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

Jiancheng An (安建成)

jiancheng_an@163.com

2025.10.13

Contents

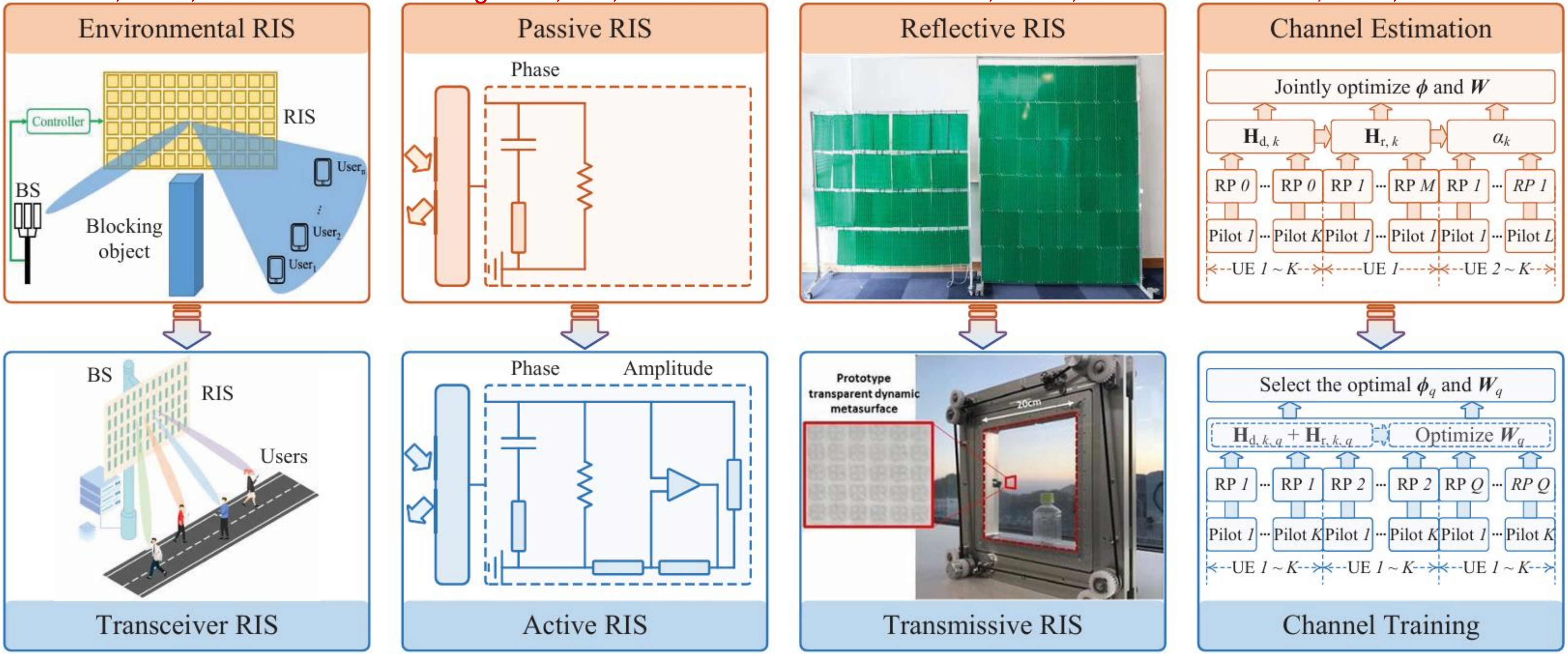
- 1 Background
- 2 Stacked Intelligent Metasurfaces (SIM)
  - 2.1 Motivation
  - 2.2 Applications
- 3 Flexible Intelligent Metasurfaces (FIM)
  - 3.1 Motivation
  - 3.2 Applications
- 4 Future Directions

Contents

- 1 Background
- 2 Stacked Intelligent Metasurfaces (SIM)
  - 2.1 Motivation
  - 2.2 Applications
- 3 Flexible Intelligent Metasurfaces (FIM)
  - 3.1 Motivation
  - 3.2 Applications
- 4 Future Directions

❖ 1 Background

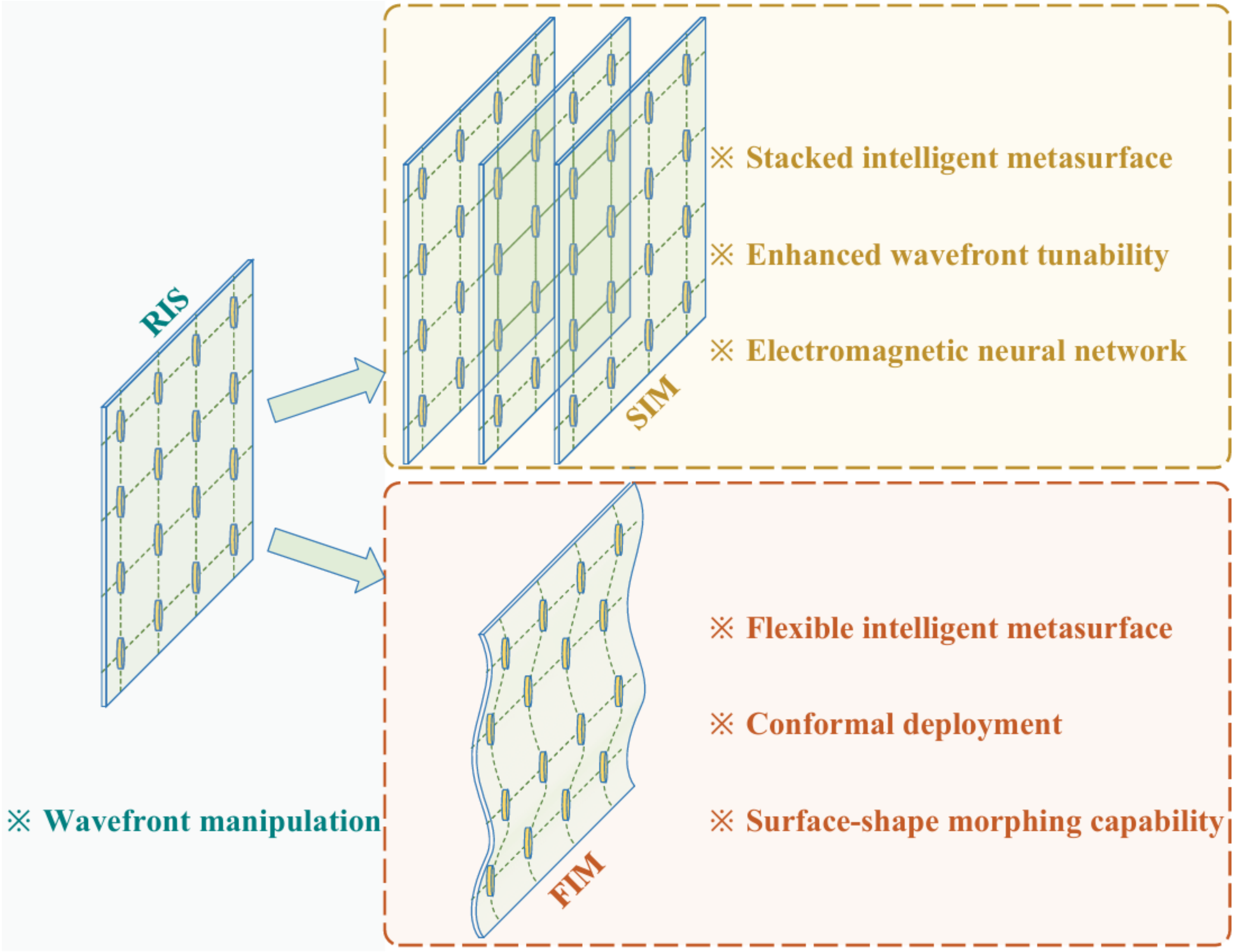
Jin et al., TWC, 2021 Zhang et al., CM, 2020 Di Renzo et al., JSAC, 2020 Cui et al., TWC, 2020



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*

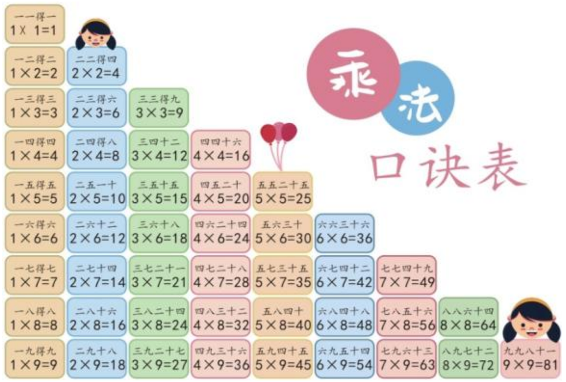
[R01] J. An, M. Debbah, T. J. Cui, Z. N. Chen and C. Yuen, “Emerging technologies in intelligent metasurfaces: Shaping the future of wireless communications,” *IEEE Trans. Antennas Propag.*, 2025, Early Access. (**Invited Paper**)

Contents

- 1 Background
- 2 Stacked Intelligent Metasurfaces (SIM)
  - 2.1 Motivation
  - 2.2 Applications
- 3 Flexible Intelligent Metasurfaces (FIM)
  - 3.1 Motivation
  - 3.2 Applications
- 4 Future Directions

❖ 2.1 Re-understanding multiplication & RIS

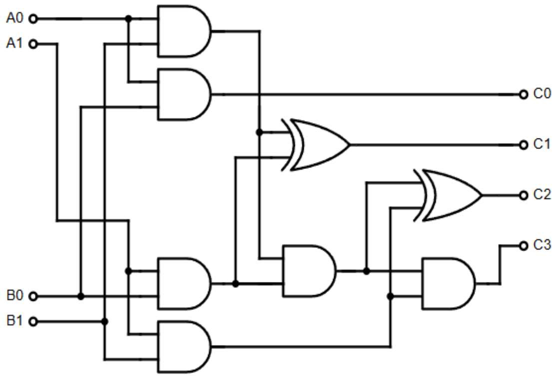
Human



Rule-based lookup table

⇨

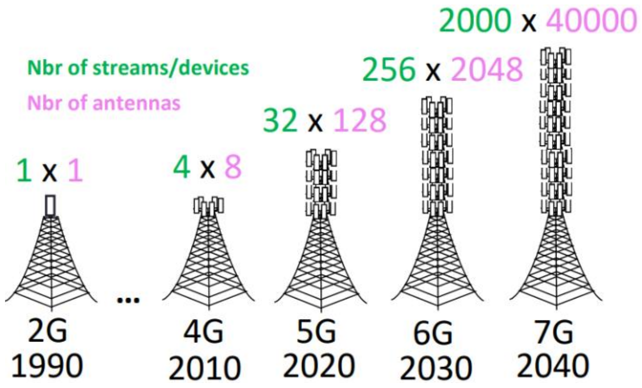
Precoding: $\mathbf{x} = \mathbf{W}\mathbf{s}$



Energy-consuming,
time-consuming

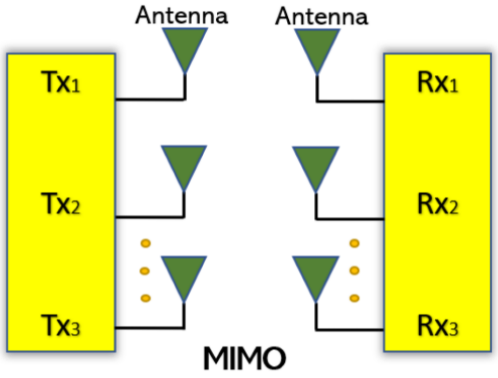
⇨

As # of antennas increases



Poor scalability

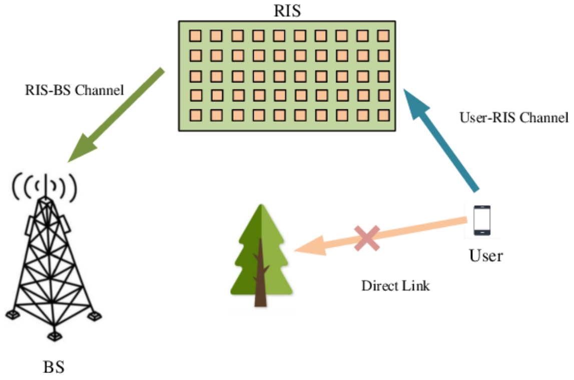
MIMO: $\mathbf{y} = \mathbf{H}\mathbf{x}$



Automatically completed,
not controllable

⇨

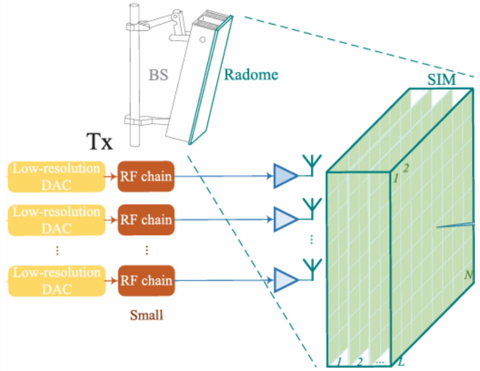
RIS: $\mathbf{y} = \mathbf{H}_2\mathbf{\Phi}\mathbf{H}_1\mathbf{x}$



Controllable,
insufficient DoF

⇨

SIM

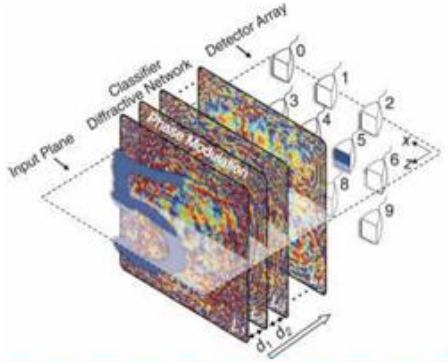


Does it work❓

❖ 2.1 SIM: Prototypes

2018

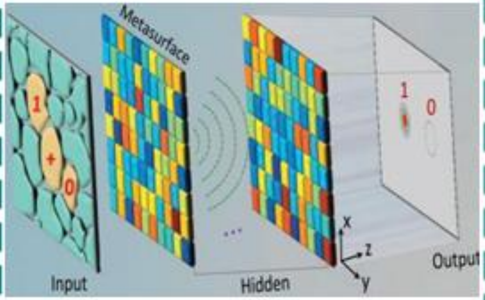
- *400 GHz*
- *Five layers*
- *Image classification*
- *Lin et al. [23]*



UCLA

2020

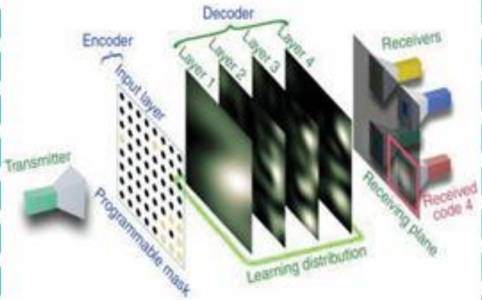
- *17 GHz*
- *Two layers*
- *Logic operation*
- *Qian et al. [74]*



ZJU

2022

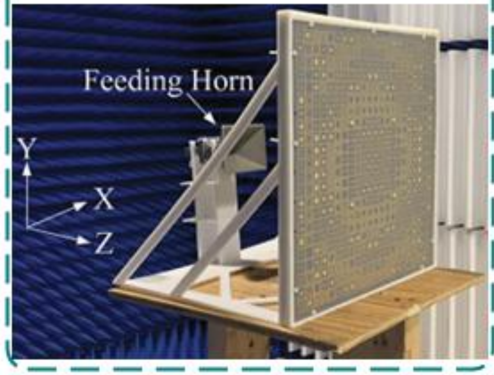
- *5.4 GHz*
- *Five layers*
- *CDMA decoder*
- *Liu et al. [24]*



SEU

2023

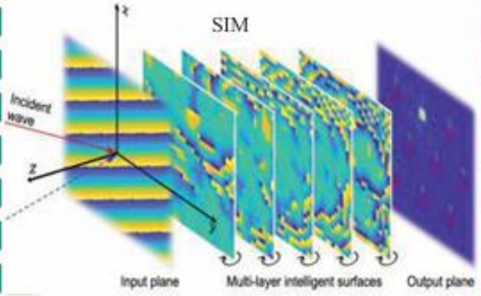
- *12 GHz*
- *Three layers*
- *Sidelobe suppression*
- *Liu et al. [78]*



NUS

2024

- *27.5 GHz*
- *Five layers*
- *DOA estimation*
- *Gao et al. [75]*

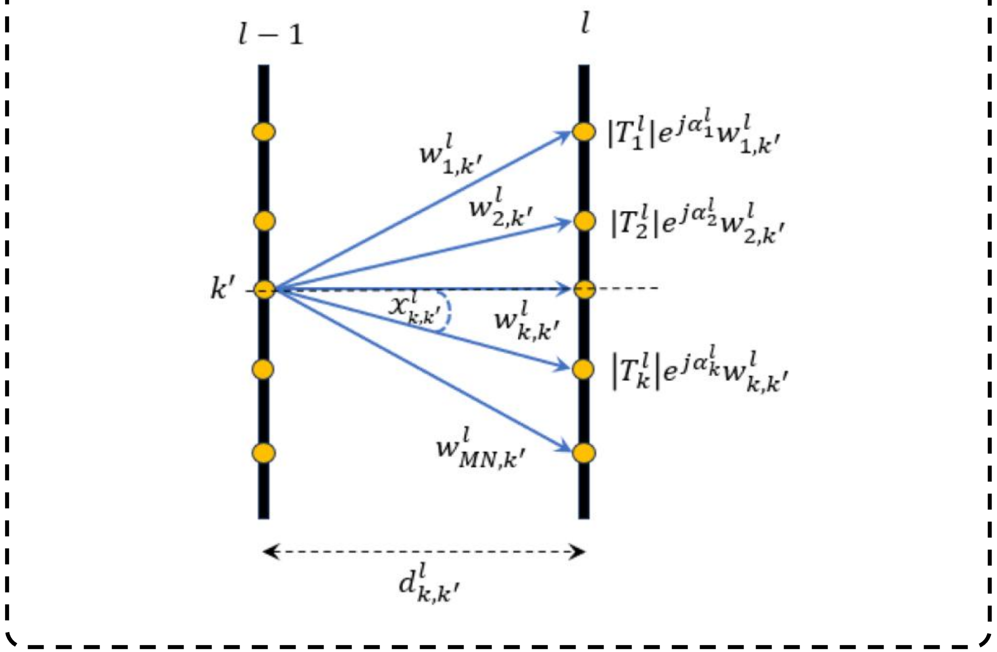


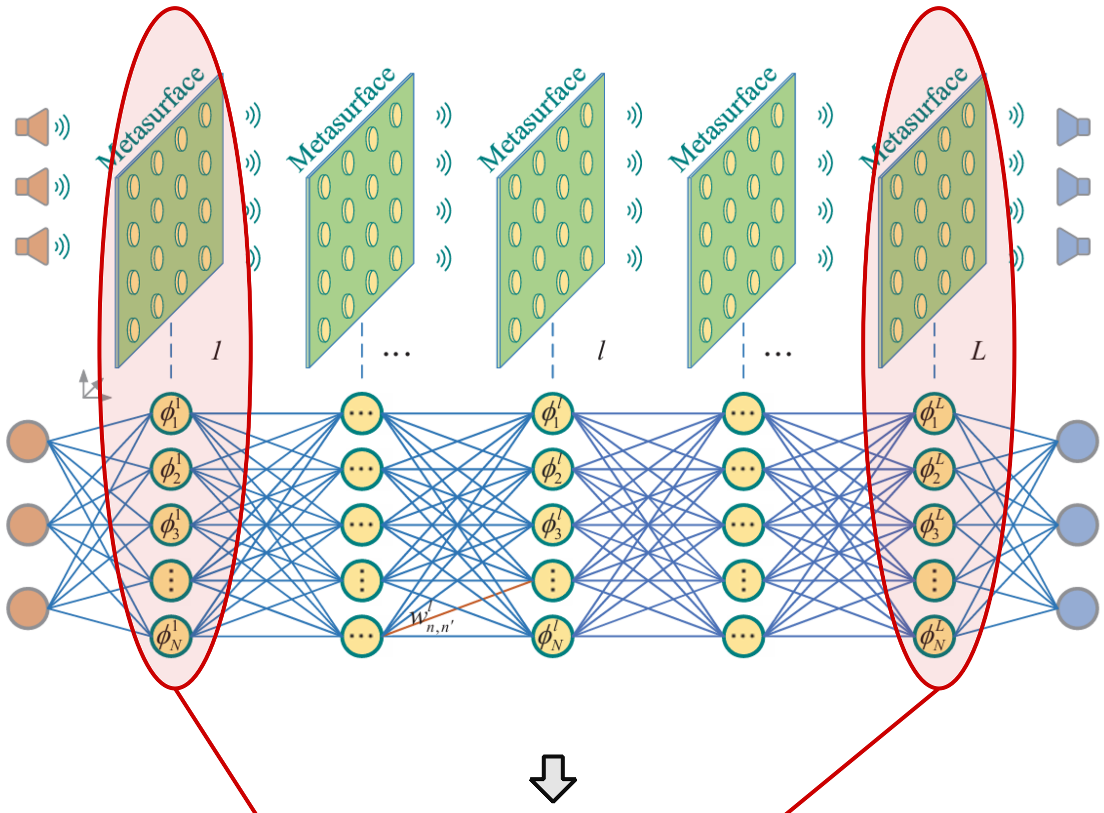
THU

[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

Inter-layer Propagation





Rayleigh-Sommerfeld Diffraction Theory

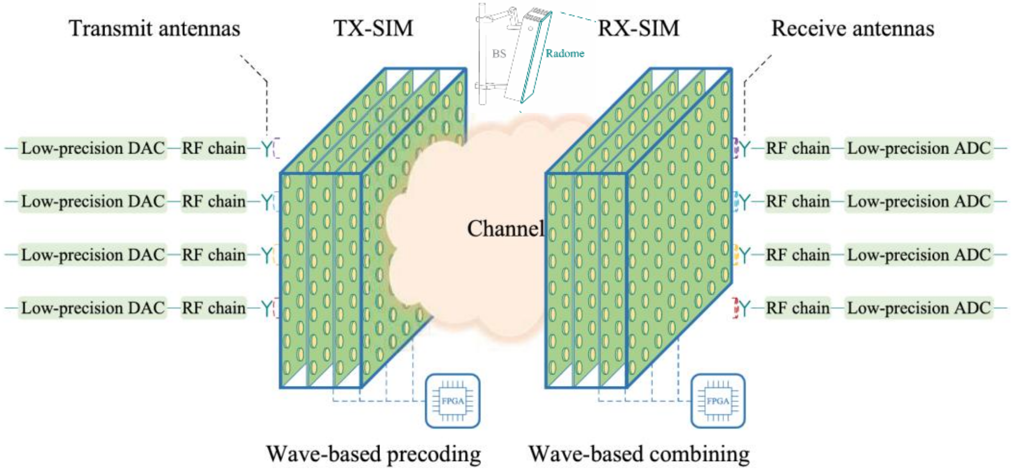
$$w^l_{n,n'} = \frac{A\cos\chi^l_{n,n'}}{r^l_{n,n'}}\left(\frac{1}{2\pi r^l_{n,n'}} - j\frac{1}{\lambda}\right)e^{j2\pi r^l_{n,n'}/\lambda}$$

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

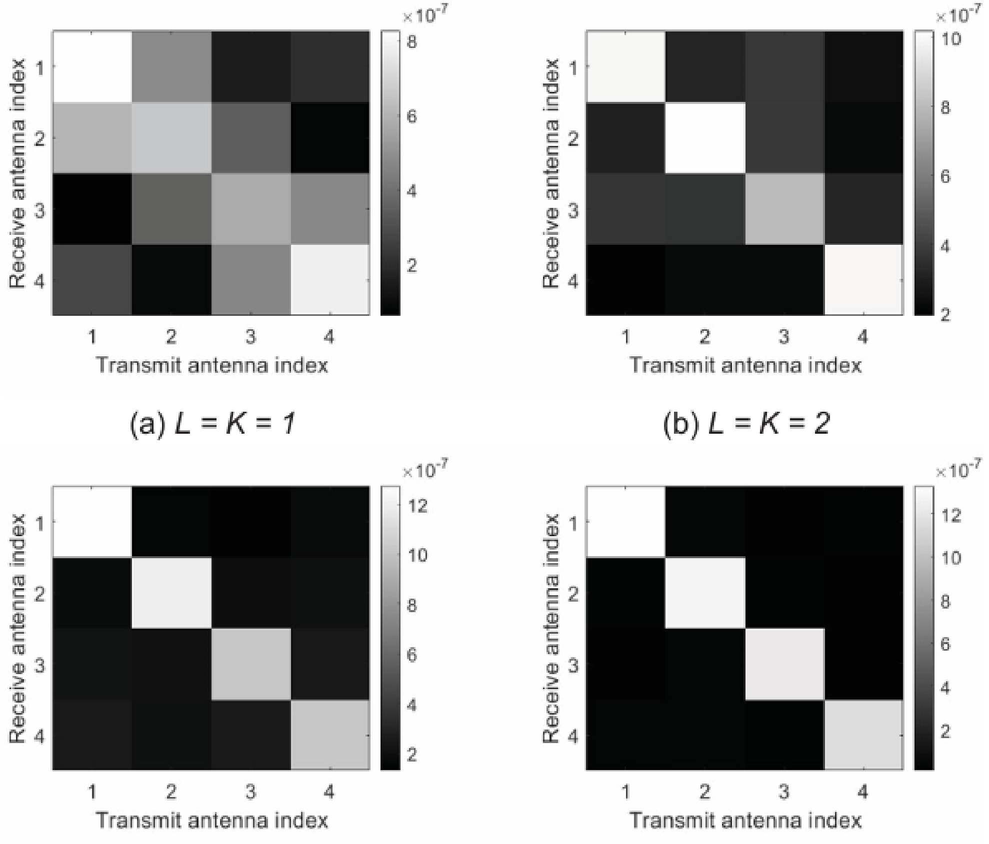
[R02] X. Lin, Y. Rivenson, N. T. Yardimci, M. Veli, Y. Luo, M. Jarrahi, and **A. Ozcan**, “All-optical machine learning using diffractive deep neural networks,” *Science*, vol. 361, no. 6406, pp.1004-1008, 2018.

❖ 2.1 SIM: MIMO Precoding

SIM-aided MIMO Transmission

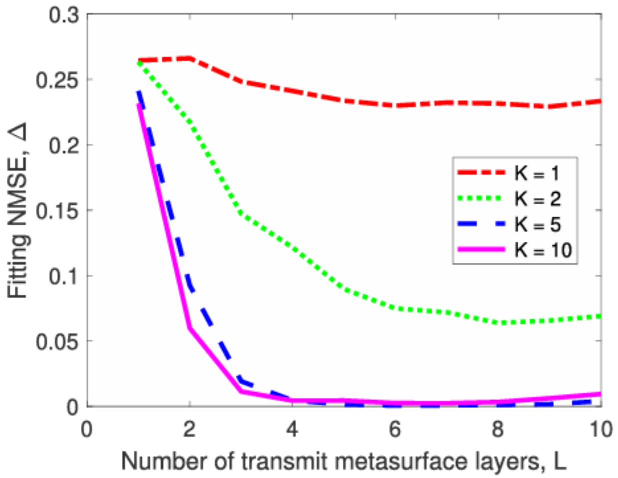


End-to-end channel

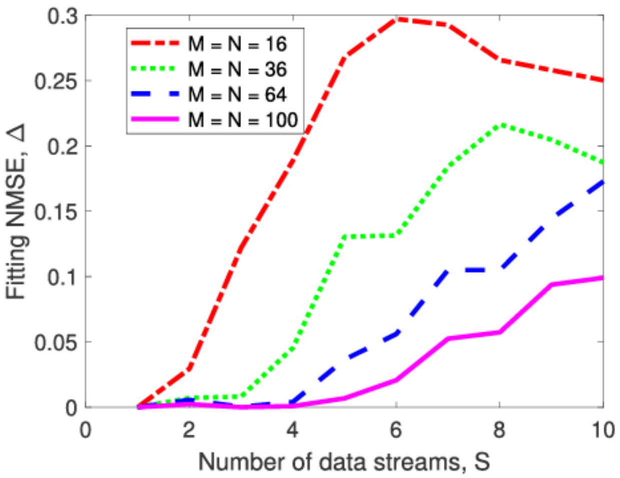


(a) $L = K = 1$ (b) $L = K = 2$ (c) $L = K = 3$ (d) $L = K = 4$

NMSE vs *L* & *K*

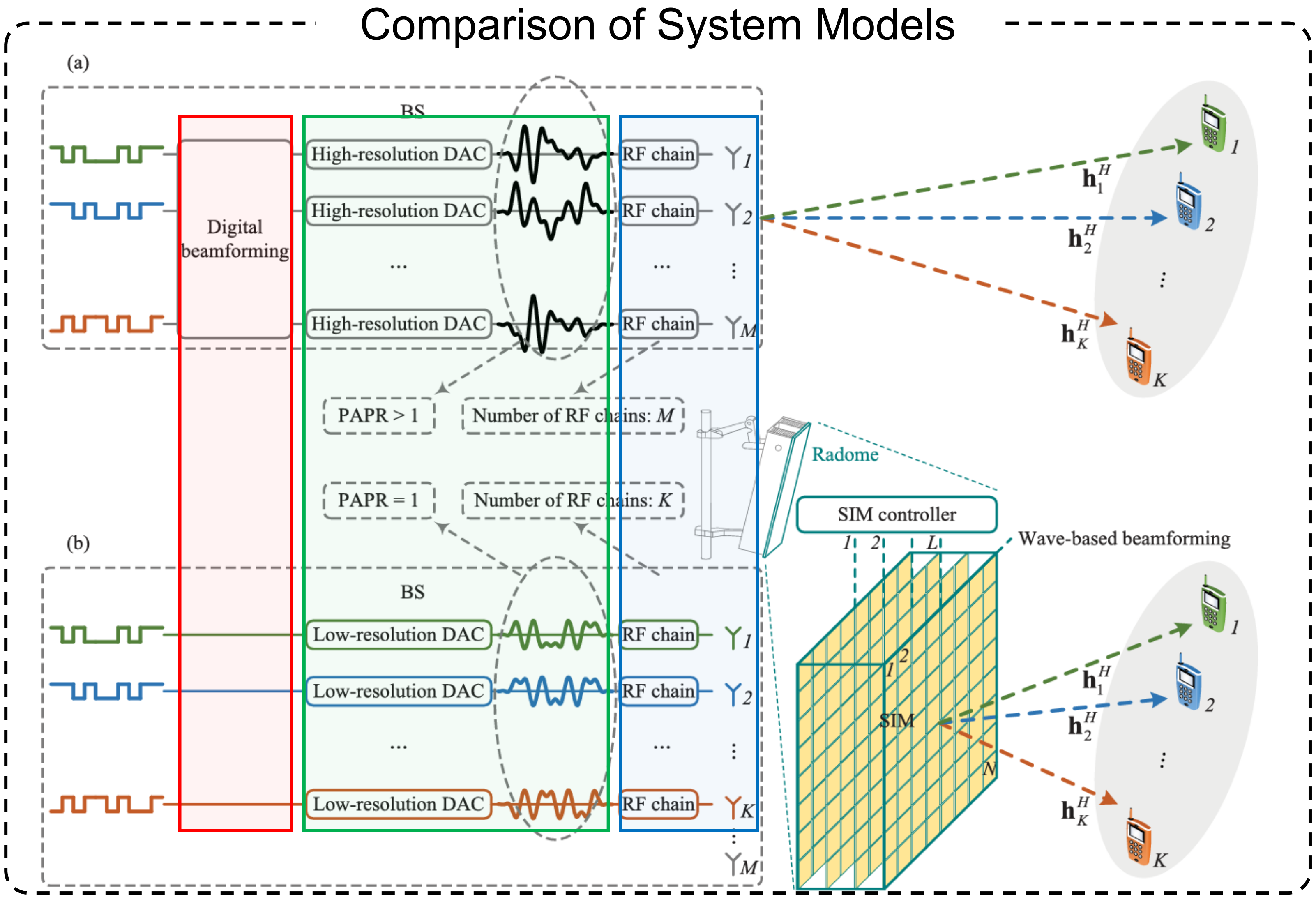


NMSE vs *S* & *M*

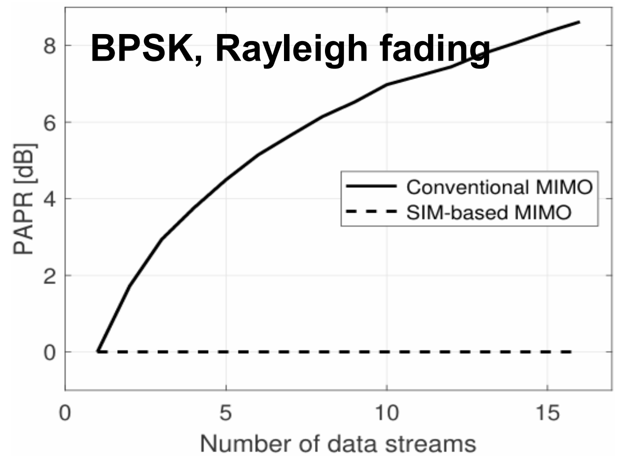


[R03] J. An, C. Xu, D. W. K. Ng, G. C. Alexandropoulos, C. Huang, C. Yuen and L. Hanzo, "**Stacked intelligent metasurfaces** for efficient holographic MIMO communications in 6G," *IEEE J. Sel. Areas Commun.*, vol. 41, no. 8, pp. 2380-2396, Aug. 2023.

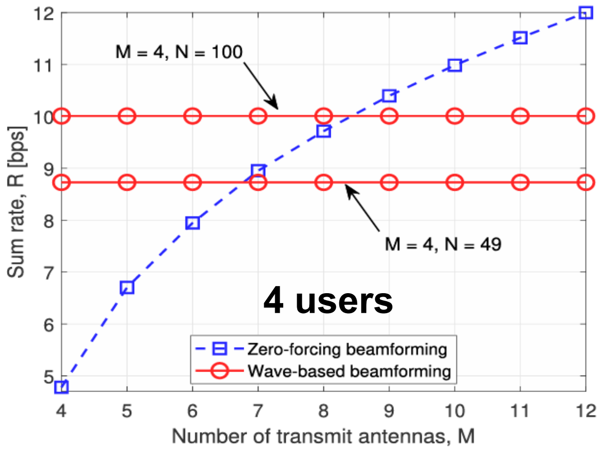
❖ 2.1 SIM: Benefits



PAPR vs. # of Streams

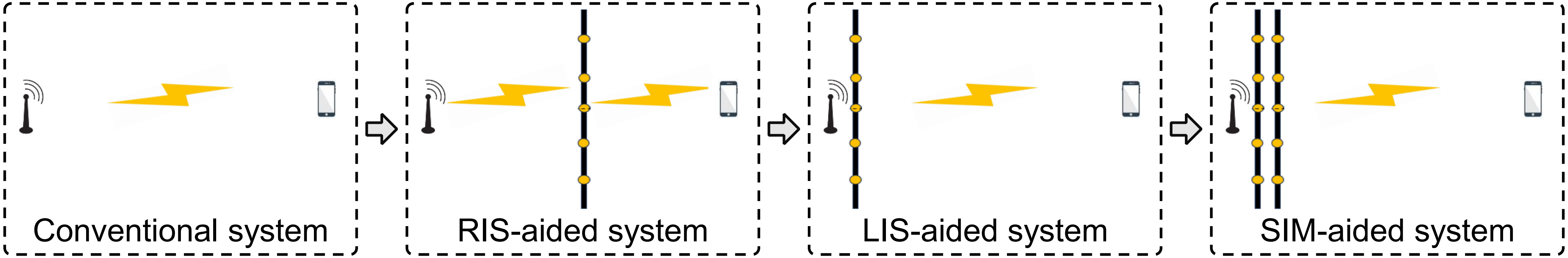


Performance Comparison



[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?



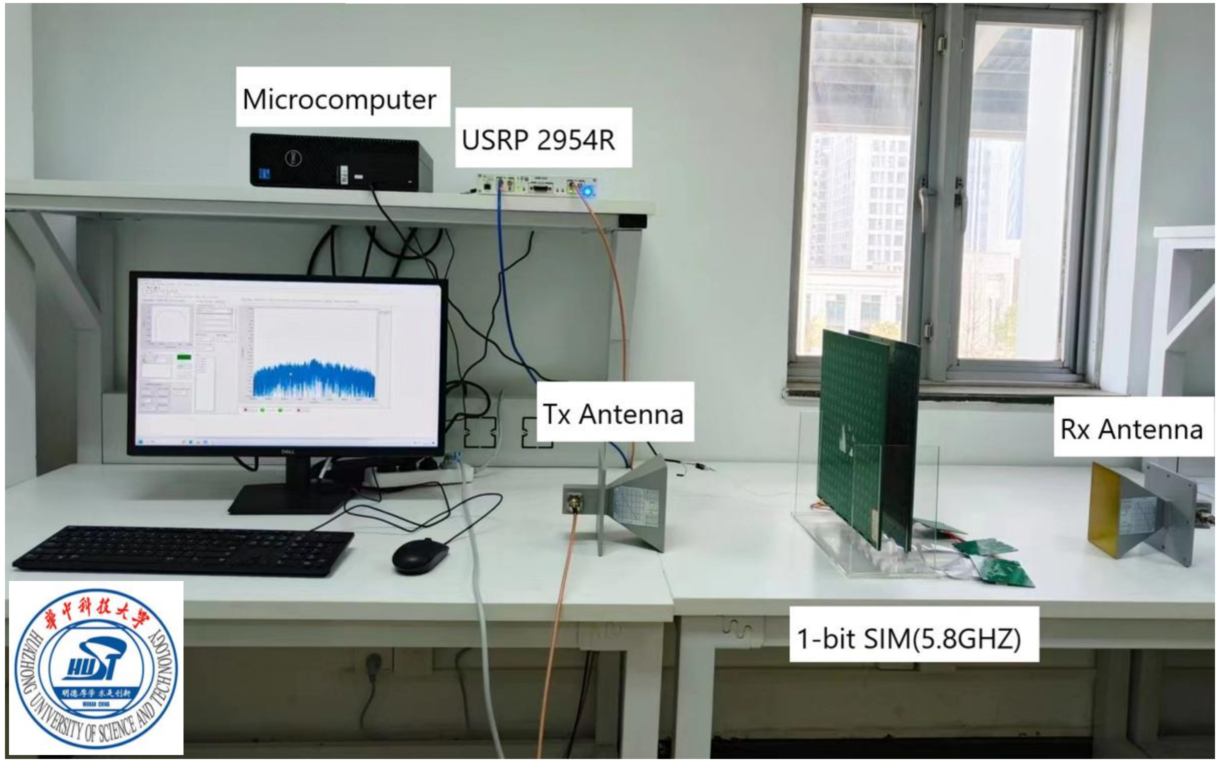
- Uncontrollable channel
- Severe path loss

RIS-aided system	LIS-aided system	SIM-aided system
↘ Path loss	↘ Path loss	↘ Path loss
↘ Penetration loss	↘ Penetration loss	↘ Penetration loss
↗ Array gain	↗ Array gain	↗ Array gain

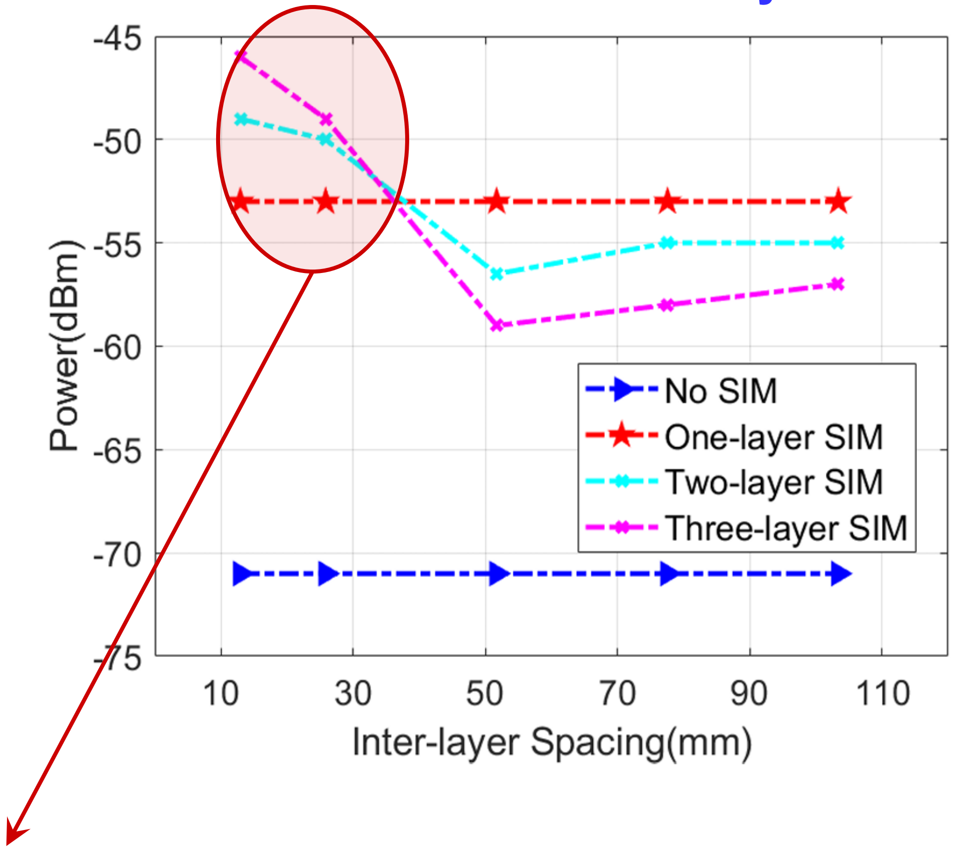
Which one dominates? = ↗ Array gain + ↘ Penetration loss + ↘ Path loss

❖ 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.

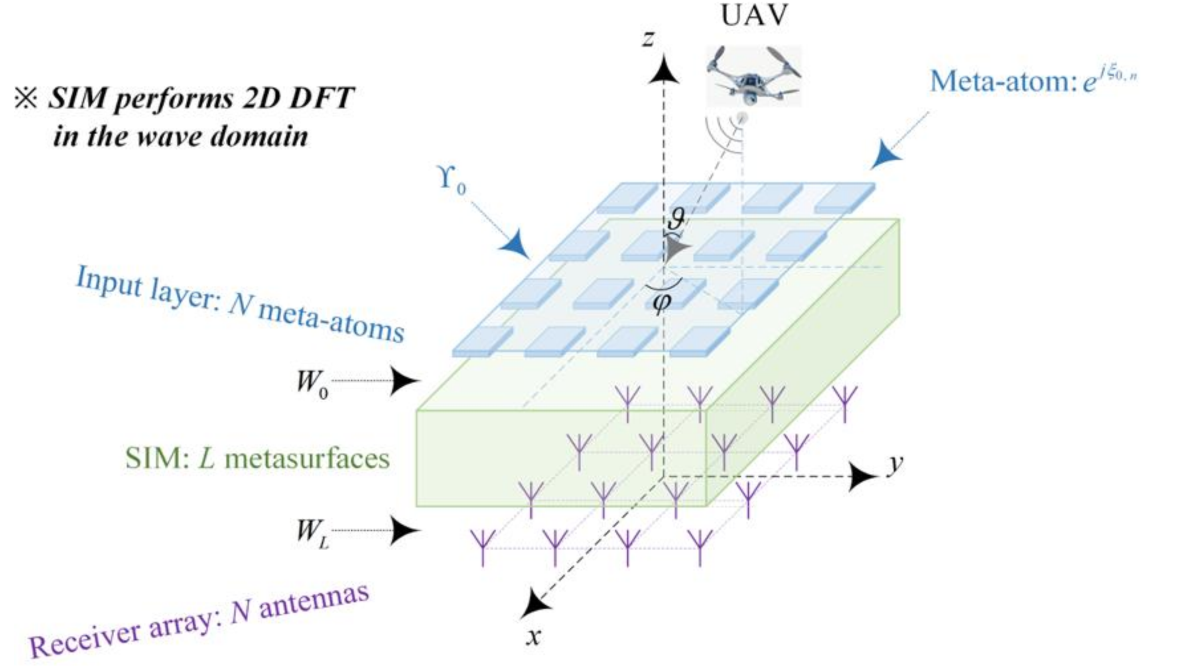
[R05] Z. Wang, H. Liu, J. Zhang, R. Xiong, K. Wan, X. Qian, M. Di Renzo and **R. C. Qiu**, "Multi-user ISAC through **stacked intelligent metasurfaces**: New algorithms and experiments," *Proc. GLOBECOM 2024*, Cape Town, South Africa, 2024, pp. 4442-4447.

Contents

- 1 Background
- 2 Stacked Intelligent Metasurfaces (SIM)
  - 2.1 Motivation
  - **2.2 Applications**
- 3 Flexible Intelligent Metasurfaces (FIM)
  - 3.1 Motivation
  - 3.2 Applications
- 4 Future Directions

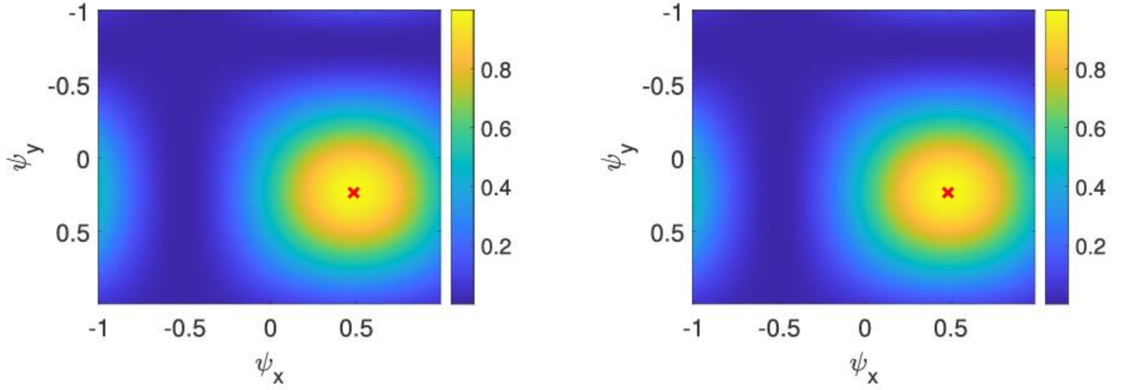
❖ 2.2 SIM for DOA Estimation

SIM-aided Array System



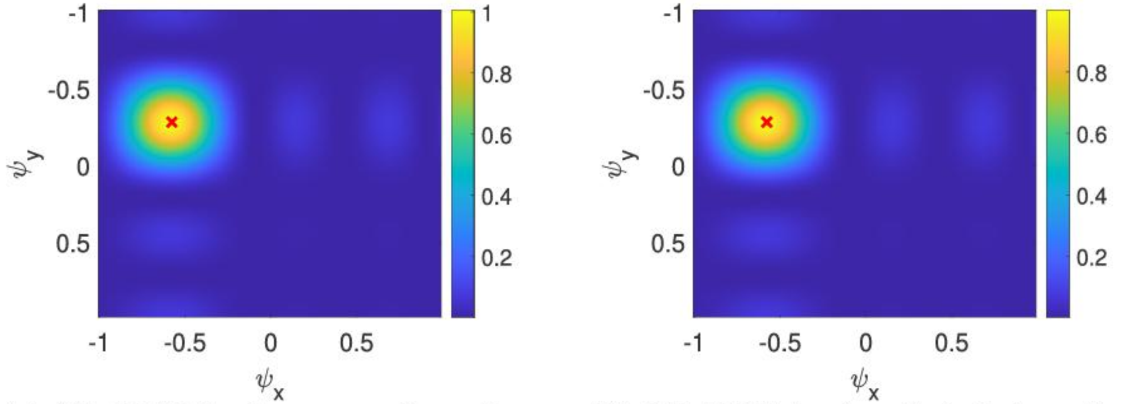
Low-precision spectrum → Multi-snapshot combination → High-precision spectrum

Receiver array: 2×2



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

Receiver array: 4×4

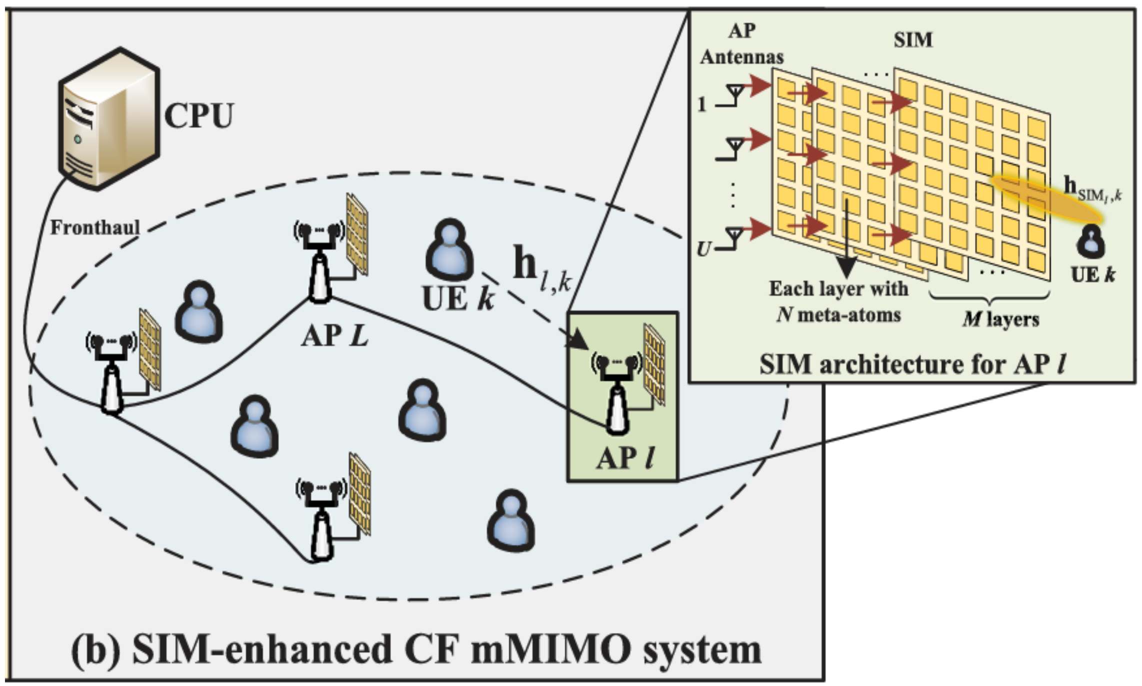


(a) 2D DFT in the wave domain; (b) 2D DFT in the digital domain.

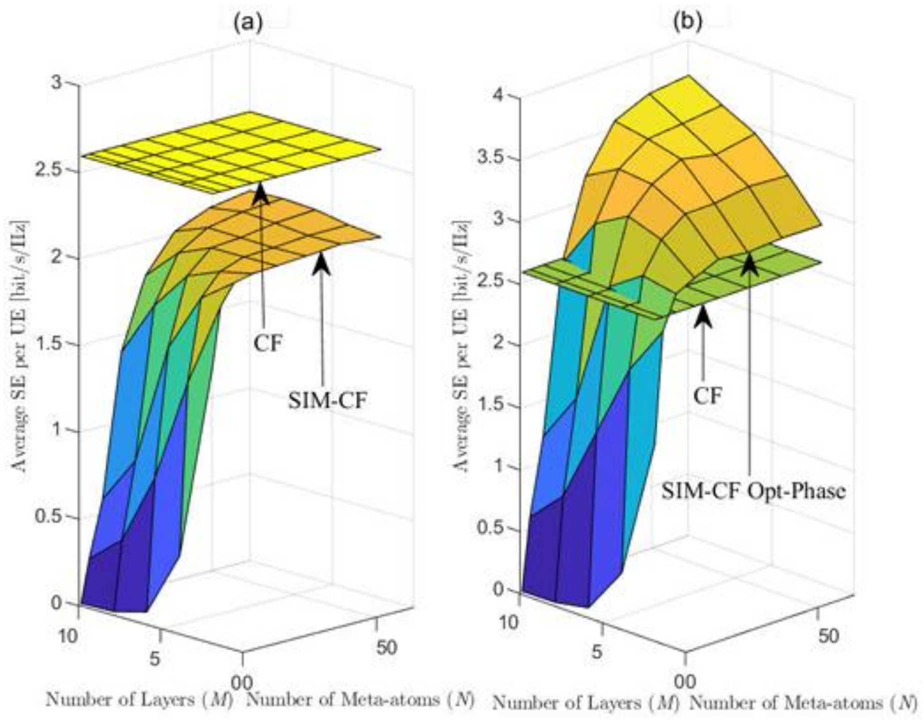
[R06] J. An, C. Yuen, Y. L. Guan, M. Di Renzo, M. Debbah, H. V. Poor and L. Hanzo, “Two-dimensional direction-of-arrival estimation using **stacked intelligent metasurfaces**,” *IEEE J. Sel. Areas Commun.*, vol. 42, no. 10, pp. 2786-2802, Oct. 2024.

❖ 2.2 SIM for CF mMIMO: Distributed Deployment

SIM-Aided Uplink CF mMIMO



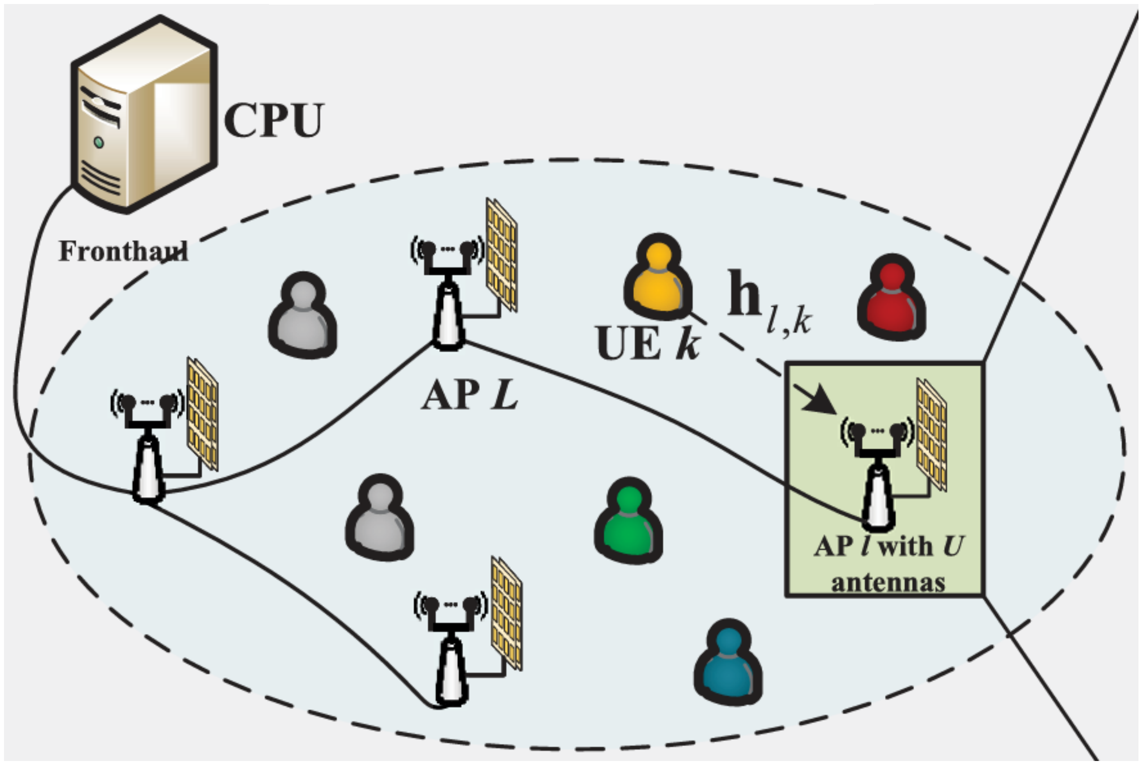
SE vs. # of layers and meta-atoms



[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.

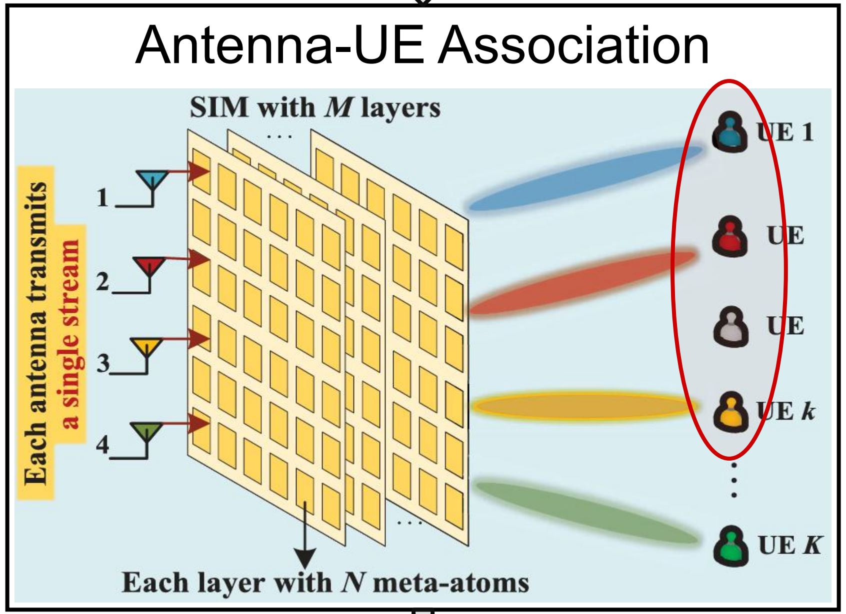
❖ 2.2 SIM for CF mMIMO: Antenna-UE Association

SIM-Aided CF mMIMO



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

⇩



⇩

Heuristic method

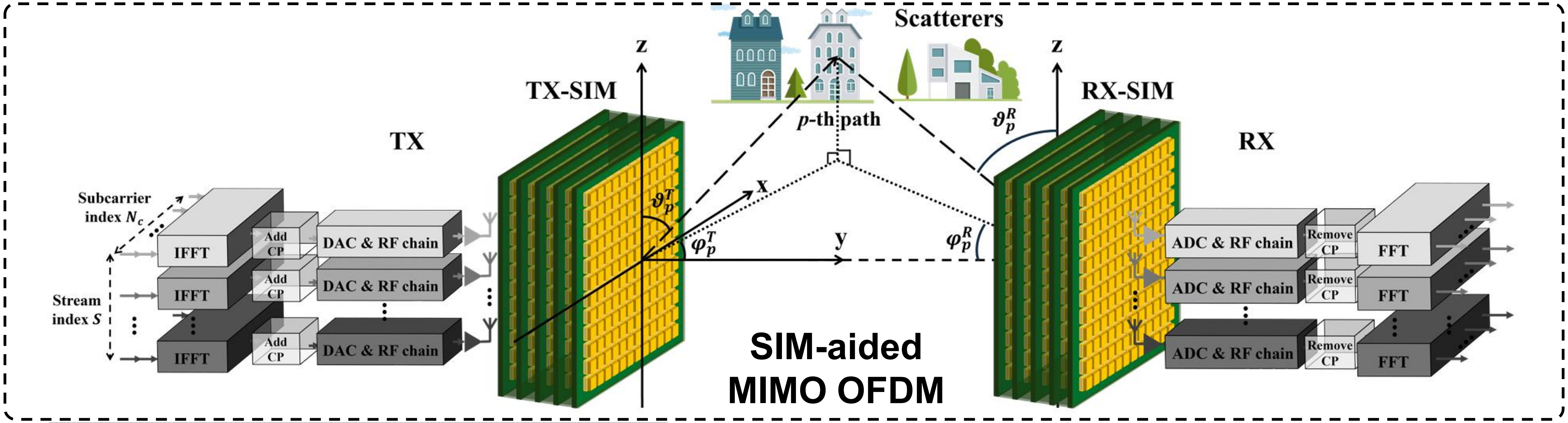
For each AP: Find the Nearest M UEs → *As L increases infinitely* → Asymptotically Optimal

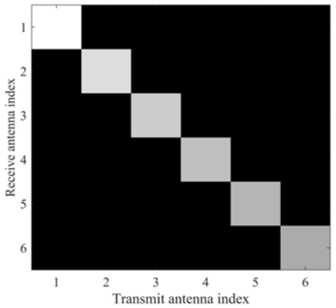
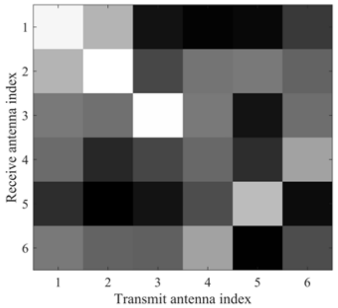
⇩

Gain Dominant --- MRT

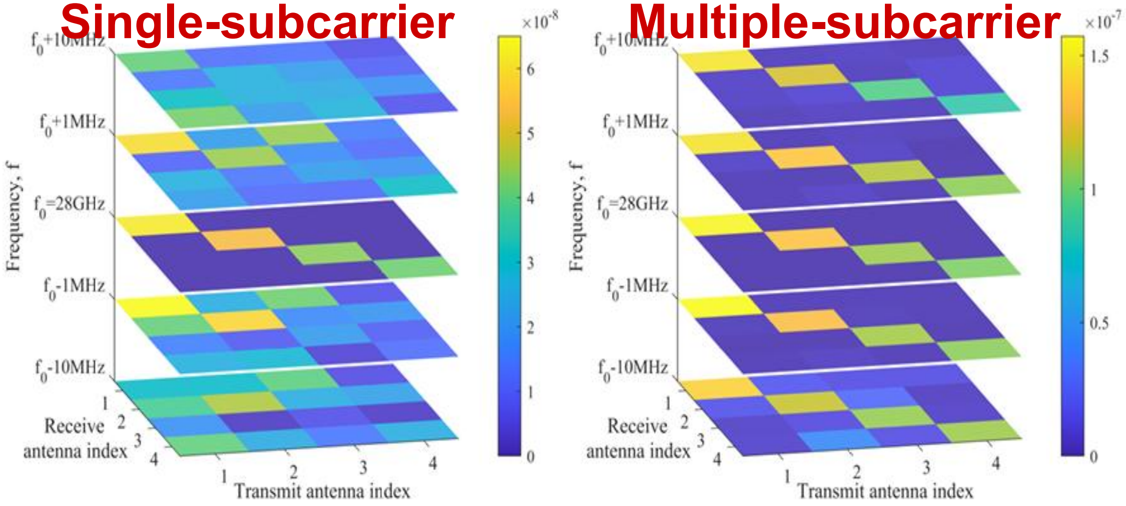
[R10] E. Shi, J. Zhang, J. An, G. Zhang, Z. Liu, C. Yuen and B. Ai, "Joint AP-UE association and precoding for **SIM**-aided cell-free massive MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 24, no. 6, pp. 5352-5367, Jun. 2025.

❖ 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		

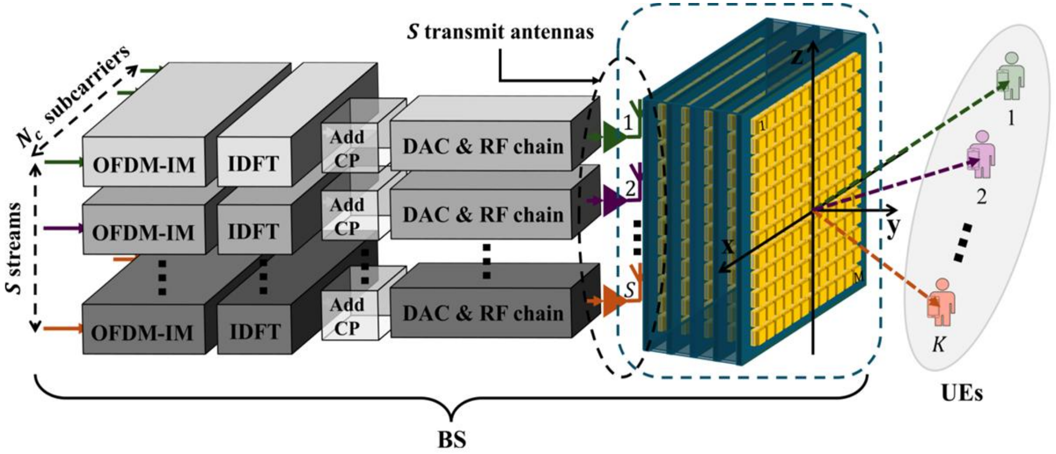
Maximum effective bandwidth



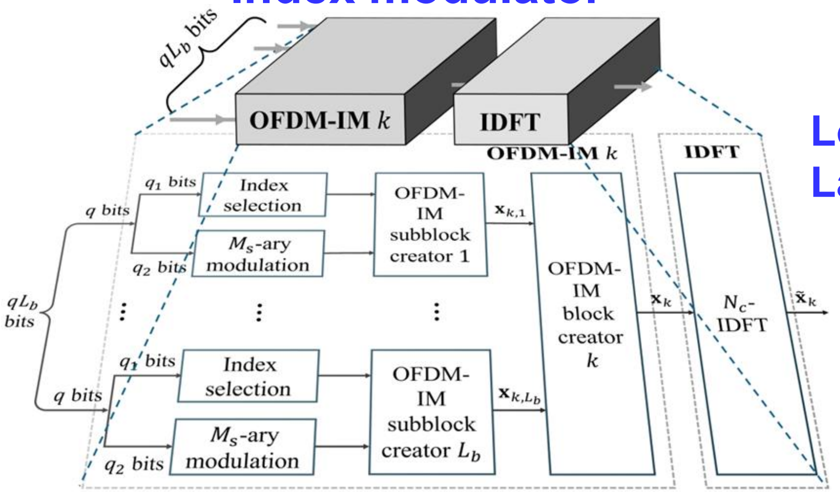
[R11] Z. Li, J. An and C. Yuen, "**Stacked intelligent metasurfaces**-enhanced MIMO OFDM wideband communication systems," *IEEE Trans. Wireless Commun.*, (Minor Revision) Online: https://arxiv.org/abs/2503.00368

❖ 2.2 SIM for Wideband Communications (OFDM-IM)

SIM-aided wideband MIMO OFDM

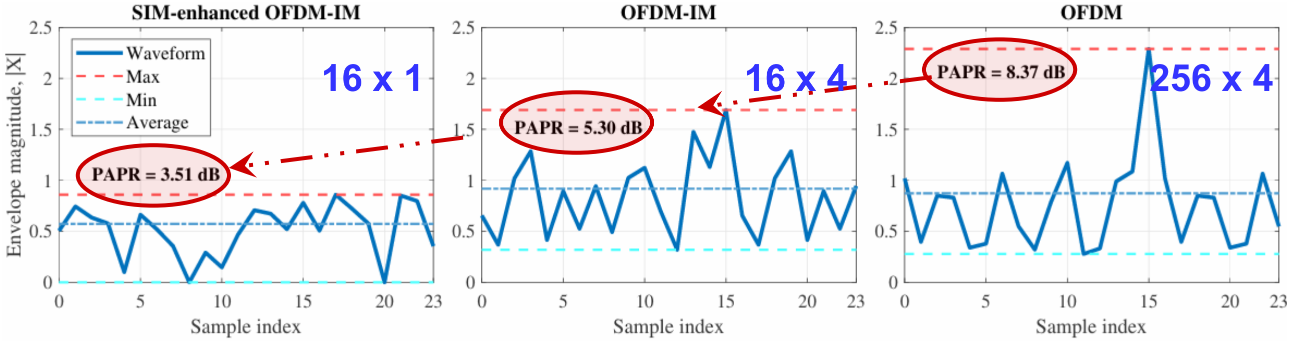


Index modulator

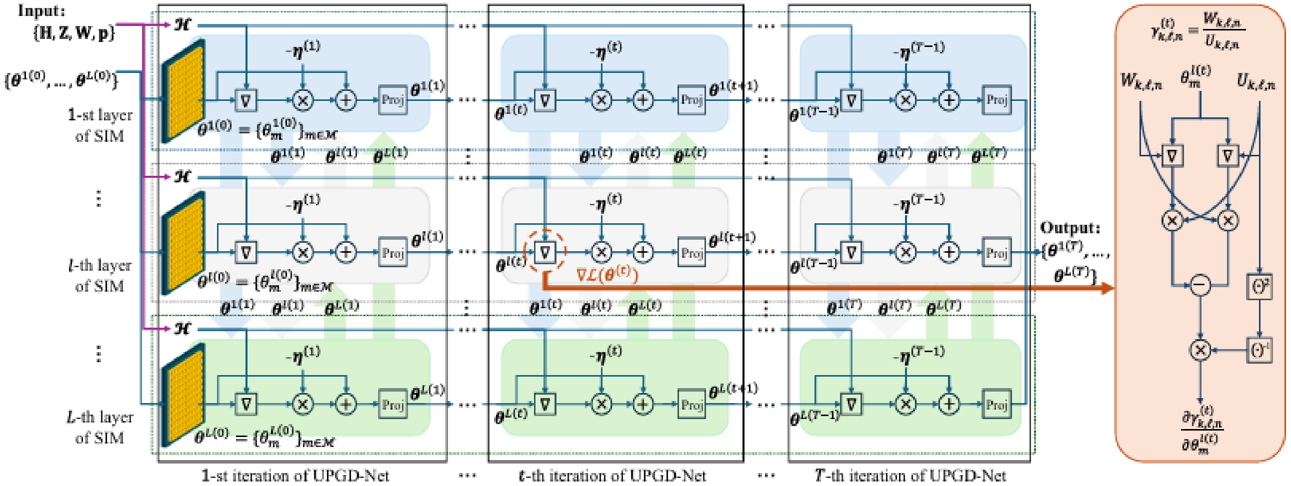


Lower PAPR
Larger BW

PAPR Comparison



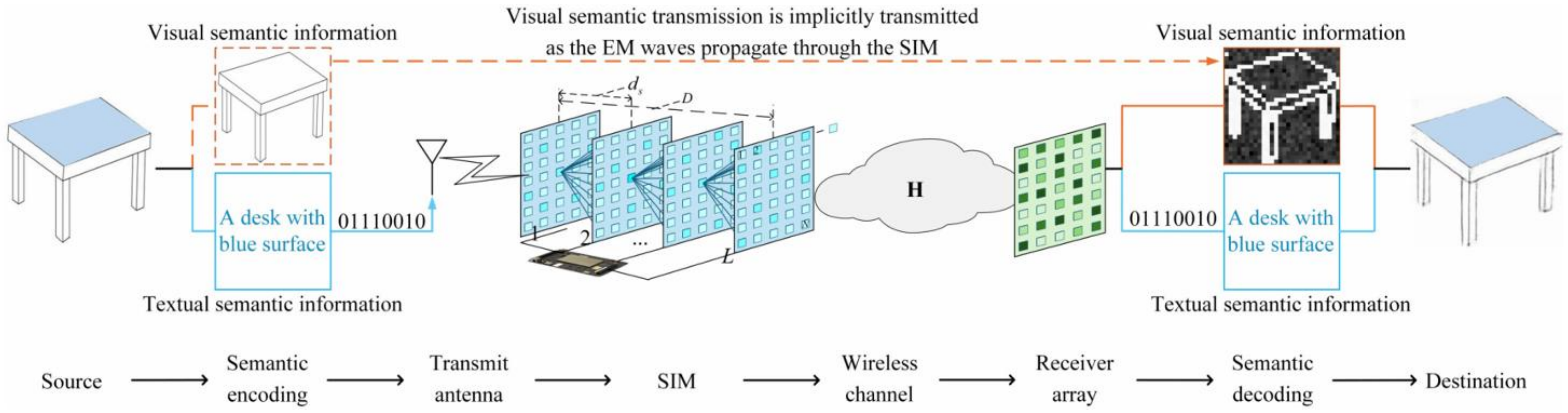
Deep unfolding strategy



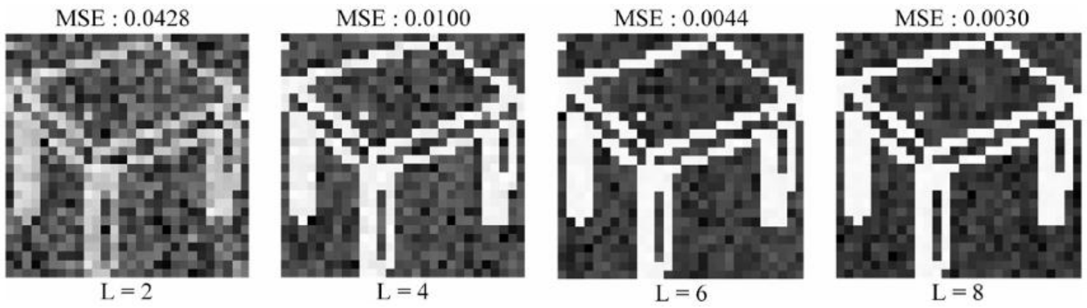
[R12] Z. Li, J. An and C. Yuen, "**Stacked intelligent metasurface**-enhanced wideband multiuser MIMO OFDM-IM communications," *IEEE Trans. Wireless Commun.*, (Submitted) Online: https://arxiv.org/abs/2509.22327

❖ 2.2 SIM for Multi-Modal Semantic Communications

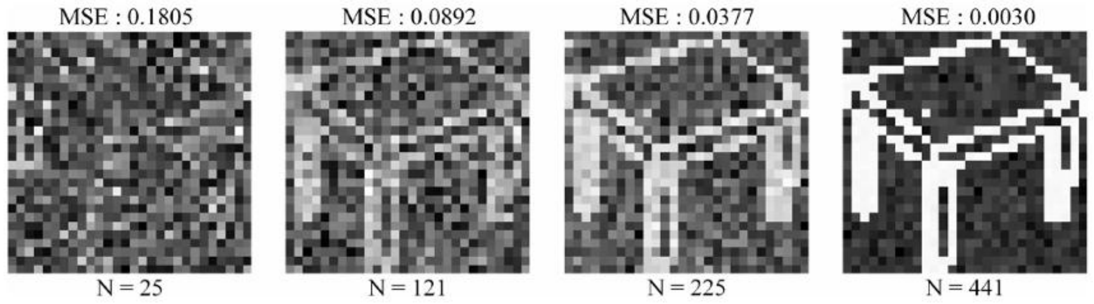
System Model



MSE vs. # of layers



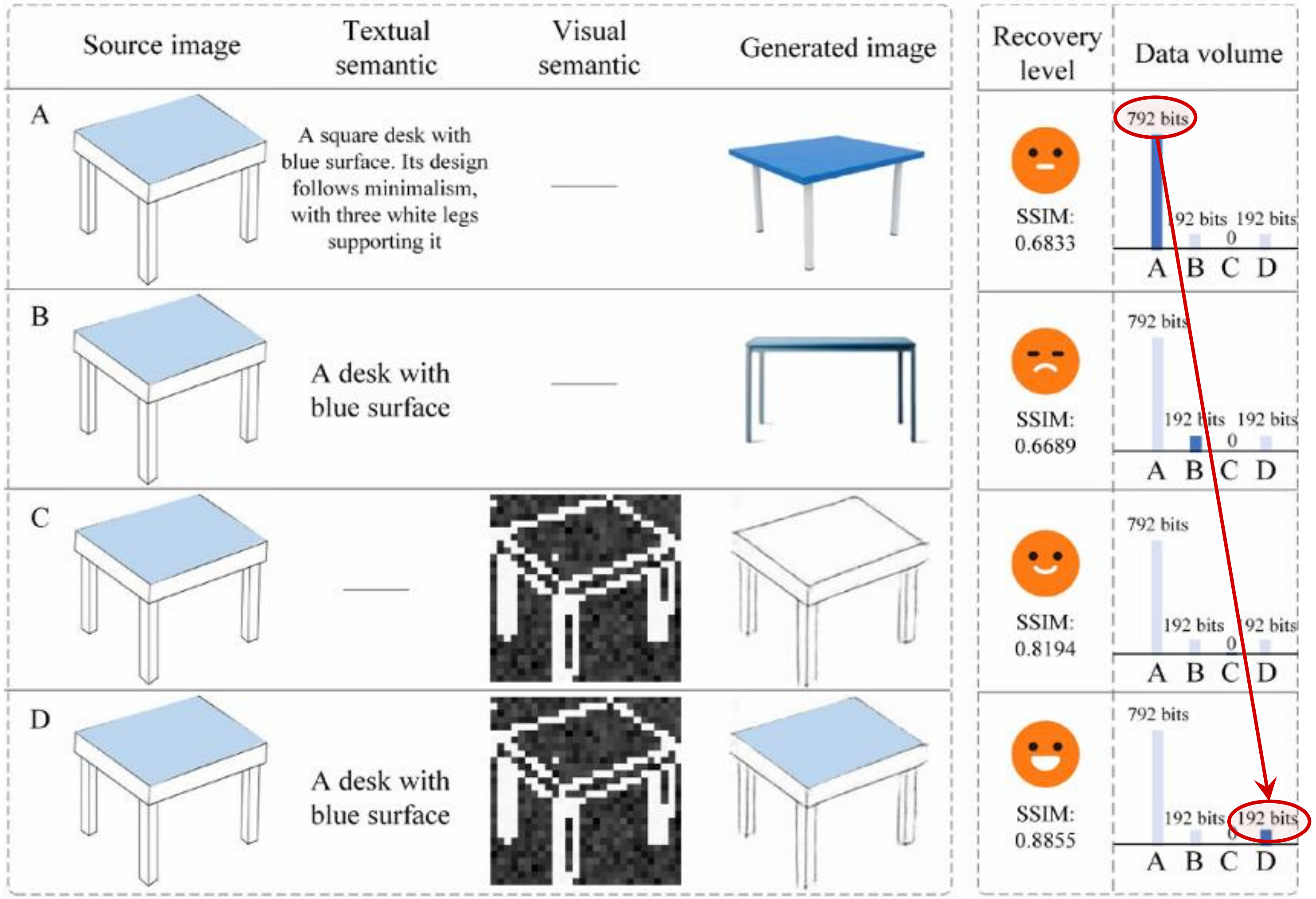
MSE vs. # of meta-atoms on each layer



[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.

❖ 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.

Contents

- 1 Background
- 2 Stacked Intelligent Metasurfaces (SIM)
  - 2.1 Motivation
  - 2.2 Applications
- **3 Flexible Intelligent Metasurfaces (FIM)**
  - **3.1 Motivation**
  - 3.2 Applications
- 4 Future Directions

❖ 3.1 FIM: Motivation

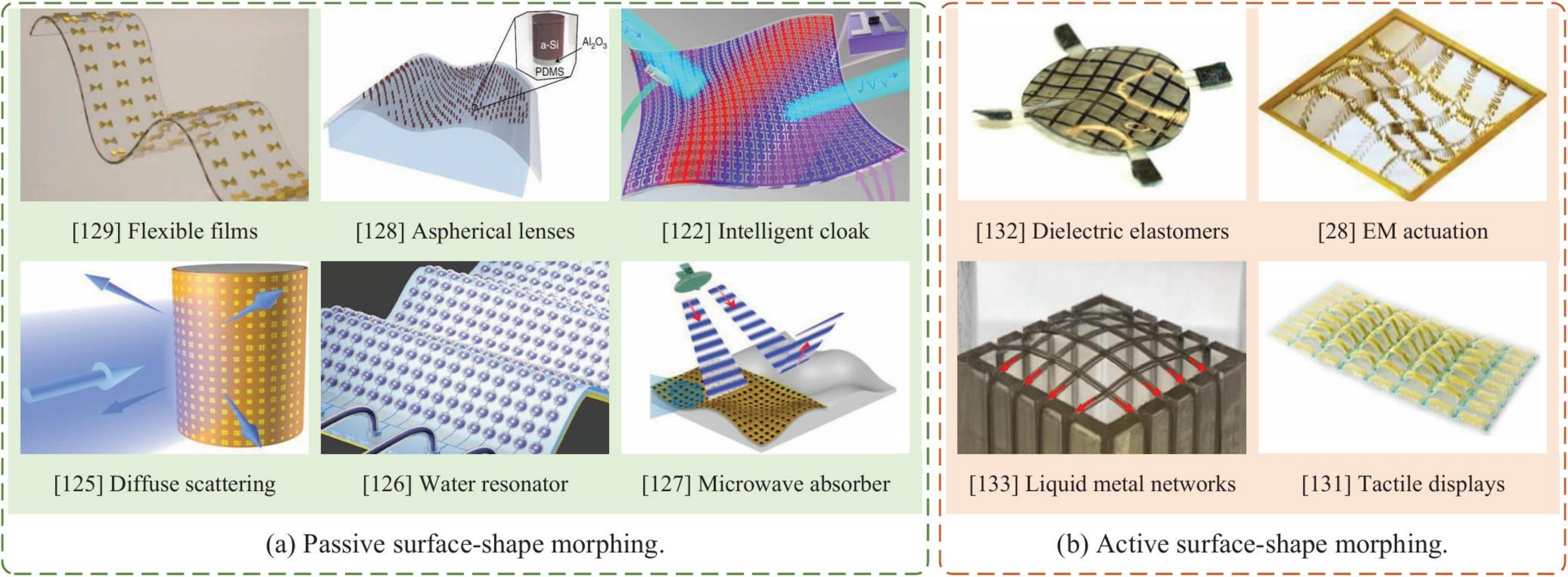
❖ Flexible textile

❖ Flexible aircraft in remote areas

❖ Flexible wearable devices

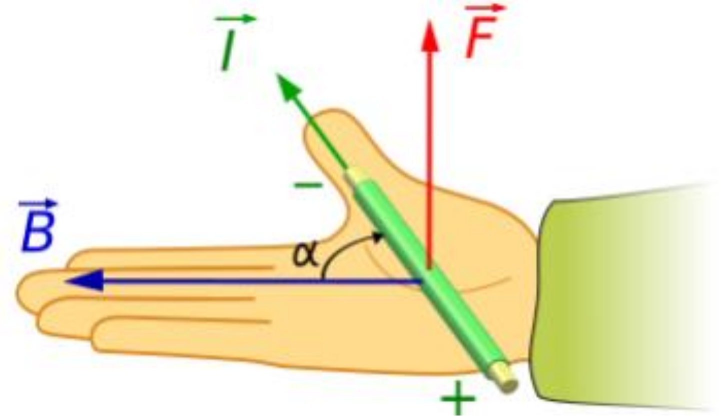
❖ Flexible cape for robots

❖ 3.1 FIM: Prototypes

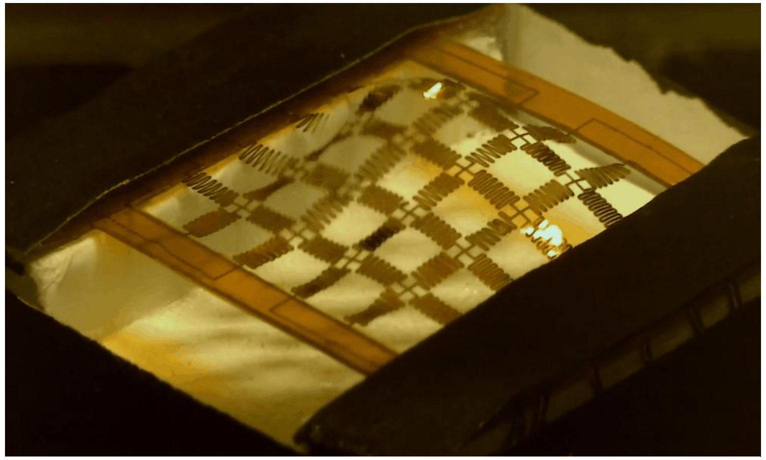


[R01] J. An, M. Debbah, T. J. Cui, Z. N. Chen and C. Yuen, “Emerging technologies in intelligent metasurfaces: Shaping the future of wireless communications,” *IEEE Trans. Antennas Propag.*, 2025, Early Access. (**Invited Paper**)

❖ 3.1 FIM: Surface Shape Morphing

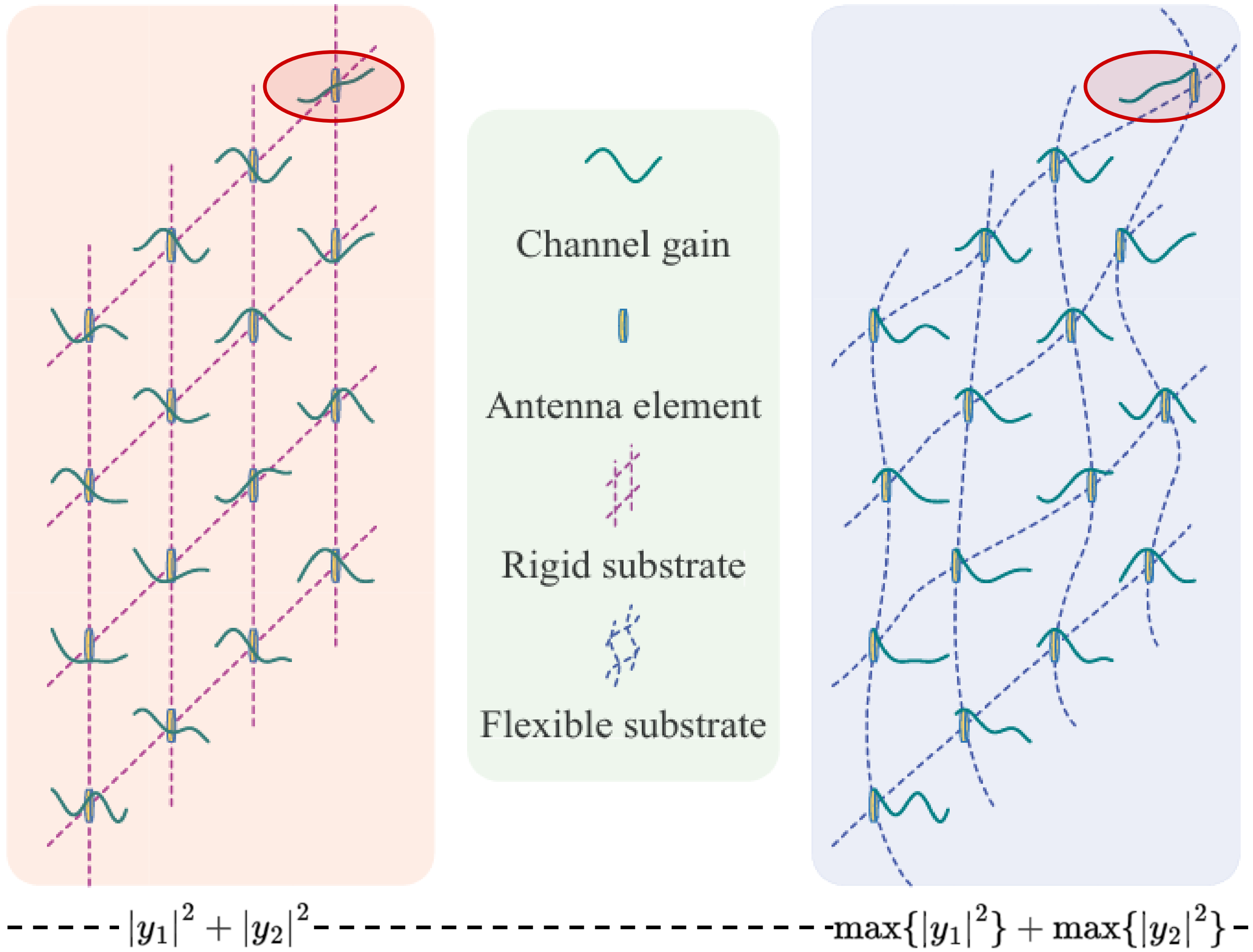


Distributed Lorentz Force



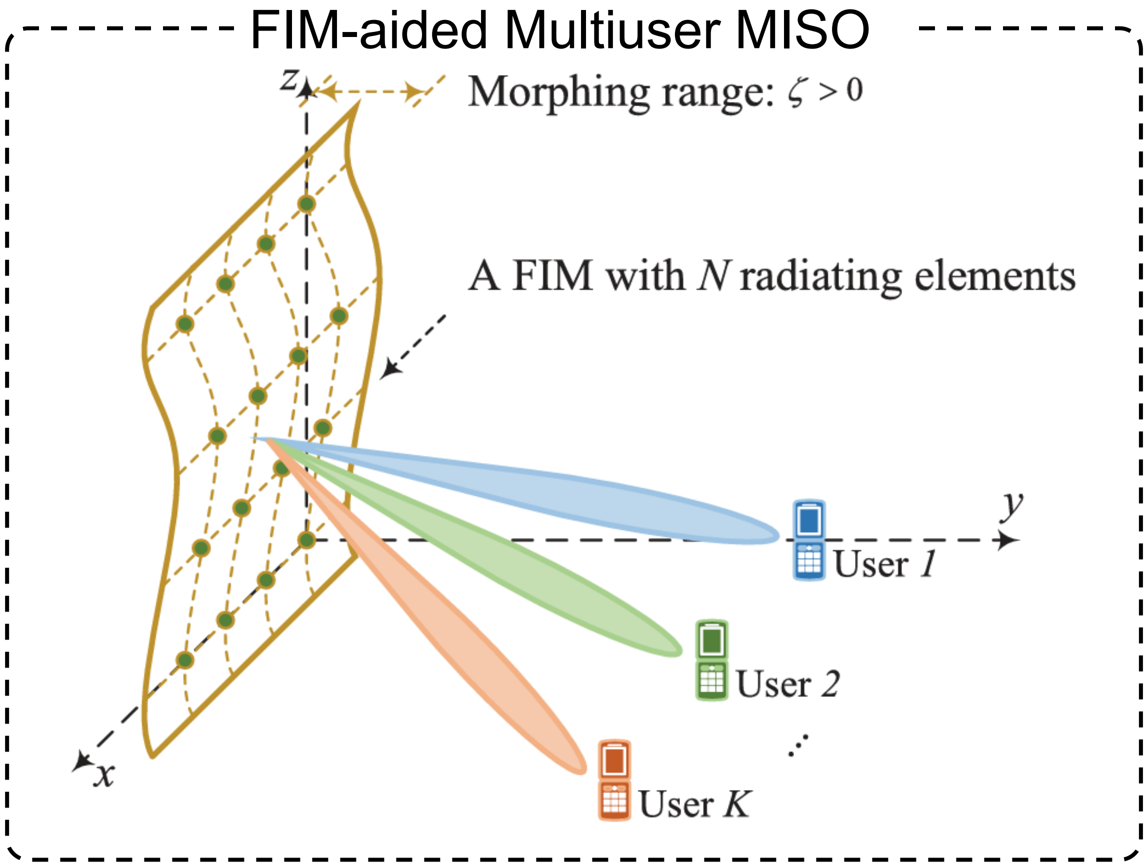
ms shape morphing speed

Potential of FIMs in Wireless Communications



[R19] Y. Bai, H. Wang, Y. Xue, Y. Pan, J.-T. Kim, **X. Ni**, T.-L. Liu, Y. Yang, M. Han, Y. Huang et al., "A dynamically reprogrammable surface with self-evolving shape morphing," *Nature*, vol. 609, no. 7928, pp. 701-708, Sep. 2022.

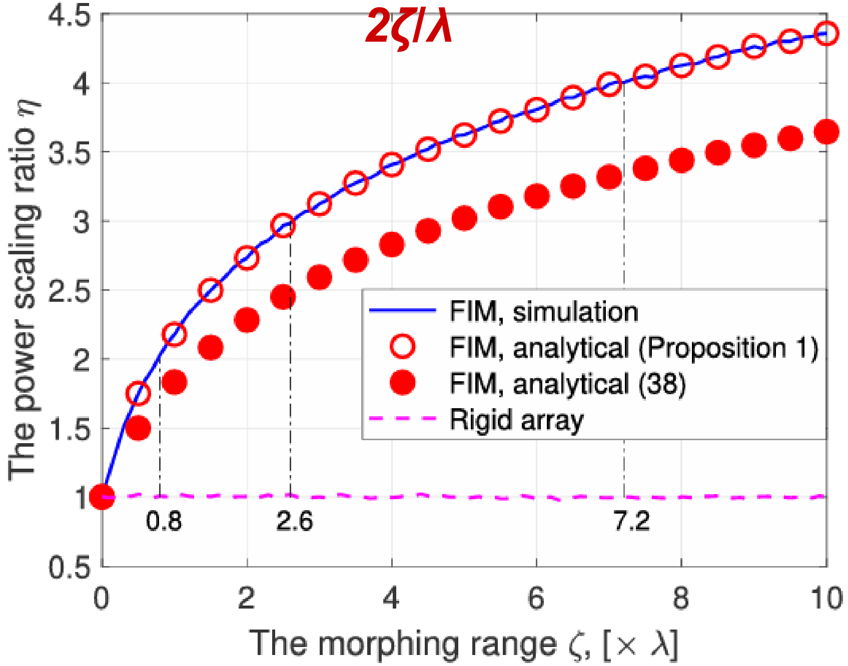
❖ 3.1 FIM-Aided Downlink Multiuser Communications



Scaling Law: Power vs. Morphing Range

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

$2\zeta/\lambda$



$$\mathrm{SINR}_k = \frac{\left|\boldsymbol{h}_k^H(\boldsymbol{y})\boldsymbol{w}_k\right|^2}{\sum_{k'=1,\ k'\neq k}^{K}\left|\boldsymbol{h}_k^H(\boldsymbol{y})\boldsymbol{w}_{k'}\right|^2 + \sigma_k^2}$$

⇦

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

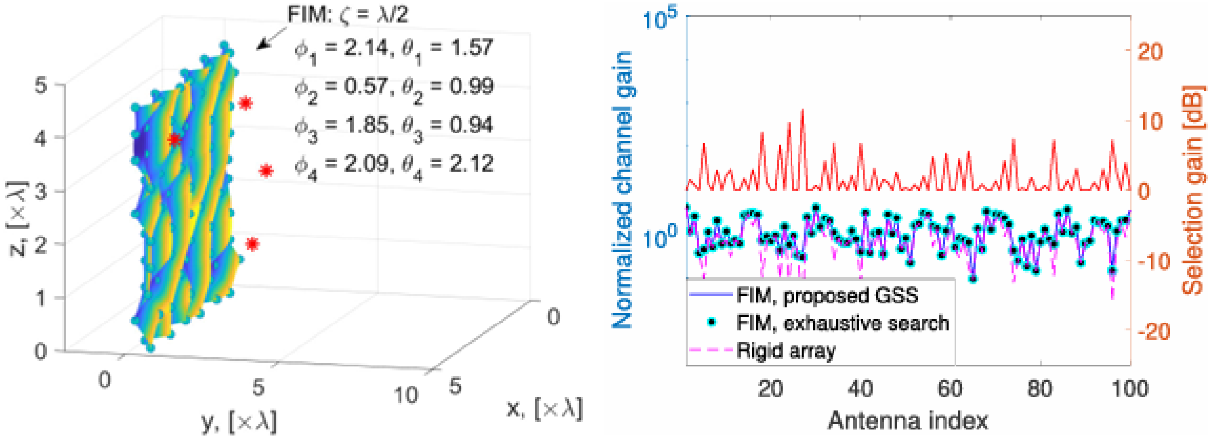
⇦

$$\boldsymbol{a}(\boldsymbol{y},\phi,\theta) = \left[1,\cdots,e^{j\kappa(x_n\sin\theta\cos\phi + y_n\sin\theta\sin\phi + z_n\cos\theta)},\cdots,e^{j\kappa(x_N\sin\theta\cos\phi + y_N\sin\theta\sin\phi + z_N\cos\theta)}\right]^T$$

[R20] J. An, C. Yuen, M. D. Renzo, M. Debbah, H. V. Poor and L. Hanzo, "**Flexible intelligent metasurfaces** for downlink multiuser MISO communications," *IEEE Trans. Wireless Commun.*, vol. 24, no. 4, pp. 2940-2955, Apr. 2025.

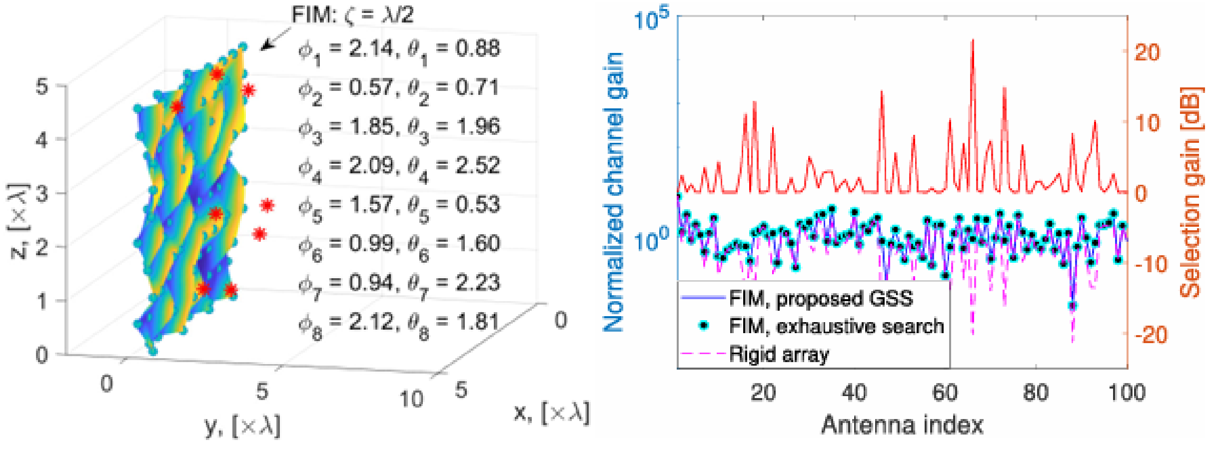
❖ 3.1 FIM-Aided Downlink Multiuser Communications

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



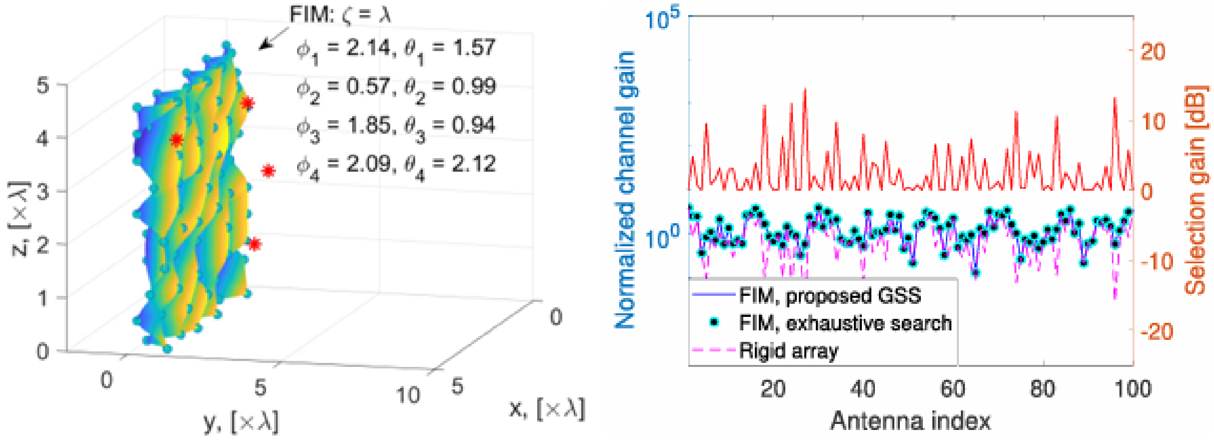
(a) (b)

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



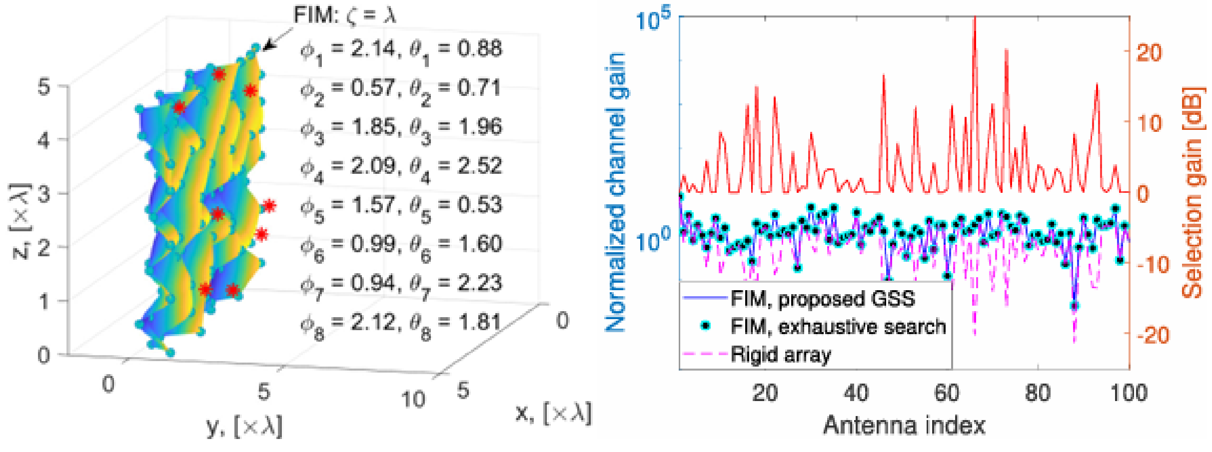
(a) (b)

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



(a) (b)

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



(a) (b)

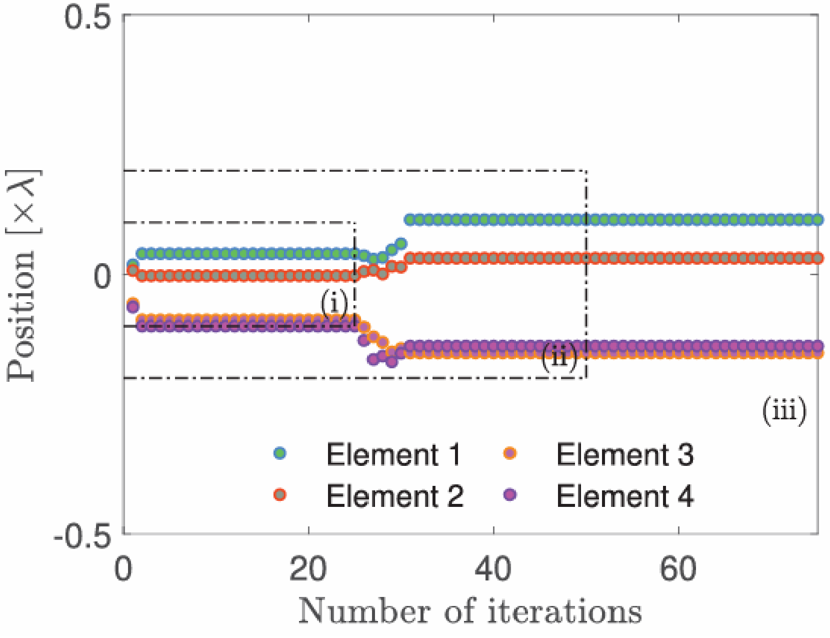
[R20] J. An, C. Yuen, M. D. Renzo, M. Debbah, H. V. Poor and L. Hanzo, "**Flexible intelligent metasurfaces** for downlink multiuser MISO communications," *IEEE Trans. Wireless Commun.*, vol. 24, no. 4, pp. 2940-2955, Apr. 2025.

Contents

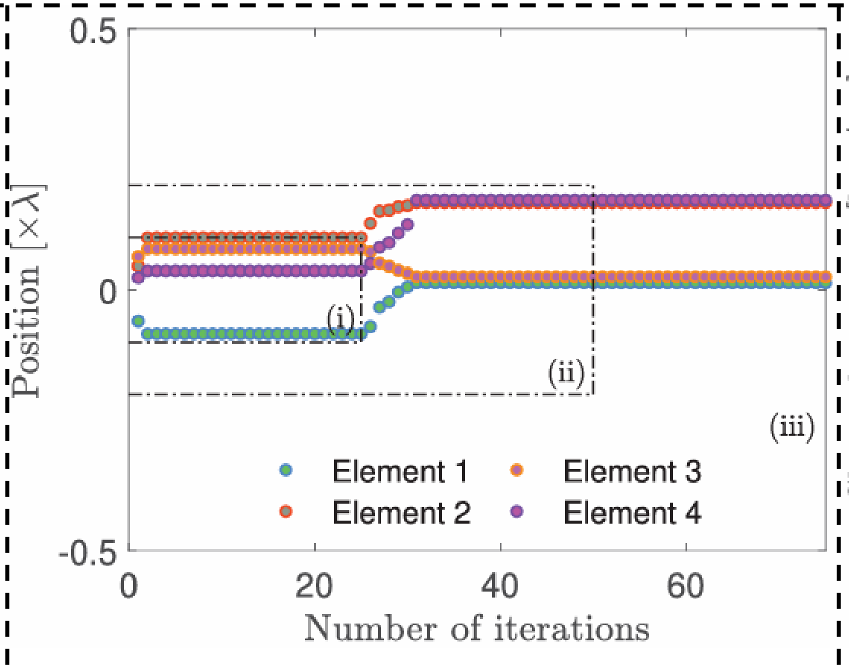
- 1 Background
- 2 Stacked Intelligent Metasurfaces (SIM)
  - 2.1 Motivation
  - 2.2 Applications
- 3 Flexible Intelligent Metasurfaces (FIM)
  - 3.1 Motivation
  - **3.2 Applications**
- 4 Future Directions

❖ 3.2 FIM for MIMO: Capacity vs. Morphing Range

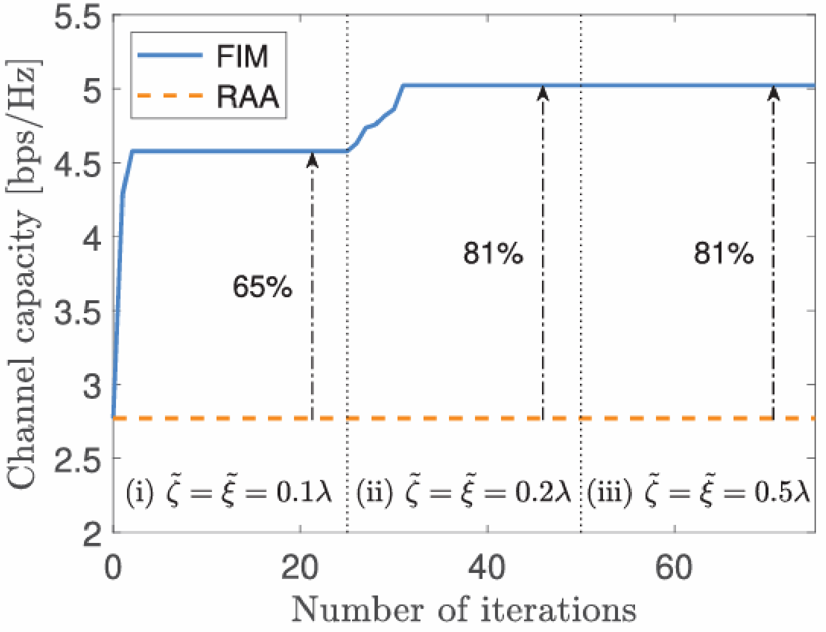
- 4 Tx elements and 4 Rx elements
- *L = 16* scattering clusters, each having 4 paths
- (i) Morphing range: 0.1λ; (ii) Morphing range: 0.2λ; (iii) Morphing range: 0.5λ



Tx FIM's surface shape



Rx FIM's surface shape

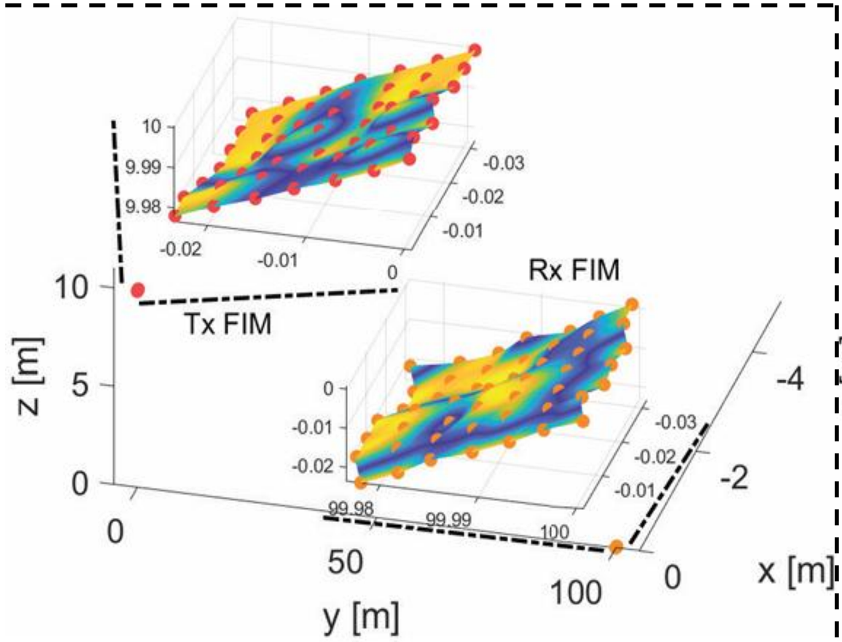


MIMO channel capacity

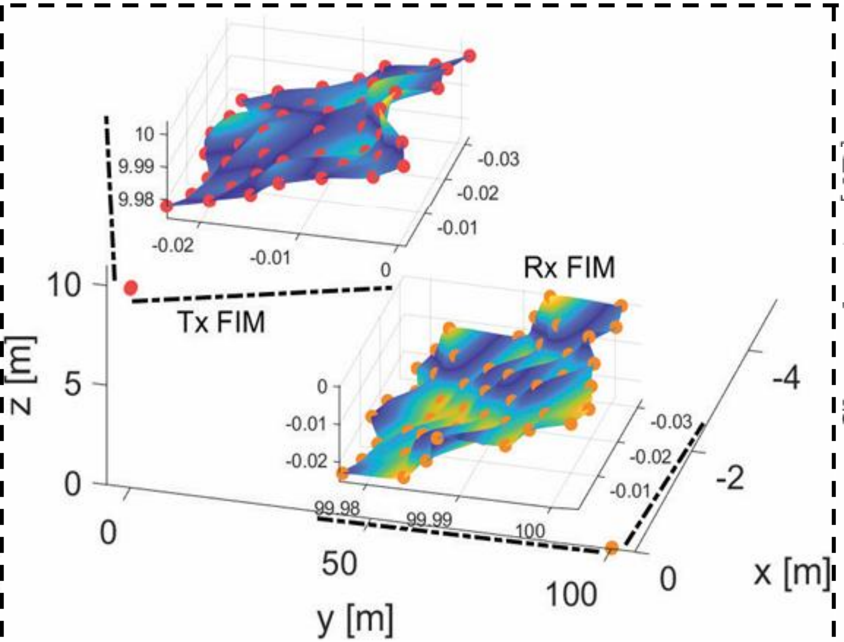
[R21] J. An, Z. Han, D. Niyato, M. Debbah, C. Yuen and L. Hanzo, "**Flexible intelligent metasurfaces** for enhancing MIMO communications," *IEEE Trans. Commun.*, vol. 73, no. 9, pp. 7349-7365, Sept. 2025.

❖ 3.2 FIM for MIMO: Multiplexing Gain

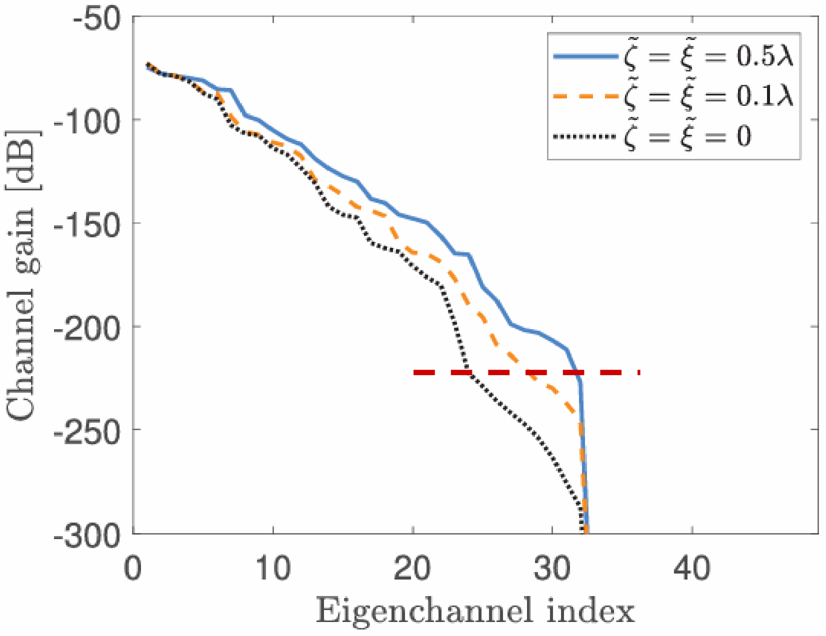
- *7 x 7 MIMO Transmission, Tx-FIM, Rx-FIM*
- *Multiplexing Gain: FIM can improve channel gain of poor eigenchannels, thus supporting more data transmission*



Morphing range: 0.1λ



Morphing range: 0.5λ

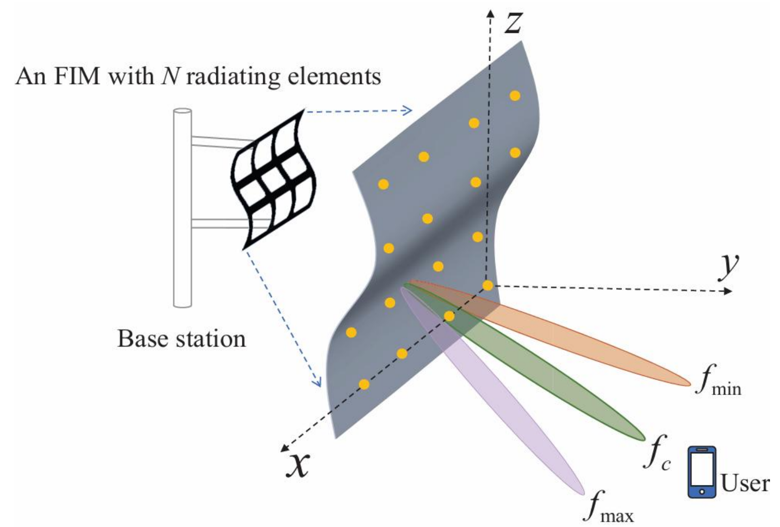


Channel gain

[R21] J. An, Z. Han, D. Niyato, M. Debbah, C. Yuen and L. Hanzo, "**Flexible intelligent metasurfaces** for enhancing MIMO communications," *IEEE Trans. Commun.*, vol. 73, no. 9, pp. 7349-7365, Sept. 2025.

❖ 3.2 FIM for **Mitigating Beam Squint**

FIM-Aided Wideband System



Optimization Problem

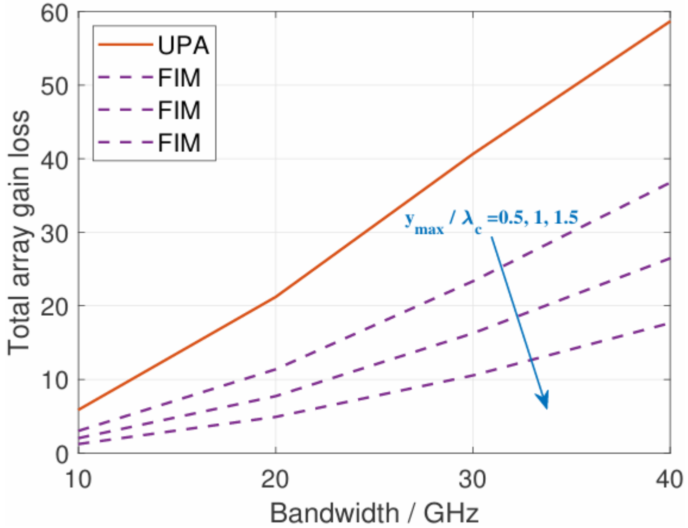
$$\min_{\mathbf{y}} \quad \mathcal{L}(\mathbf{y}) = \sum_{m=1}^{M} \left(1 - g^2(f_m, \mathbf{y})\right)$$

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

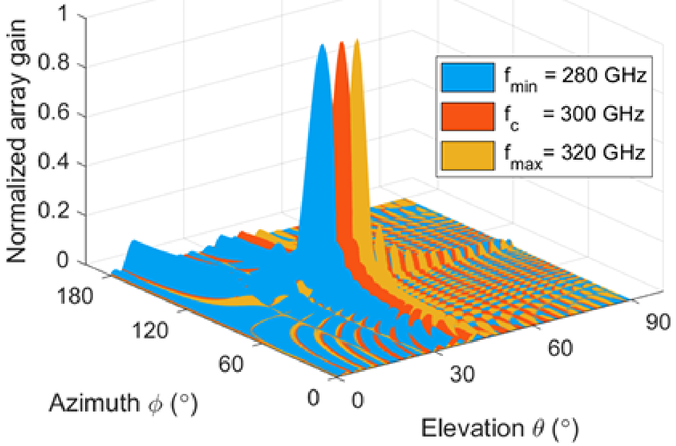
⇩

Gradient descent

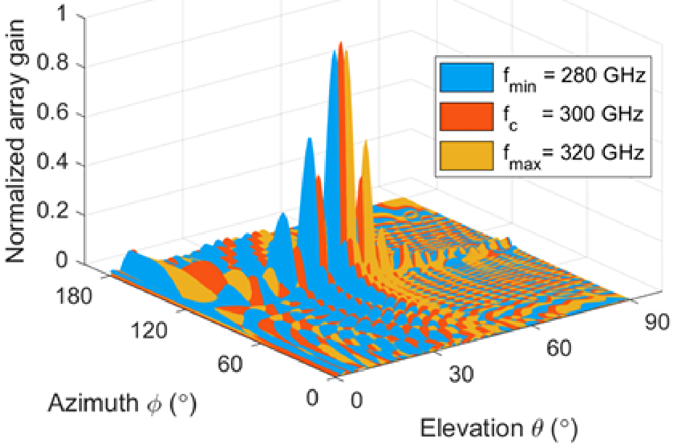
Gain Loss vs. Bandwidth



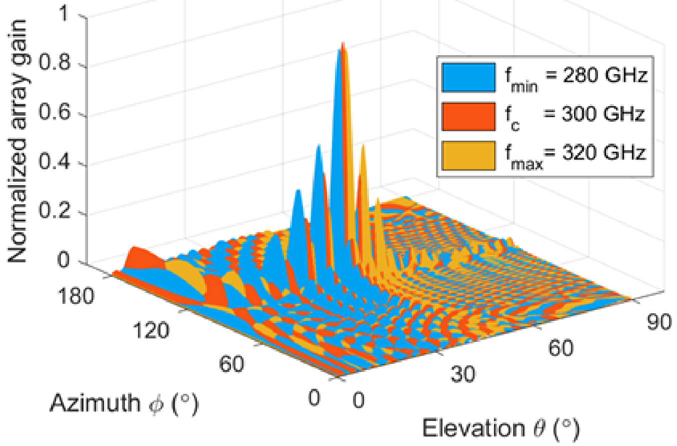
ζ = 0



ζ = λ/2

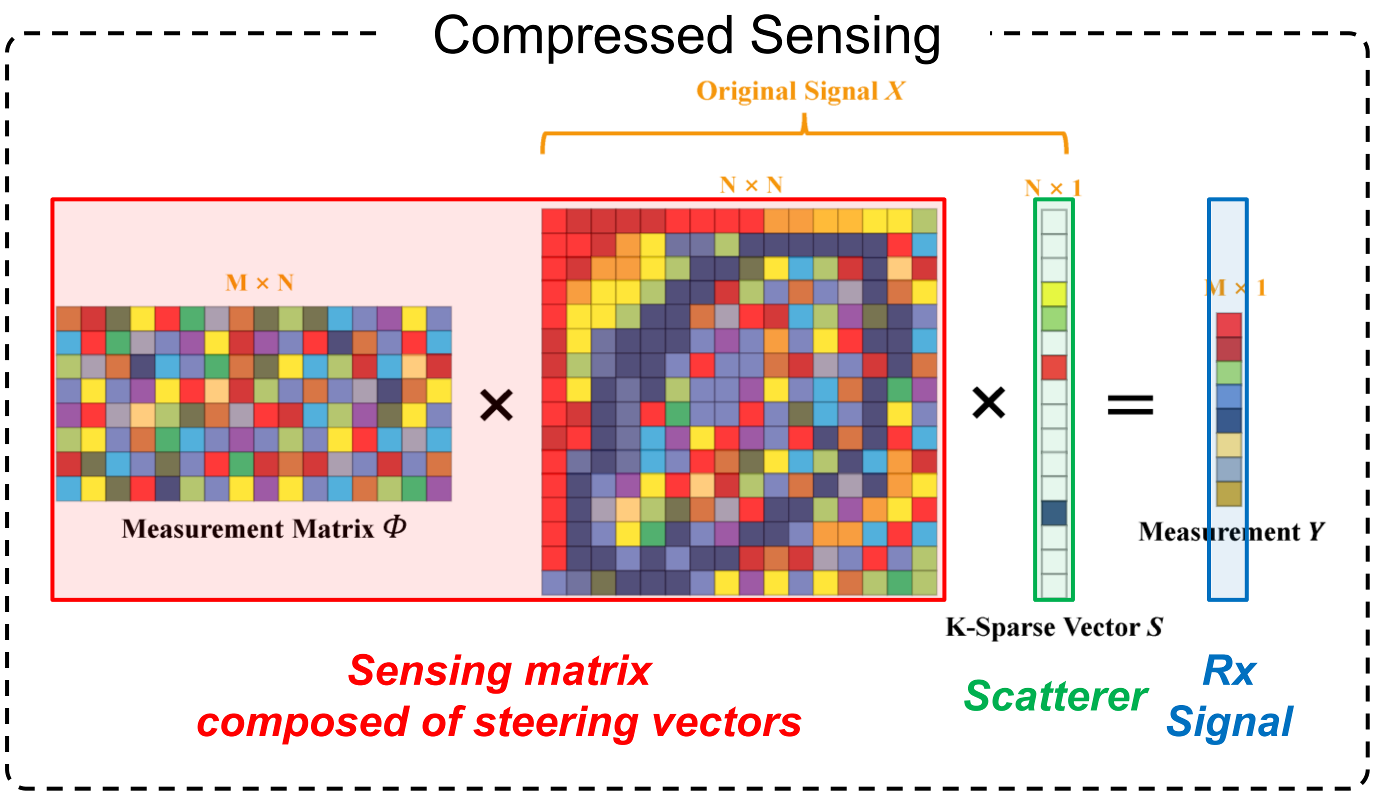


ζ = λ

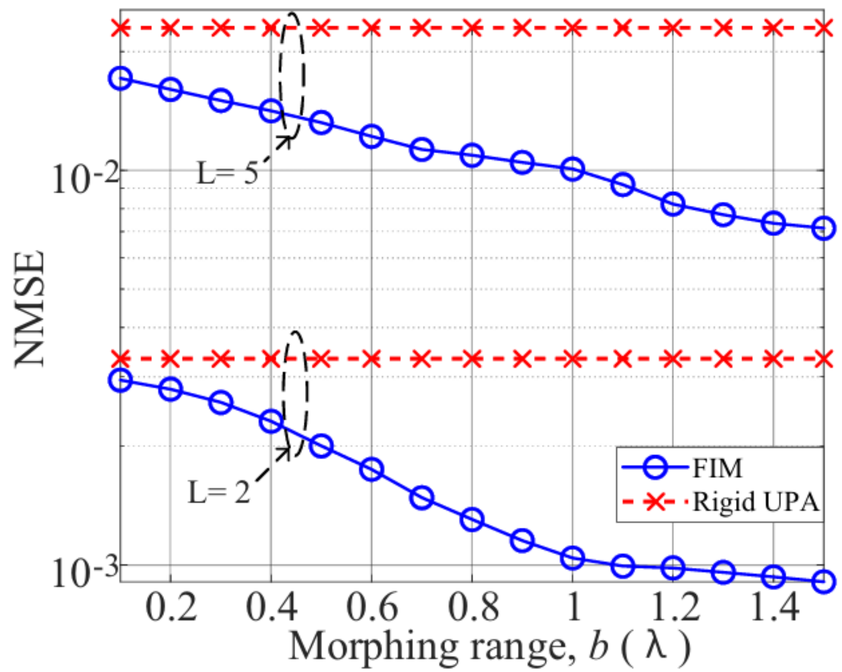


[R22] A. Ming, J. An, L. Gan, A. Nallanathan and N. Al-Dhahir, "**Flexible Intelligent Metasurface** for Mitigating Beam Squint in Wideband Communications," *IEEE Trans. Veh. Technol.*, 2025, Early Access.

❖ 3.2 FIM-Enhanced Channel Estimation



NMSE vs. Morphing Range

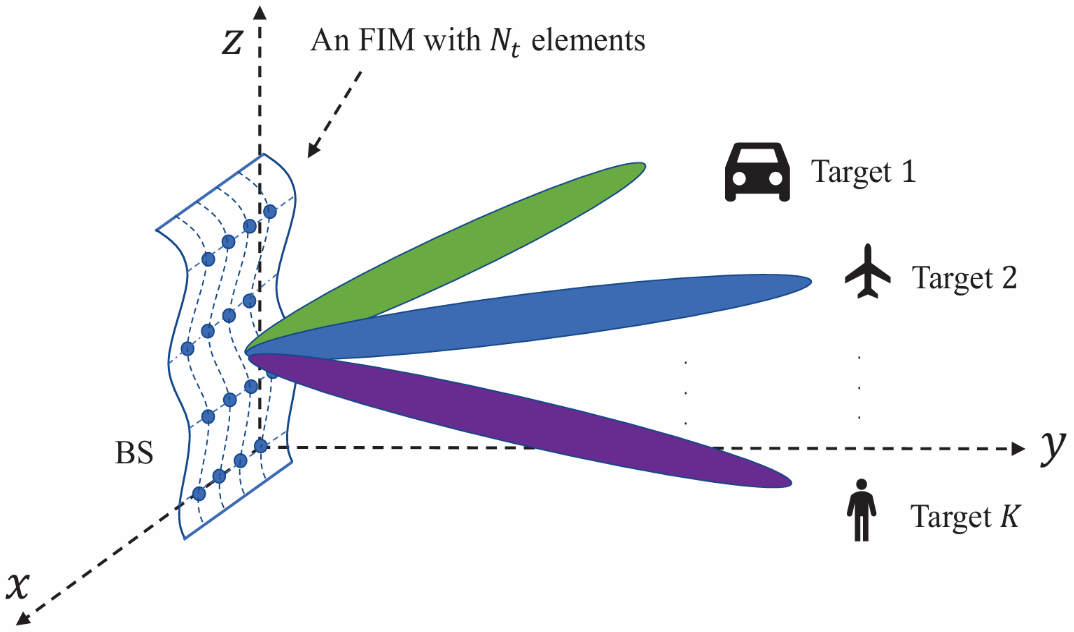


Recovery Performance ⇦ *Column coherence of sensing matrix* ⇦ *Steering vector* ⇦ *FIM's surface shape*

[R23] J. Jiang, J. An, L. Gan, N. Al-Dhahir, A. Nallanathan and Z. Han, "Enhanced channel estimation for **flexible intelligent metasurface**-aided communication systems," *IEEE Trans. Veh. Technol.*, (Major Revision)

❖ 3.2 FIM-Enhanced Wireless Sensing

System Model



$d^t_{\max}$: Maximum morphing range

$\Delta \mathbf{d}^t$: FIM surface shape

Transmit steering vector:

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

UPA　　FIM

Optimization problem:

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

$$\max_{\mathbf{R}_X, \Delta\mathbf{d}^t} \quad P_c \triangleq \mathrm{tr}\left(\mathbf{R}_X \mathbf{B}\right)$$
$$\text{s.t.} \quad \mathrm{diag}\left(\mathbf{R}_X\right) = \frac{P_t}{N_t},$$
$$\mathbf{R}_X \succeq \mathbf{0},$$
$$\left|\Delta d^t_{n_t}\right| \leq d^t_{\max}, \quad n_t = 1, 2, \ldots, N_t,$$

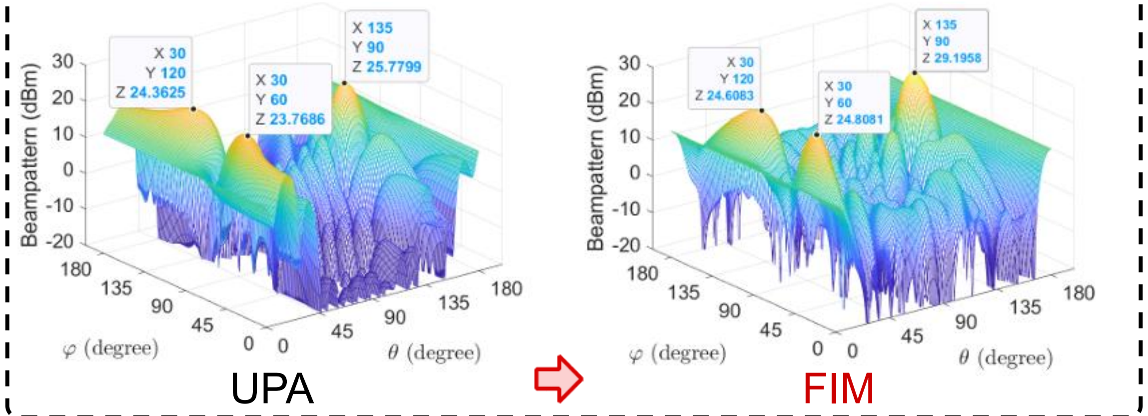
Algorithm: BCD

[R24] Z. Teng, J. An, L. Gan, N. Al-Dhahir and Z. Han, “**Flexible intelligent metasurface** for enhancing multi-target wireless sensing,” *IEEE Trans. Veh. Technol.*, 2025, Early Access.

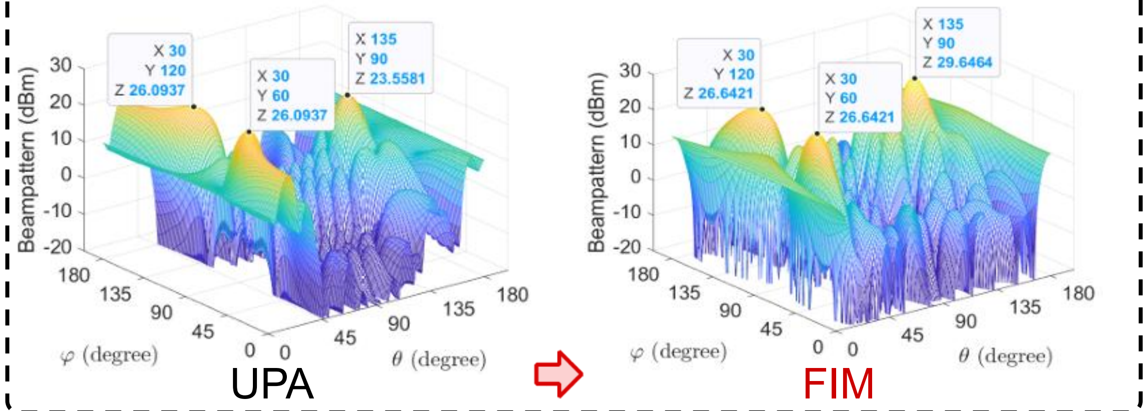
❖ 3.2 FIM-Enhanced Wireless Sensing

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

Phased Array



MIMO Radar

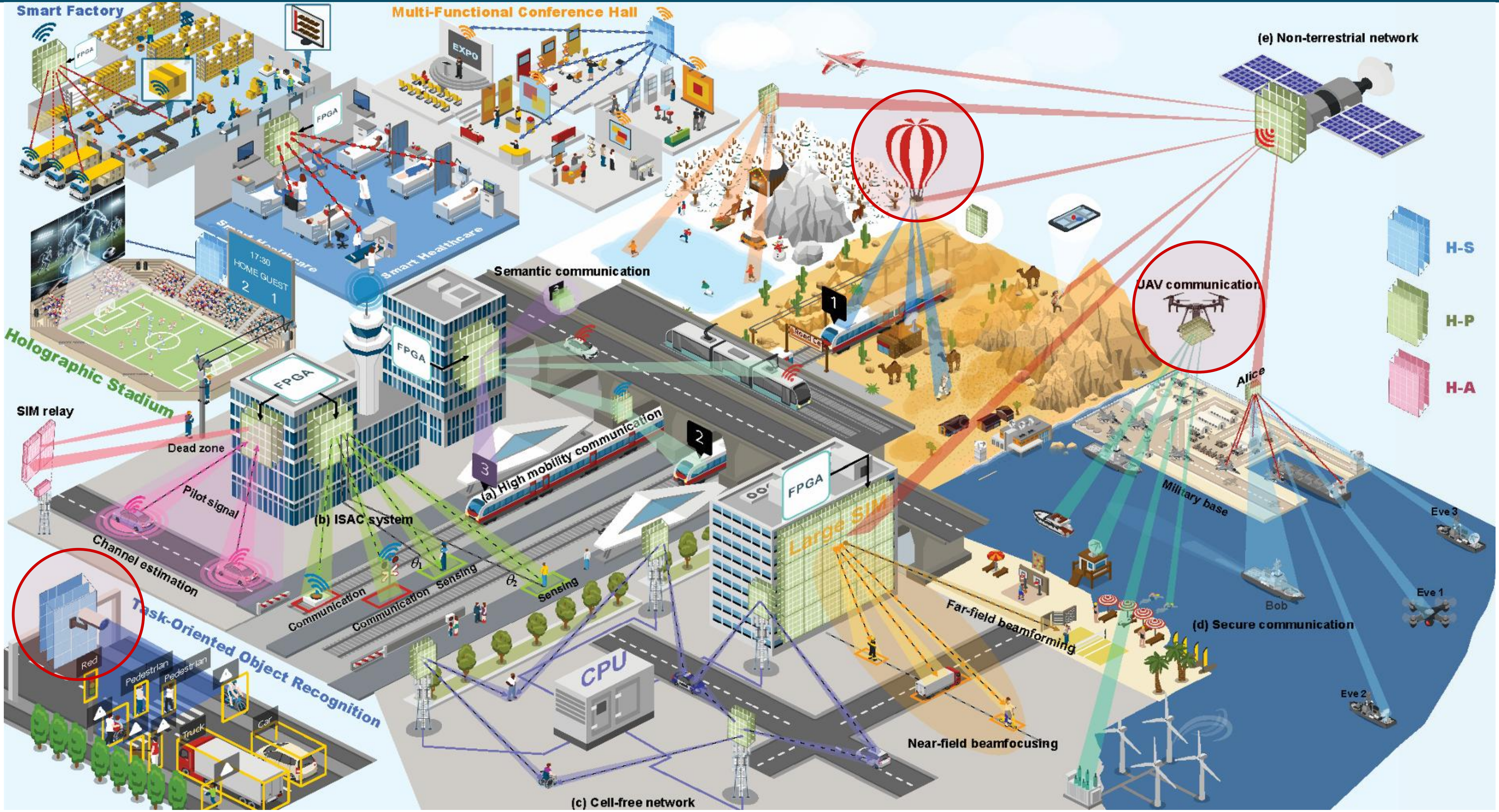


[R24] Z. Teng, J. An, L. Gan, N. Al-Dhahir and Z. Han, "**Flexible intelligent metasurface** for enhancing multi-target wireless sensing," *IEEE Trans. Veh. Technol.*, 2025, Early Access.

Contents

- 1 Background
- 2 Stacked Intelligent Metasurfaces (SIM)
  - 2.1 Motivation
  - 2.2 Applications
- 3 Flexible Intelligent Metasurfaces (FIM)
  - 3.1 Motivation
  - 3.2 Applications
- **4 Future Directions**

❖ 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.

❖ 4 Useful Links & Call for Papers

- Code: https://github.com/jiancheng-an
- Call for Papers: **IEEE Wireless Communications**

https://www.comsoc.org/publications/magazines/ieee-wireless-communications/cfp/stacked-intelligent-metasurface-empowered

Stacked Intelligent Metasurface-Empowered Advanced Signal Processing Paradigm for 6G and Beyond

Publication Date	Manuscript Submission Deadline
August 2026	**1 November 2025**

Special Issue

Call for Papers

SUBMIT A PAPER

Stacked Intelligent Metasurfaces (SIM) is an emerging technology to enable electromagnetic-domain signal processing. Unlike single-layer reconfigurable intelligent surfaces (RISs), SIMs stand out due to their structural resemblance to artificial neural networks (ANNs). In SIMs, each hidden layer is essentially a metasurface, and the meta-atoms within each layer function similarly to the artificial neurons in conventional ANNs. Once the multiple programmable metasurfaces are properly configured, a SIM is capable of processing spatial electromagnetic waves as they propagate through the hierarchical structure. Since it directly processes electromagnetic waves carrying information in free space, SIMs eliminate the need for digital storage, transmission, and information preprocessing. Remarkably, all information processing within a SIM occurs at the speed of light. Furthermore, SIMs can be easily scaled to accommodate extremely large inputs and massive connections in a cost-effective and efficient way.

Due to these unique advantages, some advanced SIMs have been designed to perform various tasks in the wave domain, such as filtering, MIMO precoding, and discrete Fourier transform (DFT). Additionally, thanks to its internal multi-path propagation, SIMs can achieve frequency-selective response by reconfiguring the meta-atom's scattering properties, making it well-suited for generating waveforms required by advanced modulation schemes, such as orthogonal frequency division multiplexing (OFDM) in the wave domain. However, as a developing field, significant work remains to deploy SIM in real-world wireless networks. This Special Issue (SI) uniquely calls for the study of SIMs from the perspectives of hardware design, modeling, performance analysis, signal processing architecture, and experiments. Consequently, the topics of interest include but are not limited to the following:

- Theoretical limit of SIMs for signal processing in wireless communication and sensing systems.
- Wave propagation-based signal processing architectures for communication and sensing.
- Hardware implementation and modeling of SIMs.
- Testbeds and technological demonstrations of SIMs across millimeter wave, terahertz, and optical frequency bands.
- Efficient algorithms for SIM configuration and channel parameter estimation.
- Implementations of various AI technologies in the electromagnetic domain.
- Advanced modulation and coding schemes based on SIMs.
- Inter-layer propagation coefficient calibration and robust SIM configuration.
- Enhanced computational capability of SIMs.
- Promising applications of SIMs in 5G-Advanced, 6G, and beyond.
- Interplay with emerging physical-layer technologies, e.g., cell-free networks, satellite communication systems.

❖ 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.

❖ References

14. 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.
15. 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.
16. 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.
17. 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.
18. 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.
19. Y. Bai, H. Wang, Y. Xue, Y. Pan, J.-T. Kim, **X. Ni**, T.-L. Liu, Y. Yang, M. Han, Y. Huang et al., "A dynamically reprogrammable surface with self-evolving shape morphing," *Nature*, vol. 609, no. 7928, pp. 701-708, Sep. 2022.
20. J. An, C. Yuen, M. D. Renzo, M. Debbah, H. V. Poor and L. Hanzo, "**Flexible intelligent metasurfaces** for downlink multiuser MISO communications," *IEEE Trans. Wireless Commun.*, vol. 24, no. 4, pp. 2940-2955, Apr. 2025.
21. J. An, Z. Han, D. Niyato, M. Debbah, C. Yuen and L. Hanzo, "**Flexible intelligent metasurfaces** for enhancing MIMO communications," *IEEE Trans. Commun.*, vol. 73, no. 9, pp. 7349-7365, Sept. 2025.
22. A. Ming, J. An, L. Gan, A. Nallanathan and N. Al-Dhahir, "**Flexible Intelligent Metasurface** for Mitigating Beam Squint in Wideband Communications," *IEEE Trans. Veh. Technol.*, 2025, Early Access.
23. J. Jiang, J. An, L. Gan, N. Al-Dhahir, A. Nallanathan and Z. Han, "Enhanced channel estimation for **flexible intelligent metasurface**-aided communication systems," *IEEE Trans. Veh. Technol.*, (Major Revision)
24. Z. Teng, J. An, L. Gan, N. Al-Dhahir and Z. Han, "**Flexible intelligent metasurface** for enhancing multi-target wireless sensing," *IEEE Trans. Veh. Technol.*, 2025, Early Access.
25. 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.

Many Thanks!