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User-Side RIS: Realizing Large-Scale Array at User Side

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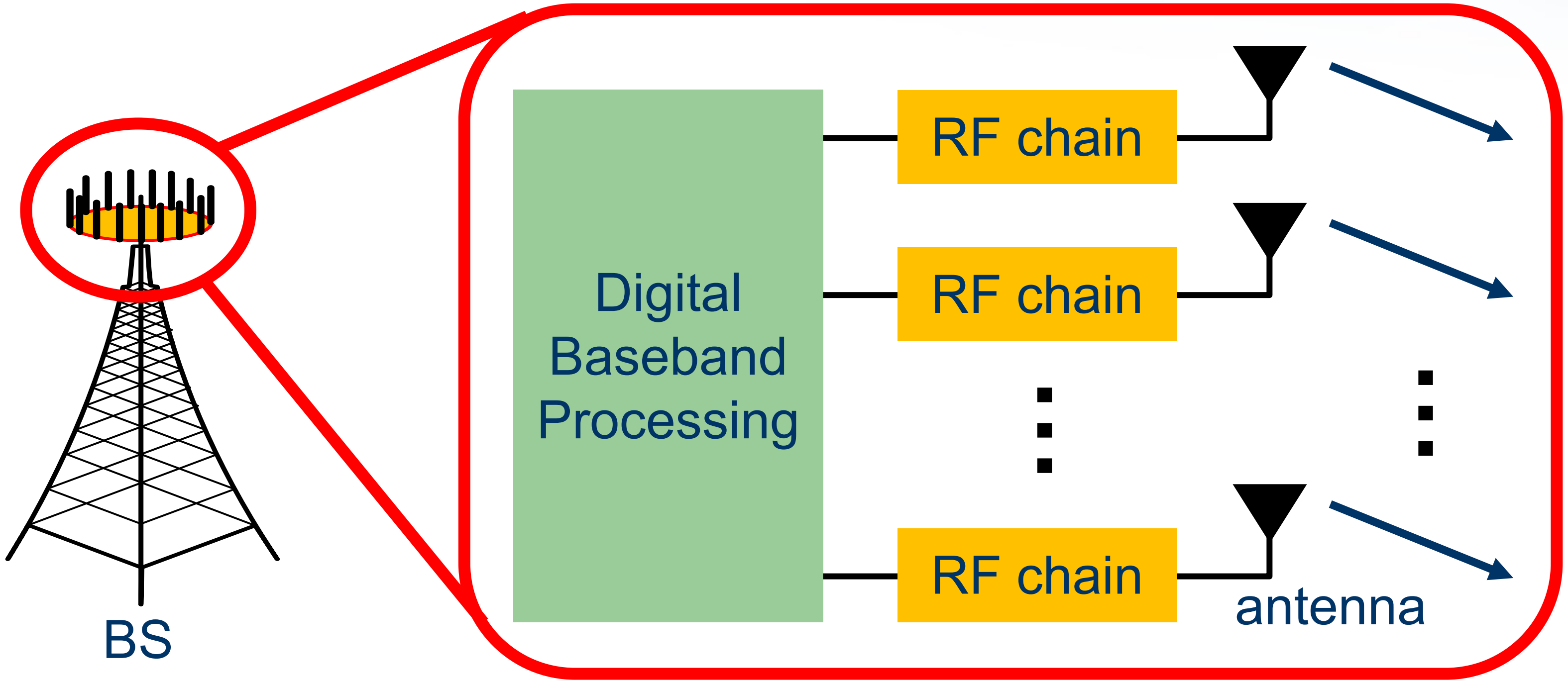
Outline

Massive MIMO

- **Massive MIMO: Deploying large-scale antenna array at the BS side for low-power communications**
- **By serving users with precoding and combining operations, orders of magnitude increase in the spectral efficiency can be achieved**

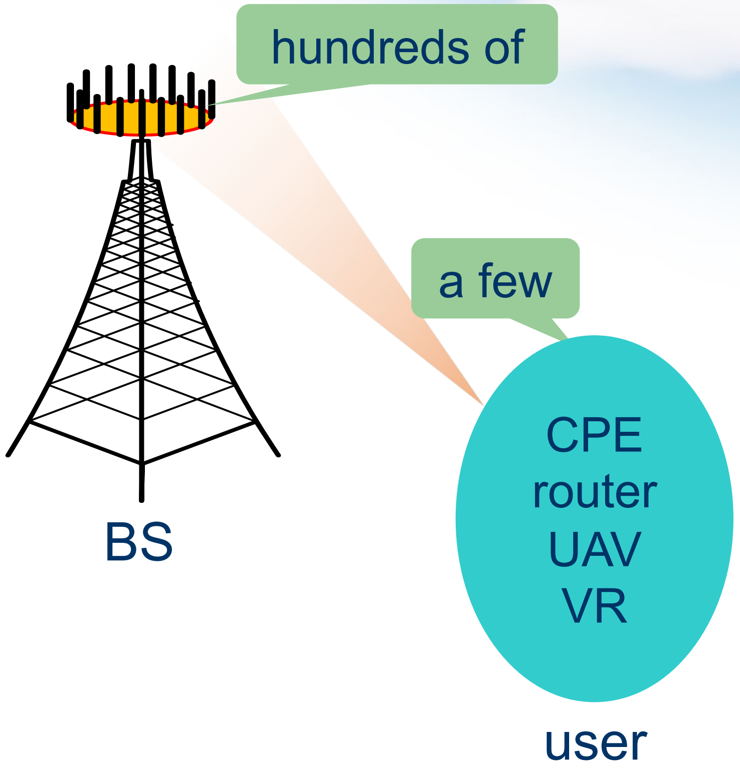


Massive MIMO

Q: Can user employ a large-scale array?

Pros

1. Save the power consumption for users, and prolong the stand-by time.
2. Enhance the wireless coverage, and enable the communications in the basement.



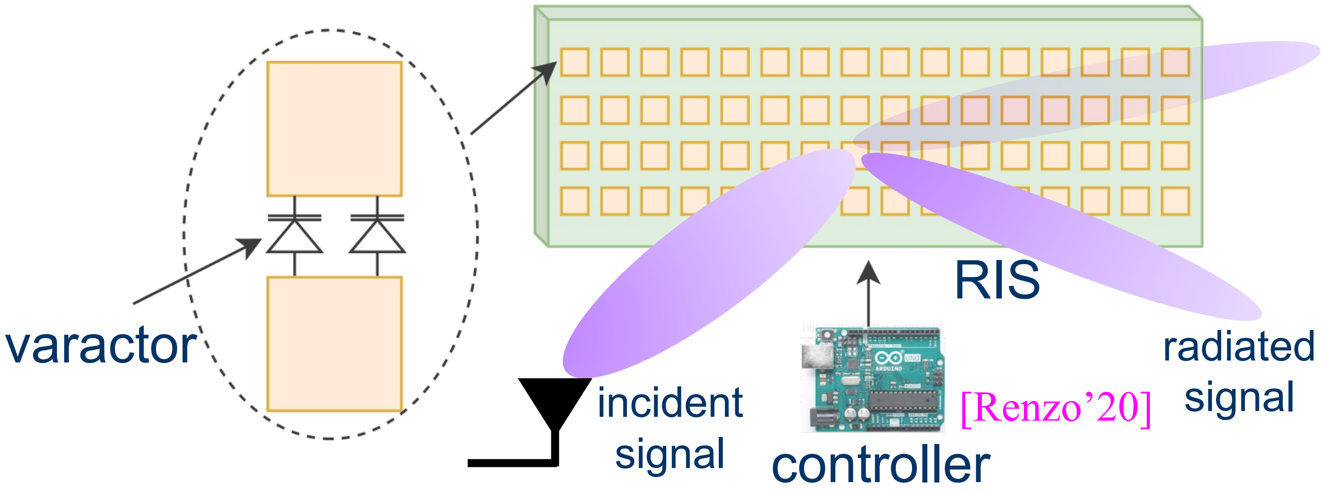
Cons

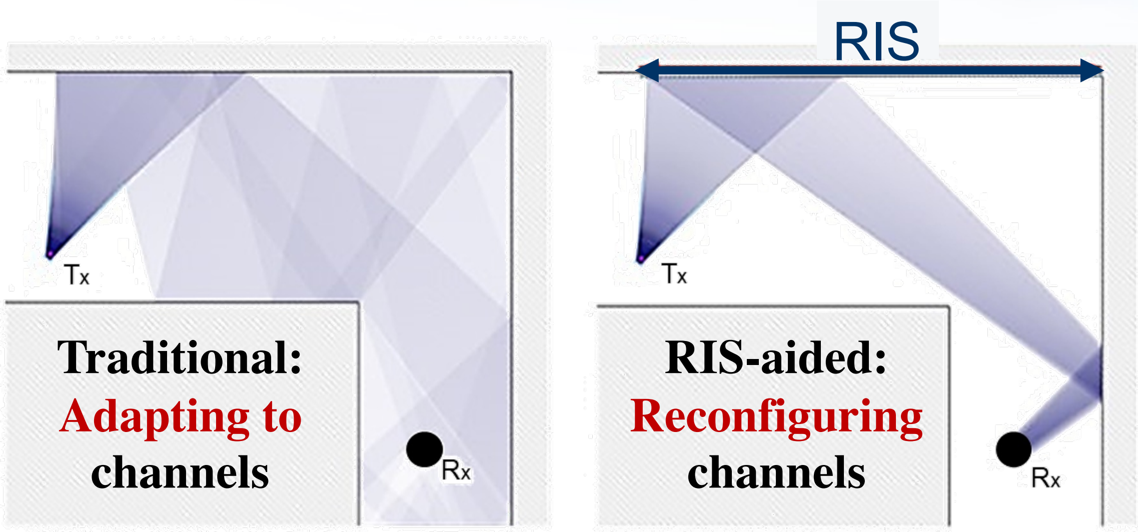
1. Every antenna has a dedicated high-cost RF chain.
2. Mismatch of the large-scale array and the user in dimensions.

It is almost impossible to employ a large-scale array at the user side.

RIS (Reconfigurable Intelligent Surfaces)

- A **large-scale array** composed of **passive** controllable meta-materials
- **Cost- and energy-efficient**, do not introduce additive noise
- Control the phase of the **reflected/penetrated** signal, and thus improve the environment of communications





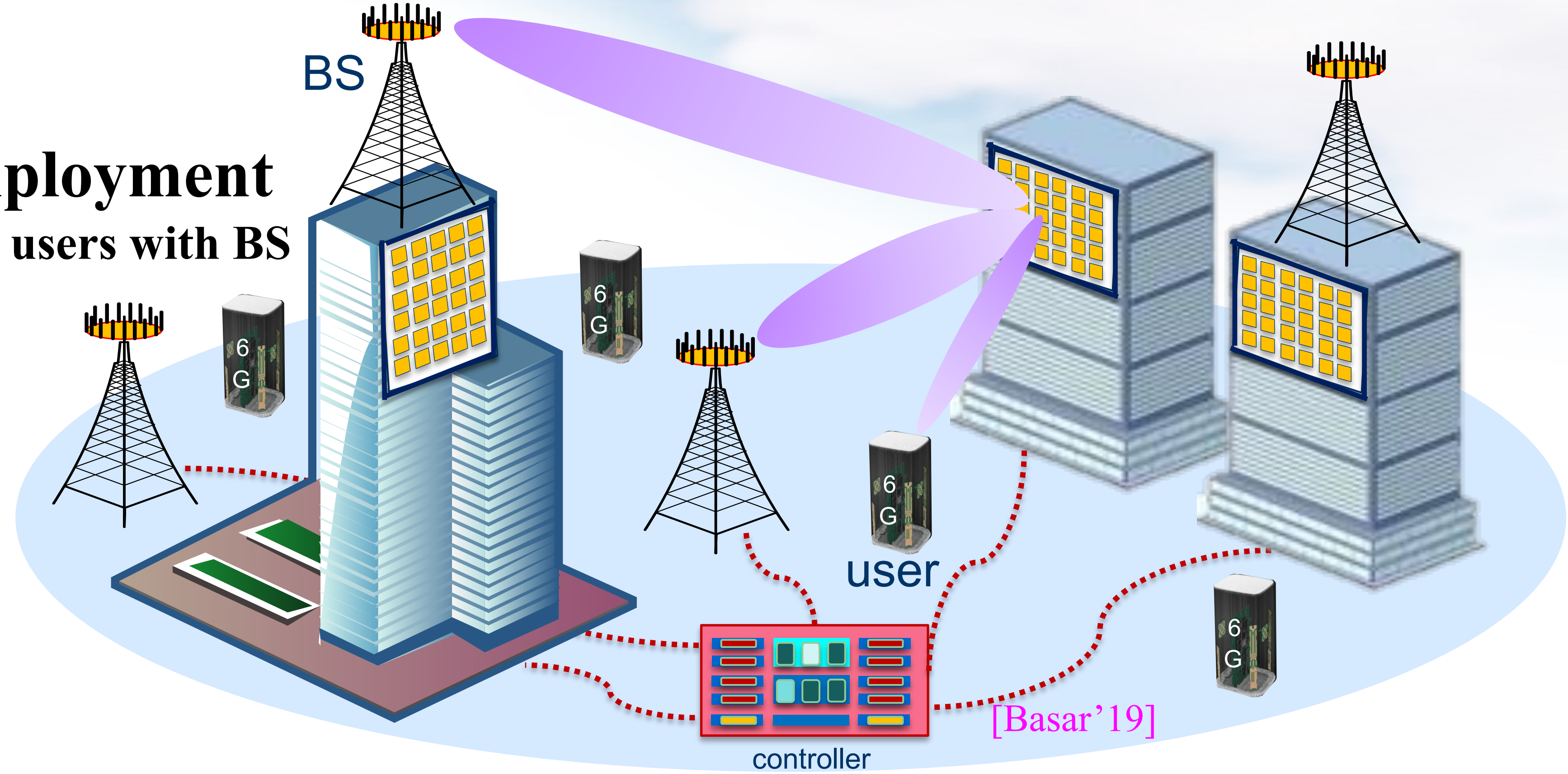
[Zhao'19]

[Renzo'20] M. Di Renzo *et al.*, "RIS vs. Relaying: Differences, Similarities, and Performance Comparison," *IEEE Open J. Commun. Society*, vol. 1, pp. 798-807, Jun. 2020.
[Zhao'19] J. Zhao and Y. Liu, "A Survey of Intelligent Reflecting Surfaces (IRSs): Towards 6G Wireless Communication Networks," *arXiv preprint arXiv:1905.00152*, Jun. 2019.

RIS-aided communications

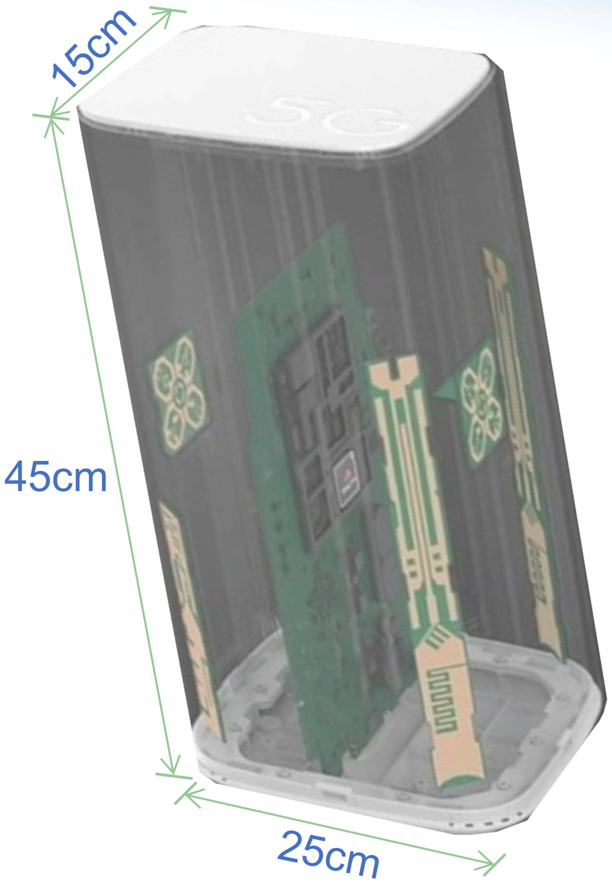
Relay-like employment

Cooperatively serve users with BS

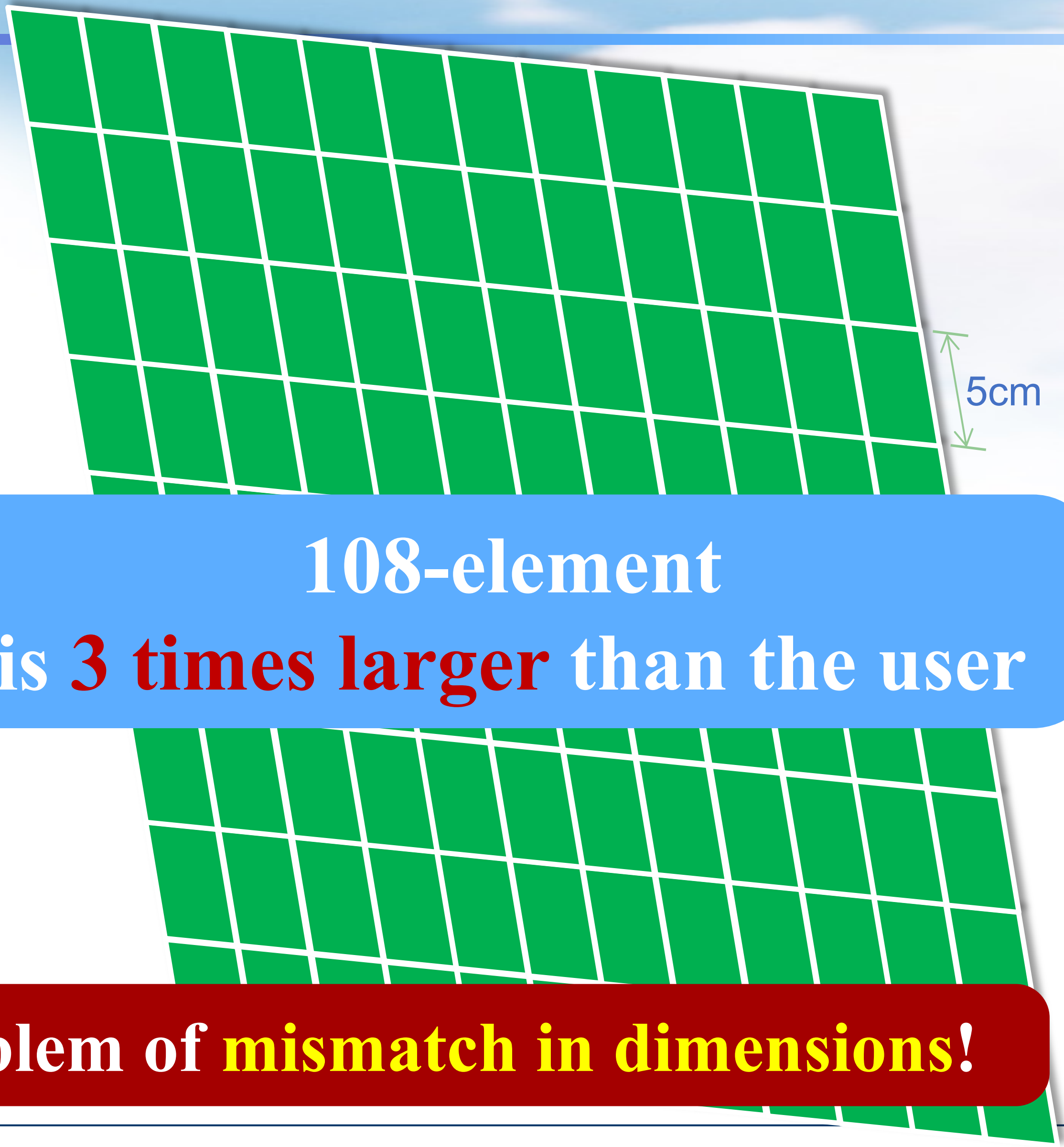


[Basar'19] E. Basar *et al.*, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116753-116773, Jul. 2019.

Can we employ RIS at the user side?



CPE (Customer-Premises Equipment)

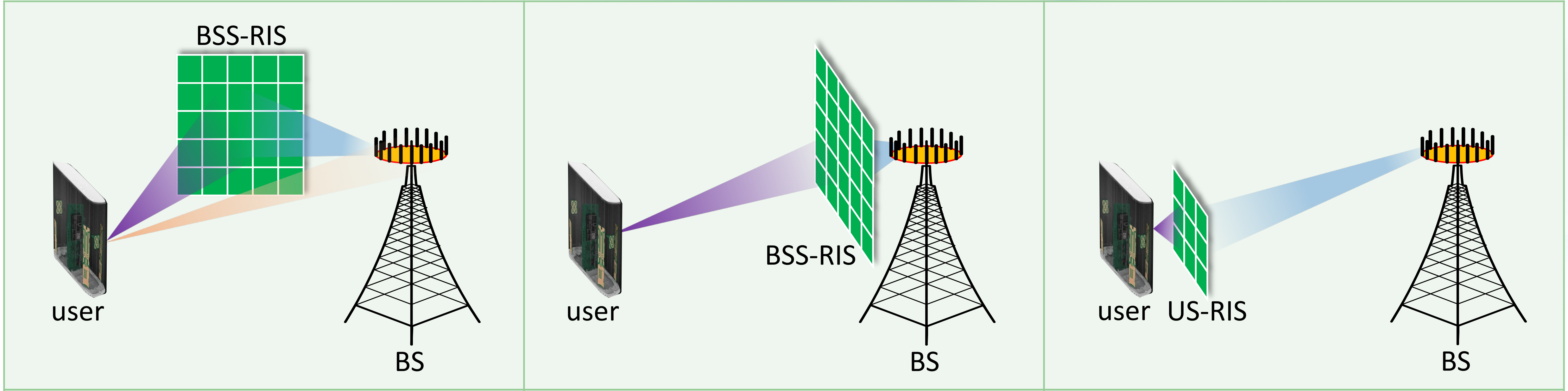


108-element
is 3 times larger than the user

Still cannot solve the problem of mismatch in dimensions!

Outline

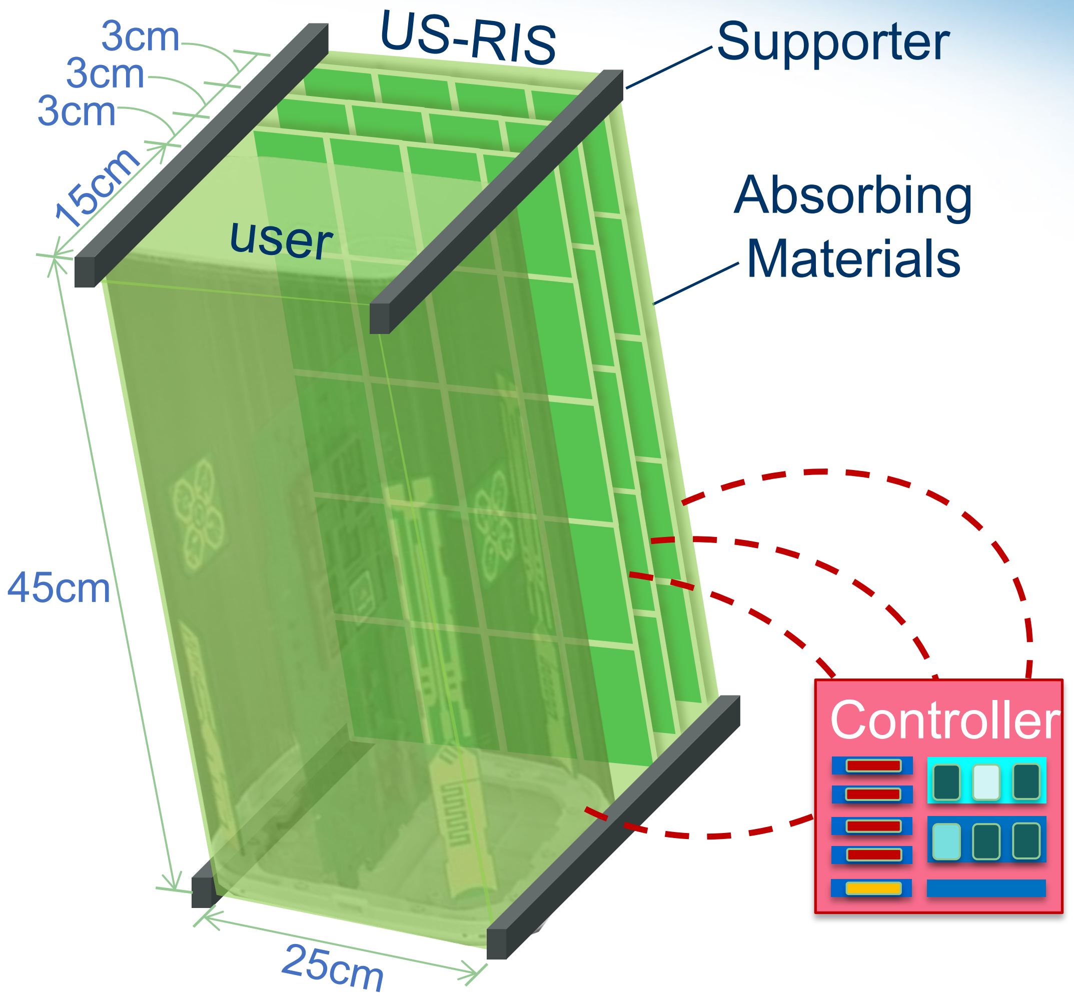
From Base-Station-Side to User-Side



RIS between the BS and the user (Relay-like RIS)	RIS close to the BS	RIS close to the user
Base-Station-Side RIS (BSS-RIS)		User-Side RIS (US-RIS)

User-side RIS employs RIS at the user side for the first time

User-Side RIS: Architecture

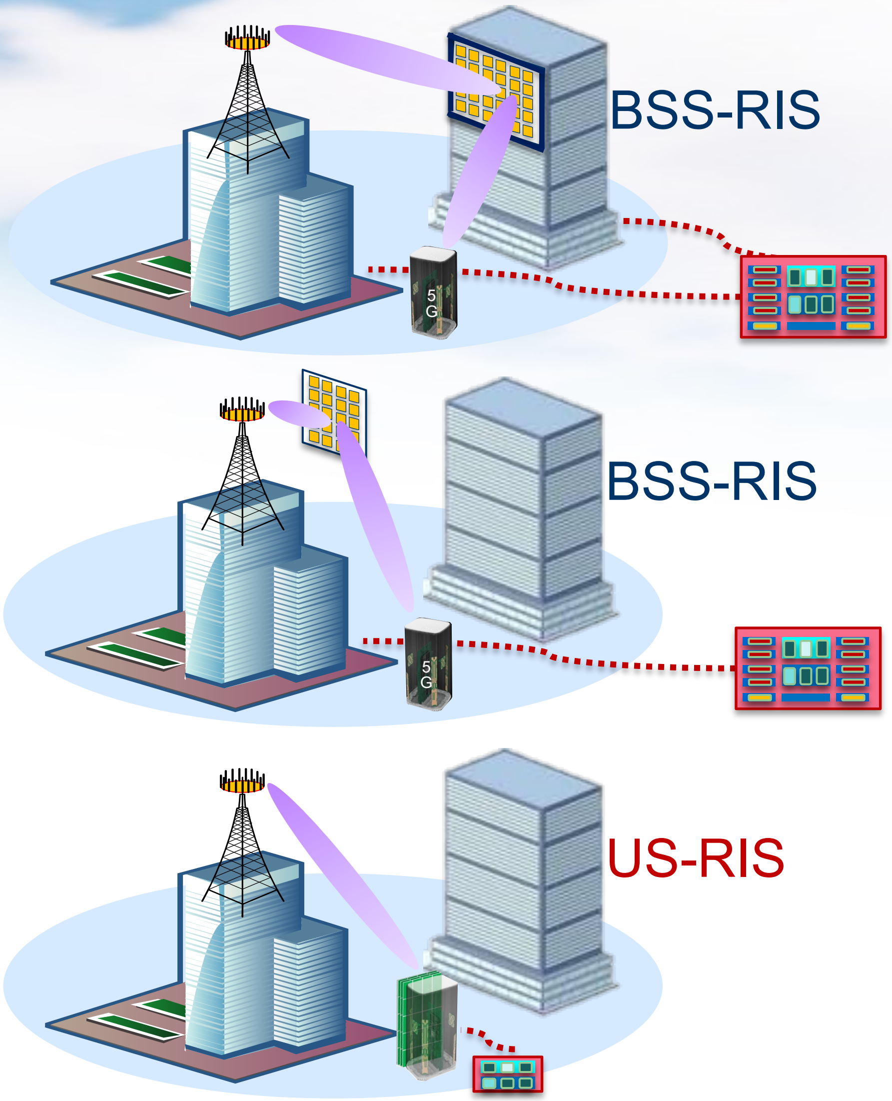


User architecture based on US-RIS

Cons
1. **Every antenna has a dedicated high-cost RF chain.** ✓ 2. **Mismatch of the large-scale array and the user in dimensions.** ✓

Comparisons

	BSS-RIS	US-RIS
Controller	one/multi BS(s)	one user
Beneficiary	one/multi user(s)	one user
Mode	mainly reflective	transmissive
Structure	single-layer	single/multi-layer
Size	very large	small

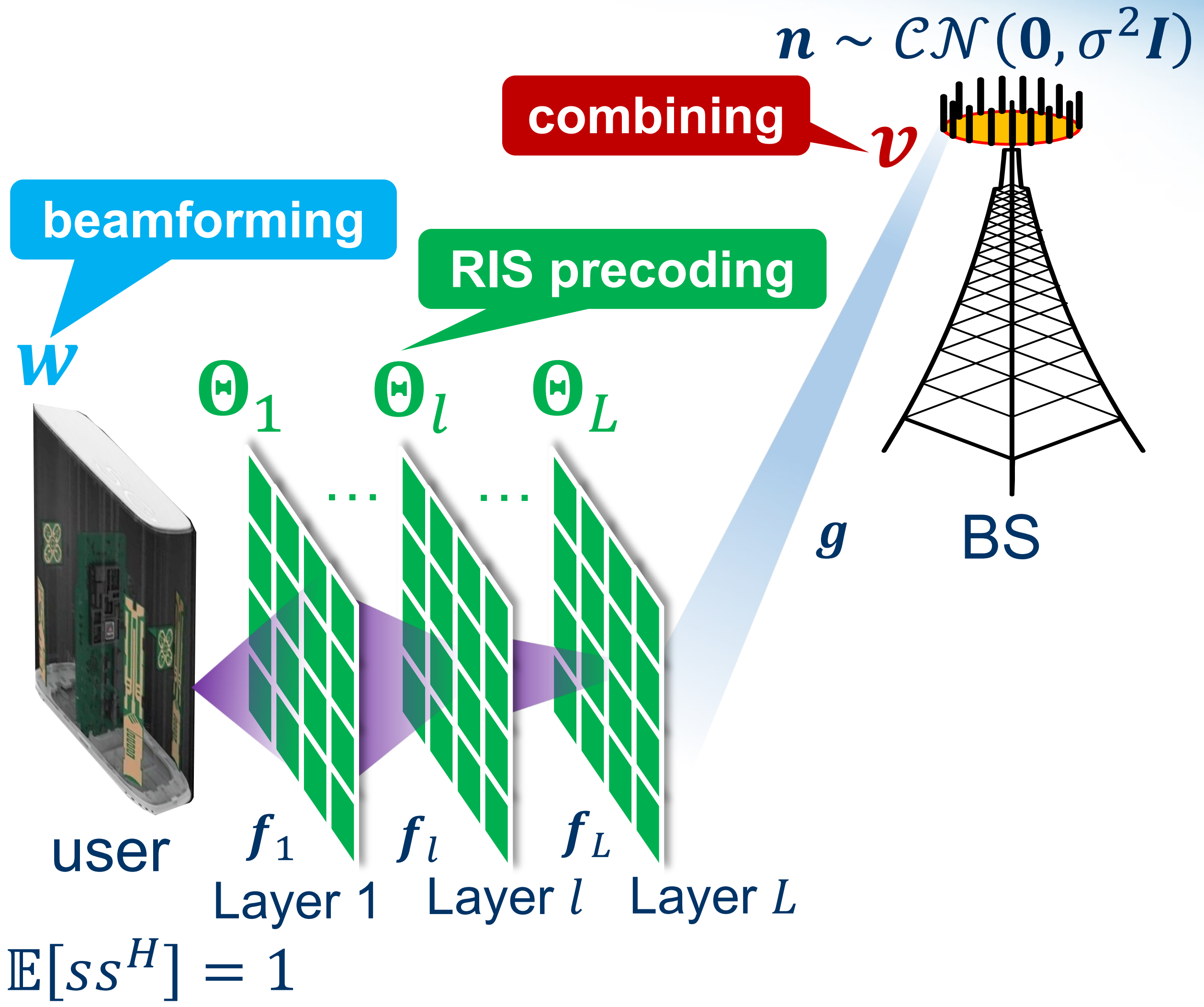


US-RIS is essentially different from BSS-RIS

Outline

- Introduction
- Concept & Architecture
- **System model & Precoding design**
- Simulation results

System Model & Problem Formulation



$$\boldsymbol{y} = \boldsymbol{g}^{\mathrm{H}} \left(\prod_{l=L}^{1} \kappa \boldsymbol{\Theta}_l \boldsymbol{f}_l \right) \boldsymbol{w} s + \boldsymbol{n}$$

$$z = \boldsymbol{v}^{\mathrm{H}} \boldsymbol{g}^{\mathrm{H}} \left(\prod_{l=L}^{1} \kappa \boldsymbol{\Theta}_l \boldsymbol{f}_l \right) \boldsymbol{w} s + \boldsymbol{v}^{\mathrm{H}} \boldsymbol{n}$$

SNR Maximization

$$\max_{\boldsymbol{w}, \boldsymbol{\Theta}_1, \ldots, \boldsymbol{\Theta}_L, \boldsymbol{v}} \quad \mathrm{SNR} = \frac{\left| \boldsymbol{v}^{\mathrm{H}} \boldsymbol{g}^{\mathrm{H}} \left(\prod_{l=L}^{1} \kappa \boldsymbol{\Theta}_l \boldsymbol{f}_l \right) \boldsymbol{w} \right|^2}{\| \boldsymbol{v}^{\mathrm{H}} \|_2^2 \sigma^2}$$

$$\text{s.t.} \quad \| \boldsymbol{w} \|_2^2 \leq P_{\max}$$

$$\left| \theta_{l,n} \right| = 1, \forall l, n$$

Precoding Design

$$\max_{\boldsymbol{v},\boldsymbol{\Theta}_1,\cdots,\boldsymbol{\Theta}_L,\boldsymbol{w}} \ \mathrm{SNR} = \frac{\left|\boldsymbol{v}^H \boldsymbol{g}^H \left(\prod_{l=L}^{1} \kappa \boldsymbol{\Theta}_l \boldsymbol{f}_l\right) \boldsymbol{w}\right|^2}{\|\boldsymbol{v}^H\|_2^2 \sigma^2}$$

$$\text{s.t.} \quad \mathrm{C}_1: \ \|\boldsymbol{w}\|_2^2 \leq P_{\max}$$

$$\mathrm{C}_2: \ |\theta_{l,n}| = 1, \ \forall l, n$$

(9) $$\boldsymbol{v}^{\mathrm{opt}} = \psi_{\max}\left(\boldsymbol{g}^H \boldsymbol{\xi}_{(L,1)} \boldsymbol{w}\boldsymbol{w}^H \boldsymbol{\xi}_{(L,1)}^H \boldsymbol{g}\right).$$

(12) $$\boldsymbol{\theta}_l^{\mathrm{opt}} = \exp\left(j\arg\left(\mathrm{diag}\left(\boldsymbol{f}_l \boldsymbol{\xi}_{(l-1,1)} \boldsymbol{w}\right)^H \boldsymbol{\xi}_{(L,l+1)}^H \boldsymbol{g}\boldsymbol{v}\right)\right).$$

(15) $$\boldsymbol{w}^{\mathrm{opt}} = \sqrt{P_{\max}} \langle \boldsymbol{w} \rangle^{\mathrm{opt}} = \sqrt{P_{\max}} \left\langle \boldsymbol{\xi}_{(L,1)}^H \boldsymbol{g}\boldsymbol{v}\right\rangle.$$

Algorithm 1 Multi-layer Precoding Design for US-RIS-Aided Communications

Input: Channel matrices $\boldsymbol{f}_1, \cdots, \boldsymbol{f}_L$, and $\boldsymbol{g}$; maximum transmit power $P_{\max}$; noise power σ^2; loss factor κ.

Output: Optimized combining vector $\boldsymbol{v}$; optimized US-RIS precoding matrix $\boldsymbol{\Theta}_1, \cdots, \boldsymbol{\Theta}_L$; optimized beamforming vector $\boldsymbol{w}$; maximized SNR.

1: Initialize $\boldsymbol{v}$, $\boldsymbol{\Theta}_1, \cdots, \boldsymbol{\Theta}_L$, and $\boldsymbol{w}$;
2: **while** no convergence of SNR **do**
3: Update $\boldsymbol{v}^{\mathrm{opt}}$ by (9);
4: Update $\boldsymbol{\Theta}_1^{\mathrm{opt}}, \cdots, \boldsymbol{\Theta}_L^{\mathrm{opt}}$ in term by (12);
5: Update $\boldsymbol{w}^{\mathrm{opt}}$ by (15);
6: Update SNR by (5);
7: **end while**
8: **return** $\boldsymbol{v}$, $\boldsymbol{\Theta}_1, \cdots, \boldsymbol{\Theta}_L$, $\boldsymbol{w}$, and SNR.

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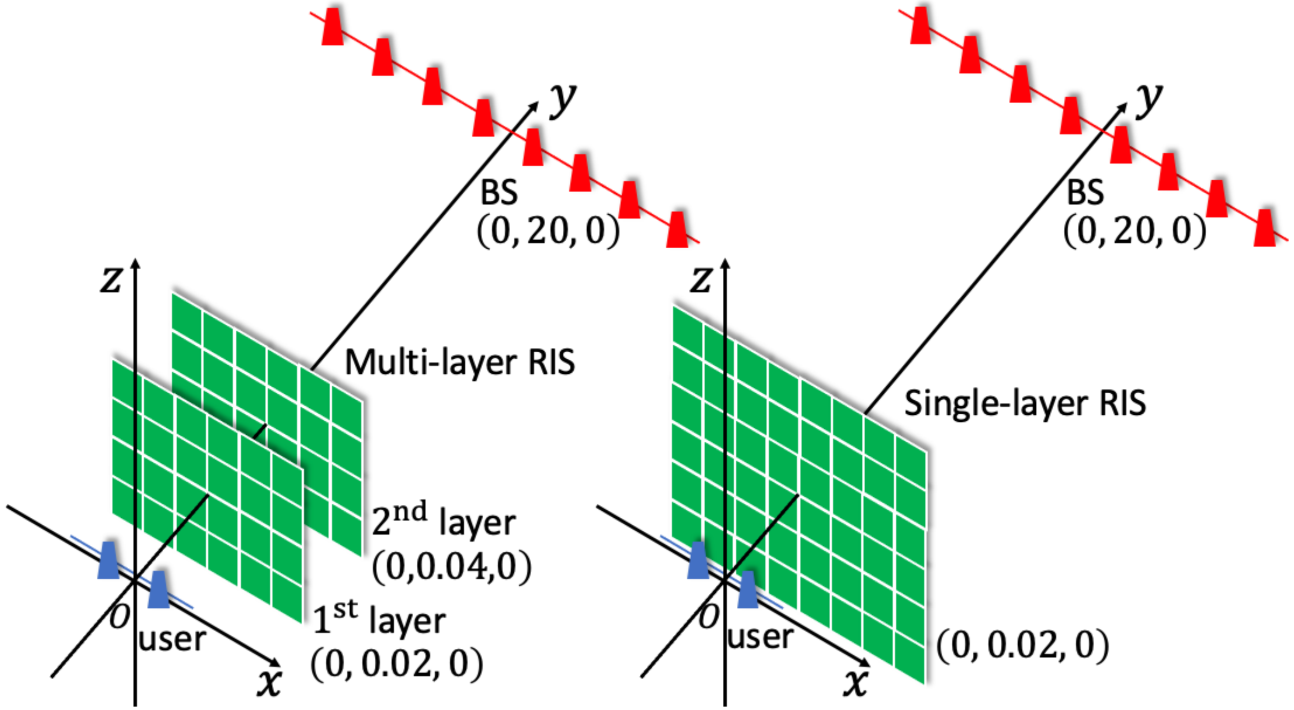
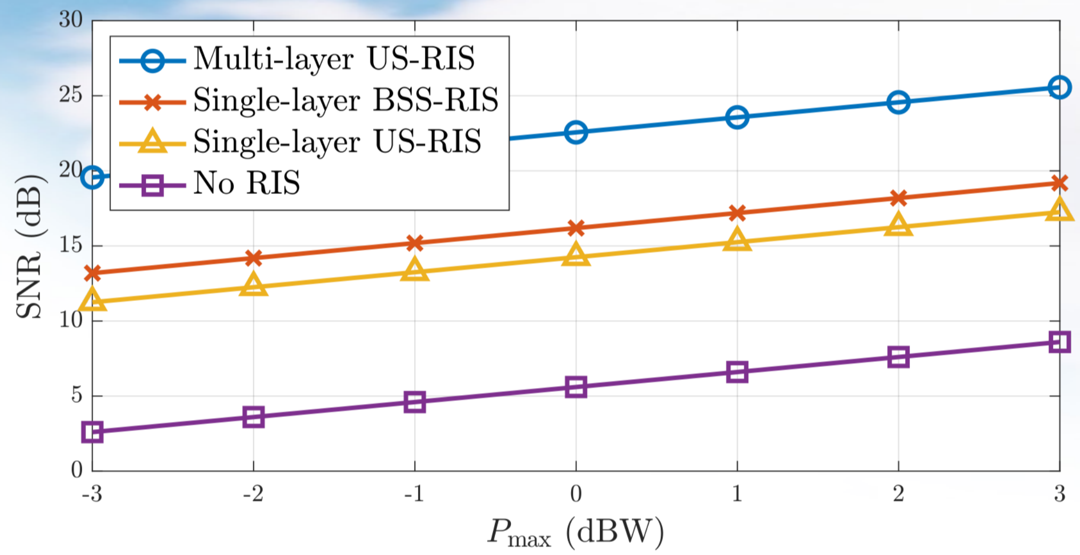
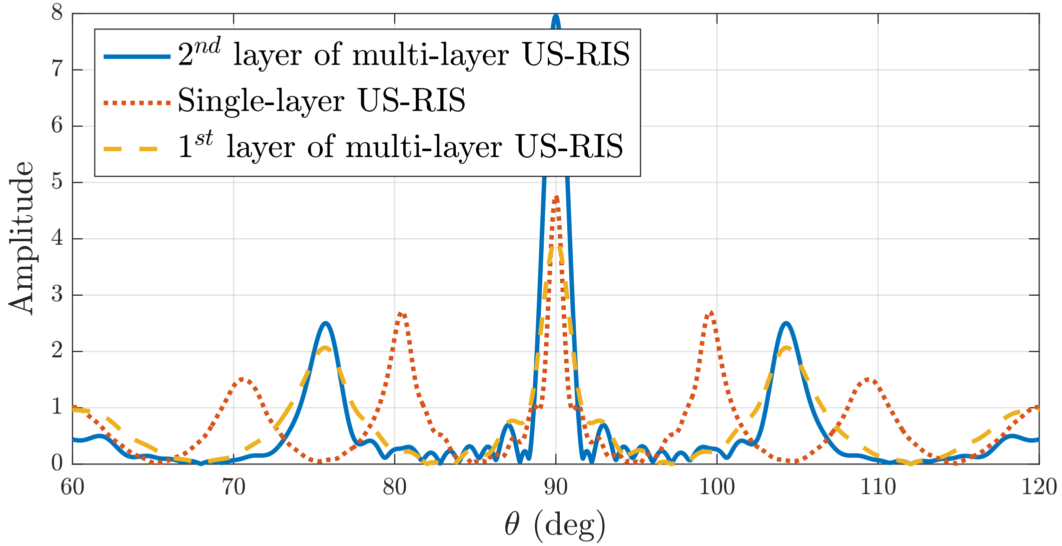
Simulation Results







Wrap Up

- **Concept**
  - **BSS-RIS: Relay-like RIS or RIS employed close to the BS**
  - **US-RIS: A component of the novel user architecture**
- **Precoding Design**
  - **A user-BS communication with the aid of a multi-layer US-RIS**
  - **Non-convex problem with iterative optimization**
- **Simulation Results**
  - **Higher decoding SNR by multi-layer RIS**
  - **Higher mainlobe and lower sidelobes by multi-layer RIS**

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