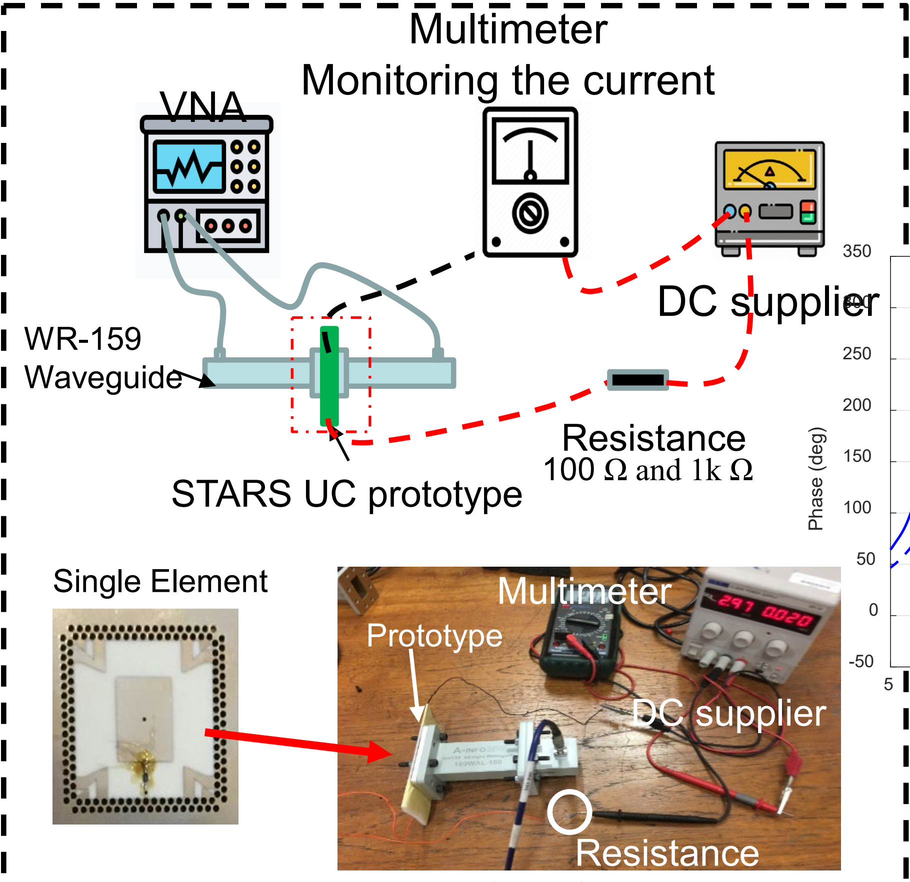
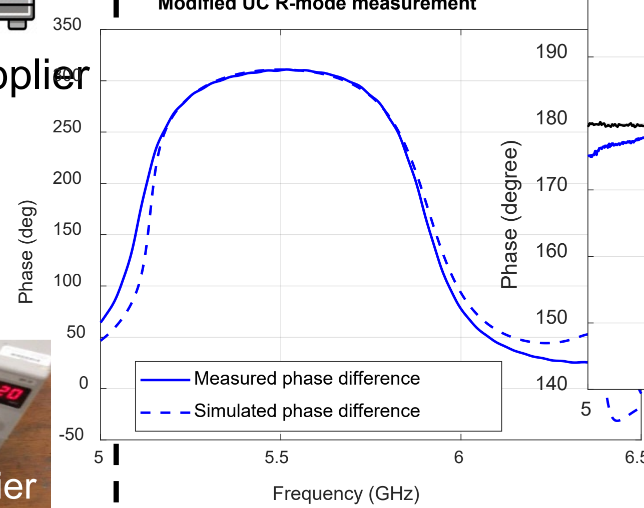
❖ Codes available: https://github.com/STAR-Yuanwei-Liu

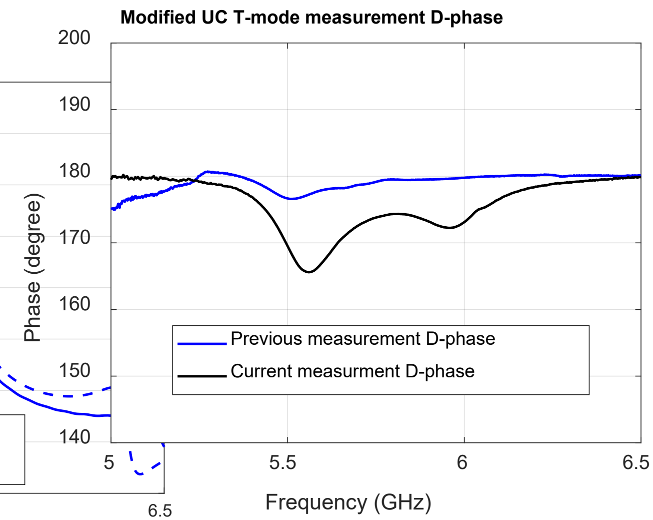
STARS Prototype Design – Single Element



Measurement setup for reflection mode

Phase Comparison **Difference**



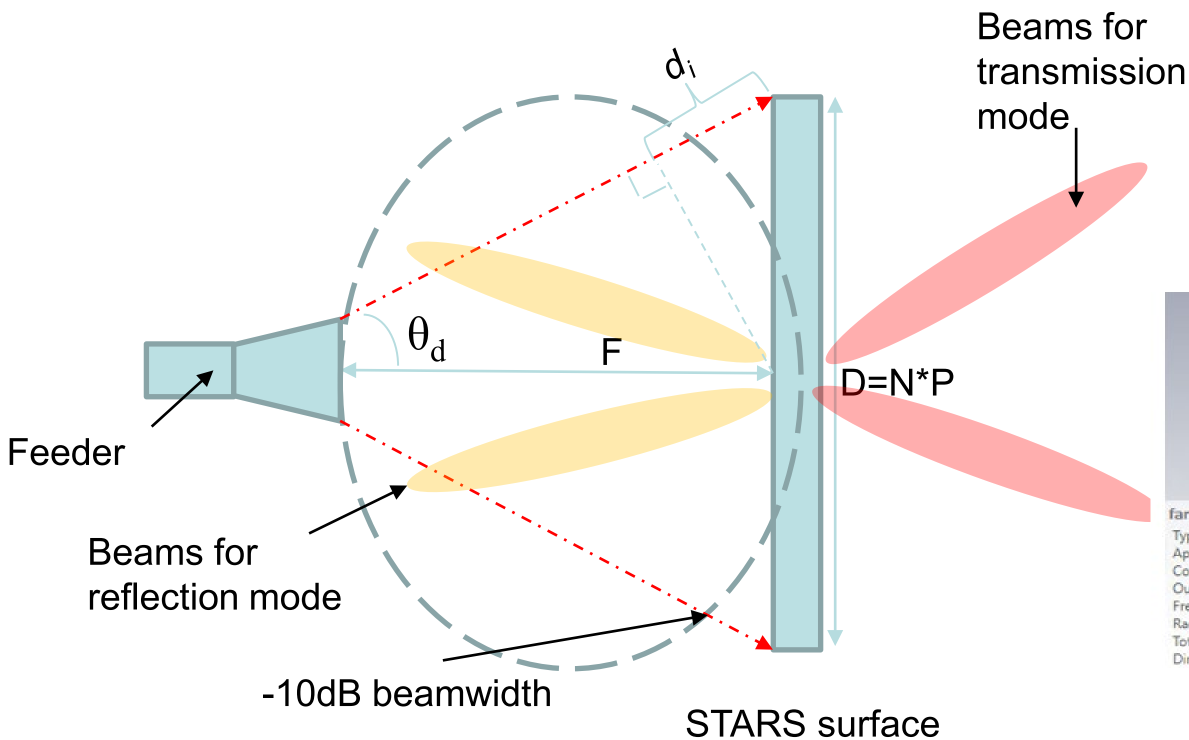


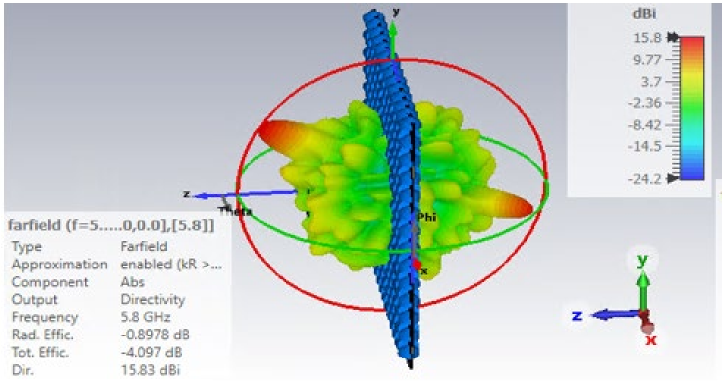
<u>Reflection Mode</u>

<u>Transmission Mode</u>

[1] Y. Liu, J. Kelly, M. Holm, S. Gopal, S. R. Aghdam and **Y. Liu**, "Unit Cell Design for Intelligent Reflecting and Refracting Surface (IRS) With Independent Electronic Control Capability," *IEEE Antennas Wirel. Propag. Lett.*., vol. 23, no. 1, pp. 414-418, Jan. 2024

STARS Prototype Design – Array





F – Distance between the feeder location and the surface
D – Surface dimension
N – Element number
P – Unit cell dimension
d_i –distance difference between i^{th} UC to the reference UC

Standardization Activity of STARS

ETSI | STANDARDS | TECHNOLOGIES | COMMITTEES | MEMBERSHIP | EDU

‹ Back

Reconfigurable Intelligent Surfaces

Introduction | Our Roles & Activities | Specifications

INTRODUCTION

Reconfigurable Intelligent Surfaces (RIS) is envisaged as a new enabling candidate wireless technology for the control of the radio signals between a transmitter and a receiver in a dynamic and goal-oriented way, turning the wireless environment into a service. This has motivated a host of potential new use cases targeting at i) the enhancement of various system key-performance-indicators (KPIs) and ii) the support of new wireless technology applications and capabilities. These include enhancements to the capacity, coverage, positioning, security, and sustainability, as well as the support of further sensing, wireless power transfer, and ambient backscattering capabilities.

- A work item on "*Multi-functional Reconfigurable Intelligent Surfaces (RIS): Modelling, Optimisation, and Operation*" has been set up in ETSI's Industry Specification Group (ISG) on RISs
- Multi-functional RIS: STAR-RIS, sensing RIS, computing RIS, etc.

ETSI ISG RIS – Current Members

Total: 50 Members, 4 Participants and 0 Counsellors.

Simple Search | Advanced Search | Pre-Defined Reports | Help

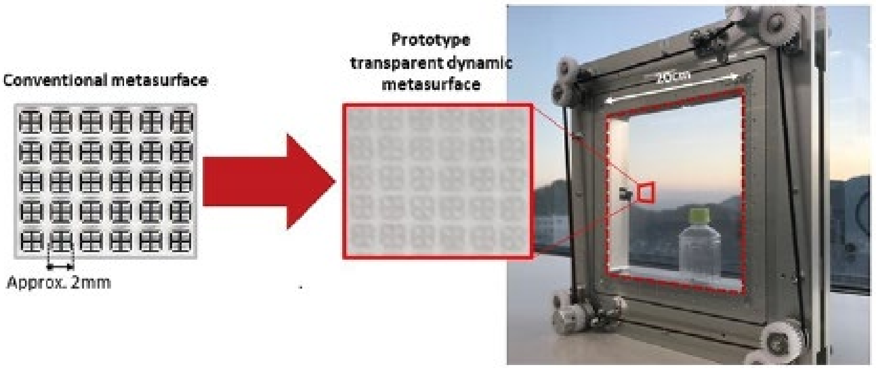
Details of 'DGR/RIS-006' Work Item

ETSI	Work Item Reference	Type	STF	Technical Body in Charge
	DGR/RIS-006	GR		RIS
	Current Status (Click to View Full Schedule)	Latest Version	Cover Date	Standstill
	TB adoption of WI (2023-06-01)			View Standstill Information
	Rapporteur	Technical Officer		Harmonised Standard
	Yuanwei Liu	Igor Minaev		

Title	Reconfigurable Intelligent Surfaces (RIS); Multi-functional Reconfigurable Intelligent Surfaces (RIS): Modelling, Optimisation, and Operation
Scope and Field of Application	The scope of the work item is to: a) identify technological challenges and summarize technical solutions for Multi-functional Reconfigurable Intelligent Surfaces (MF-RIS) incorporating tra coefficient optimization, deployment design, resource allocation and other technical aspects of MF-RIS, c) suggest possible ways of deploying MF-RIS in real-world scenarios and the ex
Supporting Organizations	China Telecommunications, ZTE Corporation, University of Athens, CNRS, Motorola Mobility UK Ltd., Apple France, B-Com, ZTE Wistron Telecom AB

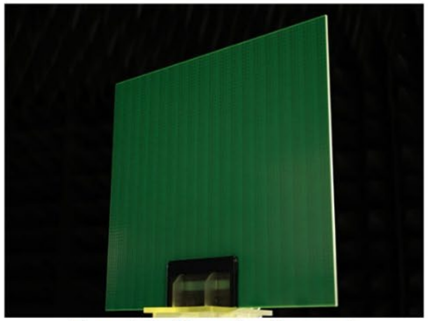
Commercial Progress of STARS

☐ NTT DOCOMO

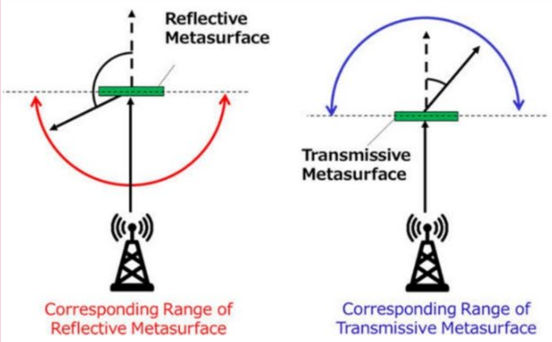


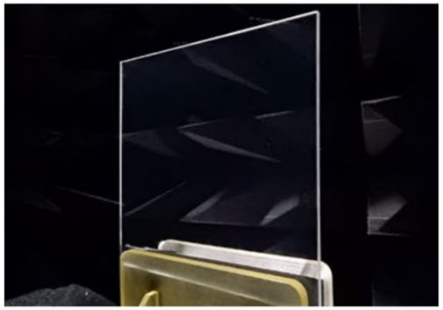
☐ ALCAN and AGC

☐ Kyocera



Transmissive Metasurface (Prototype)





Transparent Transmissive Metasurface (Prototype)

Will be more in the future !

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Research Opportunities and Challenges for STARS

- ✓ Hardware implementation for STARS
- ✓ Channel measurement for STARS modelling
- ✓ STARS NOMA design
- ✓ MIMO-STARS design
- ✓ STARS-aided coverage extension in non-terrestrial and satellite communications
- ✓ Spatial analysis of STARS using stochastic geometry
- ✓ Channel estimation for STARS
- ✓ Machine learning for STARS
- ✓ Deployment strategies for STARS
- ✓ Physical layer security for STARS
- ✓ STARS enabled ISAC
- ✓ STARS enabled THz communications
- ✓ STARS for Near field communications
- ✓ Computing-at-STARS

STARS for future 6G and IoT networks

- Let's make those

"STARS" shine in the "6G Sky"

for ***s****ustainable*, ***u****biquitous, and gree****n*** ***(SUN)*** communications!

Acknowledge: all my team members in STAR LAB@QMUL!

Introduction of IEEE ComSoc Next Generation Multiple Access Emerging Technology Initiative (NGMA-ETI)

- **Academic Chair**
  - **Yuanwei Liu,** Queen Mary University of London, UK
- **Industrial Chair**
  - **Yan Chen**, Huawei Technologies, Canada
- **Vice Chairs**
  - **Zhiguo Ding**, The University of Manchester, UK (Vice Chair for UK & Ireland Region)
  - **Octavia A. Dobre**, Memorial University, Canada (Vice Chair for Canada Region)
  - **Wei Yu**, University of Toronto, Canada (Vice Chair for USA & Latin America Region)
  - **Petar Popovski**, Aalborg University, Denmark (Vice Chair for Africa & EU Region)
  - **Pingzhi Fan**, Southwest Jiaotong University, China (Vice Chair for Asia-Pacific Region)
  - **Peiying Zhu**, Huawei Technologies, Canada (Vice Chair for Industry)
- **NGMA-ETI Officers**
  - **7 work groups** for Tutorial and Best Reading, Journal Special Issue, Conference Symposium and Workshop, Seminar and Invited Talk, Industrial Activity, Standardization, Publicity, etc
  - **3 liaison officers**

Introduction of NGMA-ETI

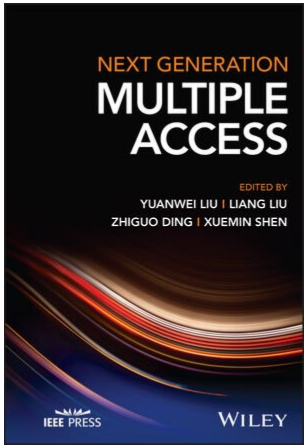
❑ Motivation:

- **Large Network Capacity**: The number of mobile broadband users are expected to expand quickly in 6G, e.g., AR/VR applications
- **Heterogenous QoS Requirements**: New IoT applications with both connectivity and latency requirements
- **Multi-Functional Networks**: The integration of communication, sensing, computation, etc.
- **Native AI Services**: The frequent data/model transfer between massive agents for efficient AI learning and inference
- ….

Multiple access has long been the "***pearls in the crown***" for each generation of mobile communication networks

Activities of NGMA-ETI

- ❑ **Book**
  - ❖ Next Generation Multiple Access, Wiley-IEEE Press, 2024



- ❑ **Journal Special Issues**
  - ❖ Proceedings of the IEEE SI on NGMA, March 14, 2024
  - ❖ IEEE JSTSP on NGMA, March 15, 2024
  - ❖ IEEE IoT-J SI on NGMA, March 15, 2024
  - ❖ IEEE JSAC/Network, etc

- ❑ **Regular workshops at IEEE GLOBECOM/WCNC/PIMRC/VTC**
  - ❖ IEEE GLOBECOM 2024 NGMA workshop (under preparation) (let me know if you would like to give a keynote)

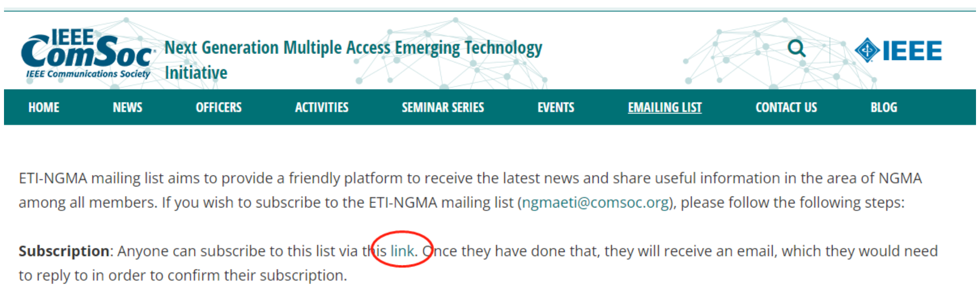
- ❑ **NGME ETI 6G workshop (IEEE ComSoc sponsored)**
  - ❖ 2024 (proposal under preparation)
  - ❖ 2023 held on QMUL campus with 6 invited talks and 1 panel discussion

Introduction of NGMA-ETI

Website: https://ngma.committees.comsoc.org/

Become a member of NGMA-ETI

- Subscribe the ETI-NGMA mailing list ngmaeti@comsoc.org
  - ✓ Activity annoucements (e.g., ETI meeting, seminar, etc)
  - ✓ Call for nominations
  - ✓ CFP distributions for signed-up members
  - ✓ ...



Thanks for your attention
Q & A