Stacked Intelligent Metasurface for Signal Processing in the Wave Domain

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Outline

- What is Stacked Intelligent Metasurface (SIM)
- Applications of SIM in Communication, Sensing and Computing Systems
    - Multiuser/MIMO Precoding
    - DOA Estimation
    - Semantic Encoding
- Hybrid Optical-Electronic Neural Network (HOENN)
- Future Research Opportunities

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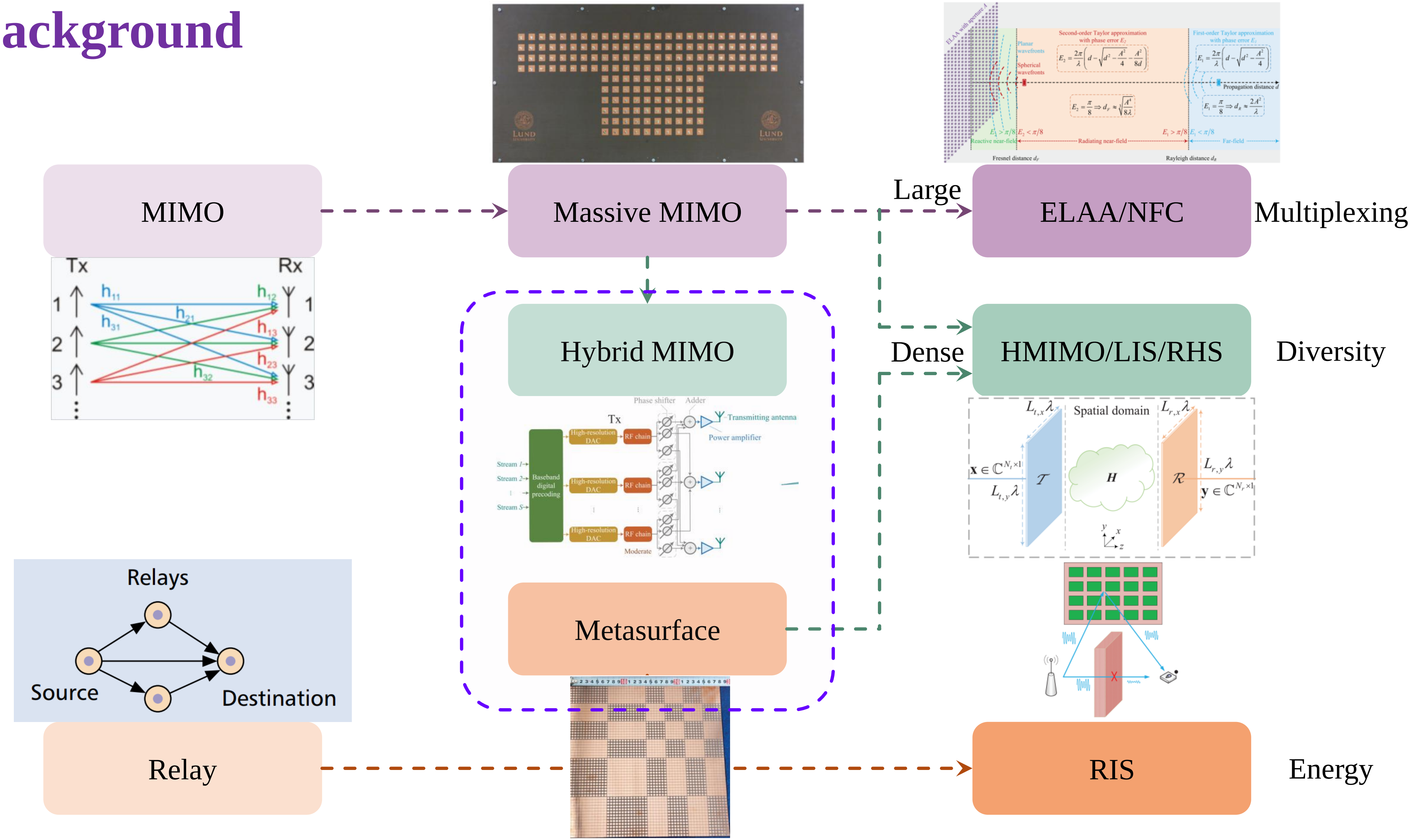
➢ Background


MIMO
Tx
Rx
Massive MIMO
Large
ELAA/NFC
Multiplexing
Hybrid MIMO
Dense
HMIMO/LIS/RHS
Diversity
Spatial domain
Metasurface
Relays
Source
Destination
Relay
RIS
Energy

➢ What is Stacked Intelligent Metasurface (SIM)

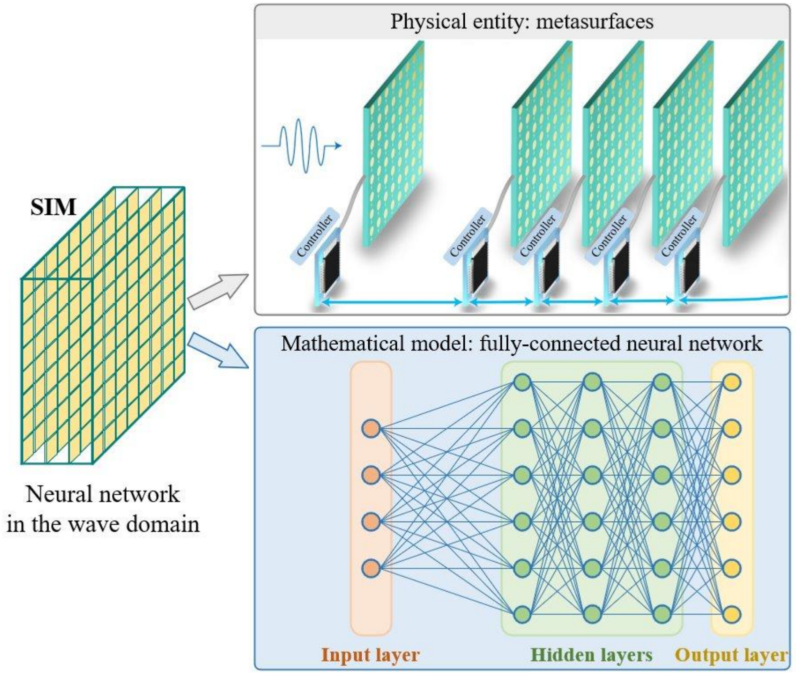
Stacked Intelligent Metasurface (SIM)

➢ **Physical entity**: Have the capability of reconfiguring the EM behavior.

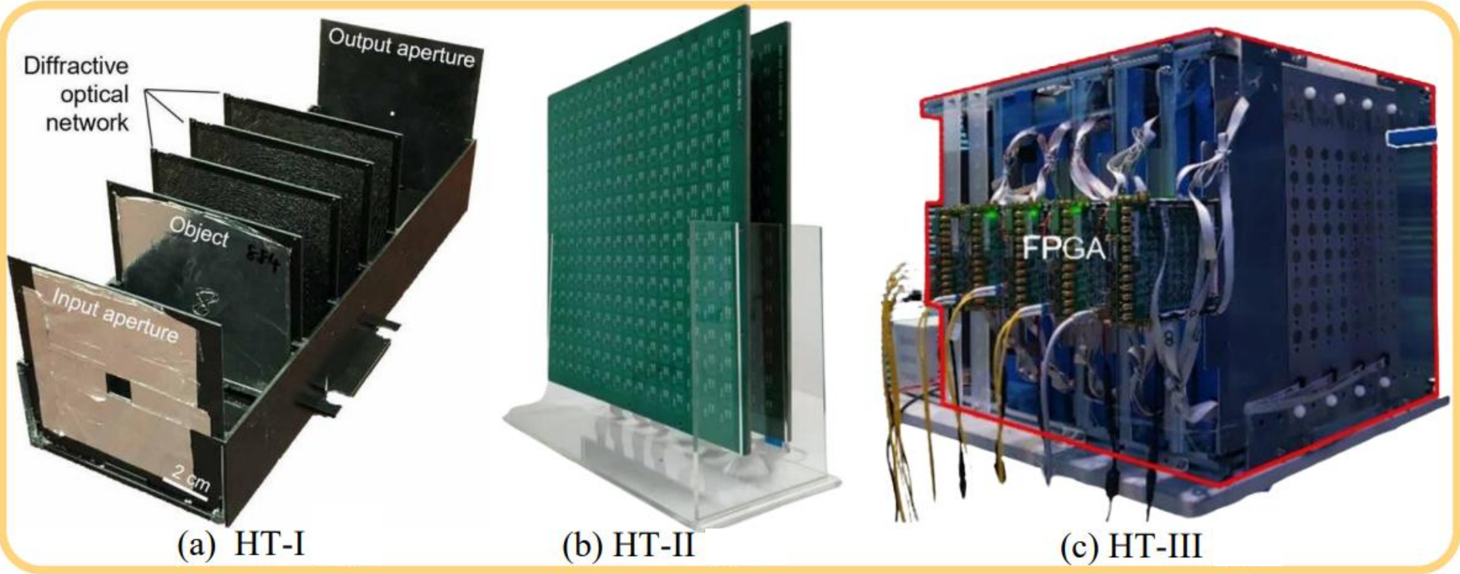
➢ **Capability**: Achieve artificial intelligence via a physical neural network.

➢ **Architecture**: Multi-layer structure to mimic a neural network in the wave domain.

- [ ] **Function**: Carry out various signal processing and computing tasks in the wave domain.



➢ Hardware Foundation – SIM Prototype



Prototype	HT-I	HT-II	HT-III
Feature	**Non-programmable & Passive**	**Programmable & Passive**	**Programmable & Active**
Operating frequency	206 ~ 300 GHz	5.8 GHz	5.4 GHz
Function	Image reconstruction	Beamforming	Image recognition
# of meta-atoms per layer	$40\times40=1600$	$16\times16=256$	$8\times8=64$
# of layers	4	1 ~ 3	5
Layer spacing	0.03 m	1.5λ (0.078 m)	1.8λ (0.1 m)
Material	VeroBlackPlus RGD875	Copper	F4B, prepreg

[HT-I] J. Li et al., "Spectrally encoded single-pixel machine vision using diffractive networks," *Science Advances*, vol. 7, no. 13, Mar. 2021.
[HT-II] Z. Wang et al., "Multi-user ISAC through stacked intelligent metasurfaces: New algorithms and experiments," *arXiv preprint arXiv:2405.01104*, 2024.
[HT-III] C. Liu et al., "A programmable diffractive deep neural network based on a digital-coding metasurface array," *Nature Electronics*, vol. 5, no. 2, pp. 113–122, Feb. 2022.

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- **Applications of SIM in Communication, Sensing and Computing Systems**
  - **Multiuser/MIMO Precoding**
  - DOA Estimation
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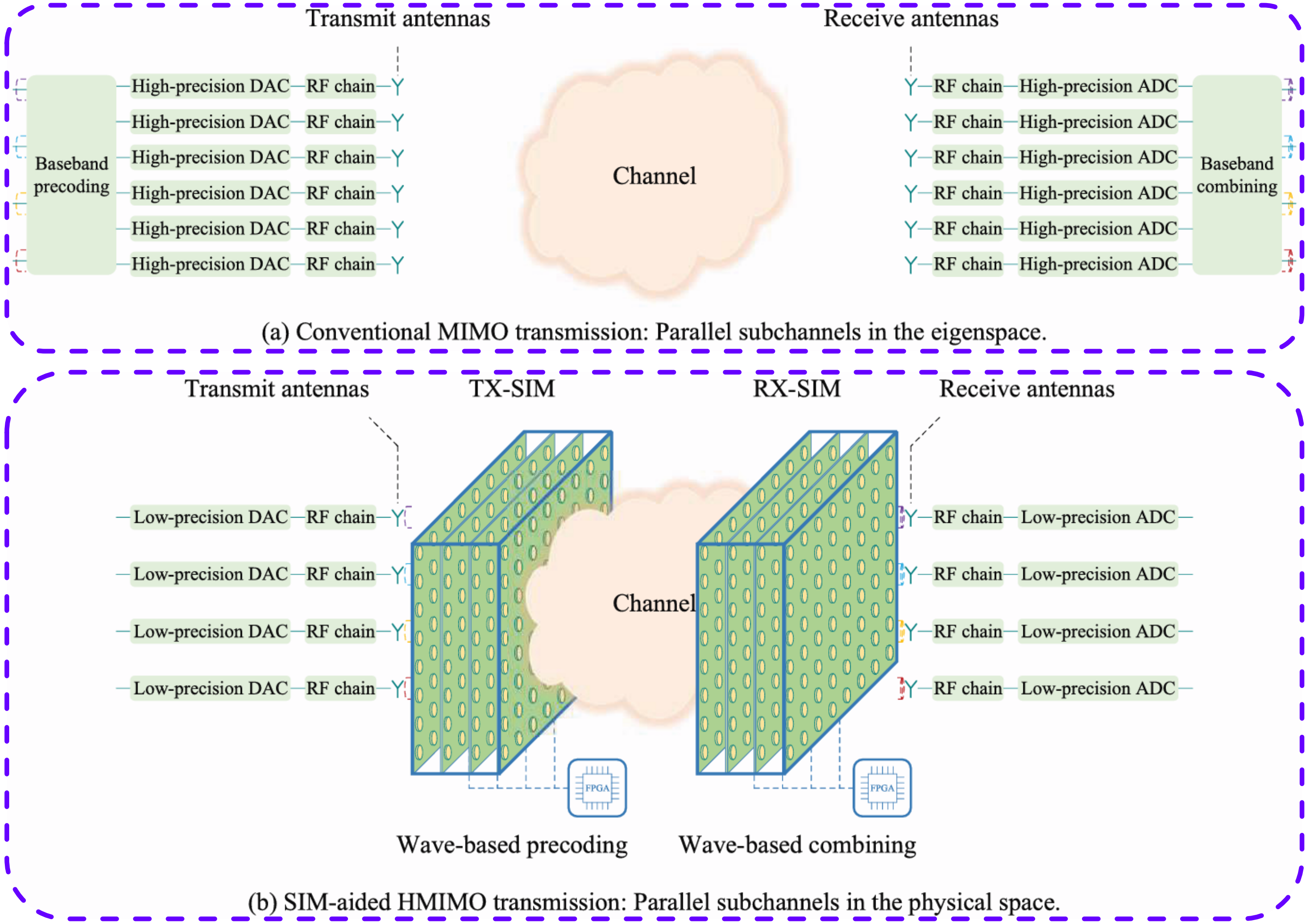
➢ A Comparison of Conventional MIMO and SIM-aided MIMO



(a) Conventional MIMO transmission: Parallel subchannels in the eigenspace.

(b) SIM-aided HMIMO transmission: Parallel subchannels in the physical space.

- ❑ Number of active RF chains: **Large**
- ❑ Precision of DACs/ADCs: **High**
- ❑ Energy consumption: **High**

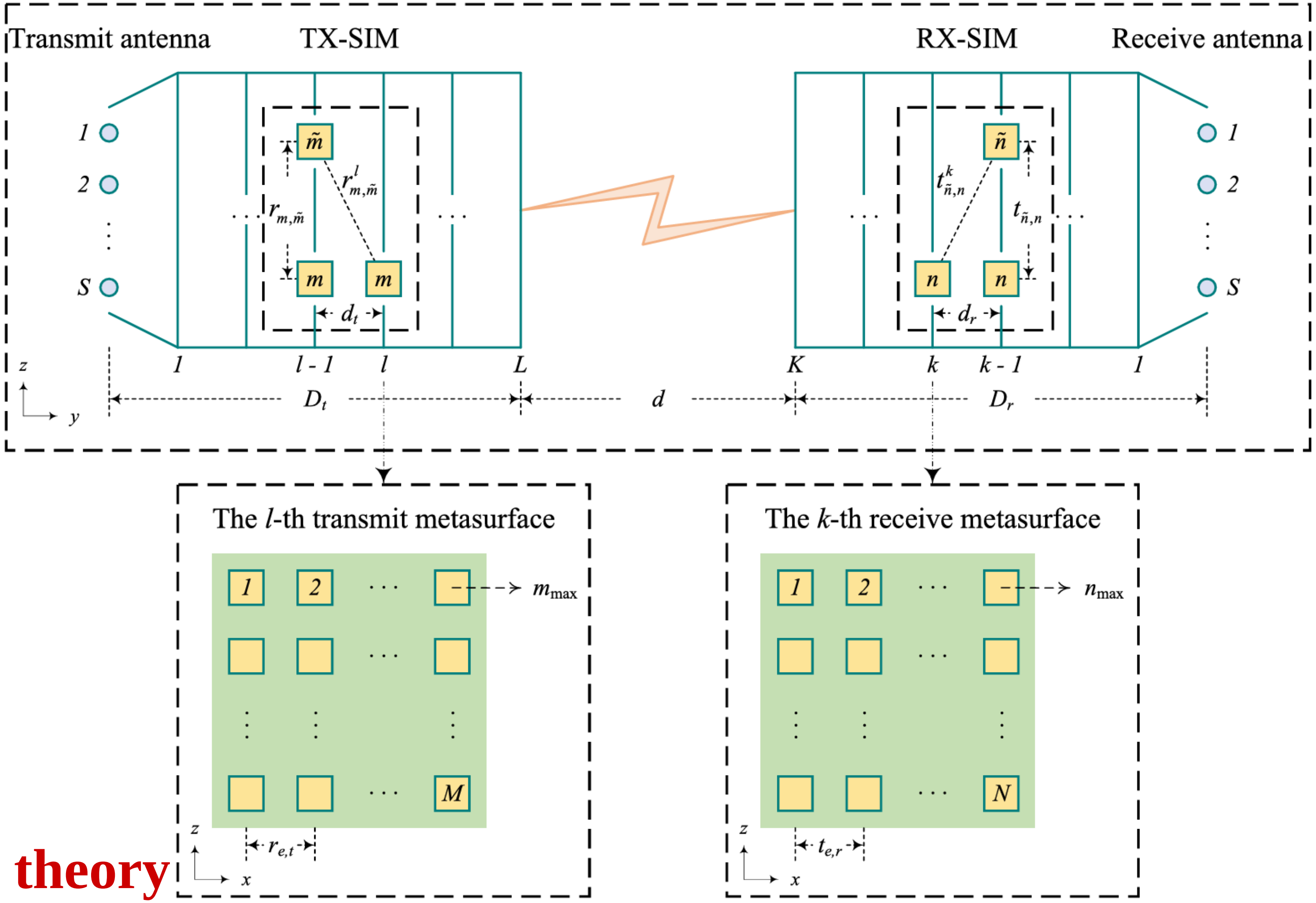
- ❑ Number of active RF chains: **Small**
- ❑ Precision of DACs/ADCs: **Low**
- ❑ Energy consumption: **Low**

[R1] **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.

➢ SIM-aided HMIMO System Model

- $\mathbf{\Phi}^l$: Transmission coefficient matrix of the l-th transmit layer;
- $\mathbf{\Psi}^k$: Transmission coefficient matrix of the k-th receive layer;
- $\mathbf{W}^l$: Propagation coefficient matrix from the (l - 1)-st transmit layer to the l-th transmit layer;
- $\mathbf{U}^k$: Propagation coefficient matrix from the k-th receive layer to the (k - 1)-st receive layer.

○ **Rayleigh-Sommerfeld diffraction theory**



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➢ SIM-aided HMIMO System Model

- The EM response of the TX-SIM is

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

- The EM response of the RX-SIM is

$$\mathbf{Q} = \mathbf{U}^1 \mathbf{\Psi}^1 \mathbf{U}^2 \mathbf{\Psi}^2 \cdots \mathbf{U}^K \mathbf{\Psi}^K \in \mathbb{C}^{S \times N}.$$

- The spatially-correlated HMIMO channel is

$$\mathbf{G} = \mathbf{R}_{\mathrm{Rx}}^{1/2} \tilde{\mathbf{G}} \mathbf{R}_{\mathrm{Tx}}^{1/2} \in \mathbb{C}^{N \times M}$$

Spatial correlation matrix at the RX-SIM

Spatial correlation matrix at the TX-SIM

i.i.d. Rayleigh fading channel

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➢ Problem Formulation

- Utilize two SIMs to perform the MIMO precoding and combining in the wave domain. The optimization problem is formulated as

$$\begin{aligned}\underset{\phi_m^l,\,\psi_n^k,\,\alpha}{\text{minimize}}\ & \Gamma = \left\|\alpha\mathbf{QGP} - \boxed{\mathbf{\Lambda}_{1:S,1:S}}\right\|_{\mathrm{F}}^2 \\ \text{subject to}\ & \mathbf{P} = \mathbf{\Phi}^L\mathbf{W}^L\cdots\mathbf{\Phi}^2\mathbf{W}^2\mathbf{\Phi}^1\mathbf{W}^1, \\ & \mathbf{Q} = \mathbf{U}^1\mathbf{\Psi}^1\mathbf{U}^2\mathbf{\Psi}^2\cdots\mathbf{U}^K\mathbf{\Psi}^K, \\ & \mathbf{\Phi}^l = \mathrm{diag}\left(\left[\phi_1^l,\phi_2^l,\cdots,\phi_M^l\right]^T\right),\ l\in\mathcal{L}, \\ & \mathbf{\Psi}^k = \mathrm{diag}\left(\left[\psi_1^k,\psi_2^k,\cdots,\psi_N^k\right]^T\right),\ k\in\mathcal{K}, \\ & \left|\phi_m^l\right| = 1,\ m\in\mathcal{M},\ l\in\mathcal{L}, \\ & \left|\psi_n^k\right| = 1,\ n\in\mathcal{N},\ k\in\mathcal{K}, \\ & \alpha\in\mathbb{C},\ \text{scaling factor}\end{aligned}$$

The singular values of $\mathbf{G}$

➢ Challenges

- The non-convex constant modulus constraint on each transmission coefficient;
- The highly coupled variables in the objective function

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➢ The Proposed Gradient Descent Algorithm

Step 1: Calculate the partial derivatives

$$\frac{\partial \Gamma}{\partial \theta_m^l} = 2\sum_{s=1}^{S}\sum_{\tilde{s}=1}^{S} \Im\left[\left(\alpha \phi_m^l x_{m,s,\tilde{s}}^l\right)^* \left(\alpha h_{s,\tilde{s}} - \lambda_{s,\tilde{s}}\right)\right],$$

$$\frac{\partial \Gamma}{\partial \xi_n^k} = 2\sum_{s=1}^{S}\sum_{\tilde{s}=1}^{S} \Im\left[\left(\alpha \psi_n^k y_{n,s,\tilde{s}}^k\right)^* \left(\alpha h_{s,\tilde{s}} - \lambda_{s,\tilde{s}}\right)\right],$$

Step 2: Normalize the partial derivatives

$$\frac{\partial \Gamma}{\partial \theta_m^l} \leftarrow \frac{\pi}{\varrho_l} \cdot \frac{\partial \Gamma}{\partial \theta_m^l}, \quad m \in \mathcal{M},\ l \in \mathcal{L},$$

$$\frac{\partial \Gamma}{\partial \xi_n^k} \leftarrow \frac{\pi}{\varepsilon_k} \cdot \frac{\partial \Gamma}{\partial \xi_n^k}, \quad n \in \mathcal{N},\ k \in \mathcal{K},$$

Step 3: Update the phase shifts

$$\theta_m^l \leftarrow \theta_m^l - \eta \frac{\partial \Gamma}{\partial \theta_m^l}, \quad m \in \mathcal{M},\ l \in \mathcal{L},$$

$$\xi_n^k \leftarrow \xi_n^k - \eta \frac{\partial \Gamma}{\partial \xi_n^k}, \quad n \in \mathcal{N},\ k \in \mathcal{K},$$

Step 4: Update the scaling factor and the learning rate

$$\alpha = \left(\mathbf{h}^H \mathbf{h}\right)^{-1} \mathbf{h}^H \boldsymbol{\lambda},$$

$$\eta \leftarrow \eta \beta,$$

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Simulation Setups

- The thicknesses of both the TX-SIM and RX-SIM are **0.05 m**.
- The SIM-aided HMIMO system operates at **28 GHz**.
- The propagation distance is **250 m**, with path loss exponent of **3.5**.
- The total power available at the transmitter is **20 dBm**.
- The average noise power is **−110 dBm**.

Performance Metrics

- The **NMSE** between the actual channel matrix and the target diagonal one is

$$\Delta = \mathbb{E}\left(\frac{\left\|\alpha\mathbf{QGP} - \mathbf{\Lambda}_{1:S,1:S}\right\|_{\mathrm{F}}^{2}}{\left\|\mathbf{\Lambda}_{1:S,1:S}\right\|_{\mathrm{F}}^{2}}\right)$$

- The **channel capacity** of the SIM-assisted HMIMO system is

$$C = \sum_{s=1}^{S}\log_2\left(1 + \frac{p_s\left|\alpha h_{s,s}\right|^2}{\sum_{\tilde{s}\neq s}^{S} p_{\tilde{s}}\left|\alpha h_{s,\tilde{s}}\right|^2 + \sigma^2}\right)$$

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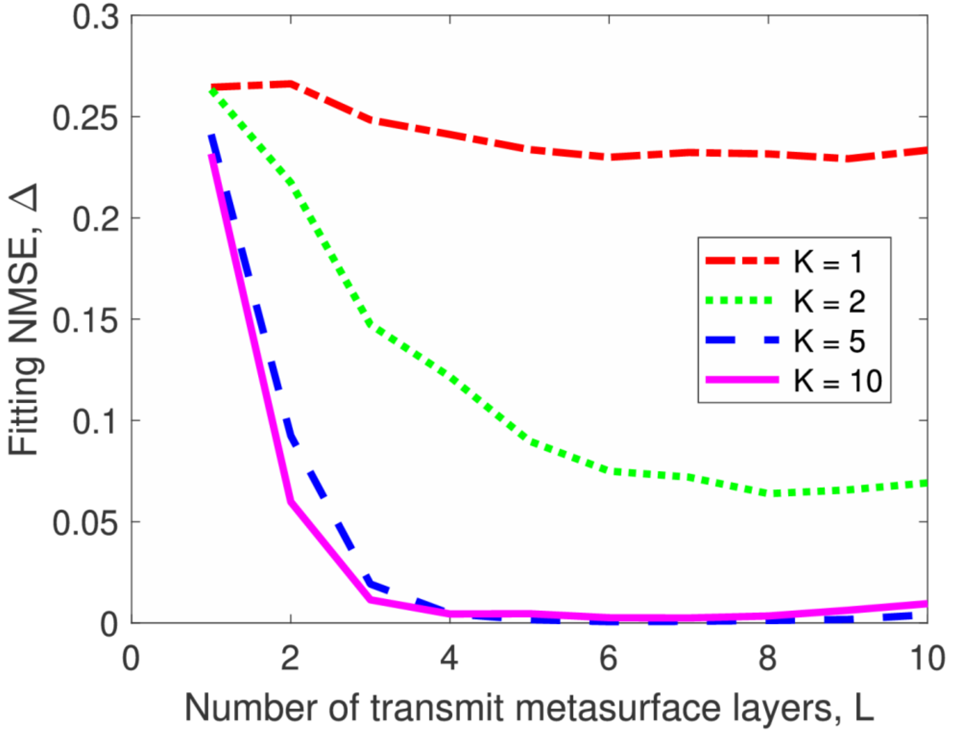
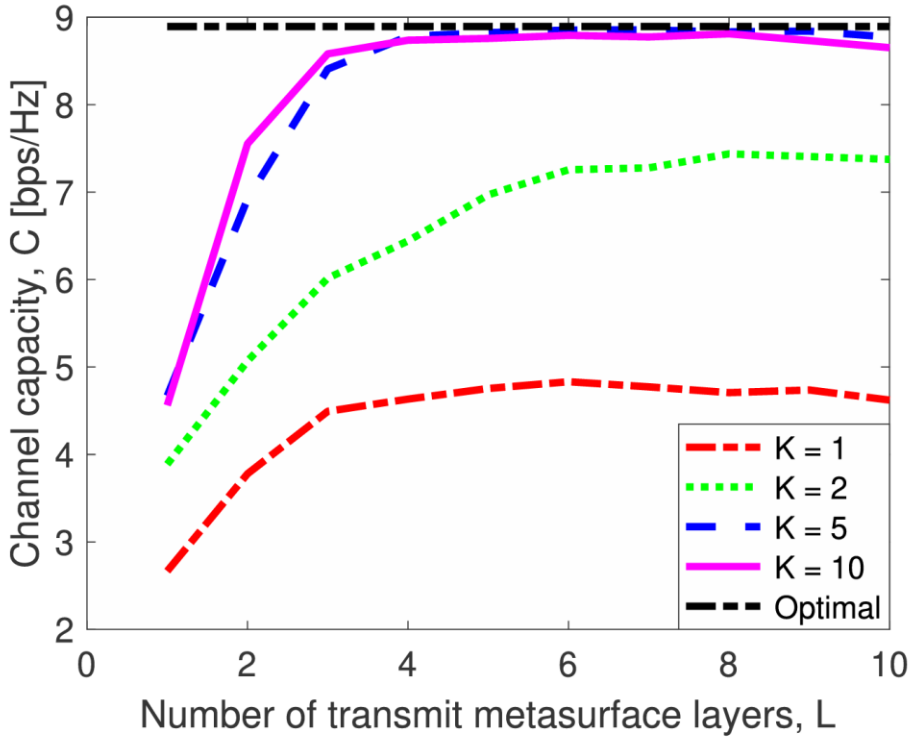
➢ Performance versus the Number of Metasurface Layers

○ 4 data streams, 100 elements per layer, half-wavelength element spacing





- ❑ Channel fitting NMSE and channel capacity approach their optimal values when using $L = 7$ metasurface layers.
- ❑ Further increasing the number of metasurface layers fail to improve the performance.

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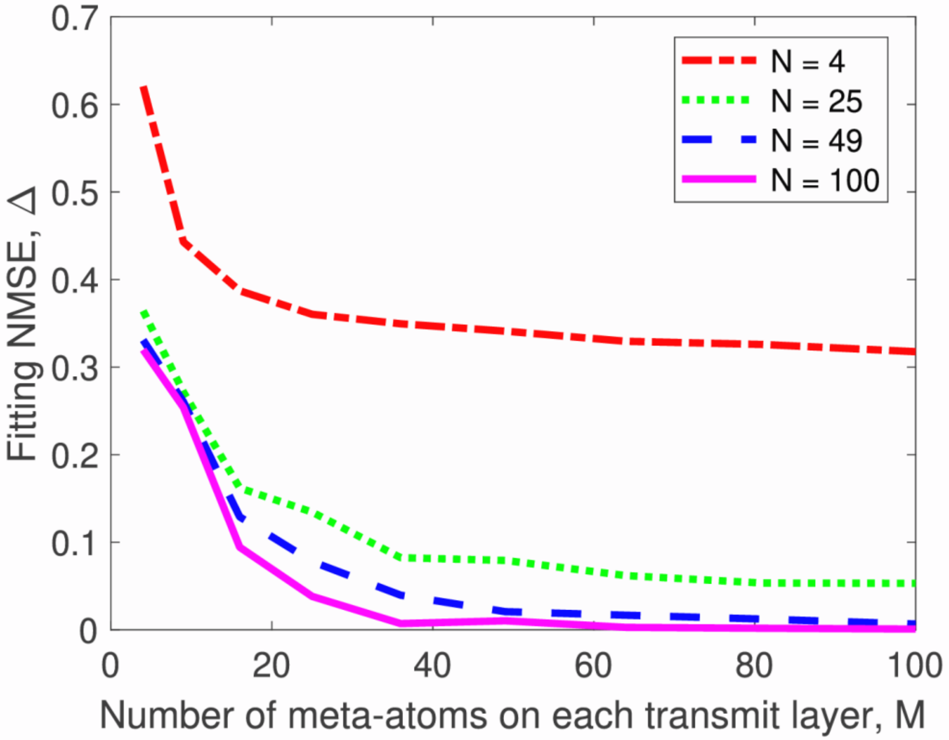
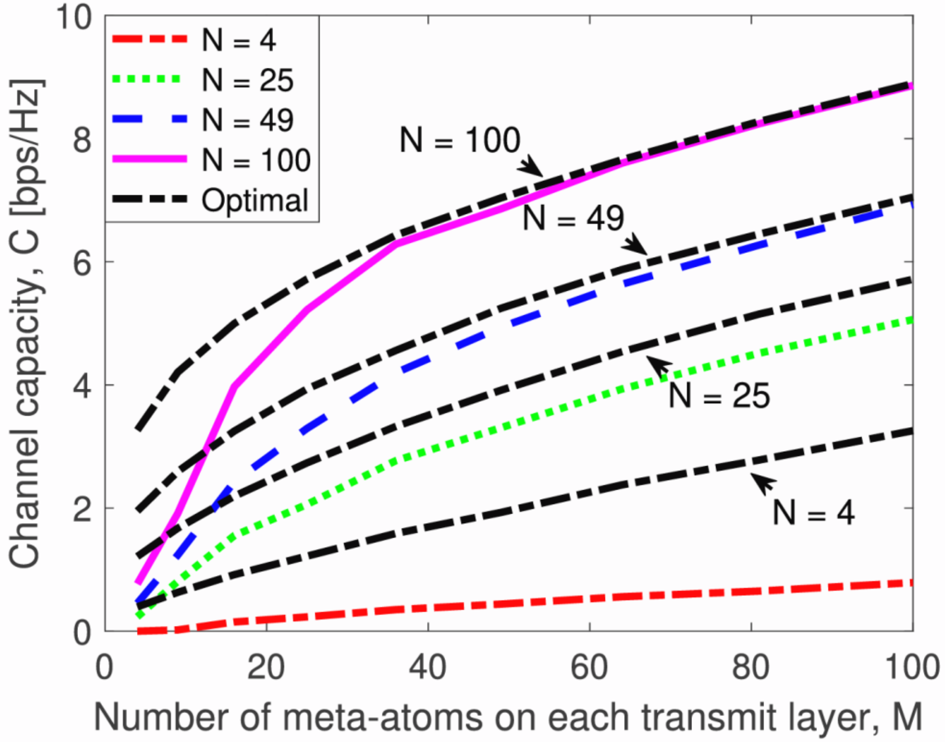
➢ Performance versus the Number of Meta-atoms per Layer

○ **4 data streams, 7 metasurface layers, half-wavelength element spacing**





❑ The fitting NMSE decreases monotonically as the number of meta-atoms per layer increases.

❑ The channel capacity is improved as the number of meta-atoms increases, albeit the number of data streams is fixed. **(Selection gain)**

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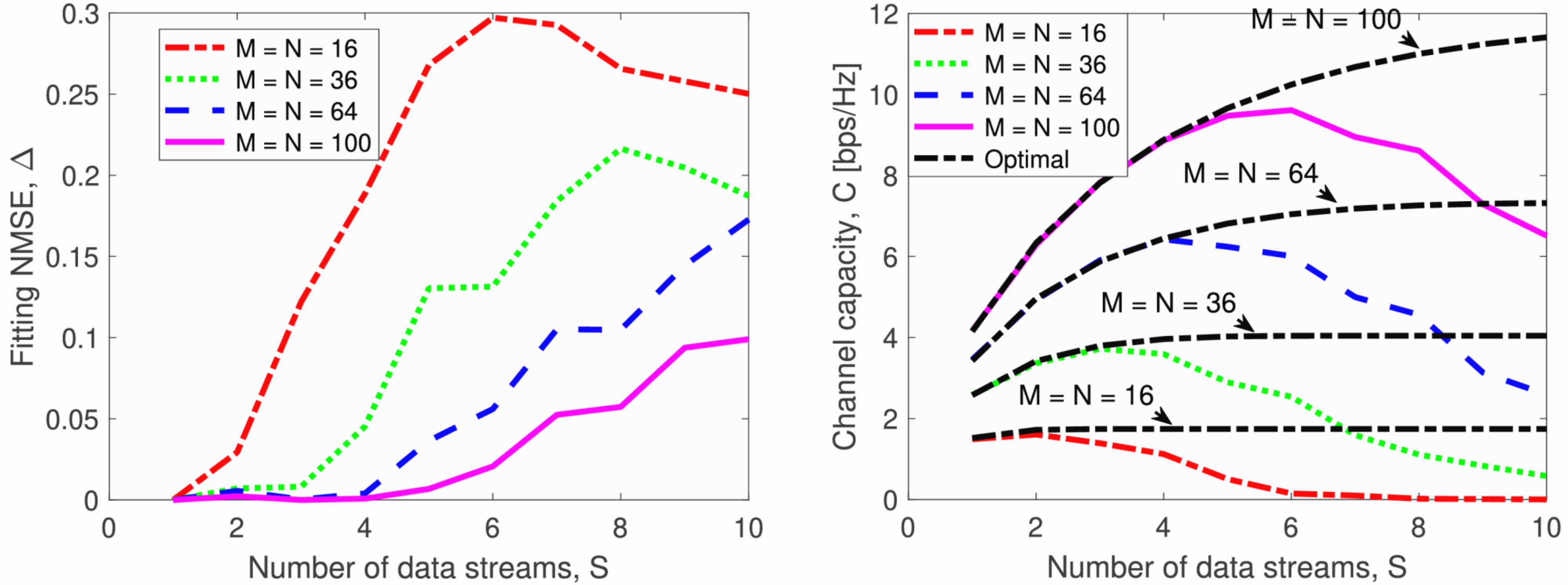
➢ Performance versus the Number of Data Streams

○ **100 meta-atoms per layer, 7 metasurface layers, half-wavelength element spacing**



❑ The increasing number of data streams offers a proportional multiplexing gain. **(Tradeoff)**

❑ It is more challenging to acquire a low channel fitting NMSE for a growing number of data streams. Hence, channel capacity achieves its maximum for a certain number of data streams.

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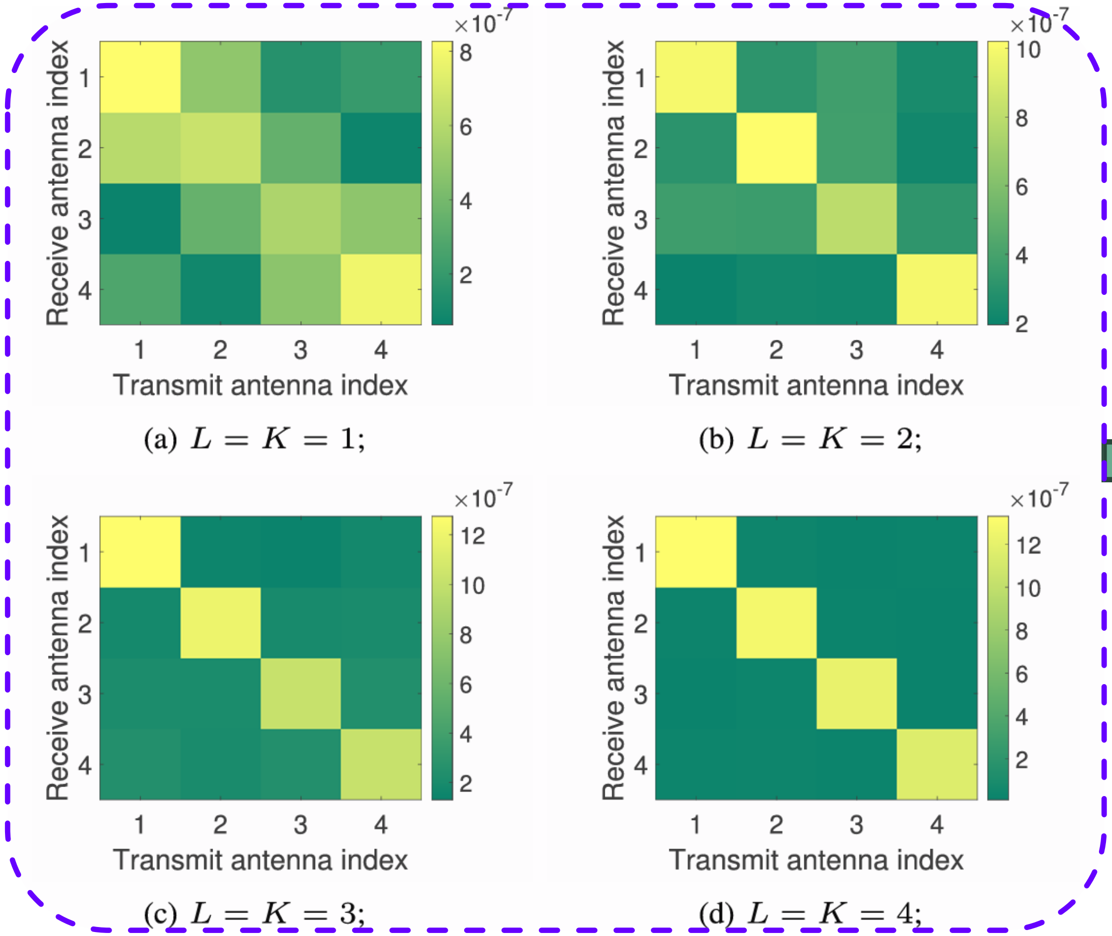
➢ The visualization of the end-to-end spatial channel matrix

○ **4 data streams, 100 elements per layer, half-wavelength element spacing**



- ❑ For a small number of metasurface layers, the TX-SIM and RX-SIM struggle to form a diagonal end-to-end channel matrix.
- ❑ As the number of metasurface layers increases, the TX-SIM and RX-SIM attain a stronger inference capability.
- ❑ The TX-SIM and RX-SIM having **four metasurface layers** respectively succeed in forming an almost perfectly diagonal channel matrix.

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➢ Conclusions

- ❑ We proposed a SIM-aided HMIMO communication paradigm, which attains substantial spatial gains while **performing the precoding and combining directly in the native EM regime at the speed of light**.
- ❑ A **7-layer SIM having half-wavelength element spacing** achieved an excellent channel fitting performance and approached the maximum channel capacity.
- ❑ Both our theoretical analysis and simulation results have shown the **quadratic channel gain when doubling the number of meta-atoms**.
- ❑ A **150% capacity gain** was attained over its conventional massive MIMO and RIS-assisted counterparts.

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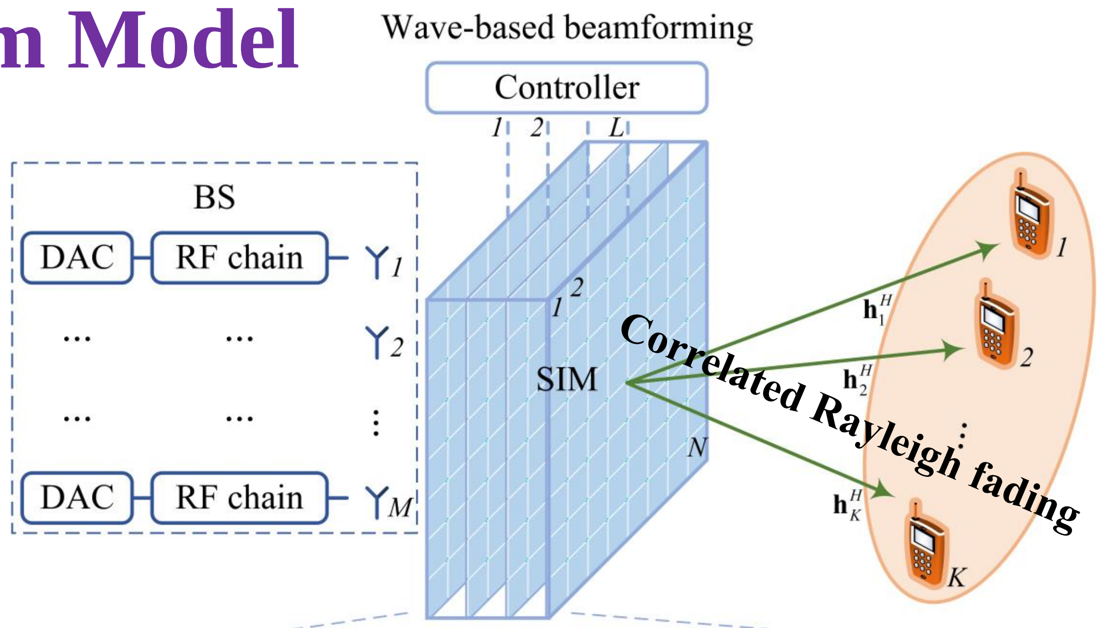
➢ SIM-aided Multiuser MISO System Model

- L: The number of metasurface layers
- N: The number of meta-atoms on each layer
- K: The number of single-antenna users
- M: The number of antennas at the BS



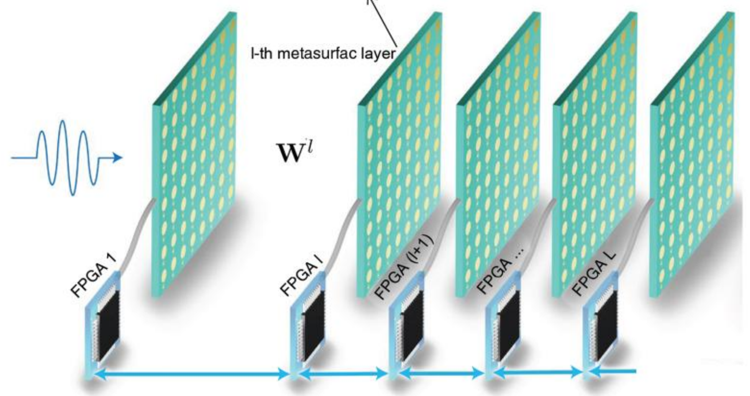
➢ Objective & Challenge

➢ Use SIM to mitigate multiuser interference in the EM wave domain.

❖ The optimization of SIM involves configuring a large number of phase shift values!

❑ The BS first selects K antennas for transmitting K independent data streams. **(M = K in this paper)**

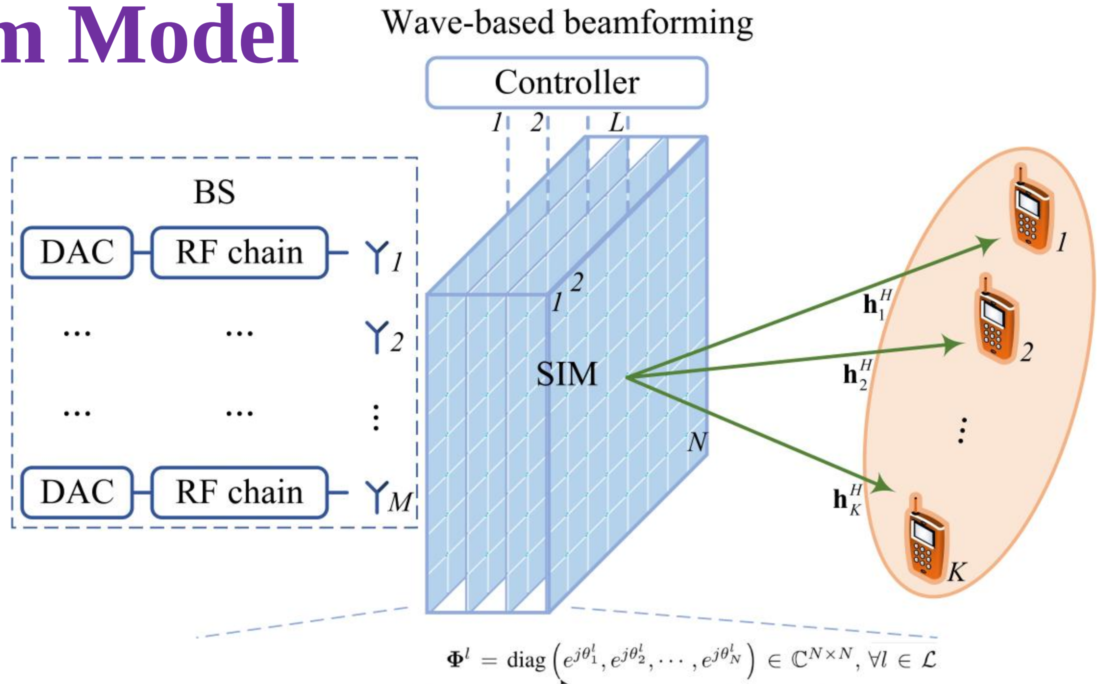
Phase shift matrix $\mathbf{\Phi}^l = \mathrm{diag}\left(e^{j\theta_1^l}, e^{j\theta_2^l}, \cdots, e^{j\theta_N^l}\right) \in \mathbb{C}^{N\times N}, \forall l \in \mathcal{L}$



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

[R2] **J. An**, M. Di Renzo, M. Debbah, and C. Yuen, "**Stacked intelligent metasurfaces** for multiuser beamforming in the wave domain," Proc. IEEE Int. Conf. Commun. (ICC), Rome, Italy, May 2023, pp. 2834 – 2839. **(ICC 2023 Best Paper Award)**
[R3] **J. An**, M. Di Renzo, M. Debbah, H. V. Poor, and C. Yuen. "**Stacked intelligent metasurfaces** for multiuser downlink beamforming in the wave domain," *arXiv preprint arXiv:2309.02687*, 2024.

➢ SIM-aided Multiuser MISO System Model



- The inter-layer propagation coefficient is

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

- The wave-domain beamforming matrix is

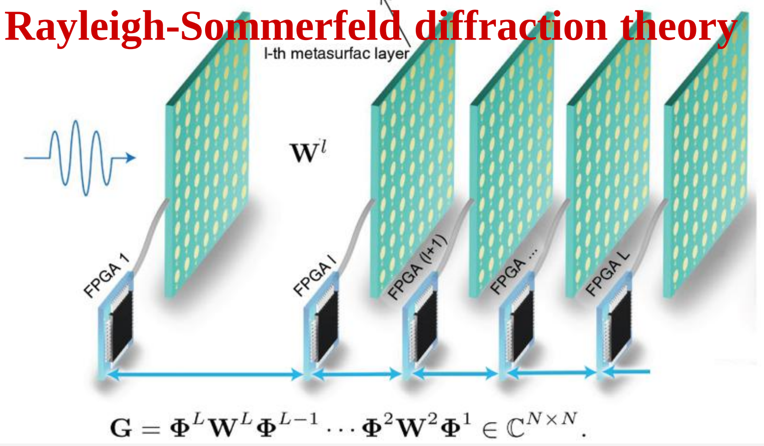
$$\mathbf{G} = \mathbf{\Phi}^L \mathbf{W}^L \mathbf{\Phi}^{L-1} \cdots \mathbf{\Phi}^2 \mathbf{W}^2 \mathbf{\Phi}^1 \in \mathbb{C}^{N\times N}$$

- The signal received at the k-th user is

$$y_k = \mathbf{h}_k^H \mathbf{G} \sum_{k'=1}^{K} \mathbf{w}_{k'}^1 \sqrt{p_{k'}} s_{k'} + n_k, \ \forall k \in \mathcal{K},$$

- The SINR at the k-th user is

$$\gamma_k = \frac{\left|\mathbf{h}_k^H \mathbf{G} \mathbf{w}_k^1\right|^2 p_k}{\sum_{k'\neq k}^{K} \left|\mathbf{h}_k^H \mathbf{G} \mathbf{w}_{k'}^1\right|^2 p_{k'} + \sigma_k^2}, \ \forall k \in \mathcal{K}$$



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➢ Problem Formulation

- **Optimization objective**: Maximizing the sum rate of all the users.
- **Optimization variables**: Transmit power allocation at the BS, SIM phase shifts.
- **Assumption**: The CSI of all the channels is perfectly known by the BS, i.e., h_k.

The k-th user's channel

❖ **Optimization problem:**

$$\begin{aligned} \max_{\mathbf{p},\,\boldsymbol{\vartheta}} \quad & R = \sum_{k=1}^{K} \log_2\left(1+\gamma_k\right) \\ \text{s.t.} \quad & \sum_{k=1}^{K} p_k \leq P_T, \\ & p_k \geq 0, \ \forall k \in \mathcal{K}, \\ & \theta_n^l \in [0, 2\pi), \ \forall n \in \mathcal{N}, \ \forall l \in \mathcal{L}. \end{aligned}$$

- Objective function
- Sum power constraint at the BS
- Individual power constraint at the BS
- Phase shift constraint at the SIM

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➢ Alternating Optimization Algorithm

➢ Given the SIM phase shifts $\boldsymbol{\vartheta}$, the power allocation is solved by using the iterative water-filling algorithm.

$$p_k = \left(p_o - \frac{\sum_{k' \neq k}^{K} \left| \mathbf{h}_k^H \mathbf{G} \mathbf{w}_{k'}^1 \right|^2 p_{k'} + \sigma_k^2}{\left| \mathbf{h}_k^H \mathbf{G} \mathbf{w}_k^1 \right|^2} \right)^+$$

Add a damping term to enhance the robustness

I

➢ Given the power allocation $\mathbf{p}$, the phase shift optimization subproblem is solved by applying the gradient ascent algorithm.

$$\theta_n^l \leftarrow \theta_n^l + \mu \frac{\partial R}{\partial \theta_n^l}, \ \forall n \in \mathcal{N}, \ \forall l \in \mathcal{L}$$

Partial derivative

$$\frac{\partial R}{\partial \theta_n^l} = 2 \log_2 e \sum_{k=1}^{K} \delta_k \left(p_k \eta_{k,k} - \gamma_k \sum_{k' \neq k}^{K} p_{k'} \eta_{k,k'} \right)$$

II

[R2] **J. An**, M. Di Renzo, M. Debbah, and C. Yuen, "**Stacked intelligent metasurfaces** for multiuser beamforming in the wave domain," Proc. IEEE Int. Conf. Commun. (ICC), Rome, Italy, May 2023, pp. 2834 – 2839. **(ICC 2023 Best Paper Award)**

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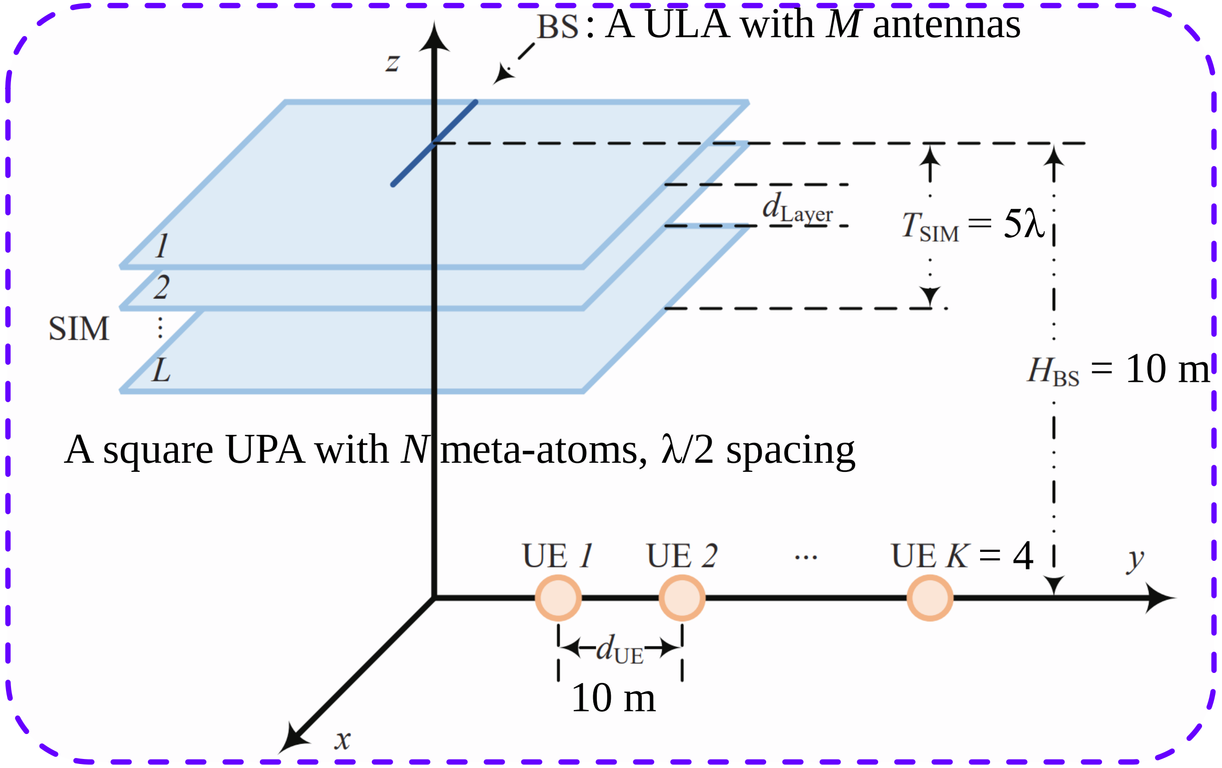
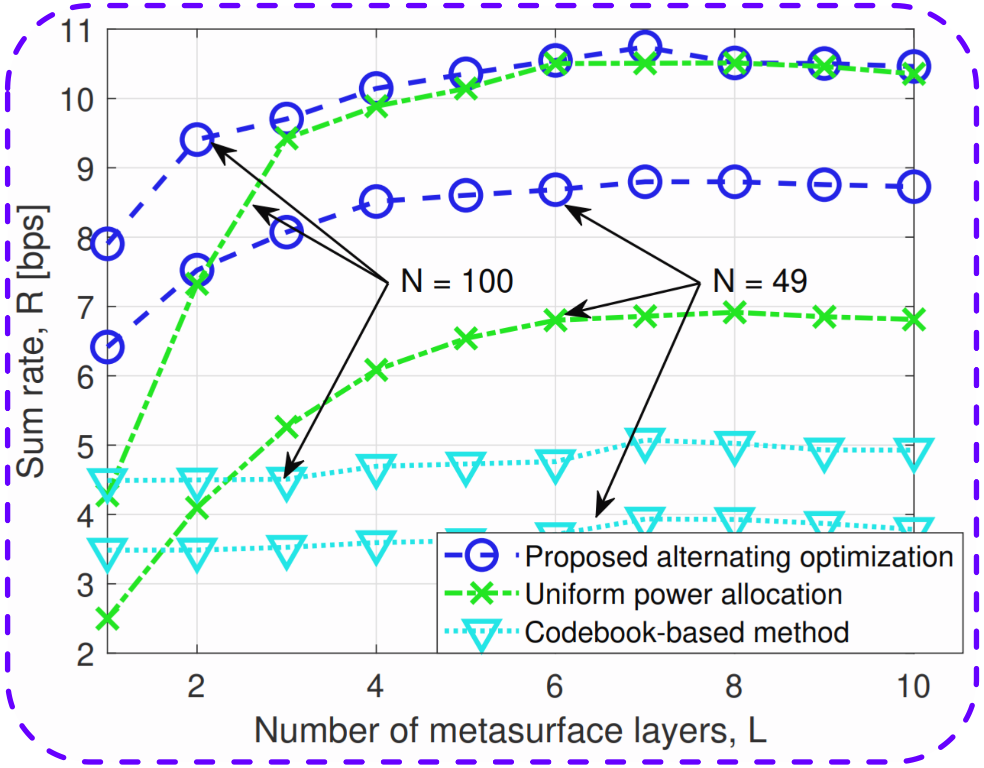
➢ Simulation Results

Carrier frequency: 28 GHz, transmit power: 10 dBm, noise power: -104 dBm





R increases as *L* increases and reaches the maximum at approximately *L* = *7*.

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➢ Conclusions

- A SIM-enabled wave-domain beamforming design was proposed, which substantially **reduces the precoding delay and hardware cost compared to its digital counterpart**.
- A joint transmit power allocation and phase shift optimization problem has been formulated to maximize the sum rate. The former has been tackled by applying the **modified iterative water-filling algorithm**, while the latter have been optimized by leveraging the **gradient ascent algorithm**.
- Simulation results have demonstrated that the wave-domain beamforming design achieves **significant performance gains** compared to the state-of-the-art benchmarks.

[R2] **J. An**, M. Di Renzo, M. Debbah, and C. Yuen, "**Stacked intelligent metasurfaces** for multiuser beamforming in the wave domain," Proc. IEEE Int. Conf. Commun. (ICC), Rome, Italy, May 2023, pp. 2834 – 2839. **(ICC 2023 Best Paper Award)**
[R3] **J. An**, M. Di Renzo, M. Debbah, H. V. Poor, and C. Yuen. "**Stacked intelligent metasurfaces** for multiuser downlink beamforming in the wave domain," *arXiv preprint arXiv:2309.02687*, 2024.

Outline

- What is Stacked Intelligent Metasurface (SIM)
- **Applications of SIM in Communication, Sensing and Computing Systems**
  - Multiuser/MIMO Precoding
  - **DOA Estimation**
  - Semantic Encoding
- Hybrid Optical-Electronic Neural Network (HOENN)
- Future Research Opportunities

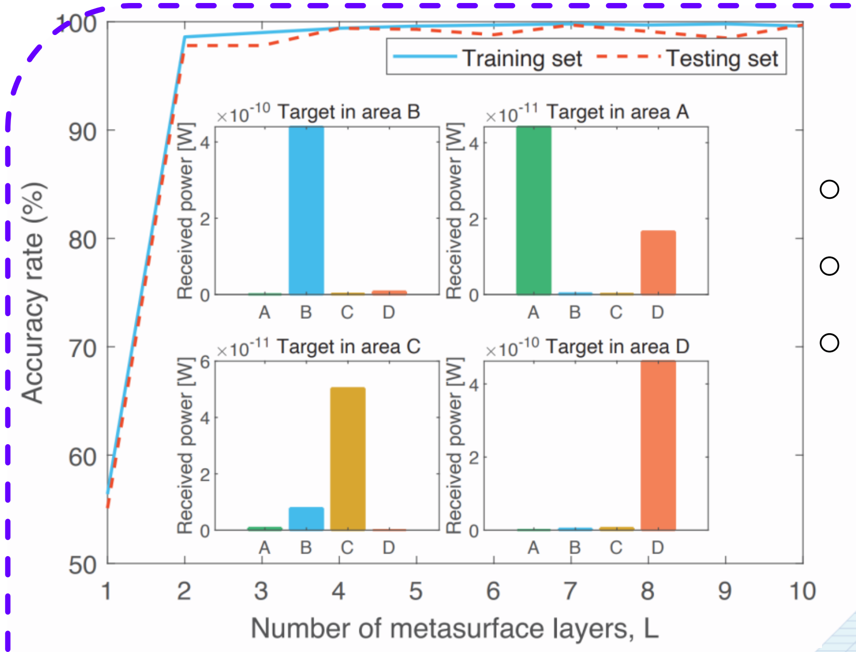
1950 Beamforming methods

1986 Super resolution approaches (MUSIC, ESPRIT)

2018 Deep neural network

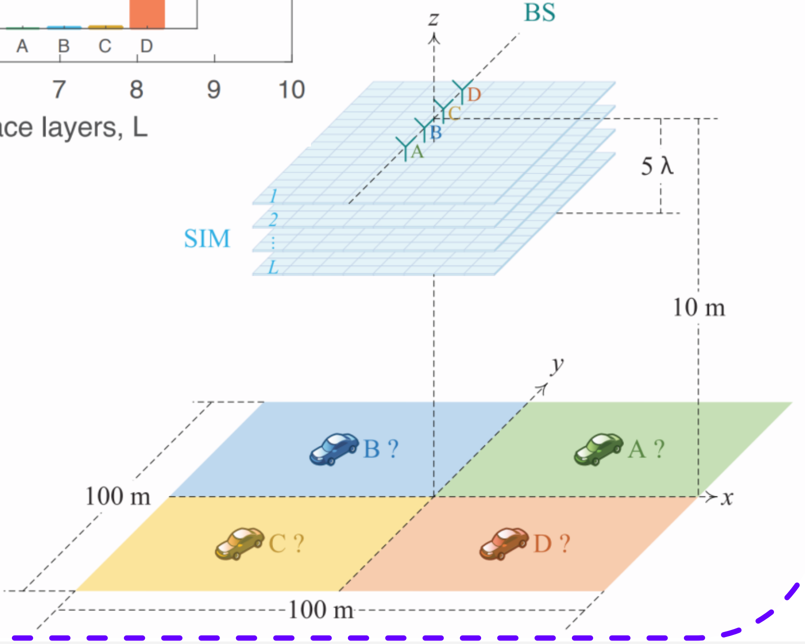
2022 Diffractive neural network

➢ SIM as a Diffractive Neural Network



- ○ 100 meta-atoms per layer
- ○ Signal power: 20 dBm
- ○ Noise power: -140 dBm

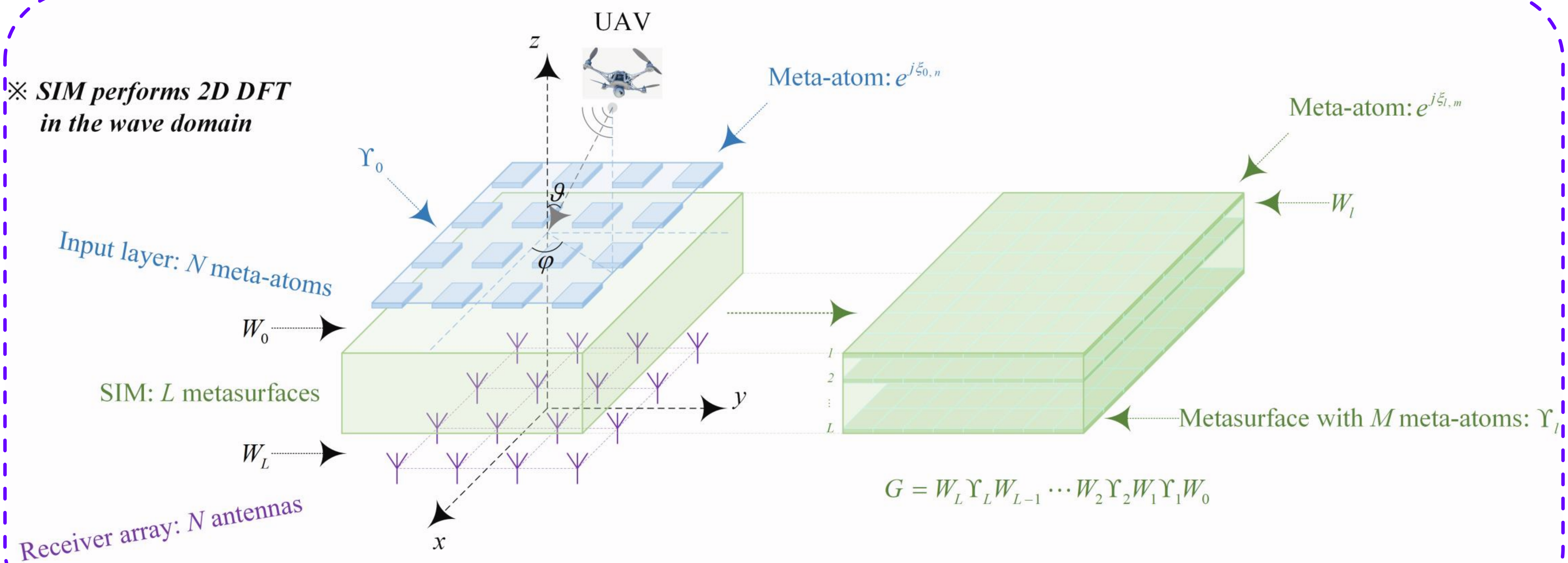
- ○ 1000 training samples
- ○ 100 testing samples
- ○ Loss function: MSE
- ○ Reinforcement learning



- ❑ A 4-layer SIM is capable of correctly estimating the DOA of a target of interest with a detection success rate of 99.5% in the training set and 99% in the testing set, as the EM wave propagates through it.
- ❑ The EM waves radiated from the target would be focused on the corresponding receive antenna with the aid of a well-trained SIM.

[R4] **J. An**, C. Yuen, C. Xu, H. Li, D. W. K. Ng, M. Di Renzo, M. Debbah, and L. Hanzo, "**Stacked intelligent metasurface**-aided MIMO transceiver design," *IEEE Wireless Commun.*, 2024, Early Access.

➢ SIM-aided Array System Model



(a) Array layout.

(b) A schematic of SIM.

[R6] **J. An**, C. Yuen, Y. 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.*, 2024, Early Access.

➢ SIM-aided Array System Model

➢ The electrical angles in the *x*- and *y*-directions are

$$\psi_{\mathrm{x}} = \kappa d_{\mathrm{x}} \sin(\vartheta) \cos(\varphi)$$
$$\psi_{\mathrm{y}} = \kappa d_{\mathrm{y}} \sin(\vartheta) \sin(\varphi)$$

➢ The steering vector *w.r.t.* the input layer of the SIM

$$\boldsymbol{a}(\psi_{\mathrm{x}}, \psi_{\mathrm{y}}) = \boldsymbol{a}_{\mathrm{y}}(\psi_{\mathrm{y}}) \otimes \boldsymbol{a}_{\mathrm{x}}(\psi_{\mathrm{x}})$$

$$[\boldsymbol{a}_{\mathrm{x}}(\psi_{\mathrm{x}})]_{n_{\mathrm{x}}} \triangleq e^{j\psi_{\mathrm{x}}(n_{\mathrm{x}}-1)}$$
$$[\boldsymbol{a}_{\mathrm{y}}(\psi_{\mathrm{y}})]_{n_{\mathrm{y}}} \triangleq e^{j\psi_{\mathrm{y}}(n_{\mathrm{y}}-1)}$$

➢ The signal being incident upon the input layer is

$$\boldsymbol{x} = \boldsymbol{a}(\psi_{\mathrm{x}}, \psi_{\mathrm{y}})\, s$$

❖ A single source
❖ Continuous phase tunning

➢ The inter-layer propagation coefficient is

$$[\boldsymbol{W}_l]_{m,\check{m}} = \frac{A_{\text{meta-atom}} \cos \epsilon_{m,\check{m}}}{2\pi d_{m,\check{m}}^2} \left(1 - j\kappa d_{m,\check{m}}\right) e^{j\kappa d_{m,\check{m}}}$$

➢ The transfer function matrix of the SIM is

$$\boldsymbol{G} = \boldsymbol{W}_L \boldsymbol{\Upsilon}_L \boldsymbol{W}_{L-1} \cdots \boldsymbol{W}_2 \boldsymbol{\Upsilon}_2 \boldsymbol{W}_1 \boldsymbol{\Upsilon}_1 \boldsymbol{W}_0$$

Transmission coefficient matrix

➢ The complex signal received at the array is

$$\boldsymbol{r} = \sqrt{\varrho}\, \boldsymbol{G} \boldsymbol{\Upsilon}_0 \boldsymbol{x} + \boldsymbol{u} = \sqrt{\varrho}\, \boldsymbol{G} \boldsymbol{\Upsilon}_0 \boldsymbol{a}(\psi_{\mathrm{x}}, \psi_{\mathrm{y}})\, s + \boldsymbol{u}$$

SNR   Normalized noise

[R6] **J. An**, C. Yuen, Y. 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.*, 2024, Early Access.

Problem Formulation & Solution

$$\min_{\{\xi_{l,m}\}} \quad \mathcal{L} = \|\beta \boldsymbol{G} - \boldsymbol{F}\|_F^2$$

$$\text{s.t.} \quad \boldsymbol{G} = \boldsymbol{W}_L \boldsymbol{\Upsilon}_L \boldsymbol{W}_{L-1} \cdots \boldsymbol{W}_2 \boldsymbol{\Upsilon}_2 \boldsymbol{W}_1 \boldsymbol{\Upsilon}_1 \boldsymbol{W}_0,$$

$$\boldsymbol{\Upsilon}_l = \text{diag}\left(\left[e^{j\xi_{l,1}}, e^{j\xi_{l,2}}, \cdots, e^{j\xi_{l,M}}\right]^T\right),$$

$$\xi_{l,m} \in [0, 2\pi), \; m = 1, \cdots, M, \; l = 1, \cdots, L,$$

$$\beta \in \mathbb{C}.$$

- Objective function
- The EM response of the SIM
- Transmission coefficient matrix of the *l*-th layer
- Individual phase shift constraint
- Scaling factor for normalization

$$f_{n,\breve{n}} = [\boldsymbol{F}]_{n,\breve{n}} \triangleq e^{-j2\pi \frac{(n_x-1)(\breve{n}_x-1)}{N_x}} e^{-j2\pi \frac{(n_y-1)(\breve{n}_y-1)}{N_y}}$$

- 2D DFT matrix

Gradient Calculation

$$\nabla_{\boldsymbol{\xi}_l} \mathcal{L} = 2 \sum_{n=1}^{N} \Im\left\{\beta^* \boldsymbol{\Upsilon}_l^H \boldsymbol{P}_{l,n}^H (\beta \boldsymbol{g}_n - \boldsymbol{f}_n)\right\}$$

Parameter Update

$$\boldsymbol{\xi}_l \leftarrow \boldsymbol{\xi}_l - \eta \nabla_{\boldsymbol{\xi}_l} \mathcal{L}$$

SIM phase shifts

$$\eta \leftarrow \eta \zeta$$

Learning rate

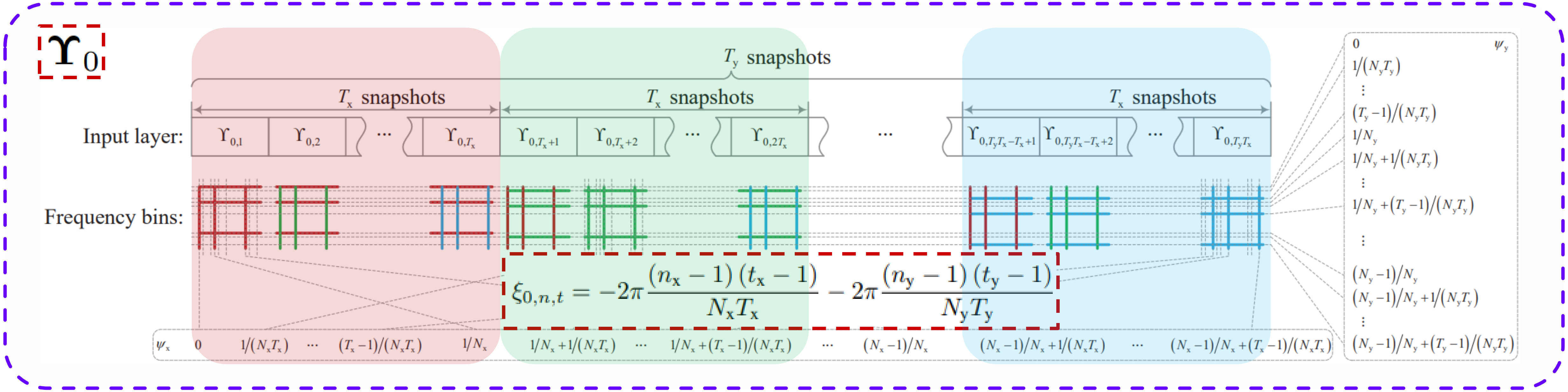
$$\beta = \left(\boldsymbol{g}^H \boldsymbol{g}\right)^{-1} \boldsymbol{g}^H \boldsymbol{f}$$

Scaling factor

[R6] **J. An**, C. Yuen, Y. 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.*, 2024, Early Access.

➢ DOA Estimation Protocol

➢ Tuning the phase shifts of the input layer to generate the angular spectrum with fine granularity.



The 2D index of the peak

The estimated electrical angles

The estimated azimuth and elevation angles

Received signal

$$[\hat{n}, \hat{t}] = \arg \max_{\substack{n=1,\cdots,N,\\ t=1,\cdots,T}} |r_{n,t}|^2$$

Antenna Snapshot

$$\hat{\psi}_x = \mathrm{mod}\left[2\left(\frac{\hat{n}_x - 1}{N_x} + \frac{\hat{t}_x - 1}{N_x T_x}\right) + 1, 2\right] - 1$$

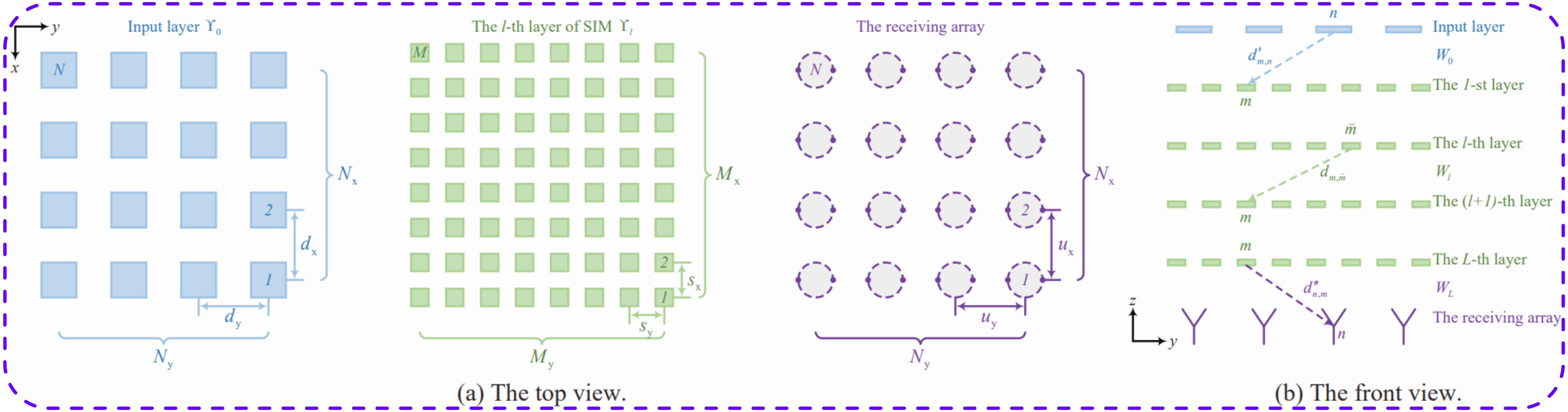
$$\hat{\psi}_y = \mathrm{mod}\left[2\left(\frac{\hat{n}_y - 1}{N_y} + \frac{\hat{t}_y - 1}{N_y T_y}\right) + 1, 2\right] - 1$$

$$\hat{\varphi} = \arctan\left(\frac{\hat{\psi}_y d_x}{\hat{\psi}_x d_y}\right),$$

$$\hat{\vartheta} = \arcsin\left(\frac{1}{\kappa}\sqrt{\frac{\hat{\psi}_x^2}{d_x^2} + \frac{\hat{\psi}_y^2}{d_y^2}}\right)$$

[R6] **J. An**, C. Yuen, Y. 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.*, 2024, Early Access.

➢ Simulation Setup



- The receiver has N probes arranged on (N_x, N_y) grids.
- The system operates at 60 GHz.
- The receiver antenna array is arranged in the same way as the input layer of the SIM, both with λ/2 element spacing.

[R6] **J. An**, C. Yuen, Y. 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.*, 2024, Early Access.

➢ Ablation Study

➢ Three rounds

The first-round experiment with coarse granularity

M	T_{SIM}	$s_x = s_y = 2\lambda/3$			$s_x = s_y = 2\lambda/6$			$s_x = s_y = 2\lambda/9$		
		$L = 3$	$L = 6$	$L = 9$	$L = 3$	$L = 6$	$L = 9$	$L = 3$	$L = 6$	$L = 9$
9	3λ	−9.04	−9.22	−5.10	−2.34	−3.10	−3.82	−1.40	−2.67	−1.28
	6λ	−3.72	−15.39	−10.59	−1.33	−1.39	−1.75	−1.10	−1.25	−1.25
	9λ	−2.03	−5.34	−12.16	−1.22	−1.27	−1.25	−0.91	−1.25	−1.25
36	3λ	−21.40	−17.70	−6.44	−19.89	−27.84	−14.24	−4.98	−4.64	−3.00
	6λ	−16.43	−51.35	−77.43	−3.98	−7.35	−3.94	−2.12	−2.42	−1.29
	9λ	−12.16	−21.44	−45.99	−2.11	−2.44	−3.88	−1.40	−1.36	−1.25
81	3λ	−32.90	−19.59	−5.42	−20.93	−15.51	−32.51	−11.39	−8.93	−4.22
	6λ	−34.65	**−186.34**	**−174.09**	−11.17	−21.12	−11.03	−4.02	−6.64	−5.23
	9λ	−20.34	**−183.78**	−149.94	−4.40	−7.17	−11.21	−1.80	−3.32	−2.81

The second-round experiment with moderate granularity

M	T_{SIM}	$s_x = s_y = 2\lambda$			$s_x = s_y = 2\lambda/3$			$s_x = s_y = 2\lambda/5$		
		$L = 4$	$L = 6$	$L = 8$	$L = 4$	$L = 6$	$L = 8$	$L = 4$	$L = 6$	$L = 8$
49	4λ	−1.58	−0.56	−0.38	−38.69	−27.79	−19.27	−22.74	−67.44	−19.13
	6λ	−8.24	−2.11	−0.83	−21.11	−64.99	−41.89	−13.64	−13.34	−41.31
	8λ	−23.36	−13.06	−2.18	−21.03	−39.62	−50.57	−6.39	−10.69	−15.80
81	4λ	−1.66	−0.52	−0.38	−39.88	−27.21	−28.59	−39.46	−49.97	−143.56
	6λ	−9.47	−2.48	−0.96	−40.76	**−186.34**	−55.88	−23.20	**−176.10**	−20.38
	8λ	−21.78	−5.61	−3.37	−31.07	−71.25	**−182.64**	−11.90	−33.63	−9.54
121	4λ	−1.28	−0.54	−0.36	−32.92	−74.72	−16.65	**−183.27**	−115.42	**−182.88**
	6λ	−10.29	−2.46	−1.40	−62.48	**−179.98**	**−179.26**	−45.93	−96.94	**−199.67**
	8λ	−24.44	−8.73	−3.35	−61.87	**−199.91**	**−192.93**	−28.65	**−194.52**	−35.18

The third-round experiment with fine granularity

M	T_{SIM}	$s_x = s_y = 2\lambda/2$			$s_x = s_y = 2\lambda/3$			$s_x = s_y = 2\lambda/4$		
		$L = 5$	$L = 6$	$L = 7$	$L = 5$	$L = 6$	$L = 7$	$L = 5$	$L = 6$	$L = 7$
100	7λ	−34.33	−31.57	−40.62	−52.49	**−183.68**	**−185.46**	−78.29	**−174.16**	−65.66
	8λ	**−181.78**	−141.26	−65.18	−47.77	**−190.77**	−100.66	**−194.17**	−114.11	**−182.10**
	9λ	−75.05	**−186.58**	−28.49	−52.09	−59.48	**−188.36**	−40.13	−68.04	**−192.96**
121	7λ	−43.44	−36.41	−17.11	−66.08	**−188.02**	**−181.77**	**−194.05**	**−188.23**	**−187.96**
	8λ	−72.48	−82.82	**−180.05**	−78.40	**−199.91**	**−194.52**	−93.94	**−192.73**	**−177.78**
	9λ	−165.68	−103.64	**−185.65**	−39.28	−78.45	**−183.62**	−117.50	**−183.12**	**−208.78**
144	7λ	−35.95	−163.67	−34.67	**−195.45**	**−191.91**	**−192.13**	**−186.43**	**−188.46**	**−179.55**
	8λ	−84.74	**−181.21**	−91.63	−72.60	**−183.46**	**−201.35**	−52.73	**−183.36**	**−178.34**
	9λ	**−183.27**	−105.71	**−186.88**	−111.27	**−174.52**	**−199.73**	−44.56	**−180.33**	**−178.95**

A four-tuple (T_{SIM}, L, M, s_x)

i) T_{SIM}: Thickness of the SIM;

ii) L: Number of metasurface layers;

iii) M: Number of meta-atoms per layer;

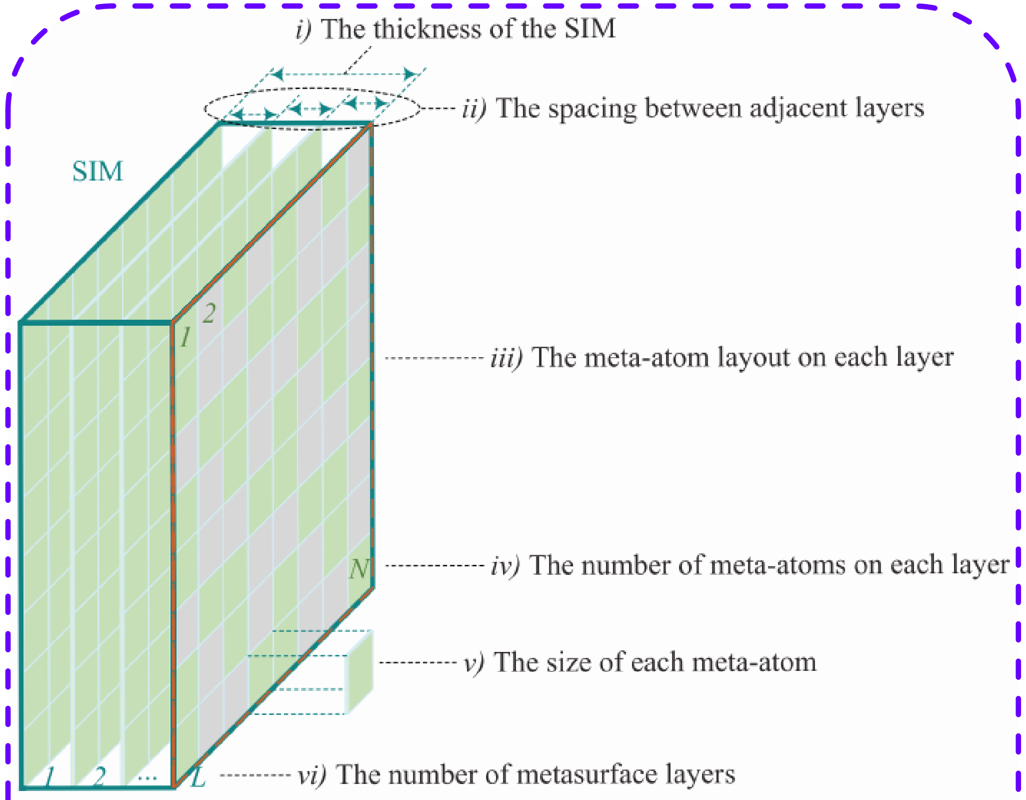
iv) $s_x = s_y$: Element spacing.

❑ $u_x = u_y = \lambda/2$.

❑ (2, 2) grids.

[R6] **J. An**, C. Yuen, Y. 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.*, 2024, Early Access.

➢ Fundamental Trade-Offs



Inter-layer propagation matrix ***W***

- ❑ A very thick SIM
- ❑ A very thin SIM
- ❑ Too much layers
- ❑ Too few layers
- ❑ Too much meta-atoms
- ❑ Too few meta-atoms
- ❑ Large element spacing
- ❑ Small element spacing

A singular ***W***

A nearly diagonal ***W***

A nearly diagonal ***W***

Insufficient design DoF

Unnecessary propagation links

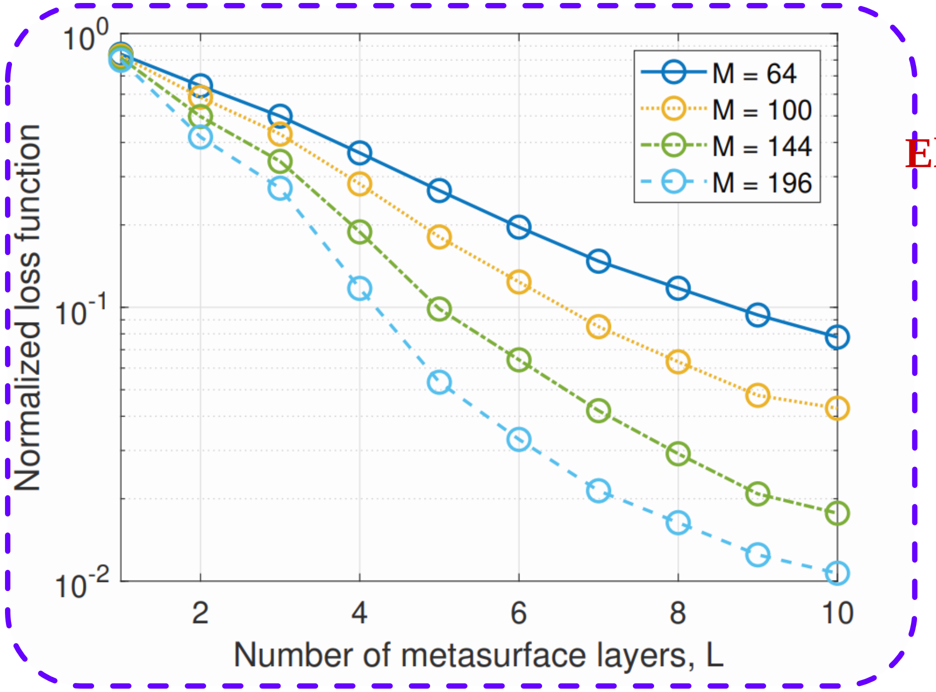
Rank deficiency

A nearly diagonal ***W***

A rank-one ***W***

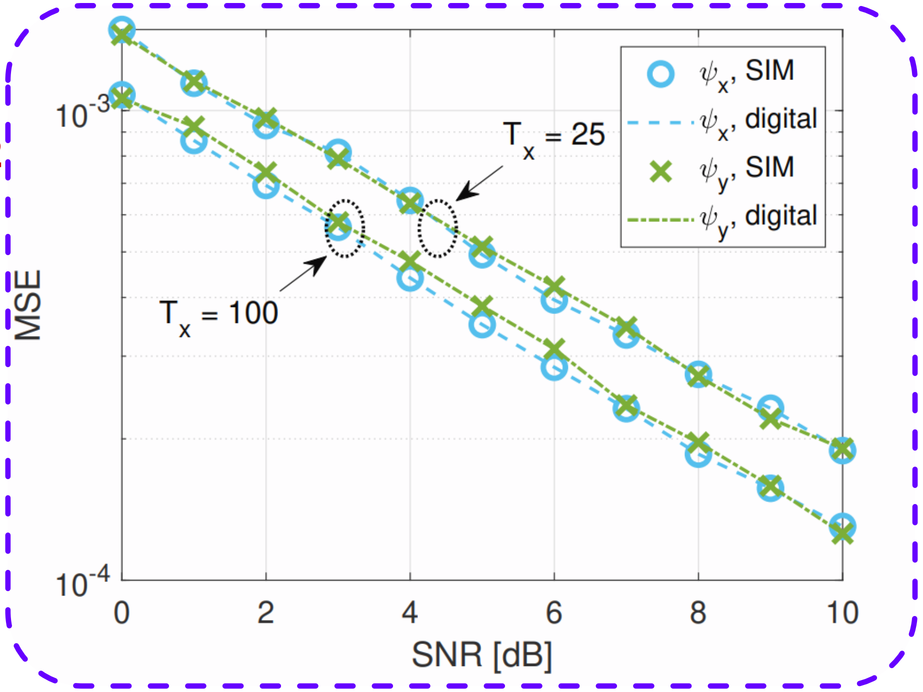
[R6] **J. An**, C. Yuen, Y. Guan, M. Di Renzo, M. Debbah, H. V. Poor, and L. Hanzo, “Two-dimensional direction-of-arrival estimation using stacked intelligent metasurfaces,” *IEEE J. Sel. Areas Commun.*, 2024, Early Access.

➢ Loss Function versus *L*



(4, 4) grid points
Layer spacing: λ
Element spacing: $\lambda/2$

➢ MSE versus SNR

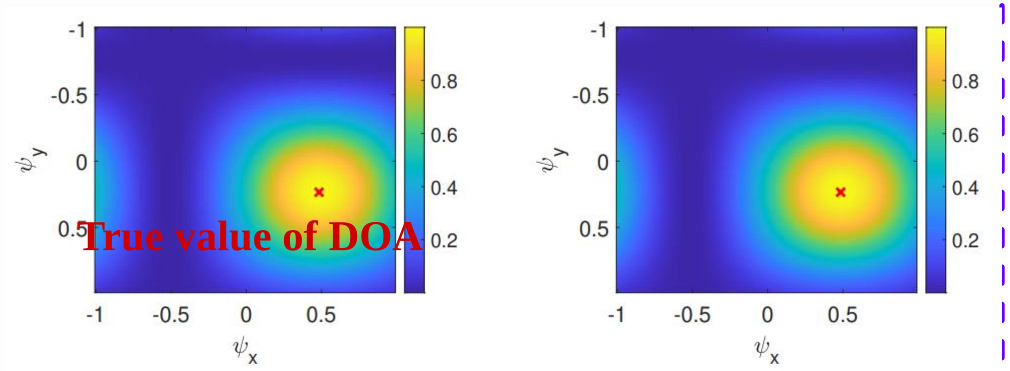


- A SIM having few layers cannot fit the 2D DFT matrix well. Increasing the number of layers succeeds in approximating the 2D DFT in the wave domain.
- The fitting performance also improves with the number of meta-atoms *M* on each layer.
- The MSE improves by 10 dB for every 10 dB increase in SNR.
- Increasing the number of snapshots per block from $T_x = 25$ to $T_x = 100$ provides an extra 2 dB performance gain, thanks to the finer granularity.

[R6] **J. An**, C. Yuen, Y. 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.*, 2024, Early Access.

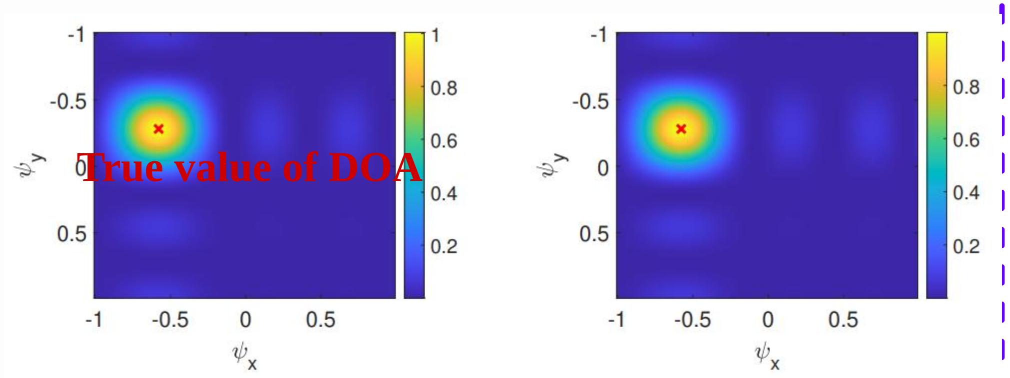
➢ Angular Spectrum

- ❑ Using a (2 × 2) receiver array



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

- ❑ Using a (4 × 4) receiver array



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

- ❑ The spectrum is obtained by laminating the outputs of 1024 2D DFTs.
- ❑ The energy peak is at the position corresponding to the incident signal's DOA.
- ❑ The SIM outputs almost the same angular spectrum as the 2D digital DFT.
- ❑ A larger array aperture can reduce the leakage.

- ❑ The SIM results in a fundamental DOA estimation paradigm shift by directly observing the angular spectrum instead of the array signal.
- ❑ The computing delay is significantly reduced, and the hardware implementation can be simplified.

[R6] **J. An**, C. Yuen, Y. 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.*, 2024, Early Access.

➢ Conclusions

- We proposed a novel SIM architecture for **estimating the 2D DOA parameters**.
- By appropriately training the SIM to **compute the 2D DFT in the wave domain**, the spatial EM waves can be directly transformed into their spatial frequency domain as they propagate through the SIM.
- We designed a protocol to **generate an angular spectrum with fine granularity** and estimated the DOA by searching for the index having the highest magnitude.
- Simulation results indicate that the proposed SIM-based DOA estimator achieves an MSE of 10^{-4} under moderate conditions, while allowing for **a substantial enhancement in the computation speed at a moderate hardware complexity**.

[R6] **J. An**, C. Yuen, Y. 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.*, 2024, Early Access.

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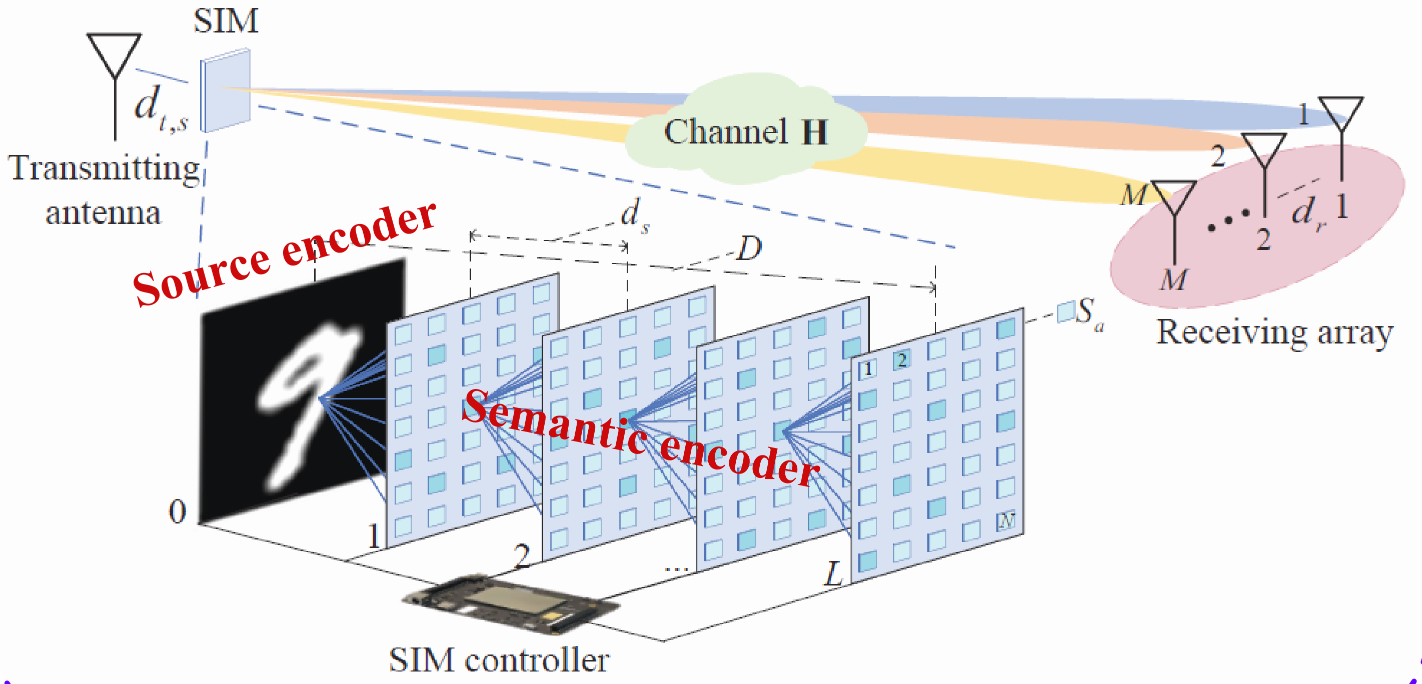
- Future Research Opportunities

➢ SIM for Semantic Encoder

- ❑ Image recognition task



- ❑ A SIM-based DNN transforms the signals passing through the input layer into a unique beam towards a receiving antenna.
- ❑ The image is recognized by probing the signal magnitude across the receiving array.

- ❑ The normalized received power is

$$\tilde{\mathbf{y}} = \mathrm{softmax}(|\mathbf{y}|^2) = [\tilde{y}_1, \tilde{y}_2, \ldots, \tilde{y}_M] \in \mathbb{R}^{M\times 1}$$

- ❑ The expected probability distribution is

$$q_m = \begin{cases} 1, & m \text{ is the class of the source image,} \\ 0, & \text{otherwise.} \end{cases}$$

- ❑ The cross entropy is defined as

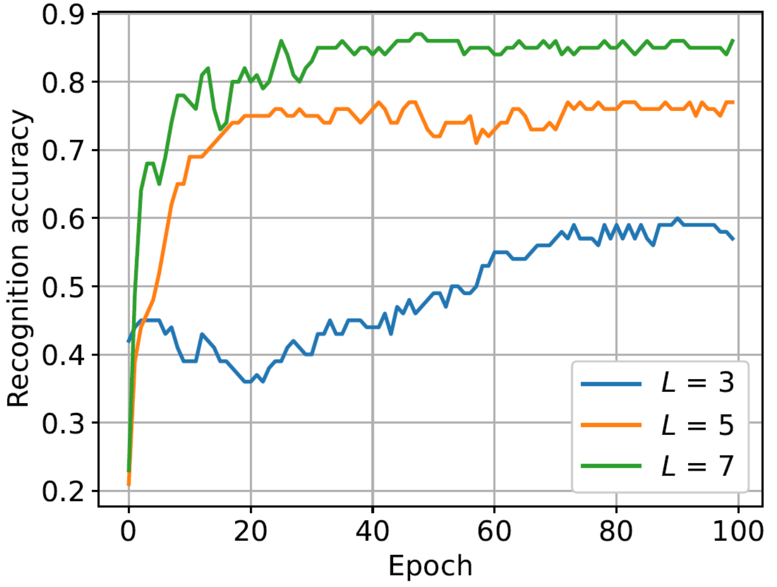
$$\mathcal{L}_{\mathrm{CE}}(\mathbf{a}^l, \phi^l) = -\sum_{m=1}^{M} q_m \log(\tilde{y}_m)$$

- ❑ Mini-batch gradient descent
- ❑ Adam optimizer.

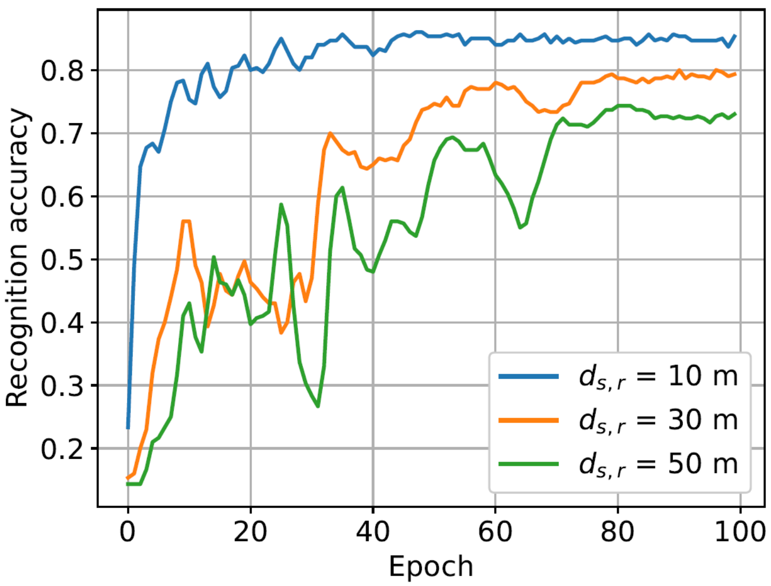
[R8] G. Huang, **J. An**, Z. Yang, and L. Gan, "**Stacked intelligent metasurfaces** for image recognition task-oriented semantic communications," *arXiv preprint*, 2024.

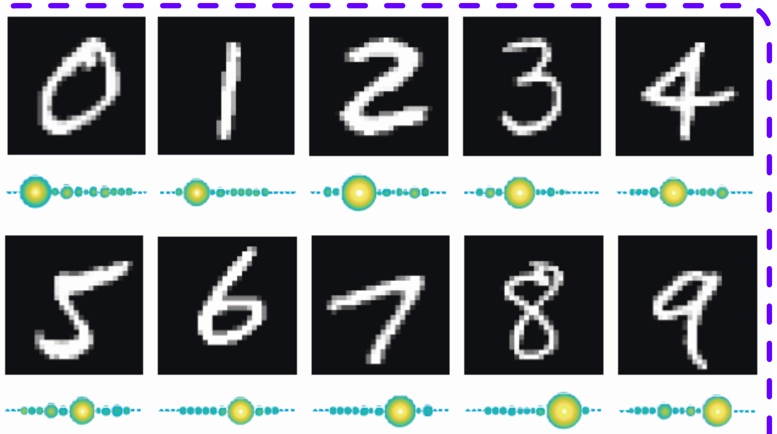
➢ Simulation Results

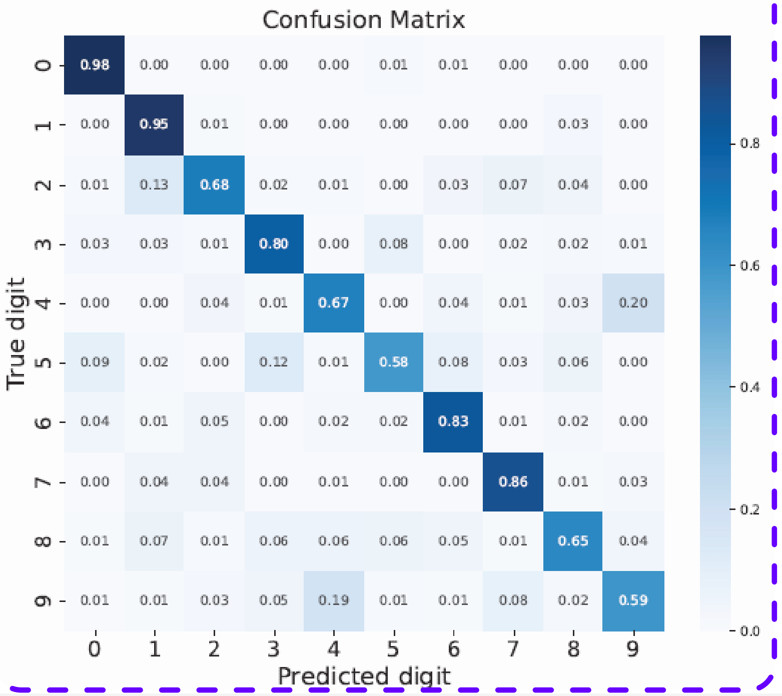
- ➢ **Accuracy versus *L***
- ➢ ***D* = 10λ, *N* = 441, $d_{s,r}$ = 10 m**



- ➢ **Accuracy versus $d_{s,r}$**
- ➢ ***D* = 10λ, *N* = 441, *L* = 7**





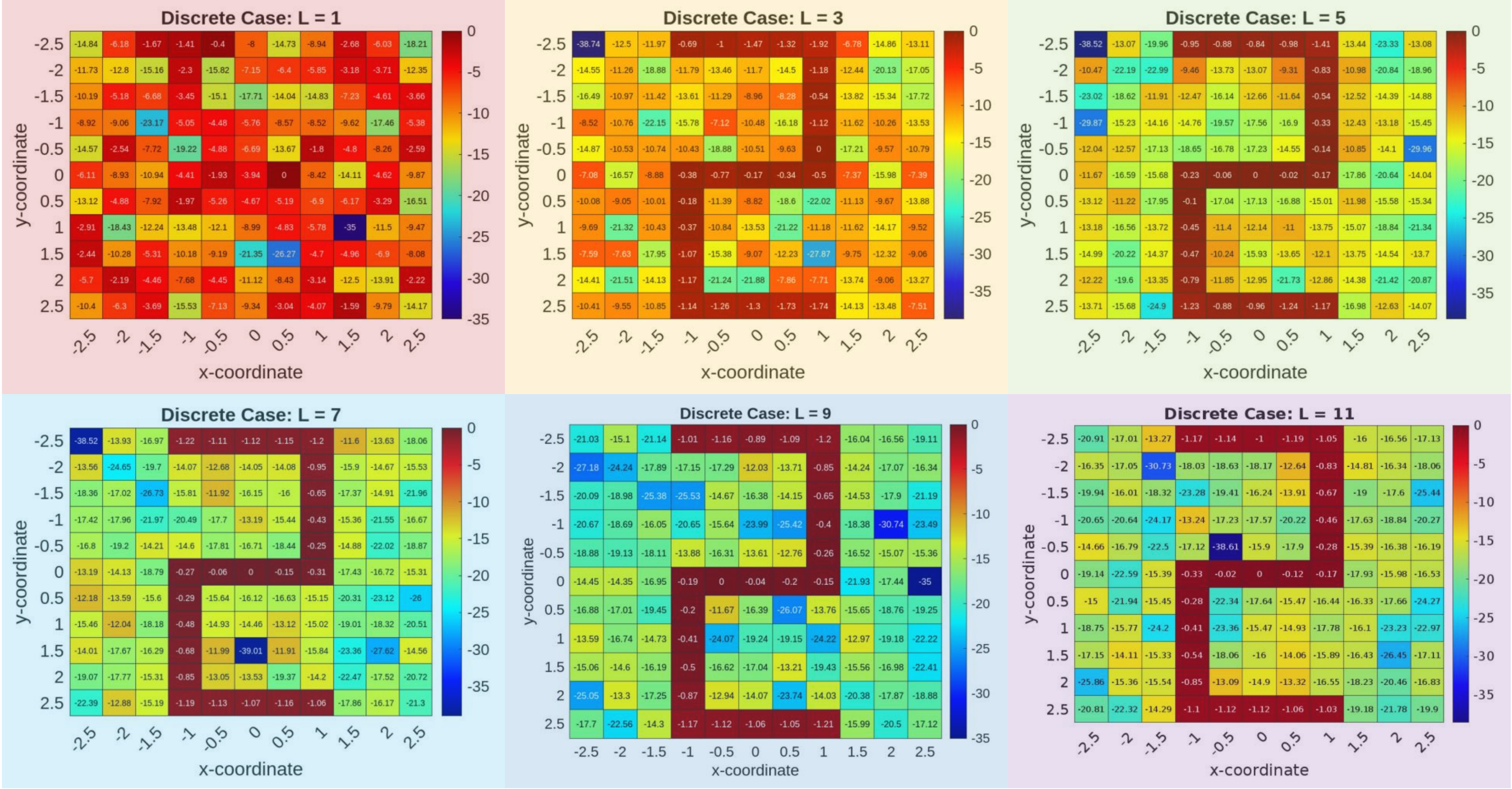


- ❑ The recognition accuracy using the DNN increases with *L*, thanks to the enhanced inference capability of the multi-layer diffractive architecture for achieving more accurate beam steering.
- ❑ A shorter propagation distance would improve the recognition accuracy. (**Less path loss**; & **More distinguishable channels**.)

[R8] G. Huang, **J. An**, Z. Yang, and L. Gan, "**Stacked intelligent metasurfaces** for image recognition task-oriented semantic communications," *arXiv preprint*, 2024.

➢ SIM for Generating Radiation Patterns

- 1-bit phase shift tuning
- 20 × 20 meta-atoms on each layer
- Thickness of the SIM: 5λ



SIM can precisely generate desired radiation patterns as the number of metasurface layers increases.

[R9] N. U. Hassan, **J. An**, M. Di Renzo, M. Debbah and C. Yuen, “Efficient beamforming and radiation pattern control using **stacked intelligent metasurfaces**,” *IEEE Open J. Commun. Society*, vol. 5, pp. 599-611, 2024.

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  - DOA Estimation
  - Semantic Encoding
- **Hybrid Optical-Electronic Neural Network (HOENN)**
- Future Research Opportunities

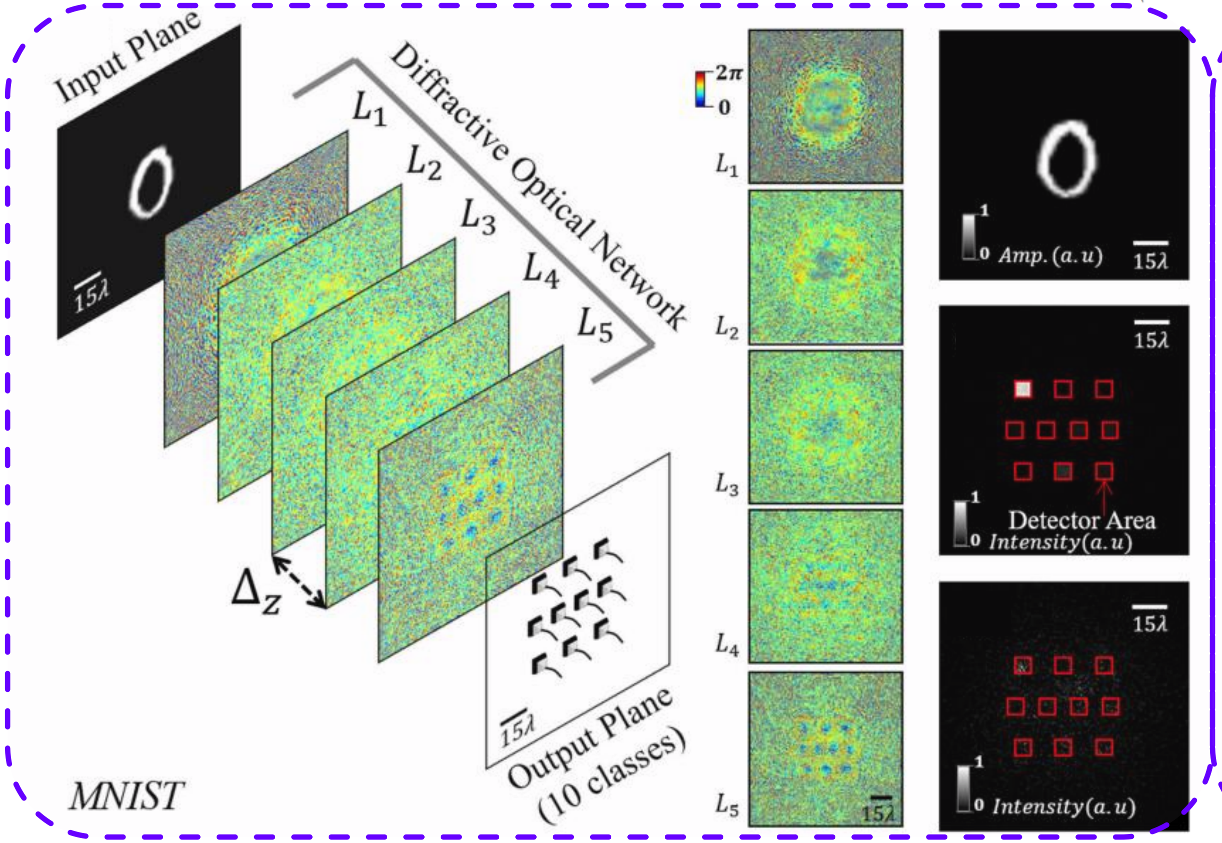
➢ Hybrid Optical-Electronic Neural Network (HOENN)

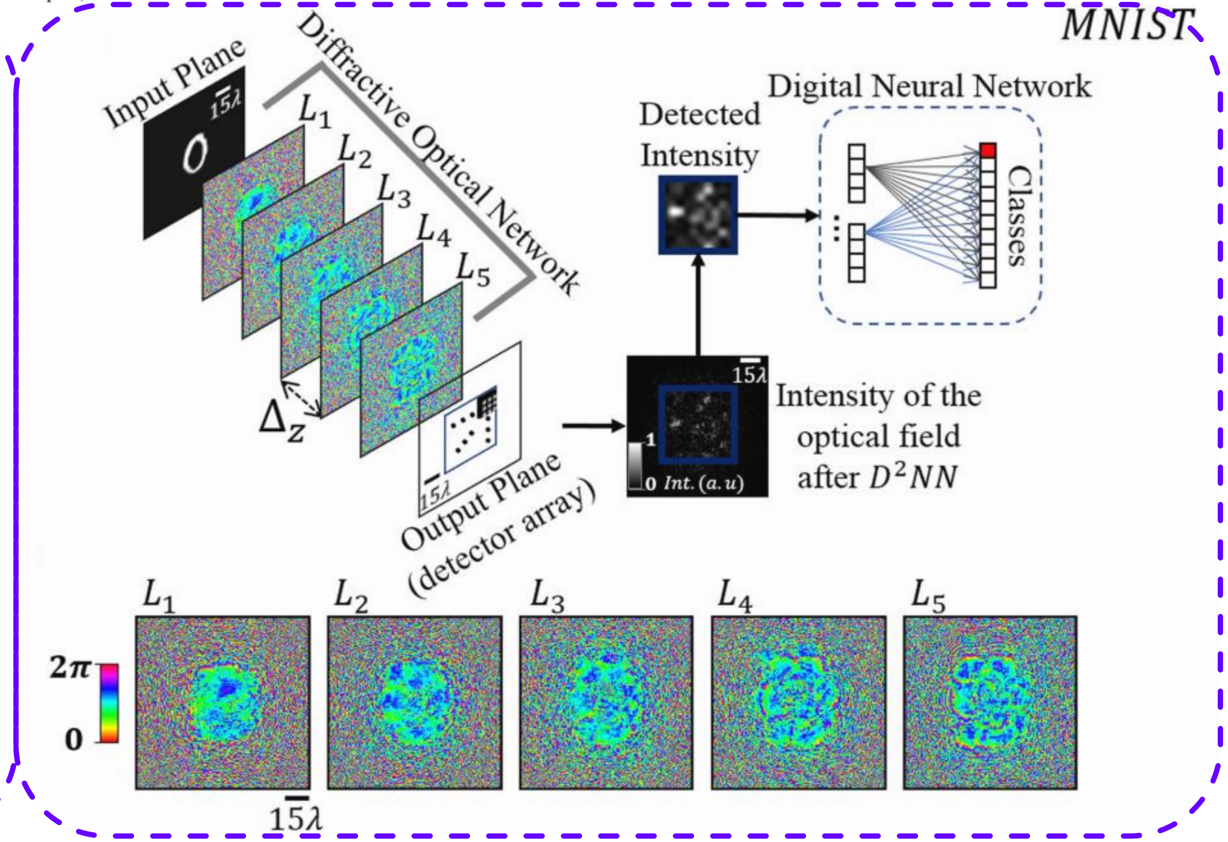
IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 26, NO. 1, JANUARY/FEBRUARY 2020 3700114

Analysis of Diffractive Optical Neural Networks and Their Integration With Electronic Neural Networks

Deniz Mengu, Yi Luo, Yair Rivenson, *Member, IEEE*, and Aydogan Ozcan, *Fellow, IEEE*

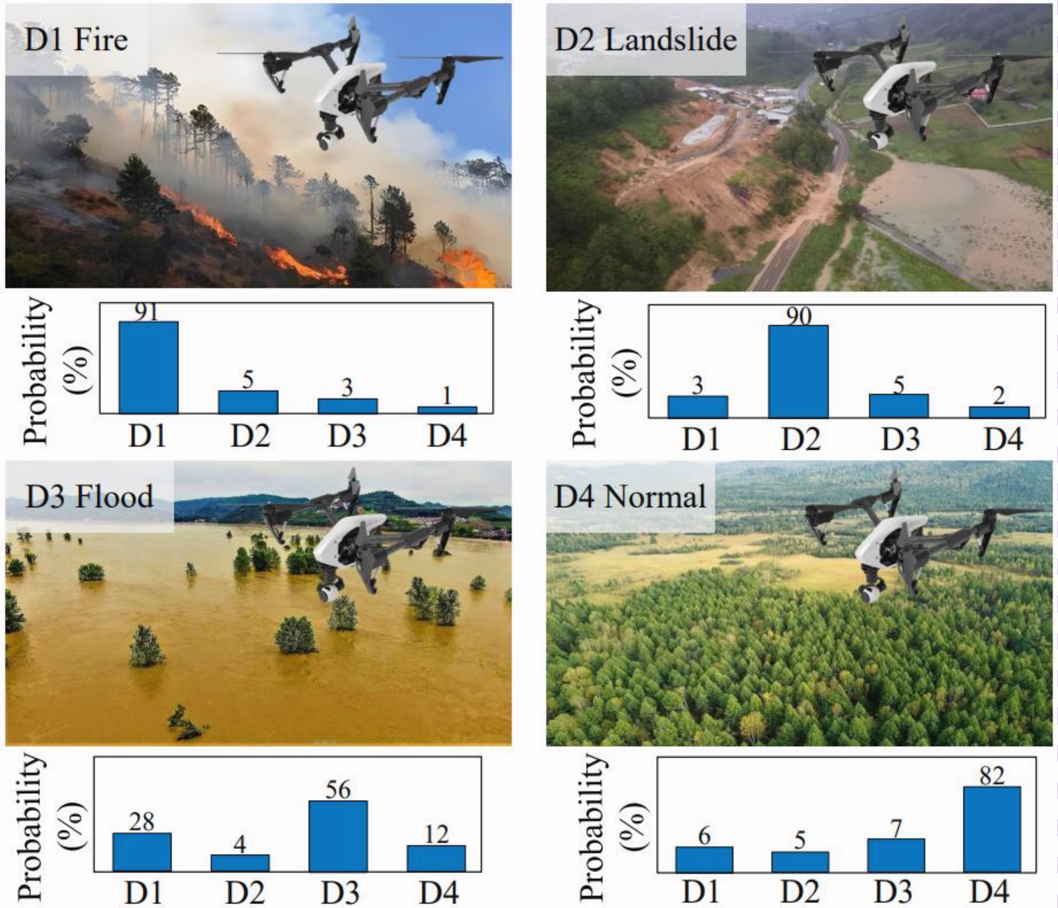
(Invited Paper)





➢ HOENN for Disaster Monitoring

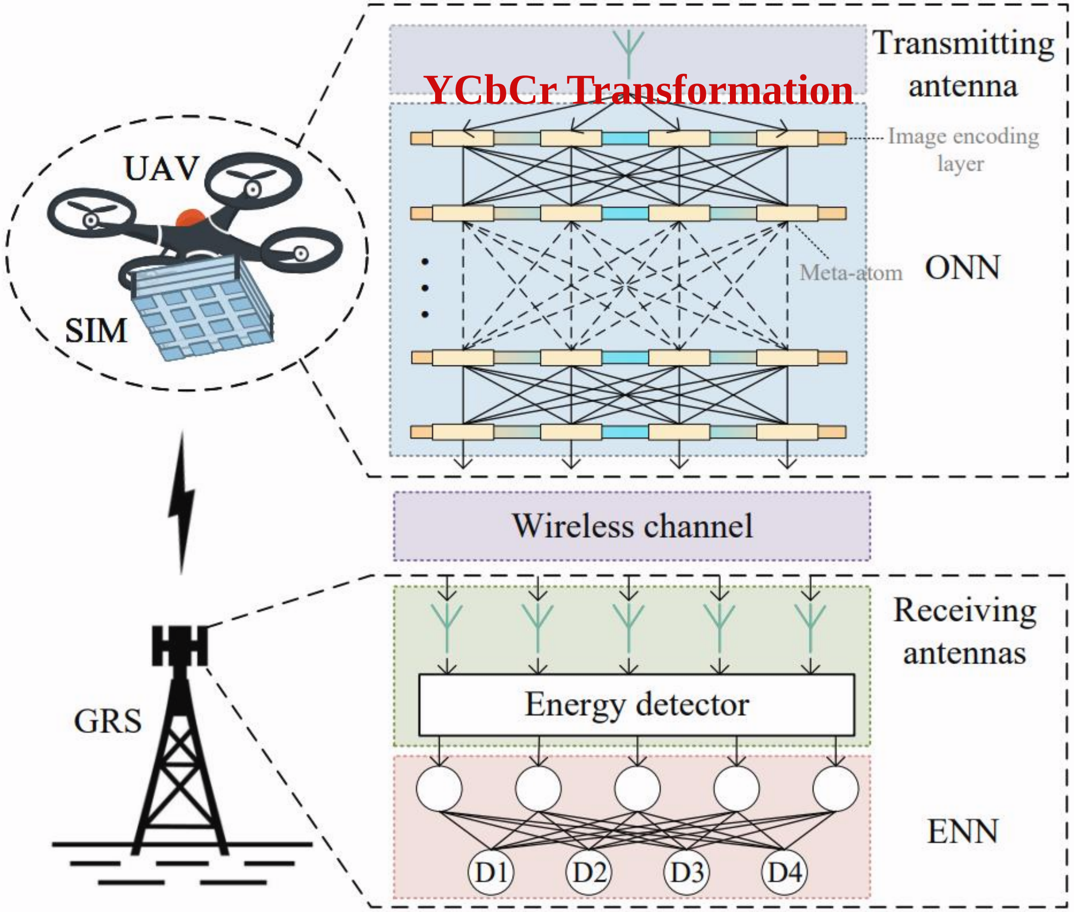
- The probability of disaster identified by HOENN



https://niloy193.github.io/Disaster-Dataset/

(a)

- An HOENN



(b)

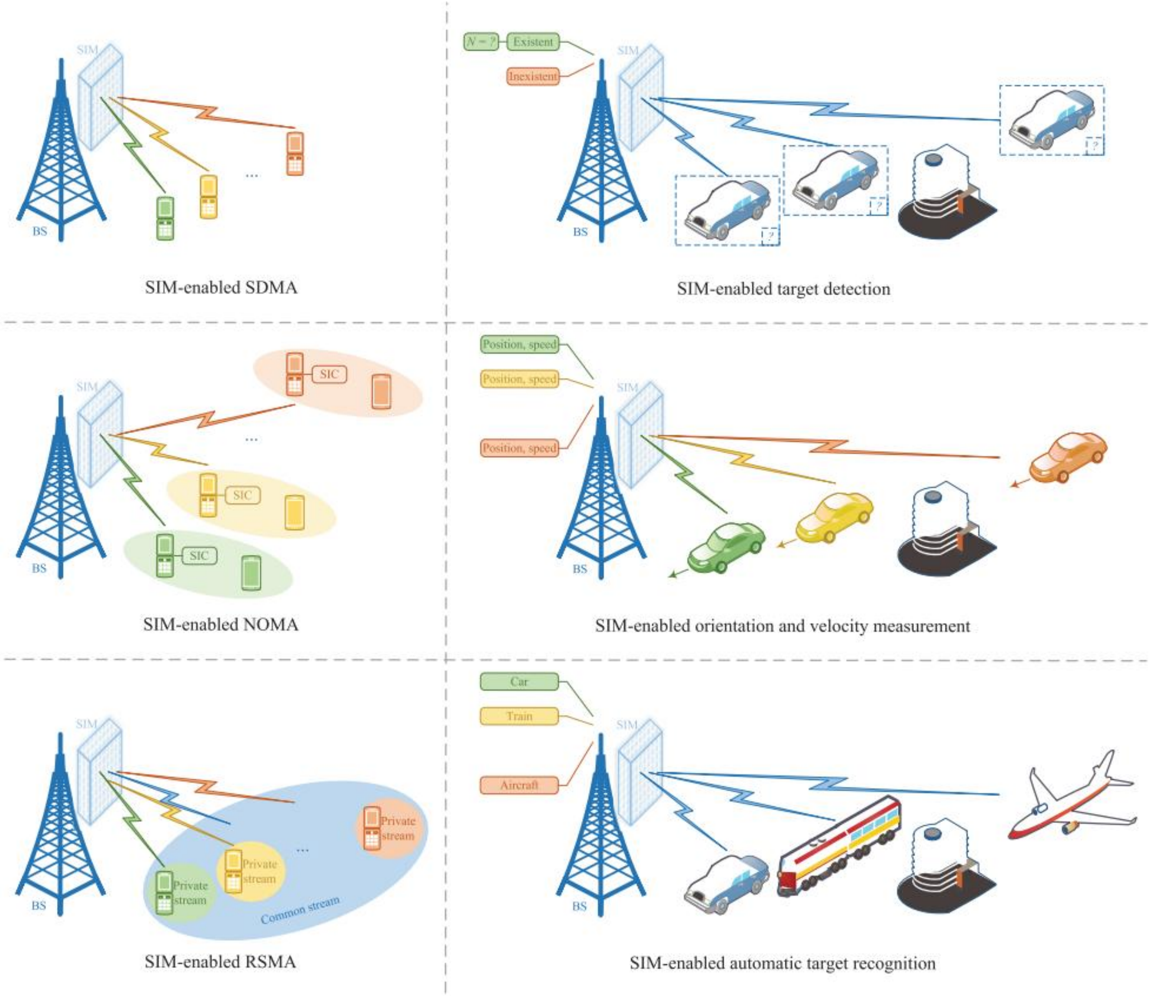
[R10] H. Liu, **J. An**, X. Jia, S. Lin, X. Yao, L. Gan, B. Clerckx, C. Yuen, M. Bennis, and M. Debbah, "**Stacked intelligent metasurfaces** for wireless sensing and communication: Applications and challenges," *arXiv preprint*, 2024.

Outline

- What is Stacked Intelligent Metasurface (SIM)
- Applications of SIM in Communication, Sensing and Computing Systems
    - Multiuser/MIMO Precoding
    - DOA Estimation
    - Semantic Encoding
- Hybrid Optical-Electronic Neural Network (HOENN)
- **Future Research Opportunities**

➢ Future Research Opportunities

SIM is capable of performing various signal processing tasks in wireless communication and sensing scenarios.



Wireless Communication

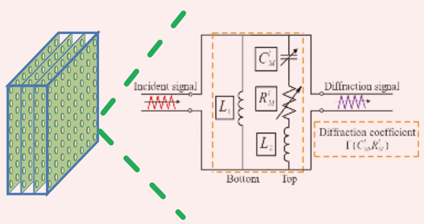
- ❑ NOMA/RSMA
- ❑ OFDM/OTFS
- ❑ CoMP/Cell-free networks
- ❑ Near-field communications/Holographic MIMO

Wireless Sensing

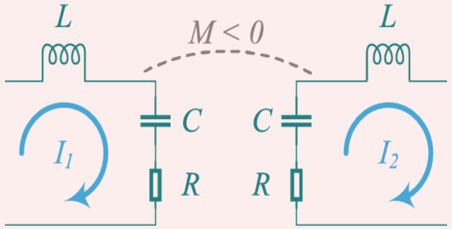
- ❑ Target detection
- ❑ Parameter estimation
- ❑ Target recognition
- ❑ Integrated sensing and communications

[R4] **J. An**, C. Yuen, C. Xu, H. Li, D. W. K. Ng, M. Di Renzo, M. Debbah, and L. Hanzo, "**Stacked intelligent metasurface**-aided MIMO transceiver design," *IEEE Wireless Commun.*, 2024, Early Access.

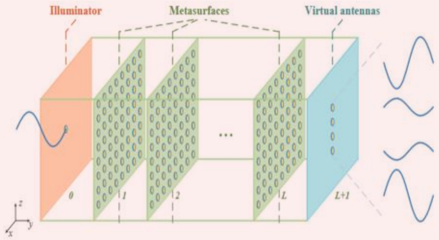
➢ Technical Challenges



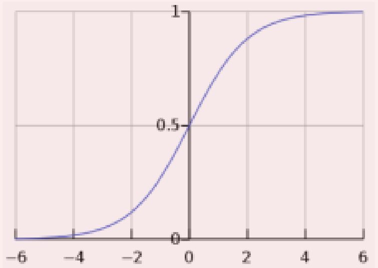
Tuning model



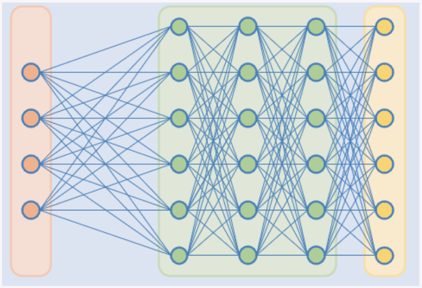
Element coupling



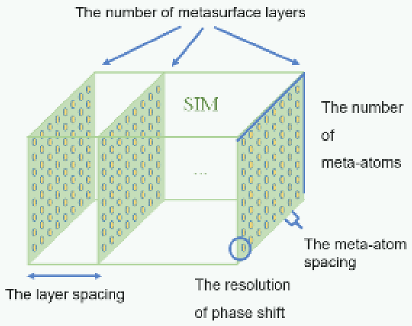
Propagation modeling



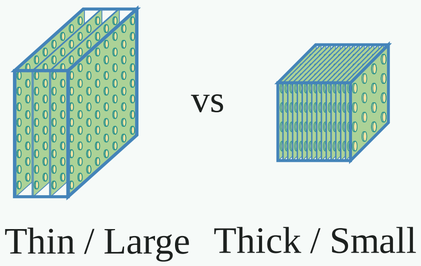
Non-linear response



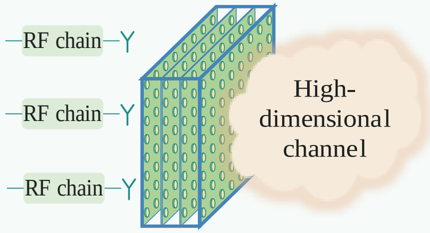
Diffractive neural network



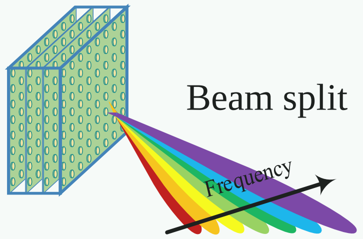
Large # parameters



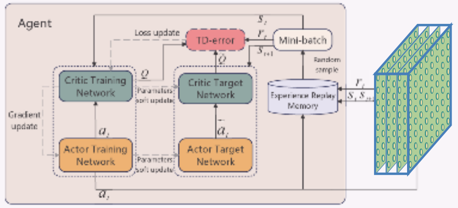
Hardware tradeoffs



Underdetermined system



Wideband signal



AI-driven orchestration

❑ Channel Estimation

[R12] 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.

[R13] Q.-U.-A. Nadeem, **J. An**, and A. Chaaban, "Hybrid digital-wave domain channel estimator for **stacked intelligent metasurface** enabled multi-user MISO systems," *arXiv preprint arXiv:2309.16204*, 2024.

❑ AI-Driven SIM Configuration

[R14] H. Liu, **J. An**, D. W. K. Ng, G. C. Alexandropoulos, and L. Gan, "DRL-based orchestration of multi-user MISO systems with **stacked intelligent metasurfaces**," *Proc. IEEE Int. Conf. Commun. (ICC)*, Denver, CO, USA, Jun. 2024.

❑ Satellite Communications

[R15] 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

❑ Cell-Free Networks

[R16] 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.*, 2024, Early Access

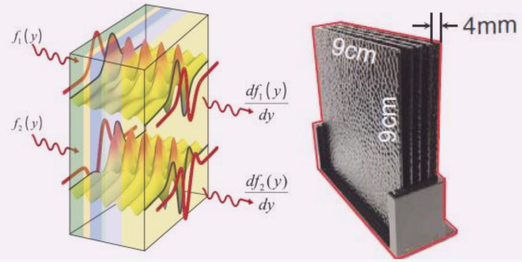
[R17] E. Shi, J. Zhang, Y. Zhu, **J. An**, C. Yuen and B. Ai, "Harnessing **stacked intelligent metasurface** for enhanced cell-free massive MIMO systems: A low-power and cost approach," *arXiv preprint*, 2024.

❑ Physical Layer Security

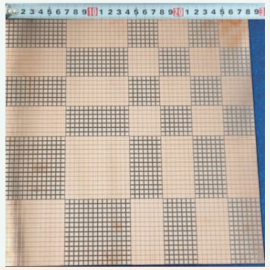
[R18] H. Niu, X. Lei, **J. An**, L. Zhang, and C. Yuen, "On the efficient design of **stacked intelligent metasurfaces** for secure SISO transmission," *arXiv preprint*, 2024.

➢ SIM: Applications & Benefits

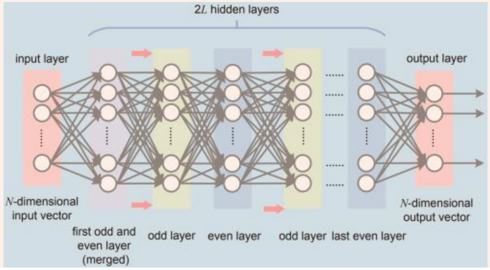
Wave-based computing
Optically computing speed



Programmable metasurface
Energy efficient tuning ability

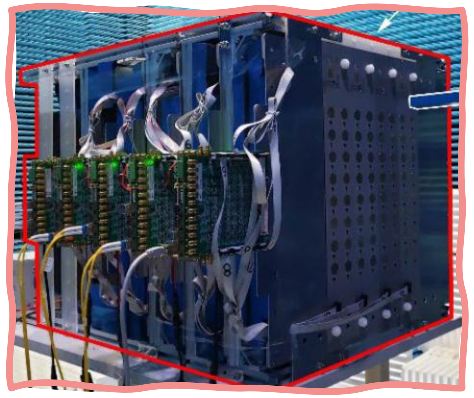


Deep neural networks
Powerful computing capability



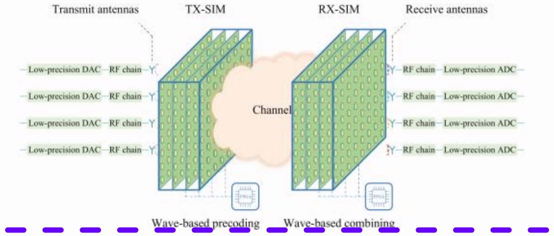
All signal processing are accomplished as the electromagnetic waves propagate through the SIM!

SIM

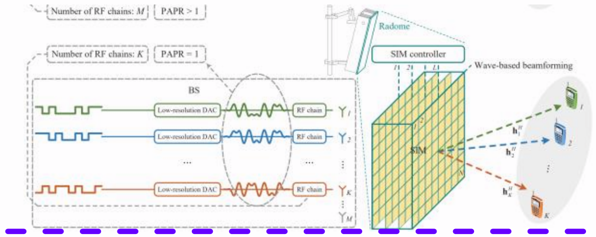


HOENN

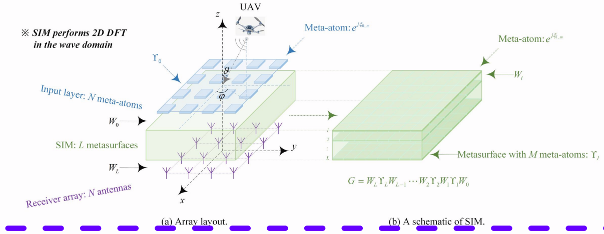
Low DAC/ADC resolution



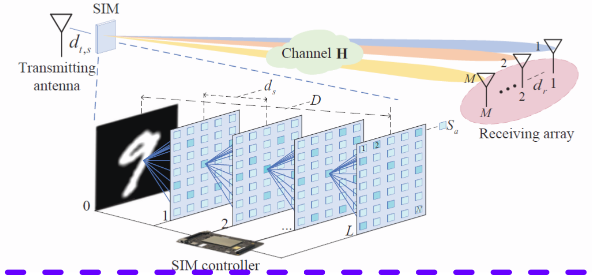
Reduced number of RF chains



Low-cost energy detection



Reduced data traffic



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[R1] **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.

[R2] **J. An**, M. Di Renzo, M. Debbah, and C. Yuen, "**Stacked intelligent metasurfaces** for multiuser beamforming in the wave domain," *Proc. IEEE Int. Conf. Commun. (ICC)*, Rome, Italy, May 2023, pp. 2834 – 2839. **(ICC 2023 Best Paper Award)**

[R3] **J. An**, M. Di Renzo, M. Debbah, H. V. Poor, and C. Yuen, "**Stacked intelligent metasurfaces** for multiuser downlink beamforming in the wave domain," *arXiv preprint arXiv:2309.02687*, 2024.

[R4] **J. An**, C. Yuen, C. Xu, H. Li, D. W. K. Ng, M. Di Renzo, M. Debbah, and L. Hanzo, "**Stacked intelligent metasurface**-aided MIMO transceiver design," *IEEE Wireless Commun.*, 2024, Early Access.

[R5] **J. An**, C. Yuen, Y. Guan, M. Di Renzo, M. Debbah, H. V. Poor, and L. Hanzo, "**Stacked intelligent metasurface** performs a 2D DFT in the wave domain for DOA estimation," *Proc. IEEE Int. Conf. Commun. (ICC)*, Denver, CO, USA, Jun. 2023, pp. 1 – 6.

[R6] **J. An**, C. Yuen, Y. 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.*, 2024, Early Access.

[R7] **J. An**, C. Yuen, L. Dai, M. Di Renzo, M. Debbah, and L. Hanzo, "Near-field communications: Research advances, potential, and challenges," IEEE Wireless Commun., vol. 31, no. 3, pp. 100-107, Jun. 2024.

[R8] G. Huang, **J. An**, Z. Yang, and L. Gan, "**Stacked intelligent metasurfaces** for image recognition task-oriented semantic communications," *arXiv preprint*, 2024.

[R9] N. U. Hassan, **J. An**, M. Di Renzo, M. Debbah and C. Yuen, "Efficient beamforming and radiation pattern control using **stacked intelligent metasurfaces**," *IEEE Open J. Commun. Society*, vol. 5, pp. 599-611, 2024.

[R10] H. Liu, **J. An**, X. Jia, S. Lin, X. Yao, L. Gan, B. Clerckx, C. Yuen, M. Bennis, and M. Debbah, "**Stacked intelligent metasurfaces** for wireless sensing and communication: Applications and challenges," *arXiv preprint*, 2024.

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[R11] H. Niu, **J. An**, A. Papazafeiropoulos, L. Gan, S. Chatzinotas, and M. Debbah, "**Stacked intelligent metasurfaces** for integrated sensing and communications," *arXiv preprint*, 2024.

[R12] 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.

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[R14] H. Liu, **J. An**, D. W. K. Ng, G. C. Alexandropoulos, and L. Gan, "DRL-based orchestration of multi-user MISO systems with **stacked intelligent metasurfaces**," *Proc. IEEE Int. Conf. Commun. (ICC)*, Denver, CO, USA, Jun. 2023, pp. 1 – 6.

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[R18] H. Niu, X. Lei, **J. An**, L. Zhang, and C. Yuen, "On the efficient design of **stacked intelligent metasurfaces** for secure SISO transmission," *arXiv preprint*, 2024.

Many thanks!

Q & A