Stacked Intelligent Metasurfaces (SIM)

Based Signal Processing in the Electromagnetic Domain

Jiancheng An (安建成)

jiancheng_an@163.com

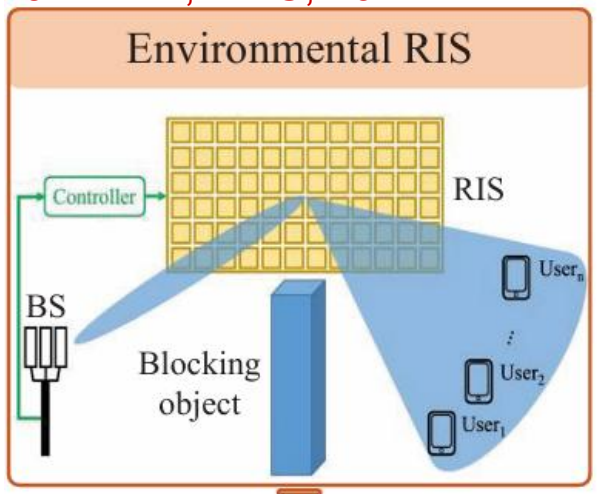
2025.12.18

Contents

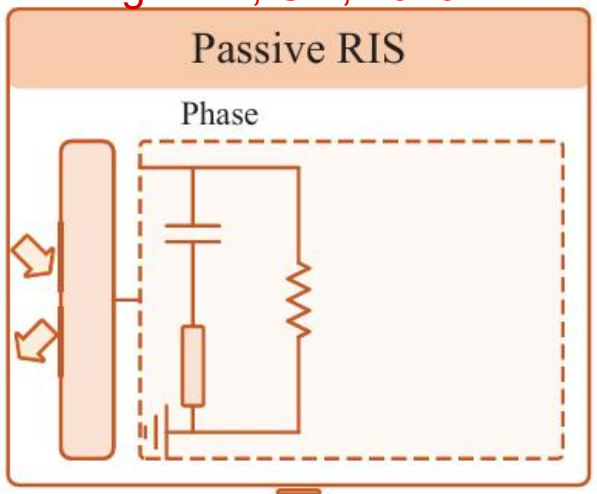
Contents

❖ 1 Background

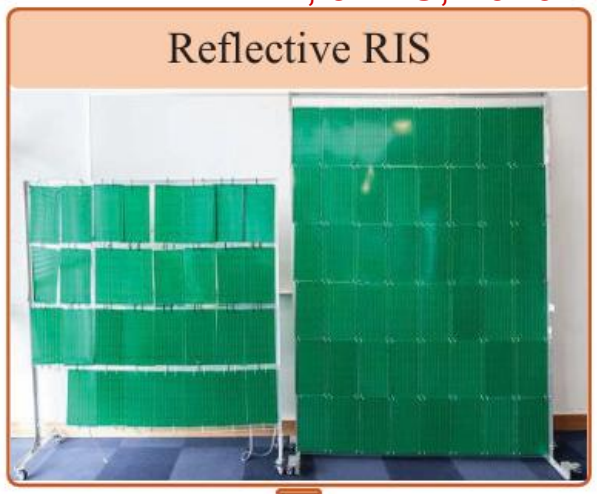
Jin et al., TWC, 2021



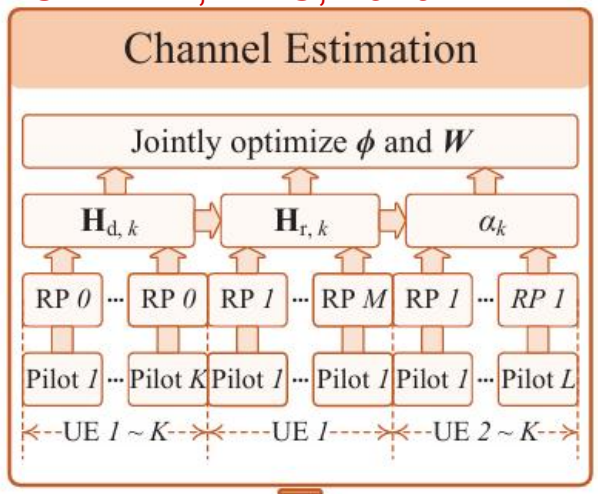
Zhang et al., CM, 2020



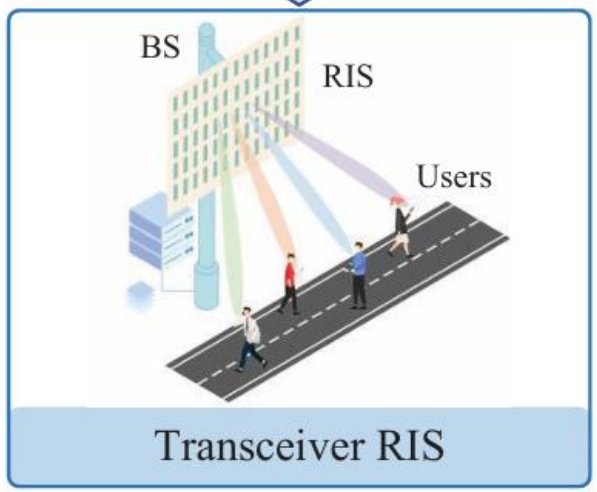
Di Renzo et al., JSAC, 2020



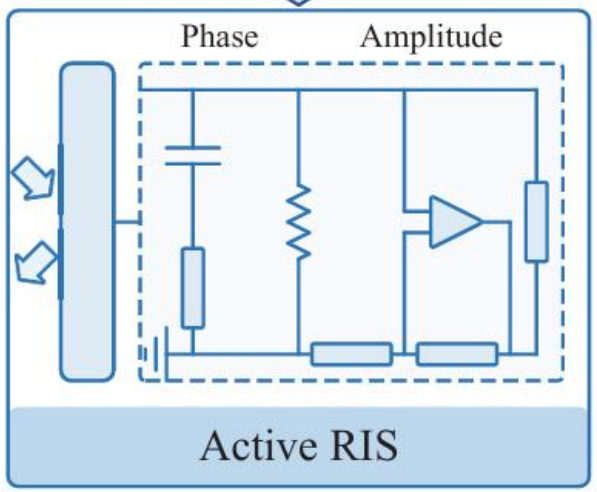
Cui et al., TWC, 2020



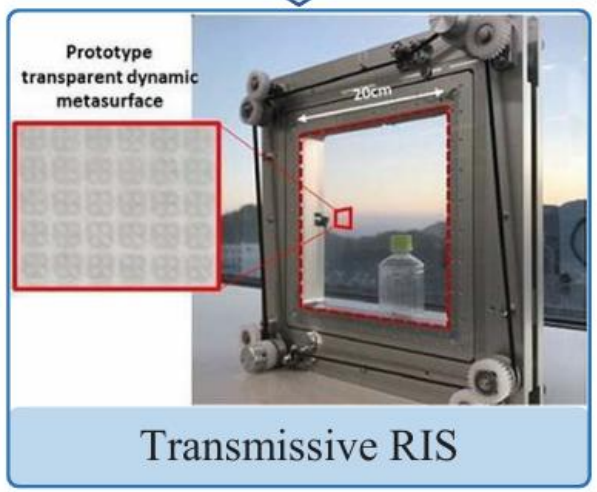
Song et al., TWC, 2022



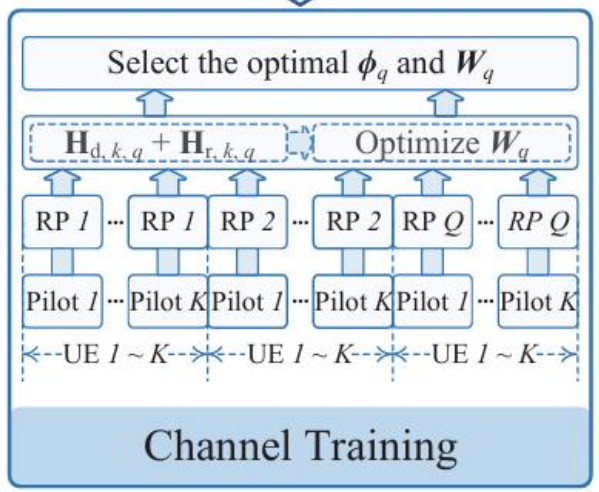
Dai et al., TCOM, 2023



NTT DOCOMO, 2021

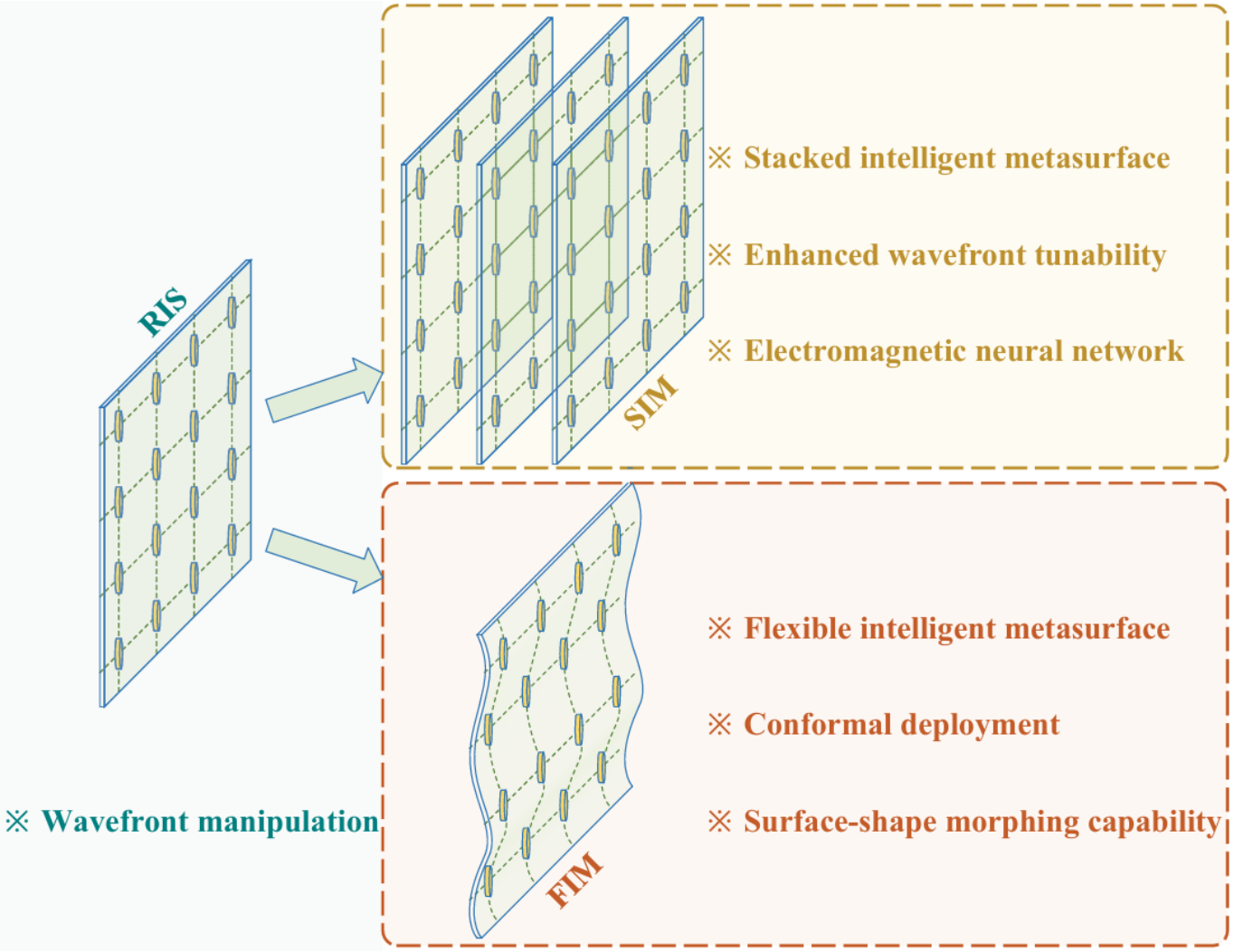


An et al., WCM, 2024



[R01] J. An, M. Debbah, T. J. Cui, Z. N. Chen and C. Yuen, “Emerging technologies in **intelligent metasurfaces**: Shaping the future of wireless communications,” *IEEE Trans. Antennas Propag.*, 2025, Early Access. (**Invited Paper**)

❖ 1 Background



Single-Layer ⇨ *Multiple-Layer*

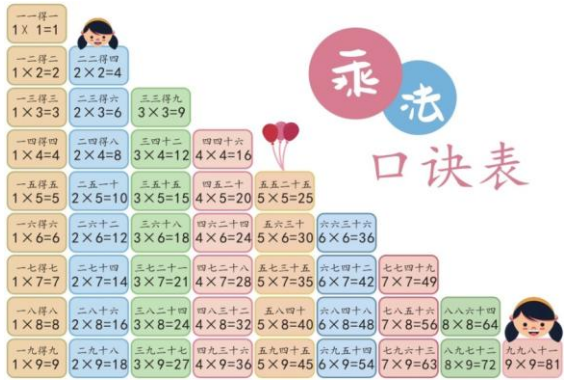
Rigid ⇨ *Flexible*

[R01] J. An, M. Debbah, T. J. Cui, Z. N. Chen and C. Yuen, “Emerging technologies in **intelligent metasurfaces**: Shaping the future of wireless communications,” *IEEE Trans. Antennas Propag.*, 2025, Early Access. (**Invited Paper**)

Contents

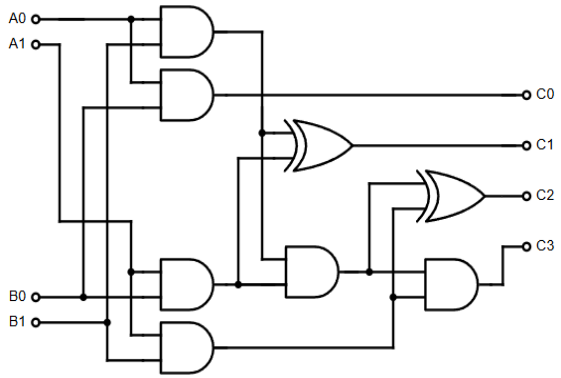
❖ 2.1 Re-understanding multiplication & RIS

Human



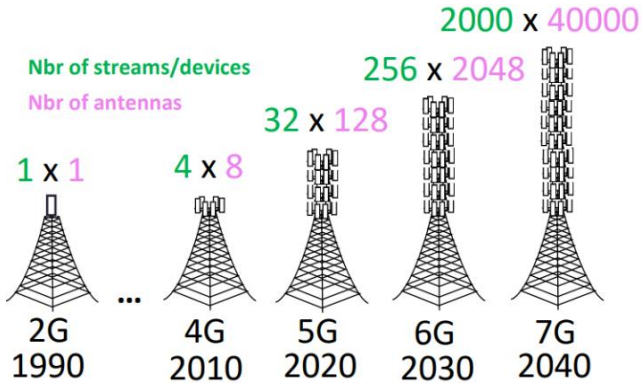
Rule-based lookup table

Precoding: $\mathbf{x} = \mathbf{W}\mathbf{s}$



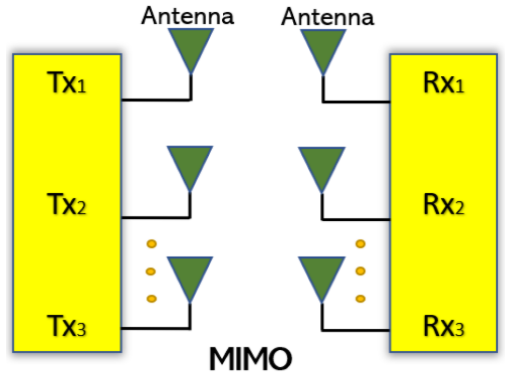
Energy-consuming, time-consuming

As # of antennas increases



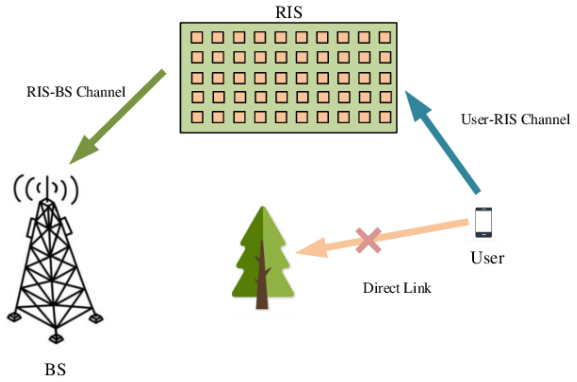
Poor scalability

MIMO: $\mathbf{y} = \mathbf{H}\mathbf{x}$



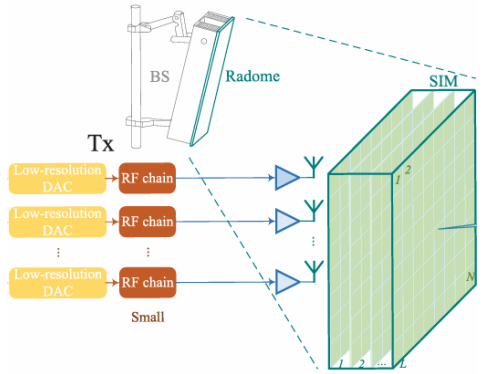
Automatically completed, not controllable

RIS: $\mathbf{y} = \mathbf{H}_2\mathbf{\Phi}\mathbf{H}_1\mathbf{x}$



Controllable, **insufficient DoF**

SIM

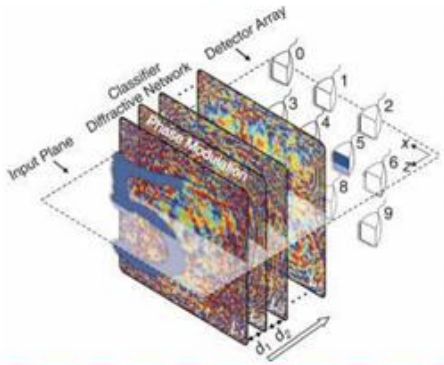


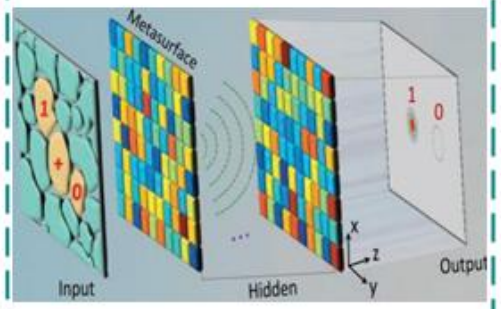
Does it work ❓

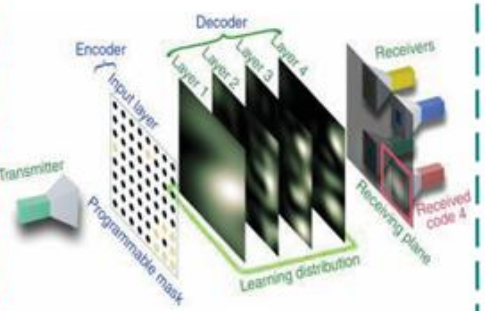
❖ 2.1 SIM: Prototypes

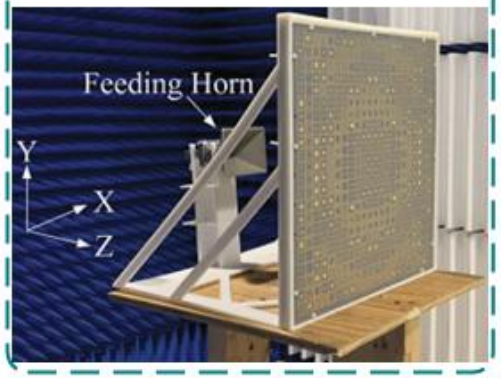
2018 — 2020 — 2022 — 2023 — 2024

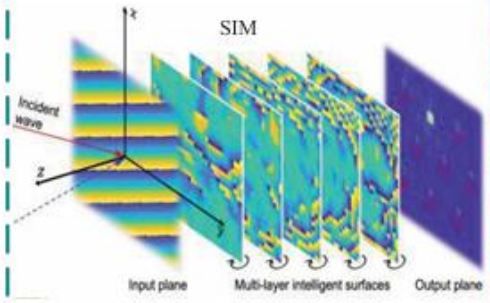
2018	2020	2022	2023	2024
400 GHz	*17 GHz*	*5.4 GHz*	*12 GHz*	*27.5 GHz*
Five layers	*Two layers*	*Five layers*	*Three layers*	*Five layers*
Image classification	*Logic operation*	*CDMA decoder*	*Sidelobe suppression*	*DOA estimation*
Lin et al. [23]	*Qian et al. [74]*	*Liu et al. [24]*	*Liu et al. [78]*	*Gao et al. [75]*
UCLA	*ZJU*	*SEU*	*NUS*	*THU*





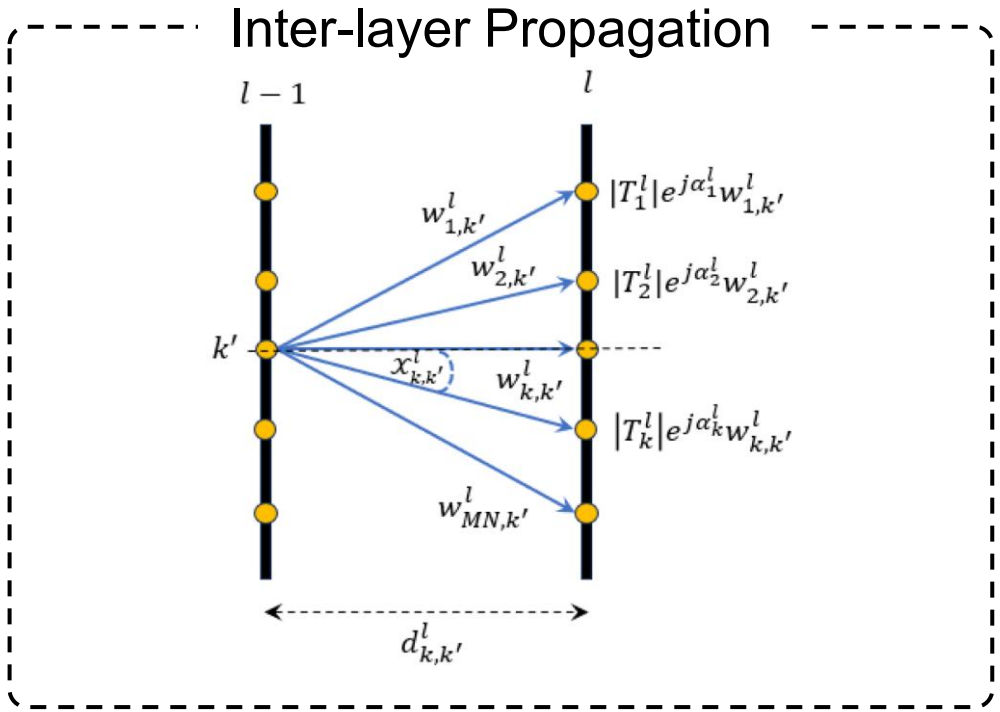


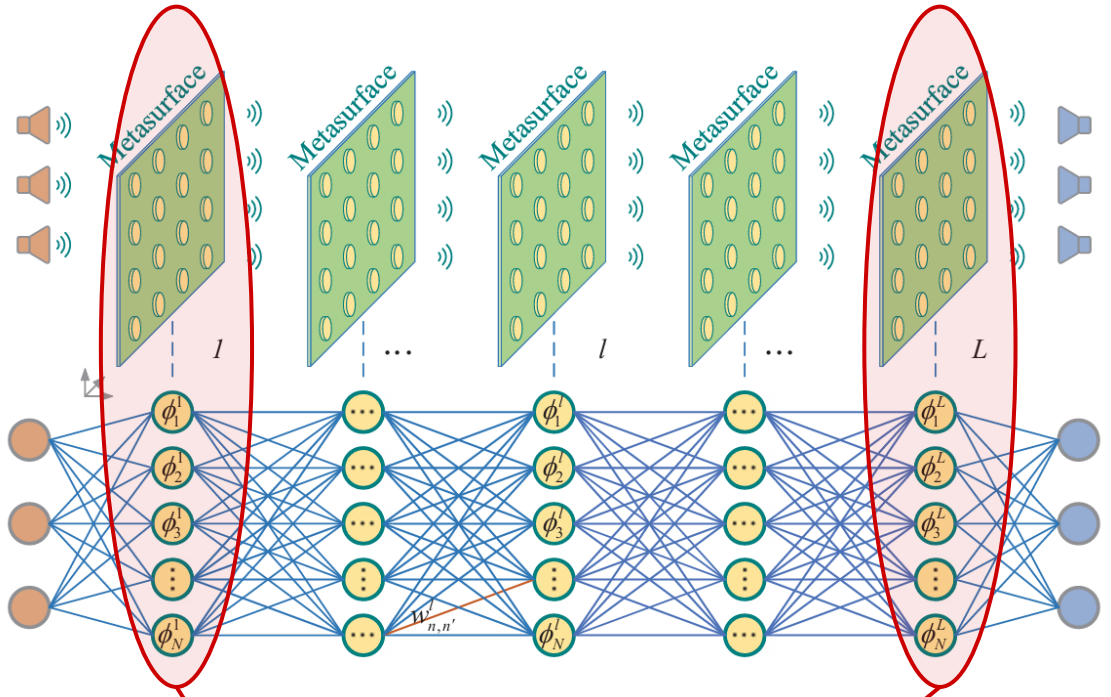




[R01] J. An, M. Debbah, T. J. Cui, Z. N. Chen and C. Yuen, “Emerging technologies in **intelligent metasurfaces**: Shaping the future of wireless communications,” *IEEE Trans. Antennas Propag.*, 2025, Early Access. (**Invited Paper**)

❖ 2.1 SIM: Propagation Modeling





Rayleigh-Sommerfeld Diffraction Theory

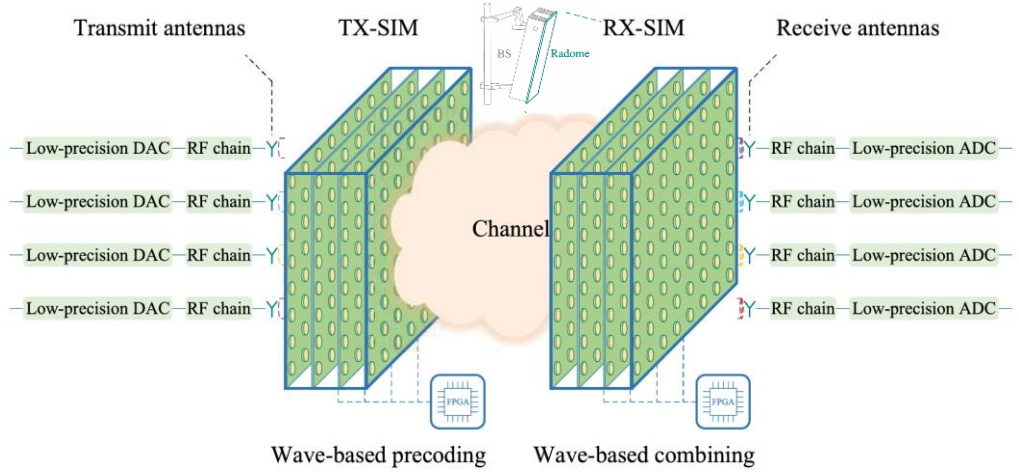
$$w^l_{n,n'} = \frac{A\cos\chi^l_{n,n'}}{r^l_{n,n'}}\left(\frac{1}{2\pi r^l_{n,n'}} - j\frac{1}{\lambda}\right)e^{j2\pi r^l_{n,n'}/\lambda}$$

$$\mathbf{S} = \mathbf{\Phi}^L\mathbf{W}^L\cdots\mathbf{\Phi}^2\mathbf{W}^2\mathbf{\Phi}^1 \in \mathbb{C}^{N\times N}$$

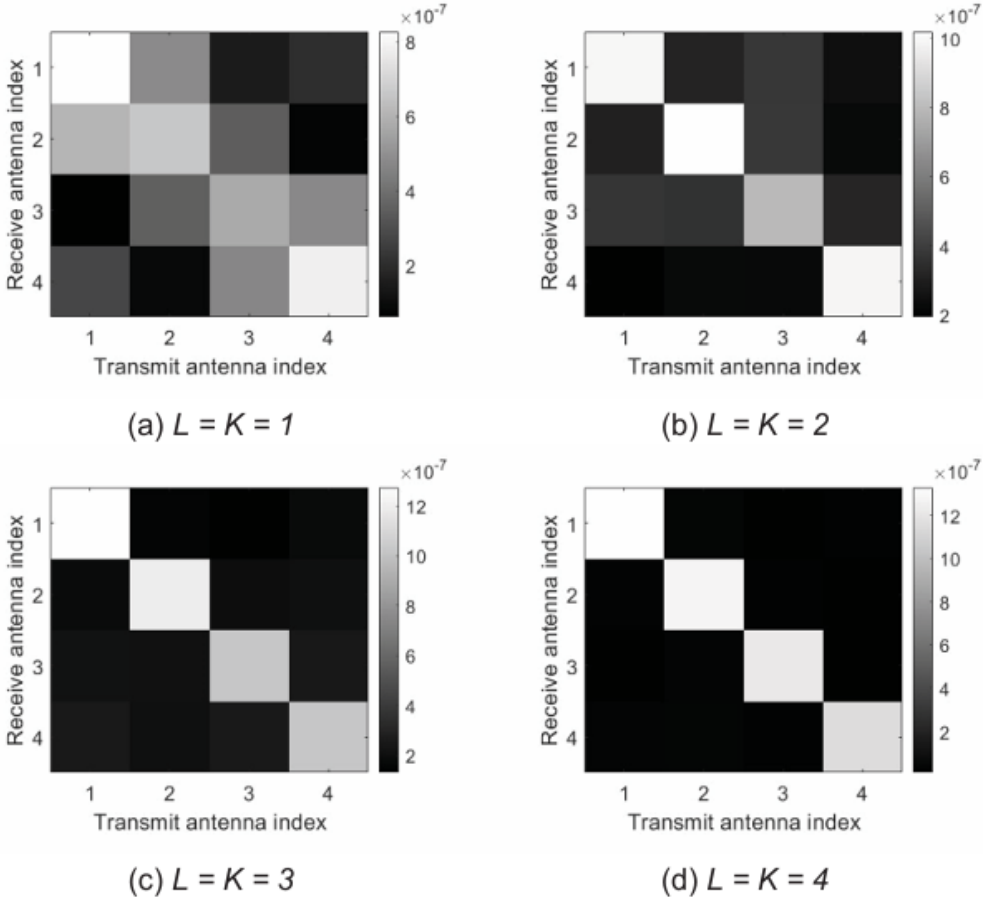
[R02] X. Lin, Y. Rivenson, N. T. Yardimci, M. Veli, Y. Luo, M. Jarrahi, and **A. Ozcan**, "All-optical machine learning using diffractive deep neural networks," *Science*, vol. 361, no. 6406, pp.1004-1008, 2018.

❖ 2.1 SIM: MIMO Precoding

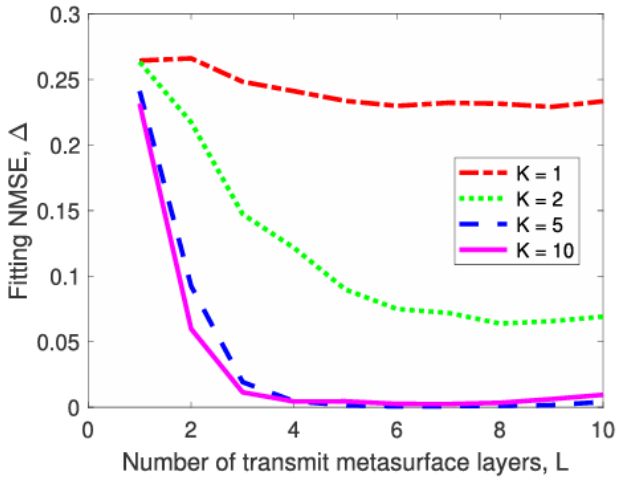
SIM-aided MIMO Transmission



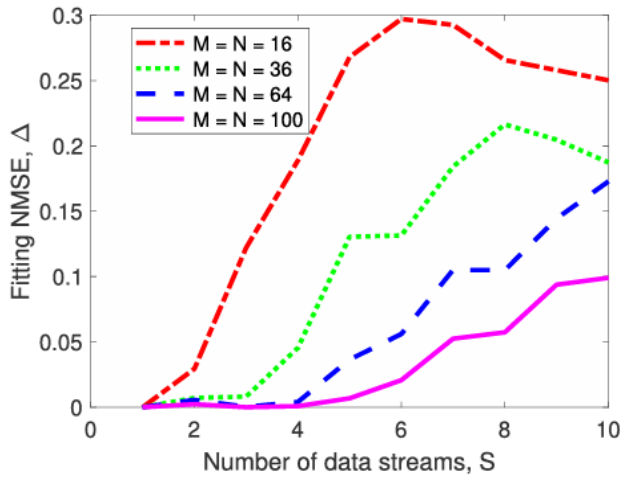
End-to-end channel



NMSE vs *L* & *K*

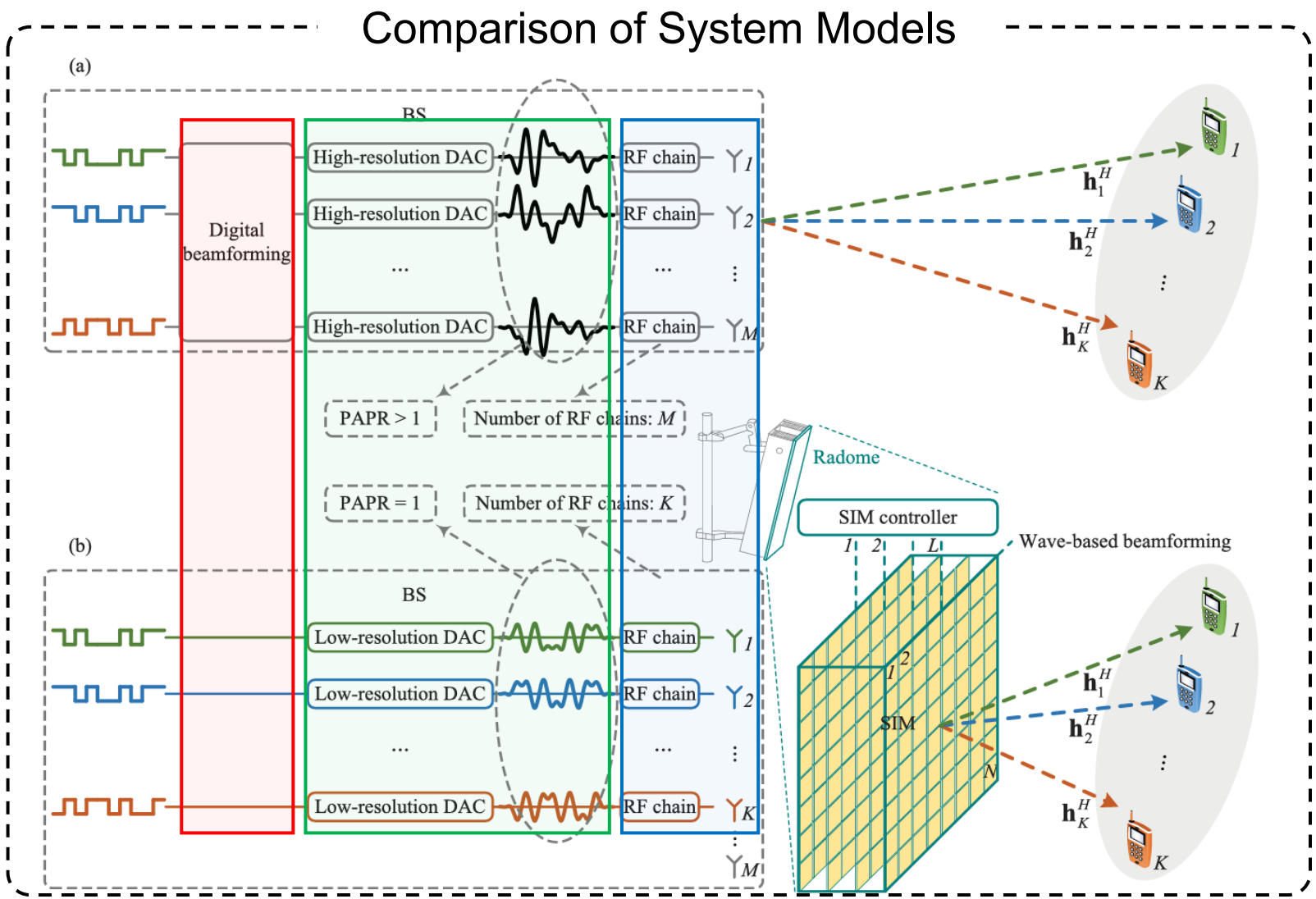


NMSE vs *S* & *M*

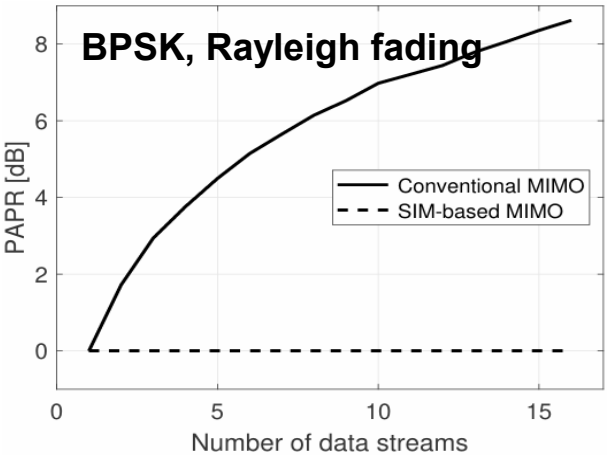


[R03] J. An, C. Xu, D. W. K. Ng, G. C. Alexandropoulos, C. Huang, C. Yuen and L. Hanzo, "**Stacked intelligent metasurfaces** for efficient holographic MIMO communications in 6G," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 8, pp. 2380-2396, Aug. 2023.

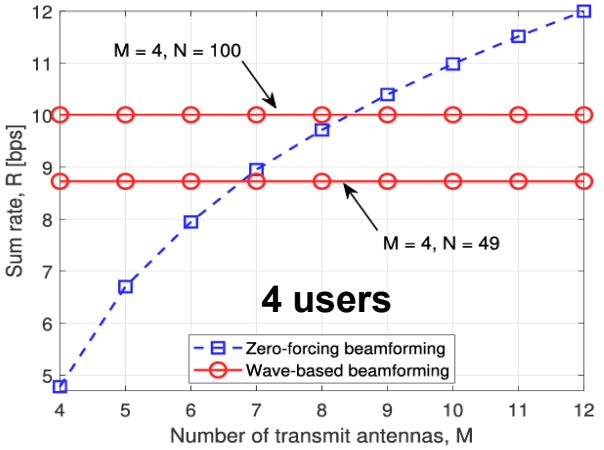
❖ 2.1 SIM: Benefits



PAPR vs. # of Streams

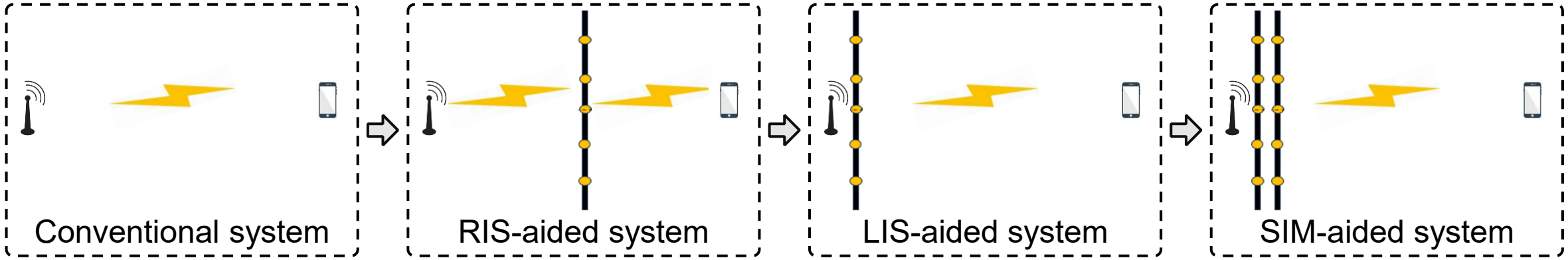


Performance Comparison



[R04] J. An, M. D. Renzo, M. Debbah, H. V. Poor and C. Yuen, "**Stacked intelligent metasurfaces** for multiuser downlink beamforming in the wave domain," *IEEE Trans. Wireless Commun.*, vol. 24, no. 7, pp. 5525-5538, Jul. 2025.

❖ 2.1 Will more layers decrease the received power?



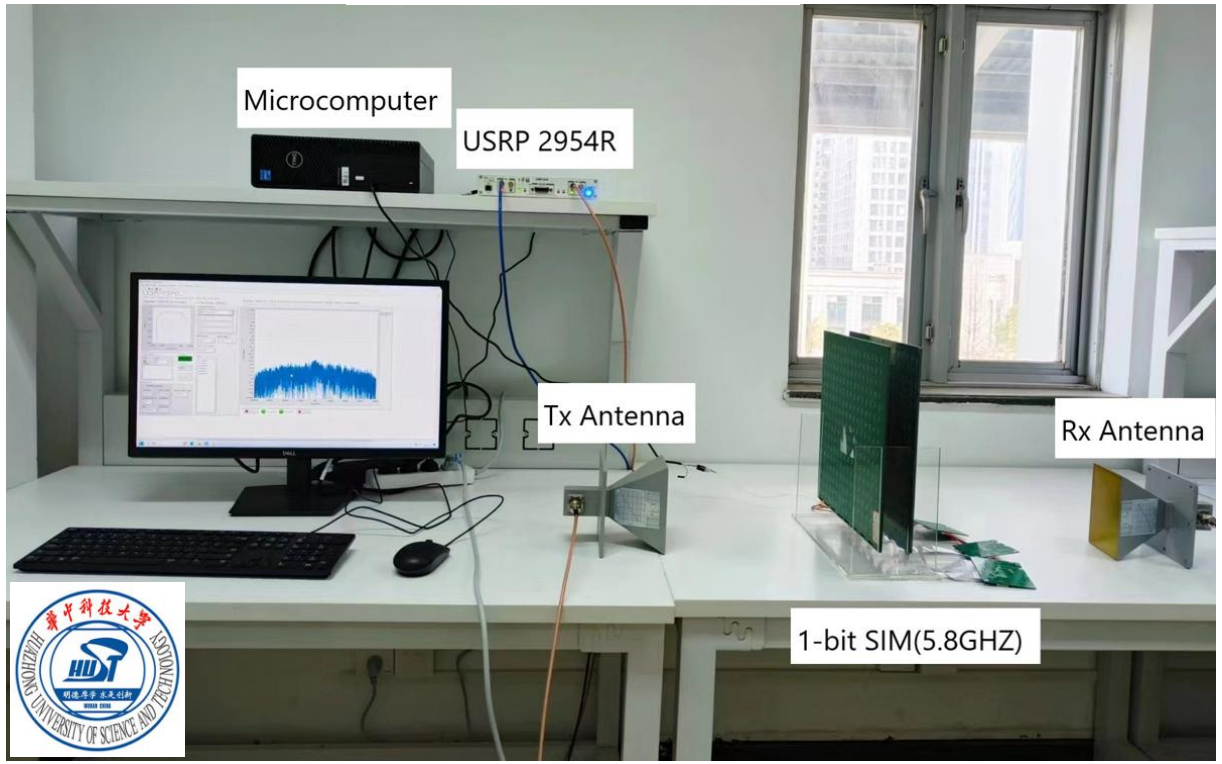
- Uncontrollable channel
- Severe path loss

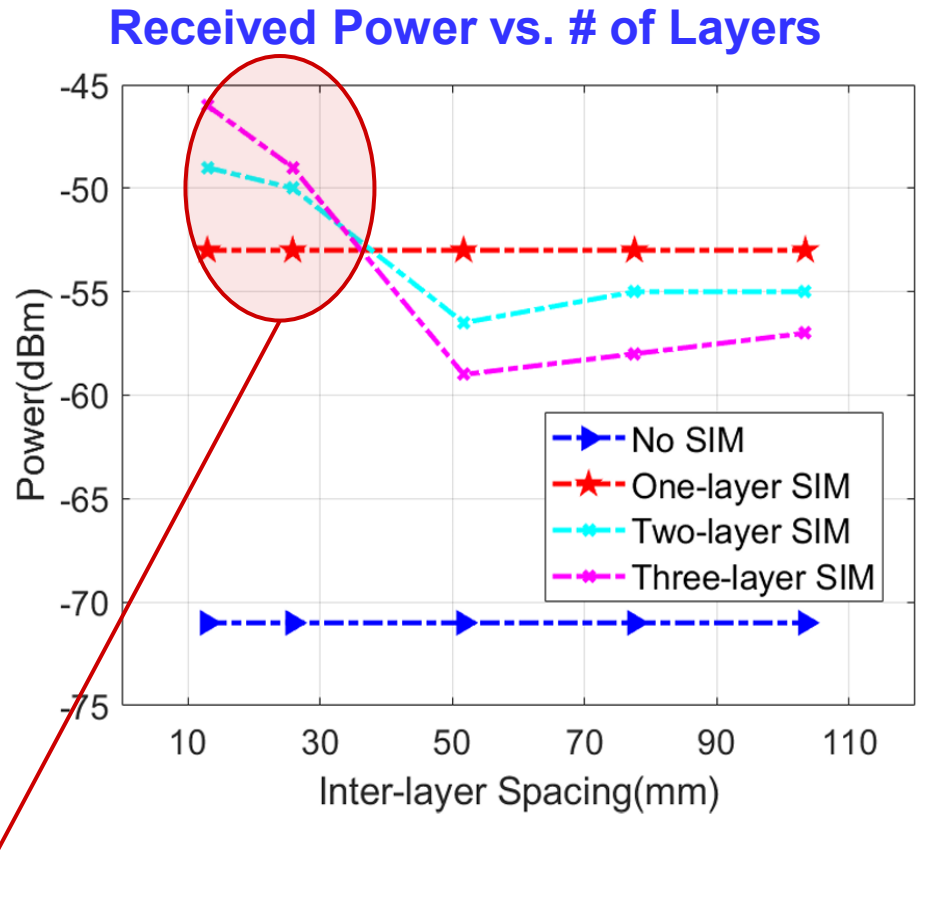
	Conventional system	RIS-aided system	LIS-aided system	SIM-aided system
Uncontrollable channel	Path loss	Path loss	Path loss	Path loss
Severe path loss	Penetration loss	Penetration loss	Penetration loss	Penetration loss
	Array gain	Array gain	Array gain	Array gain

Which one dominates? = Array gain + Penetration loss + Path loss

❖ 2.1 Will more layers decrease the received power?

SIM Prototype





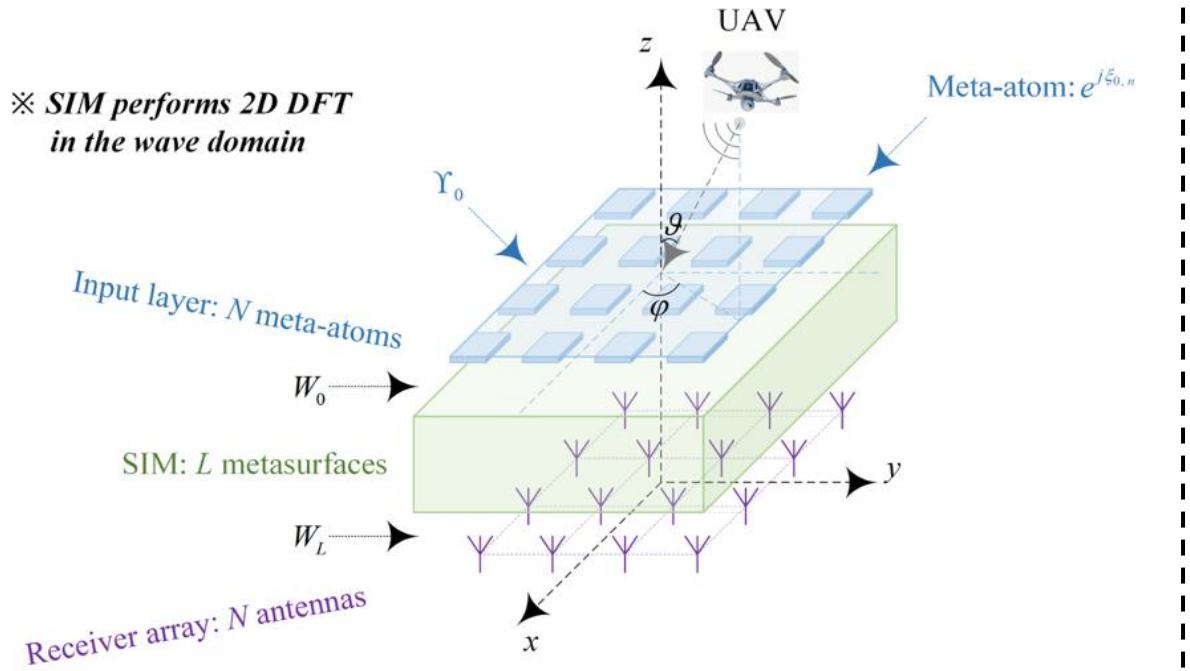
When the layers are closely placed, adding more layers doesn't reduce the power received due to the significant array gain.

[R05] Z. Wang, H. Liu, J. Zhang, R. Xiong, K. Wan, X. Qian, M. Di Renzo and **R. C. Qiu**, "Multi-user ISAC through **stacked intelligent metasurfaces**: New algorithms and experiments," *Proc. GLOBECOM 2024*, Cape Town, South Africa, 2024, pp. 4442-4447.

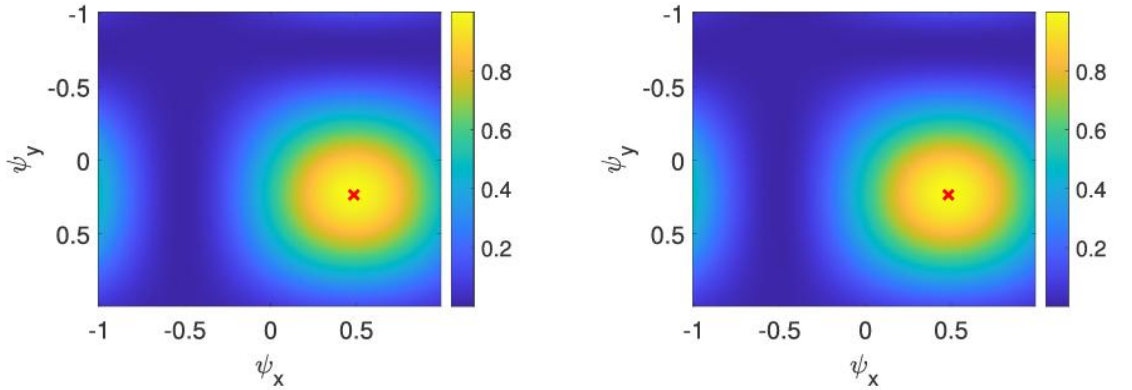
Contents

❖ 2.2 SIM for DOA Estimation

SIM-aided Array System

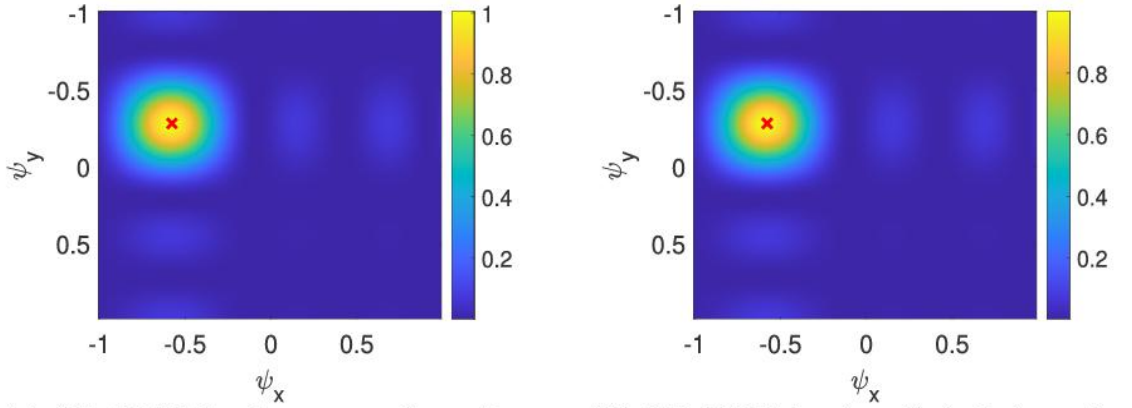


Receiver array: 2×2



(a) 2D DFT in the wave domain; (b) 2D DFT in the digital domain.

Receiver array: 4×4

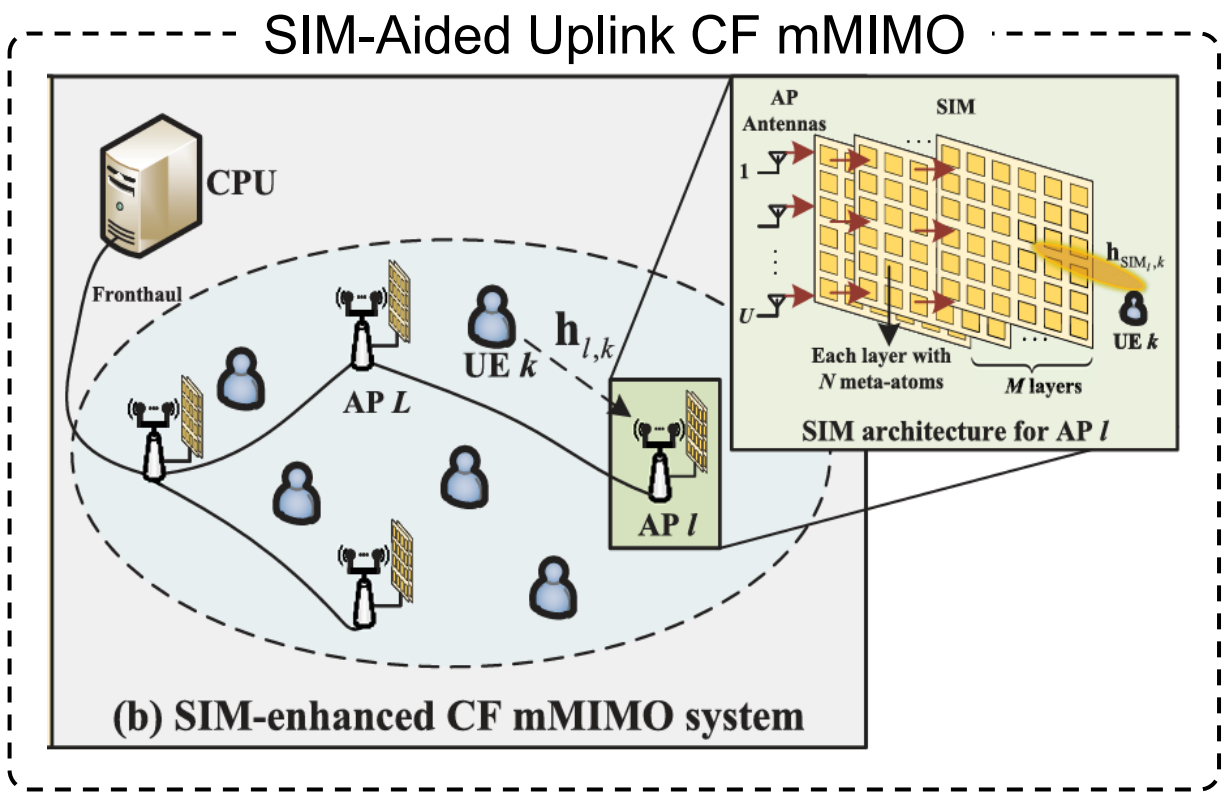


(a) 2D DFT in the wave domain; (b) 2D DFT in the digital domain.

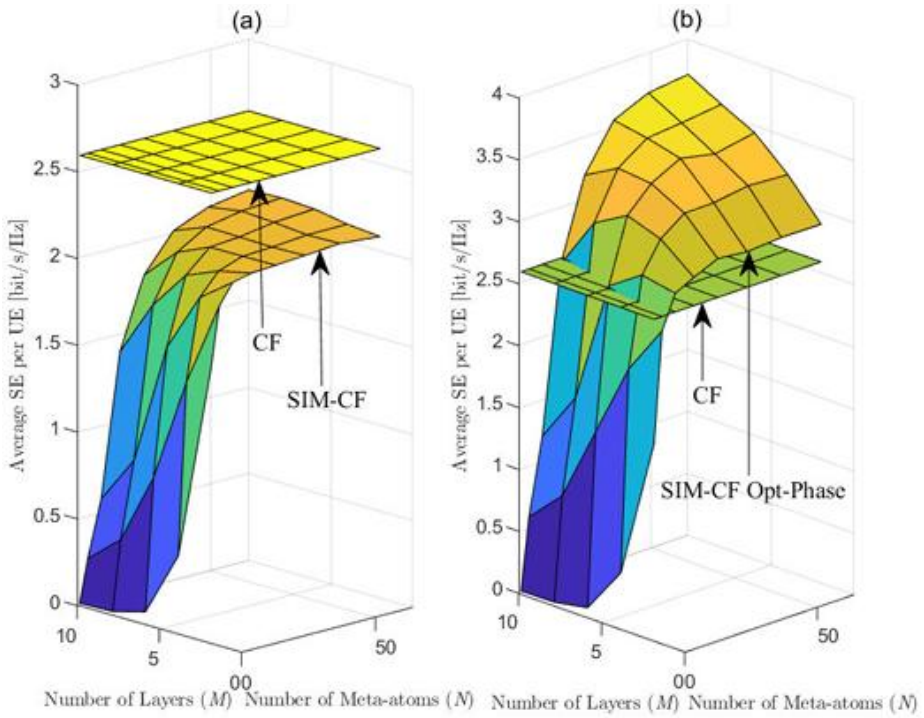
Low-precision spectrum → *Multi-snapshot combination* → *High-precision spectrum*

[R06] J. An, C. Yuen, Y. L. Guan, M. Di Renzo, M. Debbah, H. V. Poor and L. Hanzo, "Two-dimensional direction-of-arrival estimation using **stacked intelligent metasurfaces**," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 10, pp. 2786-2802, Oct. 2024.

❖ 2.2 SIM for CF mMIMO: Distributed Deployment



SE vs. # of layers and meta-atoms



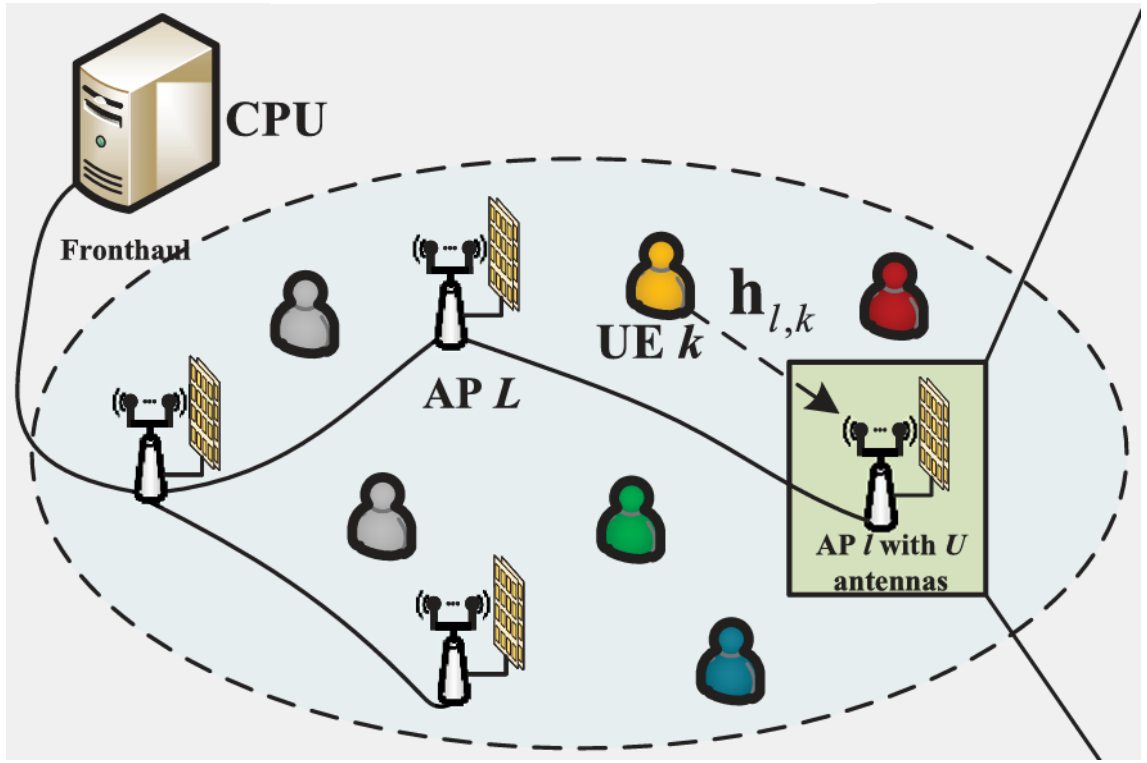
[R07] Q. Li, M. El-Hajjar, C. Xu, J. An, C. Yuen and L. Hanzo, "**Stacked intelligent metasurfaces** for holographic MIMO-aided cell-free networks," *IEEE Trans. Commun.*, vol. 72, no. 11, pp. 7139-7151, Nov. 2024.

[R8] Y. Hu, J. Zhang, E. Shi, Y. Lu, J. An, C. Yuen and B. Ai, "Joint beamforming and power allocation design for **stacked intelligent metasurfaces**-aided cell-free massive MIMO systems," *IEEE Trans. Veh. Technol.*, vol. 74, no. 3, pp. 5235-5240, Mar. 2025.

[R9] E. Shi, J. Zhang, Y. Zhu, J. An, C. Yuen and B. Ai, "Uplink performance of **stacked intelligent metasurface**-enhanced cell-free massive MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 24, no. 5, pp. 3731-3746, May 2025.

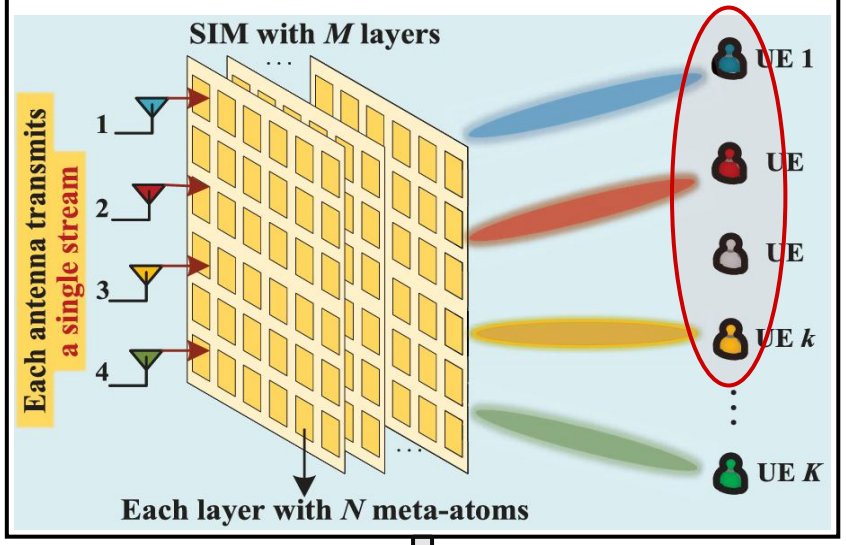
❖ 2.2 SIM for CF mMIMO: Antenna-UE Association

SIM-Aided CF mMIMO



$$x_{l,m} = \sqrt{p_{l,m,1}} w_{l,m,1} s_1 + \sqrt{p_{l,m,2}} w_{l,m,2} s_2 + \cdots + \sqrt{p_{l,m,K}} w_{l,m,K} s_K$$

Antenna-UE Association



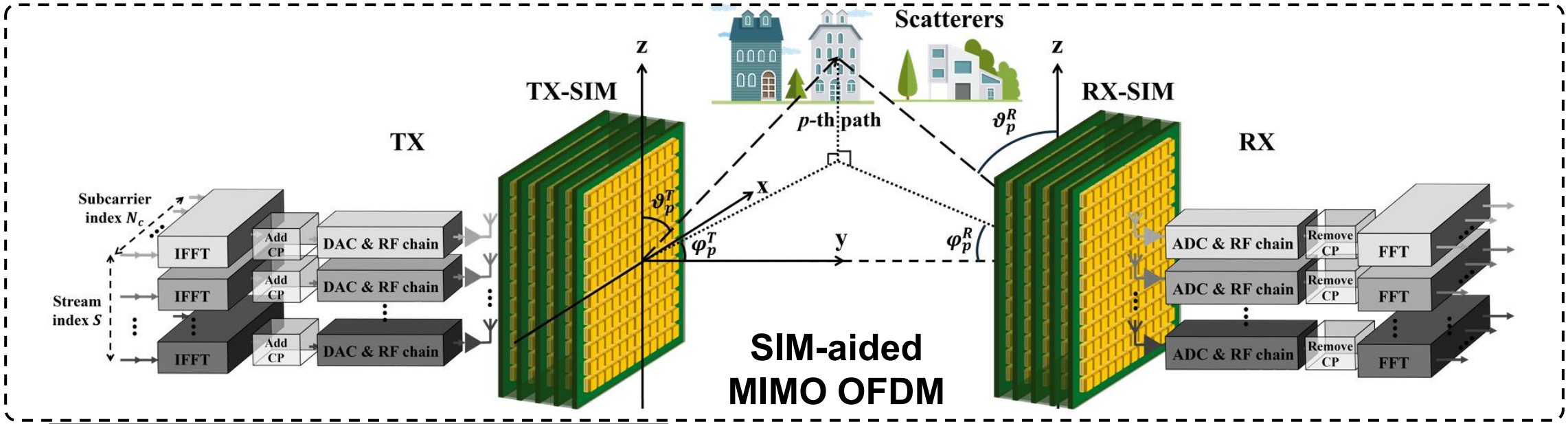
Heuristic method

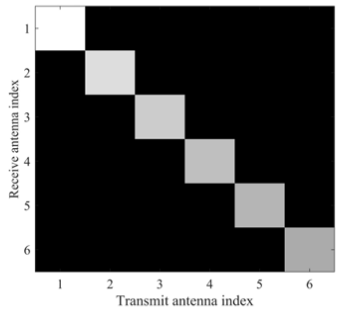
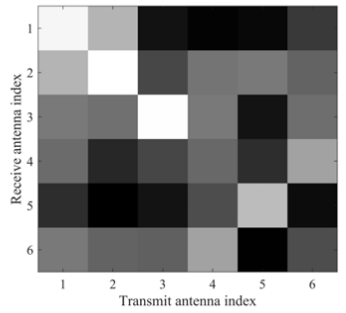
For each AP: Find the Nearest M UEs —*As L increases infinitely*→ Asymptotically Optimal

Gain Dominant --- MRT

[R10] E. Shi, J. Zhang, J. An, G. Zhang, Z. Liu, C. Yuen and B. Ai, "Joint AP-UE association and precoding for SIM-aided cell-free massive MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 24, no. 6, pp. 5352-5367, Jun. 2025.

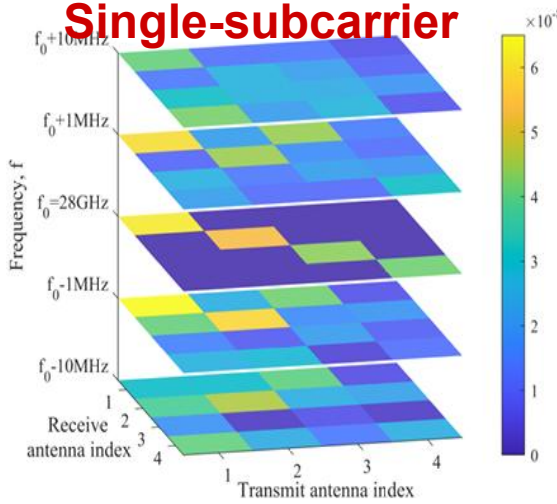
❖ 2.2 SIM for Wideband Communications (OFDM)



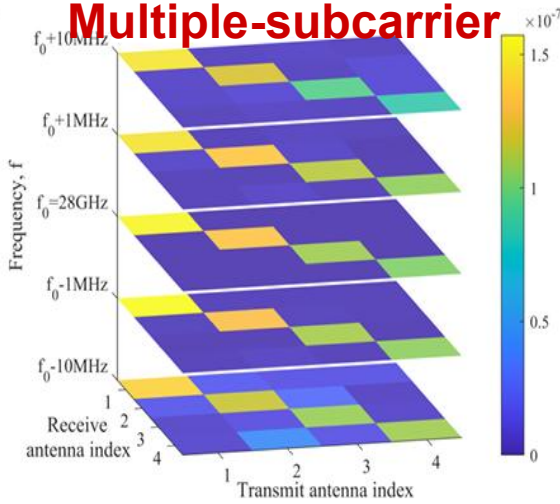
	Interference-free transmission	Interference-present transmission
Bandwidth	$B \le B_e$	$B > B_e$
Fitting error	$\Gamma_{\min} \approx 0$	$\Gamma_{\min} > 0$
Illustration of the end-to-end channel		

Maximum effective bandwidth

Single-subcarrier



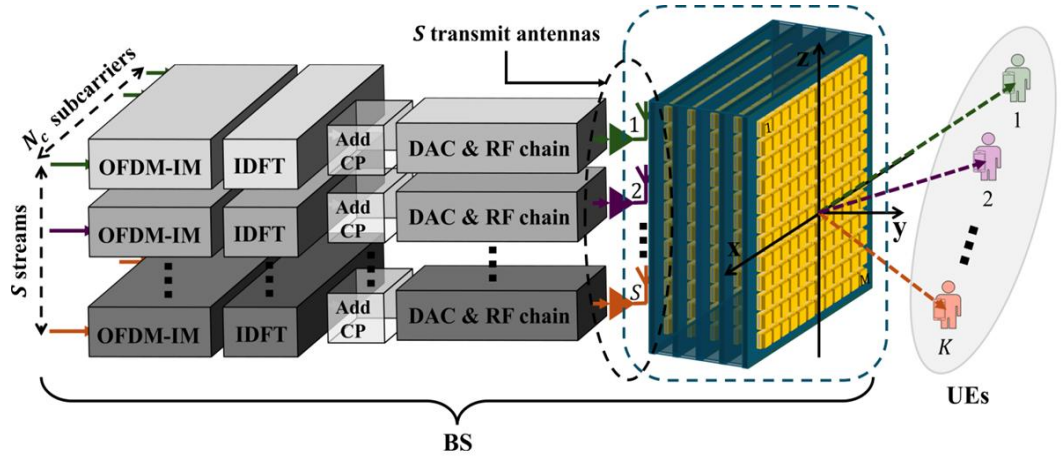
Multiple-subcarrier



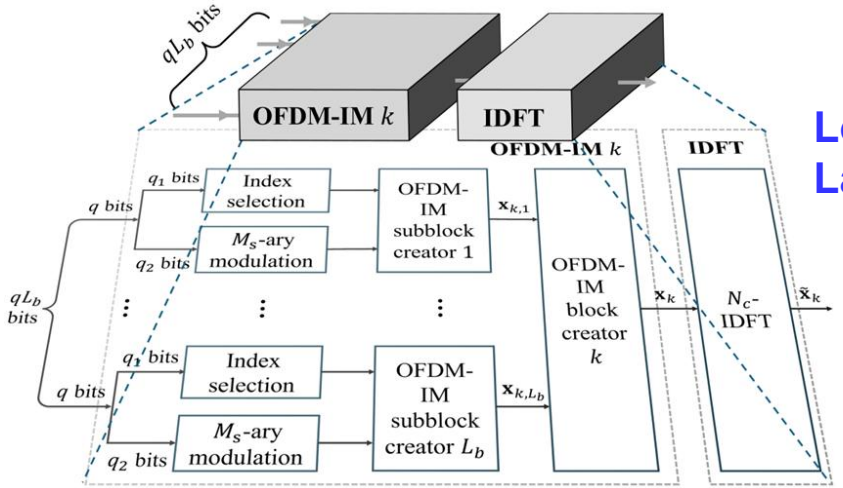
[R11] Z. Li, J. An and C. Yuen, "**Stacked intelligent metasurfaces**-enhanced MIMO OFDM wideband communication systems," *IEEE Trans. Wireless Commun.*, (Minor Revision) Online: https://arxiv.org/abs/2503.00368

❖ 2.2 SIM for Wideband Communications (OFDM-IM)

SIM-aided wideband MIMO OFDM

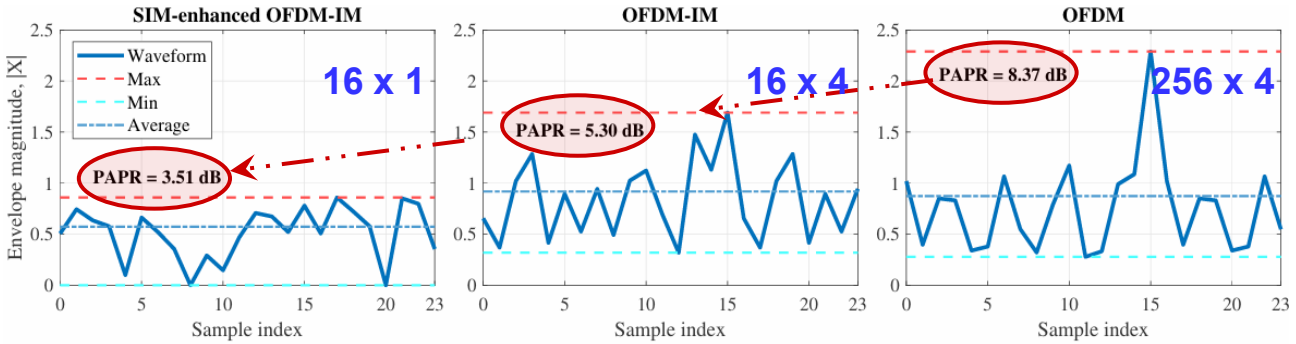


Index modulator

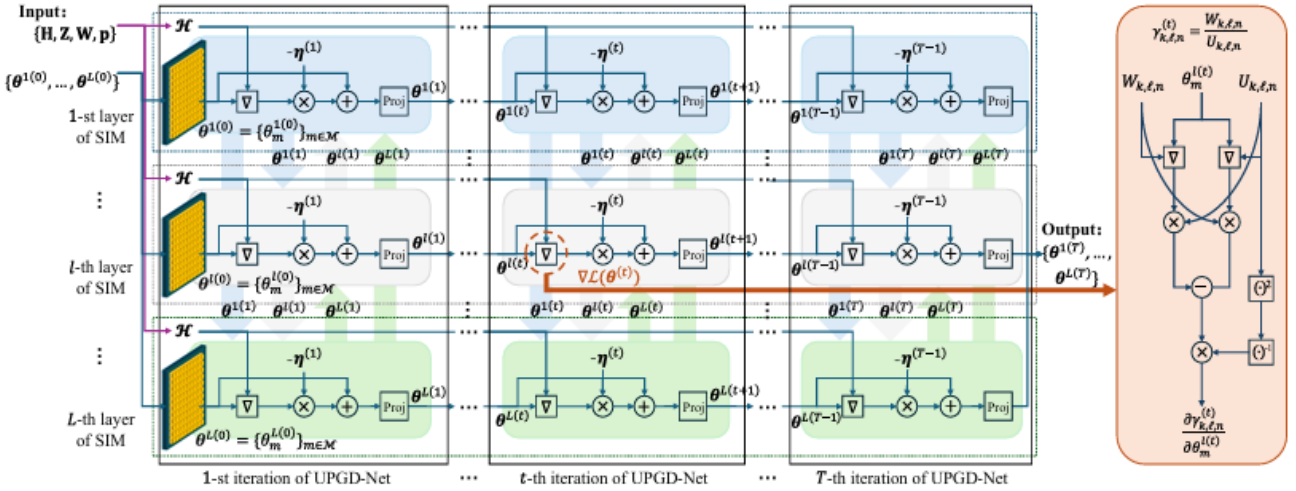


Lower PAPR
Larger BW

PAPR Comparison

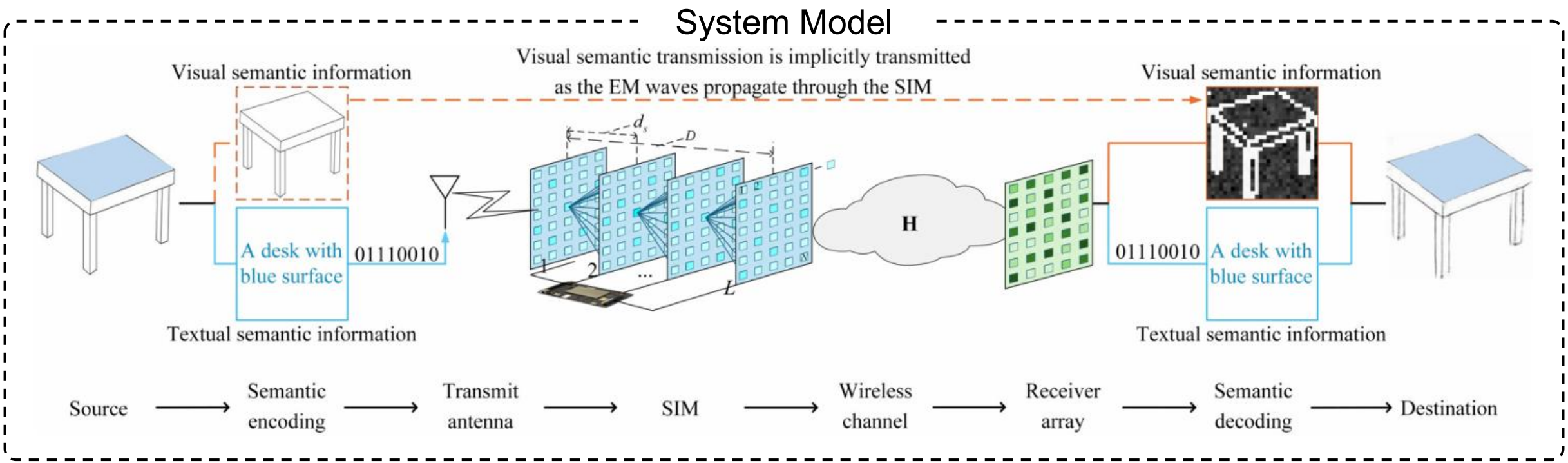


Deep unfolding strategy

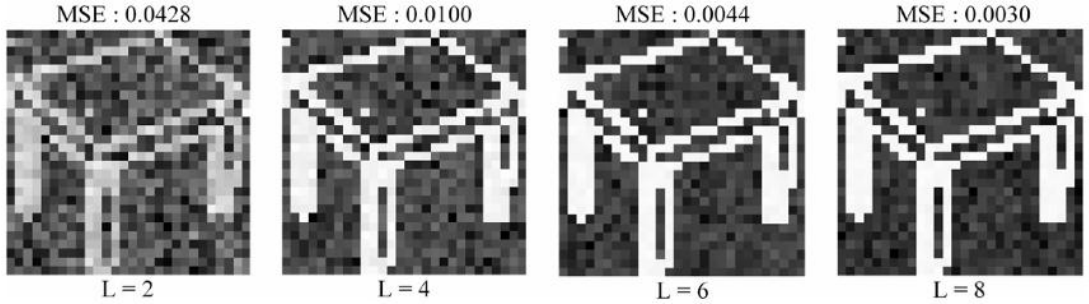


[R12] Z. Li, J. An and C. Yuen, "**Stacked intelligent metasurface**-enhanced wideband multiuser MIMO OFDM-IM communications," *IEEE Trans. Wireless Commun.*, (Submitted) Online: https://arxiv.org/abs/2509.22327

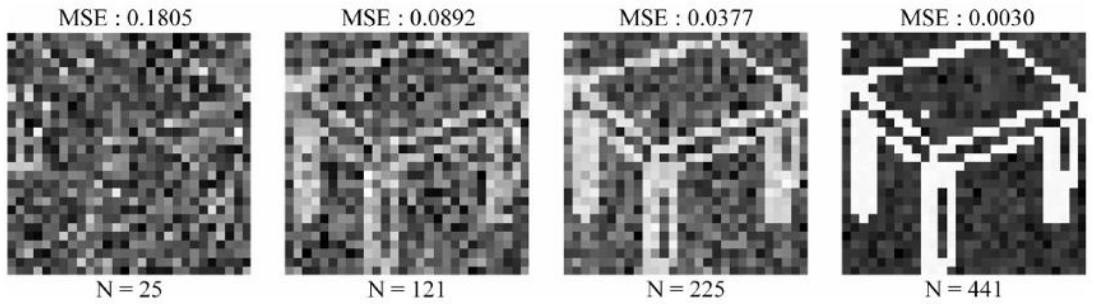
❖ 2.2 SIM for Multi-Modal Semantic Communications



MSE vs. # of layers



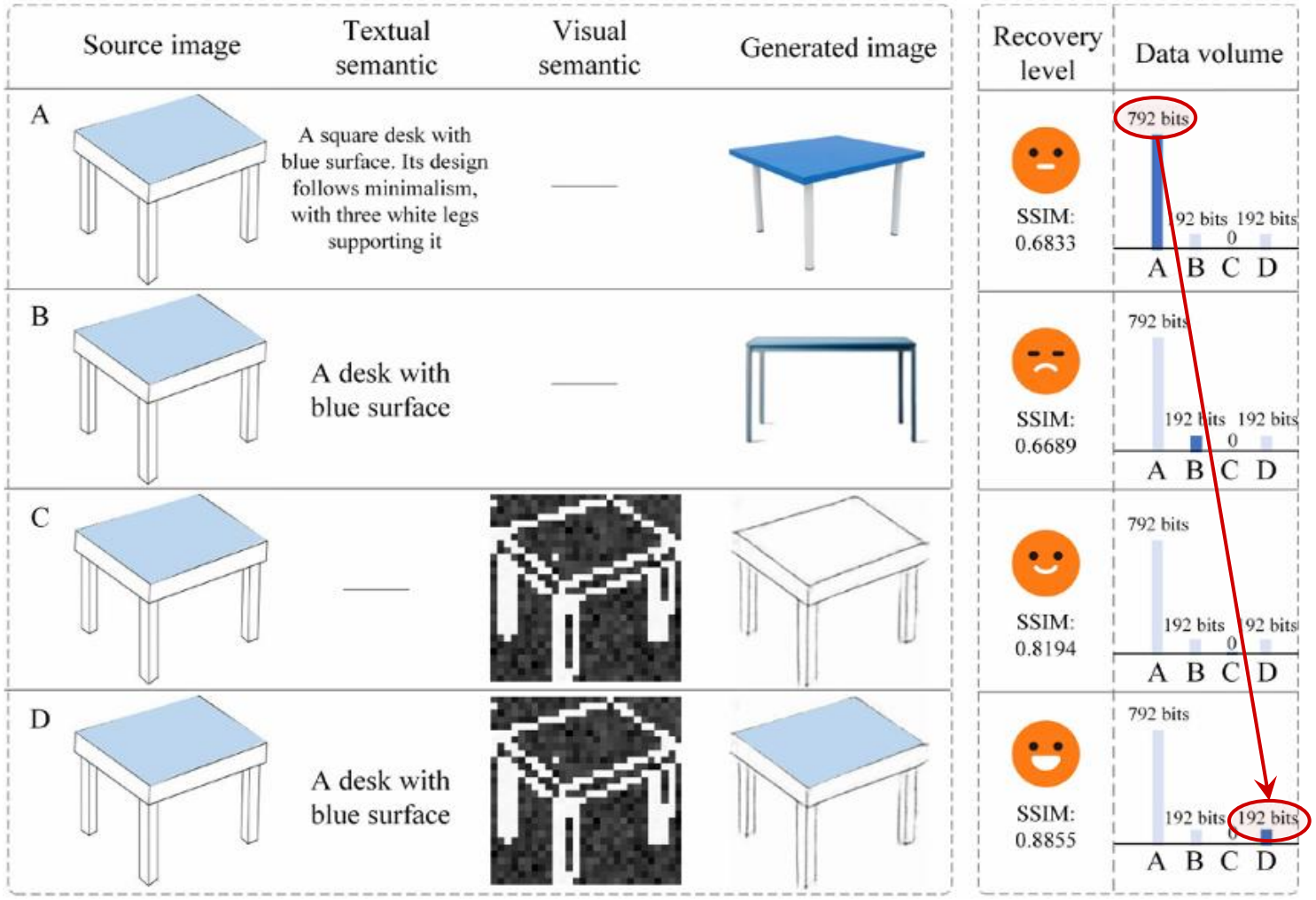
MSE vs. # of meta-atoms on each layer



[R13] G. Huang, J. An, L. Gan, D. Niyato, M. Debbah and T. J. Cui, "**Stacked intelligent metasurfaces** for multi-modal semantic communications," *IEEE Wireless Commun. Lett.*, vol. 14, no. 9, pp. 2828-2832, Sept. 2025.

❖ 2.2 SIM for Multi-Modal Semantic Communications

- Thickness of SIM: *10λ*
- Number of antennas: *28×28*
- Inter-layer distance: *λ*
- Transmit power: *40* dBm
- Noise power: *-104* dBm
- Antenna spacing: *λ/2*



[R13] G. Huang, J. An, L. Gan, D. Niyato, M. Debbah and T. J. Cui, "**Stacked intelligent metasurfaces** for multi-modal semantic communications," *IEEE Wireless Commun. Lett.*, vol. 14, no. 9, pp. 2828-2832, Sept. 2025.

❖ References

1. J. An, M. Debbah, T. J. Cui, Z. N. Chen and C. Yuen, "Emerging technologies in **intelligent metasurfaces**: Shaping the future of wireless communications," *IEEE Trans. Antennas Propag.*, 2025, Early Access. (**Invited Paper**)
2. X. Lin, Y. Rivenson, N. T. Yardimci, M. Veli, Y. Luo, M. Jarrahi, and **A. Ozcan**, "All-optical machine learning using diffractive deep neural networks," *Science*, vol. 361, no. 6406, pp.1004-1008, 2018.
3. J. An, C. Xu, D. W. K. Ng, G. C. Alexandropoulos, C. Huang, C. Yuen and L. Hanzo, "**Stacked intelligent metasurfaces** for efficient holographic MIMO communications in 6G," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 8, pp. 2380-2396, Aug. 2023.
4. J. An, M. D. Renzo, M. Debbah, H. V. Poor and C. Yuen, "**Stacked intelligent metasurfaces** for multiuser downlink beamforming in the wave domain," *IEEE Trans. Wireless Commun.*, vol. 24, no. 7, pp. 5525-5538, Jul. 2025.
5. Z. Wang, H. Liu, J. Zhang, R. Xiong, K. Wan, X. Qian, M. Di Renzo and **R. C. Qiu**, "Multi-user ISAC through **stacked intelligent metasurfaces**: New algorithms and experiments," *Proc. GLOBECOM 2024*, Cape Town, South Africa, 2024, pp. 4442-4447.
6. J. An, C. Yuen, Y. L. Guan, M. Di Renzo, M. Debbah, H. V. Poor and L. Hanzo, "Two-dimensional direction-of-arrival estimation using **stacked intelligent metasurfaces**," *IEEE J. Sel. Areas Commun.*, vol. 42, no. 10, pp. 2786-2802, Oct. 2024.
7. Q. Li, M. El-Hajjar, C. Xu, J. An, C. Yuen and L. Hanzo, "**Stacked intelligent metasurfaces** for holographic MIMO-aided cell-free networks," *IEEE Trans. Commun.*, vol. 72, no. 11, pp. 7139-7151, Nov. 2024.
8. Y. Hu, J. Zhang, E. Shi, Y. Lu, J. An, C. Yuen and B. Ai, "Joint beamforming and power allocation design for **stacked intelligent metasurfaces**-aided cell-free massive MIMO systems," *IEEE Trans. Veh. Technol.*, vol. 74, no. 3, pp. 5235-5240, Mar. 2025.
9. E. Shi, J. Zhang, Y. Zhu, J. An, C. Yuen and B. Ai, "Uplink performance of **stacked intelligent metasurface**-enhanced cell-free massive MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 24, no. 5, pp. 3731-3746, May 2025.
10. E. Shi, J. Zhang, J. An, G. Zhang, Z. Liu, C. Yuen and B. Ai, "Joint AP-UE association and precoding for **SIM**-aided cell-free massive MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 24, no. 6, pp. 5352-5367, Jun. 2025.
11. Z. Li, J. An and C. Yuen, "**Stacked intelligent metasurfaces**-enhanced MIMO OFDM wideband communication systems," *IEEE Trans. Wireless Commun.*, (Minor Revision) Online: https://arxiv.org/abs/2503.00368
12. Z. Li, J. An and C. Yuen, "**Stacked intelligent metasurface**-enhanced wideband multiuser MIMO OFDM-IM communications," *IEEE Trans. Wireless Commun.*, (Submitted) Online: https://arxiv.org/abs/2509.22327
13. G. Huang, J. An, L. Gan, D. Niyato, M. Debbah and T. J. Cui, "**Stacked intelligent metasurfaces** for multi-modal semantic communications," *IEEE Wireless Commun. Lett.*, vol. 14, no. 9, pp. 2828-2832, Sept. 2025.

Many Thanks!