

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



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Outline

☐ STARS Basis

- ☐ Signal Modelling: Performance Evaluation (**What**)
- ☐ Coverage/Capacity Characterization (**Why**)
- ☐ Operating Protocols and Joint Beamforming (**How**)
- ☐ Correlated Model
- ☐ Channel Estimation

☐ Case Study:

- ☐ STARS Aided Transmission-Reflection NOMA
- ☐ Spatial Analysis for STARS via Stochastic Geometry
- ☐ Integrating NOMA and Air Federated Learning via STARS

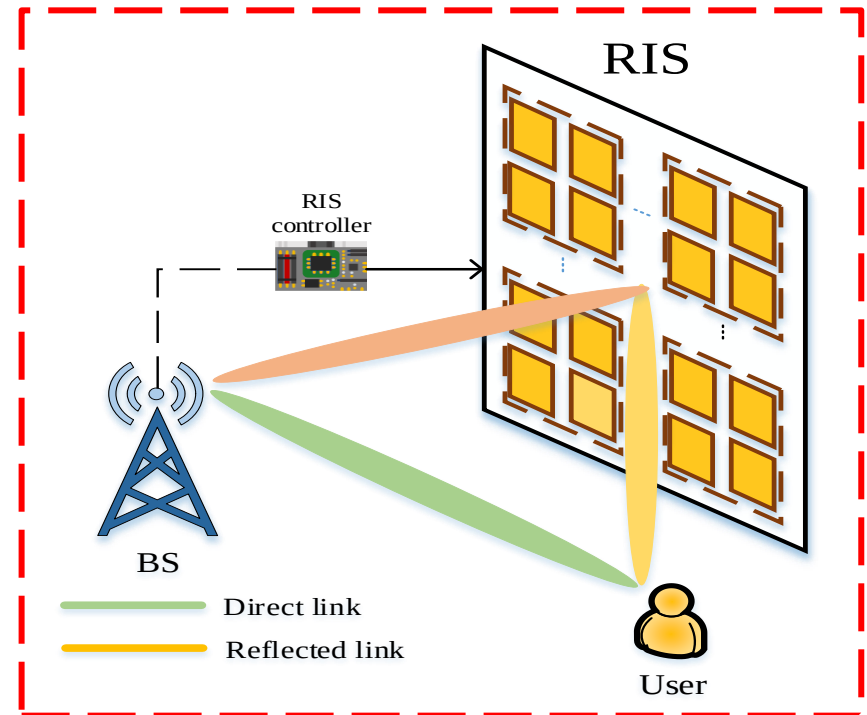
Overview of RIS

❑ 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
- ...



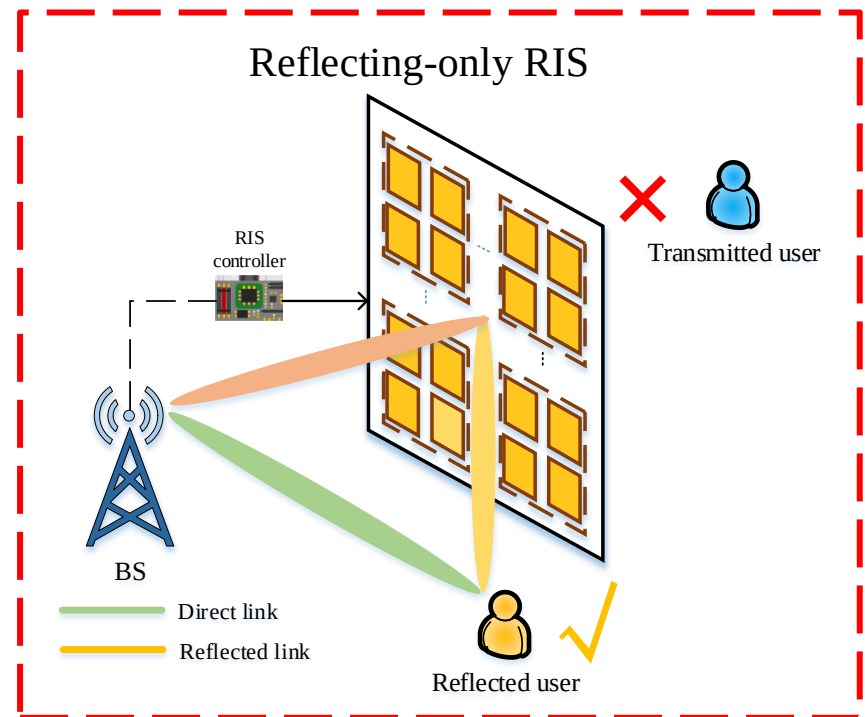
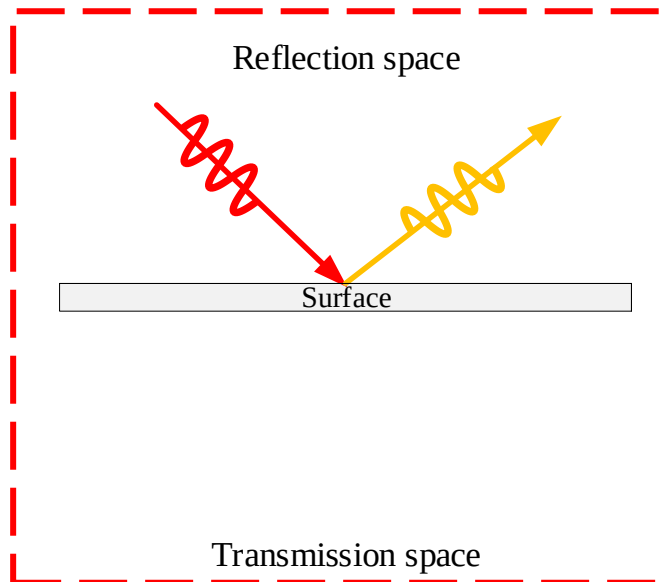
[1] Y. Liu, et al., “Reconfigurable Intelligent Surfaces: Principles and Opportunities”, *IEEE Commun. Surv. Tut.*, accept to appear., 2021 <http://arxiv.org/abs/2007.03435>.

[2] Y. Liu, et. al “Reconfigurable Intelligent Surface (RIS) Aided Multi-User Networks: Interplay Between NOMA and RIS”, *IEEE Commun. Mag.*, accept to appear., 2021 <https://arxiv.org/abs/2011.13336>.

From Reflecting-only RIS to STARS

❑ Reflecting-only RIS [T1]

- 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**

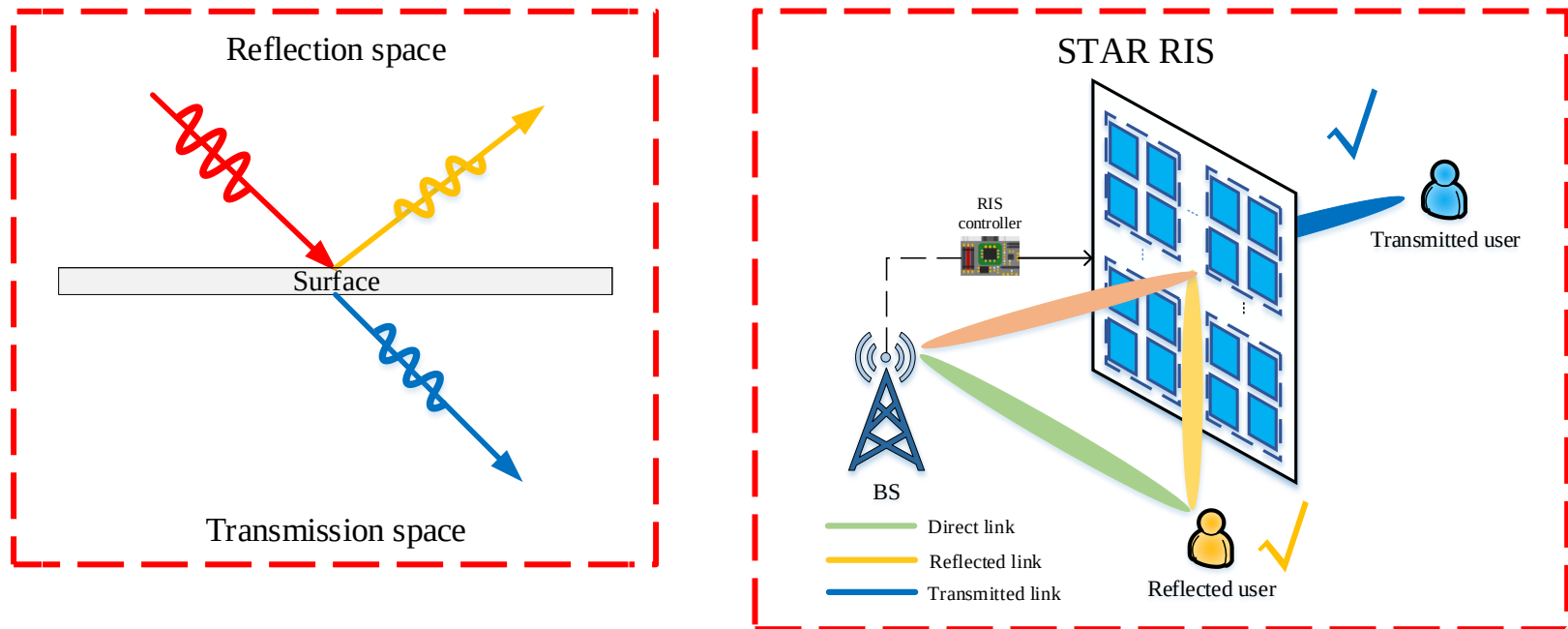


[T1] Y. Liu, [RIS tutorial](#)

From Reflecting-only RIS to STARS/STAR-RIS

❑ 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*

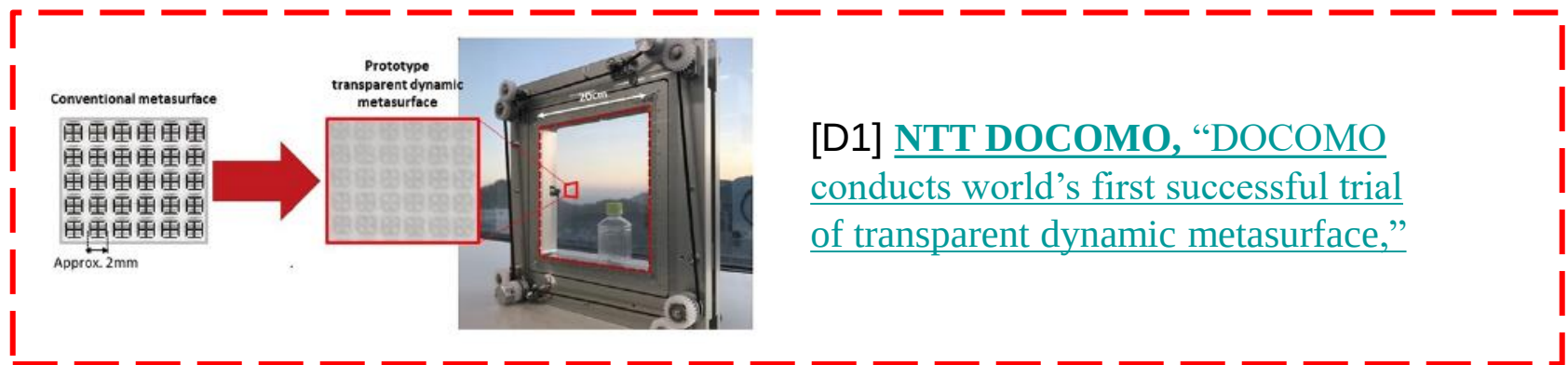


[3] Y. Liu, *et al.*, "STAR: Simultaneous Transmission And Reflection for 360° Coverage by Intelligent Surfaces", *IEEE Commun. Mag.*, accept to appear, <https://arxiv.org/abs/2103.09104>.

Key Advantages of STAR-RIS

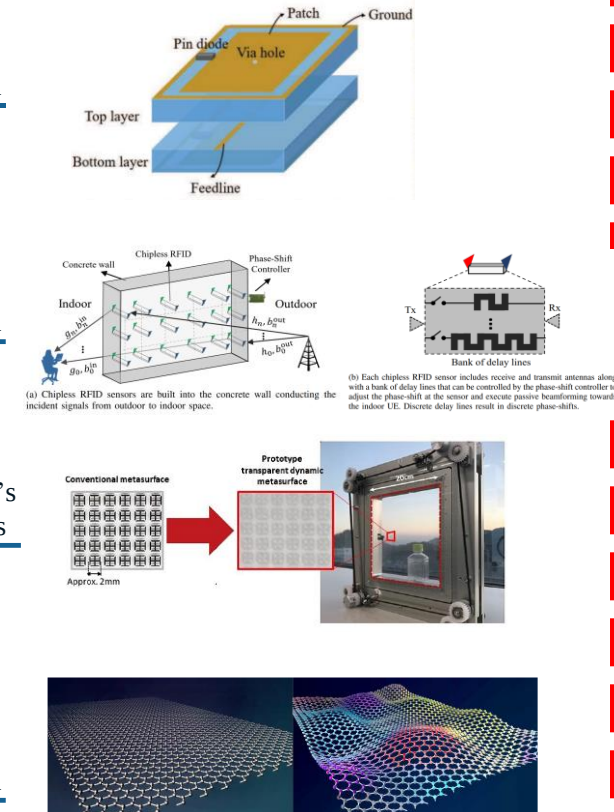
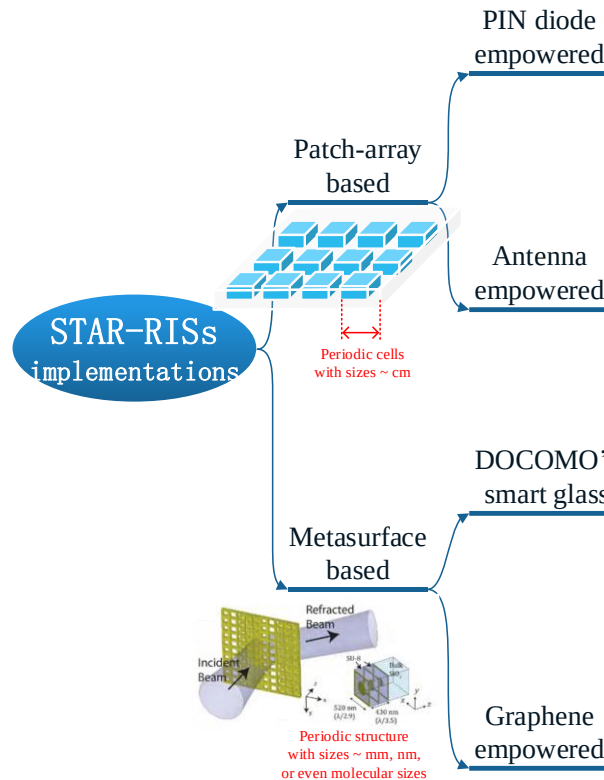
- ❑ **360° coverage**: Thanks to the STAR capability, the coverage is extended to the entire space
- ❑ **Enhanced degrees-of-freedom (DoFs)**: Generally independent transmission and reflection coefficients

[3] **Y. Liu, et al.**, “STAR: Simultaneous Transmission And Reflection for 360° Coverage by Intelligent Surfaces”, *IEEE Commun. Mag.*, accept to appear, <https://arxiv.org/abs/2103.09104>.



How STAR-RISs can be implemented?

- Patch-array based
(PIN diode, antenna)
Periodic cells with sizes about several centimeters
- Metasurface based
(DOCOMO's smart glass, graphene)
Periodic structure with sizes ~ mm, nm, or even molecular sizes



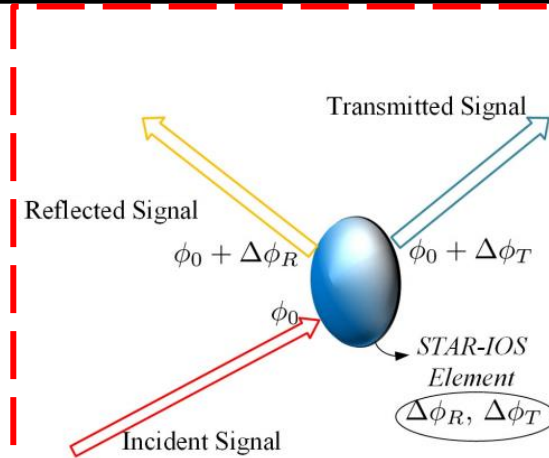
Implementations	Operating frequency	STAR-IOS prototypes	Tuning mechanism	Independent reflection/transmission control
Patch-array based	Low to high frequency (10KHz up to 1GHz)	PIN diode empowered	Bias voltages on PIN diodes	Difficult to achieve
		Antenna empowered	Lengths of delay lines	Can be achieved
Metasurface based	Super high frequency to visible light frequency	DOCOMO's smart glass	Distance between substrates	Theoretically achievable
		Graphene empowered	Conductivity of graphene	Can be achieved

[4] J. Xu, Y. Liu, et al., "Simultaneously Transmitting and Reflecting (STAR) Intelligent Omni-Surfaces, Their Modeling and Implementation," *IEEE VTM*, major revision, <https://arxiv.org/pdf/2108.06233>

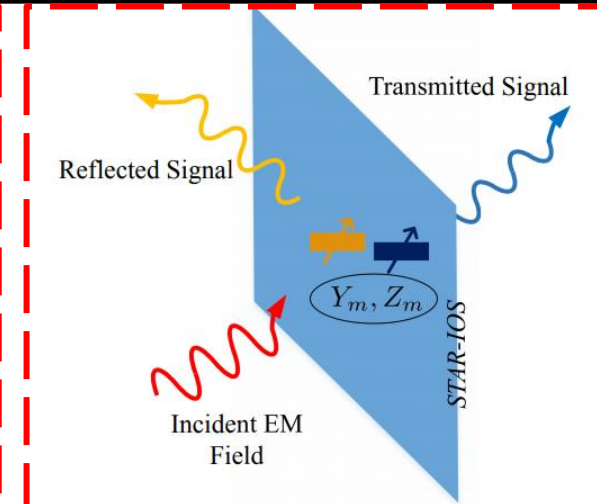
Hardware Models and Channel Models

❑ Hardware models:

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



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-IOs	Compact and easy to use	Oversimplified
Load impedance model	Surface averaged impedances	Patch-array based STAR-IOs	Compact and accurate	Not general
GSTC model	Electric and magnetic polarizability dyadics	Metasurface based STAR-IOs	General and accurate	Complicated

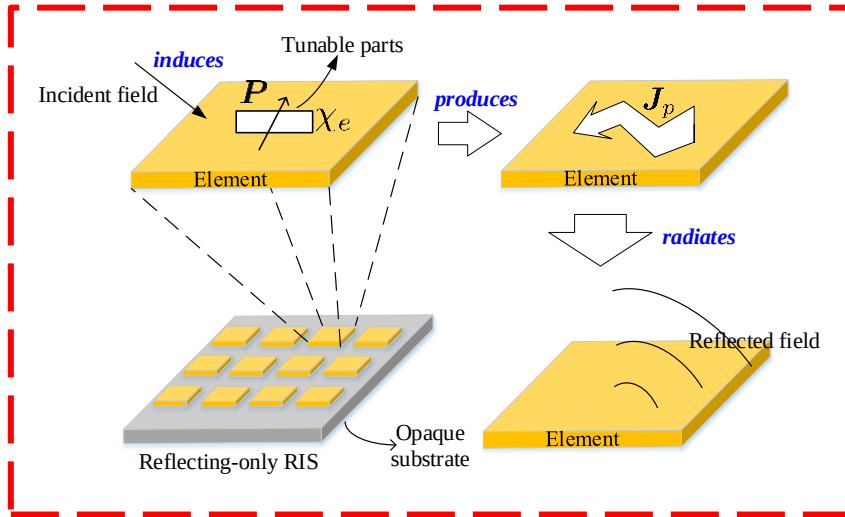
❑ Channel models:

- 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 method models

[4] J. Xu, Y. Liu, et al., "Simultaneously Transmitting and Reflecting (STAR) Intelligent Omni-Surfaces, Their Modeling and Implementation," *IEEE VTM*, major revision, <https://arxiv.org/pdf/2108.06233>

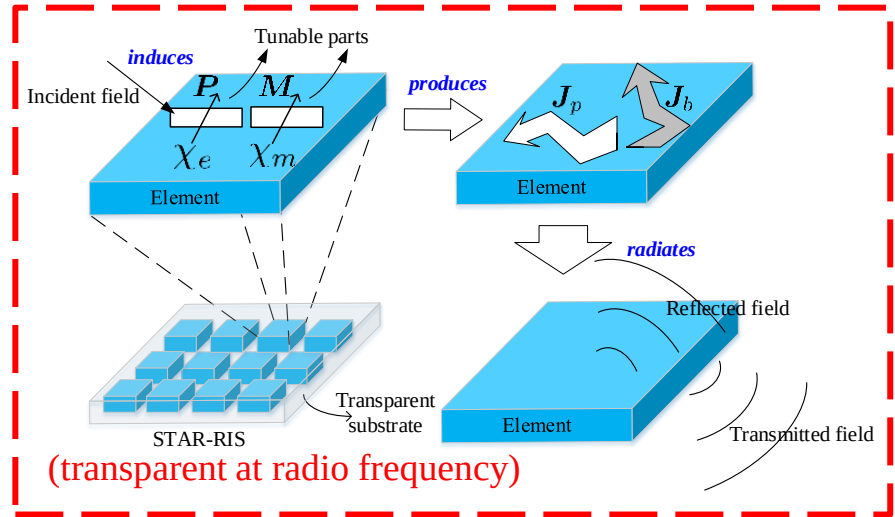
Difference Between Reflecting-Only RIS and STAR-RIS

Reflecting-Only RIS



(Biscuits placed on a metal plate)

STAR-RIS



(ice cubes in a glass of water)

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

[3] Y. Liu, *et al.*, “STAR: Simultaneous Transmission And Reflection for 360° Coverage by Intelligent Surfaces”, *IEEE Commun. Mag.*, accept to appear, <https://arxiv.org/abs/2103.09104>.

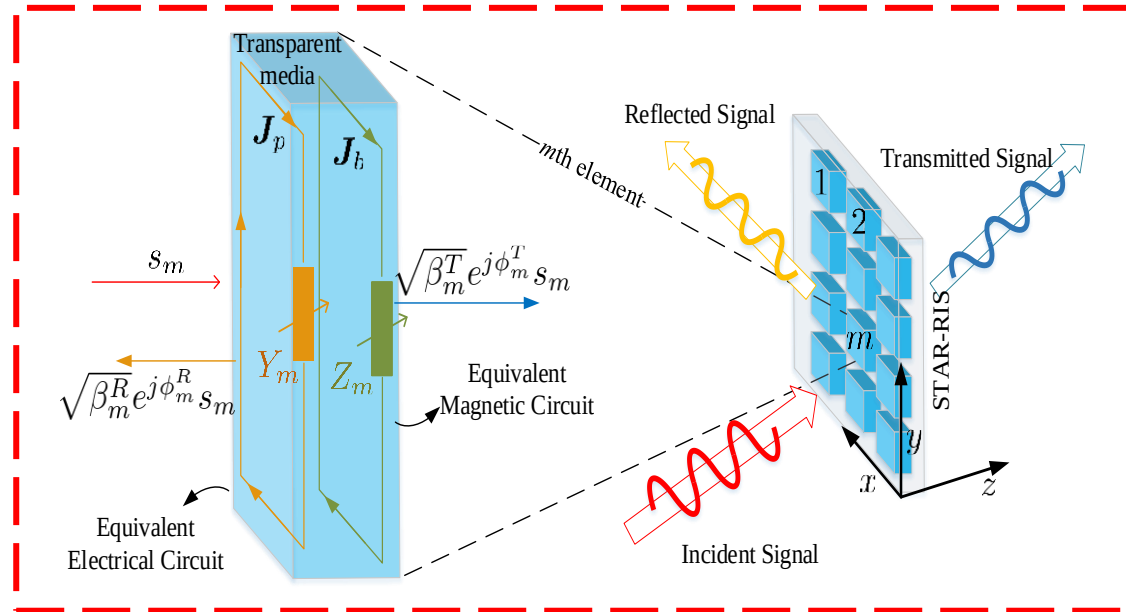
Basic Signal Model for STAR

- Incident signal on the m th 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., $\beta_m^t + \beta_m^r = 1$

[4] 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, doi: 10.1109/LCOMM.2021.3082214.

Communication Design Difference

Reflecting-Only RIS

❑ Reflection-coefficient matrix

$$\Theta = \text{diag}(\sqrt{\beta_1}e^{j\theta_1}, \sqrt{\beta_2}e^{j\theta_2}, \dots, \sqrt{\beta_M}e^{j\theta_M})$$

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

STAR-RIS

❑ Transmission-coefficient matrix

$$\Theta^t = \text{diag}(\sqrt{\beta_1^t}e^{j\theta_1^t}, \sqrt{\beta_2^t}e^{j\theta_2^t}, \dots, \sqrt{\beta_M^t}e^{j\theta_M^t})$$

❑ Reflection-coefficient matrix

$$\Theta = \text{diag}(\sqrt{\beta_1^r}e^{j\theta_1^r}, \sqrt{\beta_2^r}e^{j\theta_2^r}, \dots, \sqrt{\beta_M^r}e^{j\theta_M^r})$$

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 independently from each other**.
- ❑ For each STAR element, the **amplitude control** for transmission and reflection **are coupled by the law of energy conservation**.

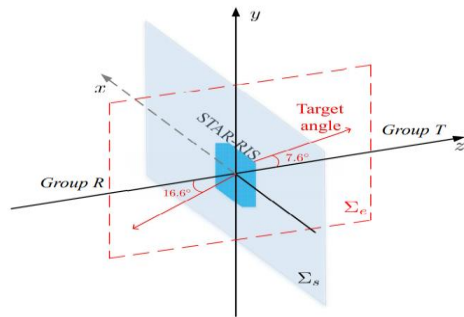
Comparison with Conventional RISs

Simulation Setup

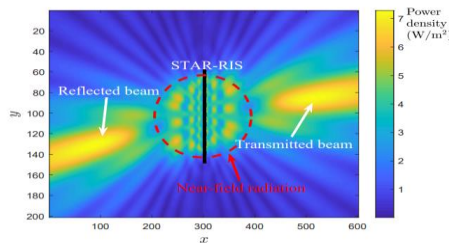
- STAR-RIS with 256 elements and equal amplitude control (i.e., $\beta_m^t = \beta_m^r$)
- **Baseline**: One reflecting-only RIS and one transmitting-only RIS, each of which has 128 elements.
- The target angles of the transmitted and reflected signals are 7.6° and 16.6° , respectively.

Signal Enhancement Comparison

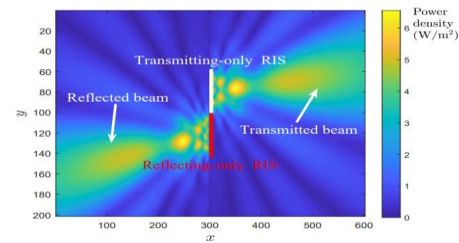
➤ STAR-RIS achieves significant signal enhancement



(a) Simulation setup



(b) STAR-RIS



(c) Conventional RIS

[4] 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, doi: 10.1109/LCOMM.2021.3082214.

Comparison with Conventional RISs

□ Diversity orders

- For **STAR-RIS**, the achievable diversity orders of receivers at both T and R are

$$d_S^T \ominus d_S^R = M + 1.$$

$$\text{i.e. } d_S^T + d_S^R = 2M + 2$$

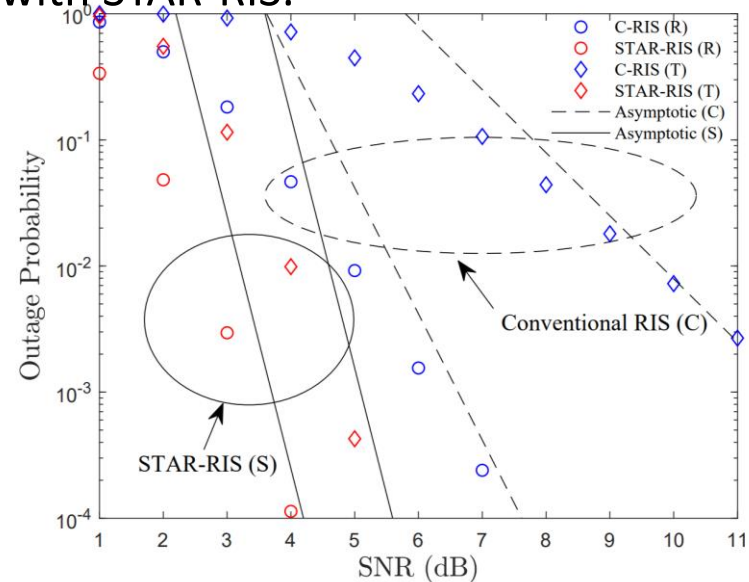
- For **conventional RISs**, the achievable diversity order for receivers in T and R follows:

$$d_C^T \oplus d_C^R = M + 2$$

which is smaller than that of STAR-RISs.

□ Power scaling laws

- For **STAR-RIS**, the achievable power scales with M^2 for both receivers.
- For **conventional RISs**, the power scales with $(M_R)^2$ for R and $(M_T)^2$ for T. Consider if $M_R = M_T = M/2$, then the power reduce by a factor of 4 compared with STAR-RIS.

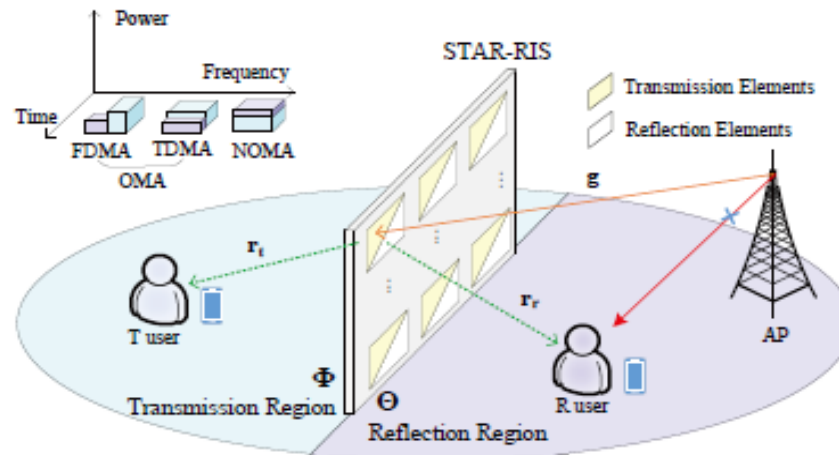


[4] J. Xu, Y. Liu, X. Mu, and O. A. Dobre, "STAR-RISs: Simultaneous transmitting and reflecting reconfigurable intelligent surfaces," *IEEE Commun. Lett.*, vol. 25, no. 9, pp. 3134-3138, Sept. 2021, doi: 10.1109/LCOMM.2021.3082214.

Coverage Characterization for STAR-RIS Networks

System Model

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



[5] C. Wu, Y. Liu, X. Mu, X. Gu, and O. A. Dobre, "Coverage Characterization of STAR-RIS Networks: NOMA and OMA," *IEEE Commun. Lett.*.
Accept to appear, <https://arxiv.org/abs/2104.10006>

Coverage Characterization for STAR-RIS Networks

Problem Formulation for NOMA

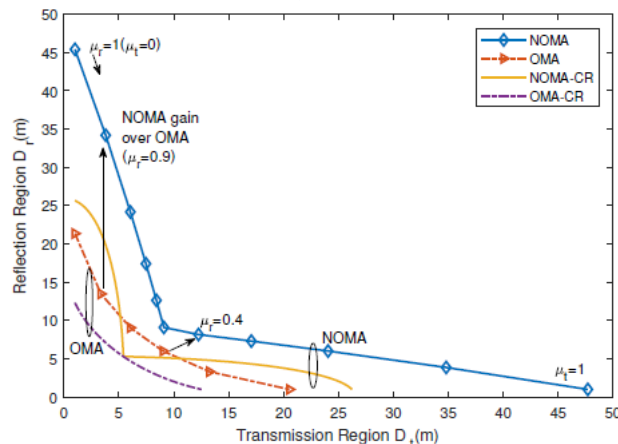
$$\begin{aligned} & \max_{\{p_k, \beta_k, D_k, \lambda(k), \mathbf{v}_k, D_0\}} D_0 \\ \text{s.t. } & D_k \geq u_k D_0, \forall k \in \mathcal{K}, \\ & D_k \geq 1, \forall k \in \mathcal{K}, \\ & r_k^N \geq \gamma_k, \forall k \in \mathcal{K}, \\ & \sum_k p_k \leq P_{\max}, \\ & \theta_m^k \in [0, 2\pi],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

- 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

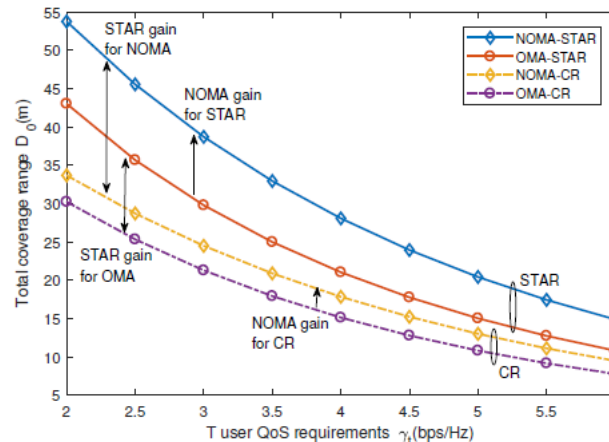
Problem Formulation for OMA

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

Coverage tradeoff



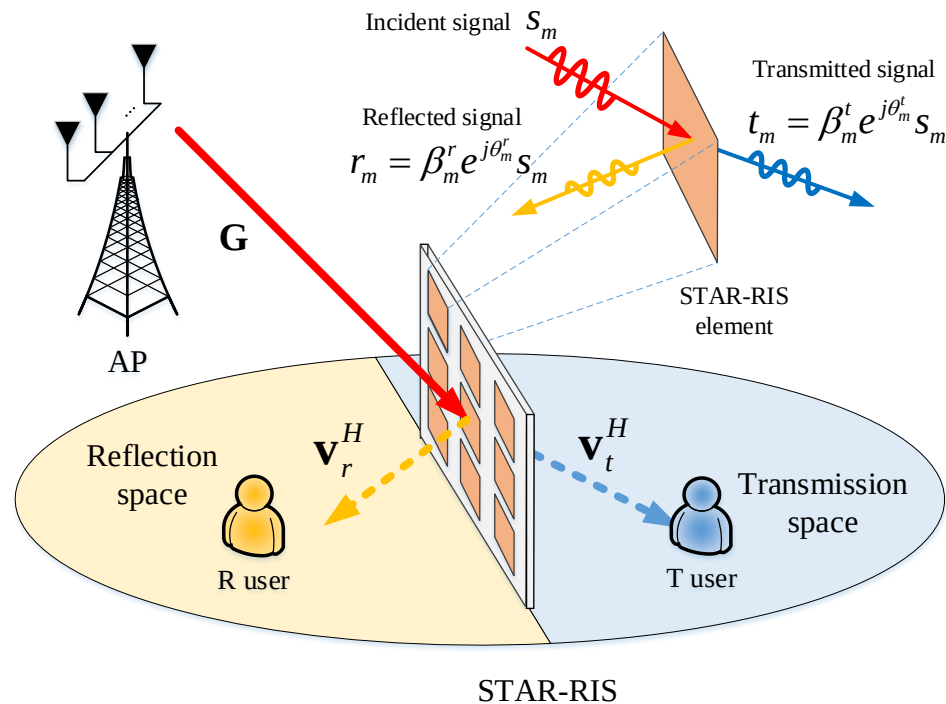
Total coverage comparison



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

[5] C. Wu, **Y. Liu**, X. Mu, X. Gu, and O. A. Dobre, "Coverage Characterization of STAR-RIS Networks: NOMA and OMA," *IEEE Commun. Lett.*, *accept to appear*, <https://arxiv.org/abs/2104.10006>

Joint Beamforming Design for STAR-RIS



- ❑ Multiple-antenna AP: Active beamforming
- ❑ STAR-RIS: 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**

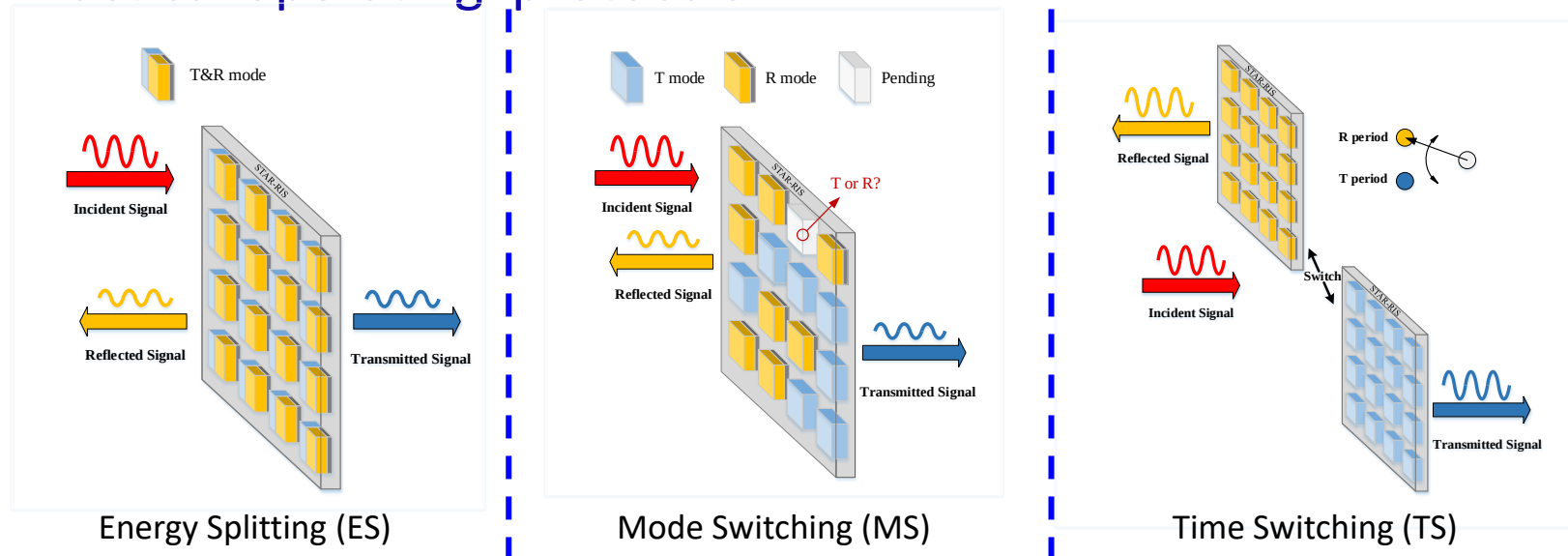
[6] X. Mu, **Y. Liu**, L. Guo, J. Lin, R. Schober, "Simultaneously Transmitting And Reflecting (STAR) RIS Aided Wireless Communications", *IEEE Trans. Wireless Commun.*, accept to appear, <https://arxiv.org/abs/2104.01421>.

Operating Protocols for STAR-RIS

❑ Based on the signal model, each STAR element can be operated in

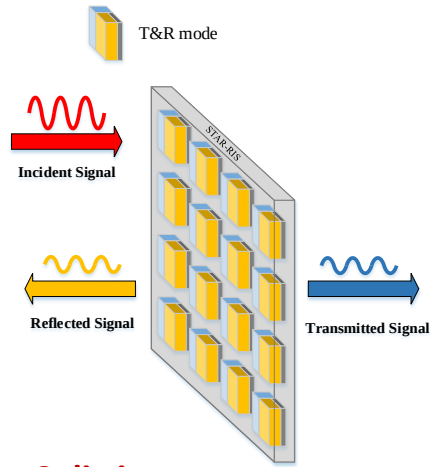
- Full transmission mode (T mode): $\beta_m^t = 1, \beta_m^r = 0$
- Full reflection mode (R mode): $\beta_m^t = 0, \beta_m^r = 1$
- Simultaneous transmission and reflection mode (T&R mode)

❑ Practical operating protocols



[3] Y. Liu, et al., "STAR: Simultaneous Transmission And Reflection for 360° Coverage by Intelligent Surfaces", *IEEE Commun. Mag.*, accept to appear, <https://arxiv.org/abs/2103.09104>.

Operating Protocols for STAR-RIS



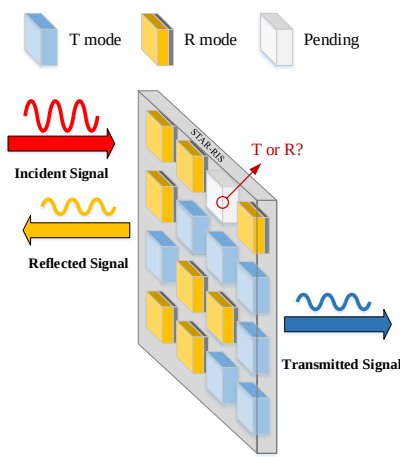
❑ Energy Splitting

- All elements are operated in T&R mode

$$\Theta_t^{\text{ES}} = \text{diag}(\sqrt{\beta_1^t} e^{j\theta_1^t}, \sqrt{\beta_2^t} e^{j\theta_2^t}, \dots, \sqrt{\beta_M^t} e^{j\theta_M^t})$$

$$\Theta_r^{\text{ES}} = \text{diag}(\sqrt{\beta_1^r} e^{j\theta_1^r}, \sqrt{\beta_2^r} e^{j\theta_2^r}, \dots, \sqrt{\beta_M^r} e^{j\theta_M^r})$$

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



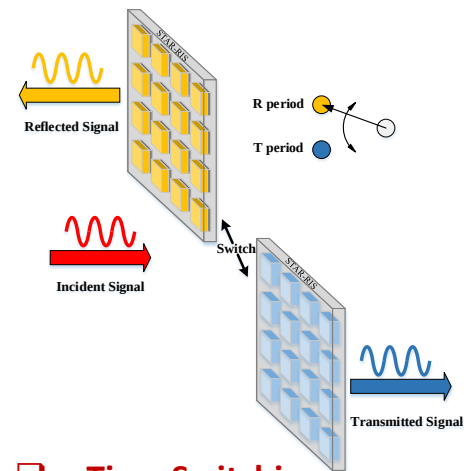
❑ Mode Switching

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

$$\Theta_t^{\text{MS}} = \text{diag}(\sqrt{\beta_1^t} e^{j\theta_1^t}, \sqrt{\beta_2^t} e^{j\theta_2^t}, \dots, \sqrt{\beta_M^t} e^{j\theta_M^t})$$

$$\Theta_r^{\text{MS}} = \text{diag}(\sqrt{\beta_1^r} e^{j\theta_1^r}, \sqrt{\beta_2^r} e^{j\theta_2^r}, \dots, \sqrt{\beta_M^r} e^{j\theta_M^r})$$

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



❑ Time Switching

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

$$\Theta_t^{\text{TS}} = \text{diag}(e^{j\theta_1^t}, e^{j\theta_2^t}, \dots, e^{j\theta_M^t}), 0 \leq t \leq \lambda^t T$$

$$\Theta_r^{\text{TS}} = \text{diag}(e^{j\theta_1^r}, e^{j\theta_2^r}, \dots, e^{j\theta_M^r}), \lambda^t T < t \leq T$$

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

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

Joint Beamforming Design for STAR-RIS

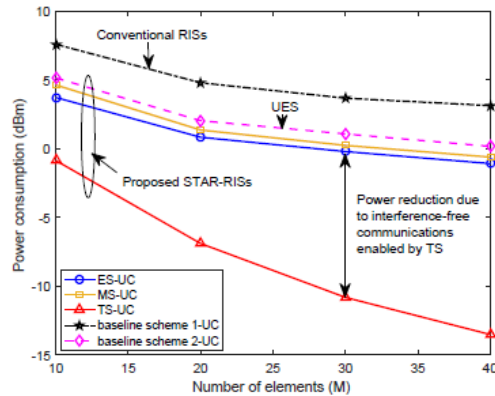
Problem Formulation for Unicast

$$\begin{aligned} \min_{\mathbf{w}_k, \Theta_k^X, \lambda^k} \quad & \|\mathbf{w}_t\|^2 + \|\mathbf{w}_r\|^2 \\ \text{s.t.} \quad & R_{UC,k}^X \geq \bar{R}_k, \forall k \in \{t, r\}, \\ & \Theta_k^X \in \mathcal{F}^X, \forall k \in \{t, r\}, \\ & 0 \leq \lambda^t \leq 1, 0 \leq \lambda^r \leq 1, \lambda^t + \lambda^r = 1, \end{aligned}$$

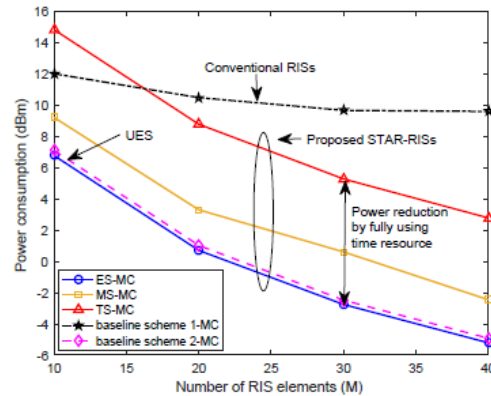
Problem Formulation for Multicast

$$\begin{aligned} \min_{\mathbf{w}_c, \Theta_k^{\text{ES/MS}}, \lambda^k} \quad & \|\mathbf{w}_c\|^2 / \min_{\mathbf{w}_c, k, \Theta_k^{\text{TS}}, \lambda^k} \|\mathbf{w}_{c,t}\|^2 + \|\mathbf{w}_{c,r}\|^2 \\ \text{s.t.} \quad & R_{MC}^X \geq \bar{R}_c, \\ & \Theta_k^X \in \mathcal{F}^X, \\ & 0 \leq \lambda^t \leq 1, 0 \leq \lambda^r \leq 1, \lambda^t + \lambda^r = 1, \end{aligned}$$

Power consumption versus number of elements



(a) Unicast communication, $\bar{\gamma}_0 = 0$ dB.



(b) Multicast communication, $\bar{\gamma}_c = 10$ dB.

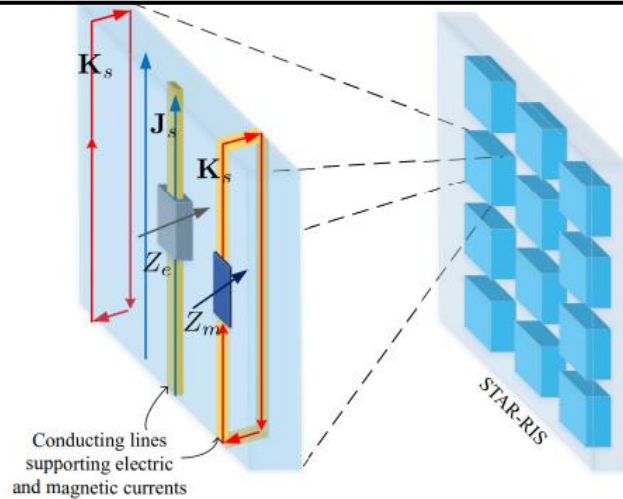
■ **Baseline 1:** Conventional reflecting and transmitting RISs

■ **Baseline 2:** Uniform energy splitting for STAR-RIS

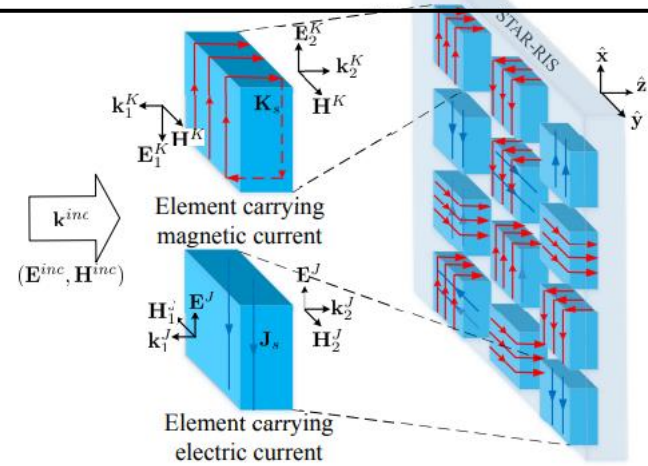
- TS and ES are preferable for unicast and multicast, respectively
- STAR-RIS significantly outperforms conventional RIS
- For ES, element-based amplitude control is essential for unicast to mitigate inter-user interference

[6] X. Mu, **Y. Liu**, L. Guo, J. Lin, R. Schober, “Simultaneously Transmitting And Reflecting (STAR) RIS Aided Wireless Communications”, *IEEE Trans. Wireless Commun.*, accept to appear, <https://arxiv.org/abs/2104.01421>.

A Correlated T&R Phase-Shift Model for STAR-RISs



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

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

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

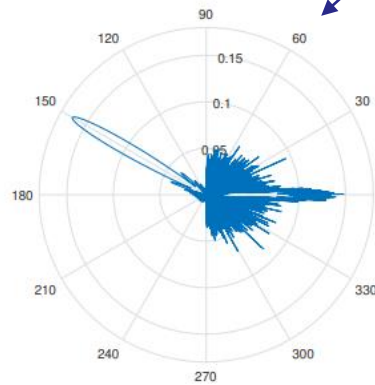
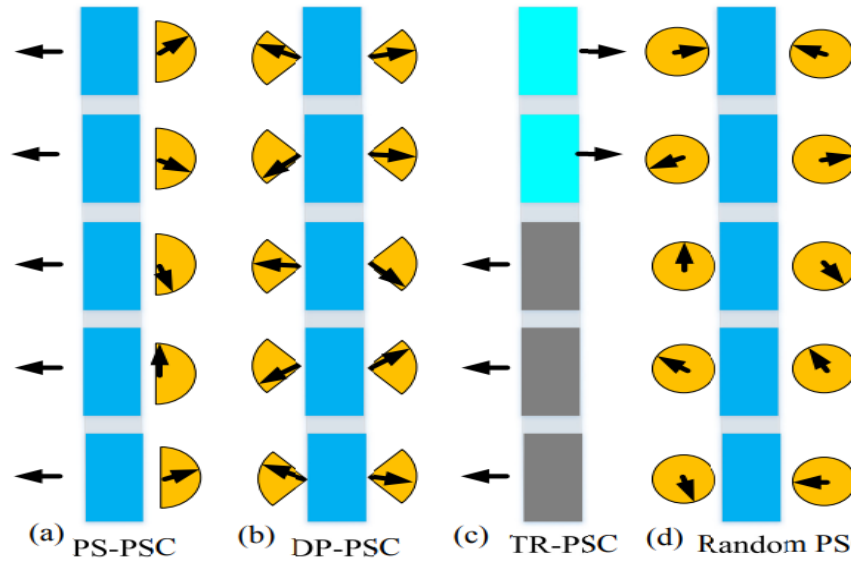
This leads to **the Proposed Model**:

$\beta_m^T = \sqrt{1 - (\beta_m^R)^2}$, **amplitude correlation**

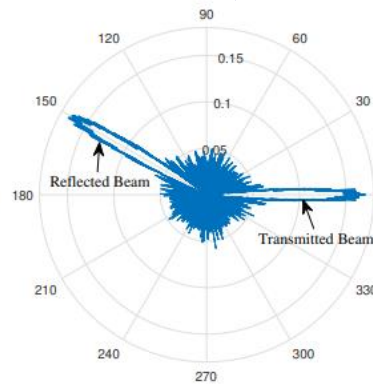
$\phi_m^R - \phi_m^T = \frac{\pi}{2} + \nu_m \pi$, $\nu_m = 0 \text{ or } 1$, $\forall m = 1, 2, \dots, M$, **phase correlation**

[7] 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", submitted to *IEEE Journal*, <https://arxiv.org/abs/2112.00299>,

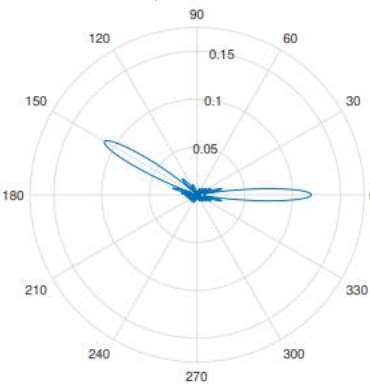
Practical Phase-Shift Configuration (PSC) Strategies for STAR-RISs



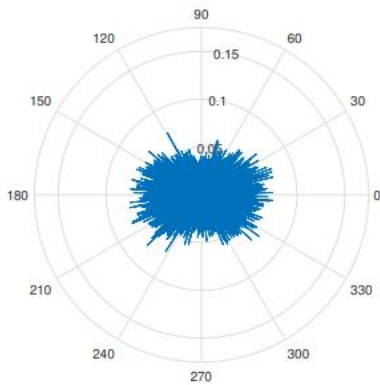
Primary-Secondary



Diversity-Preserving



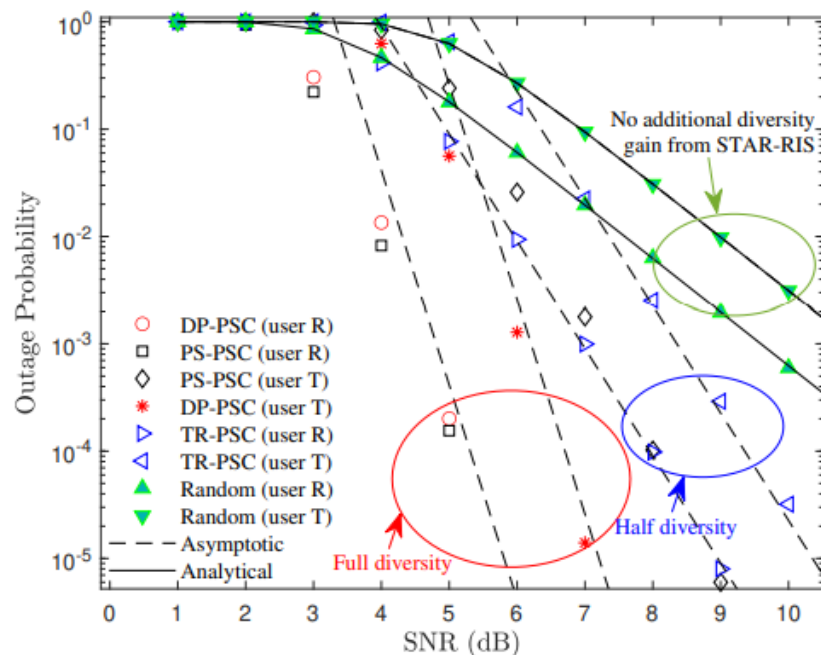
T&R-Group



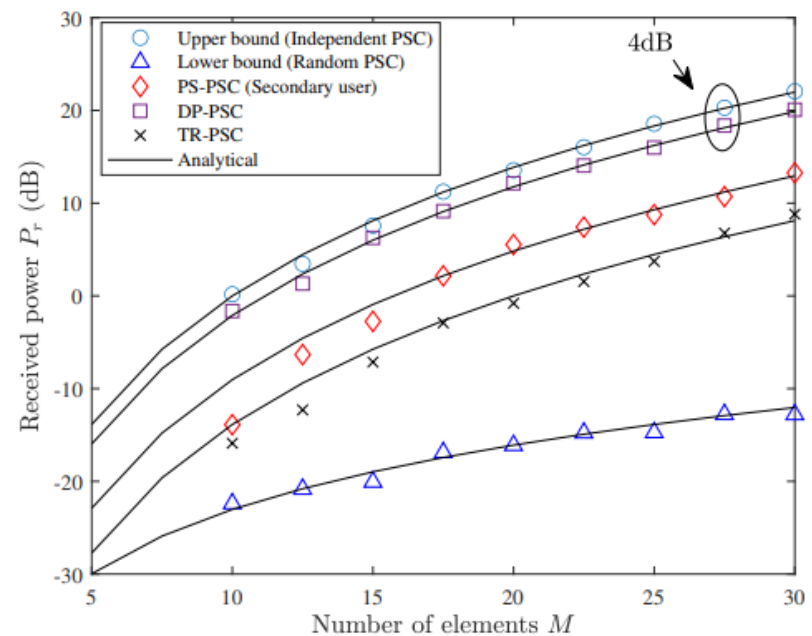
Random PSC

Performance Analysis: PSC Strategies for STAR-RISs

STAR-RIS phase-shift strategy	PS-PSC	DP-PSC	TR-PSC	Random PSC
Diversity order of user R	$M + 1$	$M + 1$	$M_R + 1$	2
Diversity order of user T	$(M + 3)/2$	$M + 1$	$M_T + 1$	2
Power scaling law	$\propto M^2$	$\propto M^2$	$\propto M_\chi^2$	$\propto M$



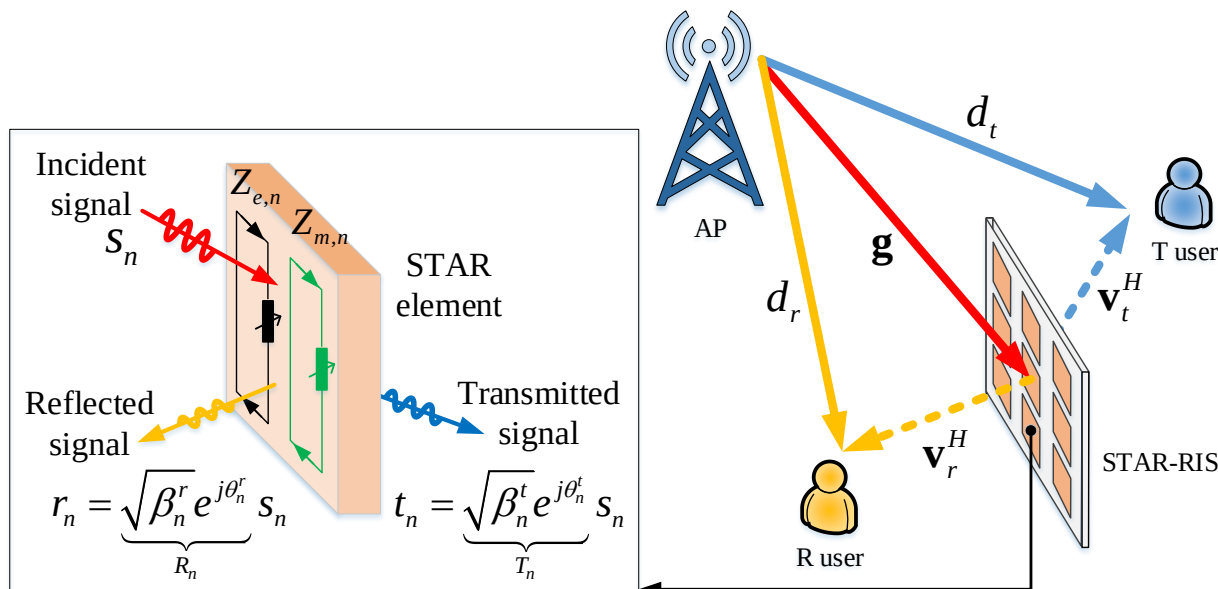
Outage probability vs. transmit SNR



Power scaling laws (log scale)

[7] 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", submitted to *IEEE Journal*, <https://arxiv.org/abs/2112.00299>

STAR Coefficient Design with A Coupling Phase-Shift Model



❑ A coupling phase-shift model for STAR-RISs: $|\theta_n^t - \theta_n^r| = \frac{\pi}{2}, \frac{3\pi}{2}$

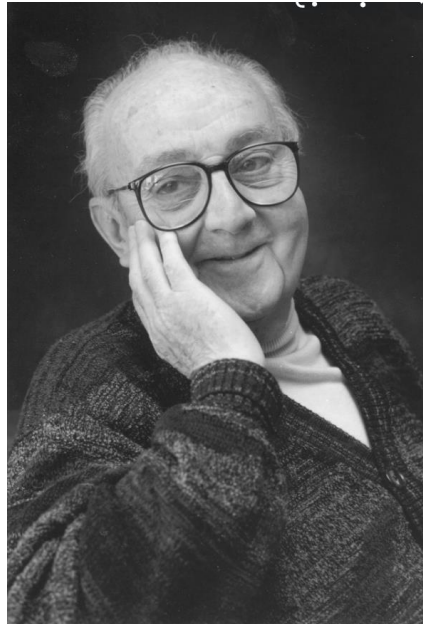
❑ **Challenge:** The design of phase-shift coefficients for transmission and reflection is highly-coupled.

❑ **Solutions:** An element-wise alternating optimization algorithm.

[7] Y. Liu, X. Mu, R. Schober, H. V. Poor, "Simultaneously Transmitting and Reflecting (STAR)-RISs: A Coupled Phase-Shift Model", submitted to IEEE ICC 2021, <https://arxiv.org/abs/2110.02374>.

Which model is better?

“Essentially, all models are wrong, but some are useful.”



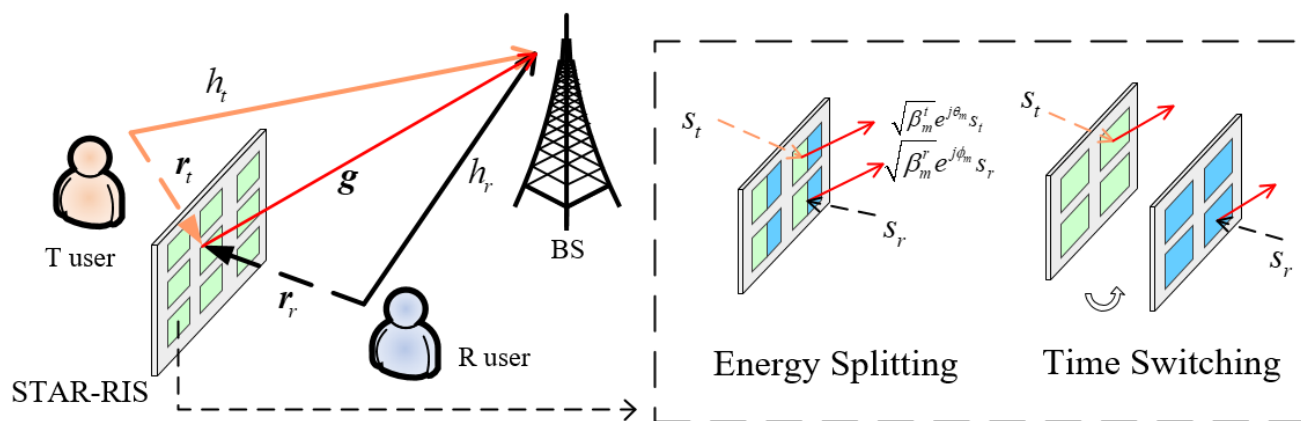
----George E. P. Box



Channel Estimation for STAR-RIS Networks

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.



[10] C. Wu, C. You, **Y. Liu**, X. Gu, and Y. Cai, "Channel Estimation for STAR-RIS aided Wireless Communication," *IEEE Commun. Lett.*, minor revision <https://arxiv.org/abs/2112.01413>

Channel Estimation for STAR-RIS Networks

Problem Formulation for TS

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

Problem Formulation for ES

$$\min_{\{s_k, \beta_m^k, \Theta, \Phi\}} \frac{2\sigma^2}{p} \text{Tr}[(\mathbf{V}^H \mathbf{V})^{-1}] \quad (12a)$$

$$\text{s.t.} \quad \theta_{m,i}, \phi_{m,i} \in [0, 2\pi), m \in \mathcal{M}, i = 1, \dots, \tau, \quad (12b)$$

$$\text{rank}(\mathbf{V}) = 2M + 2, \quad (12c)$$

$$\beta_m^t + \beta_m^r \leq 1, \quad (12d)$$

$$\beta_m^k > 0, k \in \mathcal{K}, \quad (12e)$$

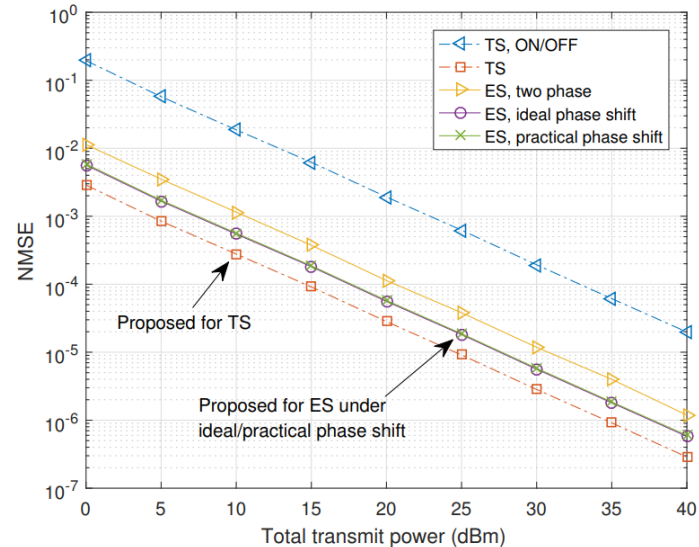
$$\cos(\theta_{m,i} - \phi_{m,i}) = 0. \quad (12f)$$

■ **Baseline 1:** ON/OFF scheme

■ **Baseline 2:** Two-phase scheme: Estimate direct link and cascaded link separately.

[10] C. Wu, C. You, **Y. Liu**, X. Gu, and Y. Cai, "Channel Estimation for STAR-RIS aided Wireless Communication," *IEEE Commun. Lett.*, minor revision, <https://arxiv.org/abs/2112.01413>

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.

Outline

❑ STARS Basis

- ❑ Signal Modelling: Performance Evaluation (**What**)
- ❑ Coverage/Capacity Characterization (**Why**)
- ❑ Operating Protocols and Joint Beamforming (**How**)
- ❑ Correlated Model
- ❑ Channel Estimation

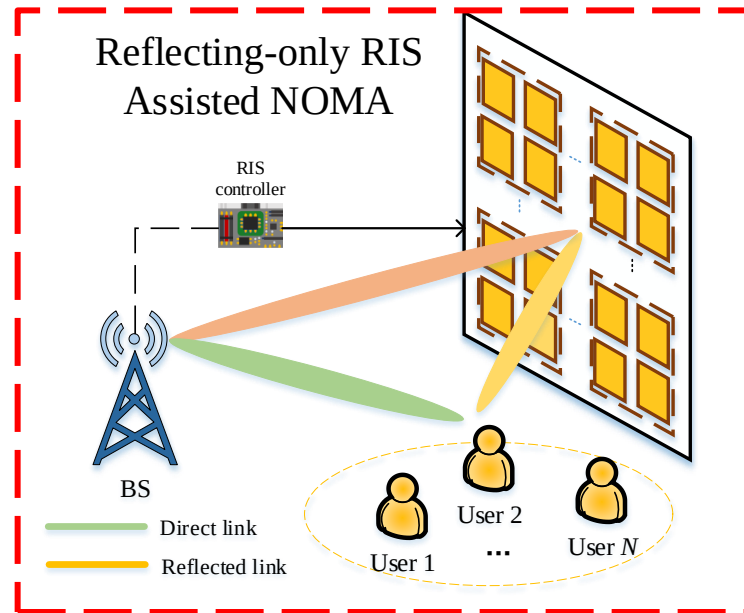
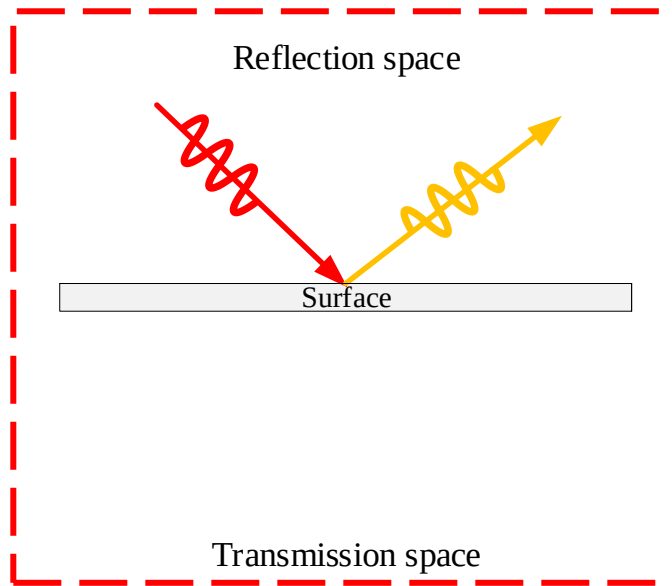
❑ Case Study

- ❑ STARS Aided Transmission-Reflection NOMA
- ❑ Spatial Analysis for STAR via Stochastic Geometry
- ❑ Integrating NOMA and Air Federated Learning via STARS



STARS Aided Transmission-Reflection NOMA

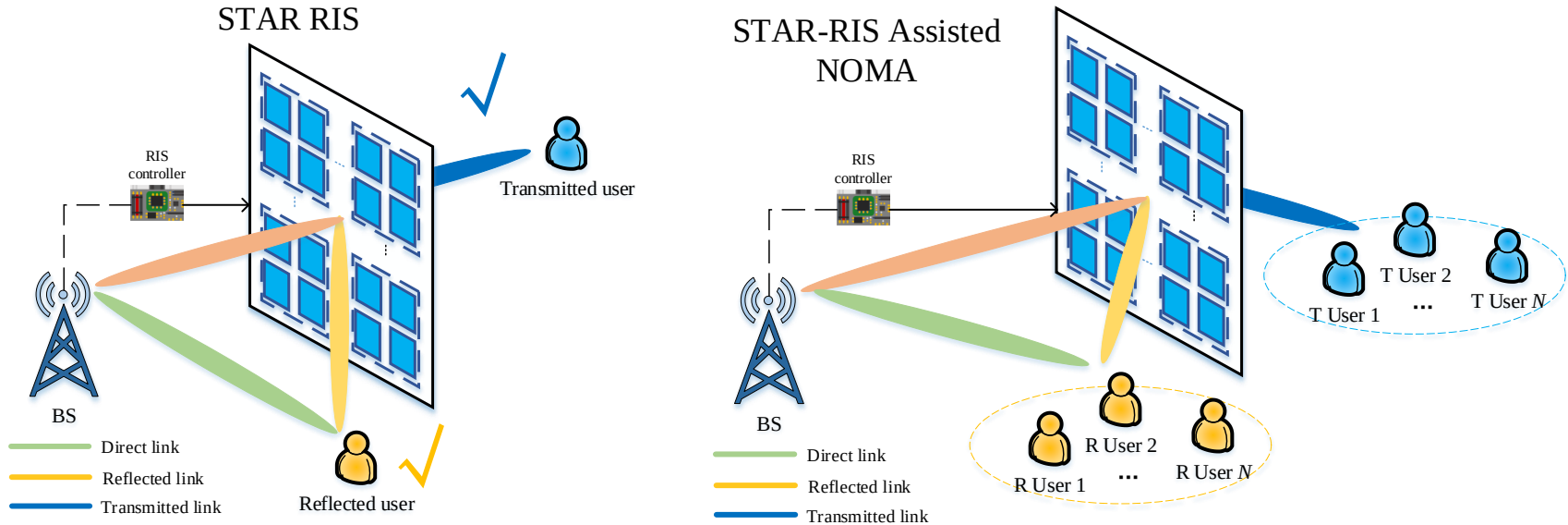
❑ Conventional Reflecting-only RIS assisted NOMA



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

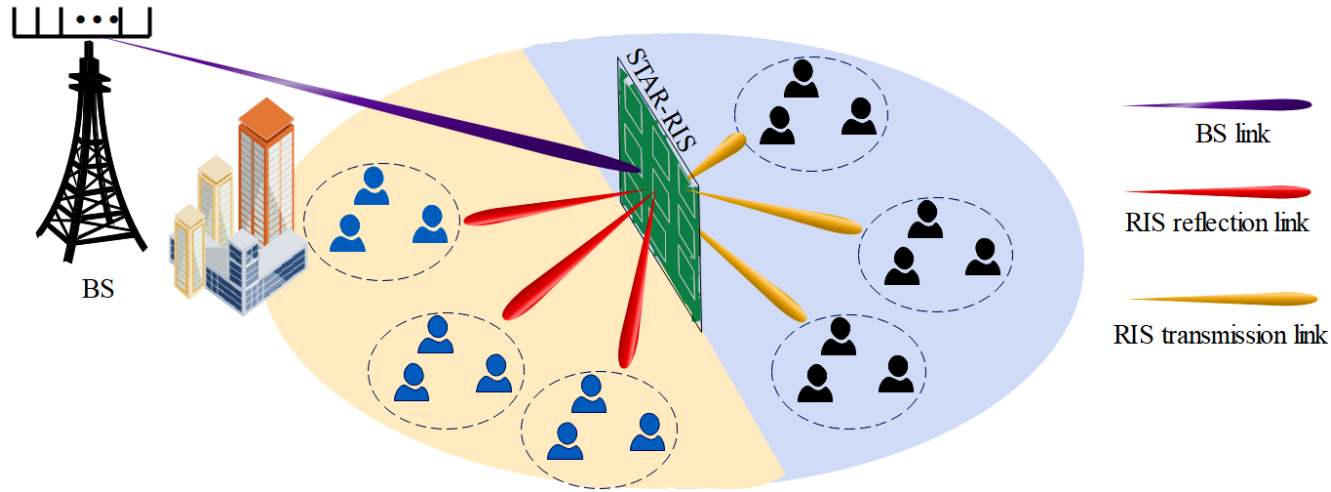
STAR-RIS NOMA

□ STAR-RIS assisted 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.

Joint Design for STAR-RIS Aided NOMA



- ❑ Multiple-antenna BS: Active beamforming
- ❑ Multiple users in each cluster: Power allocation coefficients
- ❑ NOMA users: Decoding order
- ❑ STAR-RIS: Passive transmission and reflection beamforming
- ❑ **Joint Design**: to maximize overall achievable sum rate for satisfying the QoS requirements and SIC decoding rate conditions

[8] 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.*, major revision, <https://arxiv.org/abs/2106.03001>.

Joint Design for STAR-RIS Aided NOMA

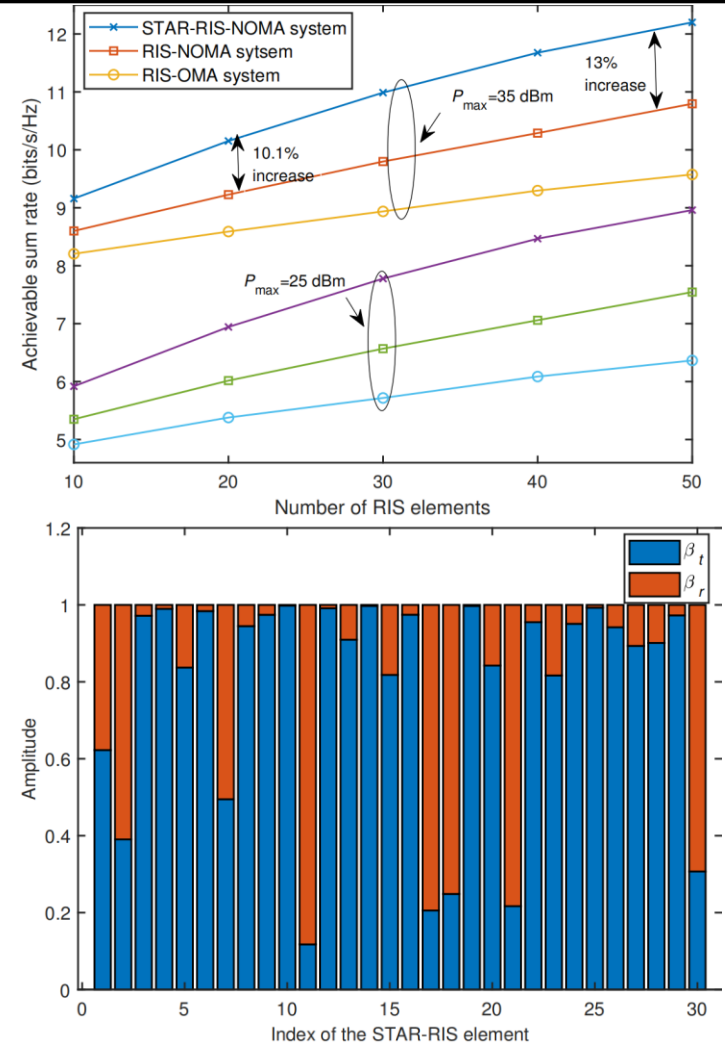
Problem formulation

$$\begin{aligned}
 & \max_{\mathcal{D}_c, \rho_c, \mathcal{D}_c(k), \mathbf{w}_c, \mathbf{u}_p} \sum_{c \in \mathbb{C}} \sum_{k \in \mathbb{K}_c} R_{\mathcal{D}_c(k) \rightarrow \mathcal{D}_c(k)}^c, \\
 & s.t. \quad R_{\mathcal{D}_c(k) \rightarrow \mathcal{D}_c(k)}^c \geq R_{c, \mathcal{D}_c(k)}^{\min}, \forall k \in \mathbb{K}_c, \forall c \in \mathbb{C}, \\
 & \quad R_{\mathcal{D}_c(j) \rightarrow \mathcal{D}_c(k)}^c \geq R_{\mathcal{D}_c(k) \rightarrow \mathcal{D}_c(k)}^c, j \geq k, \forall j, k \in \mathbb{K}_c, \forall c \in \mathbb{C}, \\
 & \quad \sum_{c \in \mathbb{C}} \|\mathbf{w}_c\|_2^2 \leq P_{\max}, \\
 & \quad \sum_{k \in \mathbb{K}_c} \rho_{c, \mathcal{D}_c(k)} = 1, \forall c \in \mathbb{C}, \\
 & \quad \beta_m^p, \theta_m^p \in \mathbb{R}_{\beta, \theta}, \forall m \in \mathbb{M}, \forall p \in \{t, r\}, \\
 & \quad \mathcal{D}_c \in \mathbb{D}, c \in \mathbb{C},
 \end{aligned}$$

■ **Baseline 1:** Conventional RIS aided NOMA

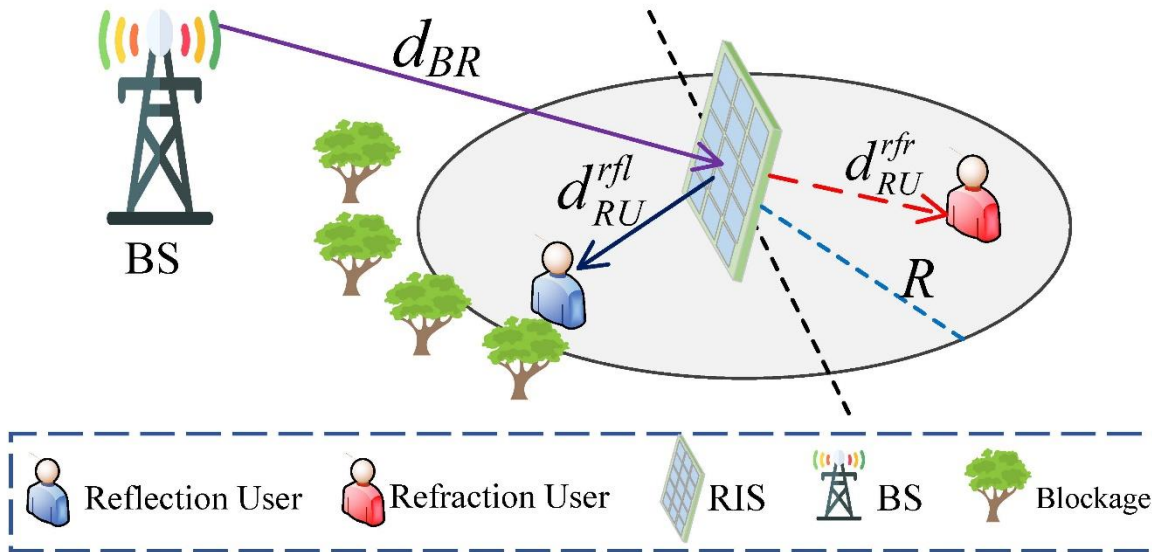
■ **Baseline 2:** Conventional RIS aided OMA

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



[8] 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.*, major revision, <https://arxiv.org/abs/2106.03001>.

Spatial Analysis of STARS

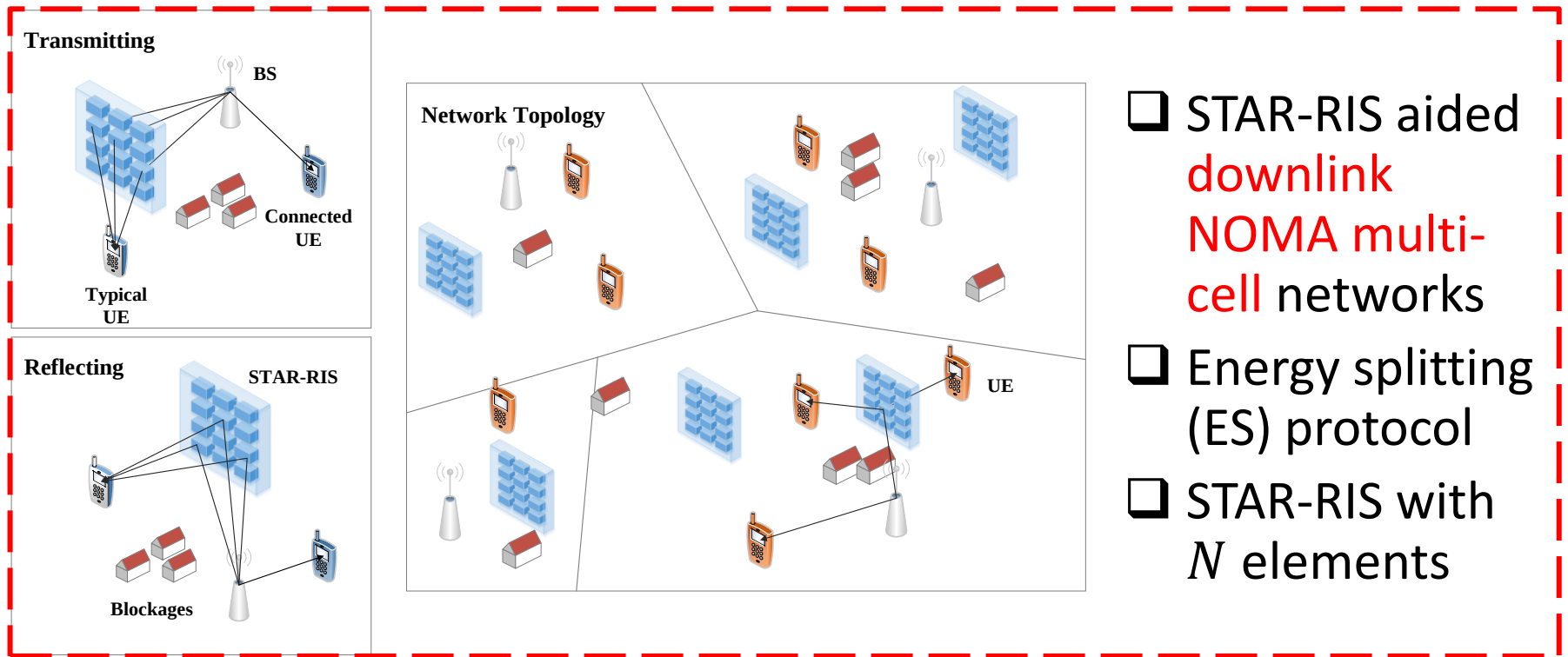


- ❑ A STAR-RIS-aided **downlink NOMA** network
- ❑ Deployment: 1) a fixed BS and a fixed RIS; 2) **randomly deployed** users in a circle area.

- ❑ Channel links: 1) the **reflecting user** is blocked by obstacles and receive signals by RIS **reflection**; 2) the **transmitting user** receive signals by RIS **transmission**
- ❑ Energy splitting (ES) protocol: **simultaneously** operate transmitting and reflecting modes with **different splitting coefficients**.
- ❑ Other protocols: mode switching protocol & time switching protocol

[9] C. Zhang, W. Yi, **Y. Liu**, Z. Ding and L. Song, "STAR-IOS Aided NOMA Networks: Channel Model Approximation and Performance Analysis", Submitted to IEEE Trans. Wireless Commun., <https://arxiv.org/abs/2107.01543>.

Spatial Analysis of STARS: Multi-Cell

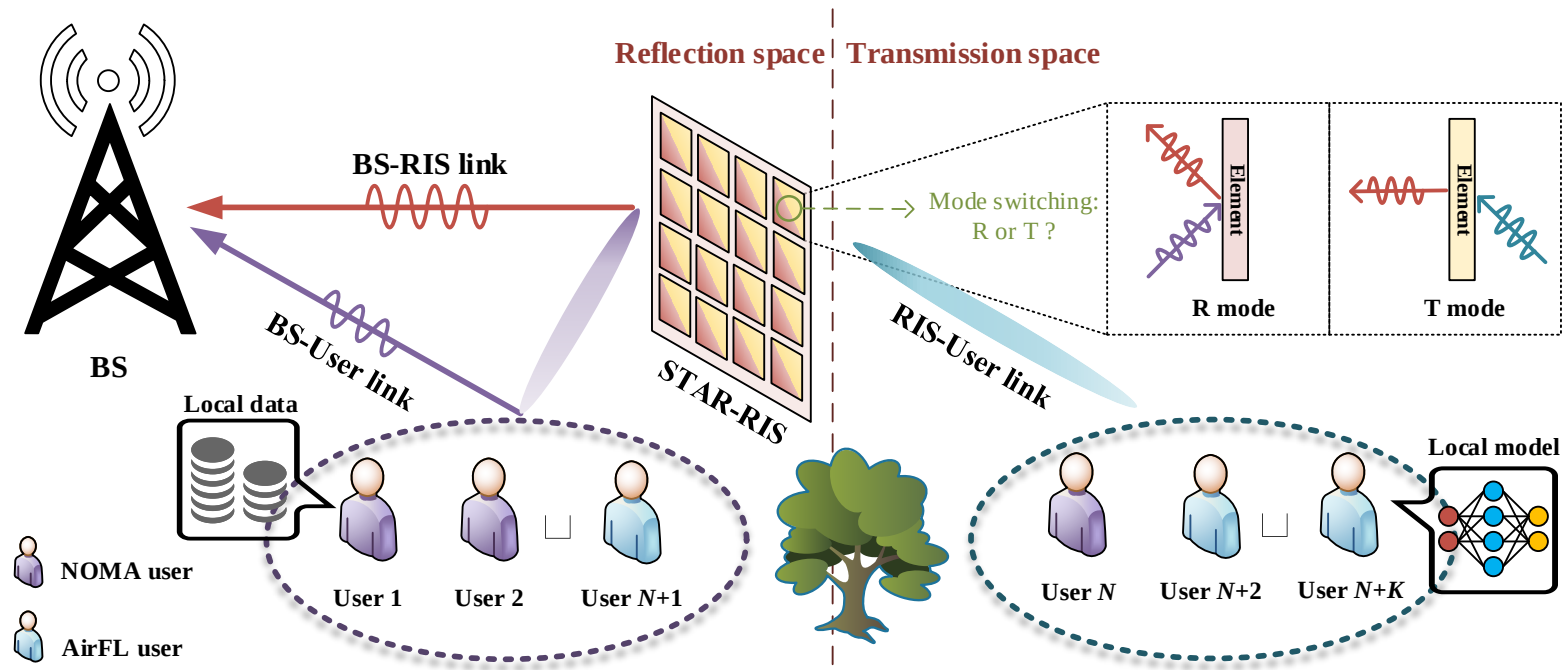


- ❑ STAR-RIS aided **downlink NOMA multi-cell** networks
- ❑ Energy splitting (ES) protocol
- ❑ STAR-RIS with N elements

- ❑ Topology: **Homogeneous Poisson point processes** (HPPPs) are used to model the locations of BSs, UEs and RISs
- ❑ Channel links: 1) the **typical UE** is blocked and receives signals with the aid of a STAR-RIS; 2) the **connected UE** receives signals through the direct BS-UE link

[10] Z. Xie, W. Yi, X. Wu, **Y. Liu**, and A. Nallanathan, "STAR-RIS Aided NOMA in Multi-Cell Networks: A General Analytical Framework with Gamma Distributed Channel Modeling", Submitted to IEEE Trans. Commun., <https://arxiv.org/abs/2108.06704>.

Integrating NOMA and AirFL via STAR-RIS

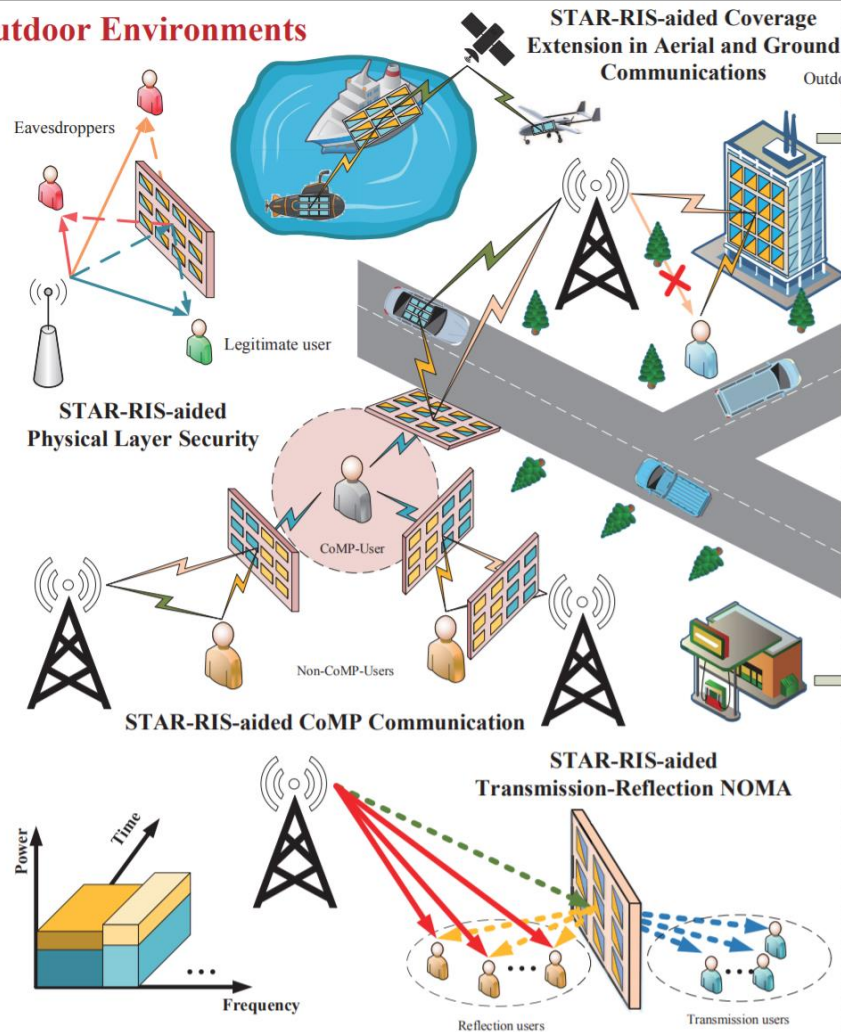


- ❑ Heterogeneous network: co-existence of NOMA users and AirFL users
- ❑ STAR-RIS protocol: Mode switching for **uplink communication**
- ❑ **Joint Beamforming Design:** to minimize the optimality gap of AirFL users while satisfying the QoS requirements of NOMA users

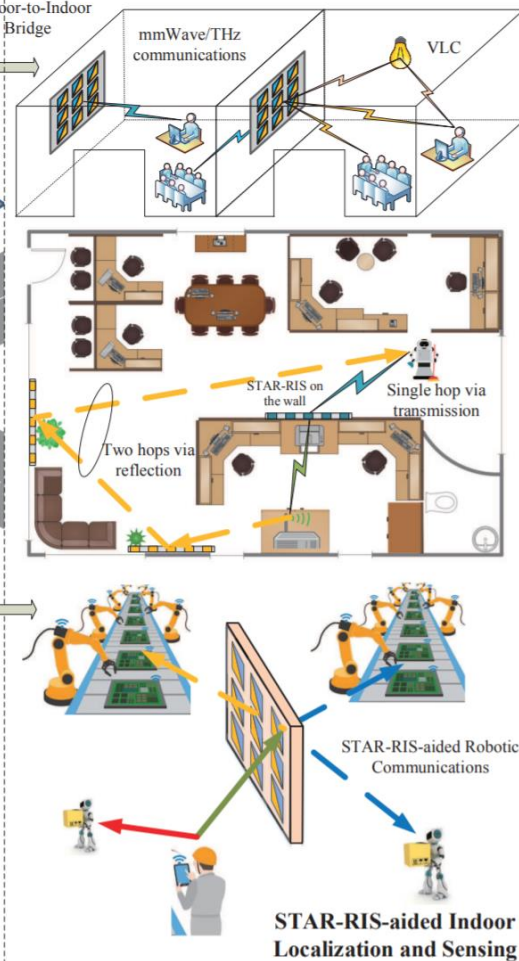
[9] W. Ni, Y. Liu, Y. C. Eldar, Z. Yang, H. Tian, "Enabling Ubiquitous Non-Orthogonal Multiple Access and Pervasive Federated Learning via STAR-RIS", *IEEE JSTSP*, major revision, <https://arxiv.org/abs/2106.08592>

Other Case Studies/Applications for STAR-RIS

Outdoor Environments



Indoor Environments



[2] Y. Liu, et al., "STAR: Simultaneous Transmission And Reflection for 360° Coverage by Intelligent Surfaces", *IEEE Commun. Mag.*, accept to appear, <https://arxiv.org/abs/2103.09104>.

Selected Research Contributions for RIS 1/2

[1] Y. Liu, et. al. "Reconfigurable Intelligent Surfaces: Principles and Opportunities", IEEE Communications Survey and Tutorial, accept to appear, <https://arxiv.org/abs/2007.03435>.

Conventional Performance Analysis and Stochastic Geometry Based Analysis

[1] J. Xu and Y. Liu, "A Novel Physics-based Channel Model for Reconfigurable Intelligent Surface-assisted Multi-user Communication Systems", *IEEE Transactions on Wireless Communications*, accept to appear. <https://arxiv.org/abs/2008.00619>.

[2] Y. Cheng, K. H. Li, Y. Liu, K. C. Teh, and H. V. Poor, "Downlink and uplink intelligent reflecting surface aided networks: NOMA and OMA", *IEEE Transactions on Wireless Communications*, accept to appear. <https://arxiv.org/abs/2005.00996>.

[3] X. Yue and Y. Liu, "Performance Analysis of Intelligent Reflecting Surface Assisted NOMA Networks", 2020. [Online]. Available: <https://arxiv.org/abs/2002.09907v2>.

[4] T. Hou, Y. Liu, Z. Song, X. Sun, Y. Chen and L. Hanzo, "Reconfigurable Intelligent Surface Aided NOMA Networks", *IEEE Journal on Selected Areas in Communications*, accept to appear.

[5] Y. Cheng, K. H. Li, Y. Liu, K. C. Teh, and G. K. Karagiannidis, "Non-orthogonal multiple access (NOMA) with multiple intelligent reflecting surfaces", *IEEE Transactions on Wireless Communications*, accept to appear. <https://arxiv.org/abs/2005.00996>.

[6] T. Hou, Y. Liu, Z. Song, X. Sun, and Y. Chen "MIMO-NOMA Networks Relying on Reconfigurable Intelligent Surface: A Signal Cancellation Based Design", *IEEE Transactions on Communications*, accept to appear, <https://arxiv.org/abs/2003.02117>.

[7] T. Hou, Y. Liu, Z. Song, X. Sun, and Y. Chen "MIMO Assisted Networks Relying on Large Intelligent Surfaces: A Stochastic Geometry Model", *IEEE Transactions on Vehicular Technology*, accept to appear, <https://arxiv.org/abs/1910.00959>.

[8] C. Zhang, W. Yi and Y. Liu, "Reconfigurable Intelligent Surfaces Aided Multi-Cell NOMA Networks: A Stochastic Geometry Model," *IEEE Transactions on Communications*, <https://arxiv.org/abs/2008.08457>.

Capacity Characterization, Beamforming and Resource Allocation

[9] X. Mu, Y. Liu, L. Guo, J. Lin, N. Al-Dhahir "Capacity and Optimal Resource Allocation for IRS-assisted Multi-user Communication Systems", *IEEE Transactions on Communications*, accept to appear, <https://arxiv.org/abs/2001.03913>.

Selected Research Contributions for NOMA-RIS 2/2

- [10] Y. Guo, Z. Qin, **Y. Liu**, N. Al-Dhahir "Intelligent Reflecting Surface Aided Multiple Access Over Fading Channels", *IEEE Transactions on Communications*, accept to appear, <https://arxiv.org/abs/2006.07090>.
- [11] X. Mu, **Y. Liu**, L. Guo, J. Lin, N. Al-Dhahir "Exploiting Intelligent Reflecting Surfaces in NOMA Networks: Joint Beamforming Optimization", *IEEE Transactions on Wireless Communications*, accept to appear, <https://arxiv.org/abs/1910.13636>.
- [12] J. Zuo, **Y. Liu**, E. Basar and O. A. Dobre, "Intelligent Reflecting Surface Enhanced Millimeter-Wave NOMA Systems", *IEEE Communications Letters*, accept to appear.
- [13] W. Ni, X. Liu, **Y. Liu**, H. Tian, and Y. Chen, "Resource Allocation for Multi-Cell IRS-Aided NOMA Networks", *IEEE Transactions on Wireless Communications*, accept to appear.
- [14] J. Zuo, **Y. Liu**, Z. Qin and N. Al-Dhahir, "Resource Allocation in Intelligent Reflecting Surface Assisted NOMA Systems", *IEEE Transactions on Communications*, accept to appear.

Deployment and Multiple Access

- [15] X. Mu, **Y. Liu**, L. Guo, J. Lin, R. Schober "Joint Deployment and Multiple Access Design for Intelligent Reflecting Surface Assisted Networks", *IEEE Transactions on Wireless Communications*, accept to appear, <https://arxiv.org/abs/2005.11544>.
- [16] X. Mu, **Y. Liu**, L. Guo, J. Lin, R. Schober "Intelligent Reflecting Surface Enhanced Indoor Robot Path Planning: A Radio Map based Approach", *IEEE Transactions on Wireless Communications*, accept to appear, <https://arxiv.org/abs/2009.12804>.

A Machine Learning Approach

- [17] X. Liu, **Y. Liu**, Y. Chen, and V. Poor "RIS Enhanced Massive Non-orthogonal Multiple Access Networks: Deployment and Passive Beamforming Design", *IEEE Journal of Selected Areas in Communications*, accept to appear, <https://arxiv.org/abs/2001.10363>.
- [18] X. Liu, **Y. Liu**, and Y. Chen, "Machine Learning Empowered Trajectory and Passive Beamforming Design in UAV-RIS Wireless Networks", *IEEE Journal of Selected Areas in Communications*, accept to appear, <https://arxiv.org/pdf/2010.02749.pdf>.



Research Opportunities and challenges for STAR-RIS

- Hardware Implementation for STAR-RIS
- STAR-RIS NOMA Design
- MIMO-STAR RIS design
- STAR-RIS-aided Coverage Extension in non-terrestrial and satellite communications
- Spatial Analysis of STAR-RIS using Stochastic Geometry
- Channel Estimation for STAR-RISs
- Machine learning for STAR-RIS
- Deployment Strategies for STAR-RISs



STAR for future 6G and IoT networks

❑ My hope is to make those

“STARS” shine in the “6G Sky”

Providing *low cost, energy efficient and coverage extended* communications!



Thanks for your
attention
Q & A

