

Stacked Intelligent Metasurfaces (SIM) and Flexible Intelligent Metasurfaces (FIM)

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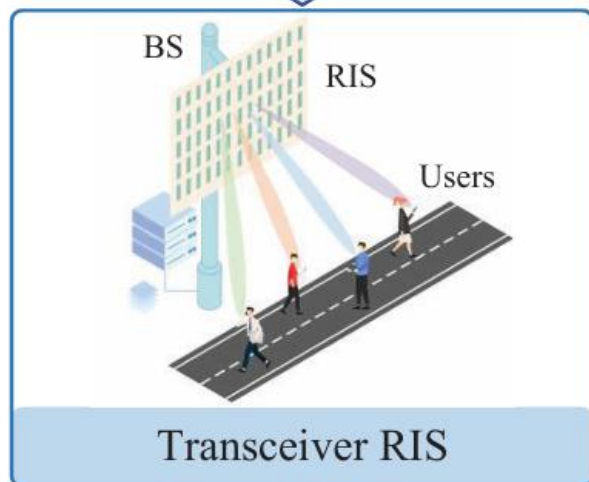
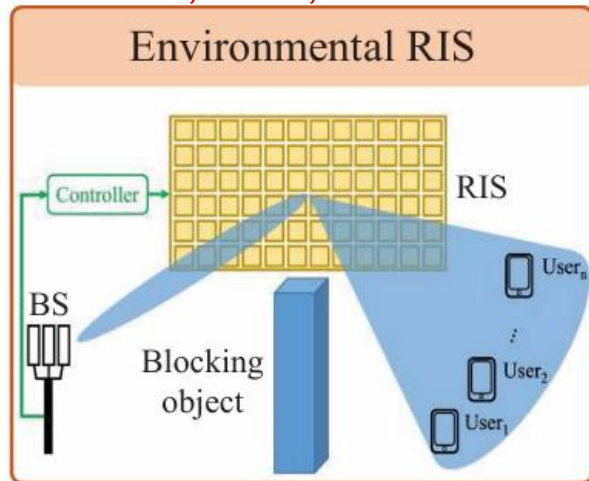
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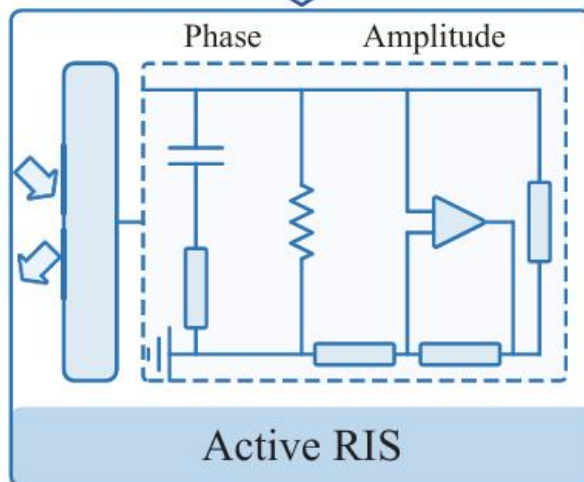
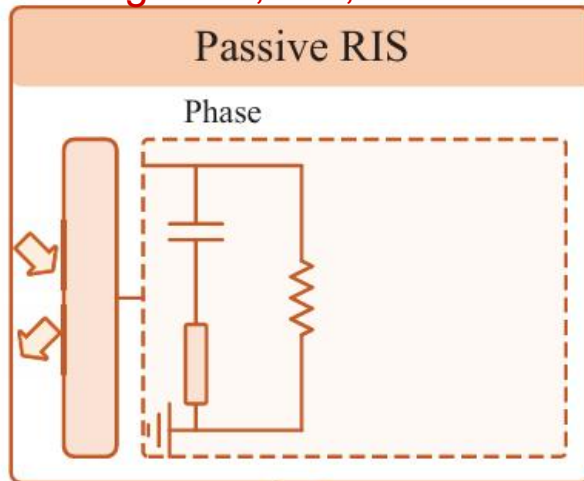
❖ 1 Background

Jin et al., TWC, 2021



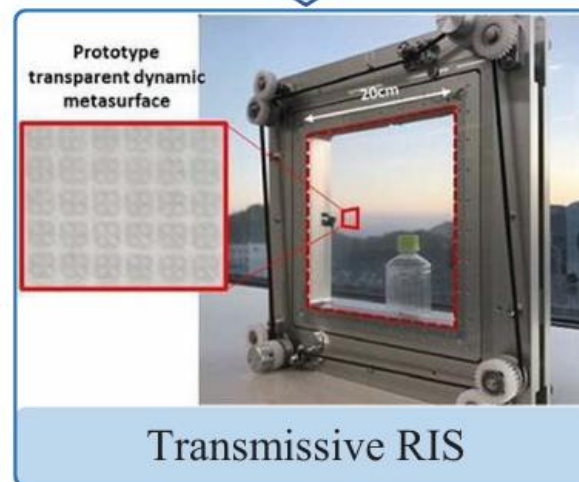
Song et al., TWC, 2022

Zhang et al., CM, 2020



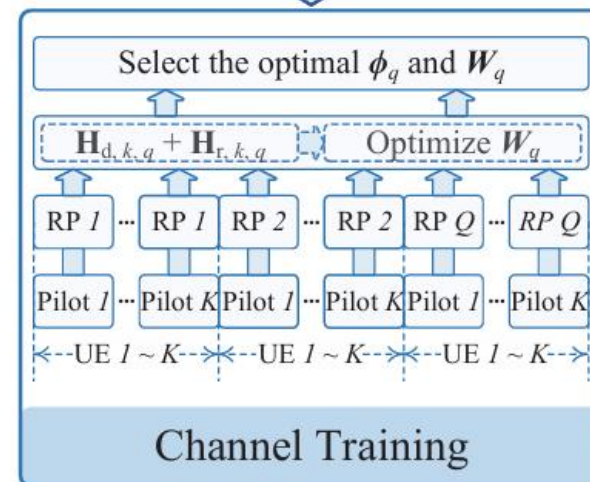
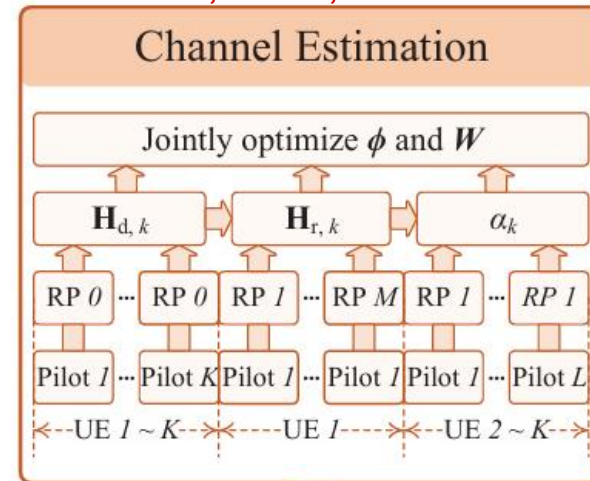
Dai et al., TCOM, 2023

Di Renzo et al., JSAC, 2020



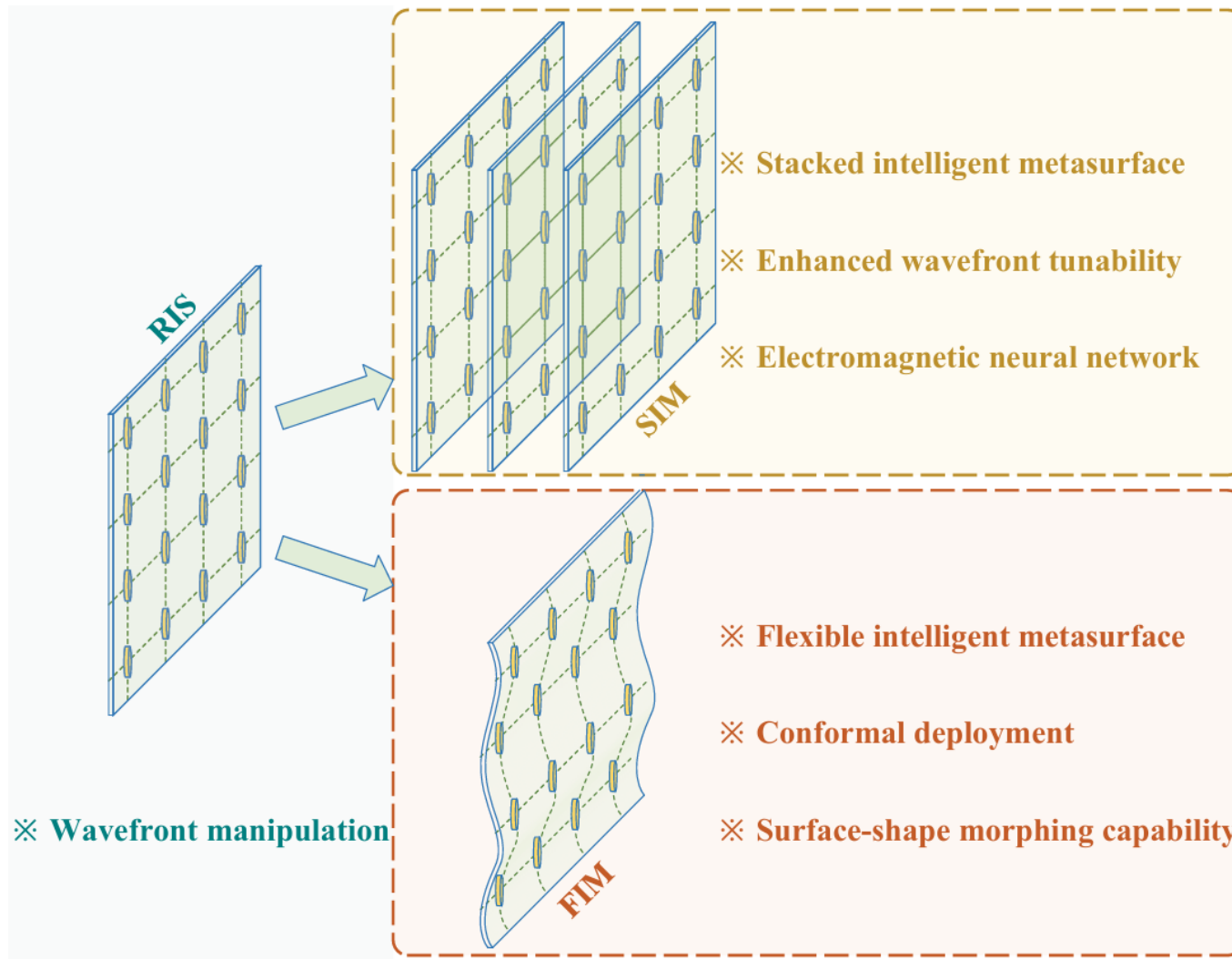
NTT DOCOMO, 2021

Cui et al., TWC, 2020



An et al., WCM, 2024

❖ 1 Background



Single-Layer ⇒ *Multiple-Layer*

Rigid ⇒ *Flexible*

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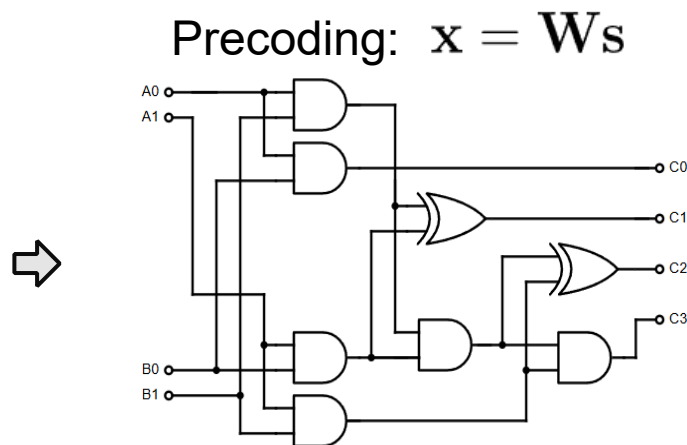
❖ 2.1 Re-understanding multiplication & RIS

Human

乘法口诀表

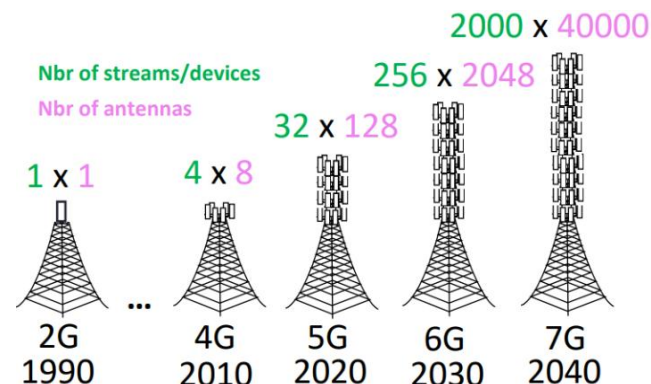
一一得一 1×1=1	一二得二 1×2=2	一三得三 1×3=3	一四得四 1×4=4	一五得五 1×5=5	一六得六 1×6=6	一七得七 1×7=7	一八得八 1×8=8	一九得九 1×9=9
二二得四 2×2=4	二三得六 2×3=6	二四得八 2×4=8	二五得十 2×5=10	二六得十二 2×6=12	二七得十四 2×7=14	二八得十六 2×8=16	二九得十八 2×9=18	
三三得九 3×3=9	三四得十二 3×4=12	三五得十五 3×5=15	三六得十八 3×6=18	三七得二十一 3×7=21	三八得二十四 3×8=24	三九得二十七 3×9=27		
四四得十六 4×4=16	四五得二十 4×5=20	四六得二十四 4×6=24	四七得二十八 4×7=28	四八得三十二 4×8=32	四九得三十六 4×9=36			
五五得二十五 5×5=25	五六得三十 5×6=30	五七得三十五 5×7=35	五八得四十 5×8=40	五九得四十五 5×9=45				
六六得三十六 6×6=36	六七得四十二 6×7=42	六八得四十八 6×8=48	六九得五十四 6×9=54					
七七得四十九 7×7=49	七八得五十六 7×8=56	七九得六十三 7×9=63						
八八得六十四 8×8=64	八九得七十二 8×9=72							
九九得八十一 9×9=81								

Rule-based lookup table



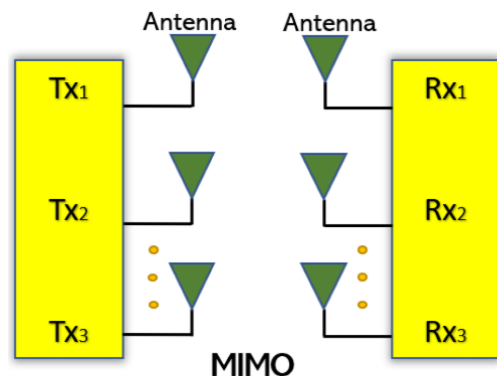
Energy-consuming,
time-consuming

As # of antennas increases



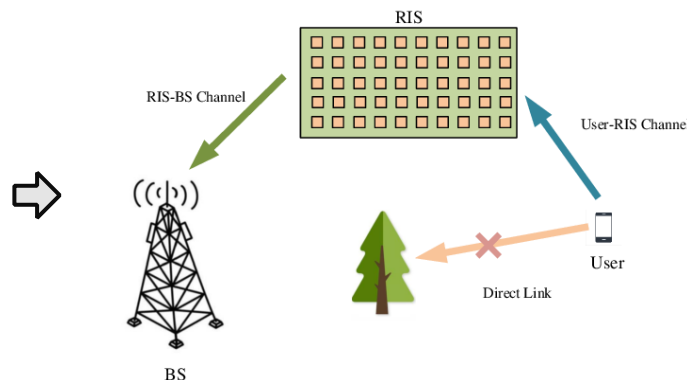
Poor scalability

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



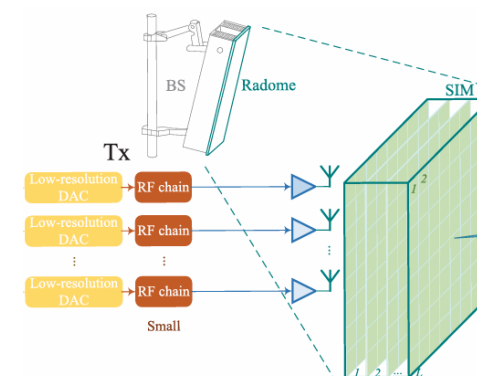
Automatically completed,
not controllable

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



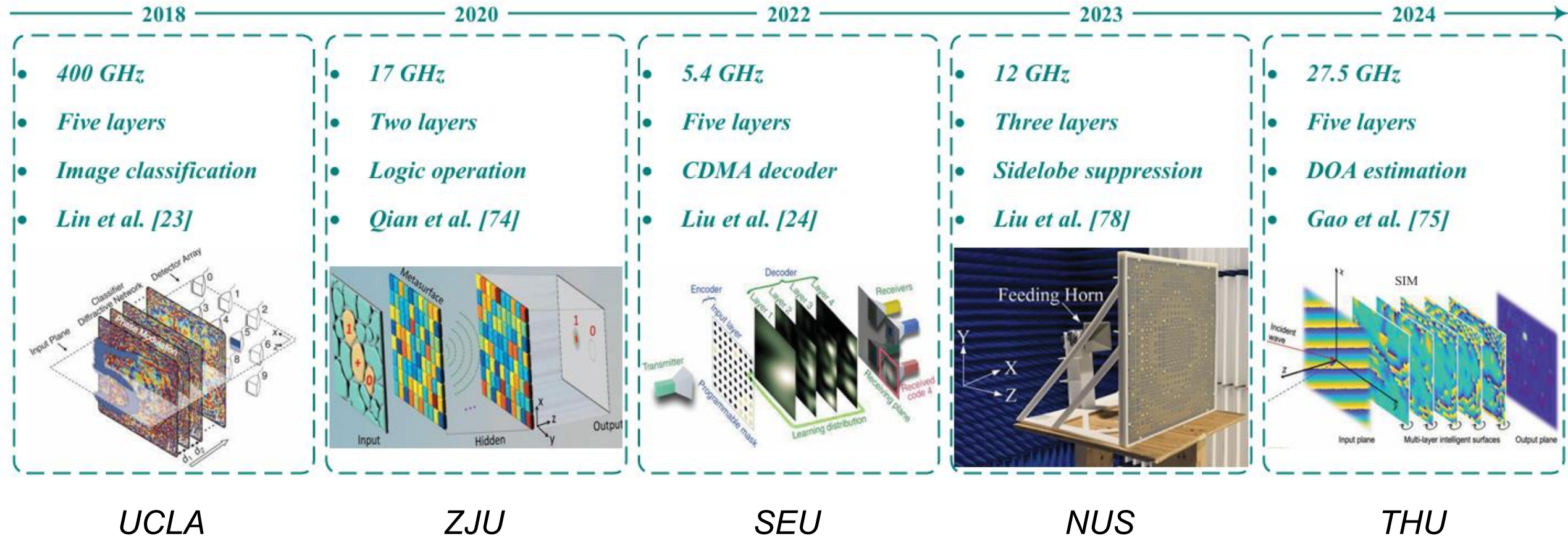
Controllable,
insufficient DoF

SIM

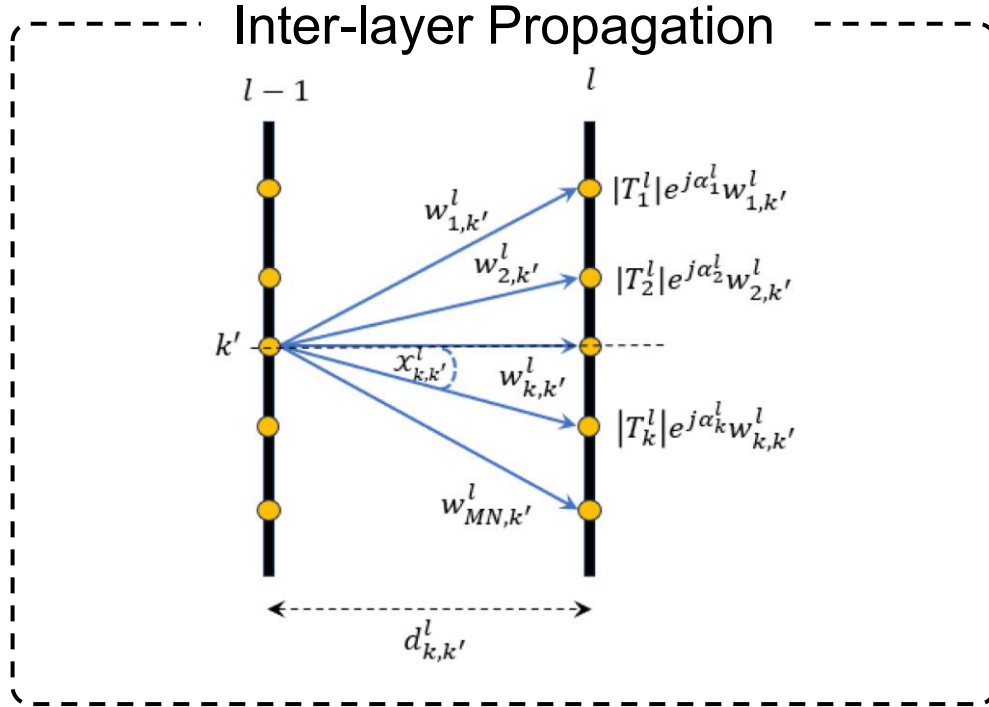


Does it work?

❖ 2.1 SIM: Prototypes

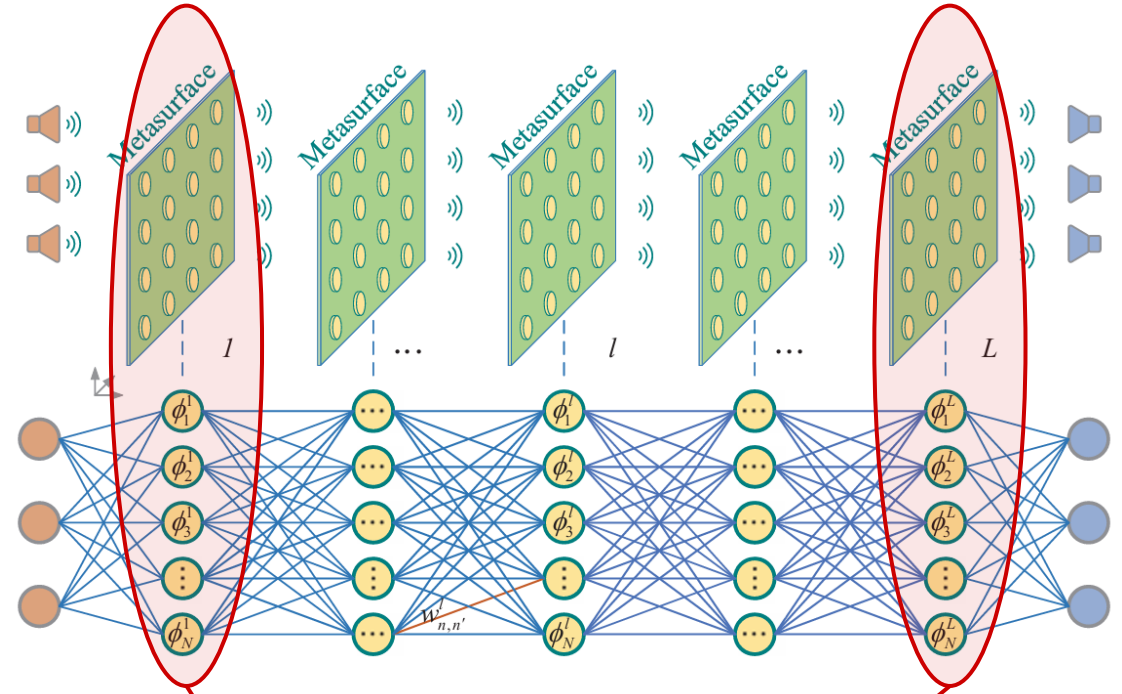


❖ 2.1 SIM: Propagation Modeling



Rayleigh-Sommerfeld Diffraction Theory

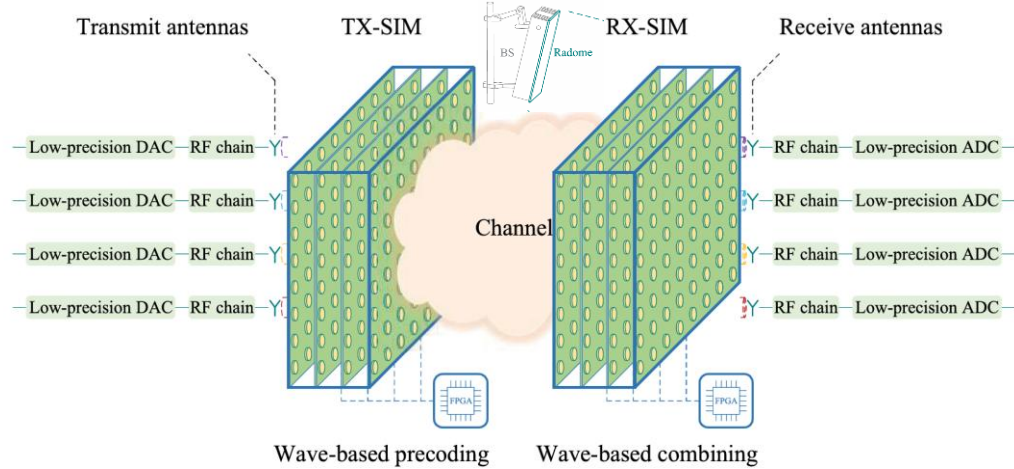
$$w_{n,n'}^l = \frac{A \cos \chi_{n,n'}^l}{r_{n,n'}^l} \left(\frac{1}{2\pi r_{n,n'}^l} - j \frac{1}{\lambda} \right) e^{j2\pi r_{n,n'}^l / \lambda}$$



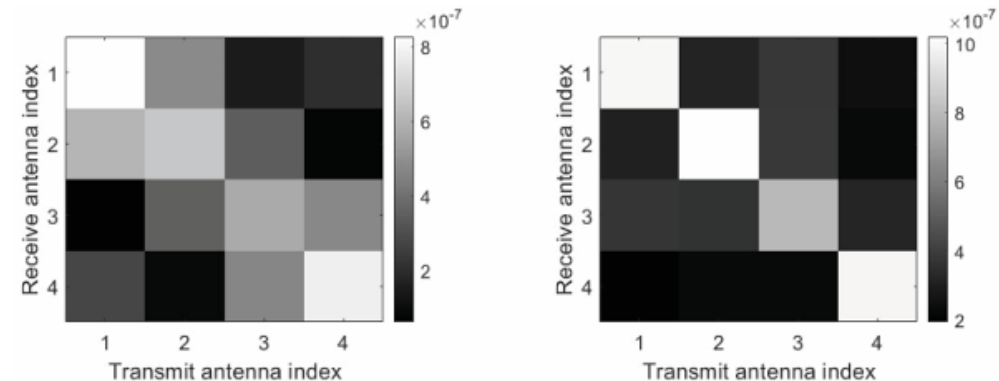
$$S = \Phi^L W^L \dots \Phi^2 W^2 \Phi^1 \in \mathbb{C}^{N \times N}$$

❖ 2.1 SIM: MIMO Precoding

- SIM-aided MIMO Transmission



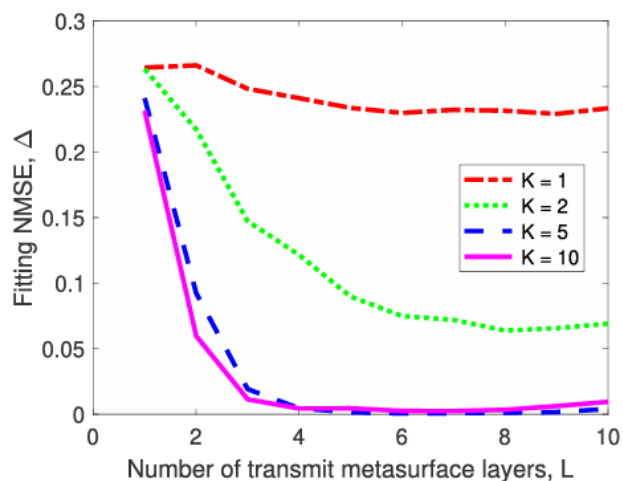
End-to-end channel



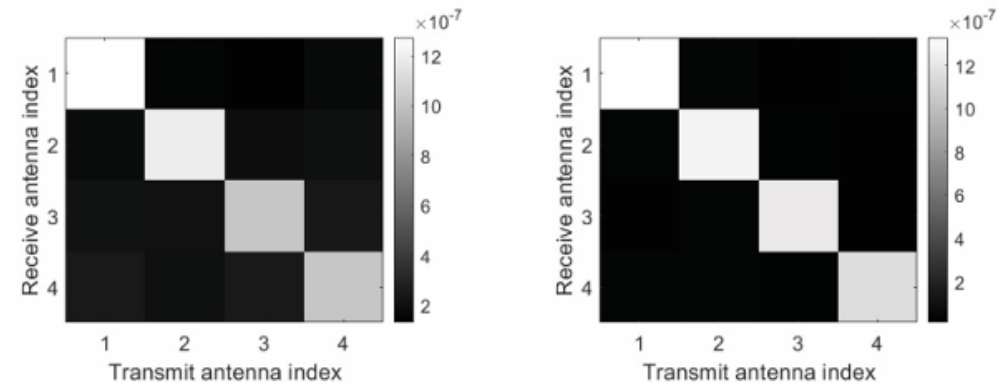
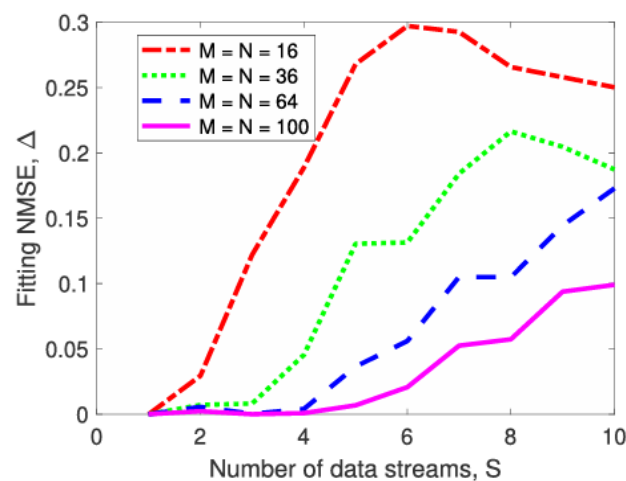
(a) $L = K = 1$

(b) $L = K = 2$

NMSE vs L & K



NMSE vs S & M

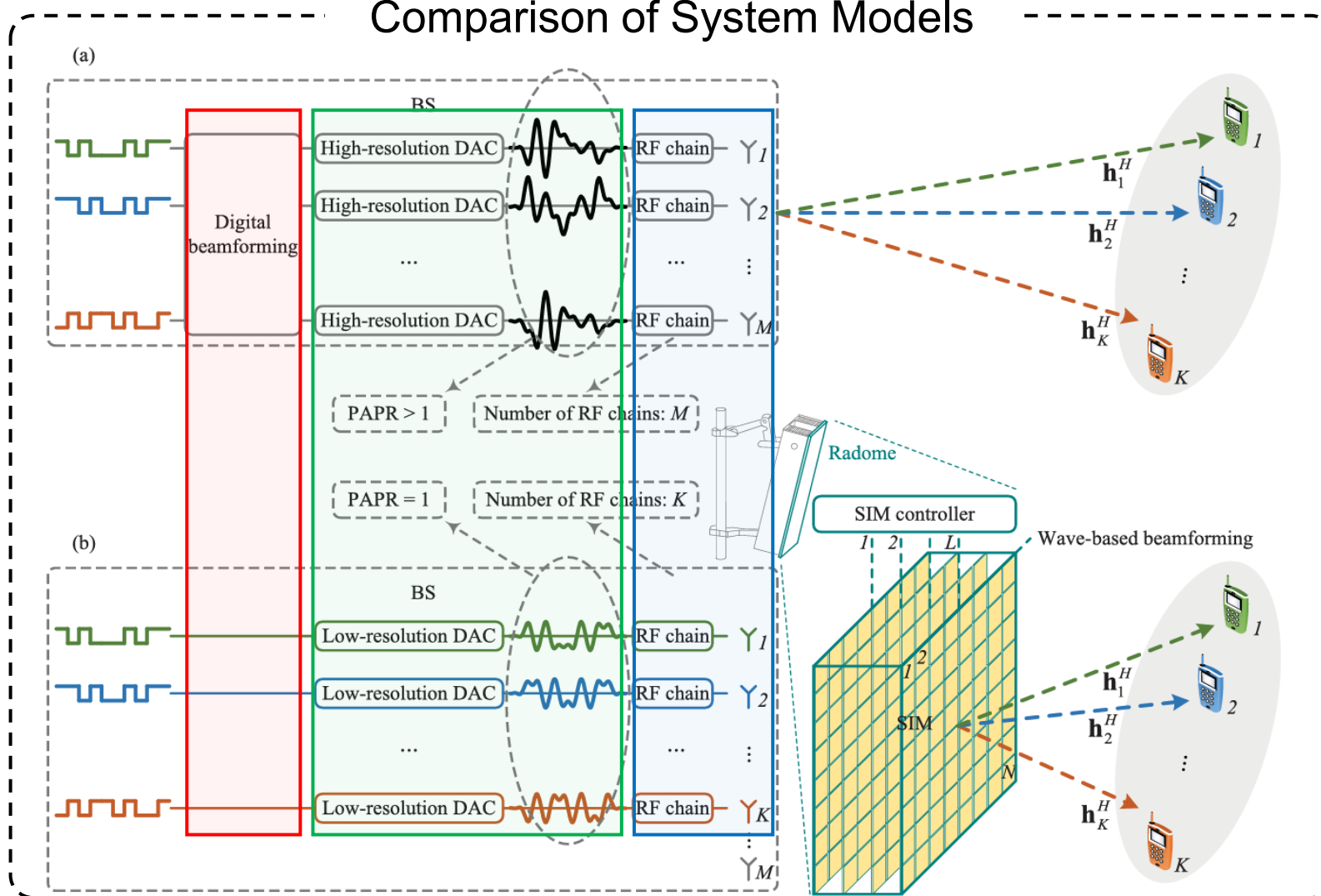


(c) $L = K = 3$

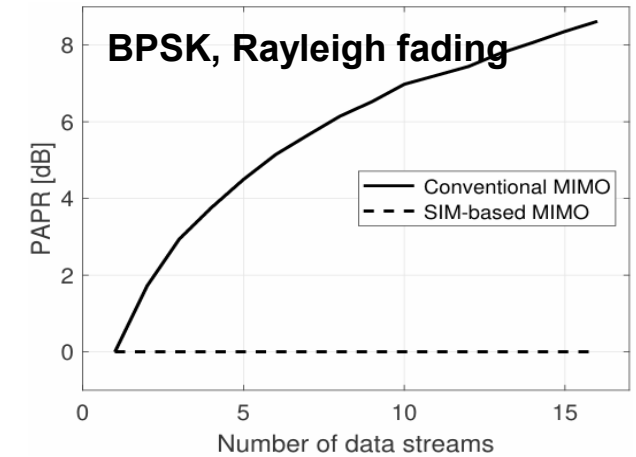
(d) $L = K = 4$

❖ 2.1 SIM: Benefits

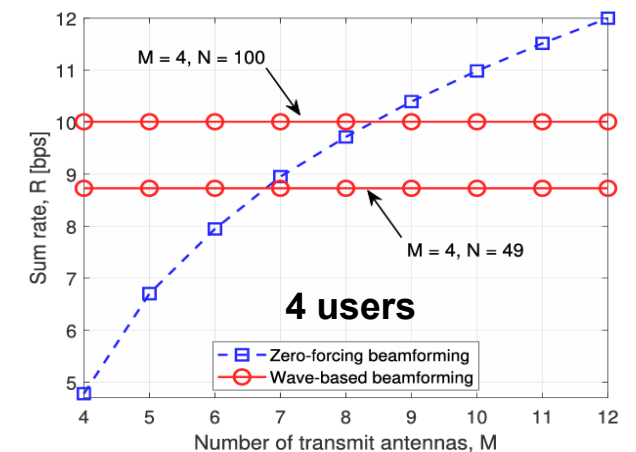
Comparison of System Models



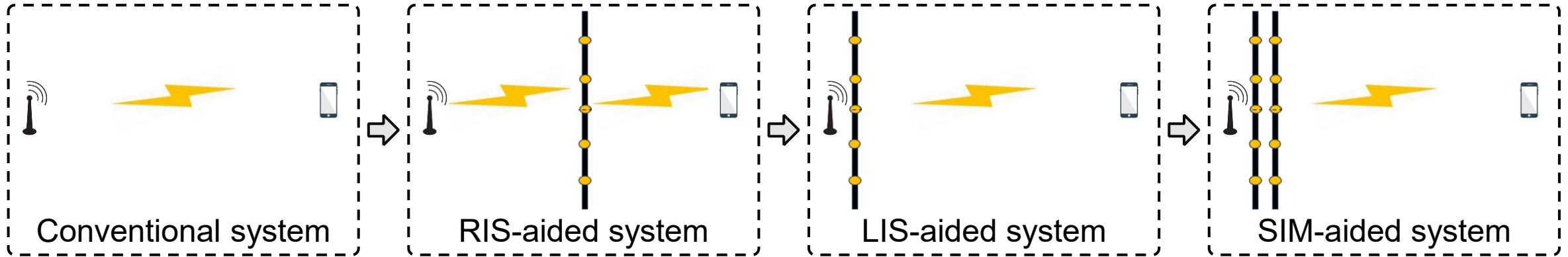
PAPR vs. # of Streams



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

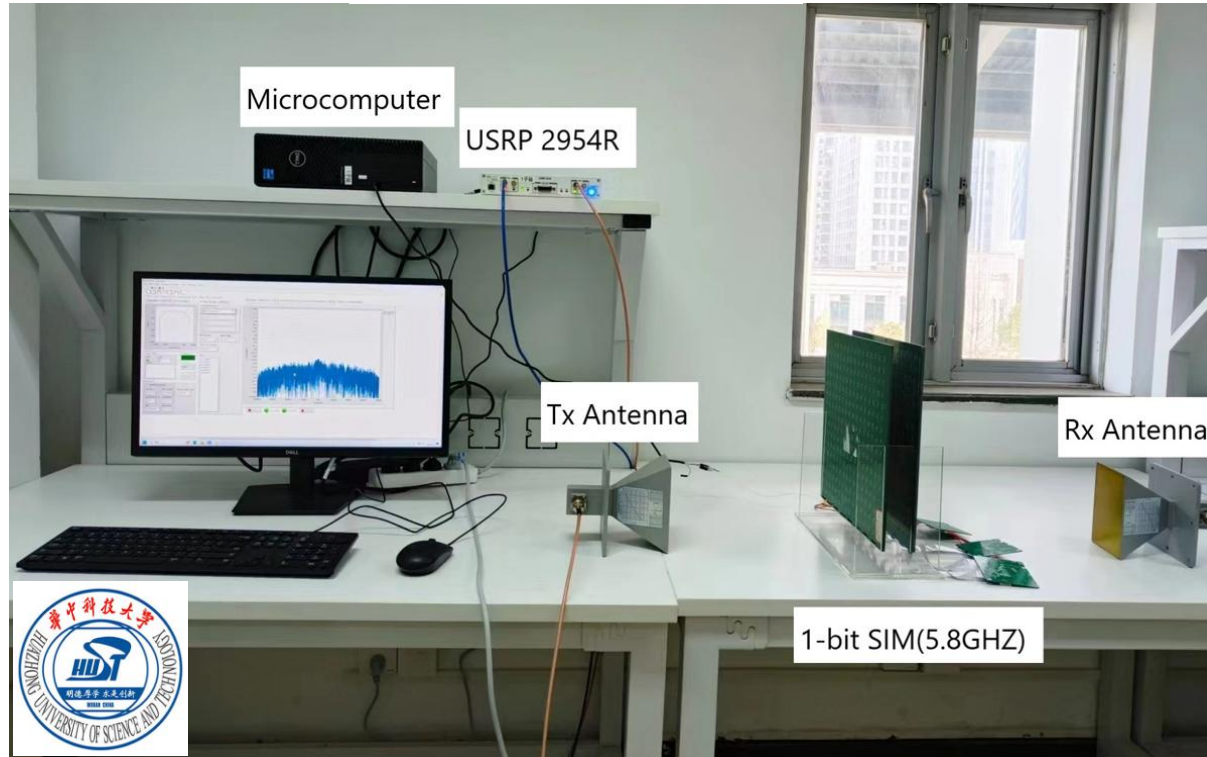
+



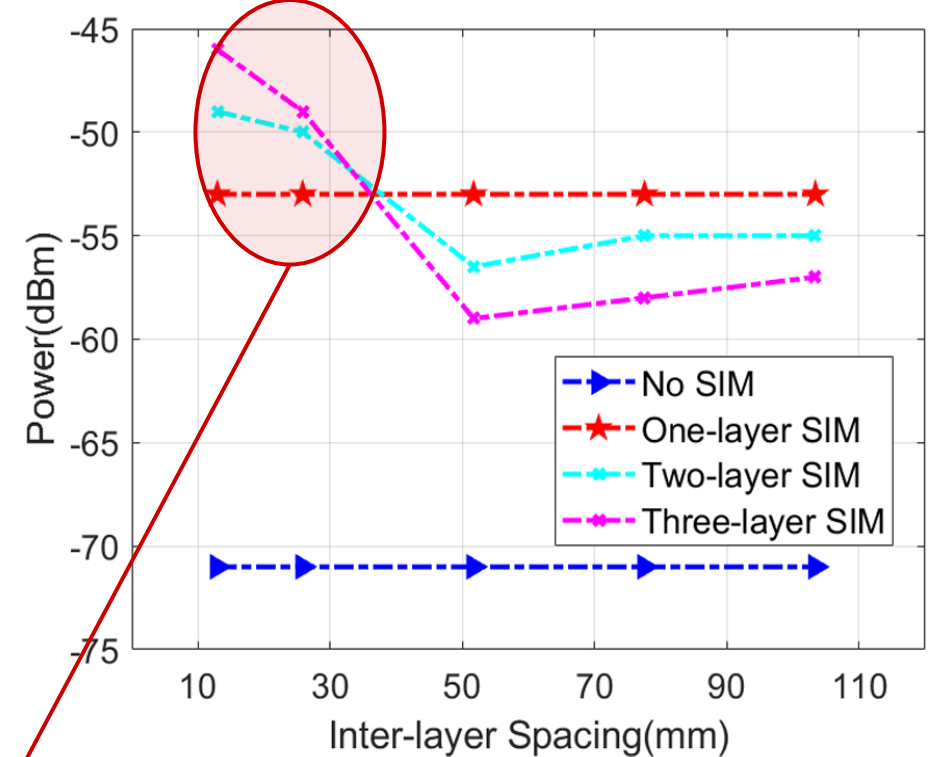
Path loss

❖ 2.1 Will more layers decrease the received power?

SIM Prototype



Received Power vs. # of Layers

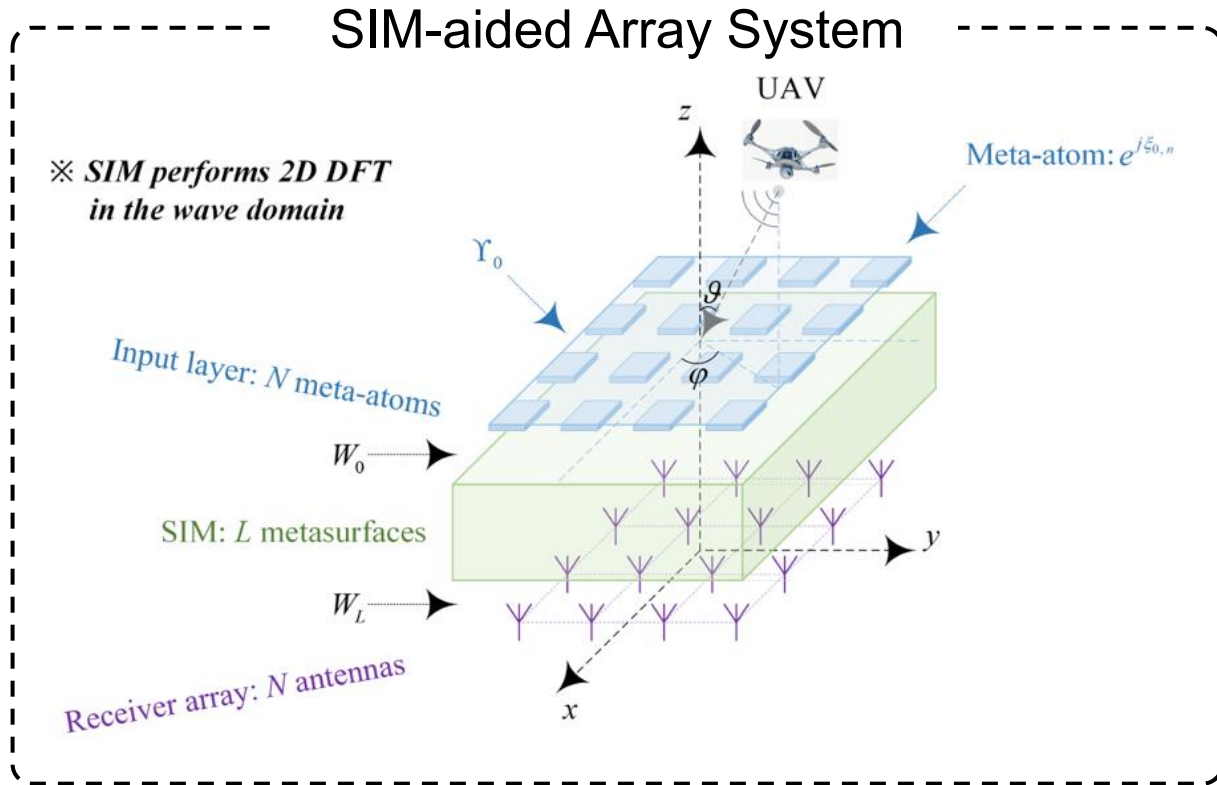


When the layers are closely placed, adding more layers doesn't reduce the power received due to the significant array gain.

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❖ 2.2 SIM for DOA Estimation

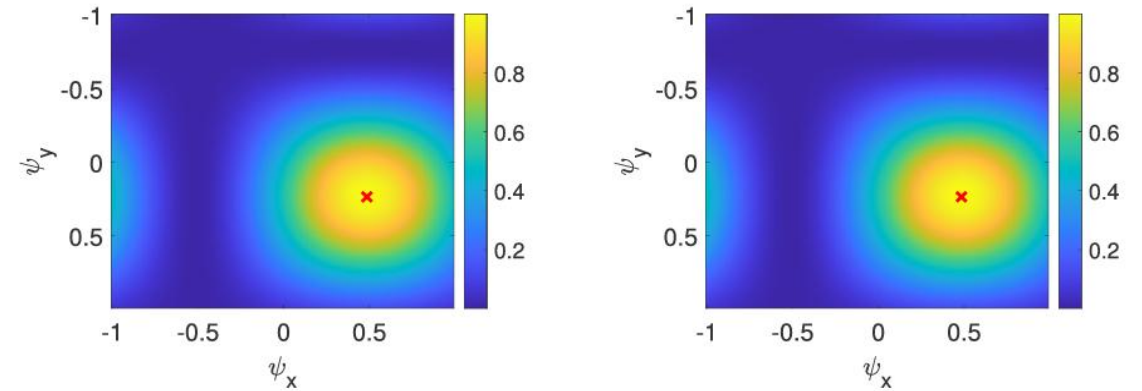


Low-
precision
spectrum

Multi-snapshot
combination

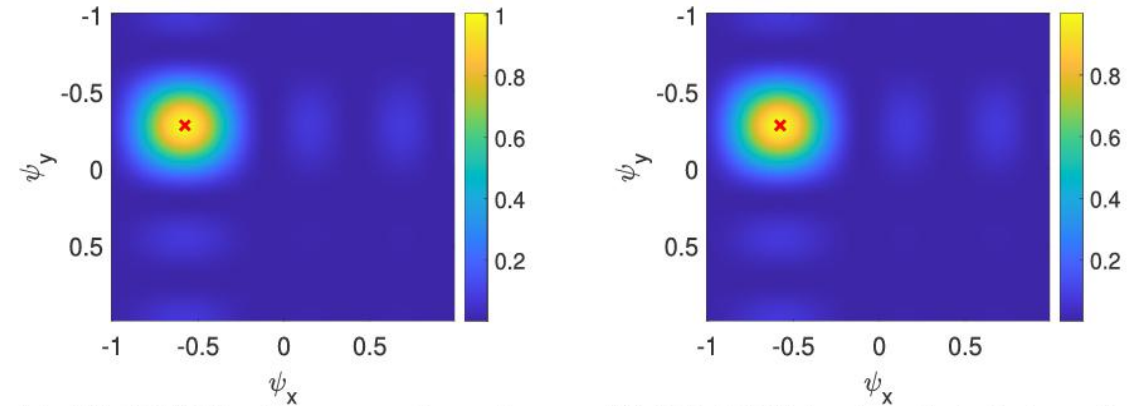
High-
precision
spectrum

Receiver array: 2×2



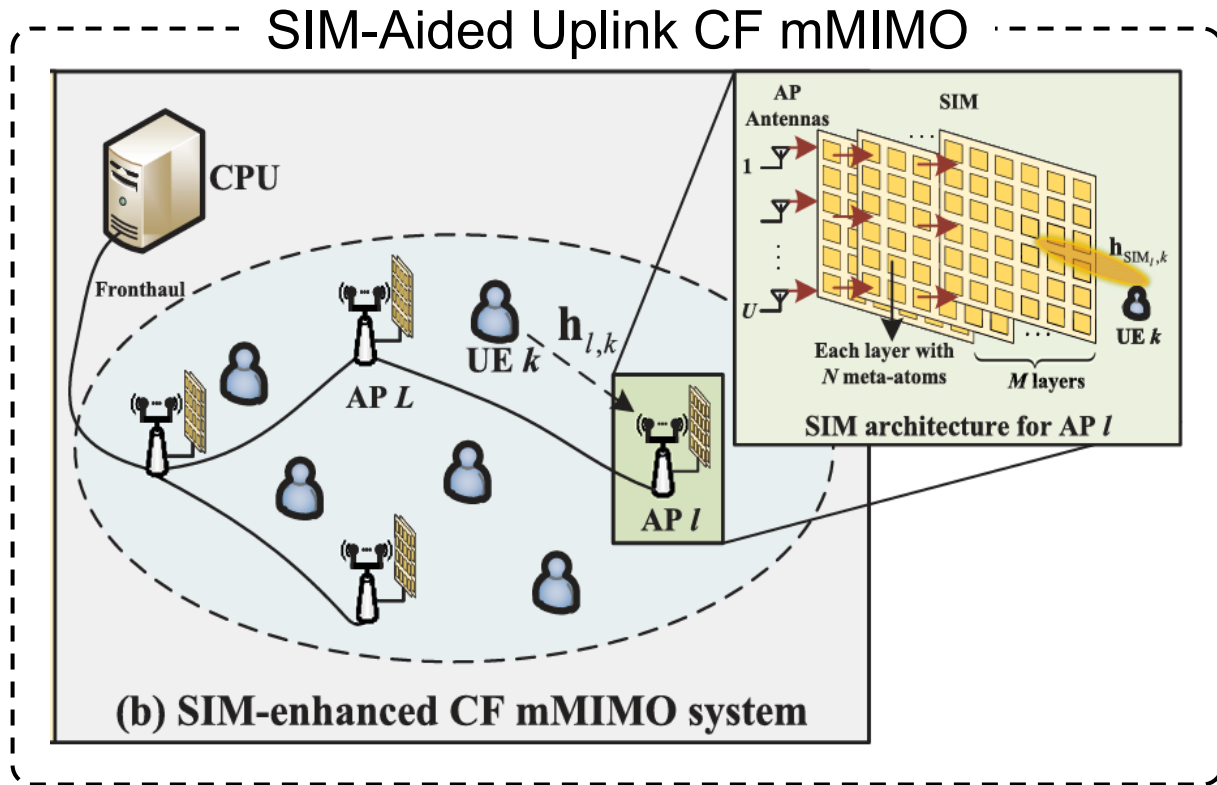
(a) 2D DFT in the wave domain; (b) 2D DFT in the digital domain.

Receiver array: 4×4

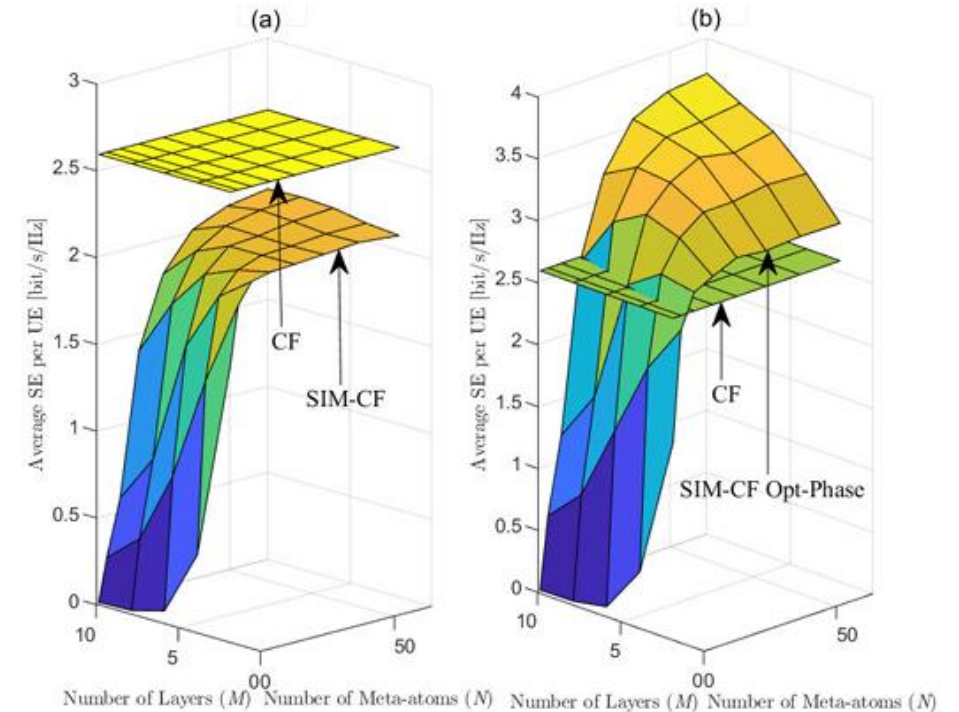


(a) 2D DFT in the wave domain; (b) 2D DFT in the digital domain.

❖ 2.2 SIM for CF mMIMO: Distributed Deployment

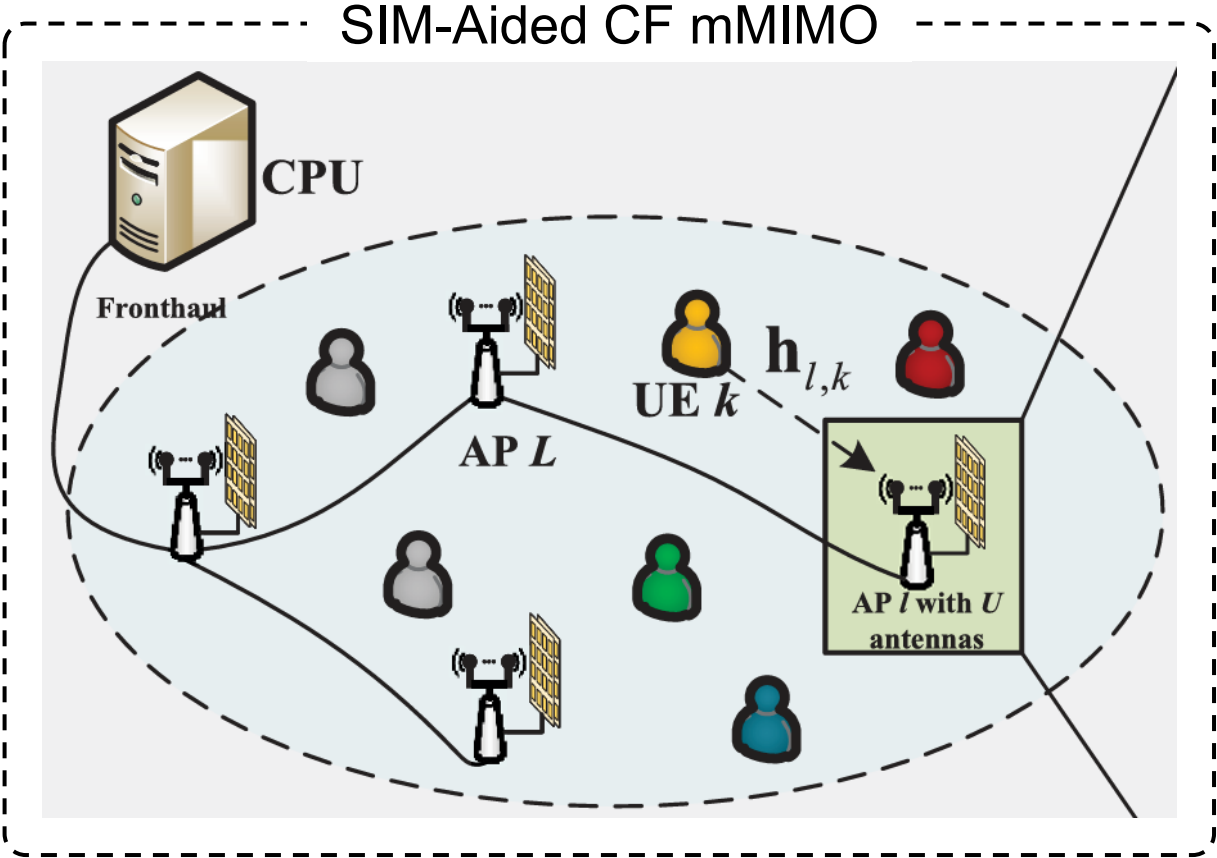


SE vs. # of layers and meta-atoms

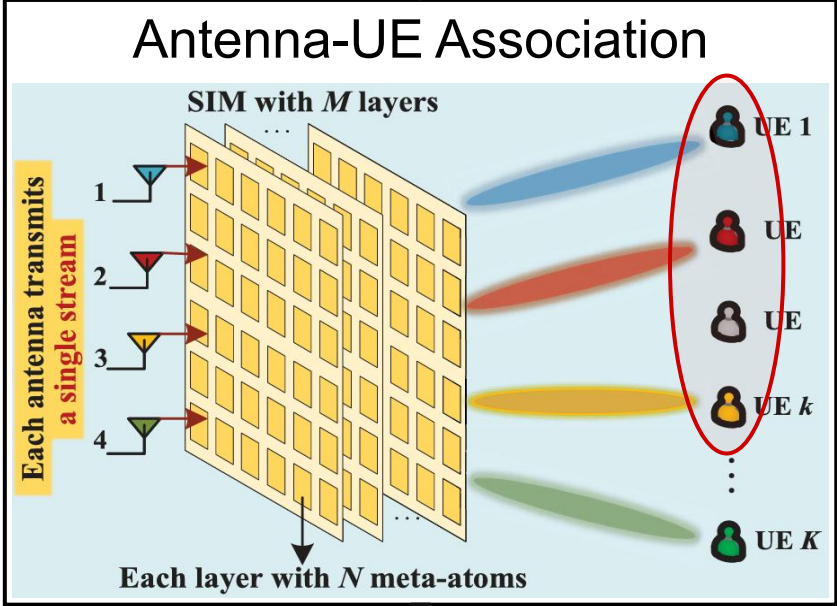


- [R07] Q. Li, M. El-Hajjar, C. Xu, J. An, C. Yuen and L. Hanzo, “**Stacked intelligent metasurfaces** for holographic MIMO-aided cell-free networks,” *IEEE Trans. Commun.*, vol. 72, no. 11, pp. 7139-7151, Nov. 2024.
- [R8] Y. Hu, J. Zhang, E. Shi, Y. Lu, J. An, C. Yuen and B. Ai, “Joint beamforming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



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



For each AP:

Find the Nearest M UEs

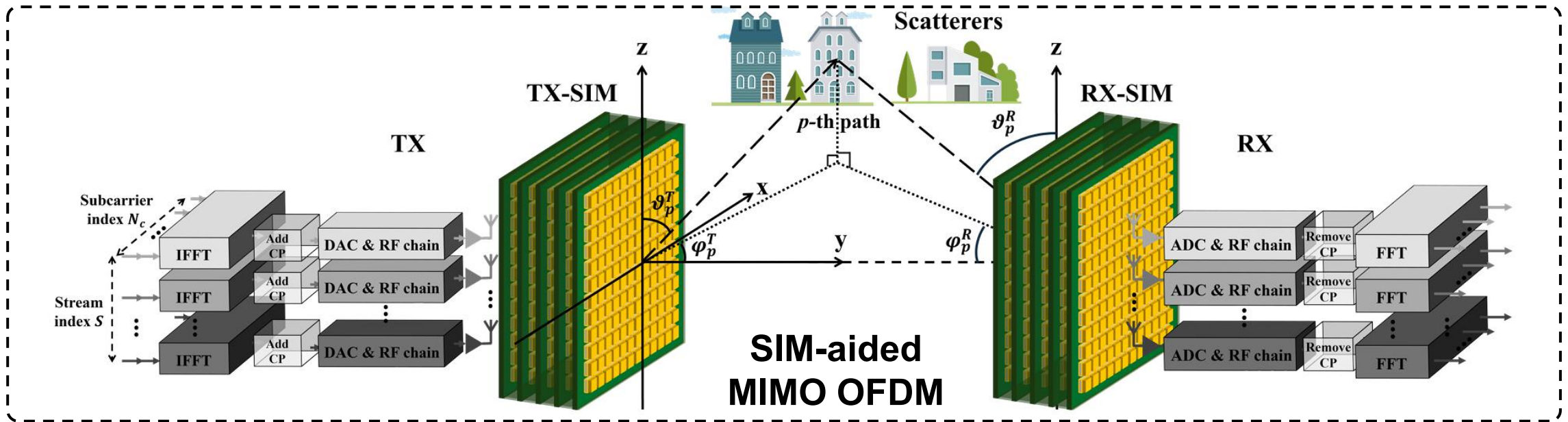
As L increases infinitely

Asymptotically Optimal

Gain Dominant --- MRT

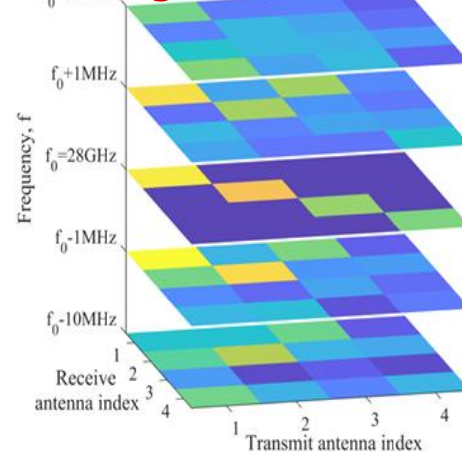
[R10] E. Shi, J. Zhang, J. An, G. Zhang, Z. Liu, C. Yuen and B. Ai, "Joint AP-UE association and precoding for SIM-aided cell-free massive MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 24, no. 6, pp. 5352-5367, Jun. 2025.

❖ 2.2 SIM for Wideband Communications (OFDM)

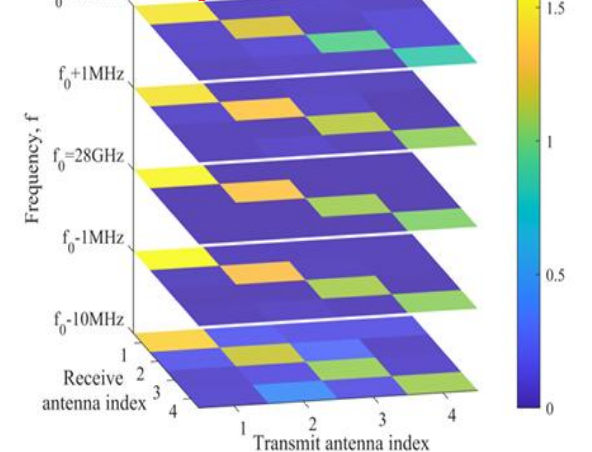


	Interference-free transmission	Interference-present transmission
Bandwidth	$B \leq B_e$	$B > B_e$
Fitting error	$\Gamma_{\min} \approx 0$	$\Gamma_{\min} > 0$
Illustration of the end-to-end channel		

Single-subcarrier

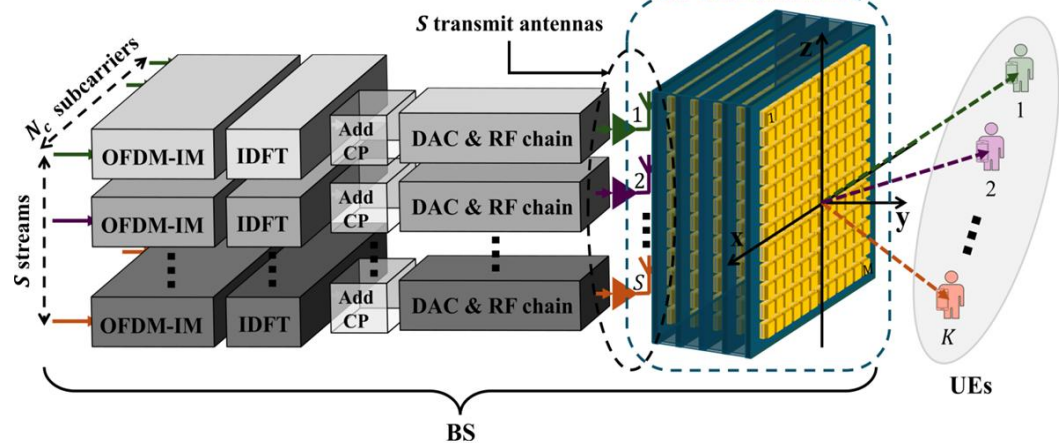


Multiple-subcarrier

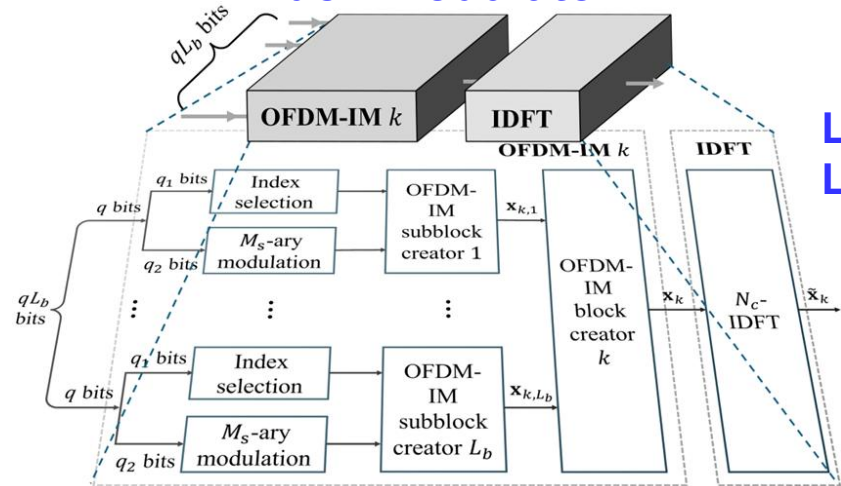


❖ 2.2 SIM for Wideband Communications (OFDM-IM)

SIM-aided wideband MIMO OFDM

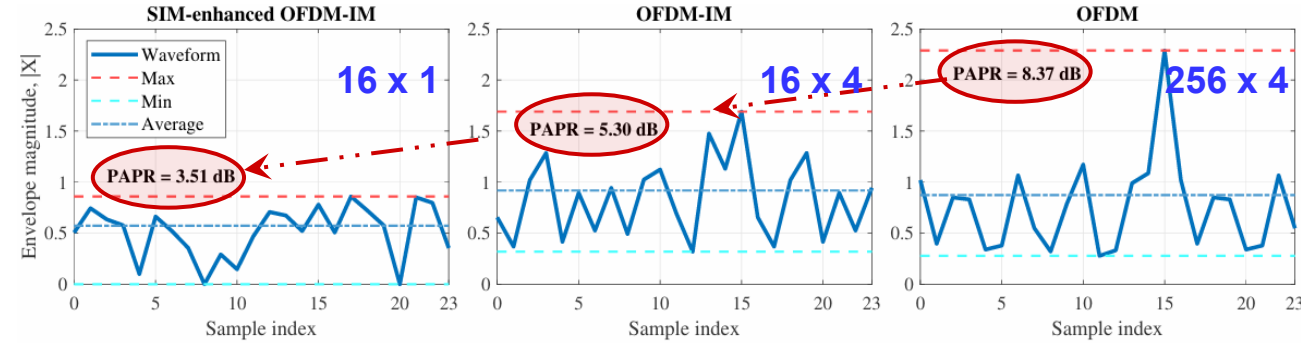


Index modulator

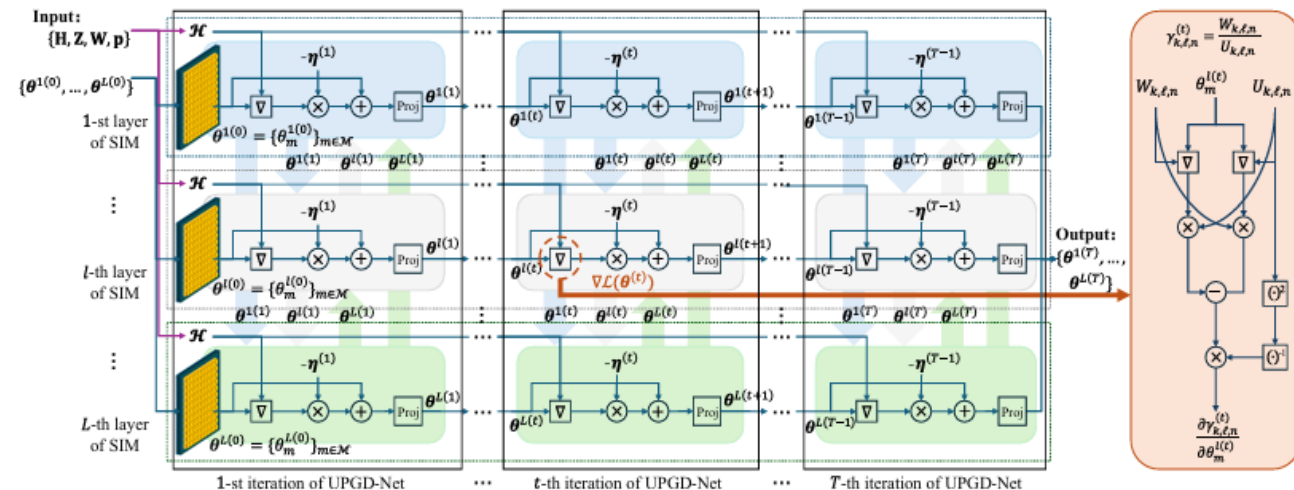


Lower PAPR
Larger BW

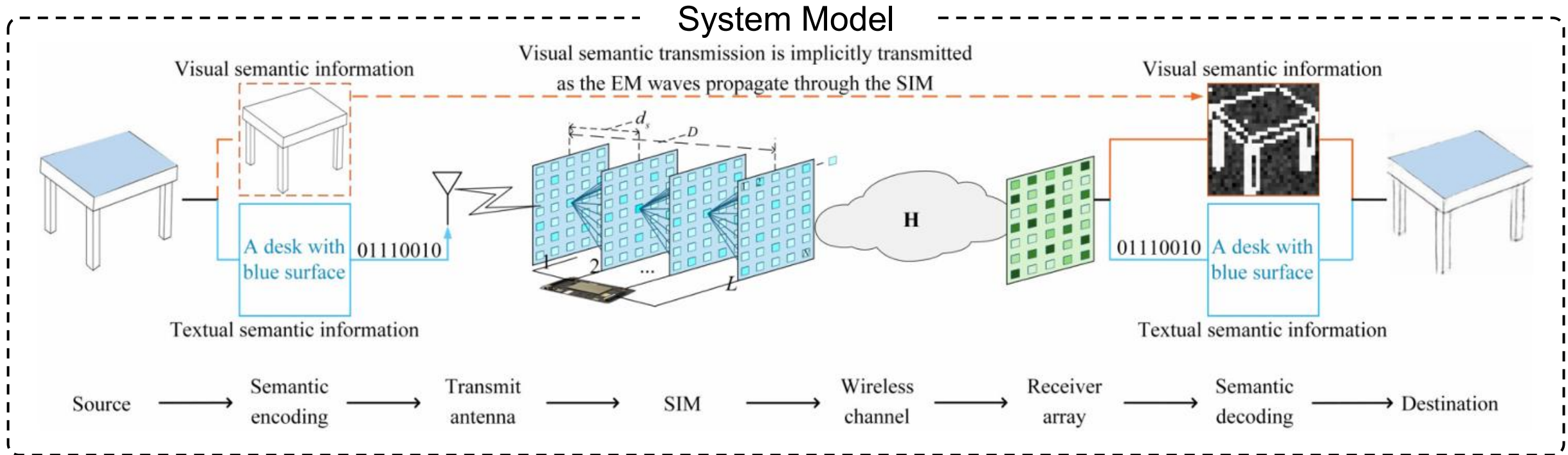
PAPR Comparison



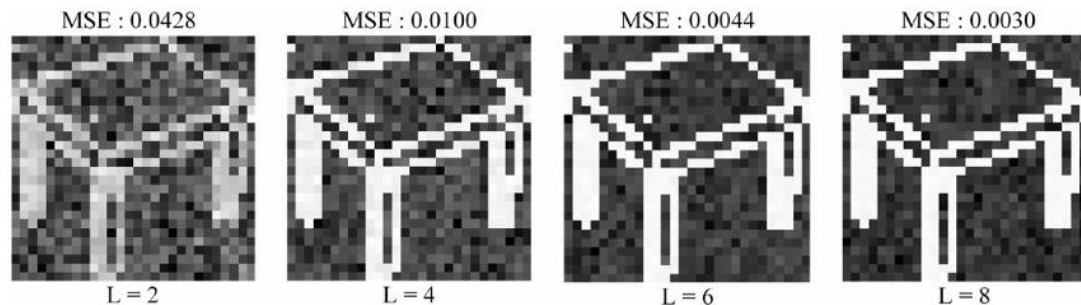
Deep unfolding strategy



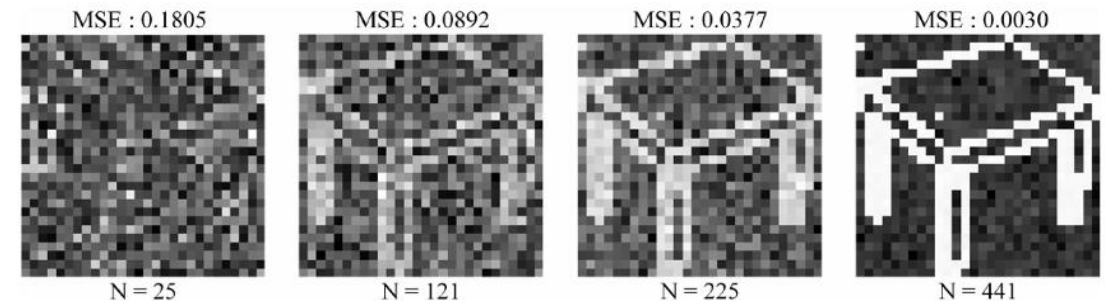
❖ 2.2 SIM for Multi-Modal Semantic Communications



MSE vs. # of layers



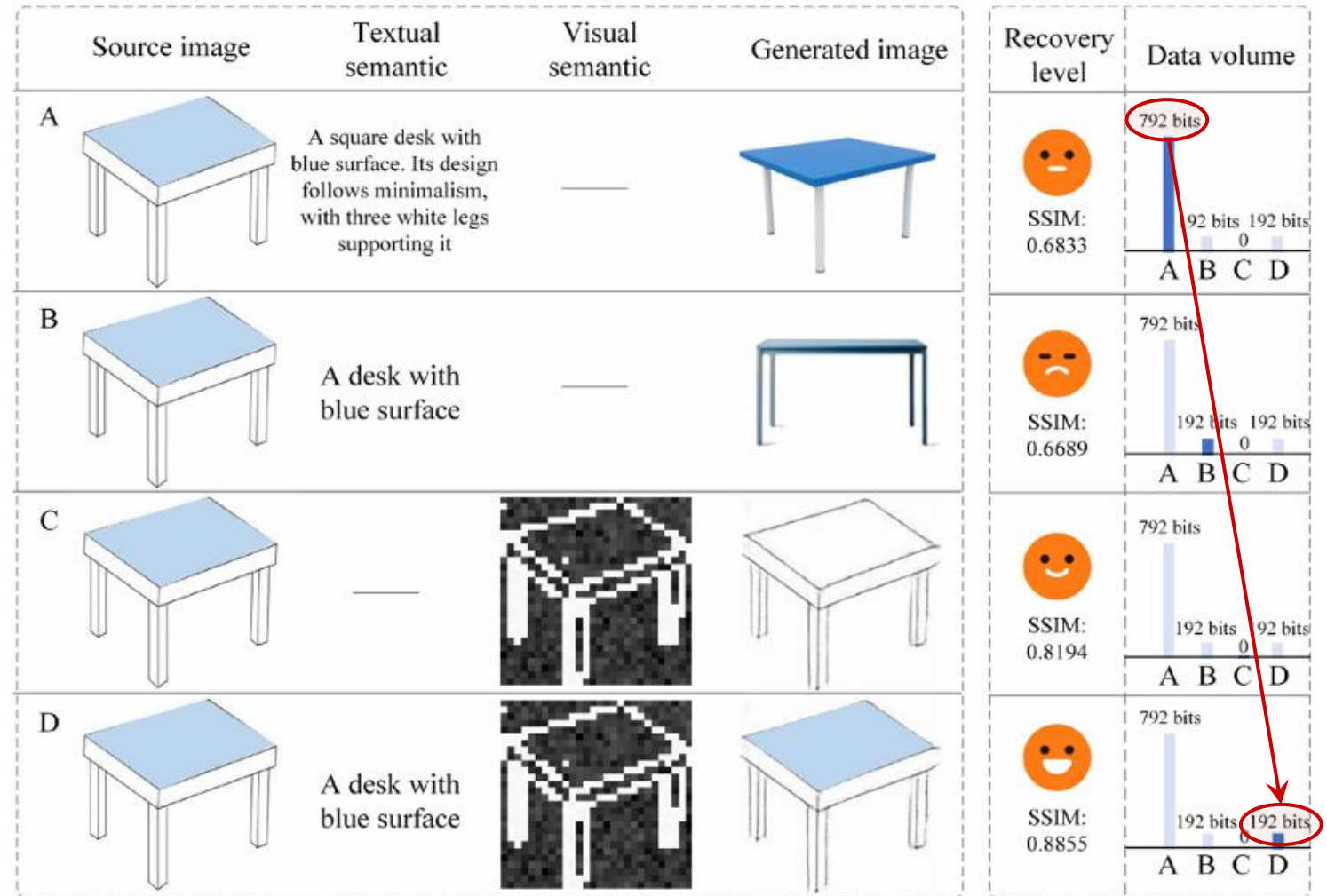
MSE vs. # of meta-atoms on each layer



[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: $\lambda/2$



❖ 2.2 Interesting Work

❑ Antenna Selection and User Grouping

[R14] **S. Lin**, J. An, L. Gan, M. Debbah and C. Yuen, “**Stacked intelligent metasurface** enabled LEO satellite communications relying on statistical CSI,” *IEEE Wireless Commun. Lett.*, vol. 13, no. 5, pp. 1295-1299, May 2024.

❑ Subspace-based Channel Estimation

[R15] **X. Yao**, J. An, L. Gan, M. Di Renzo and C. Yuen, “Channel estimation for **stacked intelligent metasurface**-assisted wireless networks,” *IEEE Wireless Commun. Lett.*, vol. 13, no. 5, pp. 1349-1353, May 2024.

❑ Energy-Efficient Design

[R16] **H. Niu**, J. An, T. Wu, J. Chen, Y. Zhao, Y. L. Guan et al., “Introducing meta-fiber into **stacked intelligent metasurfaces** for MIMO communications: A low-complexity design with only two layers,” *IEEE Trans. Wireless Commun.*, 2025, Early Access.

❑ Near-Field Communications

[R17] **Q. Li**, M. El-Hajjar, C. Xu, J. An, C. Yuen and L. Hanzo, “**Stacked intelligent metasurface**-based transceiver design for near-field wideband systems,” *IEEE Trans. Commun.*, 2025, Early Access.

❑ Energy Efficiency Analysis

[R18] **E. Shi**, J. Zhang, J. An, M. D. Renzo, B. Ai and C. Yuen, “Energy-efficient **SIM**-assisted communications: How many layers do we need?,” *IEEE Trans. Wireless Commun.*, 2025, Early Access.

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❖ 3.1 FIM: Motivation

❖ Flexible textile



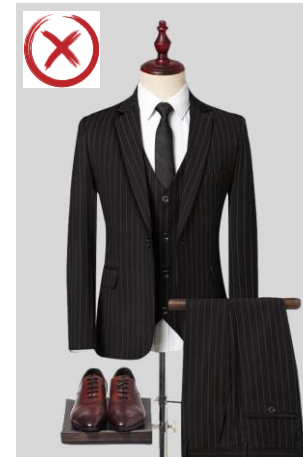
❖ Flexible aircraft in remote areas



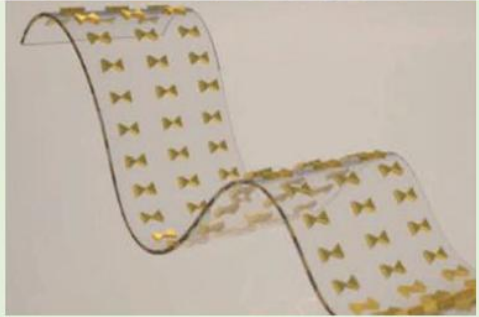
❖ Flexible wearable devices



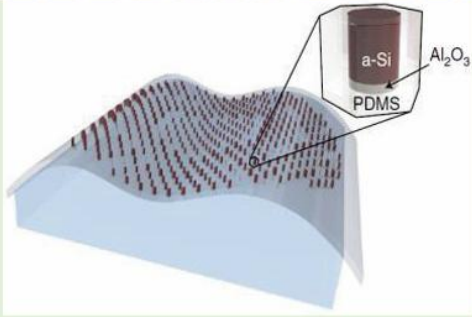
❖ Flexible cape for robots



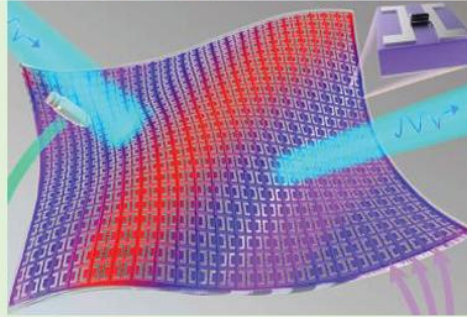
❖ 3.1 FIM: Prototypes



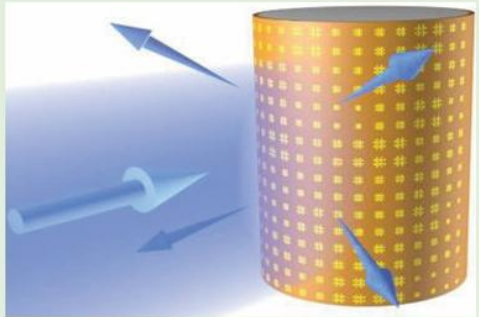
[129] Flexible films



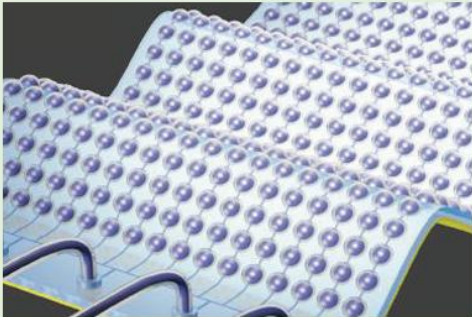
[128] Aspherical lenses



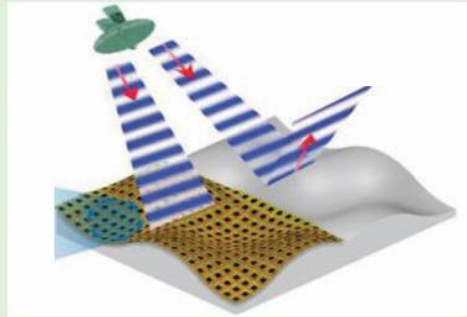
[122] Intelligent cloak



[125] Diffuse scattering



[126] Water resonator



[127] Microwave absorber

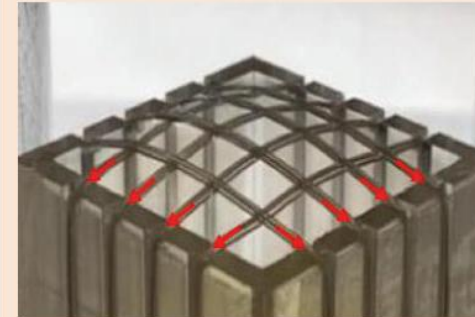
(a) Passive surface-shape morphing.



[132] Dielectric elastomers



[28] EM actuation



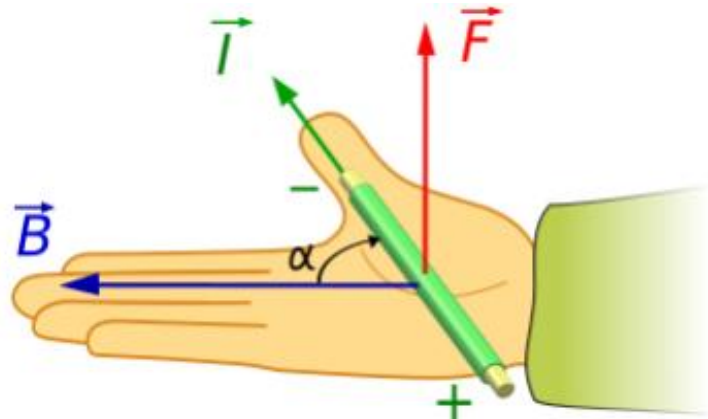
[133] Liquid metal networks



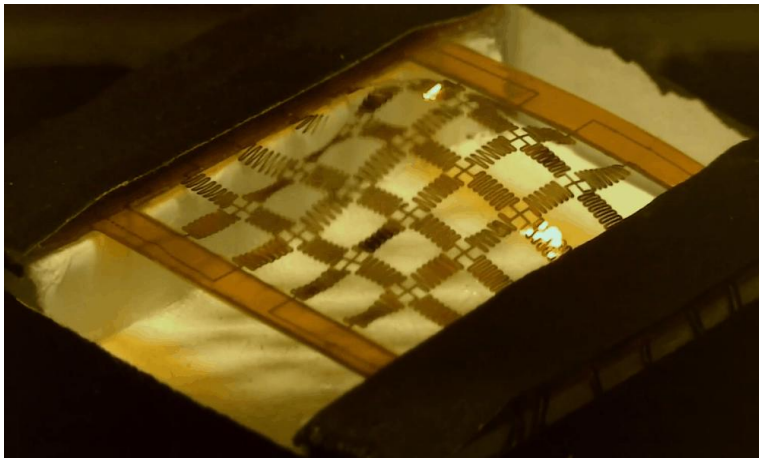
[131] Tactile displays

(b) Active surface-shape morphing.

❖ 3.1 FIM: Surface Shape Morphing

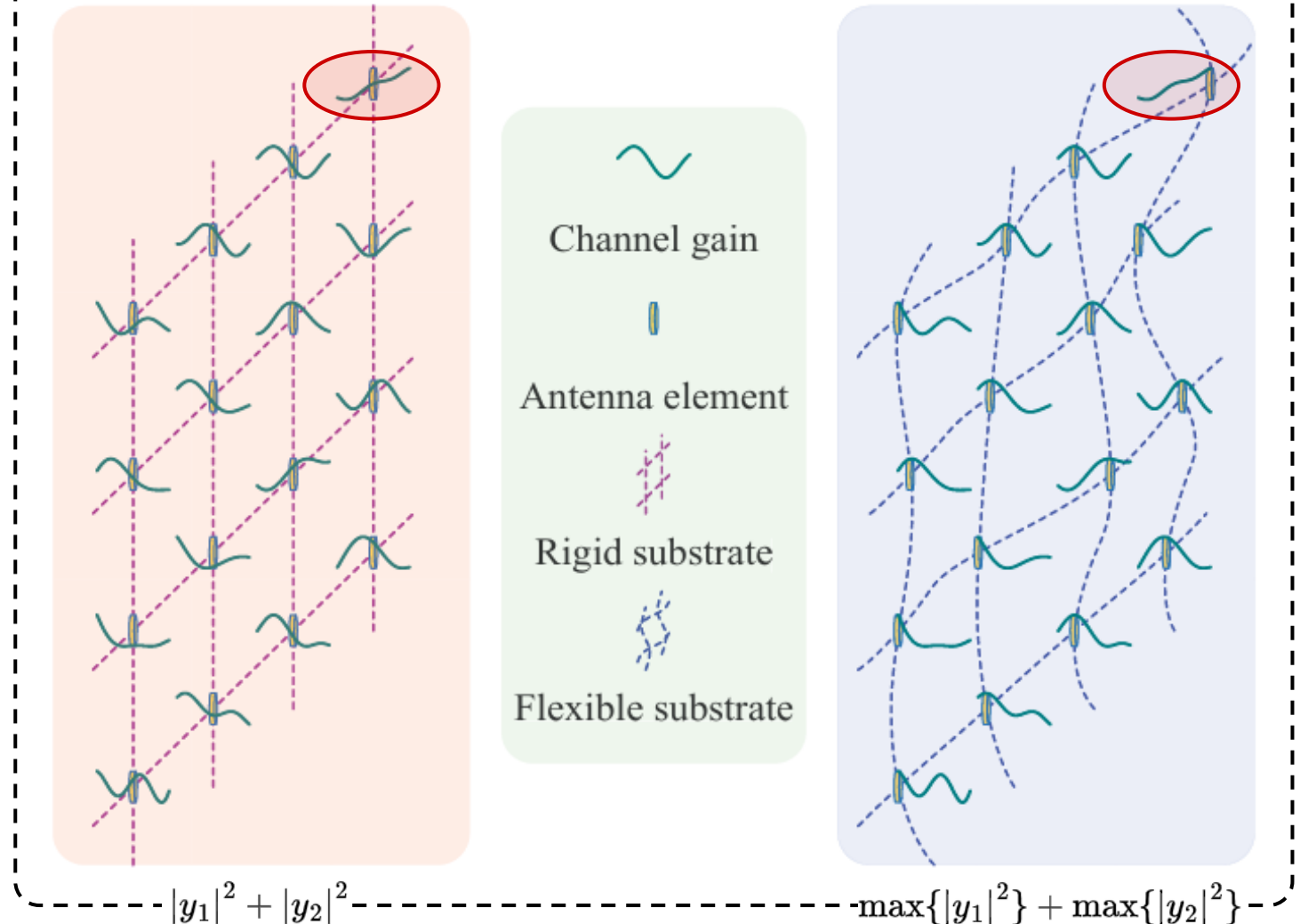


Distributed Lorentz Force

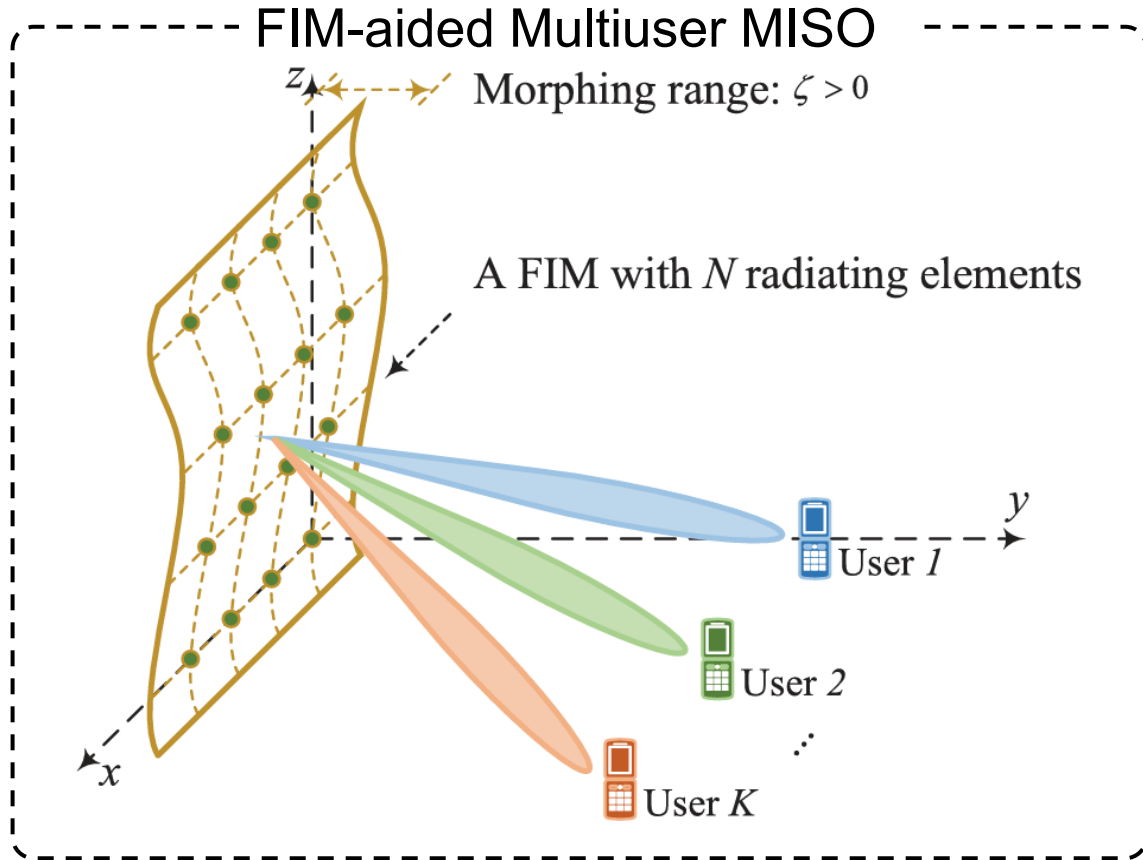


ms shape morphing speed

Potential of FIMs in Wireless Communications

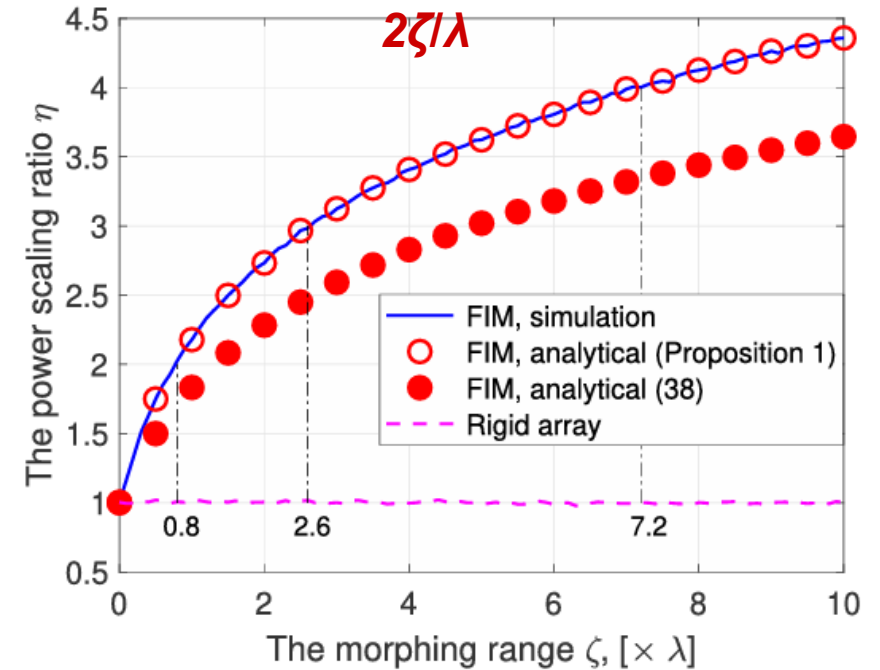


❖ 3.1 FIM-Aided Downlink Multiuser Communications



Scaling Law: Power vs. Morphing Range

$$P_r \simeq P_t N \beta^2 [\log(\kappa \zeta / \pi + 1) + C + \Delta(\zeta)]$$



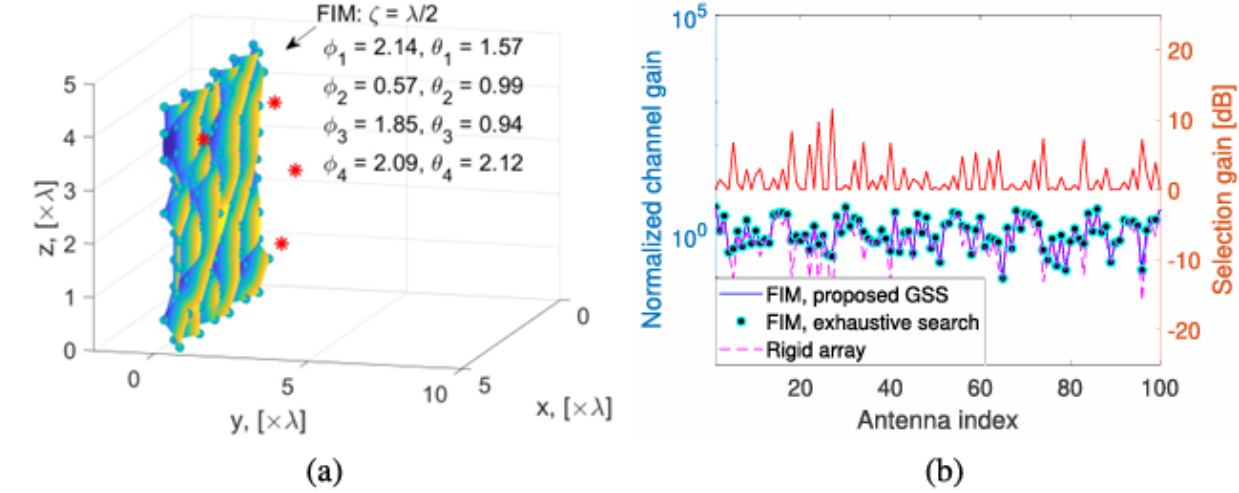
$$\text{SINR}_k = \frac{|h_k^H(\mathbf{y}) \mathbf{w}_k|^2}{\sum_{k'=1, k' \neq k}^K |h_k^H(\mathbf{y}) \mathbf{w}_{k'}|^2 + \sigma_k^2}$$

$$\mathbf{h}_k(\mathbf{y}) = \sum_{\ell=1}^L \alpha_{k,\ell} \mathbf{a}(\mathbf{y}, \phi_\ell, \theta_\ell)$$

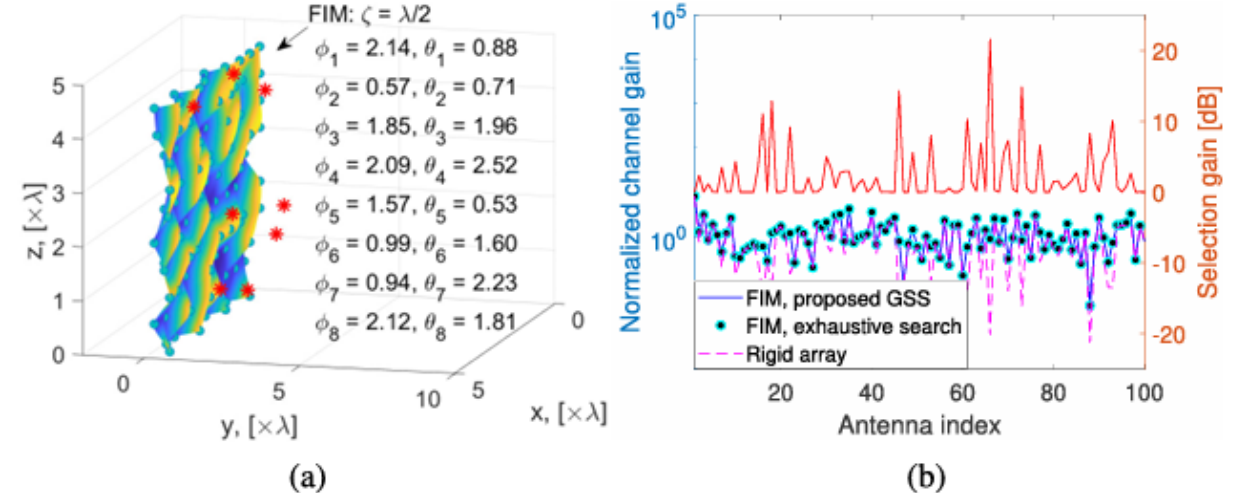
$$\mathbf{a}(\mathbf{y}, \phi, \theta) = \begin{bmatrix} 1, \dots, e^{j\kappa(x_n \sin \theta \cos \phi + y_n \sin \theta \sin \phi + z_n \cos \theta)}, \\ \dots, e^{j\kappa(x_N \sin \theta \cos \phi + y_N \sin \theta \sin \phi + z_N \cos \theta)} \end{bmatrix}^T$$

❖ 3.1 FIM-Aided Downlink Multiuser Communications

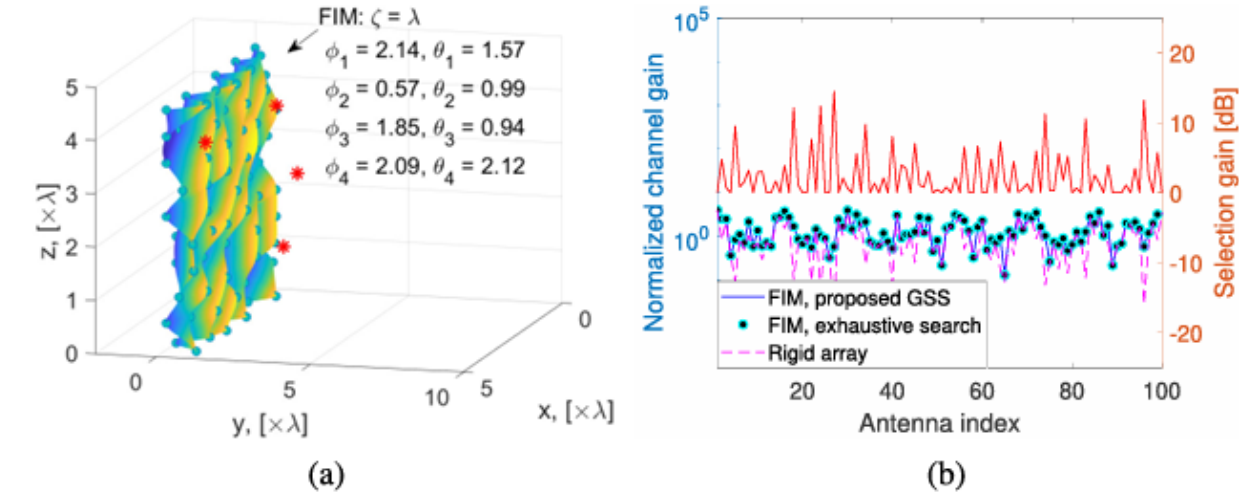
$L = 4, \zeta = \lambda/2$



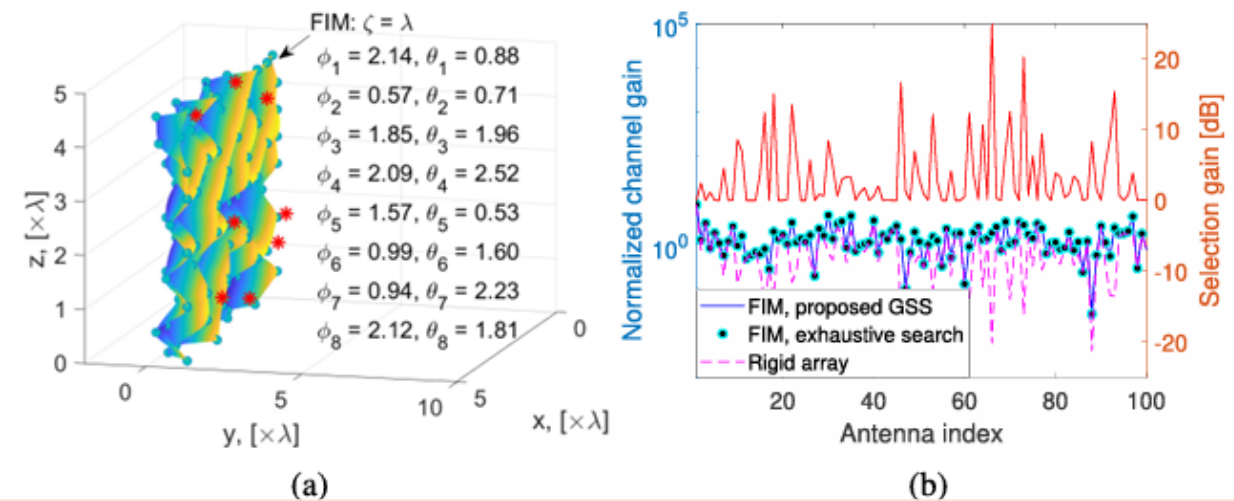
$L = 8, \zeta = \lambda/2$



$L = 4, \zeta = \lambda$



$L = 8, \zeta = \lambda$

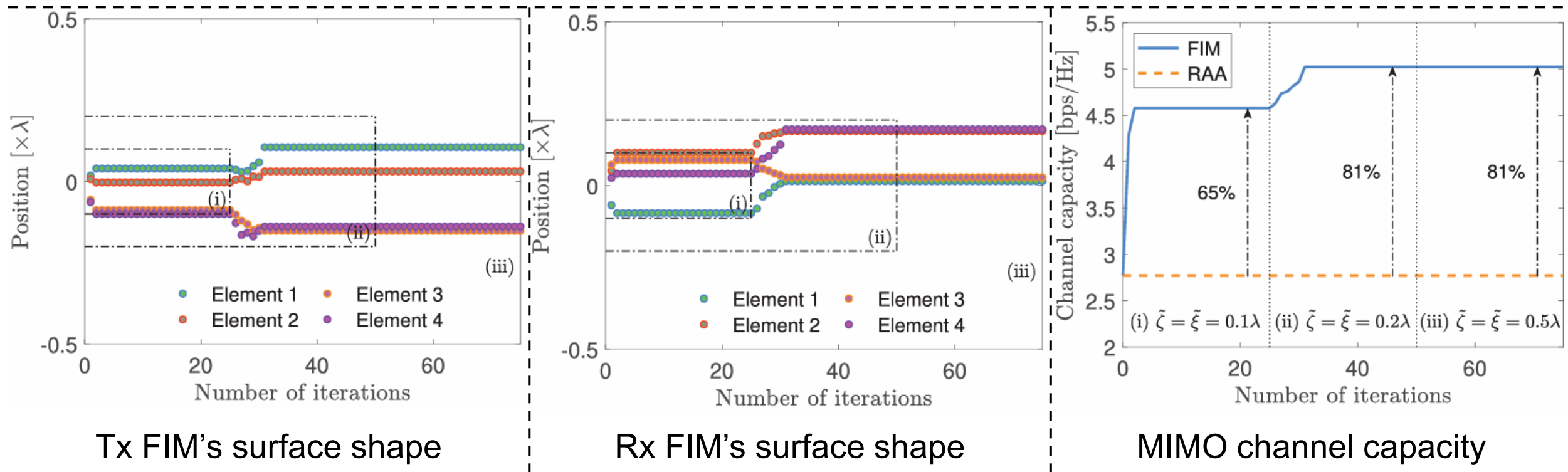


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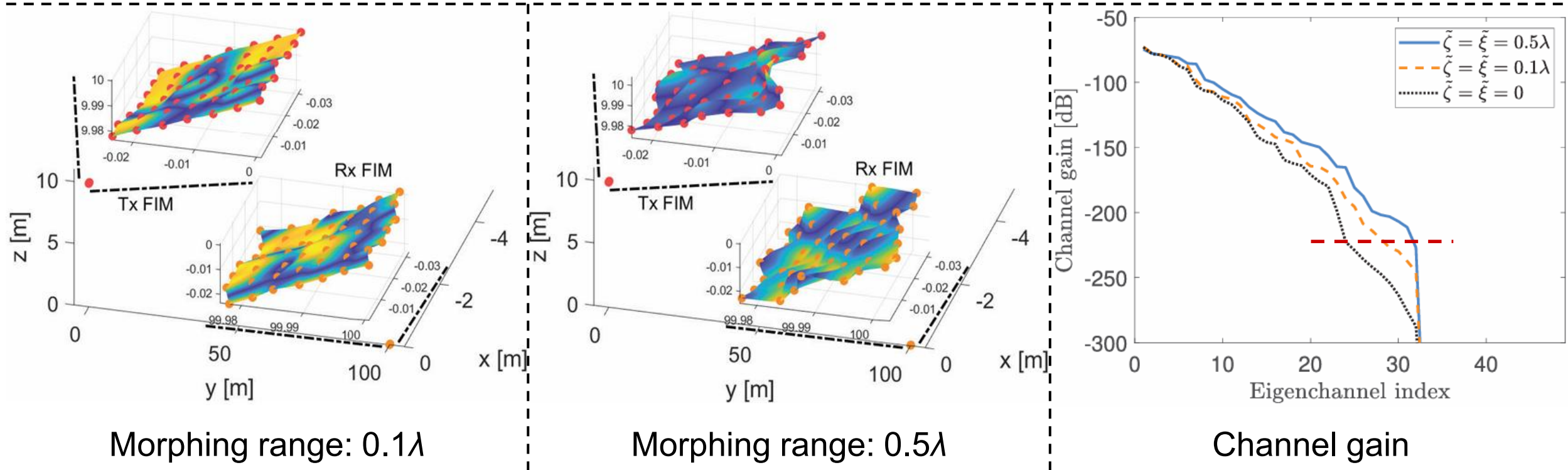
❖ 3.2 FIM for MIMO: Capacity vs. Morphing Range

- 4 Tx elements and 4 Rx elements
- $L = 16$ scattering clusters, each having 4 paths
- (i) Morphing range: 0.1λ ; (ii) Morphing range: 0.2λ ; (iii) Morphing range: 0.5λ

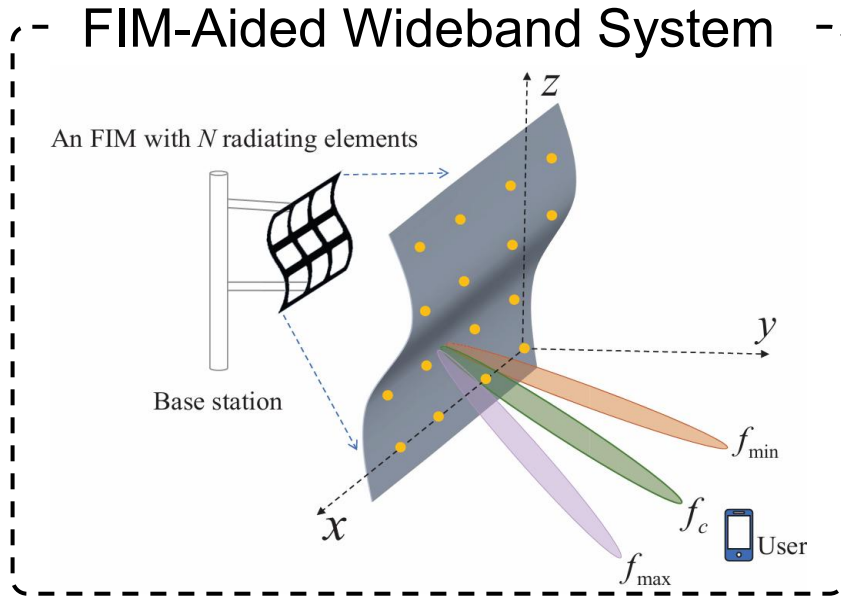


❖ 3.2 FIM for MIMO: Multiplexing Gain

- 7 x 7 MIMO Transmission, Tx-FIM, Rx-FIM
- Multiplexing Gain: FIM can improve channel gain of poor eigenchannels, thus supporting more data transmission



❖ 3.2 FIM for Mitigating Beam Squint



Optimization Problem

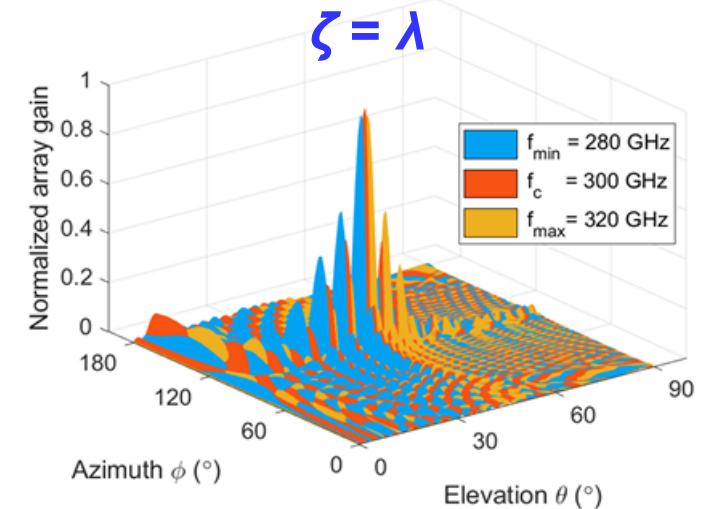
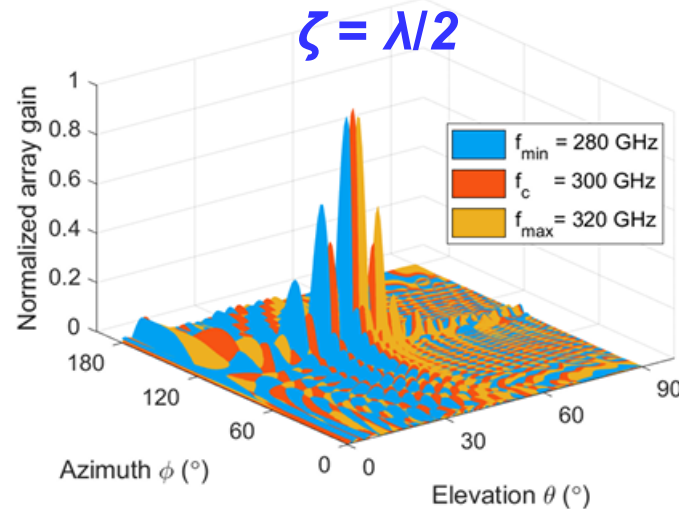
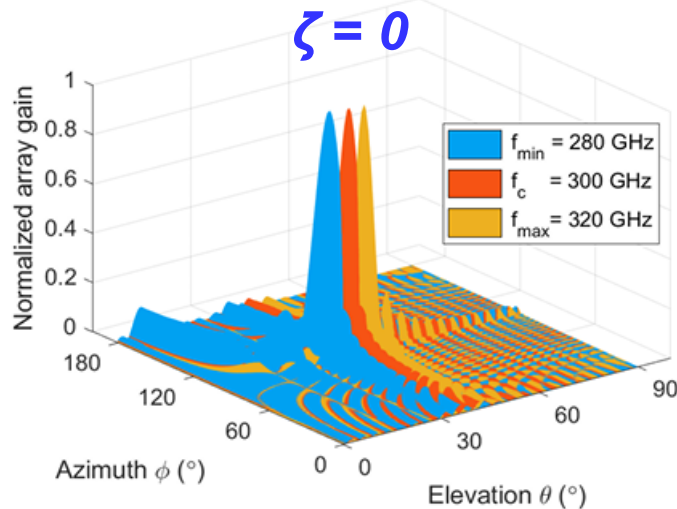
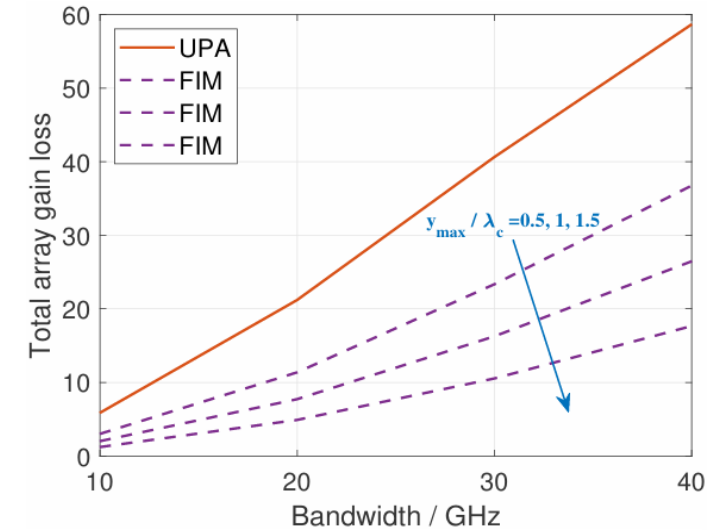
$$\min_{\mathbf{y}} \quad \mathcal{L}(\mathbf{y}) = \sum_{m=1}^M (1 - g^2(f_m, \mathbf{y}))$$

$$\text{s.t.} \quad y_{\min} \leq y_n \leq y_{\max}, \quad n = 1, 2, \dots, N.$$

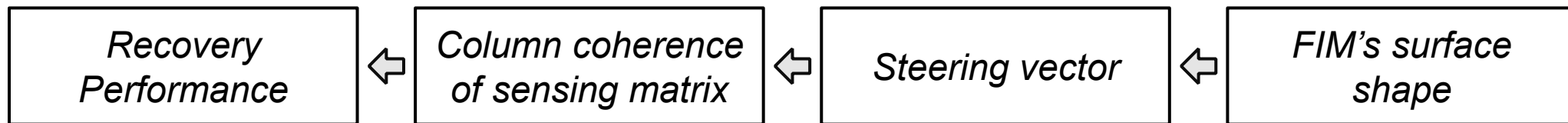
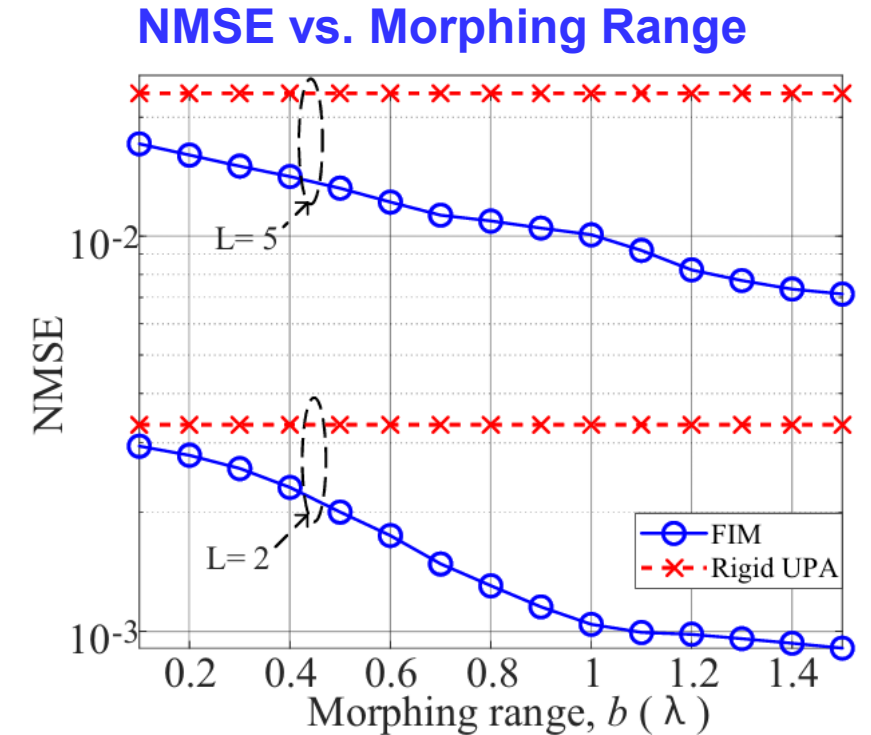
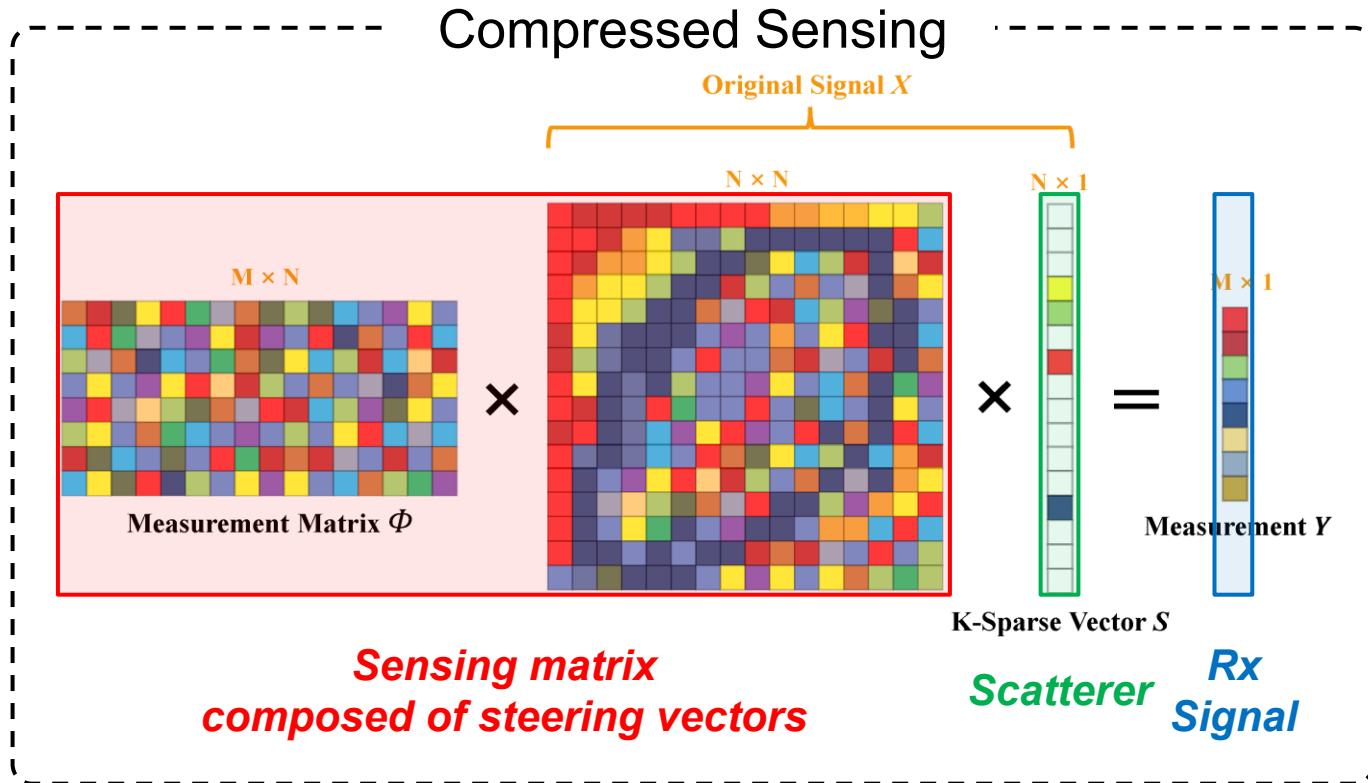


Gradient descent

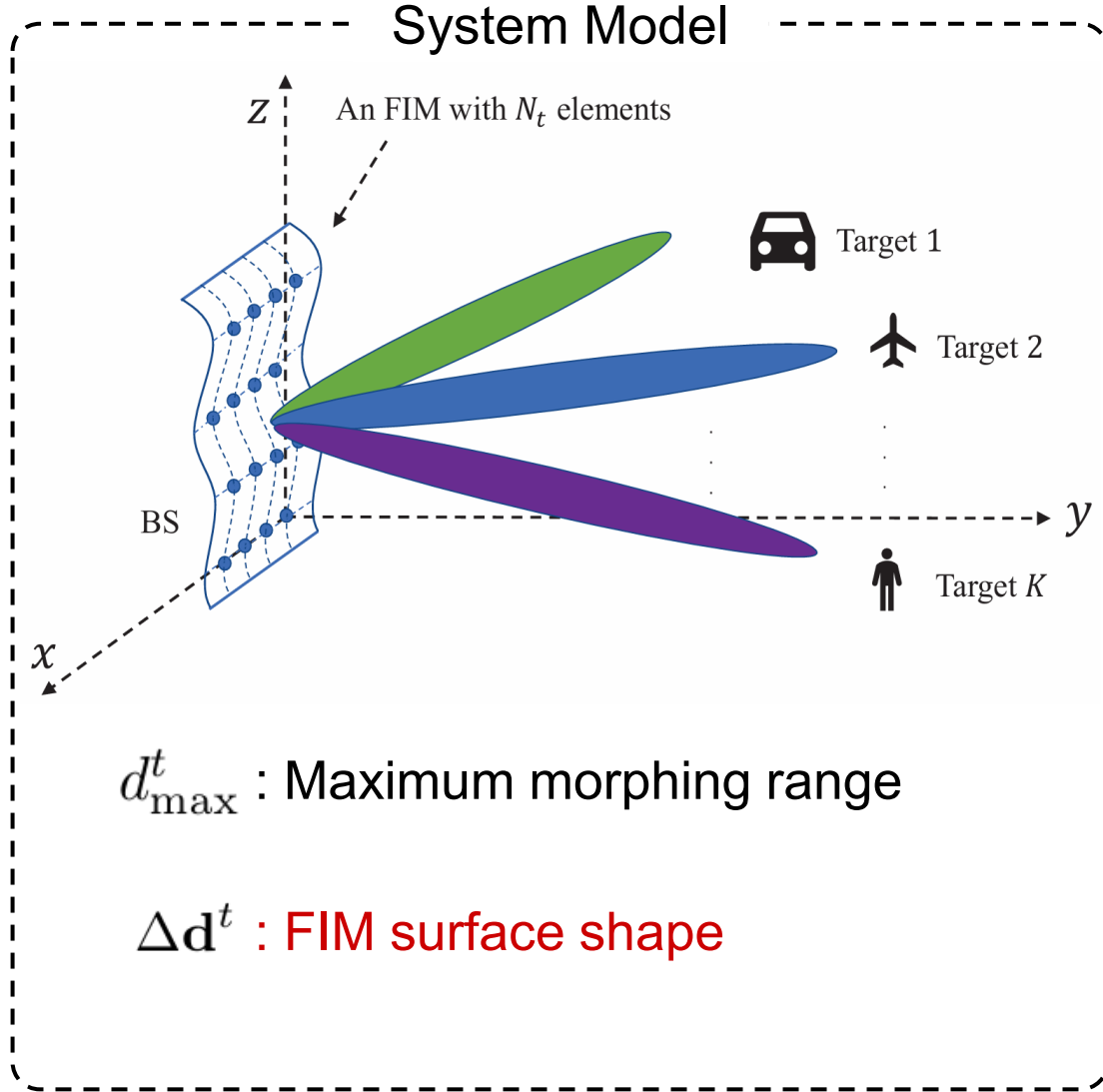
Gain Loss vs. Bandwidth



❖ 3.2 FIM-Enhanced Channel Estimation



❖ 3.2 FIM-Enhanced Wireless Sensing



Transmit steering vector:

$$\mathbf{a}(\theta_k, \varphi_k, \Delta \mathbf{d}^t) = [\mathbf{a}_z(\theta_k) \otimes \mathbf{a}_x(\theta_k, \varphi_k)] \odot \mathbf{a}_y(\theta_k, \varphi_k, \Delta \mathbf{d}^t)$$

$\downarrow$ UPA $\downarrow$ FIM

Optimization problem:

Transmit covariance matrix

$$\mathbf{B} = \sum_{k=1}^K \mathbf{a}(\theta_k, \varphi_k, \Delta \mathbf{d}^t) \mathbf{a}^H(\theta_k, \varphi_k, \Delta \mathbf{d}^t)$$

$$\max_{\mathbf{R}_X, \Delta \mathbf{d}^t} P_c \triangleq \text{tr}(\mathbf{R}_X \mathbf{B})$$

$$\text{s.t.} \quad \text{diag}(\mathbf{R}_X) = \frac{P_t}{N_t},$$

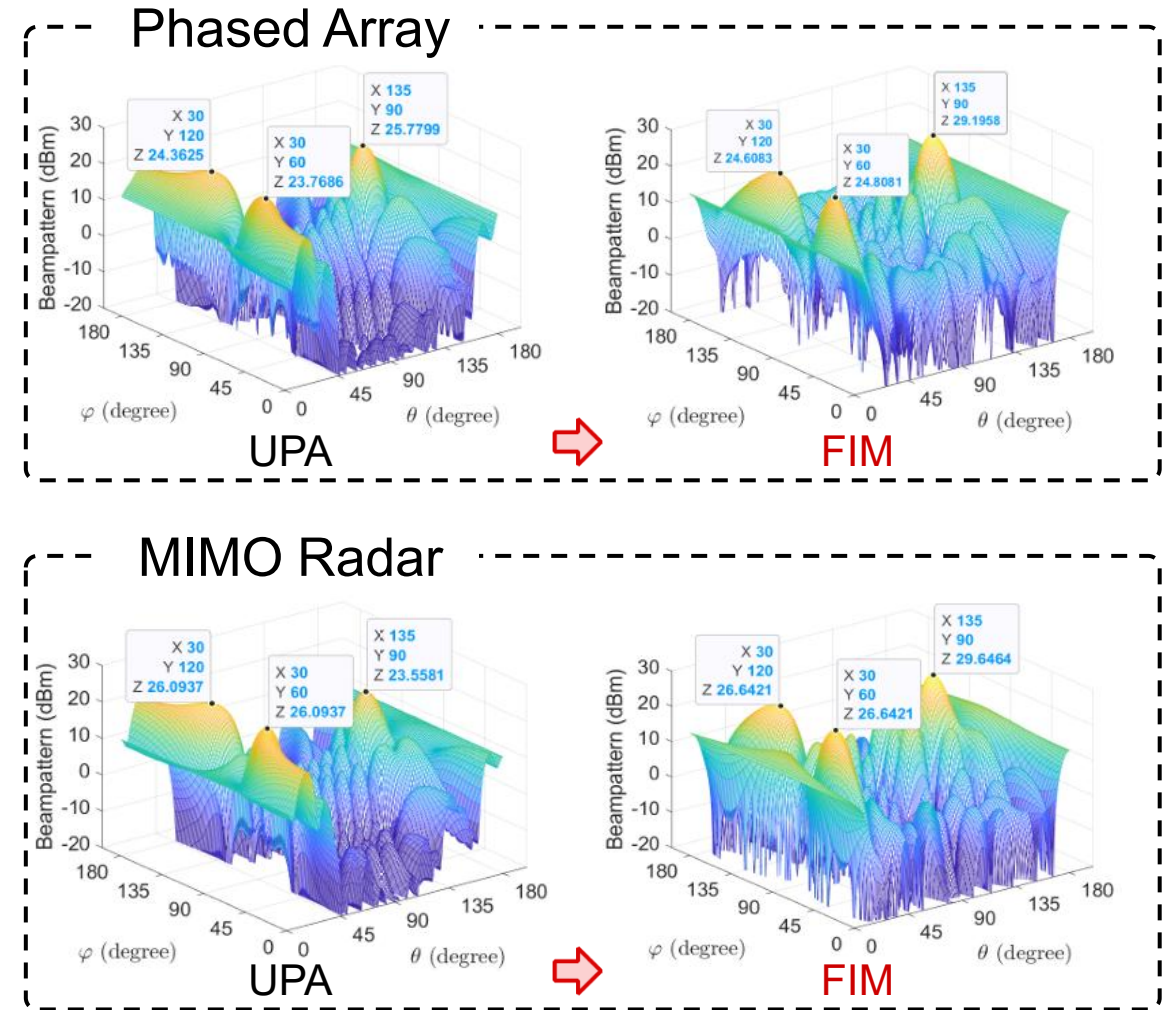
$$\mathbf{R}_X \succeq \mathbf{0},$$

$$|\Delta d_{n_t}^t| \leq d_{\max}^t, \quad n_t = 1, 2, \dots, N_t,$$

Algorithm: BCD

❖ 3.2 FIM-Enhanced Wireless Sensing

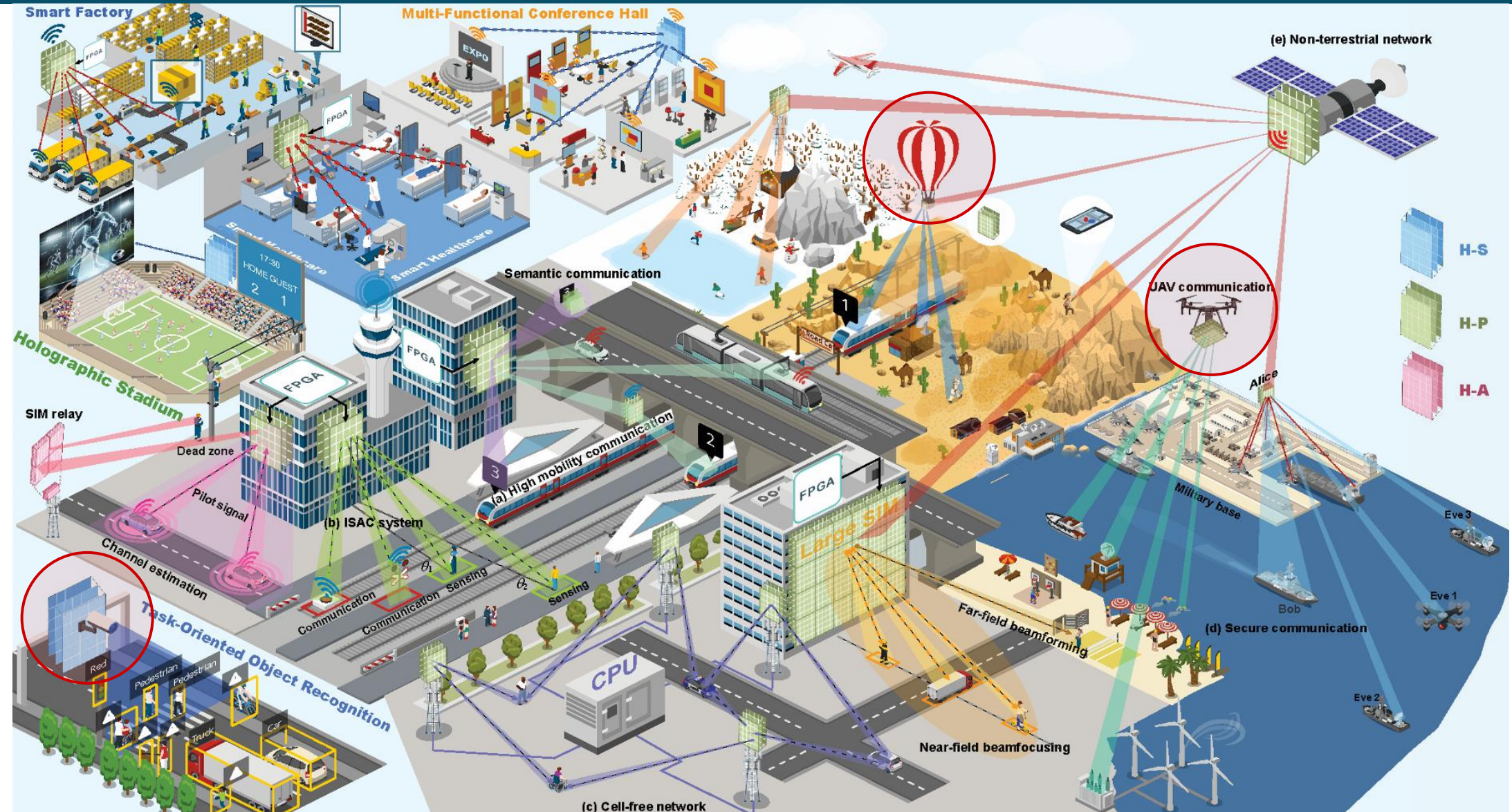
- Number of targets: $K = 3$
- Number of elements: $N_t = 100$
- Maximum morphing range: $d_{\max}^t = \lambda$
- Transmit power: $P_t = 10$ dBm



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❖ 4 Future Directions



[R25] H. Liu, J. An, X. Jia, L. Gan, G. K. Karagiannidis, B. Clerckx, M. Bennis, M. Debbah et al., “**Stacked intelligent metasurfaces** for wireless communications: Applications and challenges,” *IEEE Wireless Commun.*, vol. 32, no. 4, pp. 46-53, Aug. 2025.

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Many Thanks!