

Stacked Intelligent Metasurfaces (SIM) Based Signal Processing in the Electromagnetic Domain

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- ❑ **2 Stacked Intelligent Metasurfaces (SIM)**
 - 2.1 Motivation**
 - 2.2 Applications**

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- ❑ **1 Background**

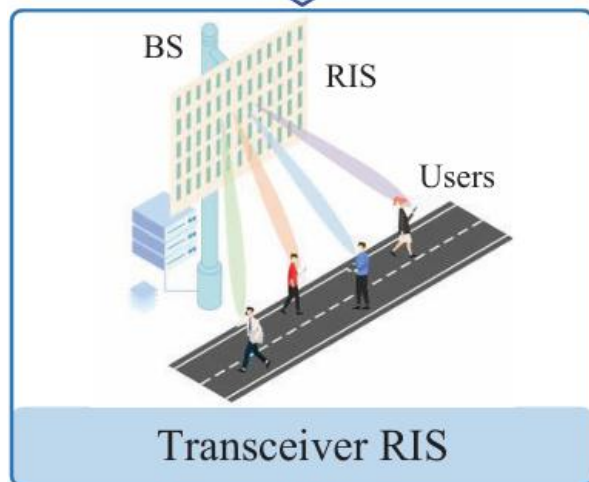
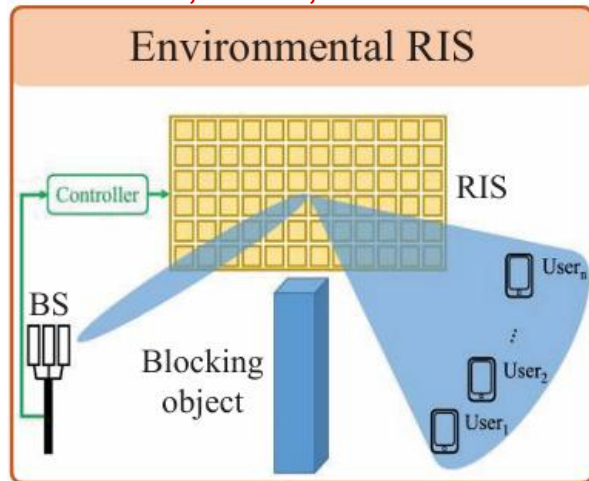
- ❑ **2 Stacked Intelligent Metasurfaces (SIM)**

 - 2.1 Motivation**

 - 2.2 Applications**

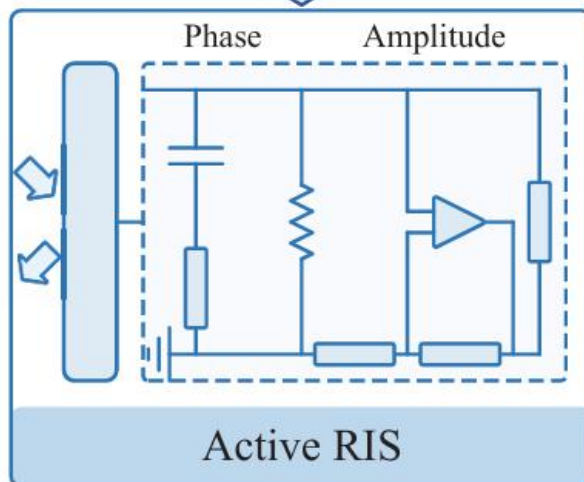
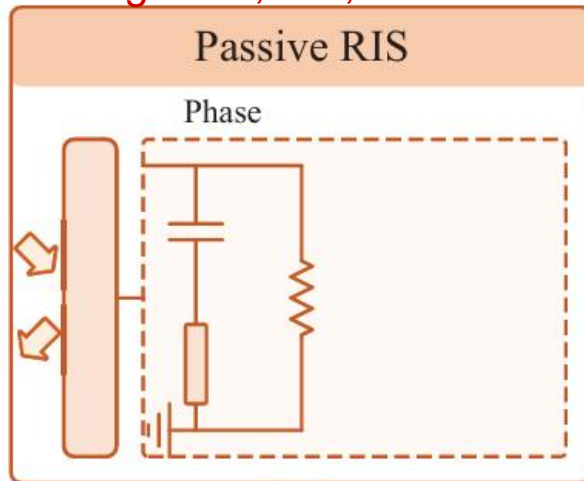
❖ 1 Background

Jin et al., TWC, 2021



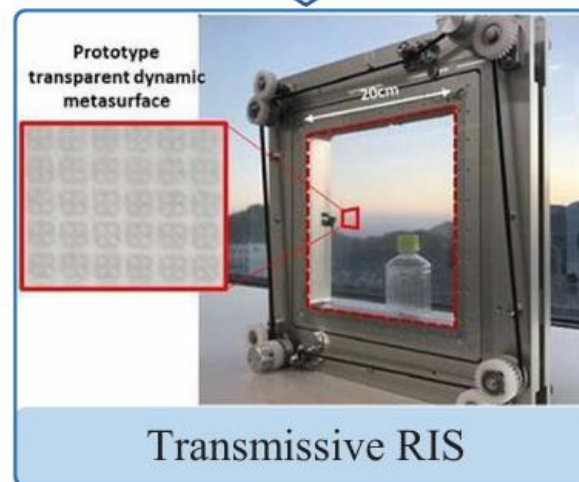
Song et al., TWC, 2022

Zhang et al., CM, 2020



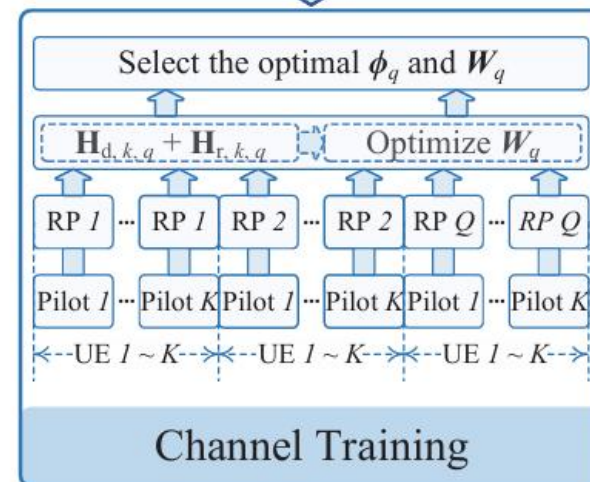
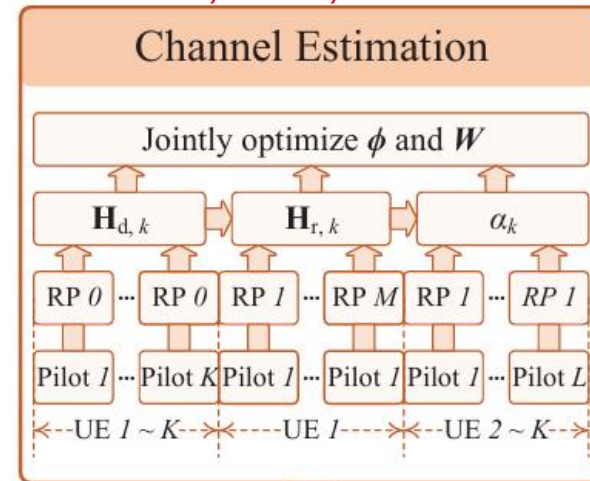
Dai et al., TCOM, 2023

Di Renzo et al., JSAC, 2020



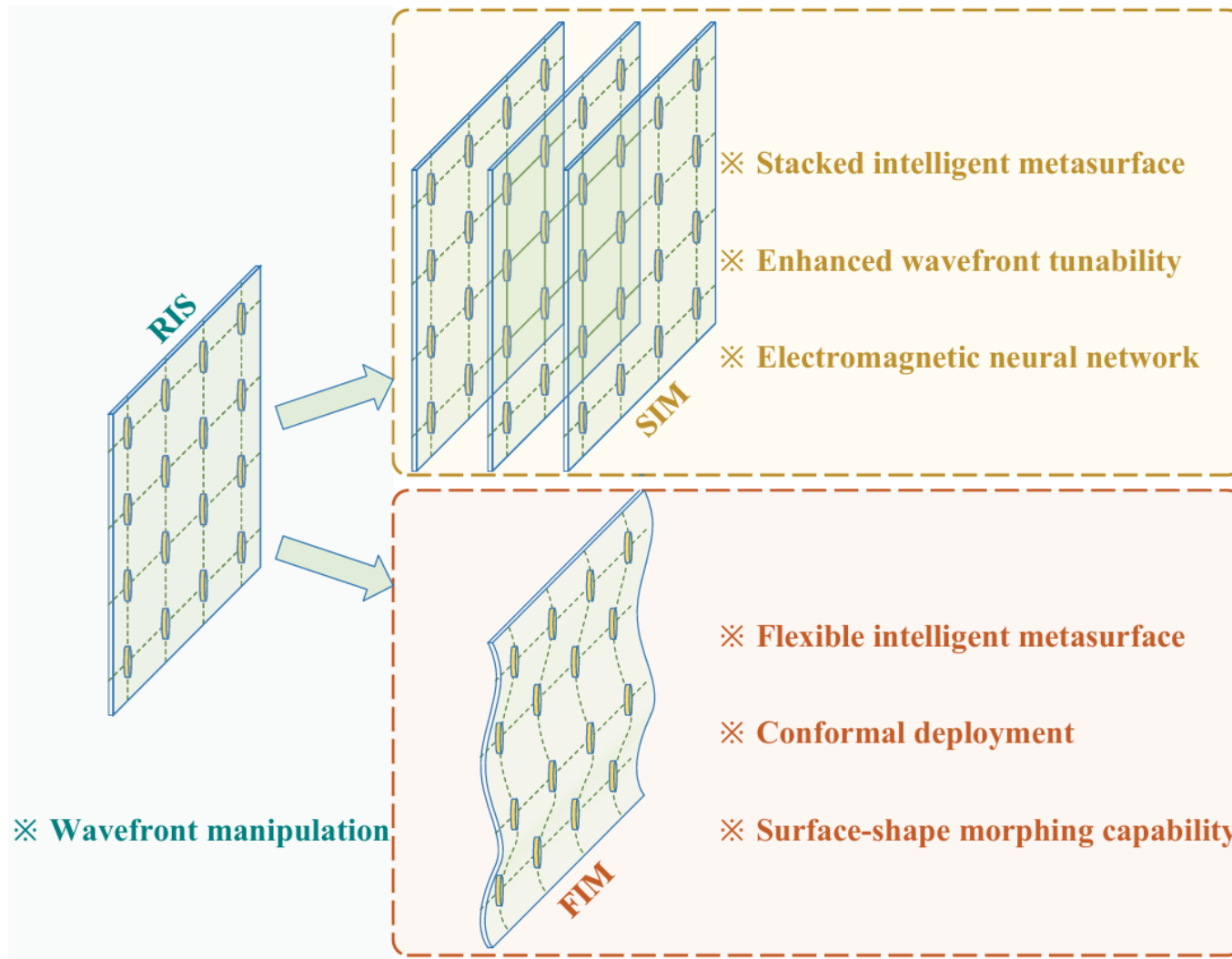
NTT DOCOMO, 2021

Cui et al., TWC, 2020



An et al., WCM, 2024

❖ 1 Background



Single-Layer ⇒ *Multiple-Layer*

Rigid ⇒ *Flexible*

Contents

❑ 1 Background

❑ **2 Stacked Intelligent Metasurfaces (SIM)**

2.1 Motivation

2.2 Applications

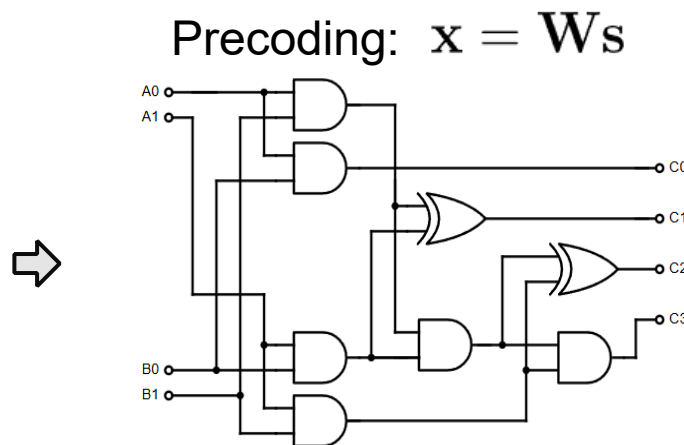
❖ 2.1 Re-understanding multiplication & RIS

Human

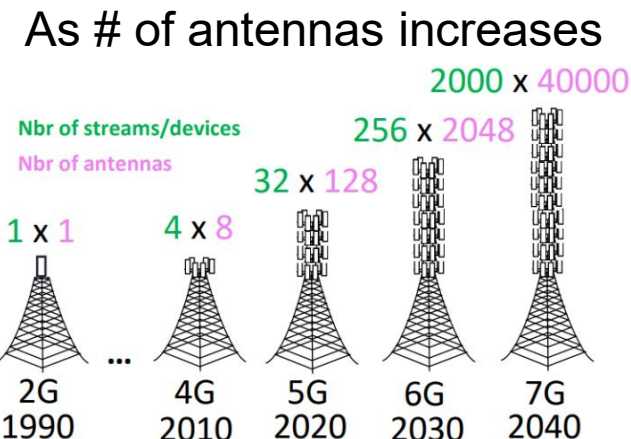
乘法口诀表

一一得一	一二得二	一三得三	一四得四	一五得五	一六得六	一七得七	一八得八	一九得九
二二得四	二三得六	二四得八	二五得十	二六得十二	二七得十四	二八得十六	二九得十八	
三三得九	三四得十二	三五得十五	三六得十八	三七得二十一	三八得二十四	三九得二十七		
四四得十六	四五得二十	四六得二十四	四七得二十八	四八得三十二	四九得三十六			
五五得二十五	五六得三十	五七得三十五	五八得四十	五九得四十五				
六六得三十六	六七得四十二	六八得四十八	六九得五十四					
七七得四十九	七八得五十六	七九得六十三						
八八得六十四	八九得七十二							
九九得八十一								

Rule-based lookup table

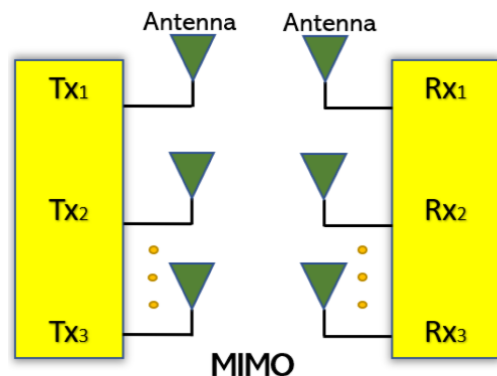


Energy-consuming,
time-consuming



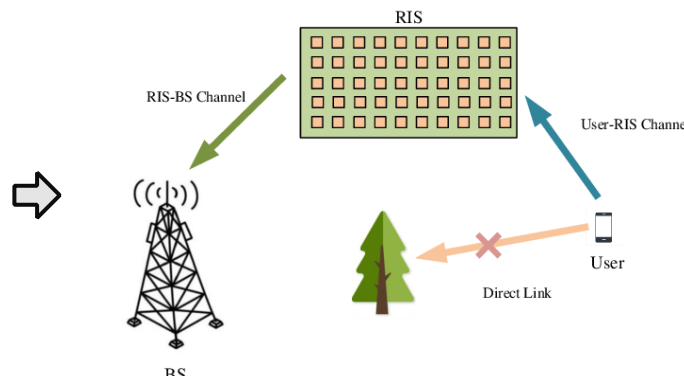
Poor scalability

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



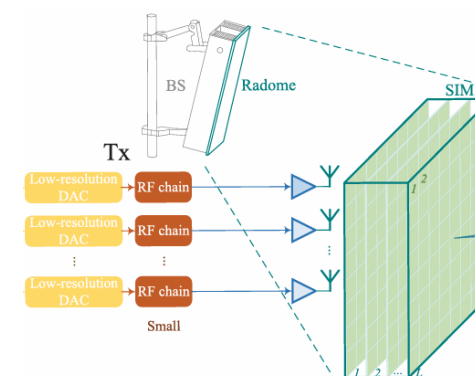
Automatically completed,
not controllable

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



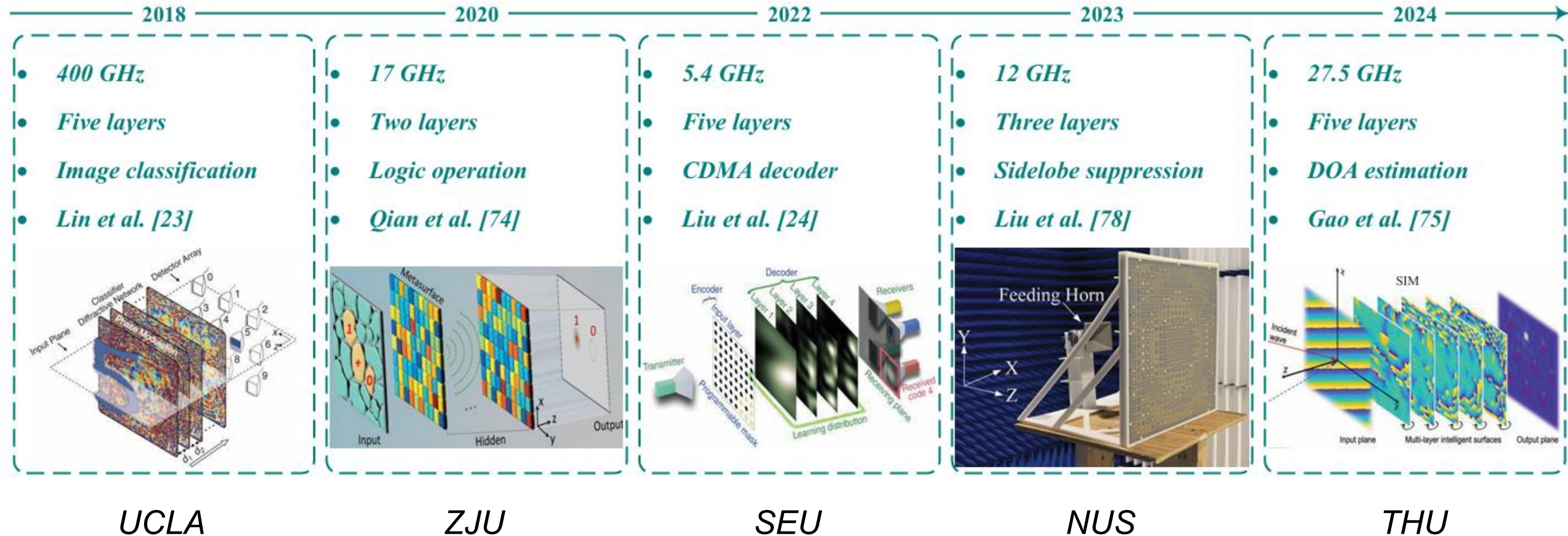
Controllable,
insufficient DoF

SIM

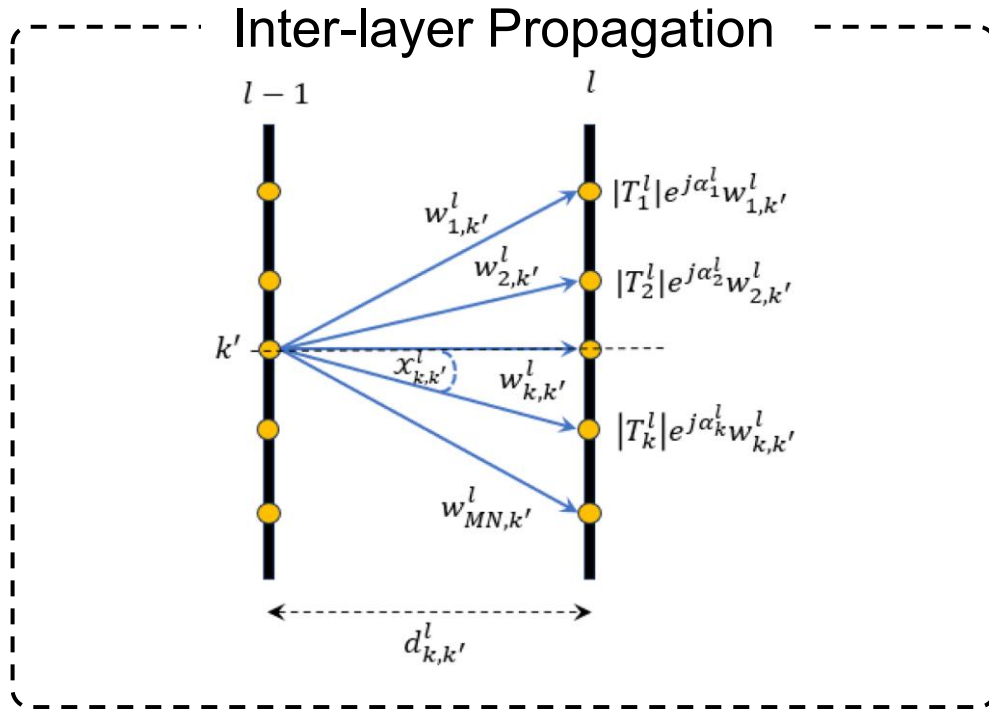


Does it work?

❖ 2.1 SIM: Prototypes

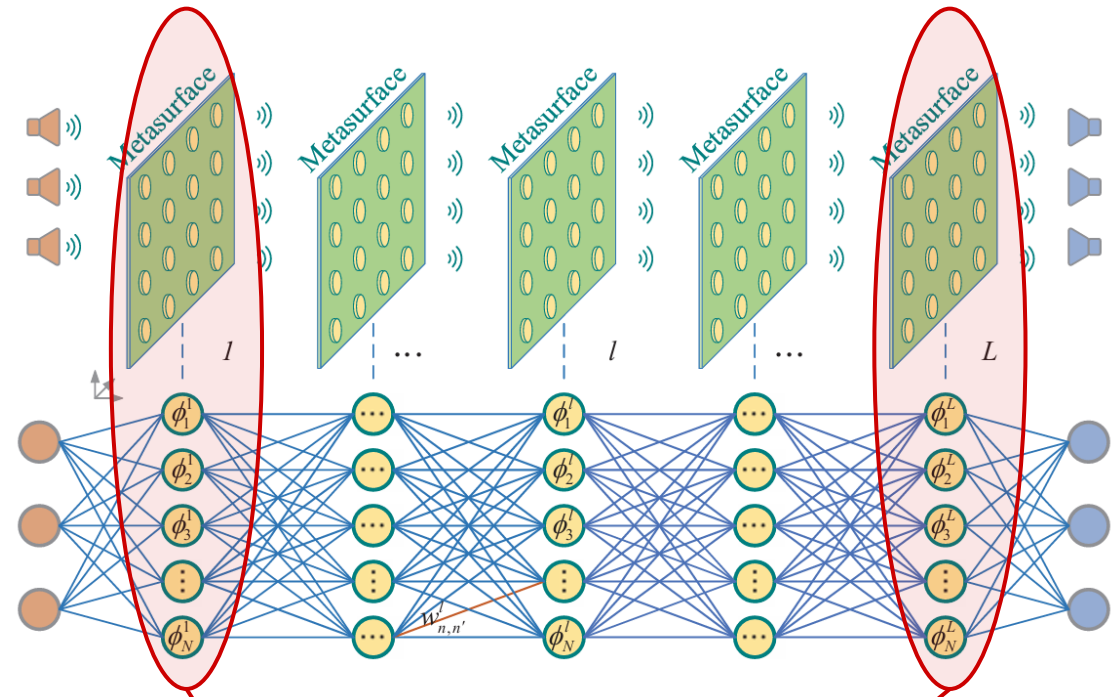


❖ 2.1 SIM: Propagation Modeling



Rayleigh-Sommerfeld Diffraction Theory

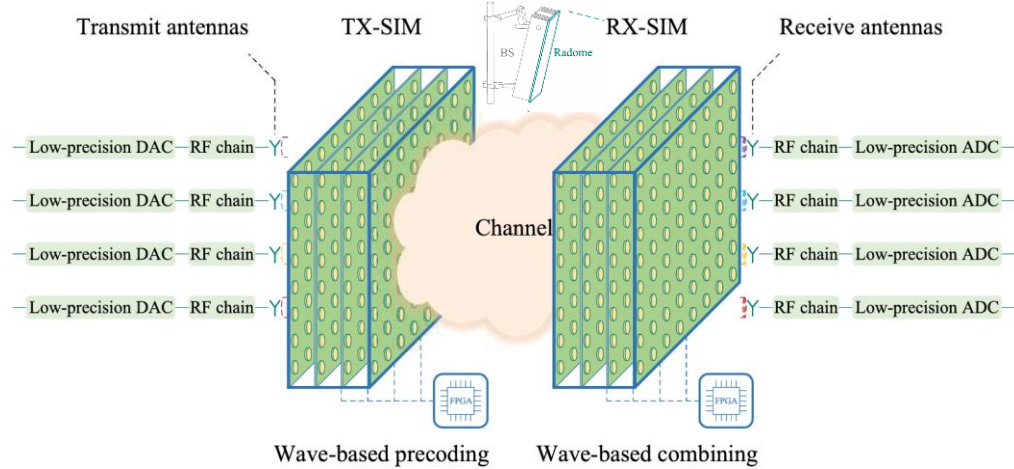
$$w_{n,n'}^l = \frac{A \cos \chi_{n,n'}^l}{r_{n,n'}^l} \left(\frac{1}{2\pi r_{n,n'}^l} - j \frac{1}{\lambda} \right) e^{j 2\pi r_{n,n'}^l / \lambda}$$



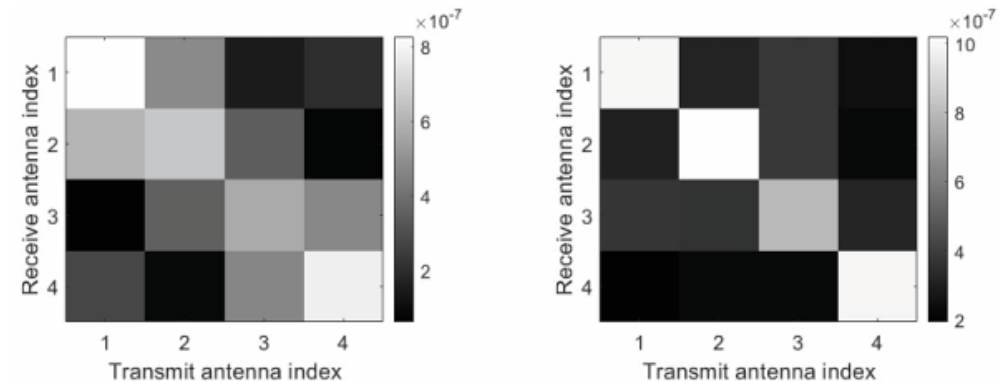
$$\mathbf{S} = \Phi^L \mathbf{W}^L \dots \Phi^2 \mathbf{W}^2 \Phi^1 \in \mathbb{C}^{N \times N}$$

❖ 2.1 SIM: MIMO Precoding

- SIM-aided MIMO Transmission



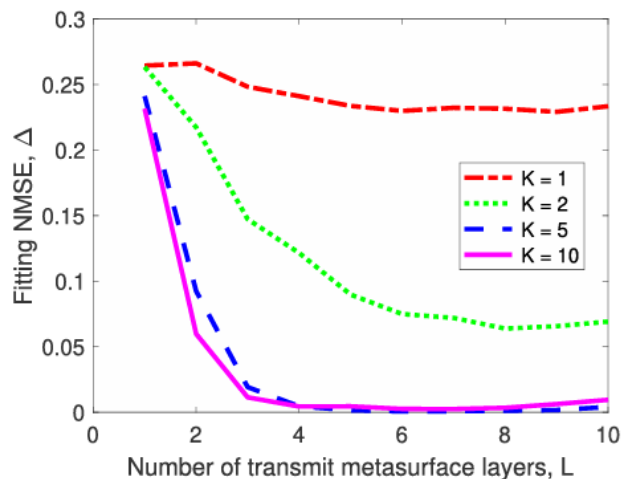
End-to-end channel



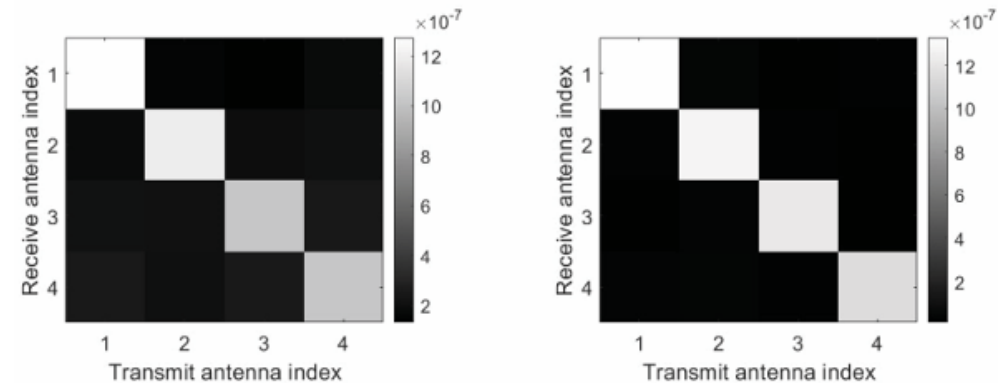
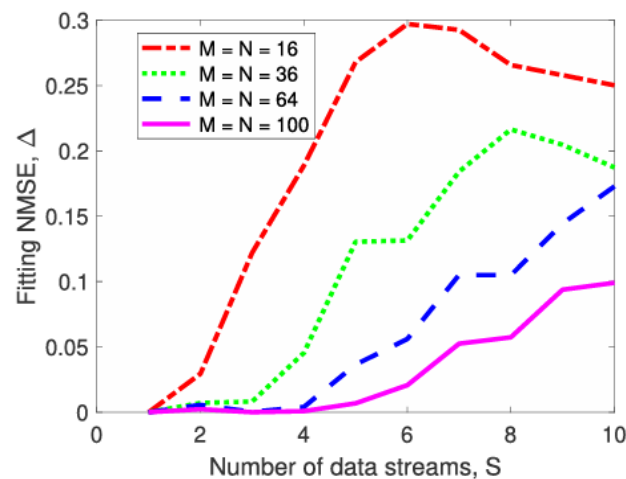
(a) $L = K = 1$

(b) $L = K = 2$

NMSE vs L & K



NMSE vs S & M

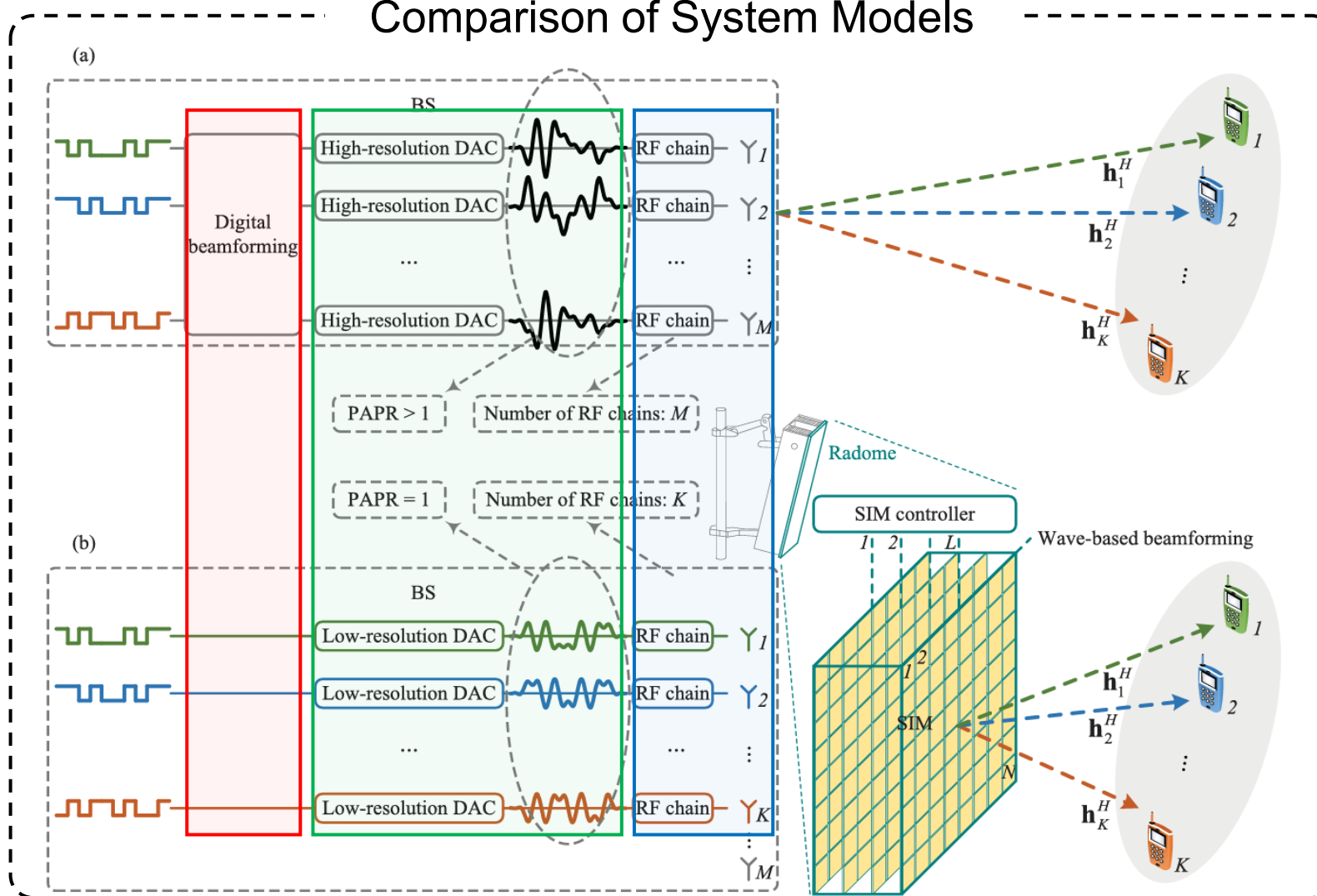


(c) $L = K = 3$

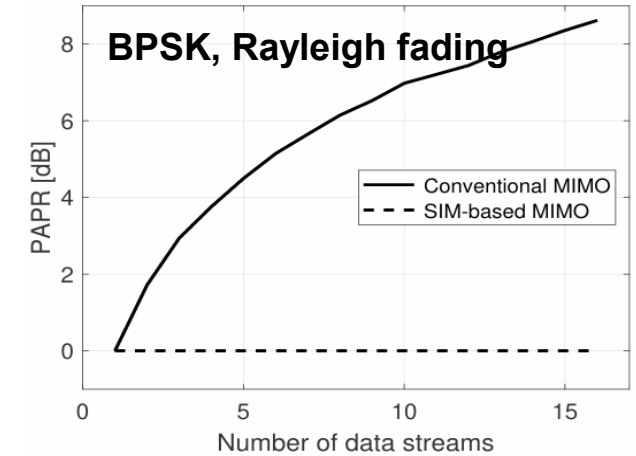
(d) $L = K = 4$

❖ 2.1 SIM: Benefits

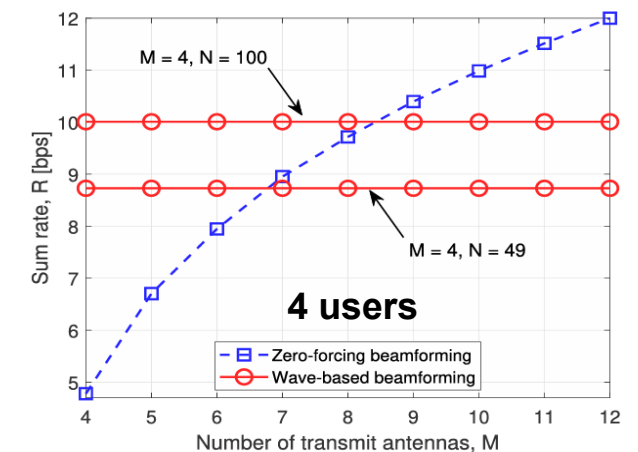
Comparison of System Models



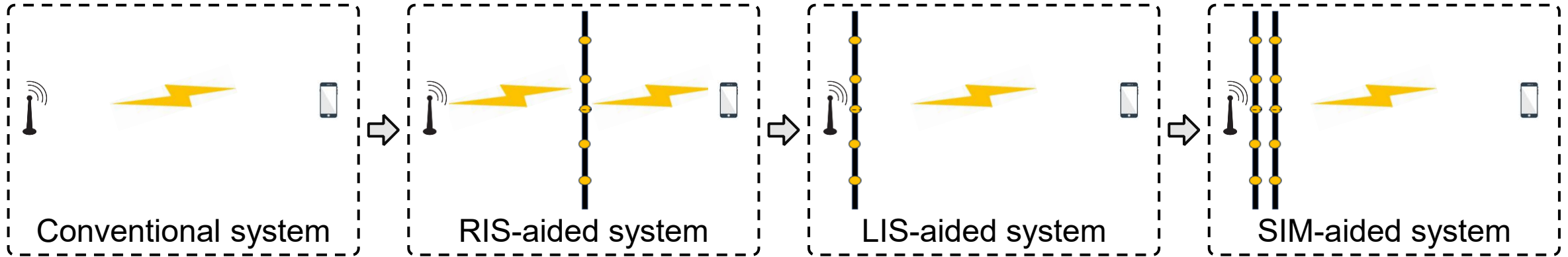
PAPR vs. # of Streams



Performance Comparison



❖ 2.1 Will more layers decrease the received power?



○ Uncontrollable channel



Path loss



Path loss



Path loss

○ Severe path loss



Penetration loss



Penetration loss



Penetration loss



Array gain



Array gain



Array gain

Which one dominates?

=



Array gain

+



Penetration loss

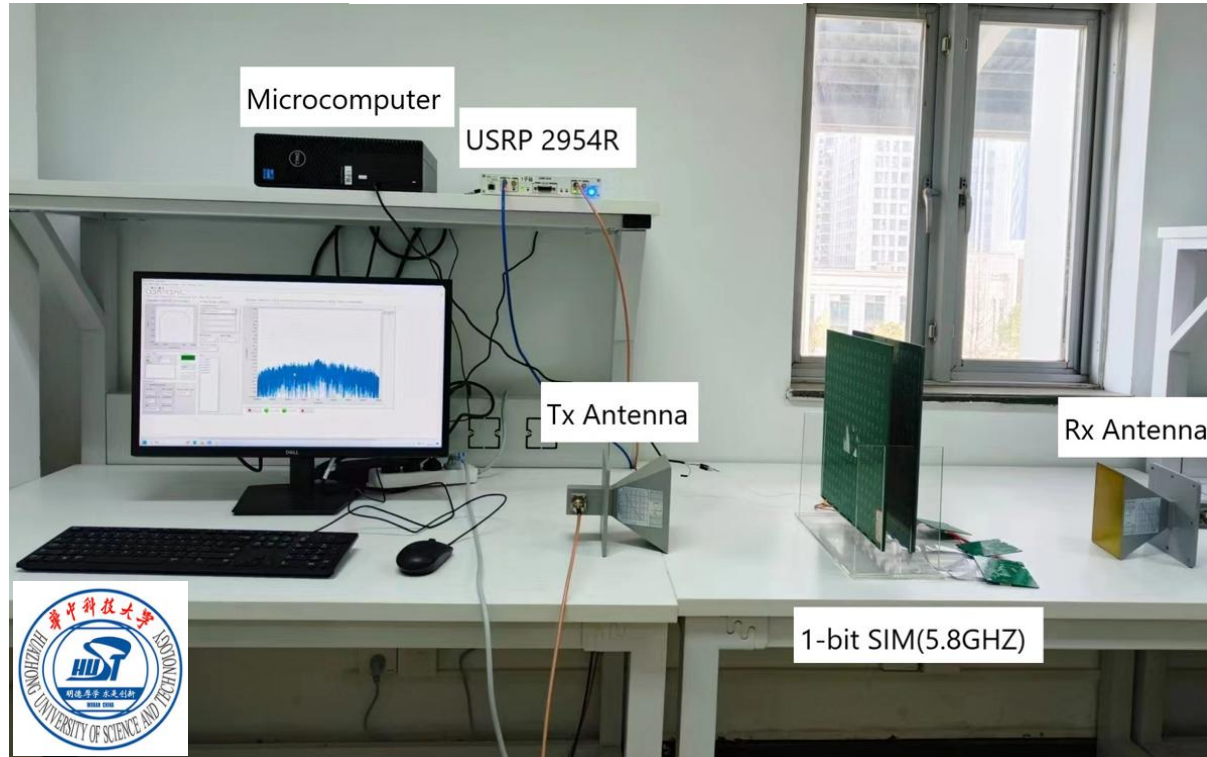
+



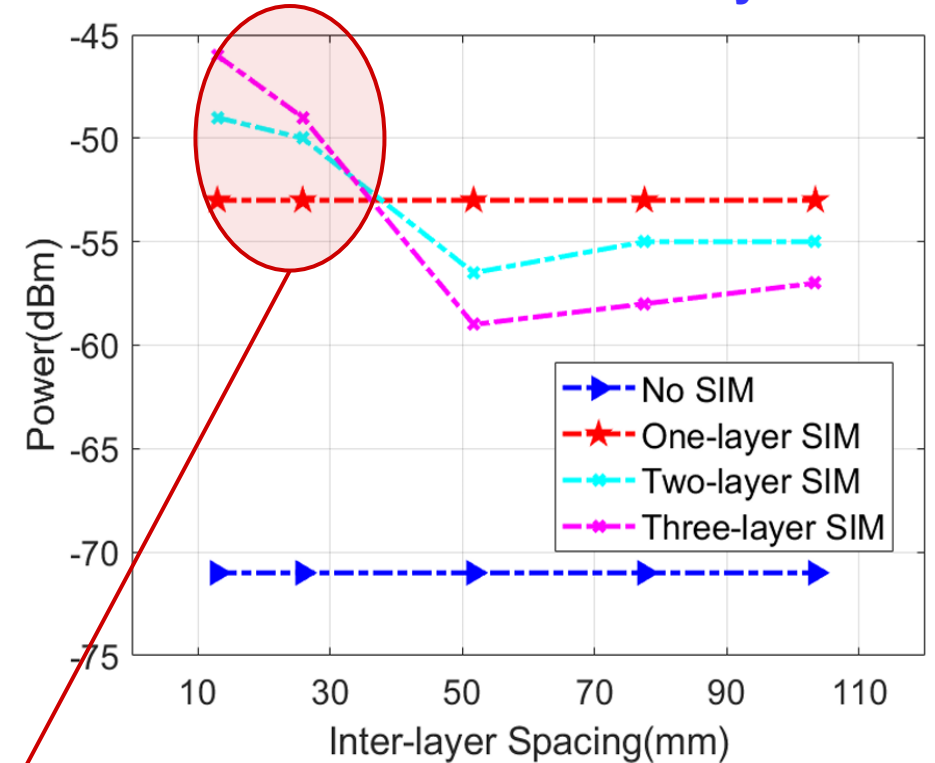
Path loss

❖ 2.1 Will more layers decrease the received power?

SIM Prototype



Received Power vs. # of Layers



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

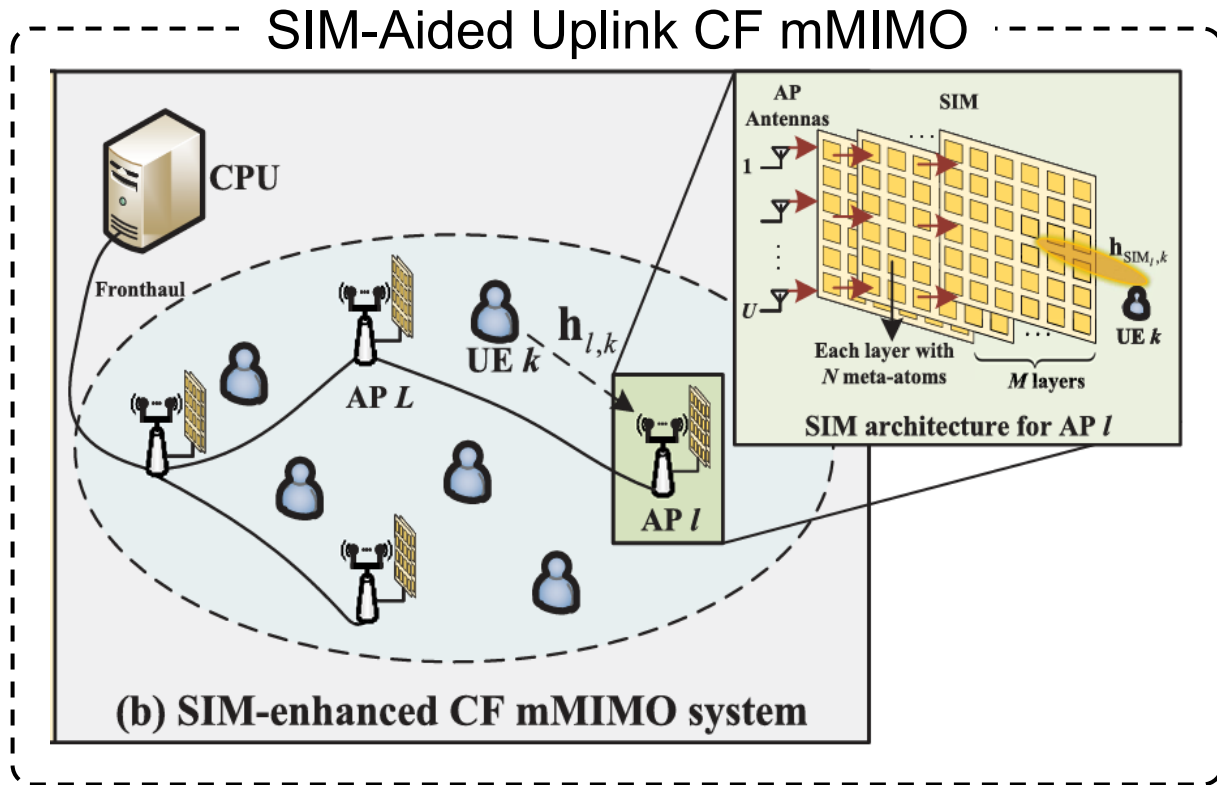
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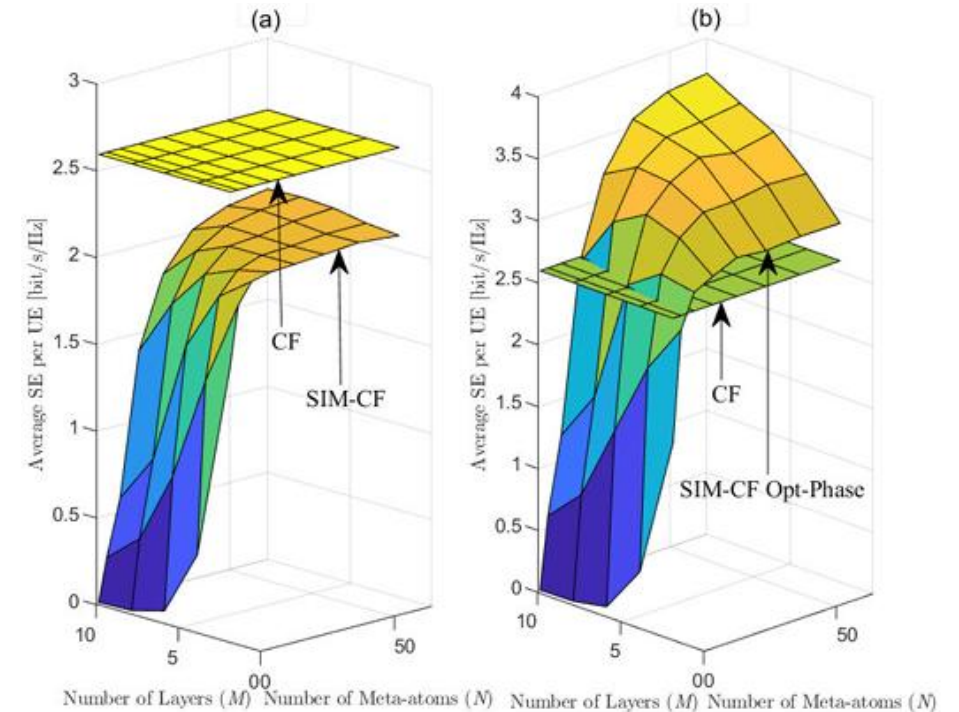
2.1 Motivation

2.2 Applications

❖ 2.2 SIM for CF mMIMO: Distributed Deployment

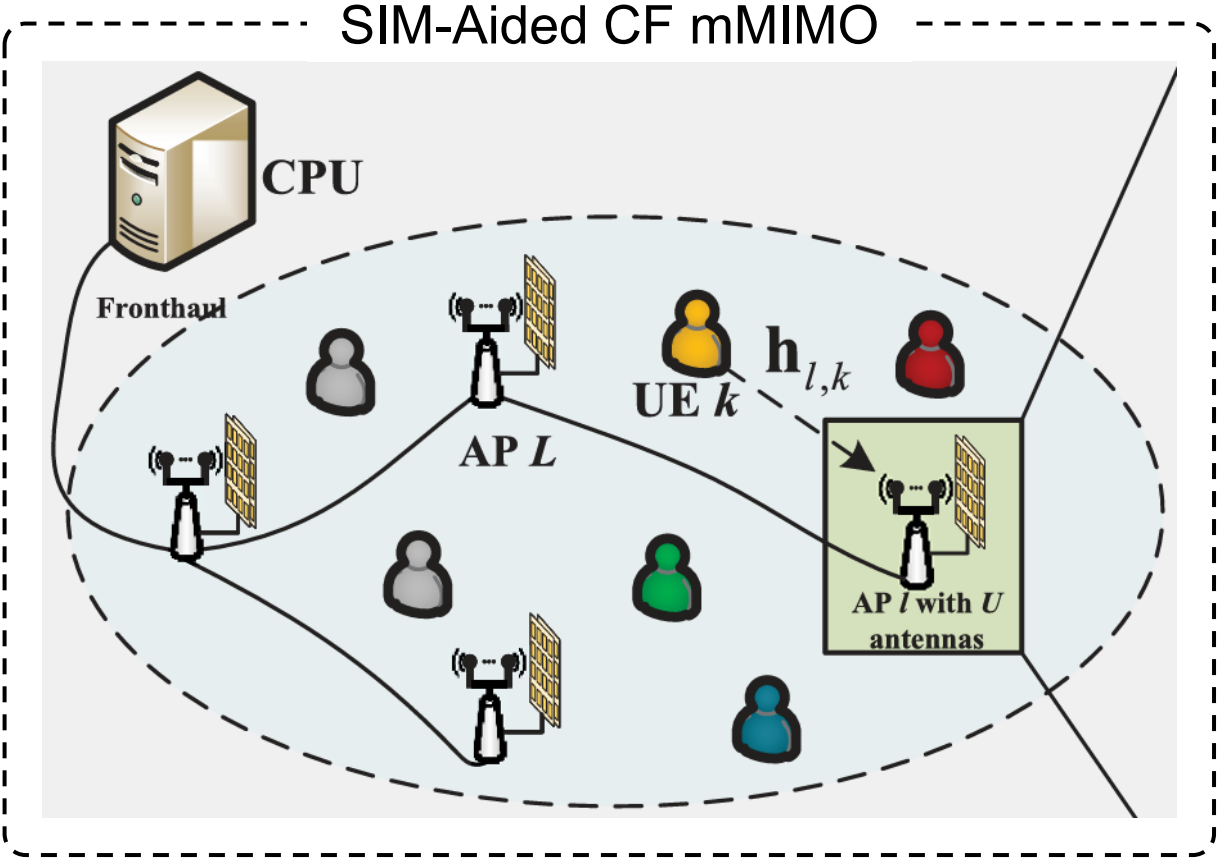


SE vs. # of layers and meta-atoms

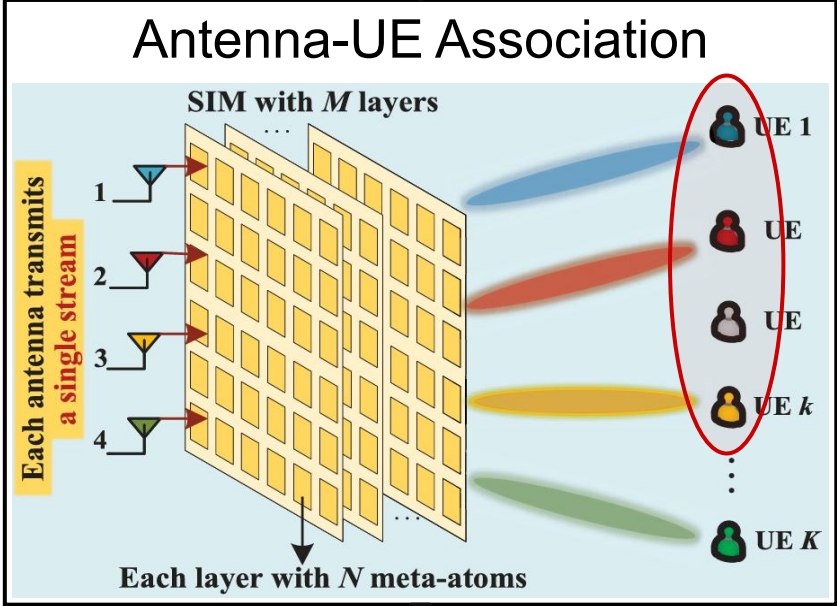


- [R07] Q. Li, M. El-Hajjar, C. Xu, J. An, C. Yuen and L. Hanzo, “**Stacked intelligent metasurfaces** for holographic MIMO-aided cell-free networks,” *IEEE Trans. Commun.*, vol. 72, no. 11, pp. 7139-7151, Nov. 2024.
- [R8] Y. Hu, J. Zhang, E. Shi, Y. Lu, J. An, C. Yuen and B. Ai, “Joint beamforming 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



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



Heuristic method

For each AP:

Find the Nearest M UEs

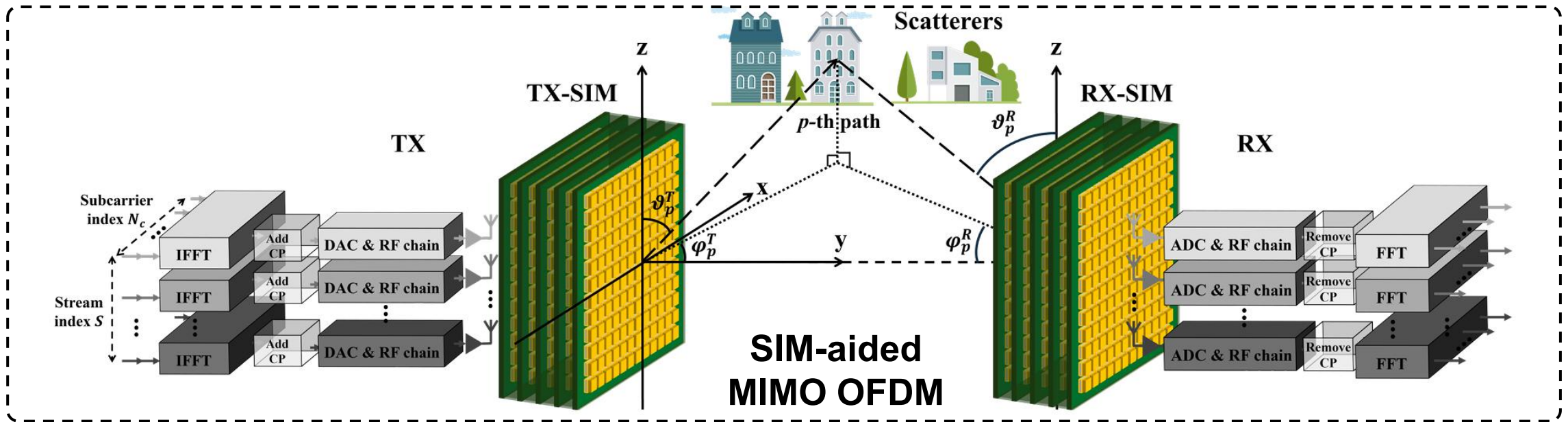
As L increases infinitely

Asymptotically Optimal

Gain Dominant --- MRT

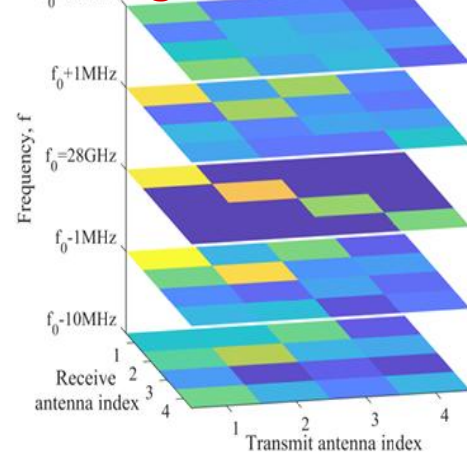
[R10] E. Shi, J. Zhang, J. An, G. Zhang, Z. Liu, C. Yuen and B. Ai, "Joint AP-UE association and precoding for SIM-aided cell-free massive MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 24, no. 6, pp. 5352-5367, Jun. 2025.

❖ 2.2 SIM for Wideband Communications (OFDM)

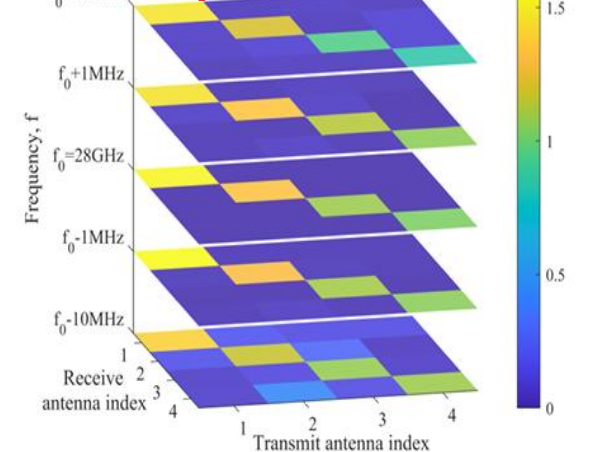


	Interference-free transmission	Interference-present transmission
Bandwidth	$B \leq B_e$	$B > B_e$
Fitting error	$\Gamma_{\min} \approx 0$	$\Gamma_{\min} > 0$
Illustration of the end-to-end channel		

Single-subcarrier

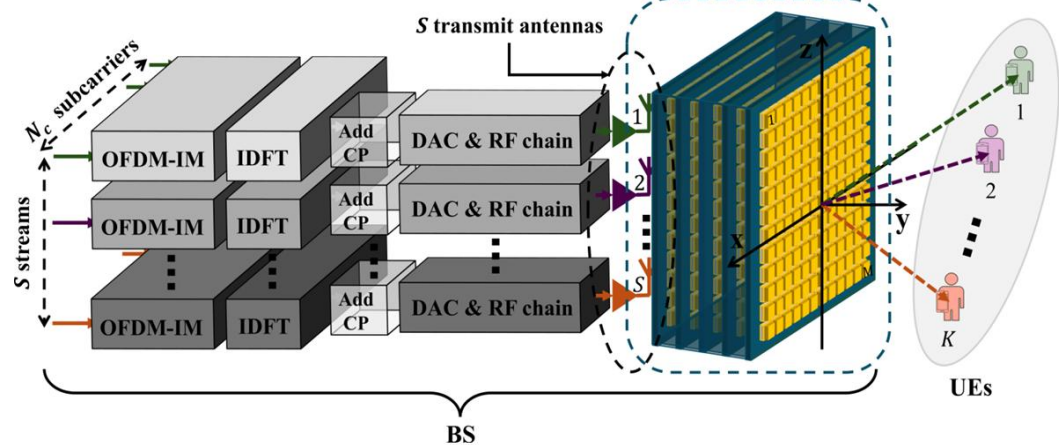


Multiple-subcarrier

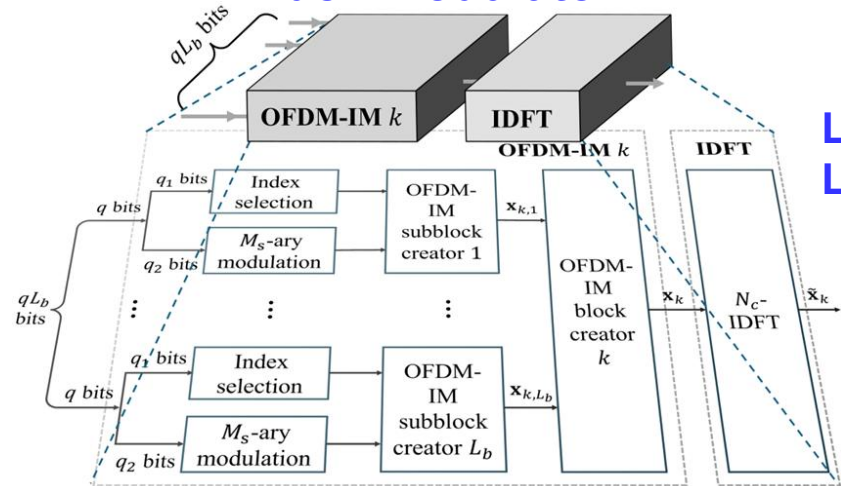


❖ 2.2 SIM for Wideband Communications (OFDM-IM)

SIM-aided wideband MIMO OFDM

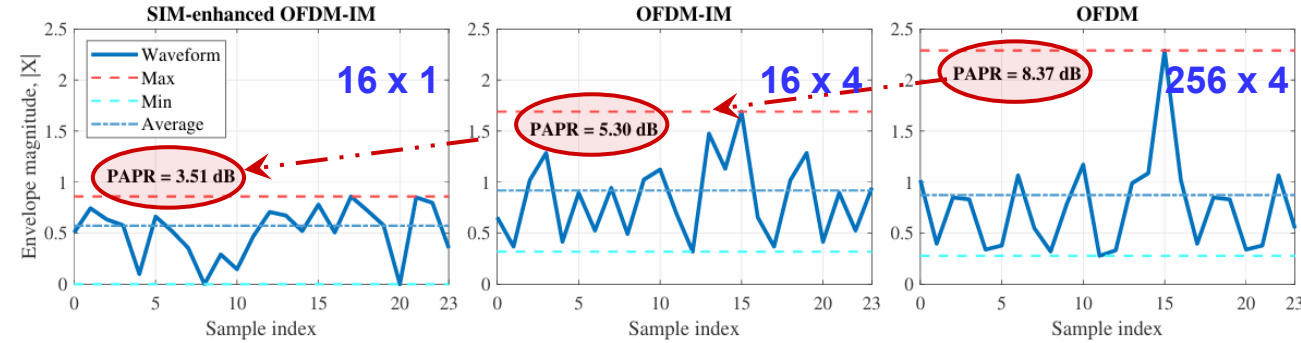


Index modulator

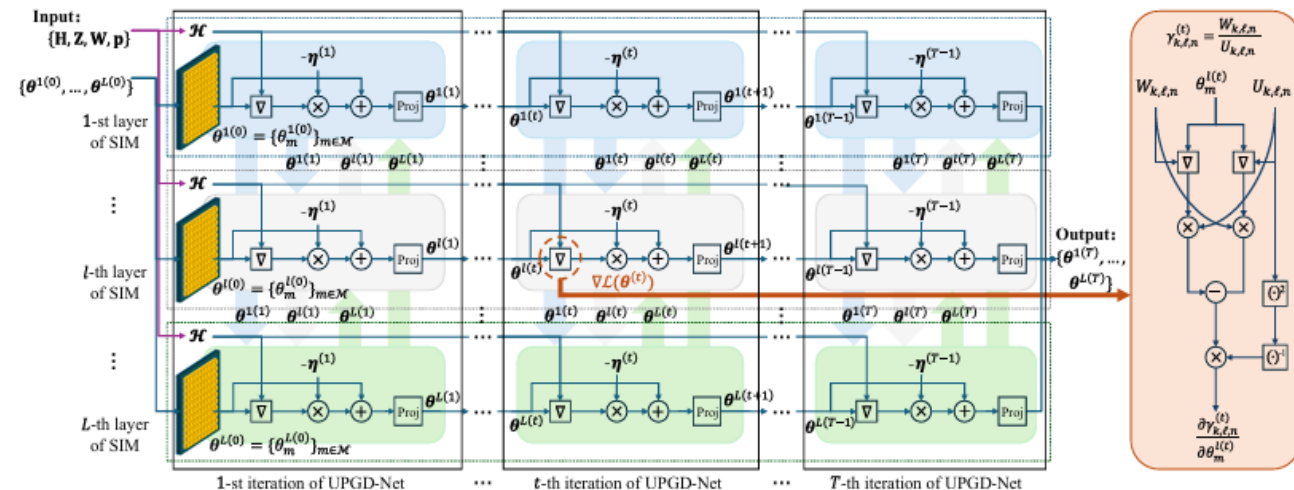


Lower PAPR
Larger BW

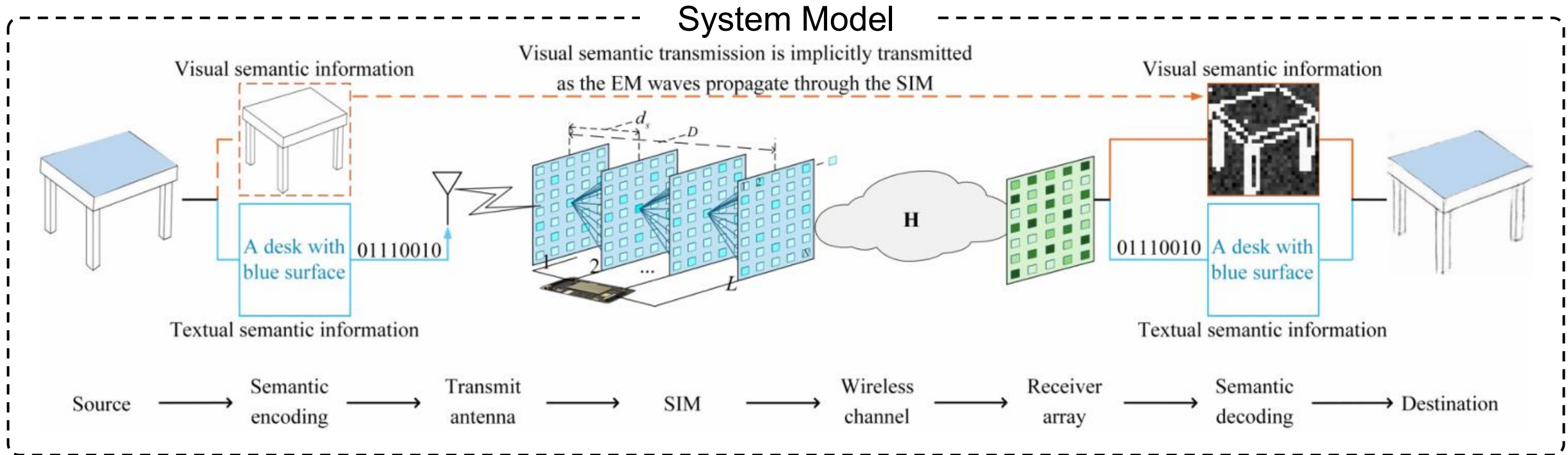
PAPR Comparison



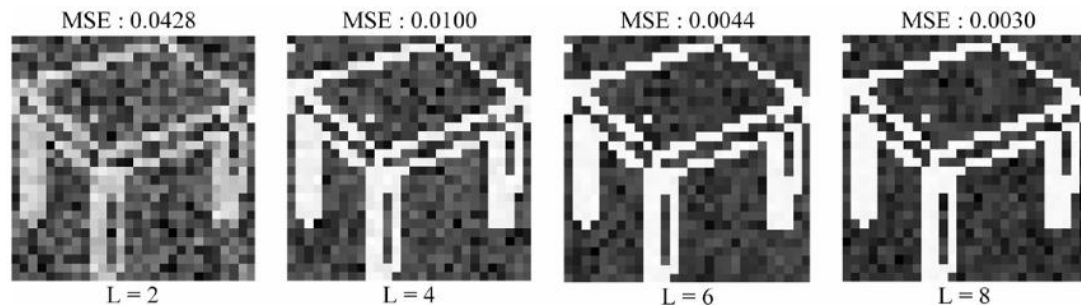
Deep unfolding strategy



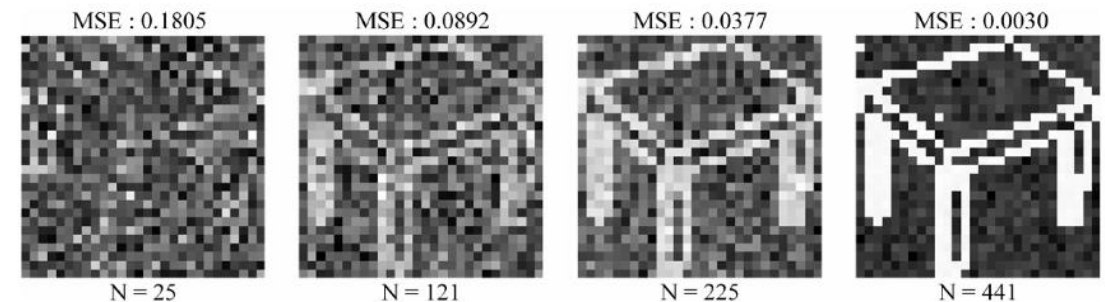
❖ 2.2 SIM for Multi-Modal Semantic Communications



MSE vs. # of layers



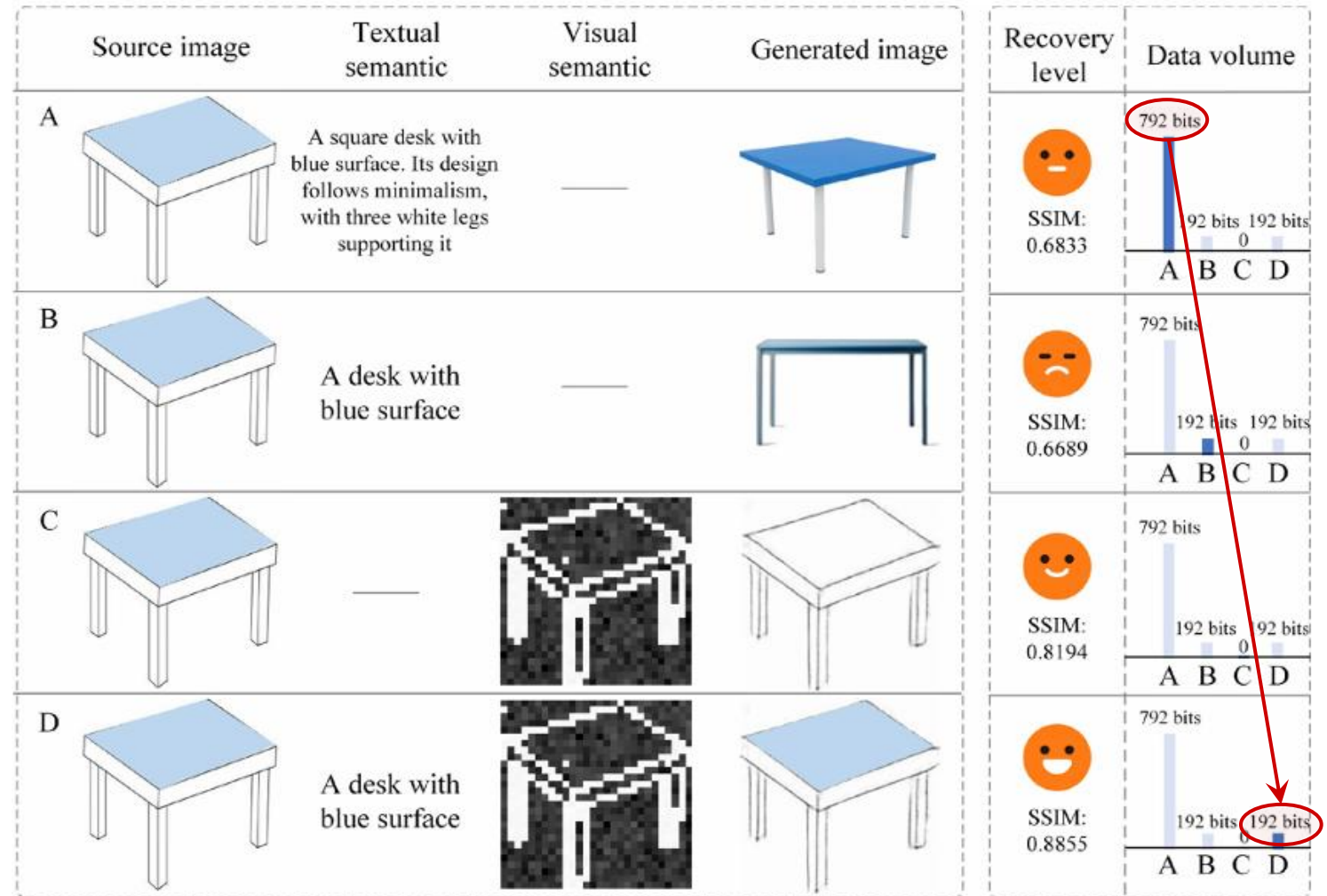
MSE vs. # of meta-atoms on each layer



[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: $\lambda/2$



❖ References

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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.
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Many Thanks!