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

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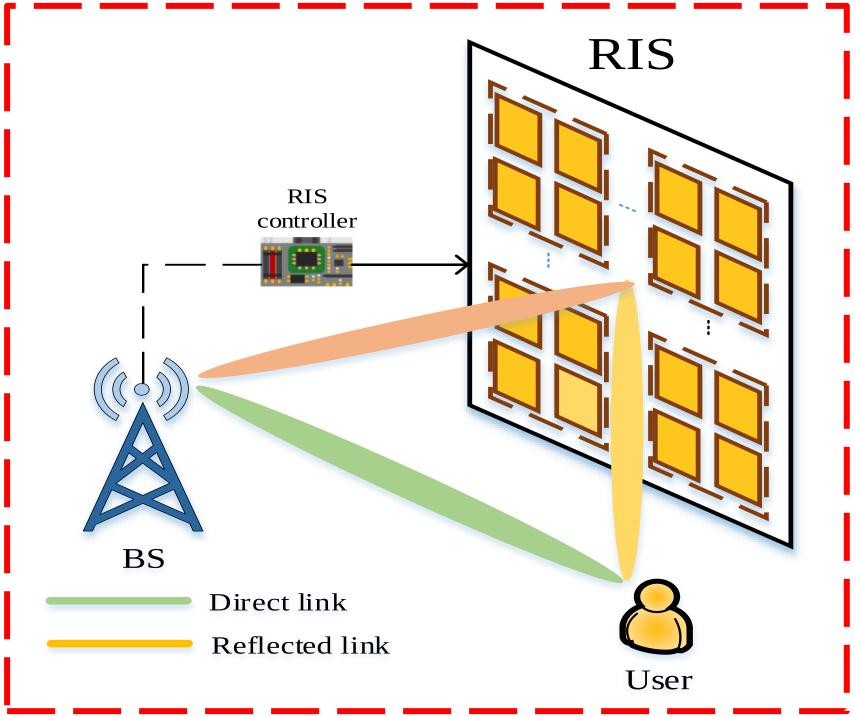
Outline

- 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
- …

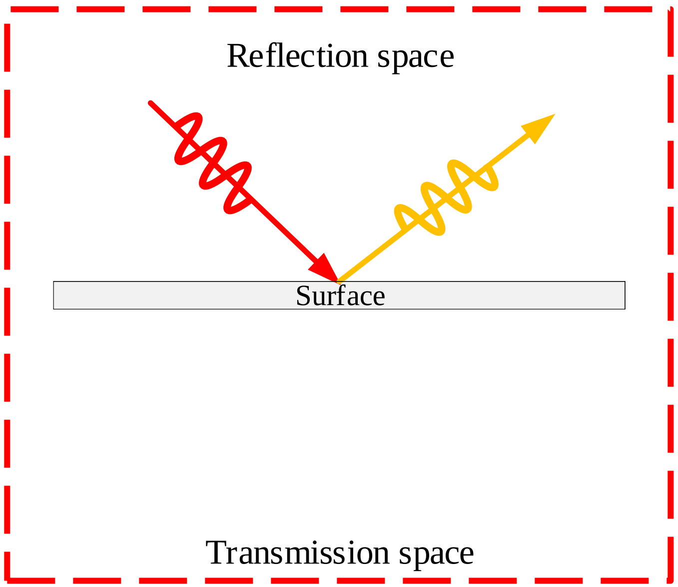
[1] **Y. Liu,** *et al*., "Reconfigurable Intelligent Surfaces: Principles and Opportunities", *IEEE Commun. Surv. Tut.*, accept to appear., 2021 http://arxiv.org/abs/2007.03435.

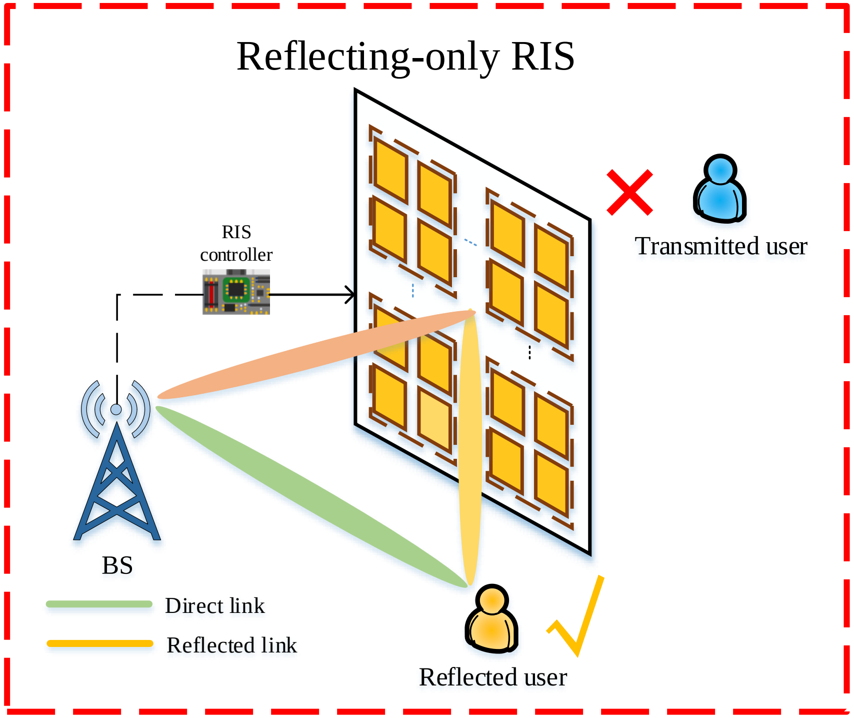
[2] **Y. Liu**, *et. al* "Reconfigurable Intelligent Surface (RIS) Aided Multi-User Networks: Interplay Between NOMA and RIS", *IEEE Commun. Mag.*, accept to appear., 2021 *https://arxiv.org/abs/2011.13336*.

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



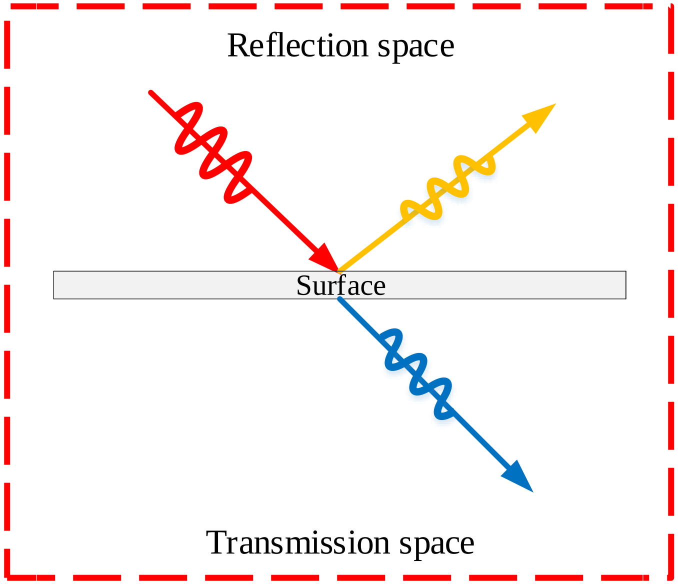


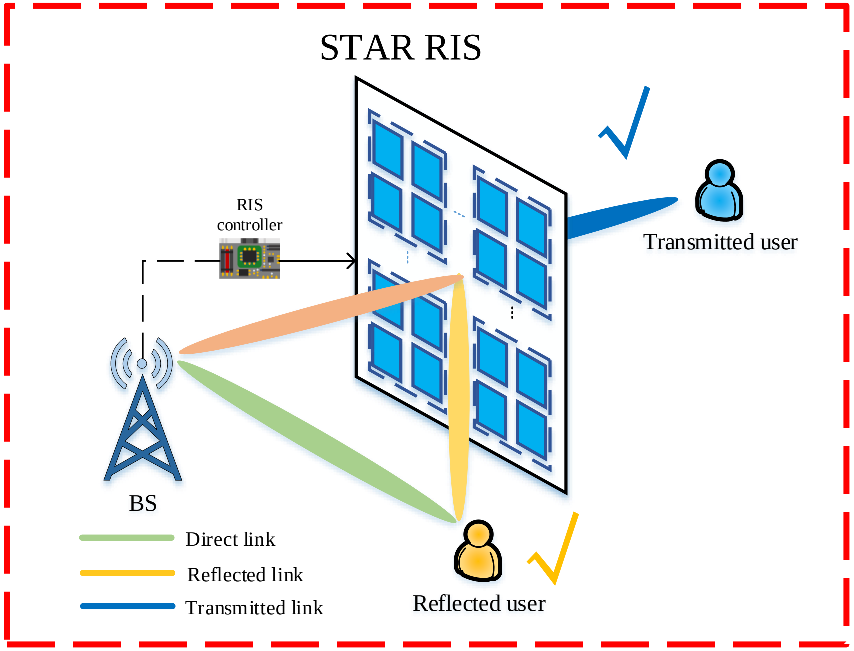
[T1] **Y. Liu**, RIS tutorial

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*



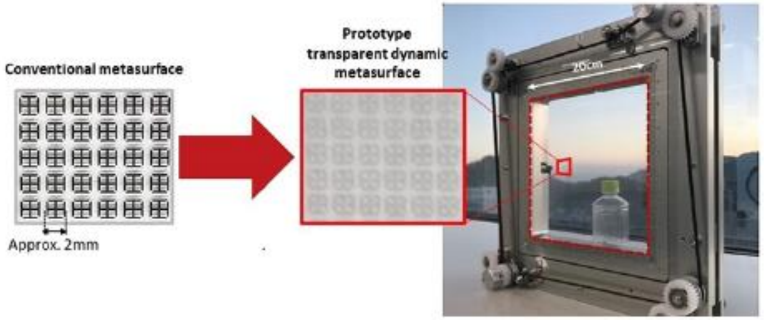


[3] **Y. Liu,** *et al*., “STAR: Simultaneous Transmission And Reflection for 360° Coverage by Intelligent Surfaces”, *IEEE Commun. Mag.*, accept to appear, https://arxiv.org/abs/2103.09104.

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.



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

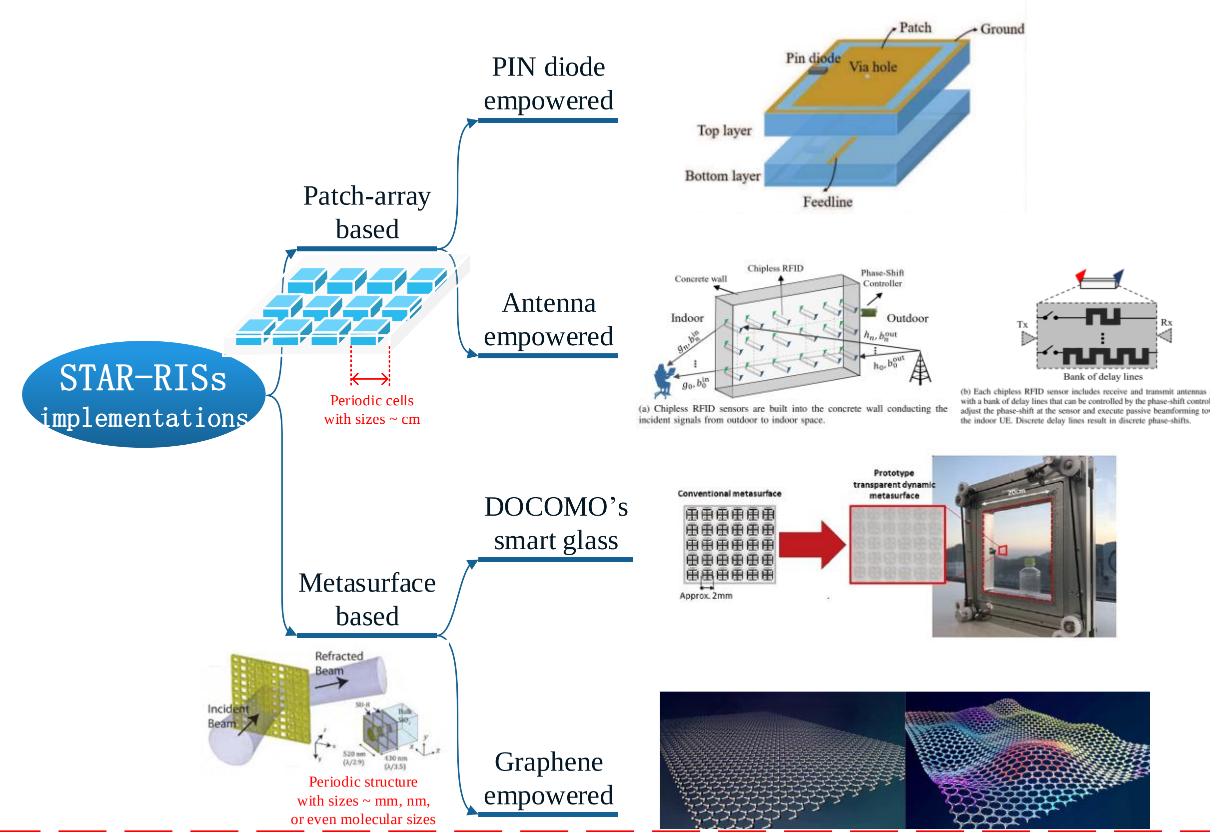
How STAR-RISs can be implemented?

- 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



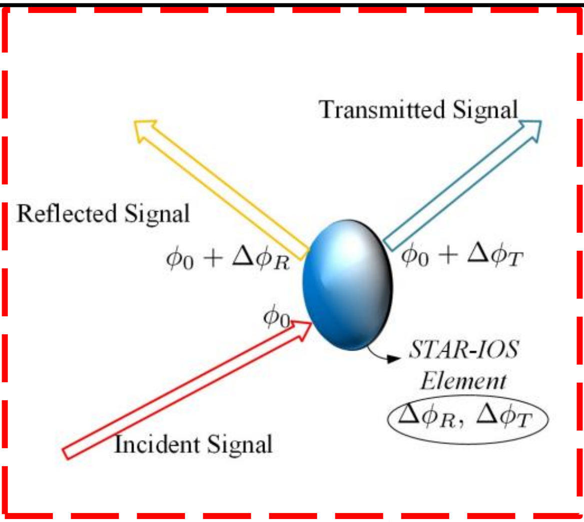
Implementations	Operating frequency	STAR-IOS prototypes	Tuning mechanism	Independent reflection/transmission control
Patch-array based	Low to high frequency (10KHz up to 1GHz)	PIN diode empowered	Bias voltages on PIN diodes	Difficult to achieve
		Antenna empowered	Lengths of delay lines	Can be achieved
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

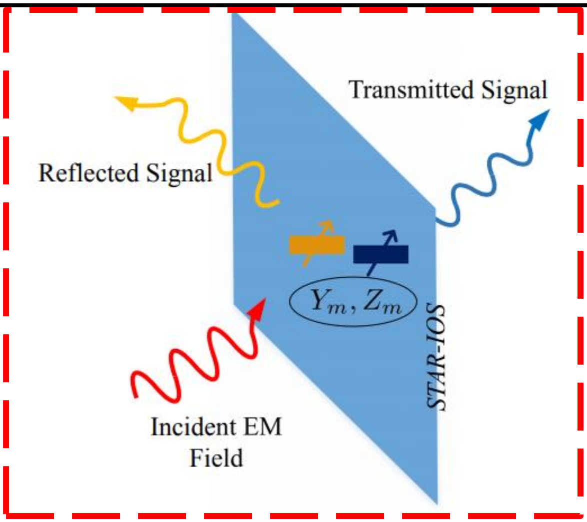
Hardware Models and Channel Models

❑ 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-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

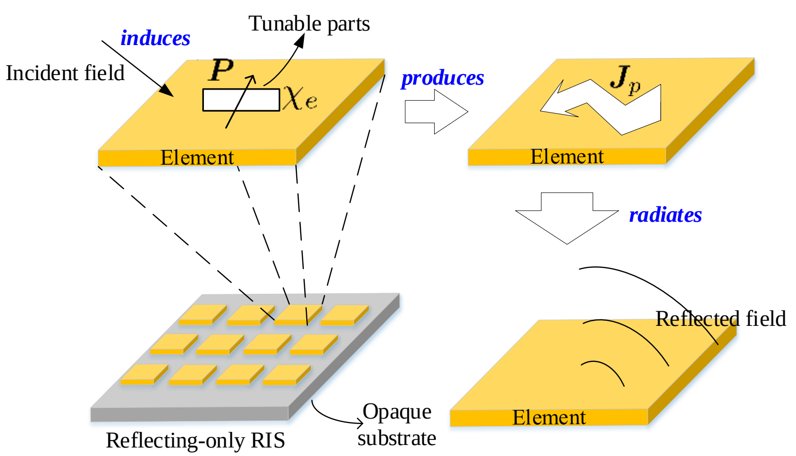
❑ Channel models:

- 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 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

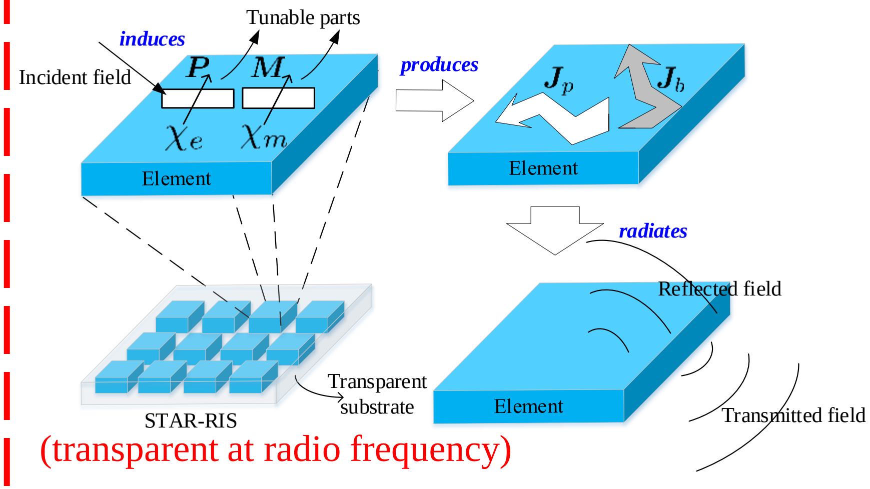
Difference Between Reflecting-Only RIS and STAR-RIS

Reflecting-Only RIS



(Biscuits placed on a metal plate)

STAR-RIS



(transparent at radio frequency)

(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.

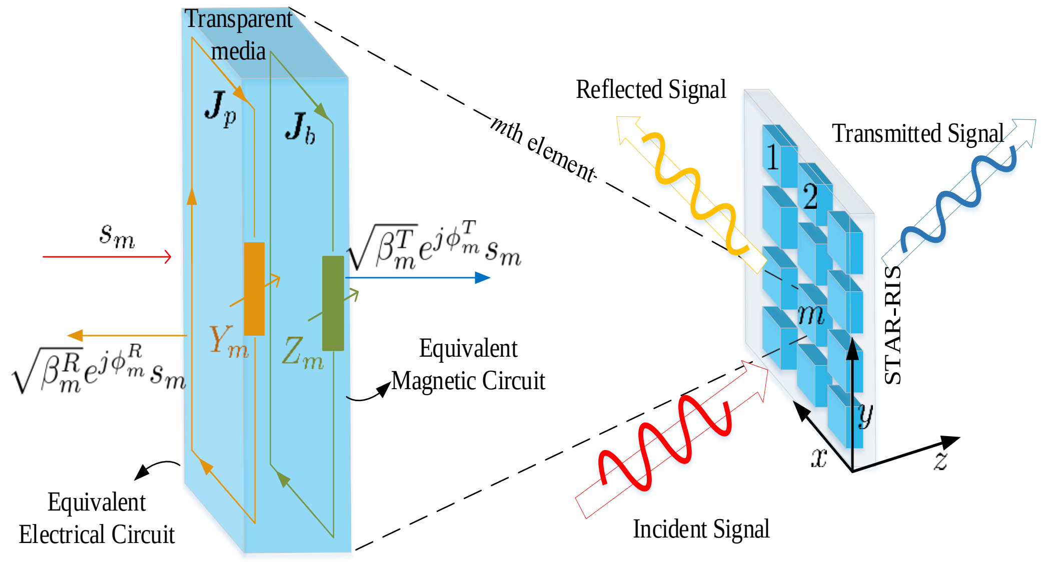
Basic Signal Model for STAR

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

[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

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

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

STAR-RIS

- Transmission-coefficient matrix

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

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

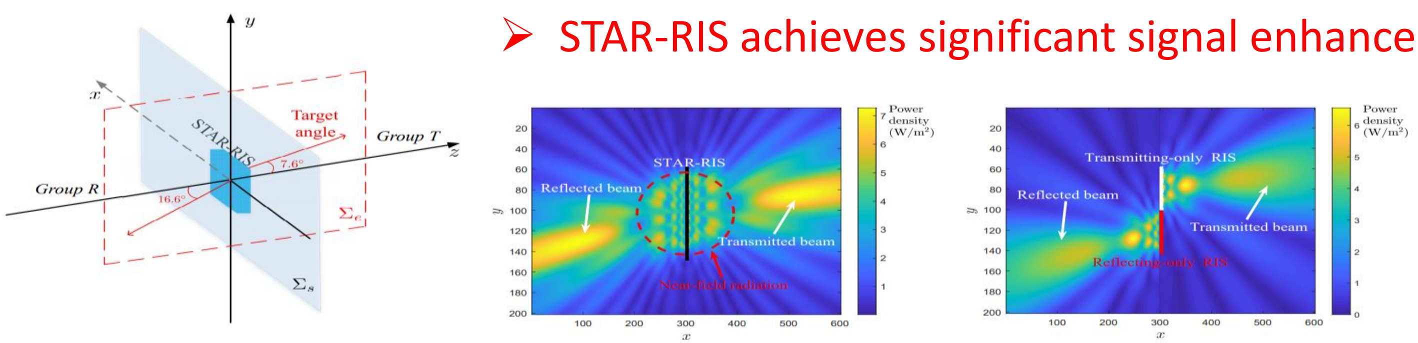
Comparison with Conventional RISs

❑ 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

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

i.e. $d_s^T + d_s^R = 2M + 2$

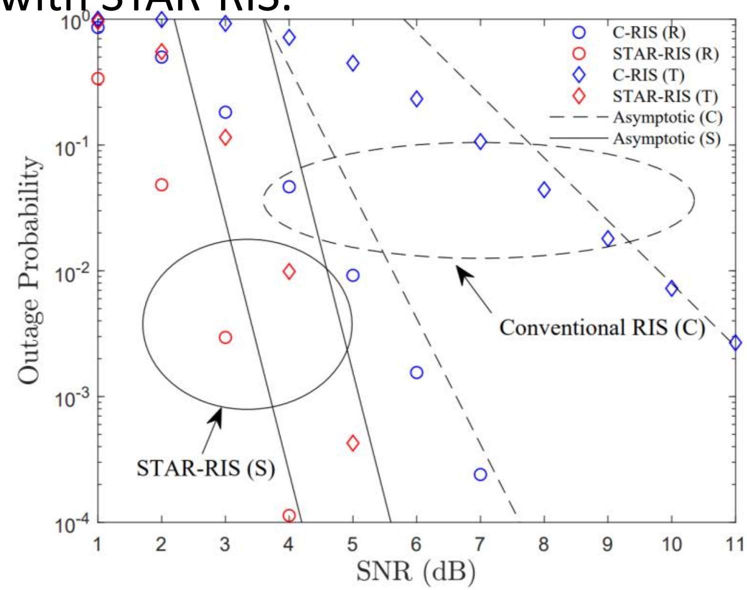
- For conventional RISs, the achievable diversity order for receivers in T and R follows:

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

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.

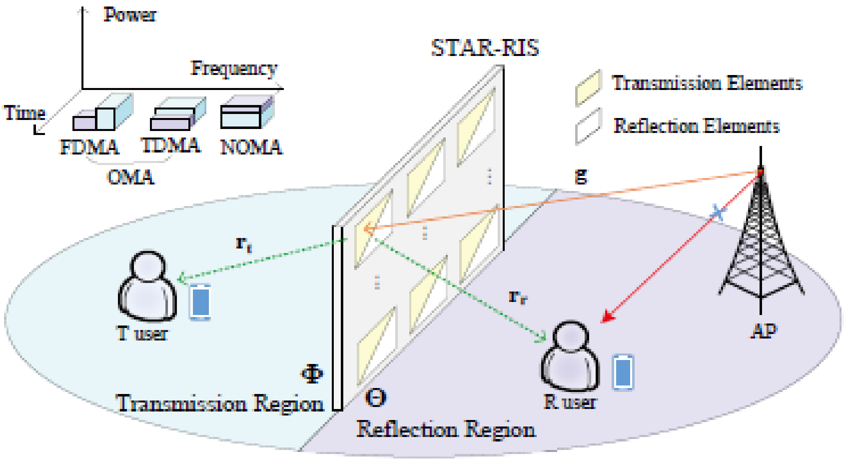


[4] J. Xu, **Y. Liu**, X. Mu, and O. A. Dobre, "STAR-RISs: Simultaneous transmitting and reflecting reconfigurable intelligent surfaces," *IEEE Commun. Lett.*, vol. 25, no. 9, pp. 3134-3138, Sept. 2021, doi: 10.1109/LCOMM.2021.3082214.

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

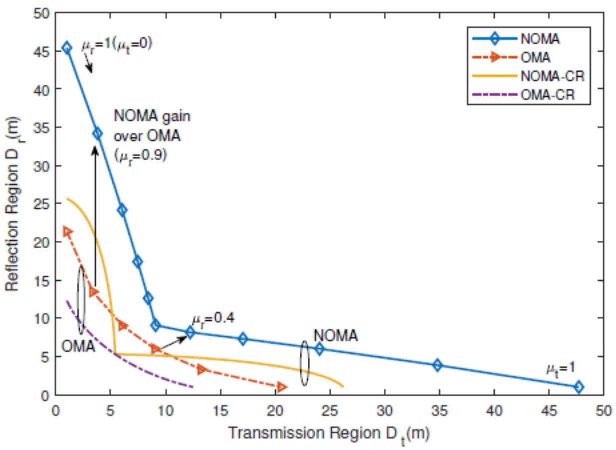
$$
\begin{aligned}
&\max_{\{p_k,\beta_k,D_k,\lambda(k),\mathbf{v}_k,D_0\}} \quad D_0\\
\text{s.t.}\quad & D_k \ge u_k D_0, \forall k \in \mathcal{K},\\
& D_k \ge 1, \forall k \in \mathcal{K},\\
& r_k^N \ge \gamma_k, \forall k \in \mathcal{K},\\
& \sum_k p_k \le P_{\max},\\
& \theta_m^k \in [0,2\pi],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

- 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

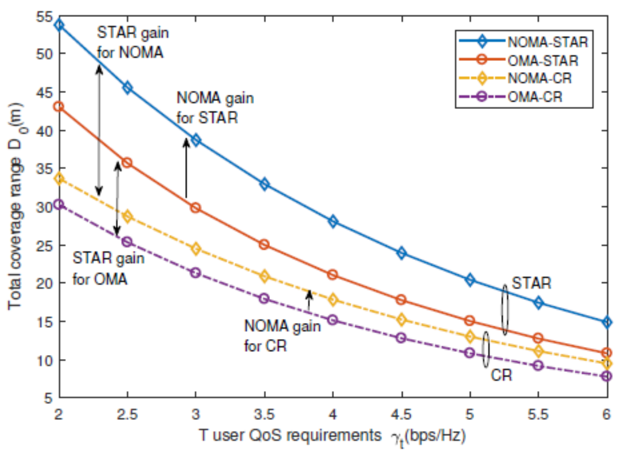
Problem Formulation for OMA

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

➢ Coverage tradeoff



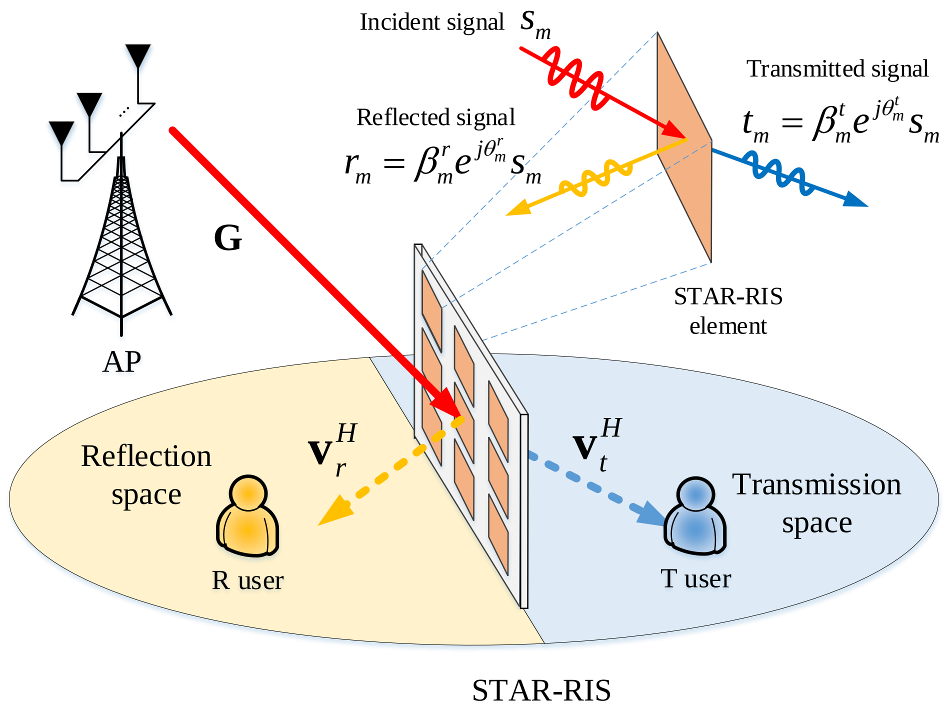
➢ Total coverage comparison



- 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

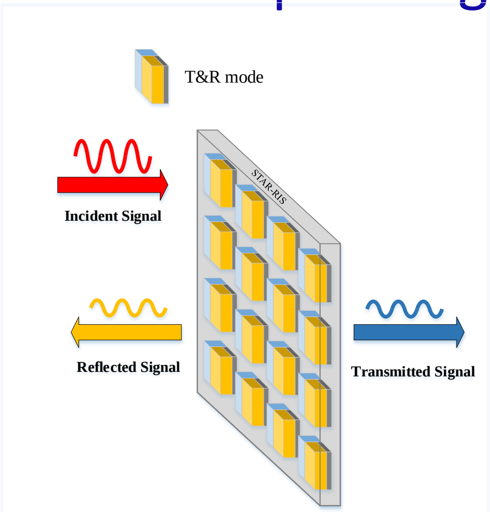


- ❑ Multiple-antenna AP: Active beamforming
- ❑ STAR-RIS: Passive transmission and reflection beamforming
- ❑ **Joint Beamforming Design**: to minimize the power consumption for satisfying the QoS requirements of each user for each proposed operating protocol

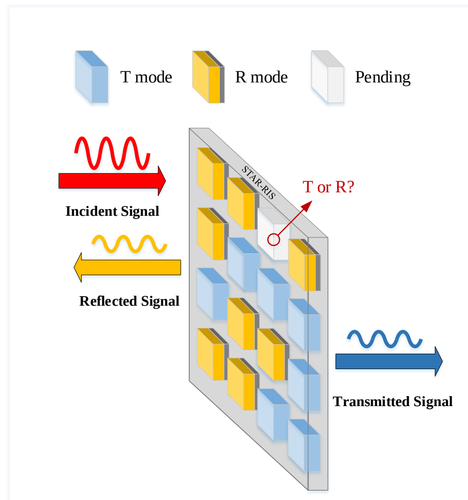
[6] X. Mu, **Y. Liu,** L. Guo, J. Lin, R. Schober, "Simultaneously Transmitting And Reflecting (STAR) RIS Aided Wireless Communications", *IEEE Trans. Wireless Commun.*, accept to appear, https://arxiv.org/abs/2104.01421.

Operating Protocols for STAR-RIS

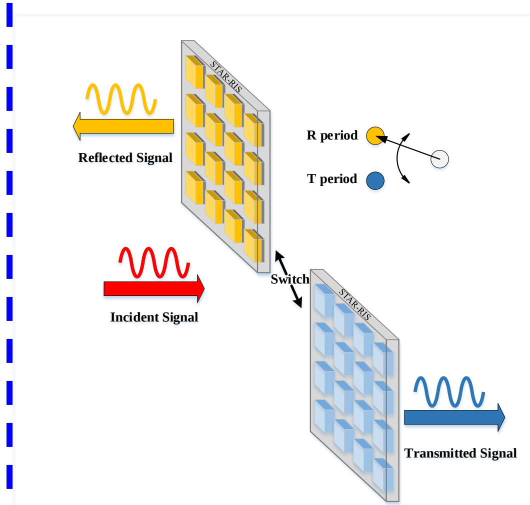
- Based on the signal model, each STAR element can be operated in
  - Full transmission mode (T mode): $\beta_m^t = 1,\ \beta_m^r = 0$
  - Full reflection mode (R mode): $\beta_m^t = 0,\ \beta_m^r = 1$
  - Simultaneous transmission and reflection mode (T&R mode)
- Practical operating protocols



Energy Splitting (ES)



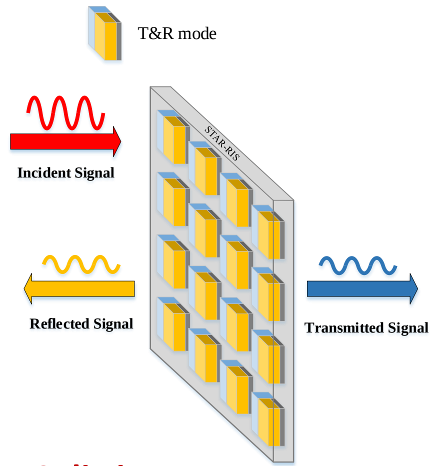
Mode Switching (MS)



Time Switching (TS)

[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



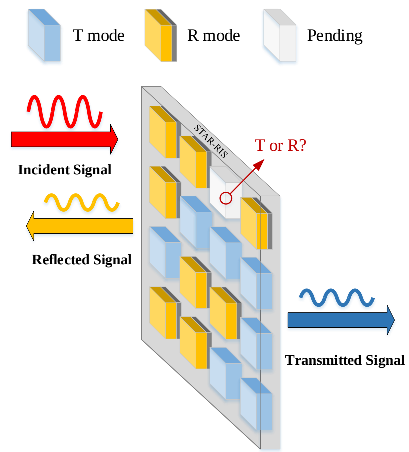
Energy Splitting

- All elements are operated in T&R mode

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

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

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



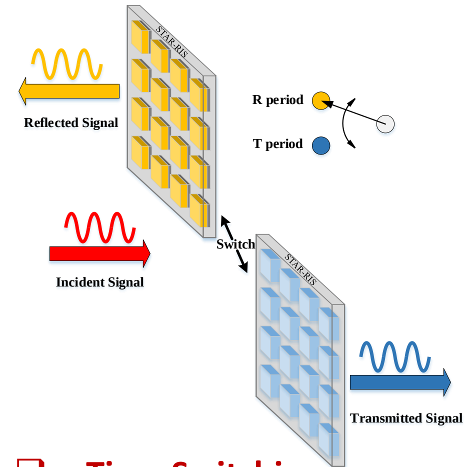
Mode Switching

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

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

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

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



Time Switching

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

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

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

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

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

Joint Beamforming Design for STAR-RIS

❑ Problem Formulation for Unicast

$$\min_{\mathbf{w}_k,\boldsymbol{\Theta}_k^{\mathrm{X}},\lambda^k} \quad \|\mathbf{w}_t\|^2 + \|\mathbf{w}_r\|^2$$

$$\text{s.t.} \quad R_{\mathrm{UC},k}^{\mathrm{X}} \geq \overline{R}_k, \forall k \in \{t,r\},$$

$$\boldsymbol{\Theta}_k^{\mathrm{X}} \in \mathcal{F}^{\mathrm{X}}, \forall k \in \{t,r\},$$

$$0 \leq \lambda^t \leq 1, 0 \leq \lambda^r \leq 1, \lambda^t + \lambda^r = 1,$$

❑ Problem Formulation for Multicast

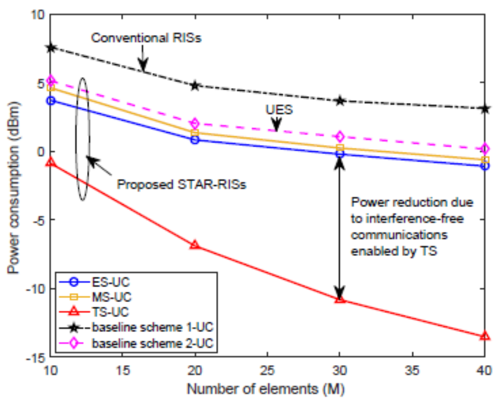
$$\min_{\mathbf{w}_c,\boldsymbol{\Theta}_k^{\mathrm{ES/MS}}} \quad \|\mathbf{w}_c\|^2 \Big/ \min_{\mathbf{w}_{c,k},\boldsymbol{\Theta}_k^{\mathrm{TS}},\lambda^k} \quad \|\mathbf{w}_{c,t}\|^2 + \|\mathbf{w}_{c,r}\|^2$$

$$\text{s.t.} \quad R_{\mathrm{MC}}^{\mathrm{X}} \geq \overline{R}_c,$$

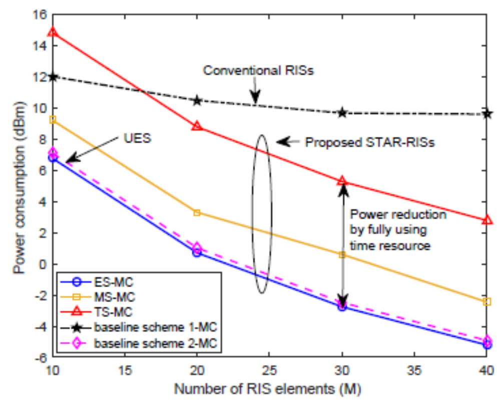
$$\boldsymbol{\Theta}_k^{\mathrm{X}} \in \mathcal{F}^{\mathrm{X}},$$

$$0 \leq \lambda^t \leq 1, 0 \leq \lambda^r \leq 1, \lambda^t + \lambda^r = 1,$$

➢ Power consumption versus number of elements



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



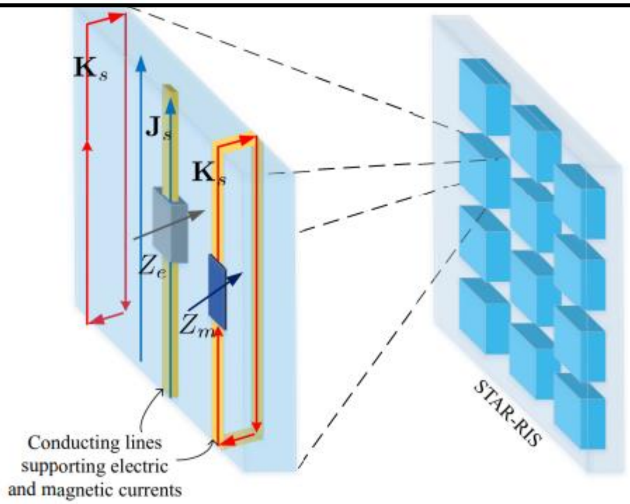
(b) Multicast communication, $\overline{\gamma}_c = 10$ dB.

- ❑ Baseline 1: Conventional reflecting and transmitting RISs
- ❑ Baseline 2: Uniform energy splitting for STAR-RIS

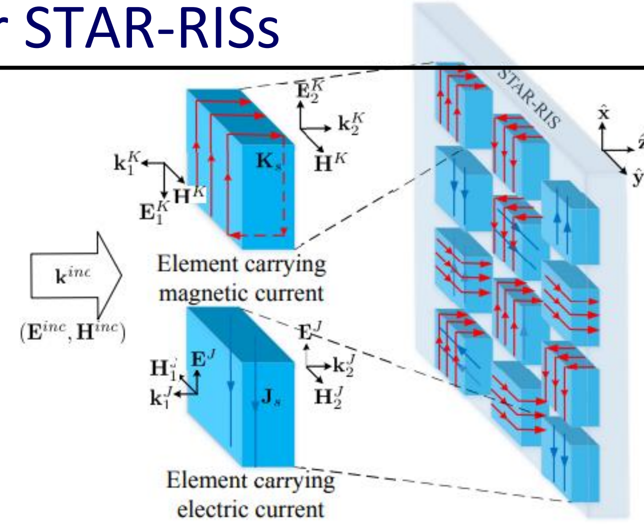
- ➢ TS and ES are preferable for unicast and multicast, respectively
- ➢ STAR-RIS significantly outperforms conventional RIS
- ➢ For ES, element-based amplitude control is essential for unicast to mitigate inter-user interference

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

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

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

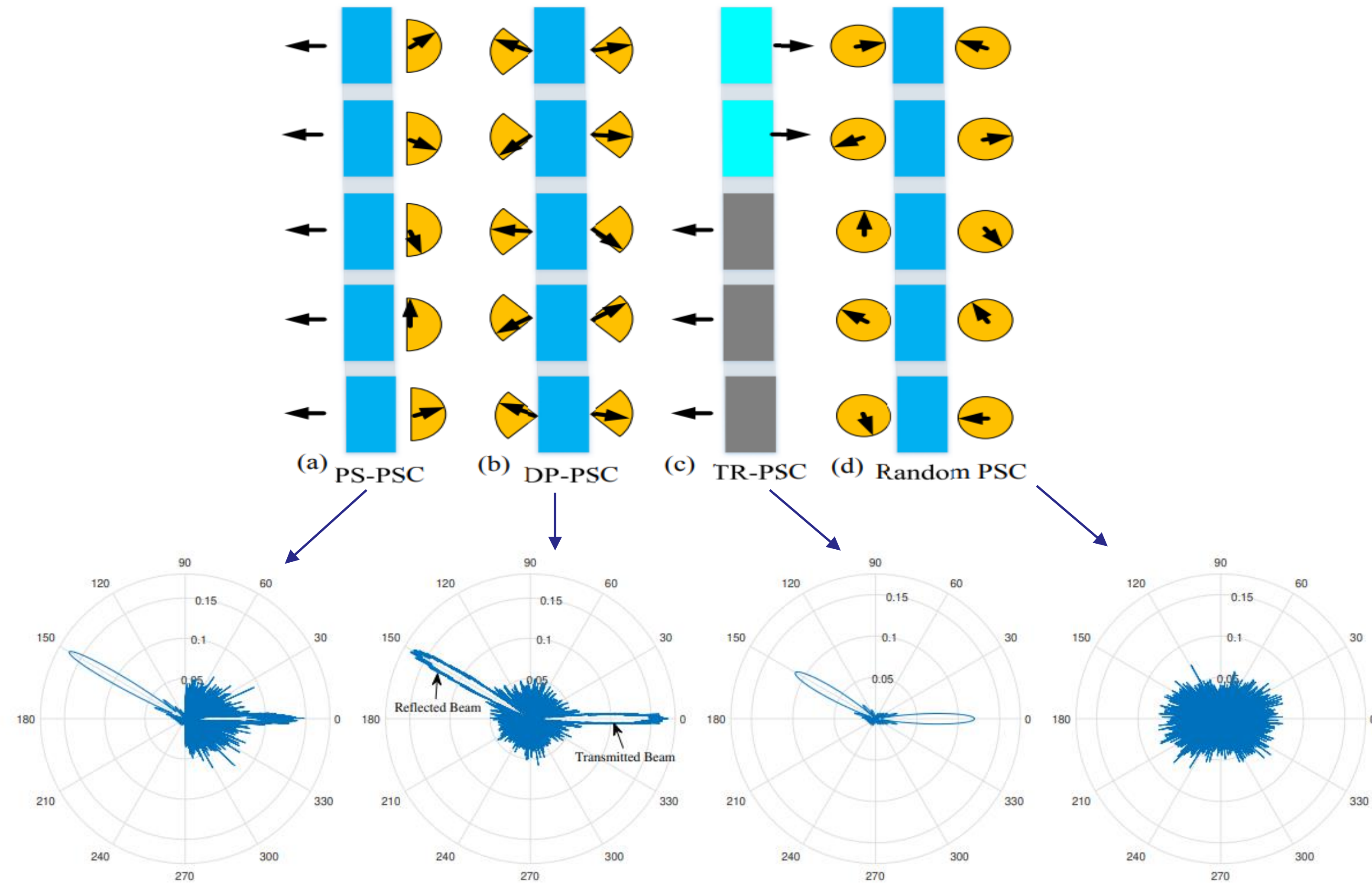
This leads to **the Proposed Model:**

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

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

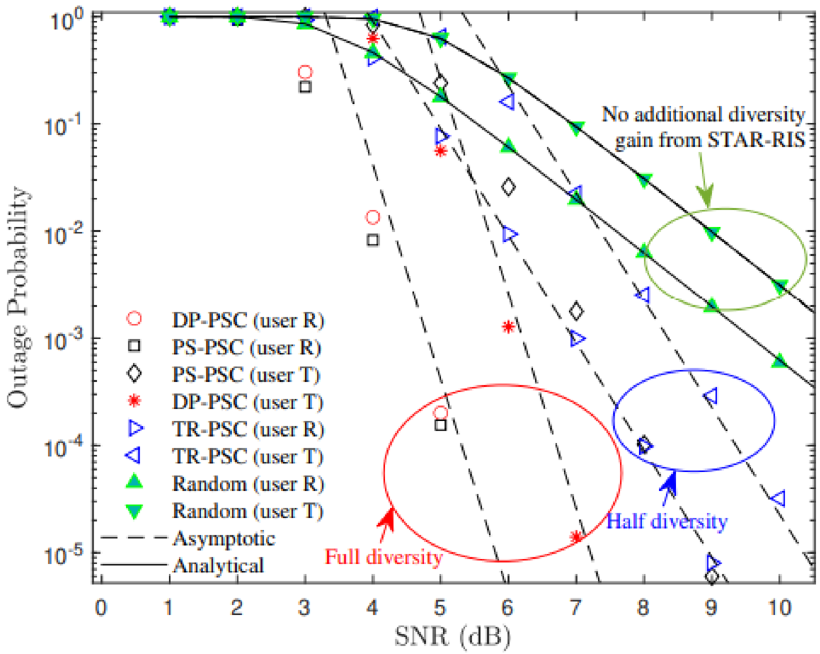


(a) PS-PSC (b) DP-PSC (c) TR-PSC (d) Random PSC

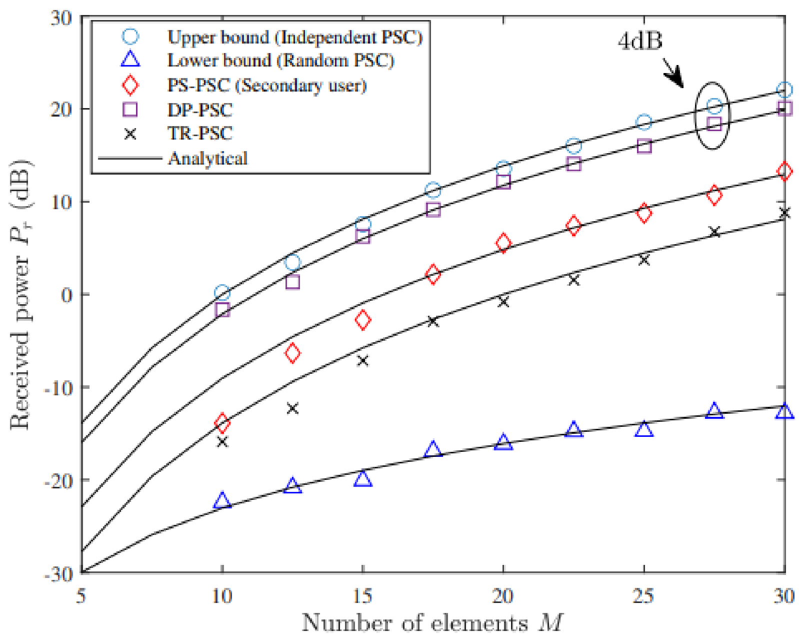
Primary-Secondary *Diversity-Preserving* *T&R-Group*

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	$\propto M^2$	$\propto M^2$	$\propto M_\chi^2$	$\propto M$



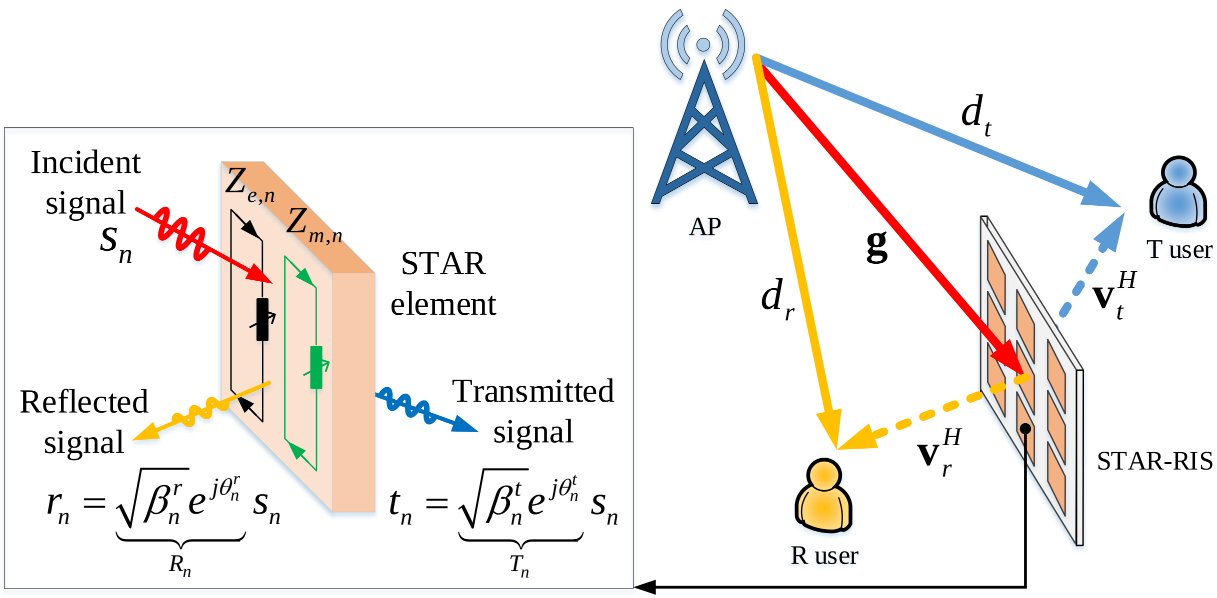
Outage probability vs. transmit SNR



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

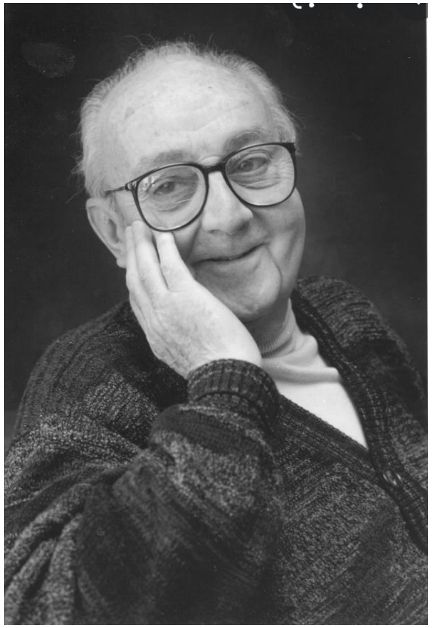


- A coupling phase-shift model for STAR-RISs: $\left|\theta_n^t - \theta_n^r\right| = \frac{\pi}{2}, \frac{3\pi}{2}$
- Challenge: The design of phase-shift coefficients for transmission and reflection is highly-coupled.
- **Solutions**: An element-wise alternating optimization algorithm.

[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."

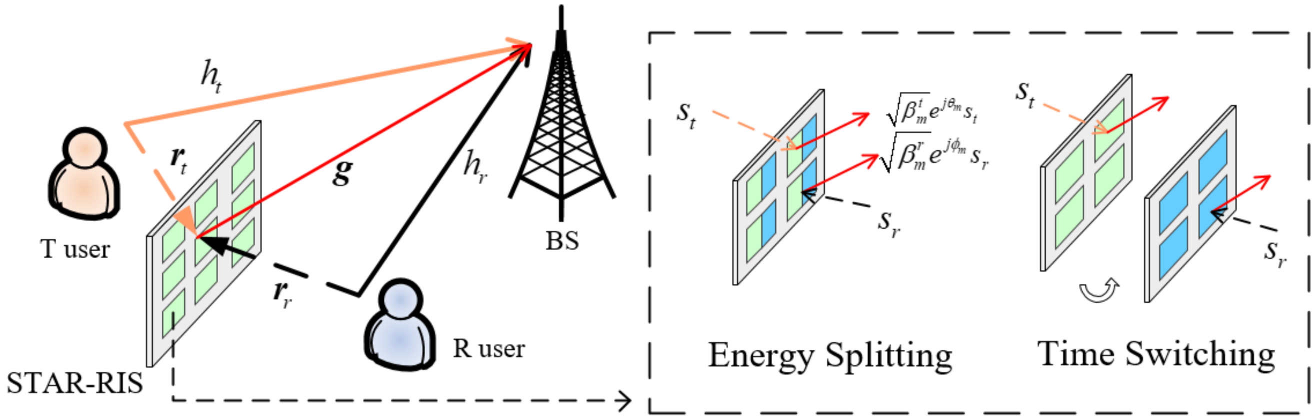


----George E. P. Box

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

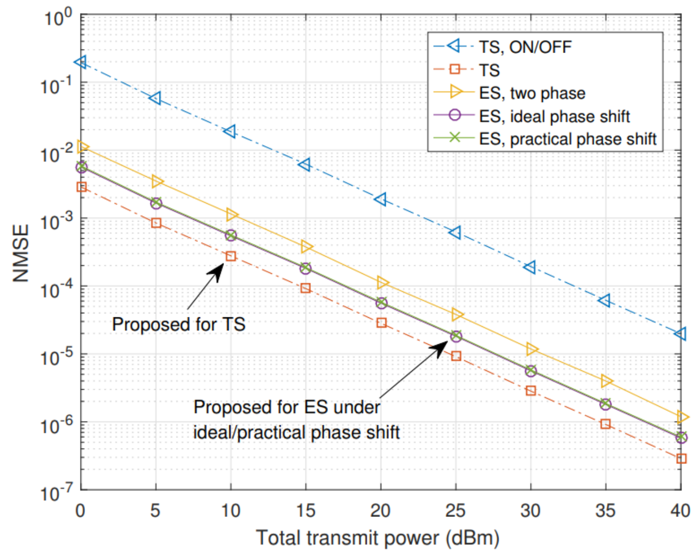
$$\min_{\boldsymbol{\Theta}} \frac{\sigma^2}{p}\mathrm{Tr}[(\boldsymbol{\Theta}^H\boldsymbol{\Theta})^{-1}]$$
$$\text{s.t. } \theta_{m,i}, \phi_{m,i} \in [0, 2\pi), m \in \mathcal{M}, i = 1, ..., \tau_t,$$
$$\mathrm{rank}(\boldsymbol{\Theta}) = M + 1.$$

❑ 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.

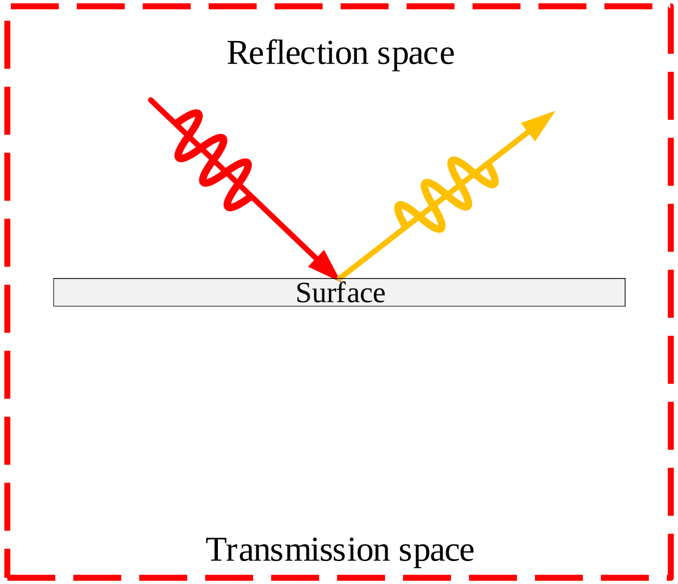
[10] C. Wu, C. You, **Y. Liu**, X. Gu, and Y. Cai, "Channel Estimation for STAR-RIS aided Wireless Communication," *IEEE Commun. Lett.*., minor revision, https://arxiv.org/abs/2112.01413

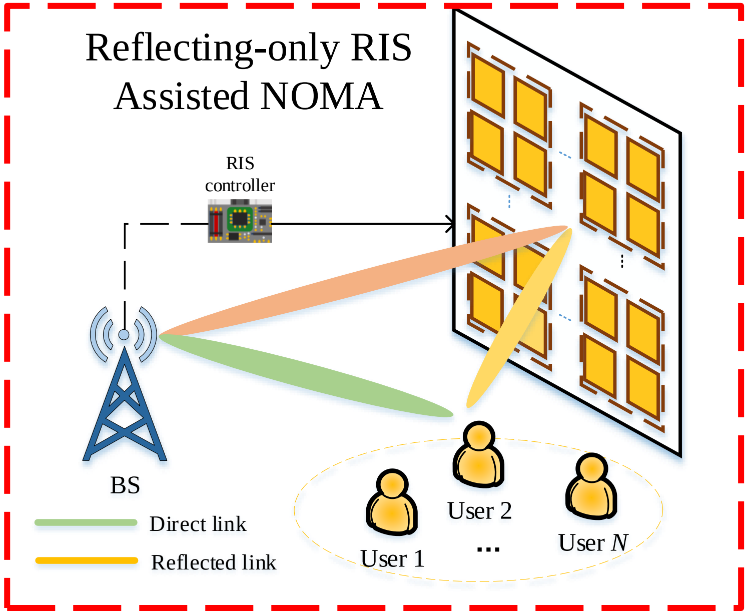
Outline

- 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

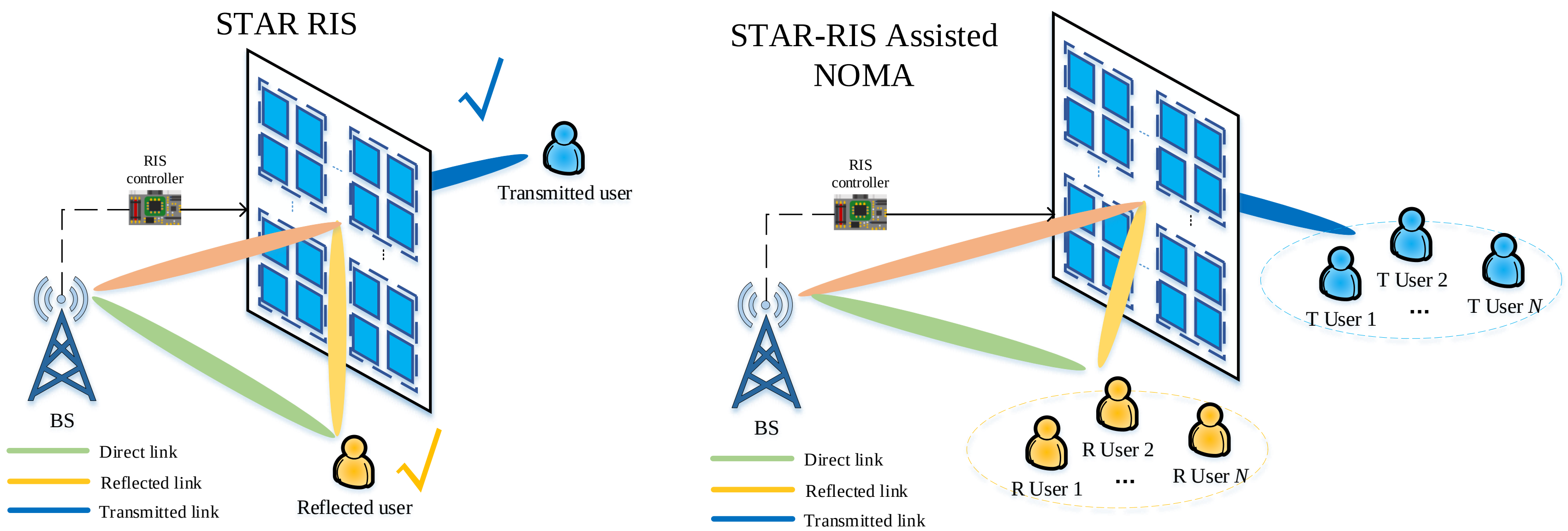




- ❑ For NOMA to achieve a large performance gain over OMA, it is important to pair users having different channel conditions.
- ❑ Limitations: the channel conditions of users in the local reflected space are generally similar, which may be not easy to fully exploit the benefits of NOMA

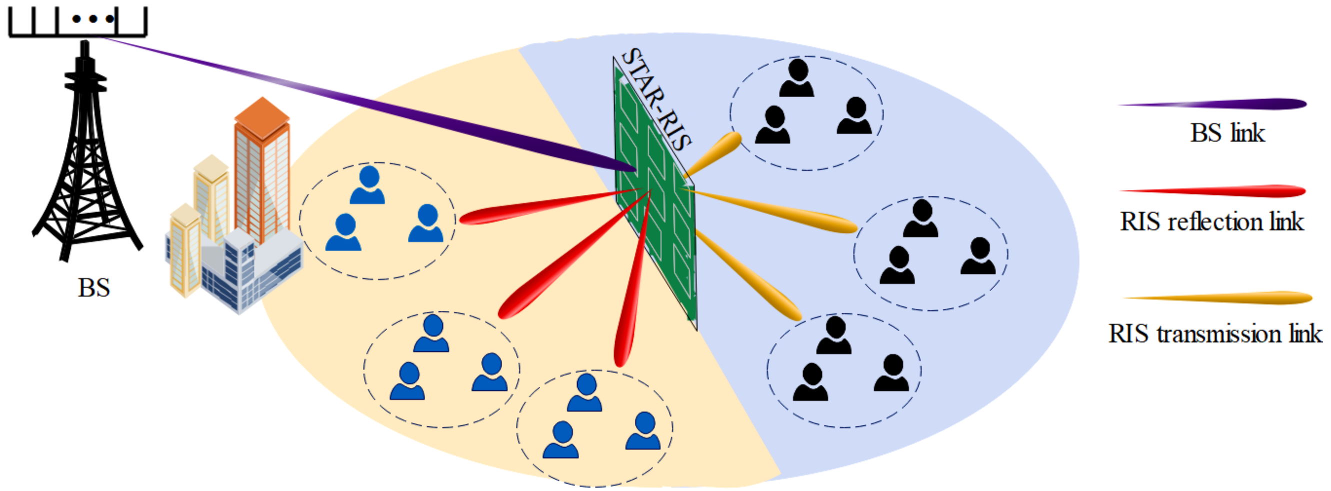
STAR-RIS NOMA

❑ 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.

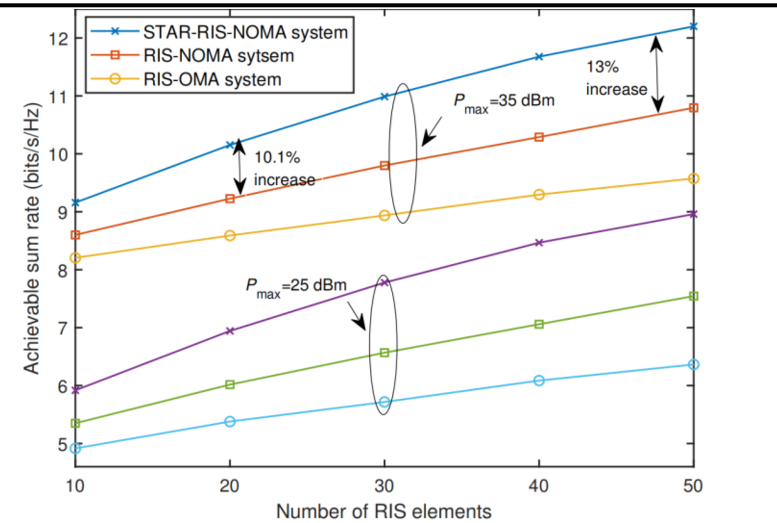
Joint Design for STAR-RIS Aided NOMA

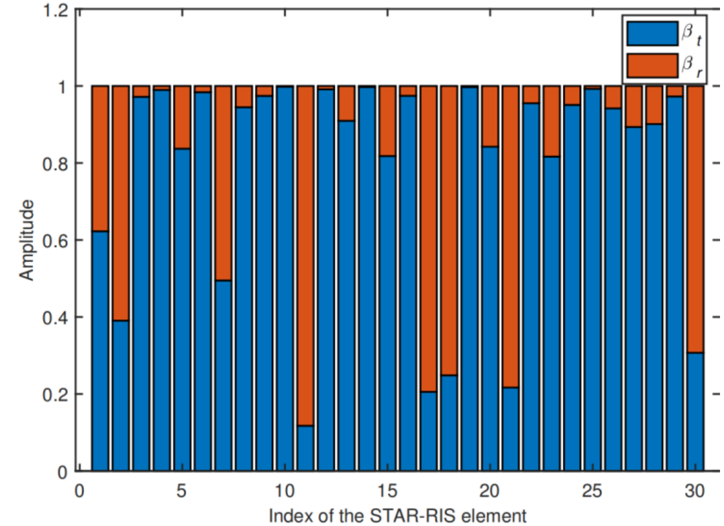
Problem formulation

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

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

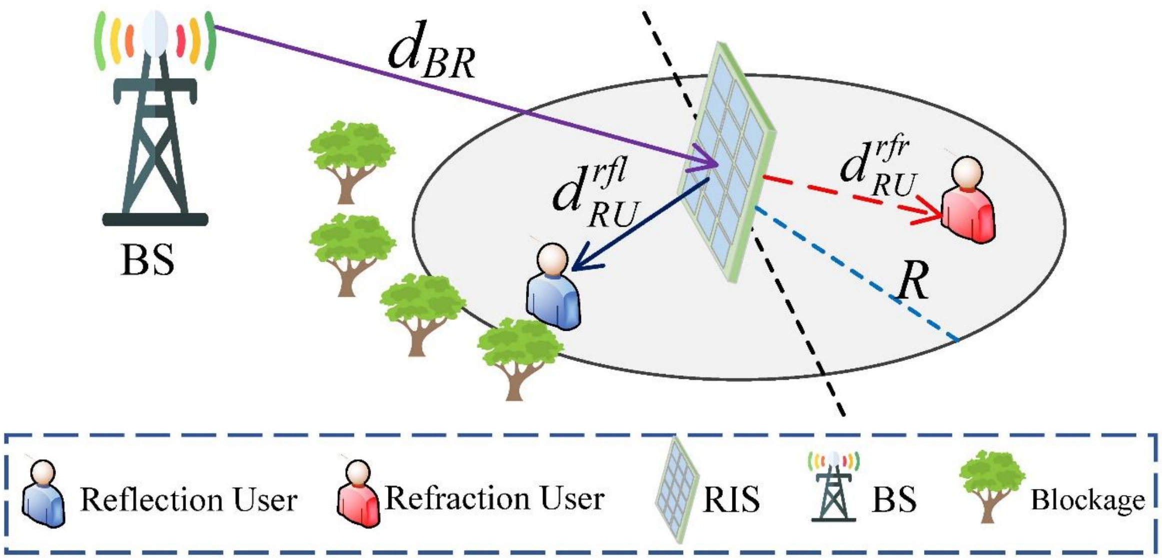
- STAR-RIS aided NOMA outperforms conventional RIS based systems
- If there are more users in the transmission space, then STAR-RIS will allocated more energy to the transmission amplitudes





[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

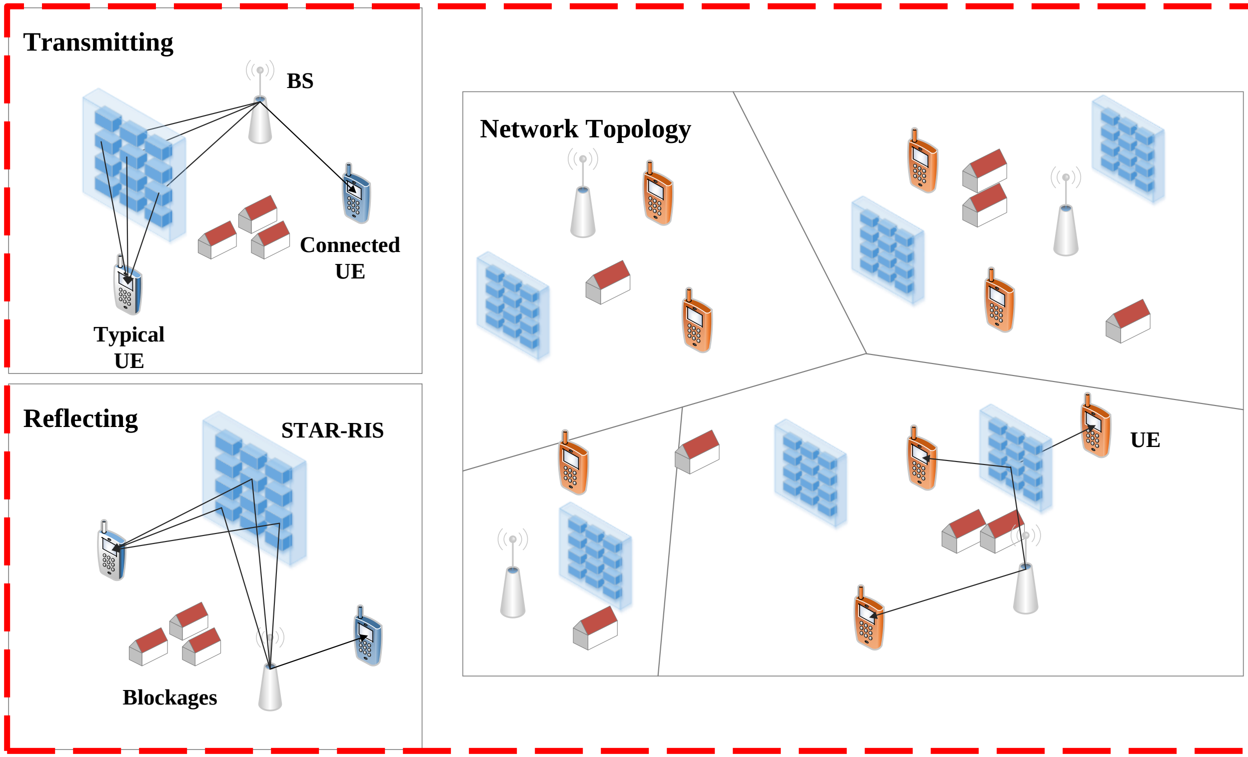


- A STAR-RIS-aided downlink NOMA network
- Deployment: 1) a fixed BS and a fixed RIS; 2) randomly deployed users in a circle area.

- 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

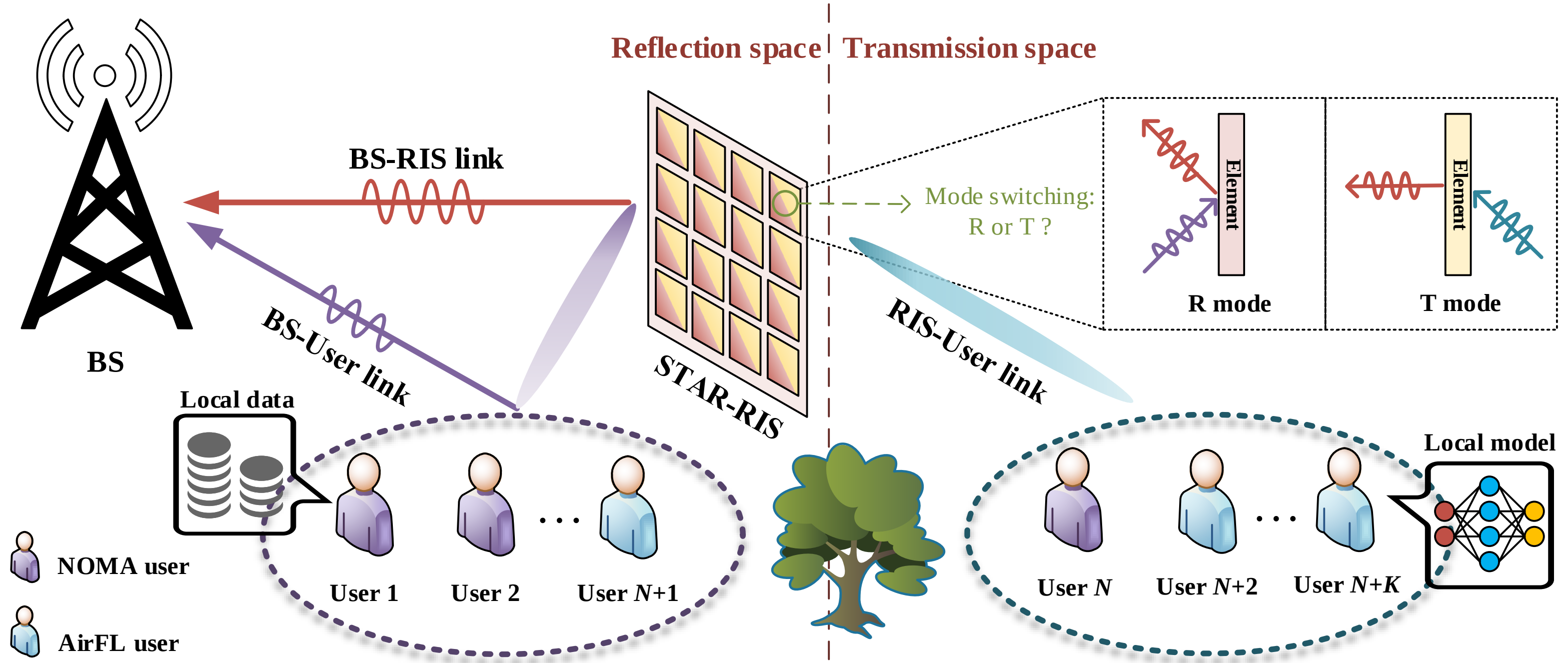


- STAR-RIS aided downlink NOMA multi-cell networks
- Energy splitting (ES) protocol
- STAR-RIS with N elements

- 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.

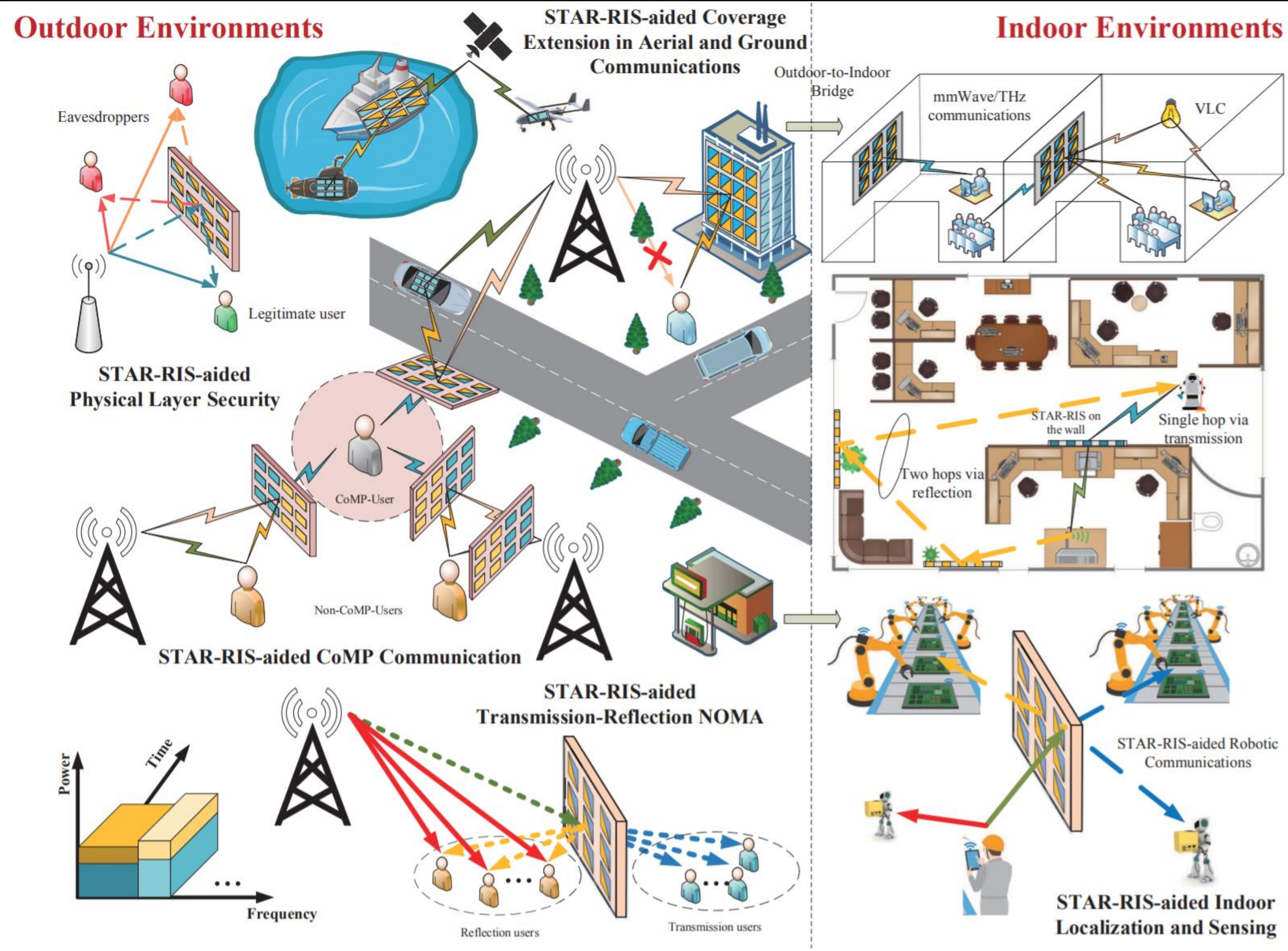
Integrating NOMA and AirFL via STAR-RIS



- 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



[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 Tutorials***, 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", ***IEEE Transactions on Wireless Communications***, accept to appear, 2021. [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 JSAC*** , 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 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