Active RISs: Signal Modeling, Asymptotic Analysis, and Beamforming Design

Zijian Zhang, Linglong Dai, Xibi Chen, Changhao Liu,

Fan Yang, Robert Schober, and H. Vincent Poor

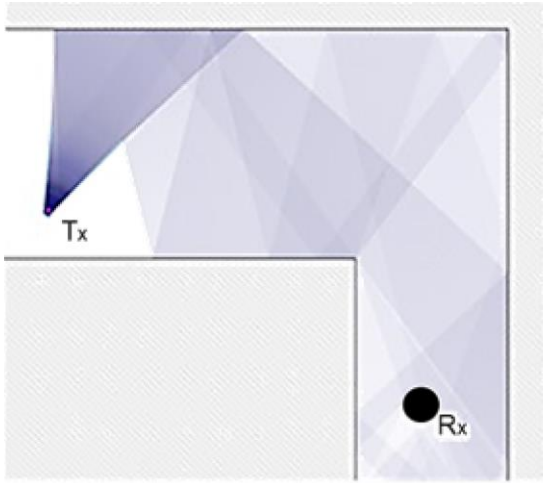
5th December, 2022

Outline

- Basics of RIS
- Existing passive RIS
- Proposed active RIS
- Conclusions

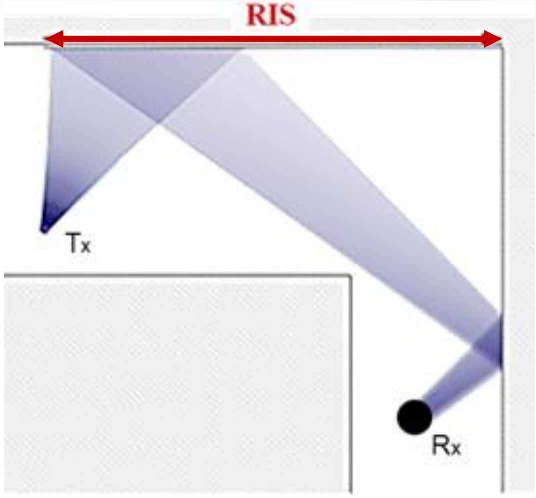
What is Reconfigurable Intelligent Surface (RIS)?

- A surface of reconfigurable **metamaterials**
- **Control** the propagation of electromagnetic wave
- **Manipulate** the channel to improve the signal quality



Traditional wireless communications:
Heavily rely on the environment

RIS →



RIS-aided wireless communications:
Control the environment

Promising technology for future 6G communications

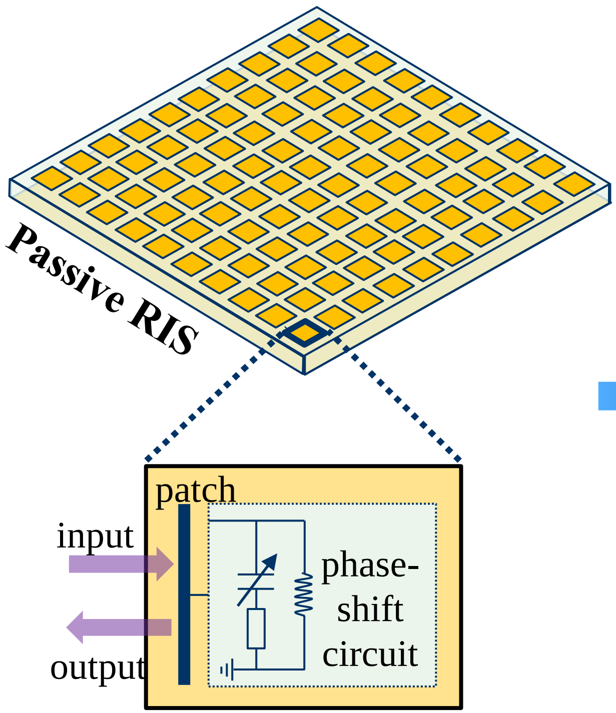
E. Basar, M. Di Renzo, J. De Rosny, M. Debbah, M. Alouini, and R. Zhang, "Wireless communications through reconfigurable intelligent surfaces," *IEEE Access*, vol. 7, pp. 116753-116773, Jul. 2019.

Outline

- Basics of RIS
- Existing passive RIS
- Proposed active RIS
- Conclusions

Realization of the existing passive RIS

- **RIS consisting of a large number of passive elements**
- **Negligible thermal noise, low cost, low power consumption**



Passive element

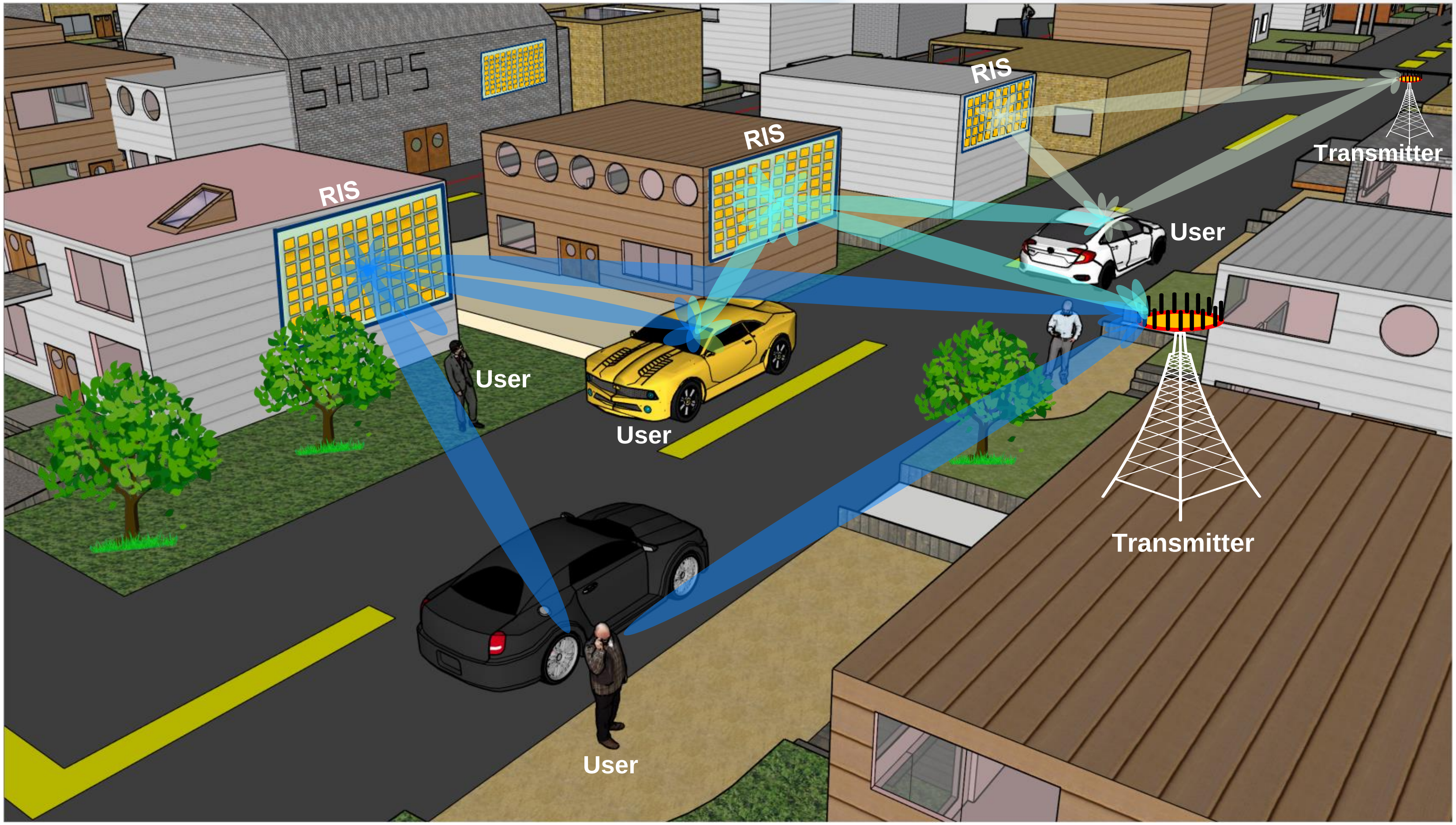
RIS-aided commutations@2.3 GHz

RIS-aided commutations@28 GHz

L. Dai, B. Wang, M. Wang, X. Yang, J. Tan, S. Bi, S. Xu, F. Yang, Z. Chen, M. D. Renzo, C.-B. Chae, and L. Hanzo, "Reconfigurable intelligent surface-based wireless communication: Antenna design, prototyping and experimental results," *IEEE Access*, vol. 8, pp. 45913-45923, Mar. 2020. (**IEEE Access Best Multimedia Award 2020**)

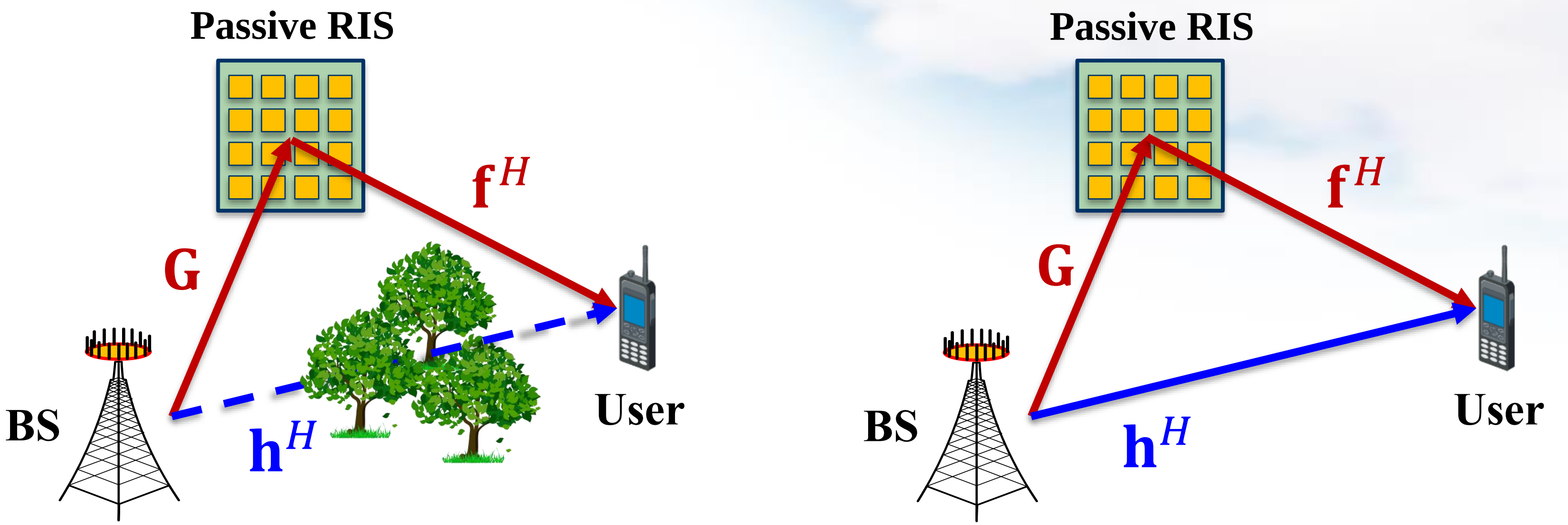
Applications of the existing passive RIS

- **An example: passive beamforming for capacity improvement**



Fundamental limit: "Multiplicative fading" effect

- **The RIS-aided reflection link suffers large-scale fading twice**



(a) Atypical scenario   (b) Typical scenario

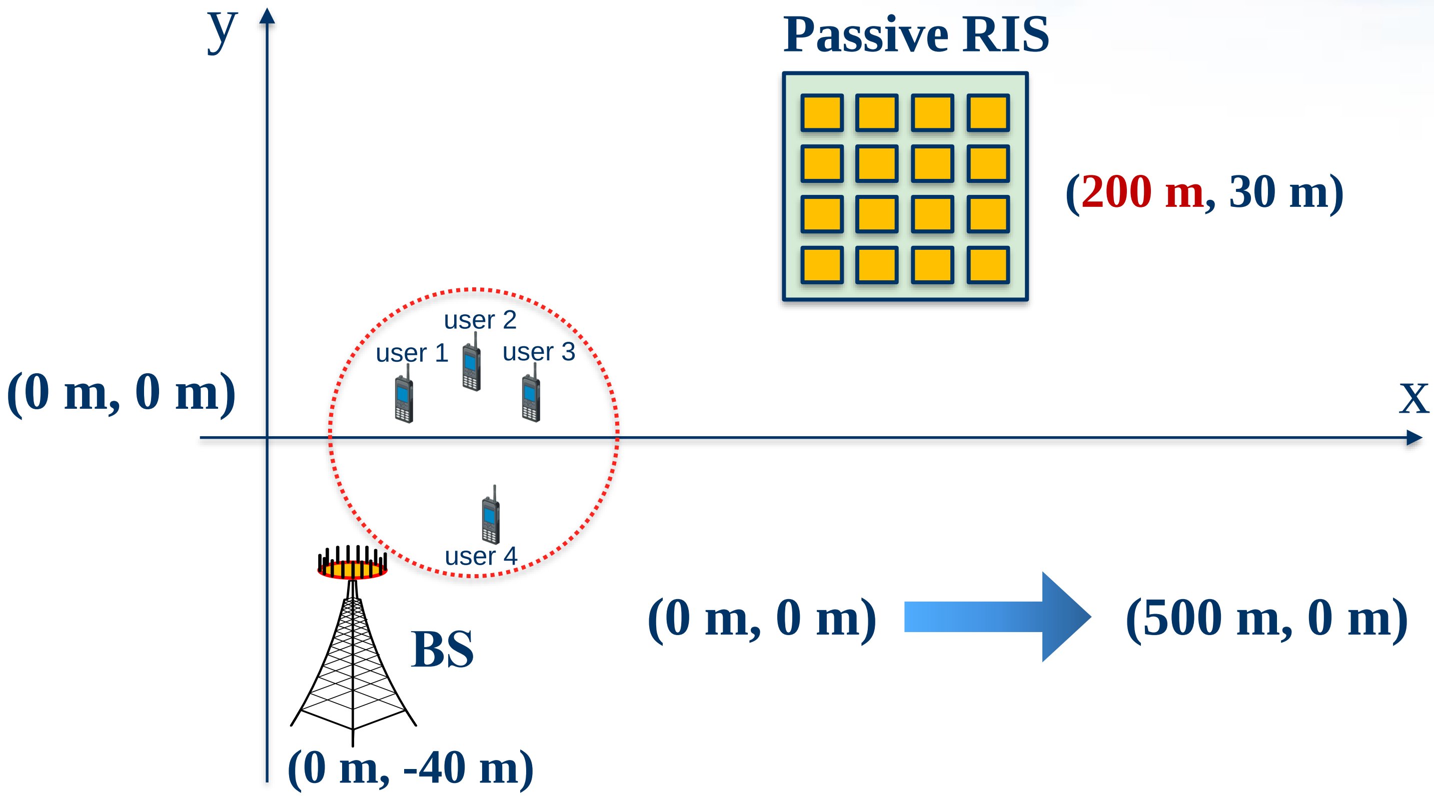
Signal model: $y = (\mathbf{h}^H + \boldsymbol{\theta}^H \mathrm{diag}(\mathbf{f}^H)\mathbf{G})\mathbf{w}s + z$

Product instead of summation

W. Tang, M. Chen, X. Chen, J. Dai, Y. Han, M. Di Renzo, Y. Zeng, S. Jin, Q. Cheng, and T. J. Cui, "Wireless communications with reconfigurable intelligent surface: Path loss modeling and experimental measurement," *IEEE Trans. Wireless Commun.*, vol. 20, no. 1, pp. 421-439, Jan. 2021.

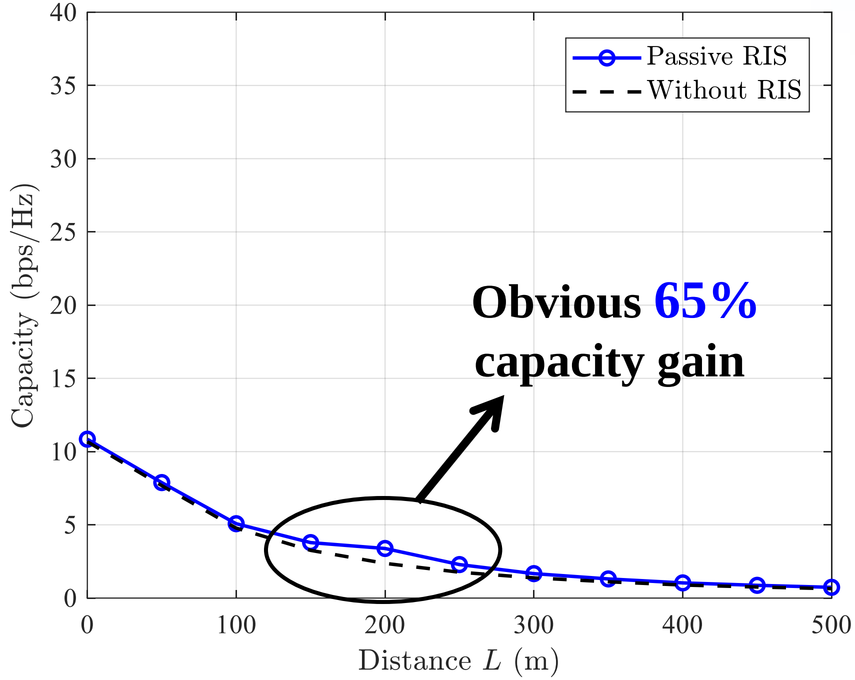
Example

- System parameters
  - BS (equipped with 4 antennas, transmit power 10 mW)
  - RIS (equipped with 256 elements)
  - 4 User (equipped with 1 antennas)

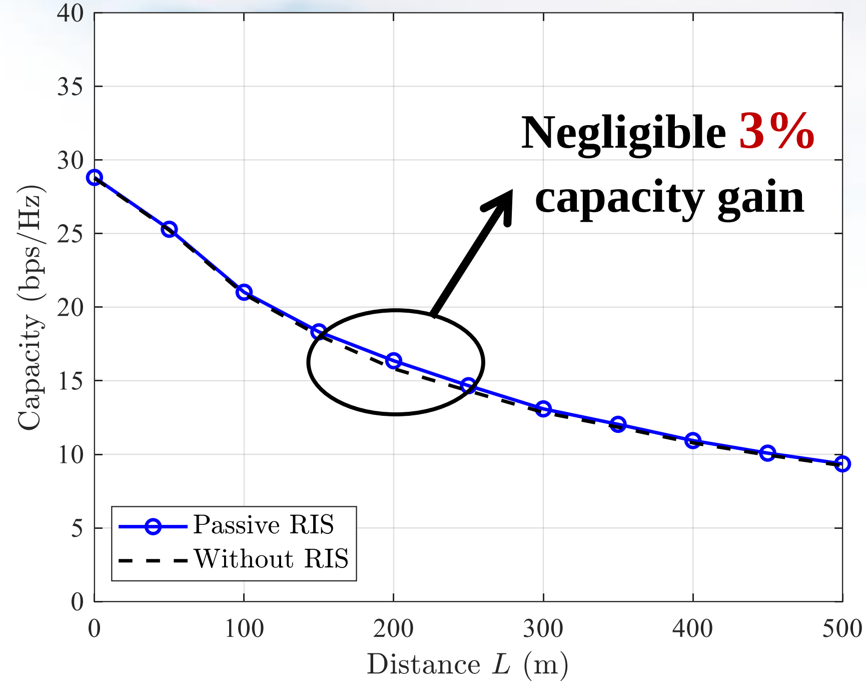


Example

- **Passive RIS can only achieve negligible capacity gain in typical communication scenarios**



(a) Atypical scenario



(b) Typical scenario

How to overcome the "multiplicative fading" effect

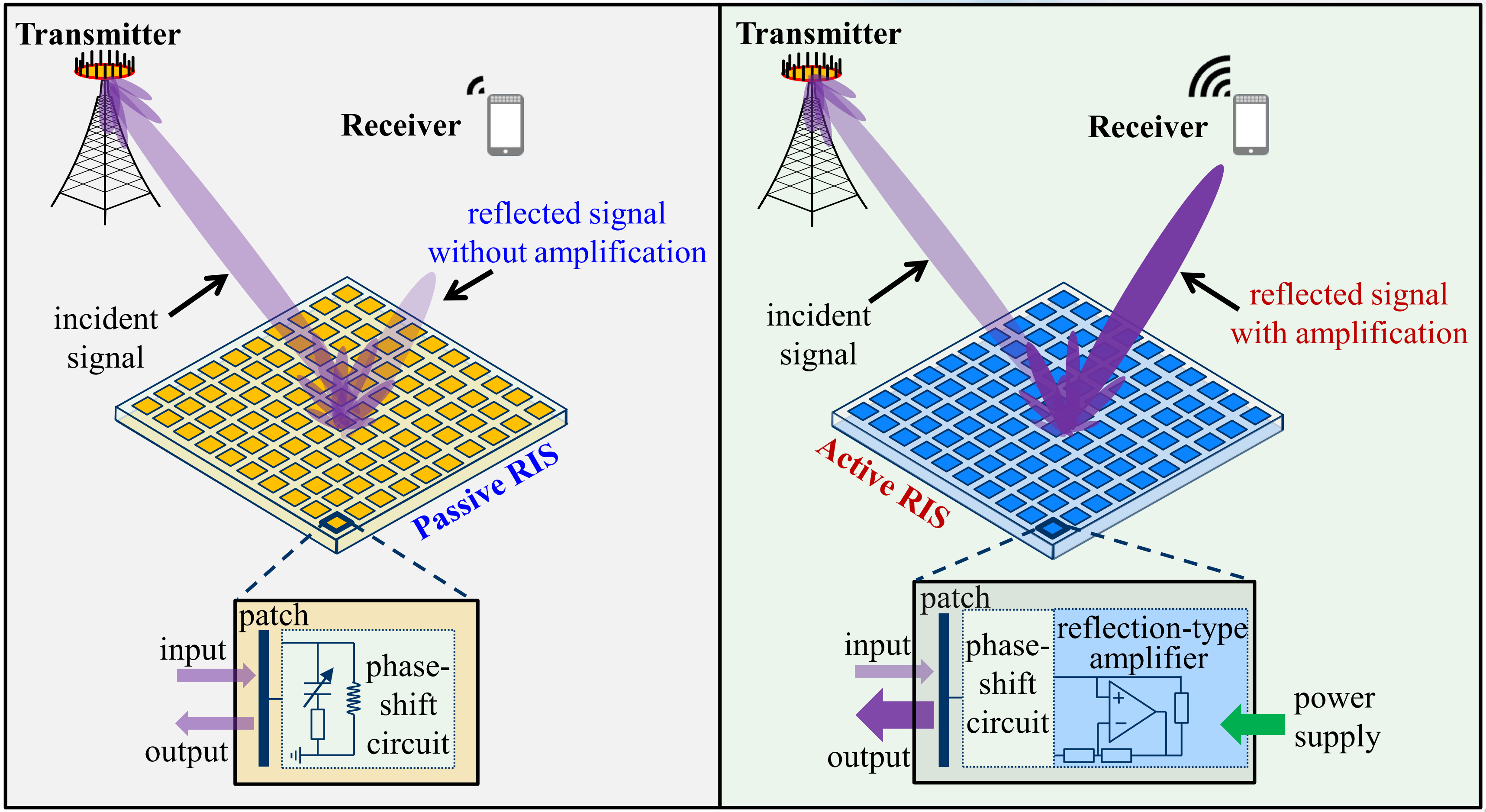
Z. Zhang, L. Dai, X. Chen, C. Liu, F. Yang, R. Schober, and H. V. Poor, "Active RISs: Signal modeling, asymptotic analysis, and beamforming design," in *Proc. 2022 IEEE Global Communications Conference (IEEE GLOBECOM'22)*, Rio de Janeiro, Brazil, Dec. 2022.

Outline

- Basics of RIS
- Existing passive RIS
- **Proposed active RIS**
- Conclusions

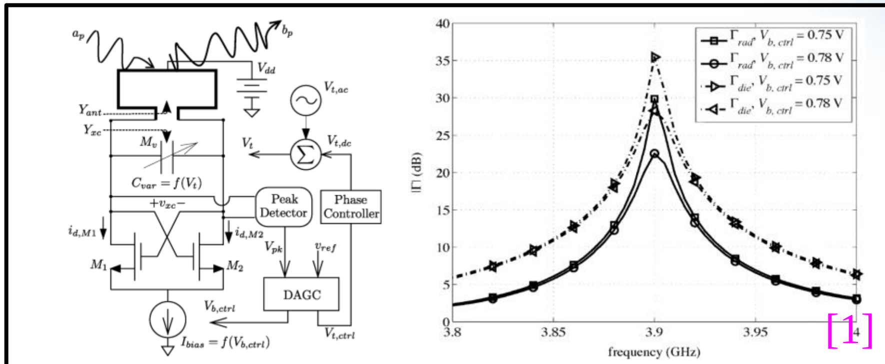
Concept of active RIS

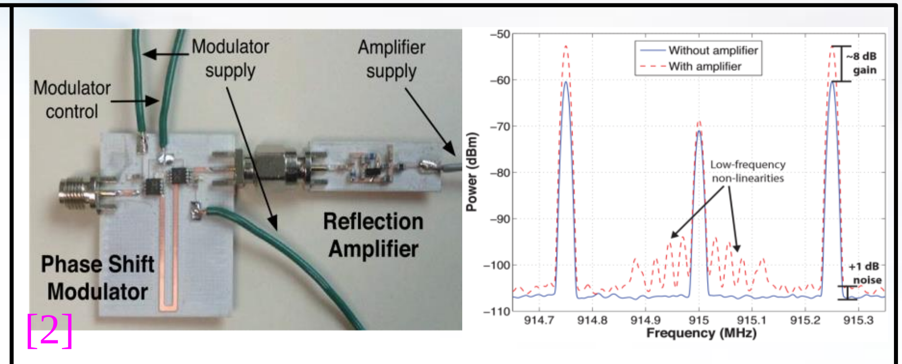
- **Passive RIS: Reflect signals directionally without amplification**
- **Active RIS: Amplify the reflected signals using power amplifiers**

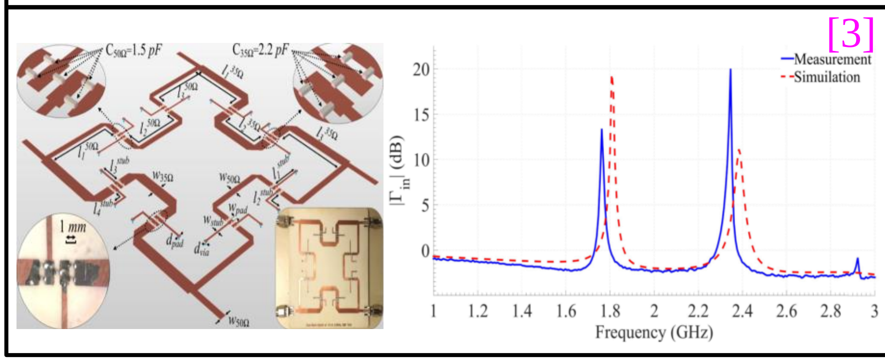


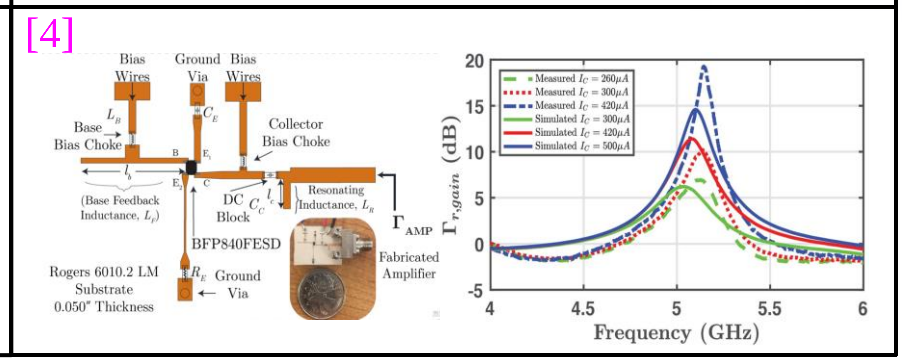
Realization of active RIS

- **Feasible realizations of active reflection-type power amplifier**









[1] J. Bousquet, S. Magierowski and G. G. Messier, "A 4-GHz active scatterer in 130-nm CMOS for phase sweep amplify-and-forward," *IEEE Trans. Circuits Sys. I*, vol. 59, no. 3, pp. 529-540, Mar. 2012.

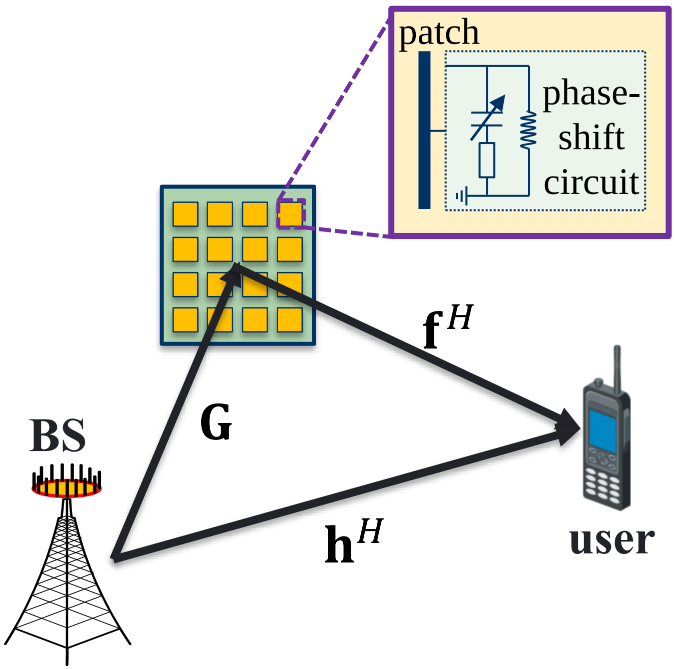
[2] J. Kimionis, A. Georgiadis, A. Collado and M. M. Tentzeris, "Enhancement of RF tag backscatter efficiency with low-power reflection amplifiers," *IEEE Trans. Micro. Theory Tech*., vol. 62, no. 12, pp. 3562-3571, Dec. 2014.

[3] F. Farzami, S. Khaledian, B. Smida and D. Erricolo, "Reconfigurable dual-band bidirectional reflection amplifier with applications in Van Atta array," IEEE Trans. Micro. Theory Tech., vol. 65, no. 11, pp. 4198-4207, Nov. 2017.

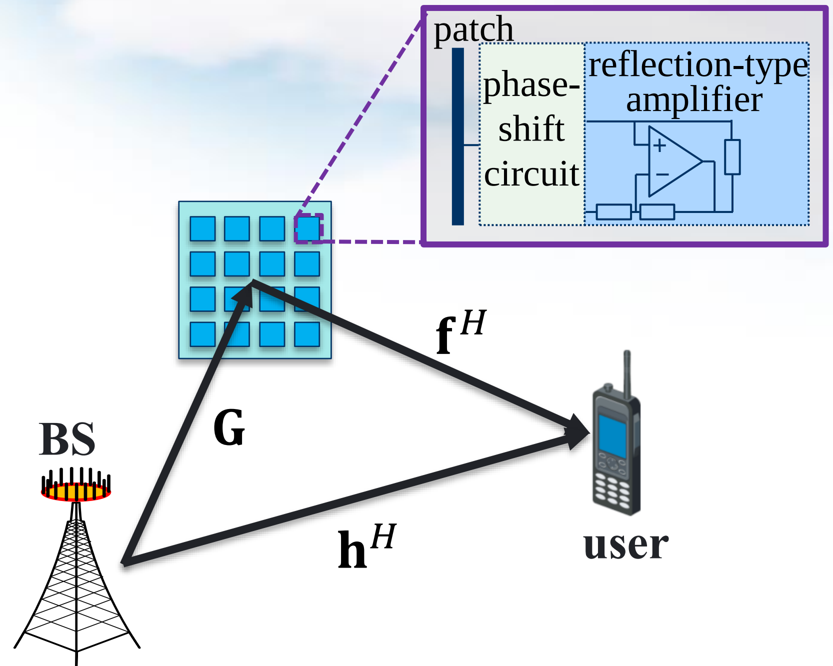
[4] P. Keshavarzian, M. Okoniewski and J. Nielsen, "Active phase-conjugating Rotman lens with reflection amplifiers for backscattering enhancement," *IEEE Trans. Micro. Theory Tech*., vol. 68, no. 1, pp. 405-413, Jan. 2020.

Signal model of active RIS

- **Different signal models of passive RIS and active RIS**



(a) Passive RIS



(b) Active RIS

$$y = (\mathbf{h}^H + \mathbf{f}^H \mathbf{\Theta}^H \mathbf{G})\mathbf{w}s + z$$

Phase shift matrix

$$y = (\mathbf{h}^H + \mathbf{f}^H \mathbf{P}\mathbf{\Theta}^H \mathbf{G})\mathbf{w}s + \mathbf{f}^H \mathbf{P}\mathbf{n} + z$$

Amplification matrix

Additional noise introduced by active components

Capacity maximization of active RIS aided MIMO

- **Three variables: BS precoding vector $\mathbf{w}$, phase shift matrix $\boldsymbol{\Theta}$, and amplification matrix $\mathbf{P}$ of active RIS**

$$\max_{\mathbf{w},\boldsymbol{\Theta},\mathbf{P}} \quad R_{\text{sum}} = \sum_{k=1}^{K} \log_2(1+\gamma_k)$$

SINR of user k

$$\text{subject to} \quad \sum_{k=1}^{K} \|\mathbf{w}_k\|^2 \le P_{\text{BS}}^{\max}$$

BS power constraint

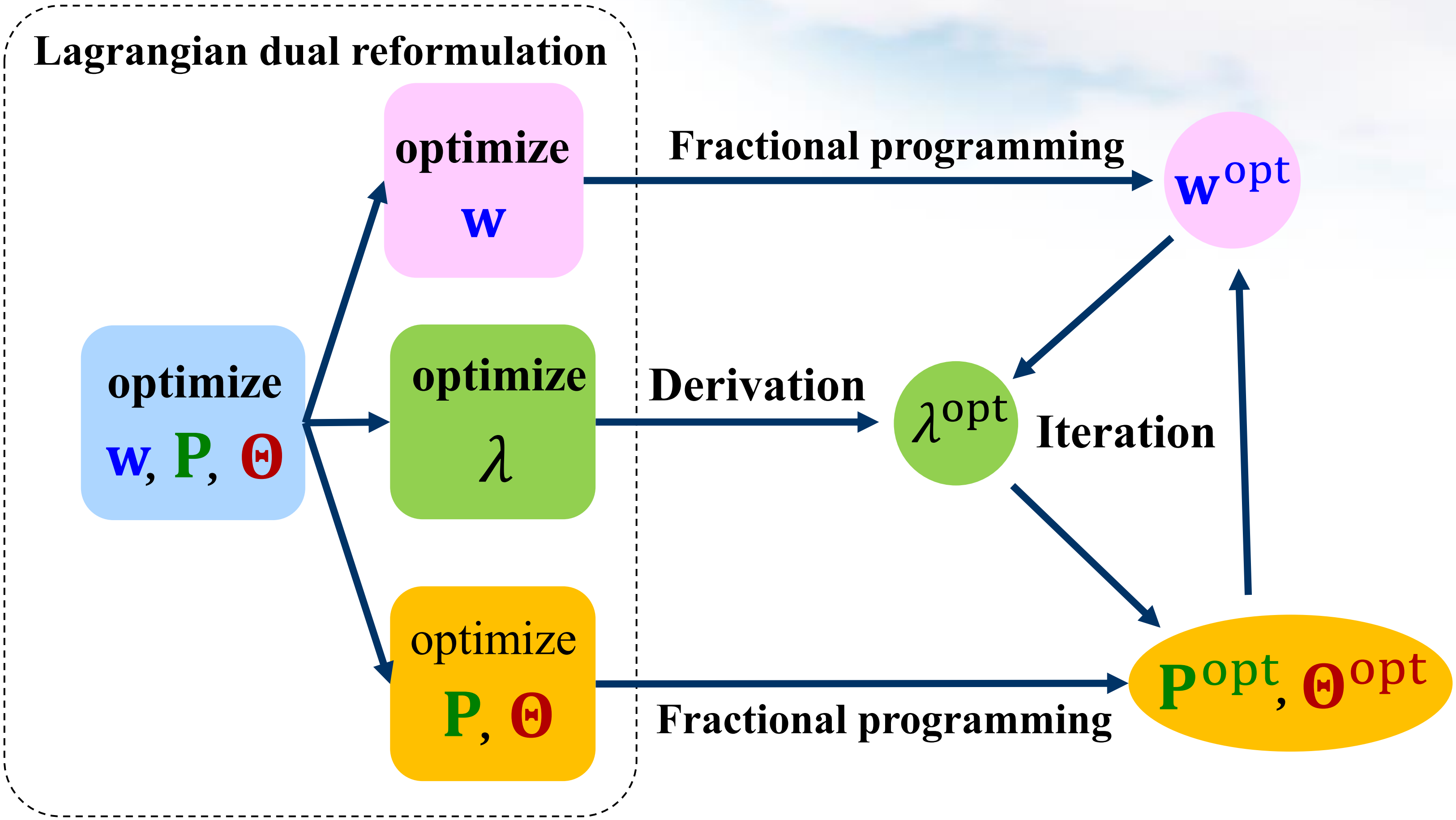
$$\sum_{k=1}^{K} \|\mathbf{P}\boldsymbol{\Theta}\mathbf{G}\mathbf{w}_k\|^2 + \|\mathbf{P}\boldsymbol{\Theta}\|^2\sigma_v^2 \le P_{\text{A}}^{\max}$$

RIS power constraint

$$\gamma_k = \frac{\left|\left(\mathbf{h}_k^H + \mathbf{f}^H\mathbf{P}\boldsymbol{\Theta}^H\mathbf{G}\right)\mathbf{w}_k\right|^2}{\sum_{j=1,j\neq k}^{K}\left|\left(\mathbf{h}_k^H + \mathbf{f}_k^H\mathbf{P}\boldsymbol{\Theta}^H\mathbf{G}\right)\mathbf{w}_j\right|^2 + \left\|\mathbf{f}_k^H\mathbf{P}\boldsymbol{\Theta}\right\|^2\sigma_v^2 + \sigma^2}$$

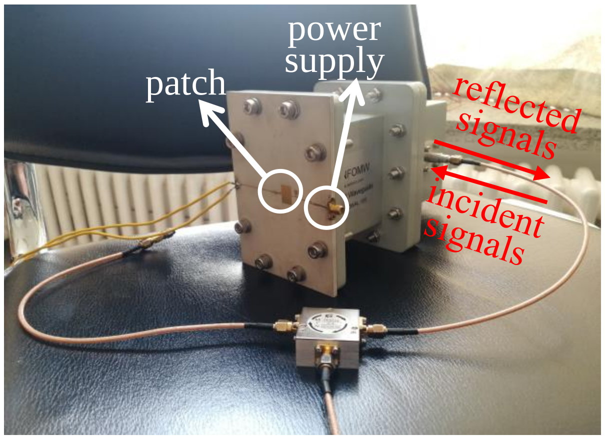
Proposed joint precoding algorithm

- Optimizing $\mathbf{w}$, $\mathbf{P}$, and $\mathbf{\Theta}$ alternatively

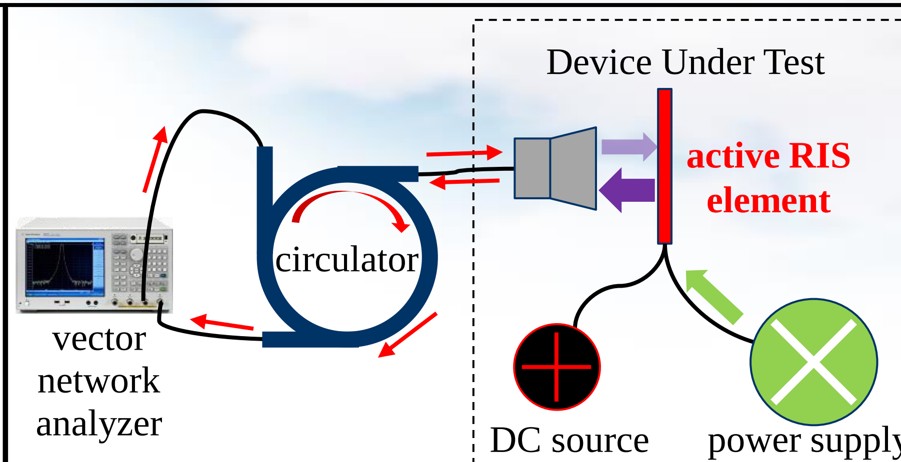


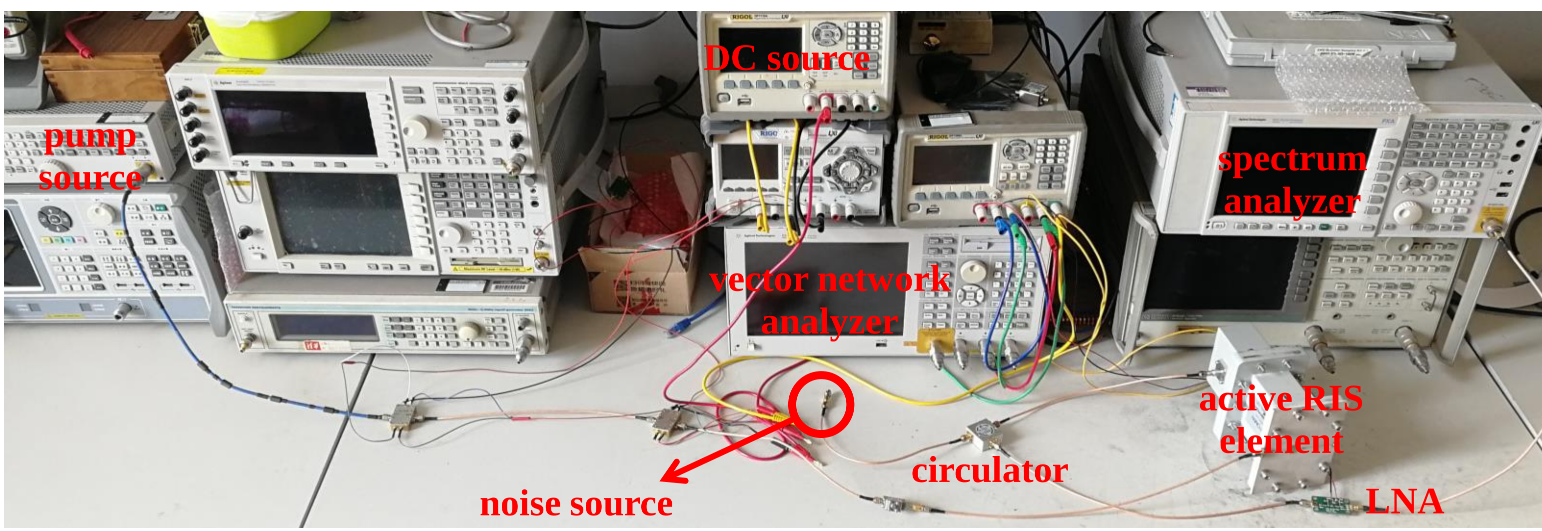
Validation of active RIS signal model

- **Experimental measurements of a fabricated active RIS element**



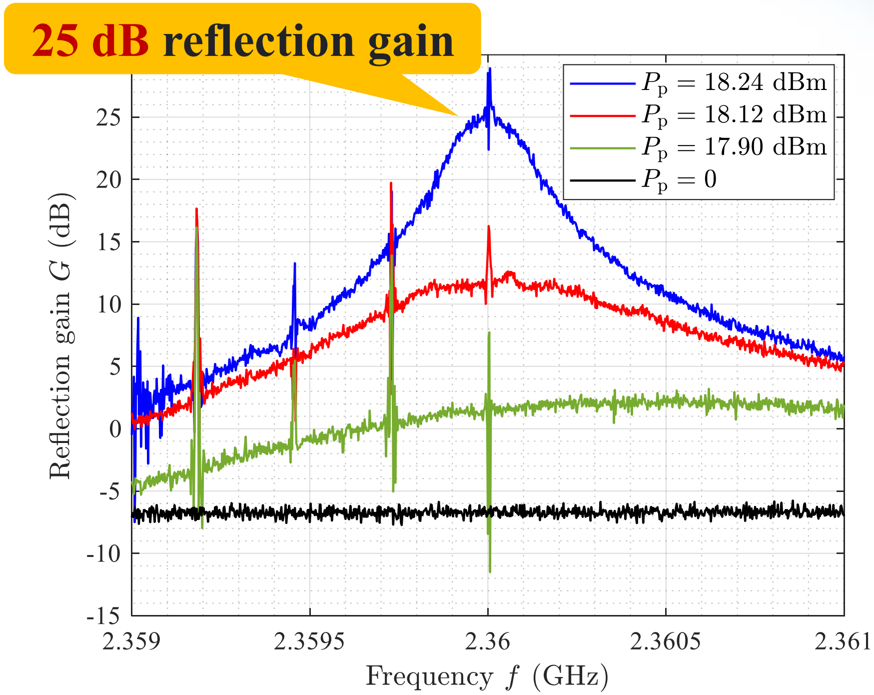
A fabricated active RIS element



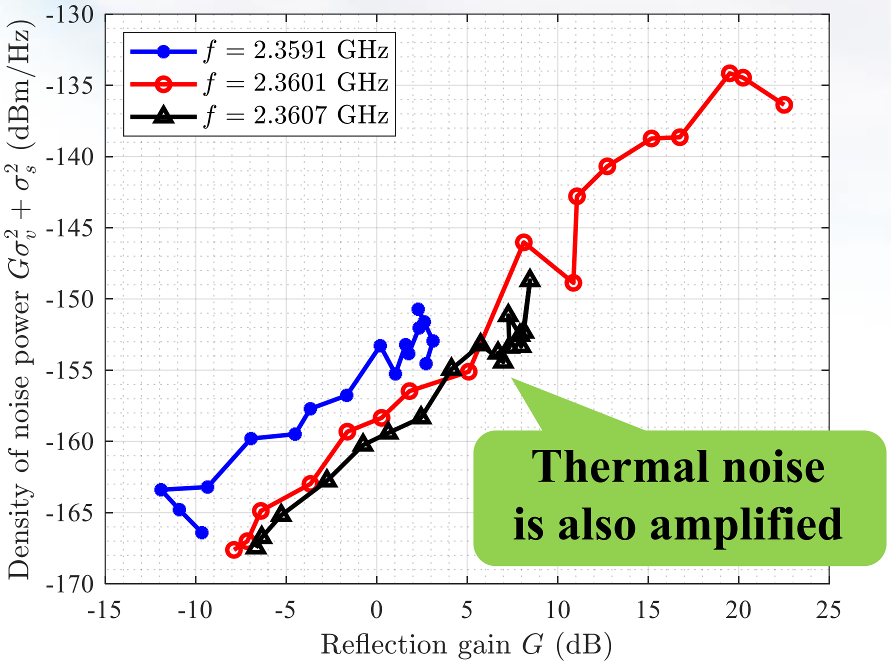


Validation results

- **Measurement results**



(a) Reflection gain vs. frequency



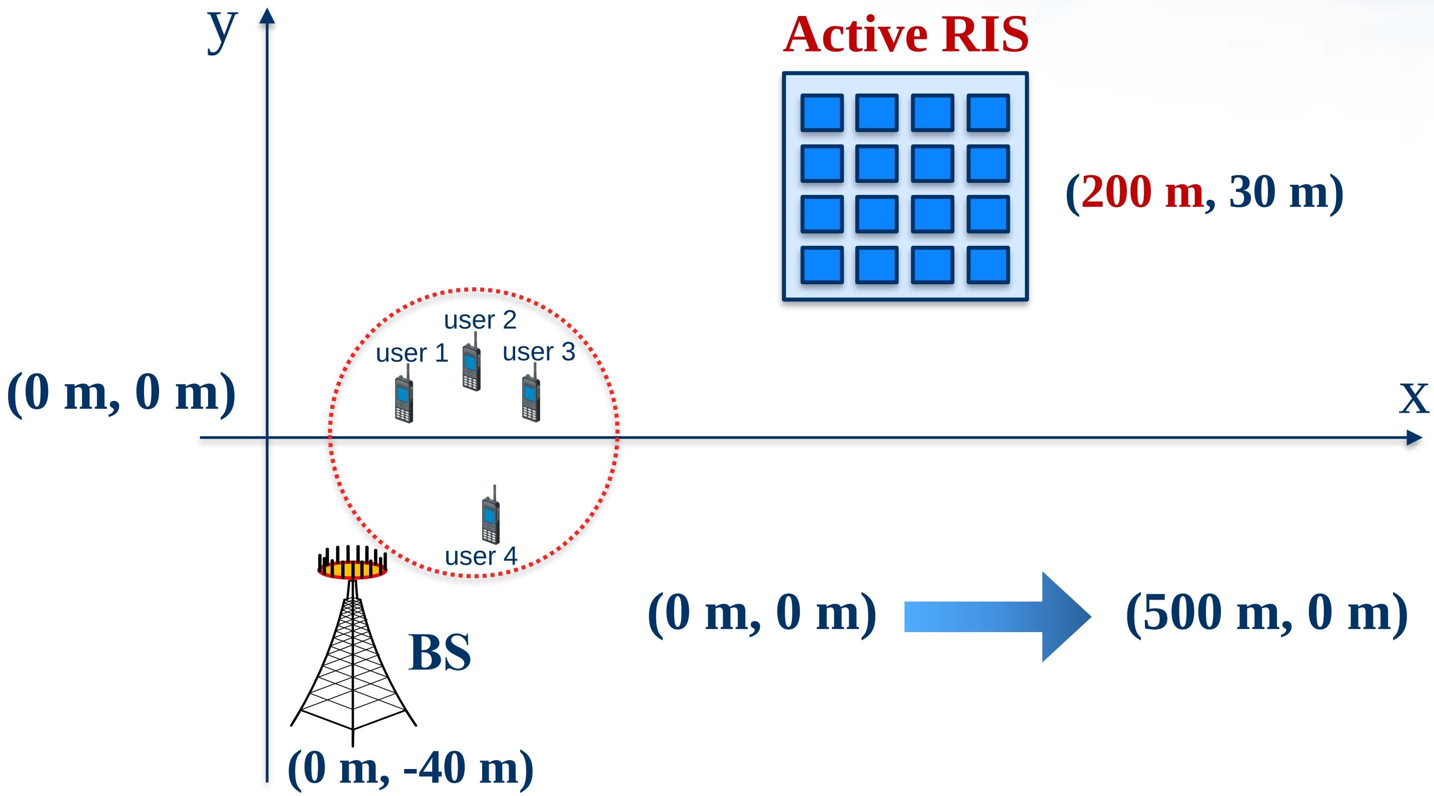
(b) Noise power vs. reflection gain

Verify the correctness of the proposed signal model

Z. Zhang, L. Dai, X. Chen, C. Liu, F. Yang, R. Schober, and H. V. Poor, "Active RISs: Signal modeling, asymptotic analysis, and beamforming design," in *Proc. 2022 IEEE Global Communications Conference (IEEE GLOBECOM'22)*, Rio de Janeiro, Brazil, Dec. 2022.

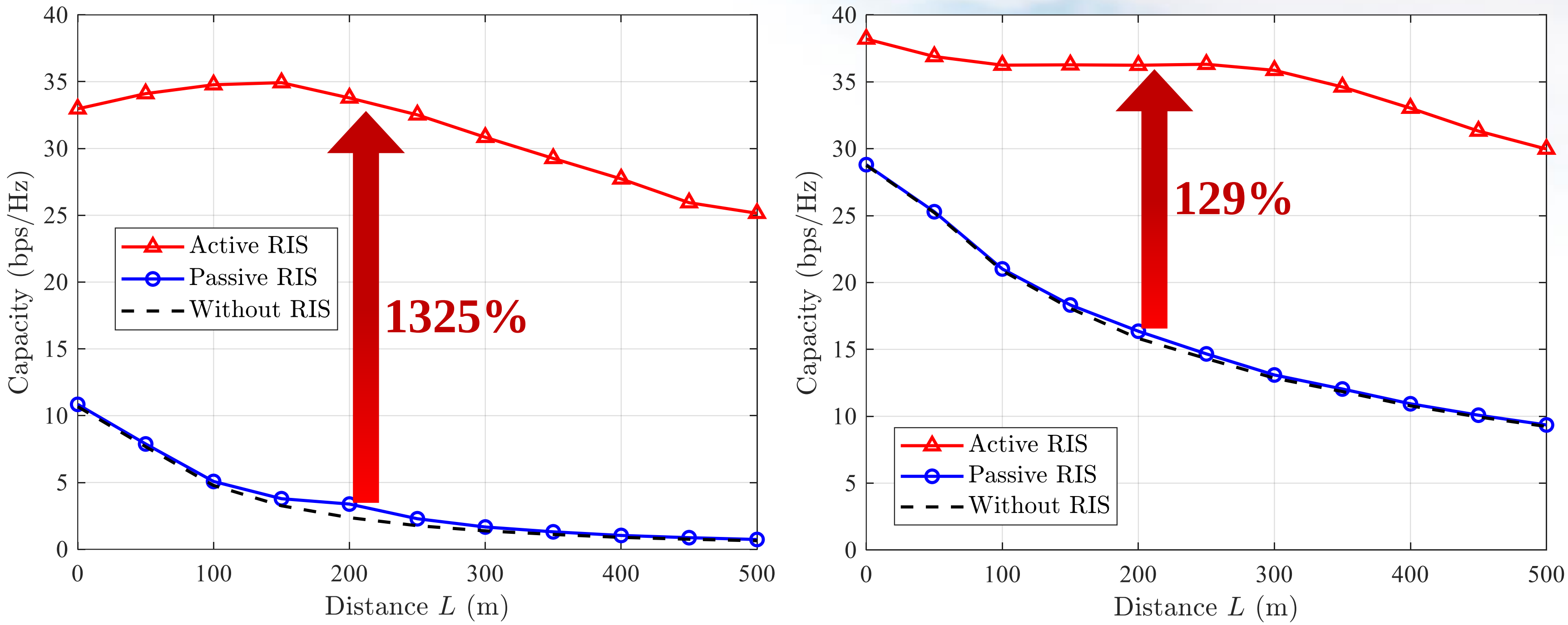
Simulation for joint precoding design

- **Simulation parameters**
  - BS (equipped with 4 antennas, transmit power 10 mW)
  - Active RIS (equipped with 256 elements, reflect power 10 mW)
  - 4 User (equipped with 1 antennas)



Simulation results

- **Active RIS** can achieve **noticeable** capacity gain in **typical** communication scenarios



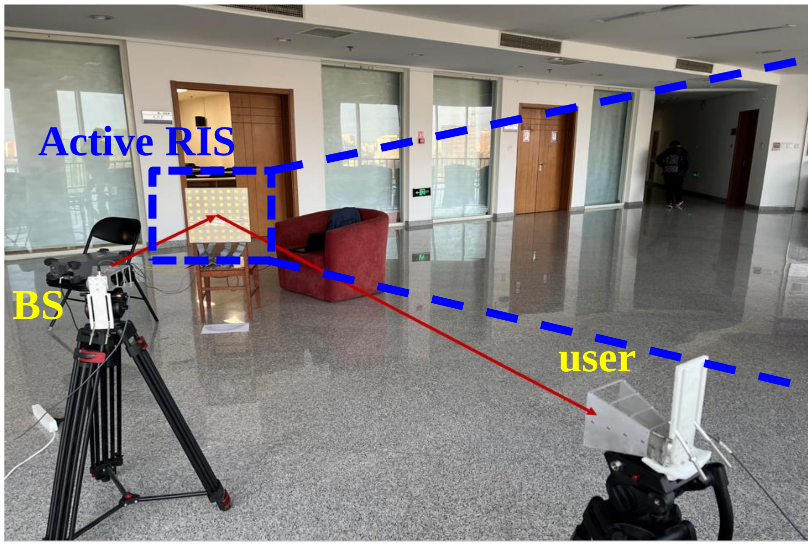
(a) **Atypical** scenario (b) **Typical** scenario

Active RIS can overcome the "multiplicative fading" effect

Z. Zhang, L. Dai, X. Chen, C. Liu, F. Yang, R. Schober, and H. V. Poor, "Active RISs: Signal modeling, asymptotic analysis, and beamforming design," in *Proc. 2022 IEEE Global Communications Conference (IEEE GLOBECOM'22)*, Rio de Janeiro, Brazil, Dec. 2022.

Experimental measurements of active RIS

- **Experimental measurements based on an 8×8 active RIS**

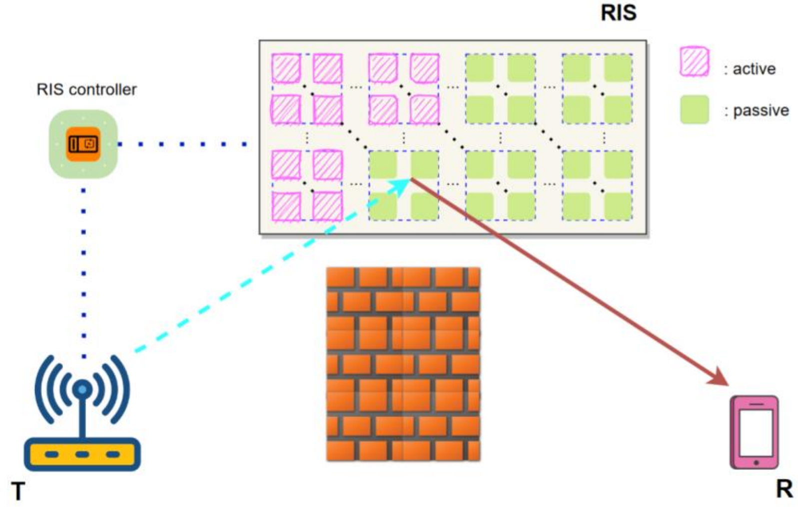


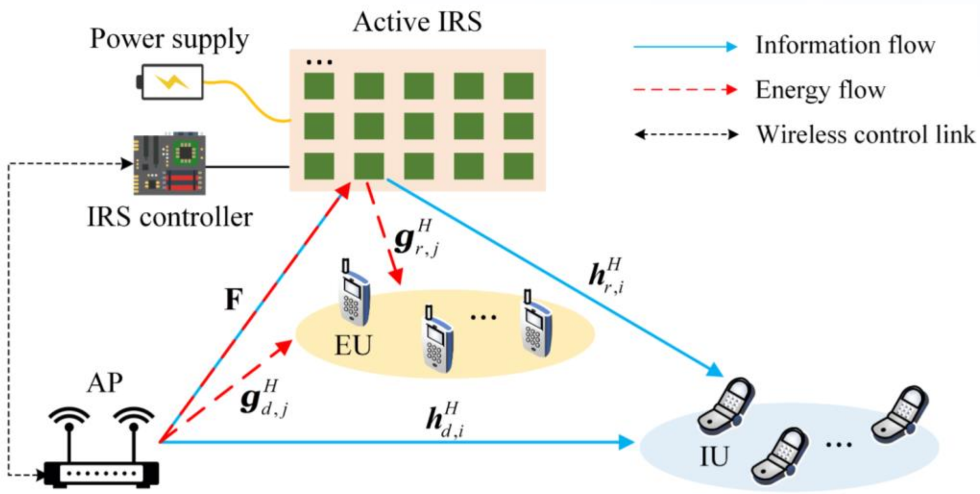
Parameter	Setting
Frequency	3.55 GHz
Bandwidth	40 MHz
Polarization	Vertical (BS) Horizontal (user)
BS-RIS distance	2 m
RIS-user distance	3.5 m
AoA	0°

Device	Reflection AoD	Received Power	Data Rate
Metal plate	15°	-110 dBm	1.2 MHz
Active RIS		-100 dBm	28.5 MHz
Metal plate	45°	-105 dBm	1.5 MHz
Active RIS		-95 dBm	30 MHz

Future opportunities of active RIS

- Other **performance metrics** optimization for active RIS
- **Channel estimation** for active RIS aided system
- **Hybrid** passive and active RIS architecture
- Active RIS for other techniques, e.g., security, NOMA, MEC, etc.





[1] E. Basar and H. V. Poor, "Present and future of reconfigurable intelligent surface-empowered communications," *IEEE Signal Process. Mag.*, vol. 38, no. 6, pp. 146-152, Nov. 2021.
[2] Z. Yigit, E. Basar, M. Wen, and I. Altunbas, "Hybrid Reflection Modulation," *arXiv preprint arXiv:2111.08355*, Nov. 2021.
[3] R. Long, Y.-C. Liang, Y. Pei, and E. G. Larsson, "Active reconfigurable intelligent surface aided wireless communications," *IEEE Trans. Wireless Commun.*, vol. 20, no. 8, pp. 4962–4975, Aug. 2021.

Outline

- Basics of RIS
- Existing passive RIS
- Proposed active RIS
- **Conclusions**

Conclusions

- **Basics of RIS**
  - **Reconfigure the wireless environment**
- **Existing passive RIS**
  - **Passively reflect signals without amplification**
  - **Fundamental limit: "multiplicative fading" effect**
  - **Only achieves negligible capacity gain in typical scenarios**
- **Proposed active RIS**
  - **Reflect signals with amplification to overcome "multiplicative fading" effect**
  - **New signal model verified by experimental measurements**
  - **Achieves noticeable capacity gain in typical scenarios**
  - **Recent test results based on an 8*8 active RIS**

Passive RIS → Active RIS

Reproducible Research: http://oa.ee.tsinghua.edu.cn/dailinglong/