Reconfigurable Antennas for Wireless Communications: Hardware Prototyping, Architecture Design, and Signal Processing

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Joint work with **Ruiqi Wang**, Prof. **Atif Shamim**, Prof. **Tareq Y. Al-Naffouri**, Prof. **MD Jahangir Hossain**, and Prof. **Anas Chaaban**.

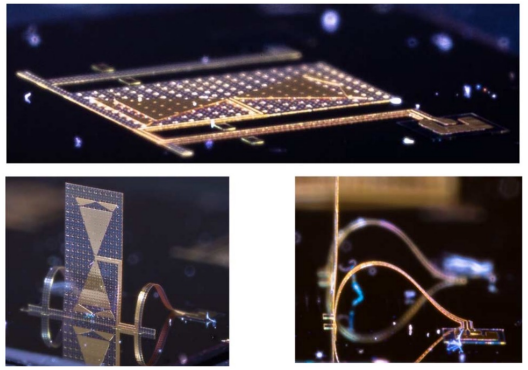
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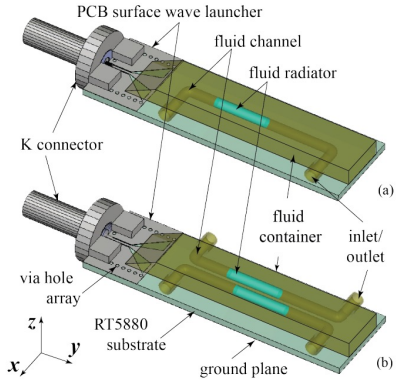
Reconfigurable Antennas

Antennas able to reconfigure their EM characteristics



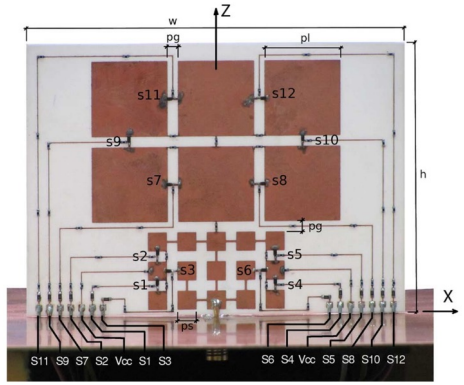
DOI: 10.1109/TAP.2013.2241720

(a) Pattern-Reconfigurable AoC on Movable Plate



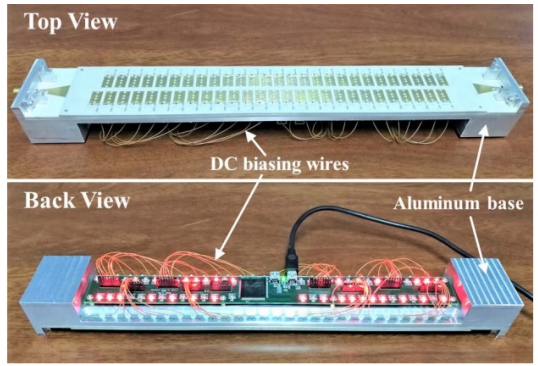
DOI: 10.48550/arXiv.2405.09663

(c) Fluid-Based Pattern-Reconfigurable Antenna



DOI: 10.1109/TAP.2012.2189739

(d) Pixel-Based Pattern-Reconfigurable Antenna



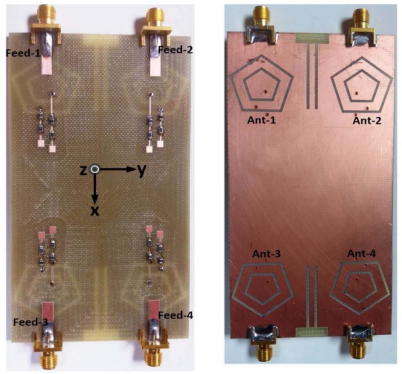
DOI: 10.1109/TAP.2019.2907636

(e) Leaky-Wave Pattern-Reconfigurable Antenna



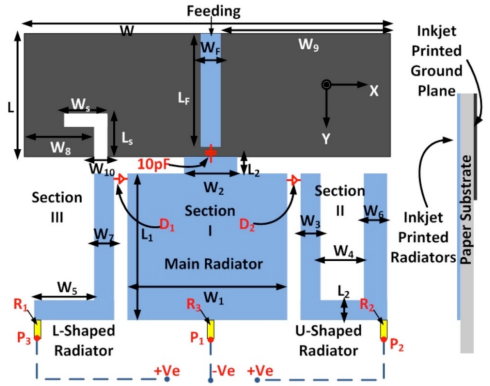
DOI: 10.1109/TAP.2012.2237003

(f) Pattern-Reconfigurable Lens



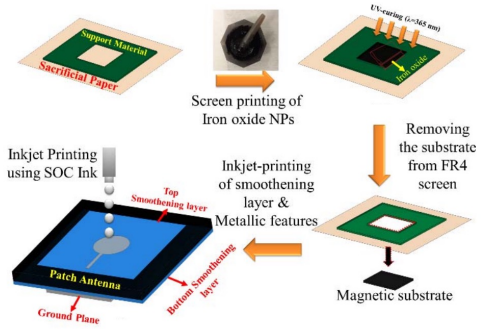
DOI: 10.1109/TAP.2018.2839970

(b) Varactor-Based Frequency-Reconfigurable Antenna



DOI: 10.1109/LAWP.2018.2861386

(a) PIN-Based Frequency-Reconfigurable Antenna



DOI: 10.1109/TAP.2018.2846796

(e) Polarization-Reconfigurable Antenna on Partially Magnetized Ferrite Substrate

[1] P. Zheng, R. Wang, Y. Zhang, M. J. Hossain, A. Chaaban, A. Shamim, and T. Y. Al-Naffouri, “Reconfigurable Antennas for Next-Generation Wireless Communications: Technologies, Prototypes, Architectures, and Signal Processing,” arXiv preprint arXiv:2506.00657, 2025.

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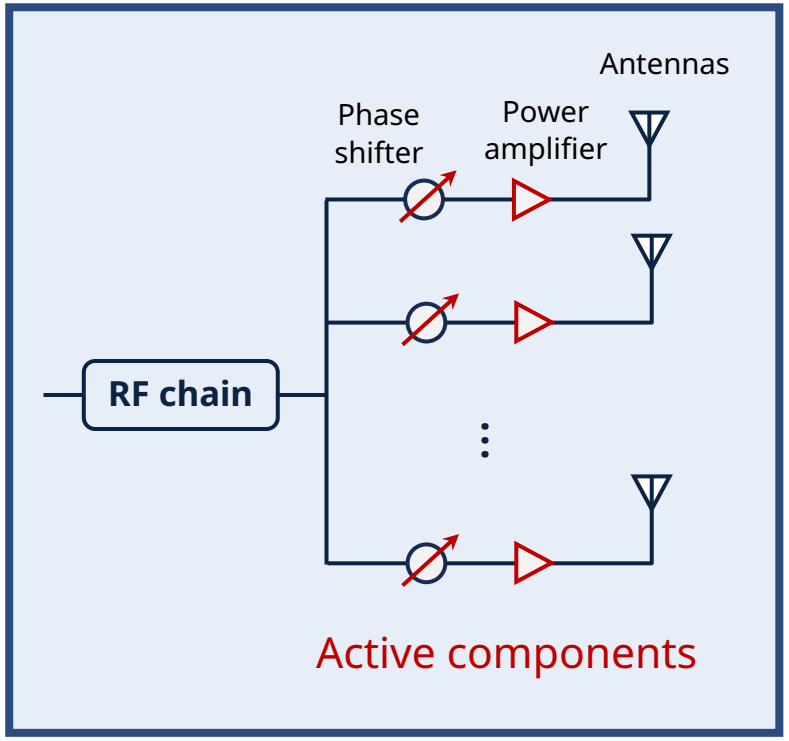
Motivation 1: Energy-Efficiency

Deployment Scenarios For 6G RAN Evaluation in 3GPP TR 38.914 [1]

Carrier Frequency	System Bandwidth	BS Antenna Elements
700 MHz	Up to 60 MHz	Up to 64
2 GHz	Up to 200 MHz	Up to 288
4 GHz	Up to 300 MHz	Up to 576
7 GHz	Up to 400 MHz	Up to 2304
15 GHz	Up to 400 MHz	Up to 2304
30 GHz	Up to 1 GHz	Up to 4096

Energy consumption is becoming a major concern!

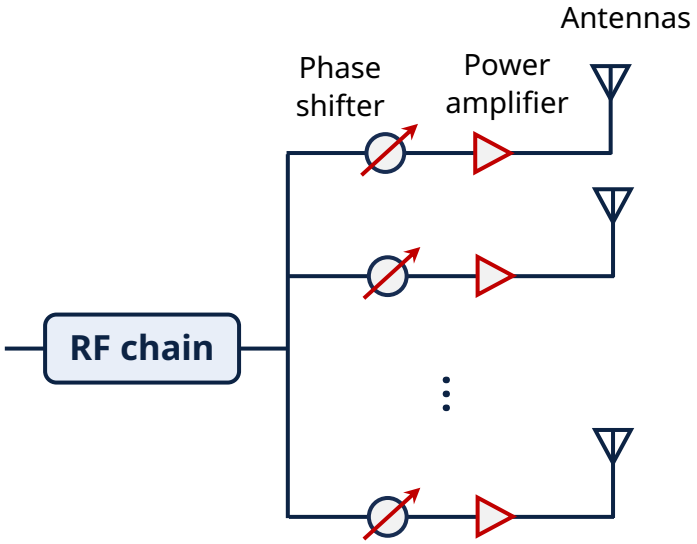
An Analog Transmitter



[1] “Study on 6G Scenarios and Requirements,” 3rd Generation Partnership Project (3GPP), Technical Specification Group Radio Access Network, 3GPP Technical Report TR 38.914 V0.2.0, Sep. 2025, (Release 20).

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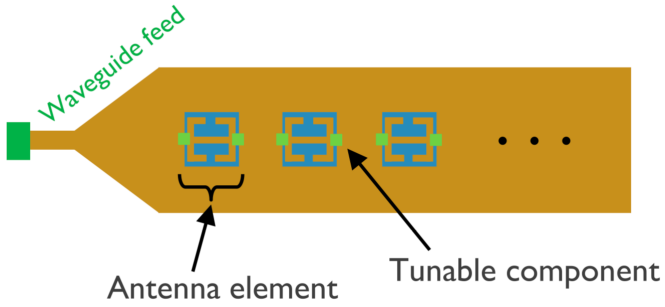
Motivation 1: Energy-Efficiency

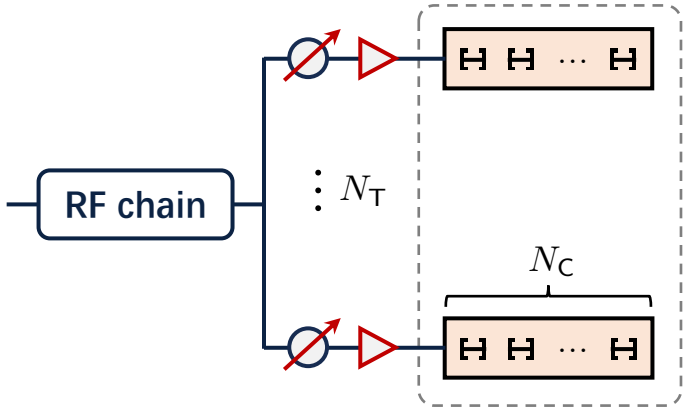


Active components

Looking for solutions from antenna technologies.

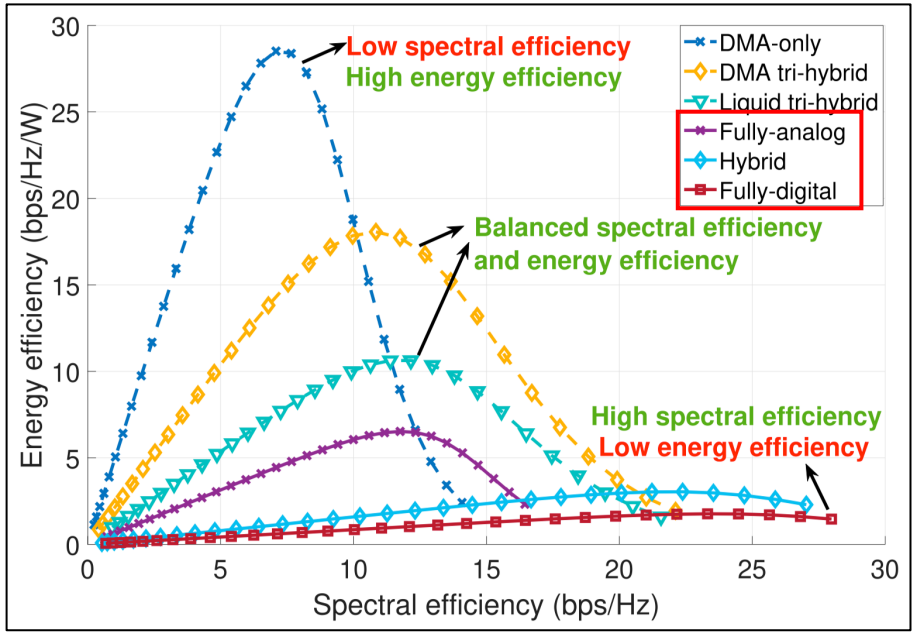
Dynamic metasurface antenna (DMA) [1]





In total $N_T N_C$ effective elements.

Reconfigurable antennas enhance energy efficiency!

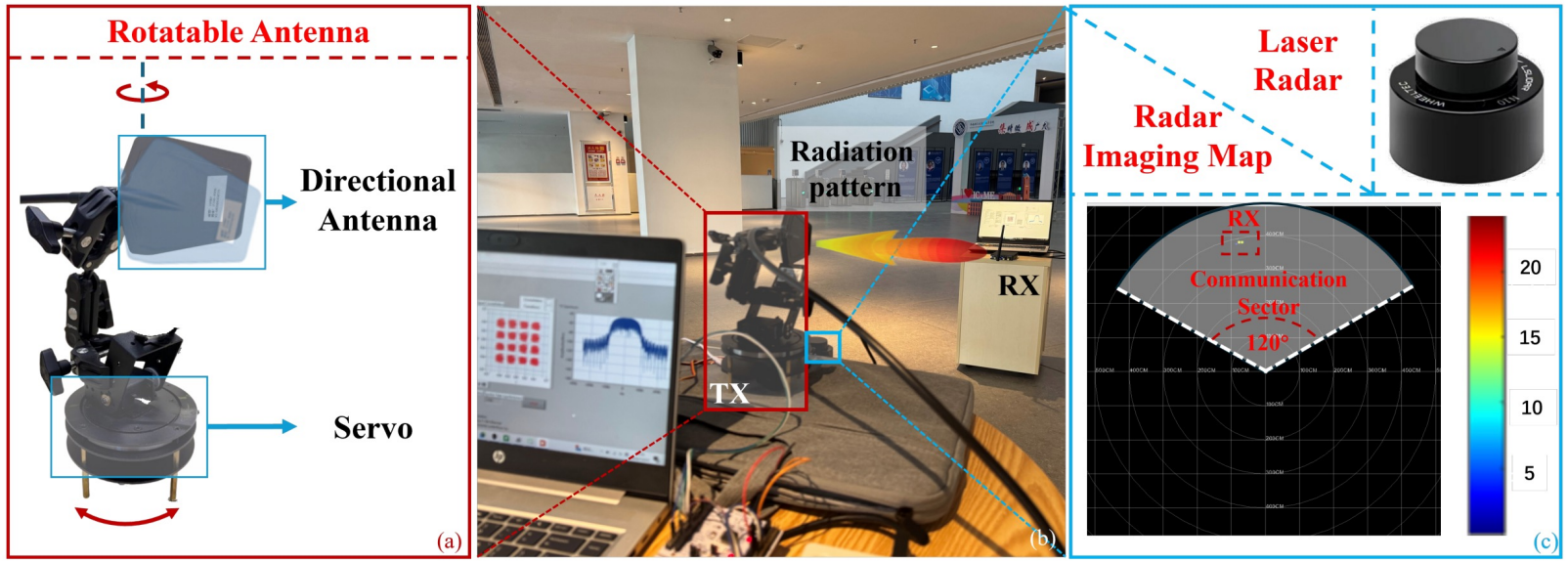


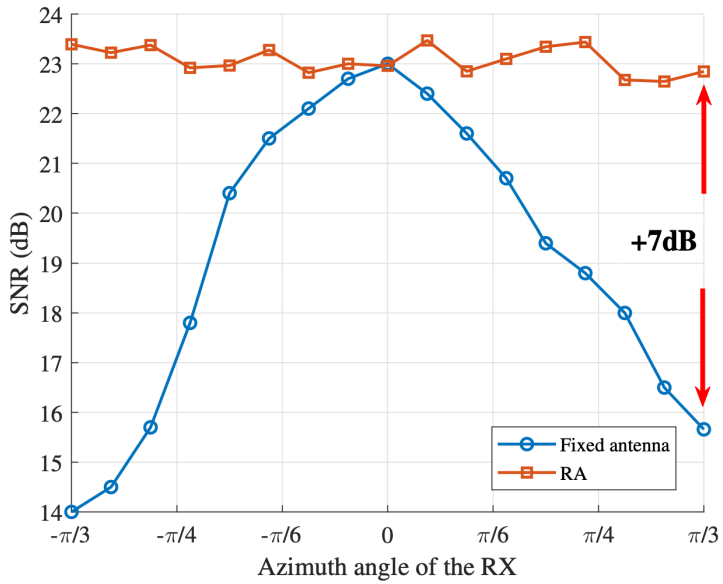
[1] R. W. Heath, J. Carlson, N. V. Deshpande, M. R. Castellanos, M. Akrout and C. -B. Chae, "The Tri-Hybrid MIMO Architecture," in IEEE Wireless Communications, vol. 33, no. 1, pp. 199-206, Feb. 2026.

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Motivation 2: Adaptivity and Coverage

Rotatable antennas enjoy boresight gain adaptively [1]





Relies on heavy mechanical moving system

→ Very hard to form an **antenna array**

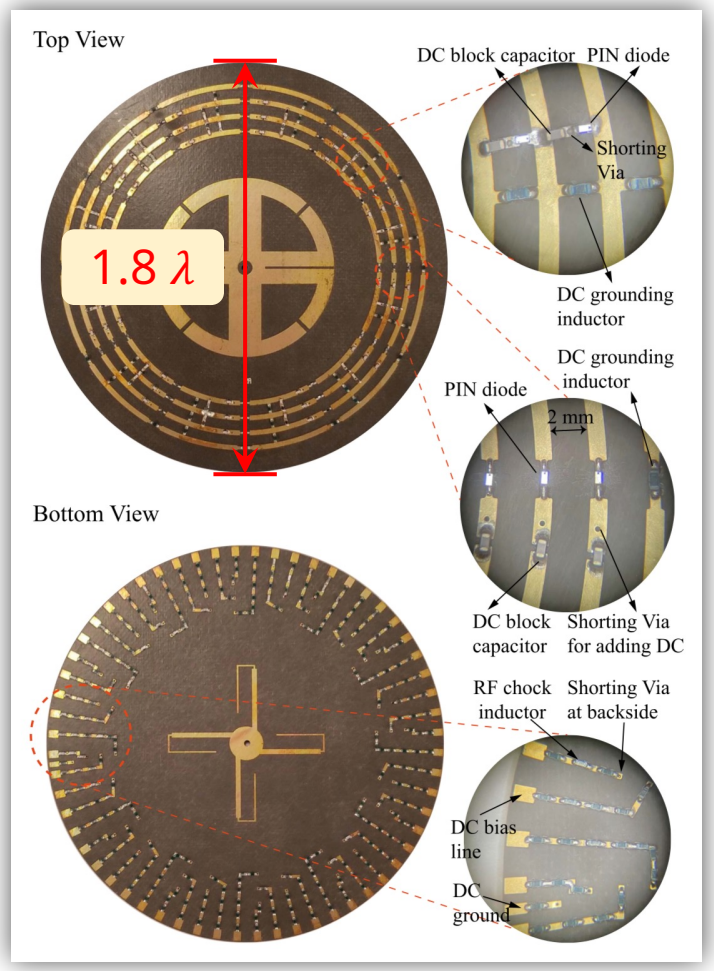
⇨

Do we really need to physically rotate antennas?

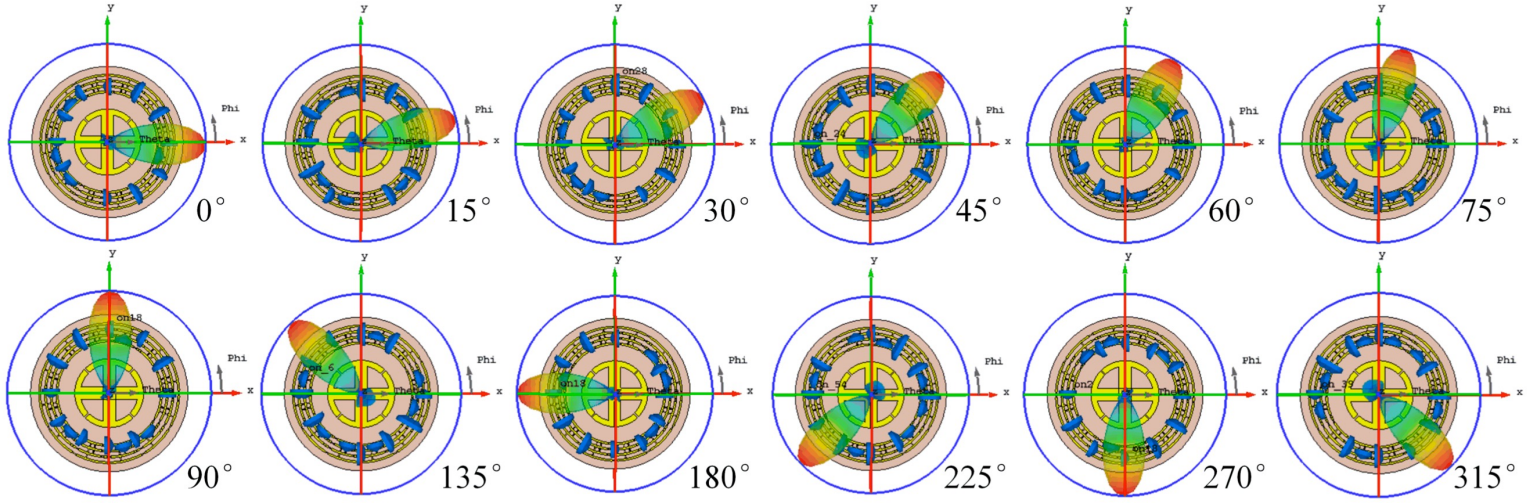
[1] Q. Dai et al., "A Demo of Radar Sensing Aided Rotatable Antenna for Wireless Communication," 5th International Conference on Electronics, Circuits and Information Engineering (ECIE), Guangzhou, China, 2025, pp. 205-208.

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Pattern-Reconfigurable Antenna (PRA)



Parasitic Pixel-based PRA for 5 GHz [1]



- Reconfigure radiation pattern by changing the pixel connections.
- Electronically reconfigurable without mechanical rotation.
- Physical size is still too large for array integration.

[1] Y. Zhang, Z. Han, S. Tang, S. Shen, C. -Y. Chiu and R. Murch, "A Highly Pattern-Reconfigurable Planar Antenna With 360° Single- and Multi-Beam Steering," in IEEE Transactions on Antennas and Propagation, vol. 70, no. 8, pp. 6490-6504, Aug. 2022.

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Pattern-Reconfigurable Antenna (PRA)

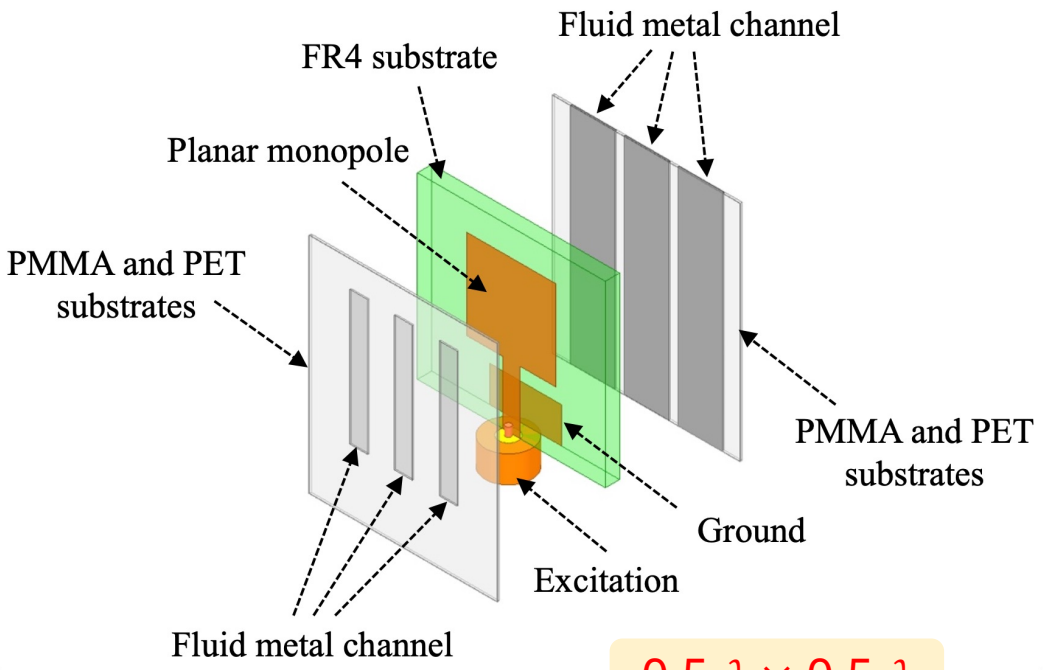
Ref.	Type & Technique	Reconfigurable Mechanism	Antenna Element Size ($\lambda \times \lambda$)
[11]	On-chip Antenna; Movable plate	MEMS-based movable plate	0.59×0.51
[12]	Metal cavity; Multimode resonances	Mechanically changing the metal cover wall	0.93×2.73
[13]	Liquid-based; Surface-wave fluid antenna	Micro-pump through silicon tubes	2.86×0.86
[14]	Pixel-based; Multiple sized pixels	PIN diode	0.735×0.53
[21]	Slot-based; MIMO antenna	Varactor diode	0.65×0.33
[18]	Lens antenna; Luneburg lens with multisources	MMIC switch	5.6×5.6
[38]	Dielectric resonator antenna; Odd/Even mode	PIN diode	0.65×0.81
[39]	Liquid-based; Directors and reflectors with planar monopole	Liquid metal controlled by pumping machine	0.5×0.5

[1] P. Zheng, R. Wang, Y. Zhang, M. J. Hossain, A. Chaaban, A. Shamim, and T. Y. Al-Naffouri, "Reconfigurable Antennas for Next-Generation Wireless Communications: Technologies, Prototypes, Architectures, and Signal Processing," arXiv preprint arXiv:2506.00657, 2025.

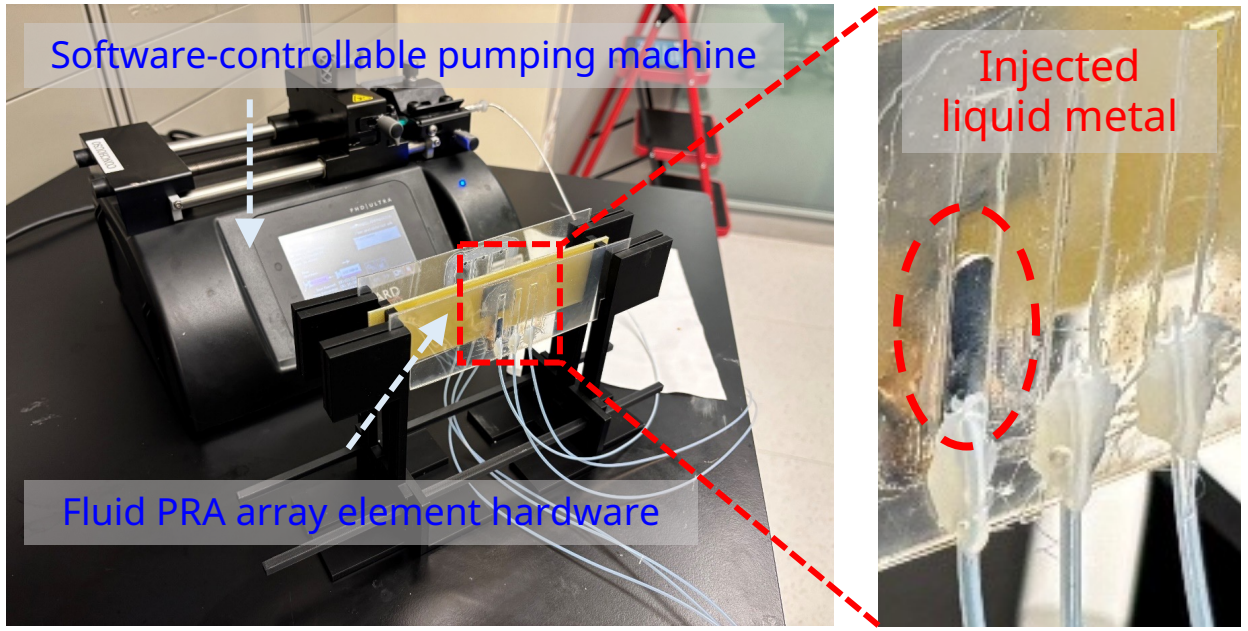
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A Prototyping Study: Fluid Pattern-Reconfigurable Antenna

- Each fluid metal channel can be filled and emptied using liquid metal and a pumping machine.
- The radiation pattern of the unit can be changed by the parasitic coupling effect [1].



$0.5\,\lambda \times 0.5\,\lambda$



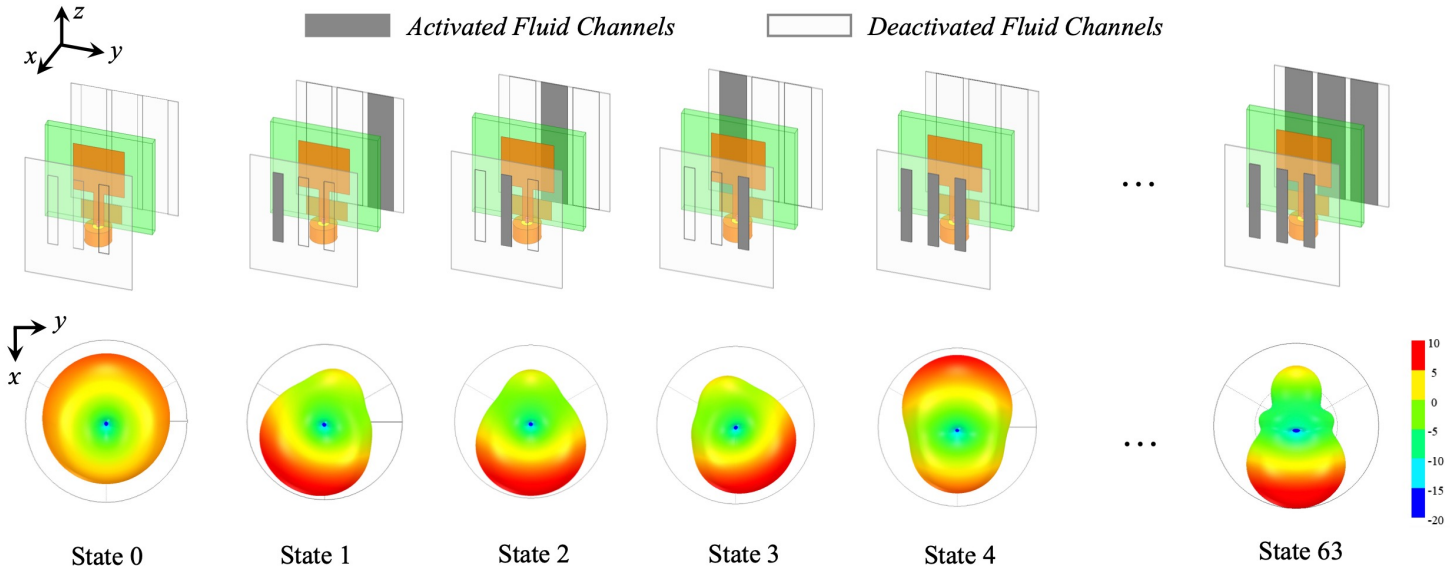
Galinstan liquid metal alloy: 68.5% gallium (Ga), 21.5% indium (In), and 10% tin (Sn)

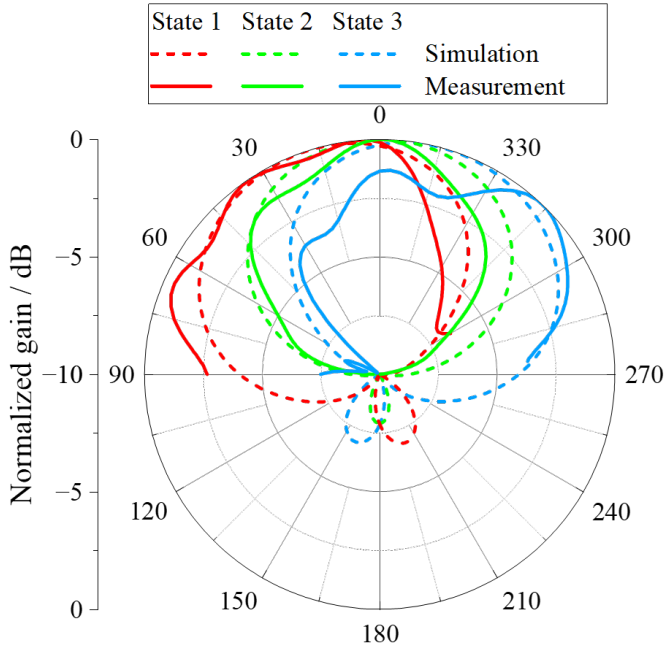
[1] R. Wang, P. Zheng et al., "Electromagnetically Reconfigurable Fluid Antenna System for Wireless Communications: Design, Modeling, Algorithm, Fabrication, and Experiment," in IEEE Journal on Selected Areas in Communications, vol. 44, pp. 1464-1479, 2026.

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A Prototyping Study: Fluid Pattern-Reconfigurable Antenna

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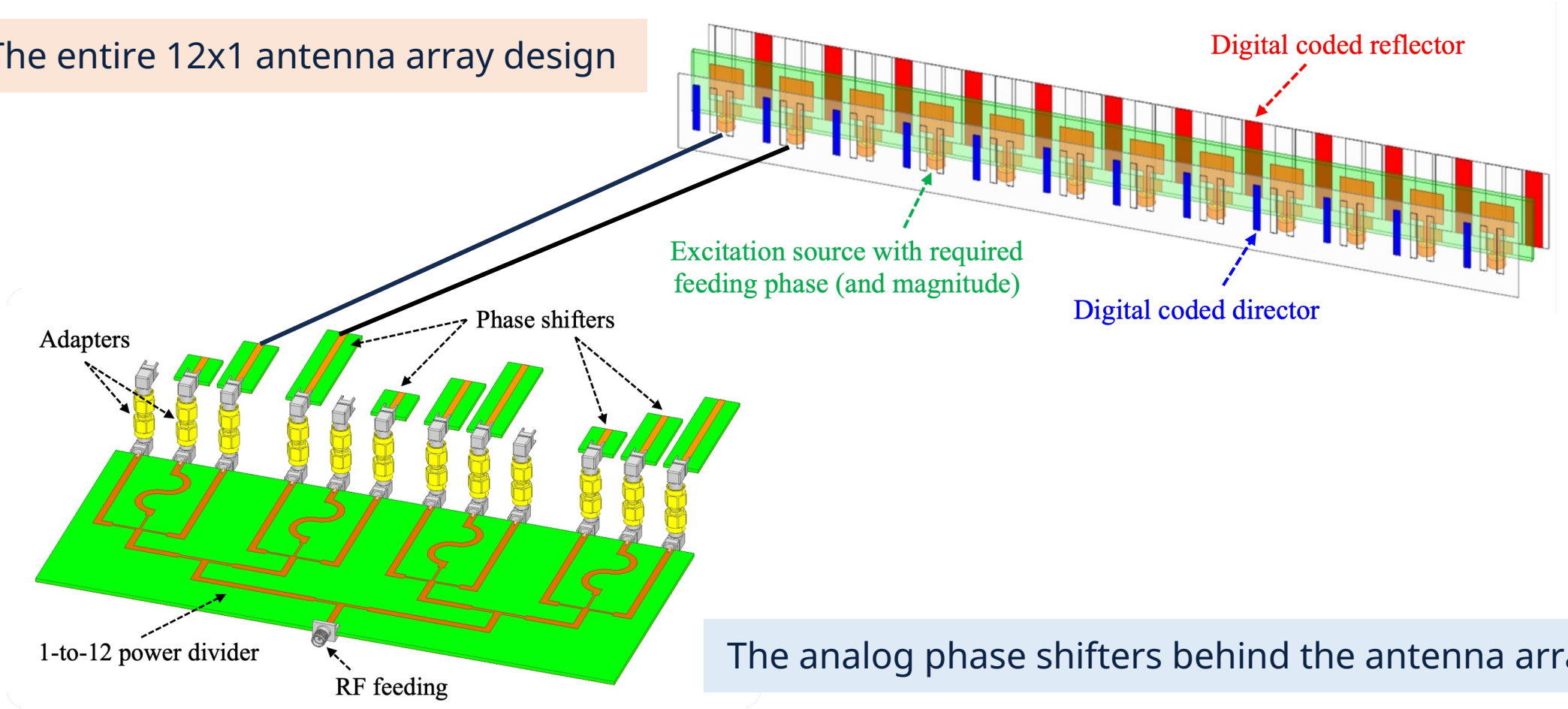


[1] R. Wang, P. Zheng et al., "Electromagnetically Reconfigurable Fluid Antenna System for Wireless Communications: Design, Modeling, Algorithm, Fabrication, and Experiment," in IEEE Journal on Selected Areas in Communications, vol. 44, pp. 1464-1479, 2026.

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A Prototyping Study: Fluid Pattern-Reconfigurable Antenna

The entire 12x1 antenna array design



The analog phase shifters behind the antenna array

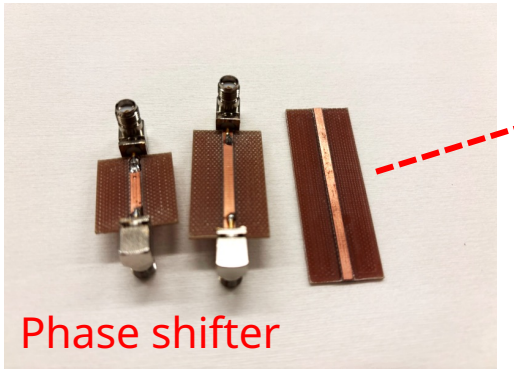
[1] R. Wang, P. Zheng et al., "Electromagnetically Reconfigurable Fluid Antenna System for Wireless Communications: Design, Modeling, Algorithm, Fabrication, and Experiment," in IEEE Journal on Selected Areas in Communications, vol. 44, pp. 1464-1479, 2026.

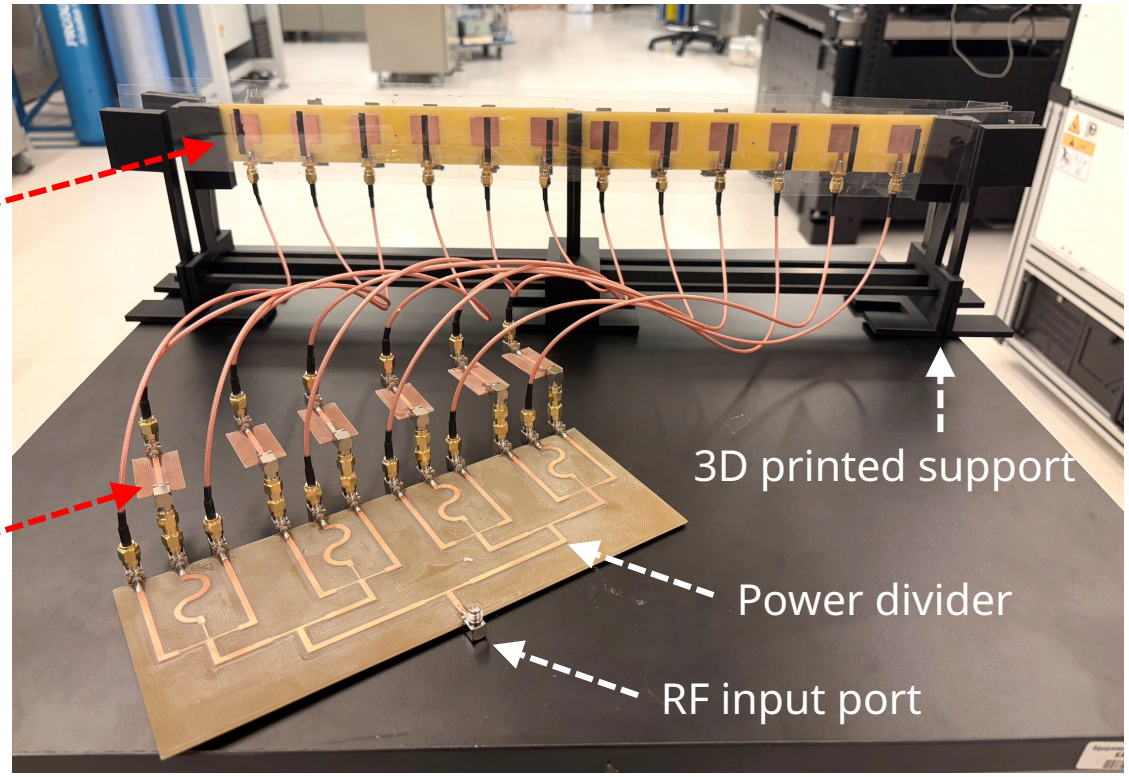
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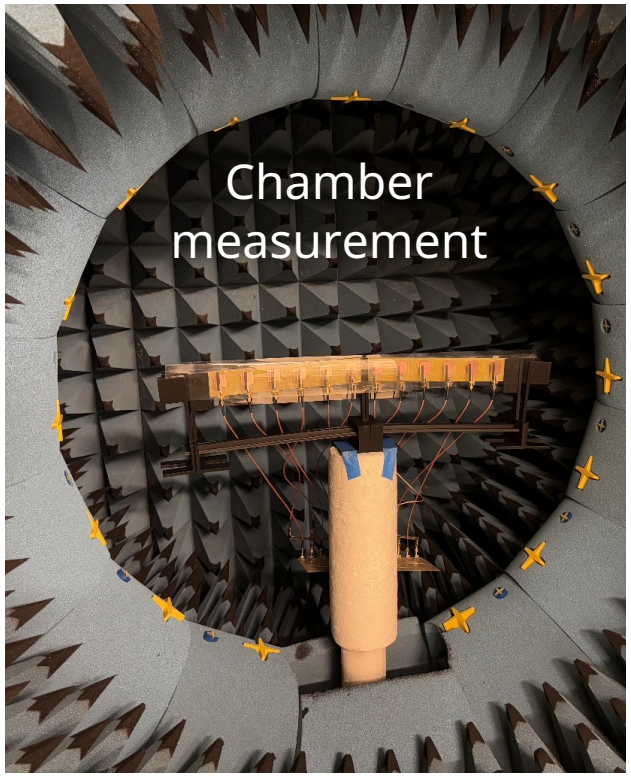
A Prototyping Study: Fluid Pattern-Reconfigurable Antenna

The fabricated prototype at KAUST (3.55 GHz) [1]





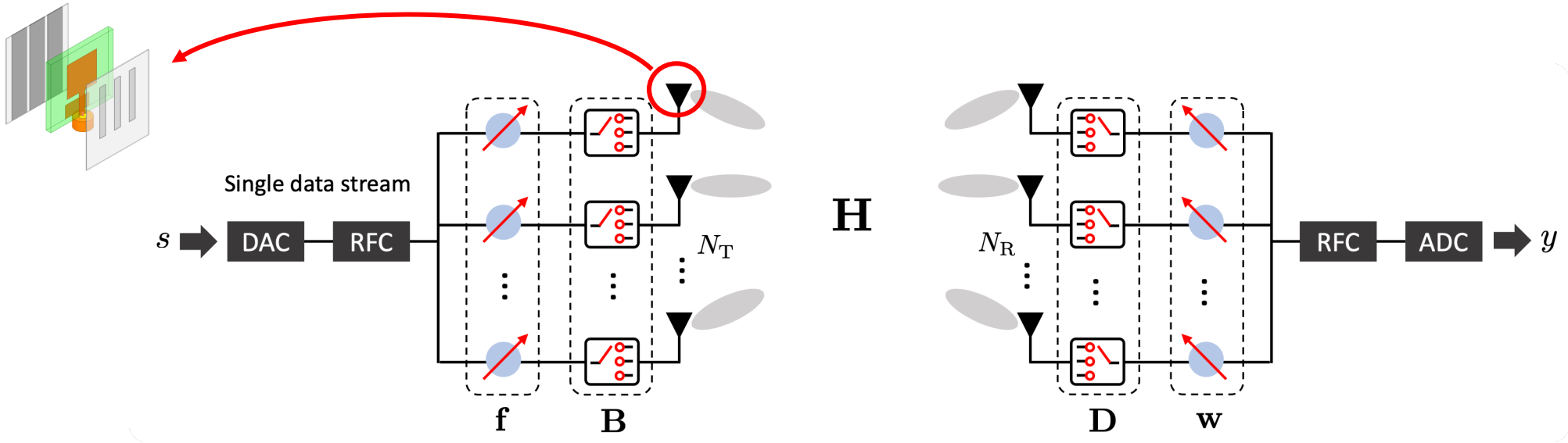




[1] R. Wang, P. Zheng et al., "Electromagnetically Reconfigurable Fluid Antenna System for Wireless Communications: Design, Modeling, Algorithm, Fabrication, and Experiment," in IEEE Journal on Selected Areas in Communications, vol. 44, pp. 1464-1479, 2026.

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A Prototyping Study: Fluid Pattern-Reconfigurable Antenna



Analog phase shifters

Antenna state selection

Formulated beamforming problem [1]:

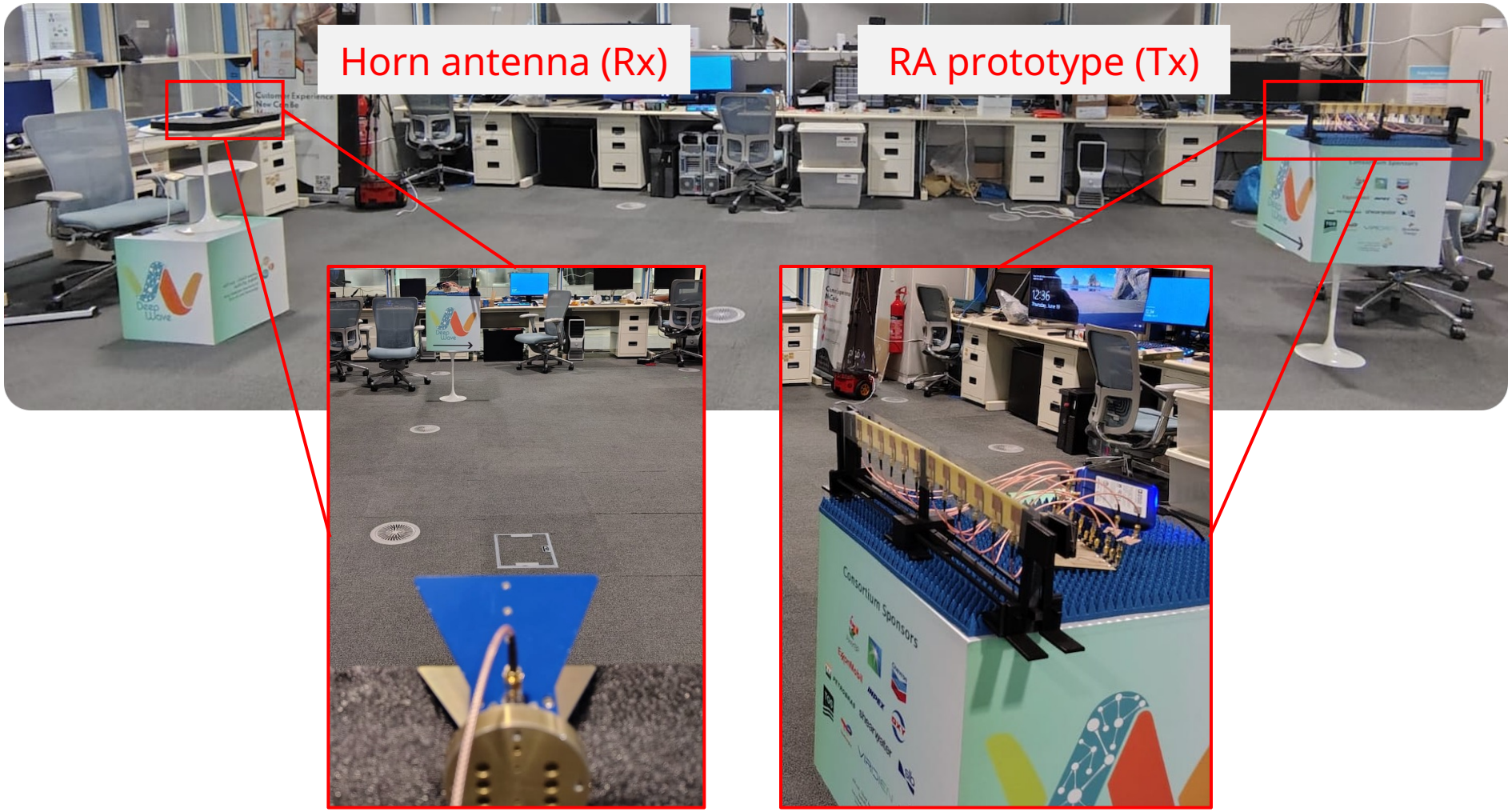
$$\max_{\mathbf{f},\mathbf{w},\mathbf{B},\mathbf{D}} \quad \log_2\left(1+\frac{\gamma P_{\mathrm{T}}|\mathbf{w}^{\mathsf{H}}\mathbf{D}\mathbf{H}_{\mathrm{EM}}\mathbf{B}^{\mathsf{T}}\mathbf{f}|^2}{\sigma^2}\right),$$
$$\text{s.t.} \quad |f_i|^2=\frac{1}{N_{\mathrm{T}}},\ |w_j|^2=\frac{1}{N_{\mathrm{R}}},\ (7),\ (9),\ (10),$$

[1] R. Wang, P. Zheng et al., "Electromagnetically Reconfigurable Fluid Antenna System for Wireless Communications: Design, Modeling, Algorithm, Fabrication, and Experiment," in IEEE Journal on Selected Areas in Communications, vol. 44, pp. 1464-1479, 2026.

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A Prototyping Study: Fluid Pattern-Reconfigurable Antenna

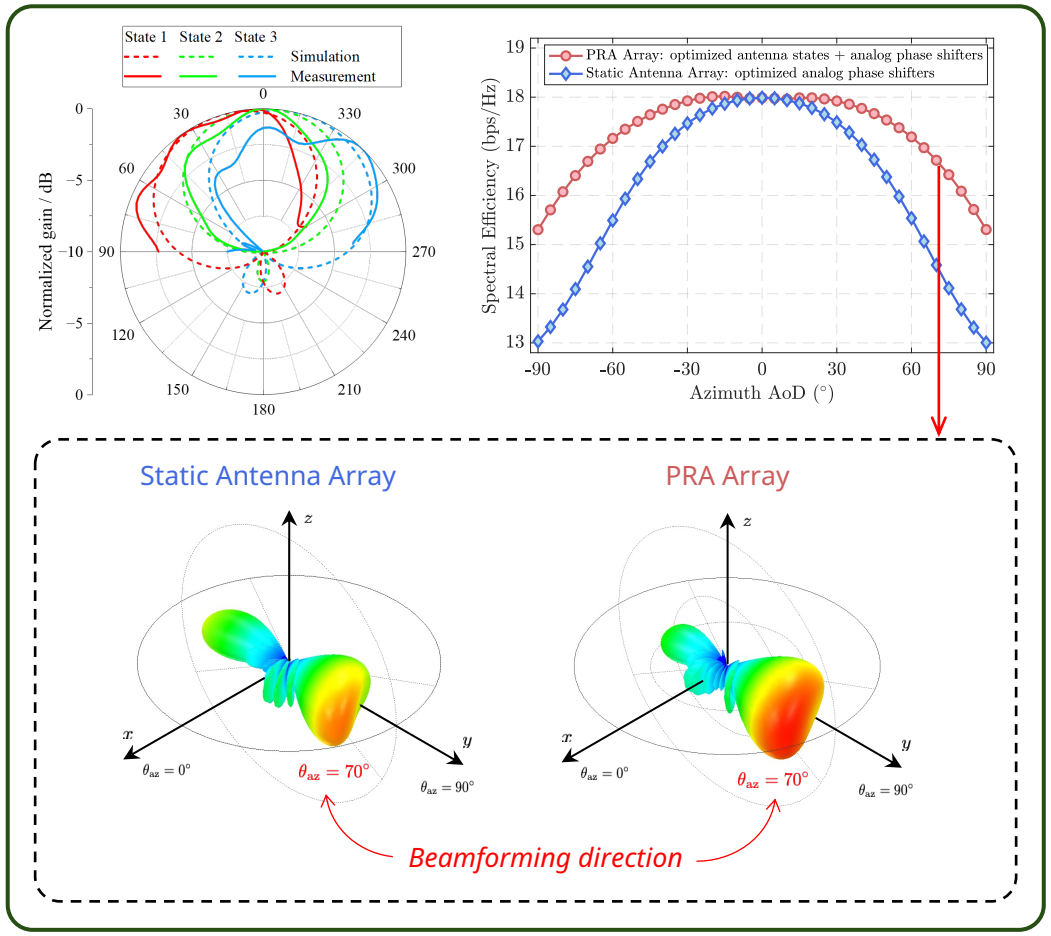
Measurement setup (3.55 GHz, 4-QAM)



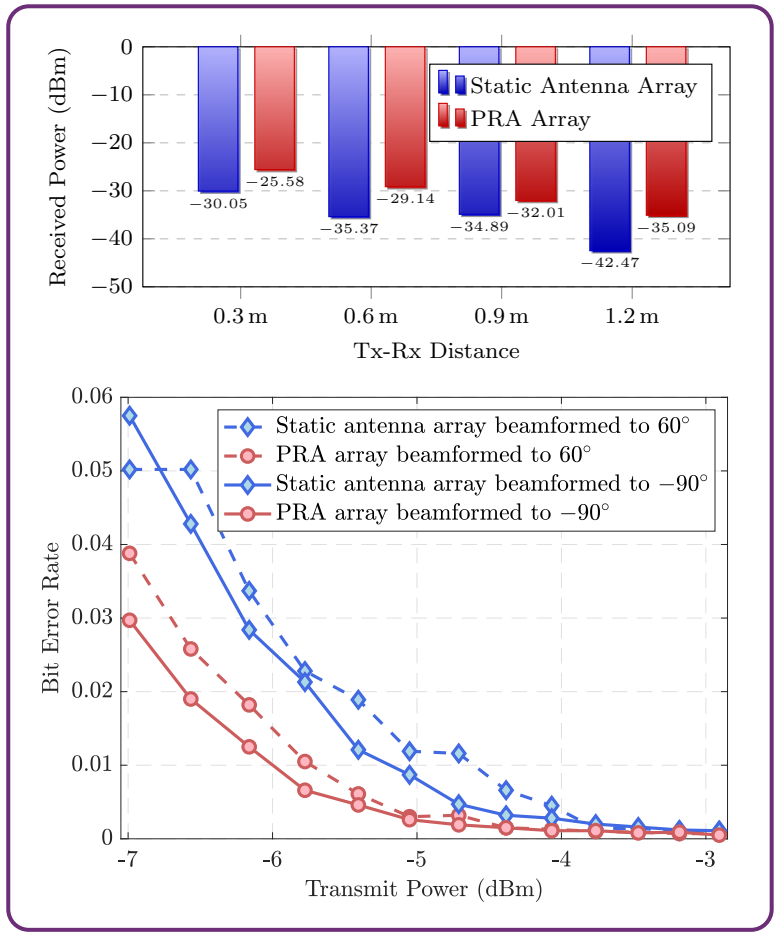
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A Prototyping Study: Fluid Pattern-Reconfigurable Antenna

Full-Wave Simulation: higher beamforming gain



Indoor Experiment: lower bit error rate



[1] R. Wang, P. Zheng et al., "Electromagnetically Reconfigurable Fluid Antenna System for Wireless Communications: Design, Modeling, Algorithm, Fabrication, and Experiment," in IEEE Journal on Selected Areas in Communications, vol. 44, pp. 1464-1479, 2026.

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A Prototyping Study: Fluid Pattern-Reconfigurable Antenna

Key Insights

- **Array integration** is a critical yet challenging problem for RAs → flexibility vs. physical size
- RA array can provide a performance gain, using energy more efficiently and adaptively.
- The gain is not associated with liquid metal implementation, but the antenna pattern reconfigurability.

Questions

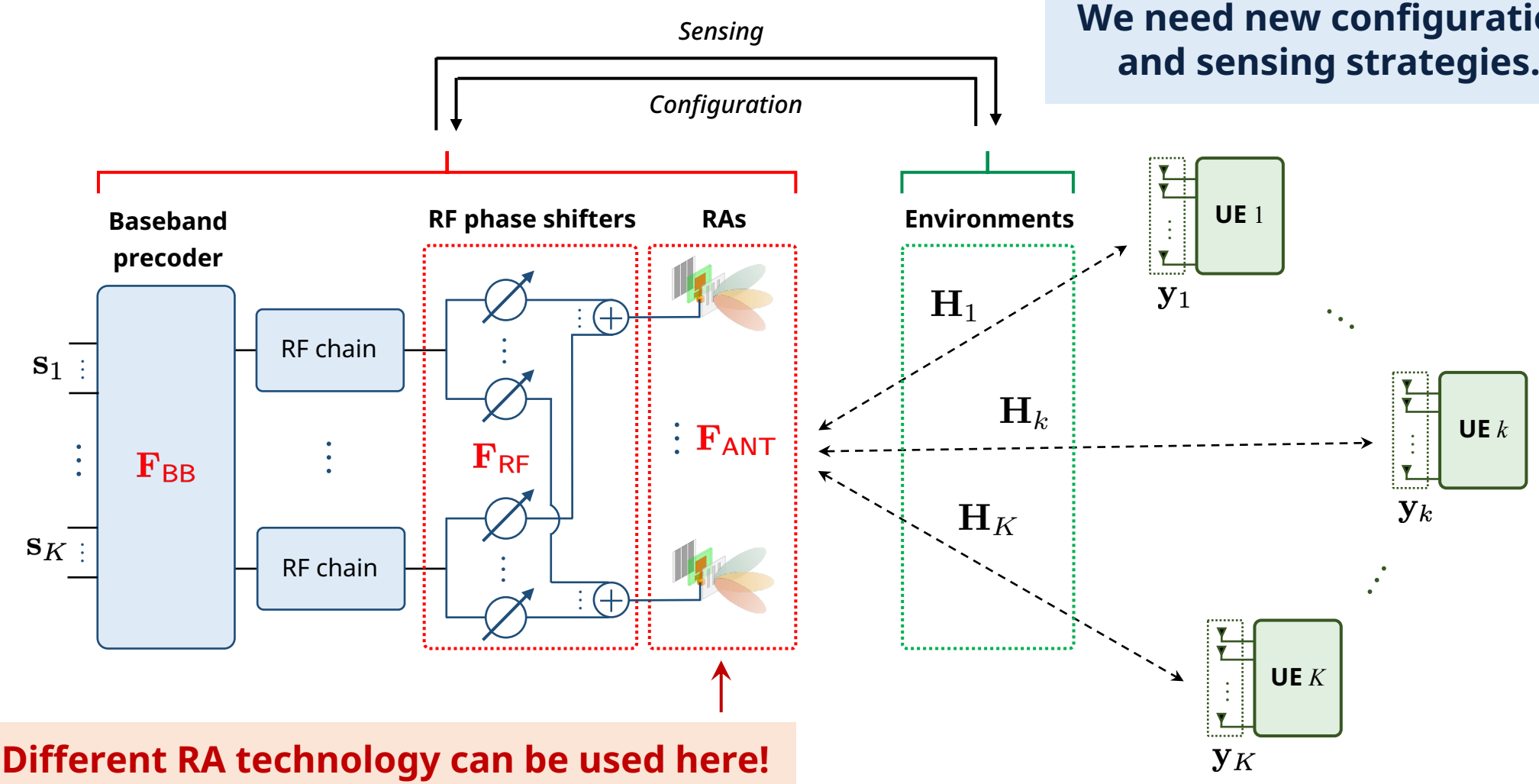
- How can this be integrated with hybrid digital-analog MIMO?
- How to **configure reconfigurable antennas** → We need new signal processing solutions!

[1] R. Wang, P. Zheng et al., "Electromagnetically Reconfigurable Fluid Antenna System for Wireless Communications: Design, Modeling, Algorithm, Fabrication, and Experiment," in IEEE Journal on Selected Areas in Communications, vol. 44, pp. 1464-1479, 2026.

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Tri-Hybrid MIMO Architecture

We need new configuration and sensing strategies.



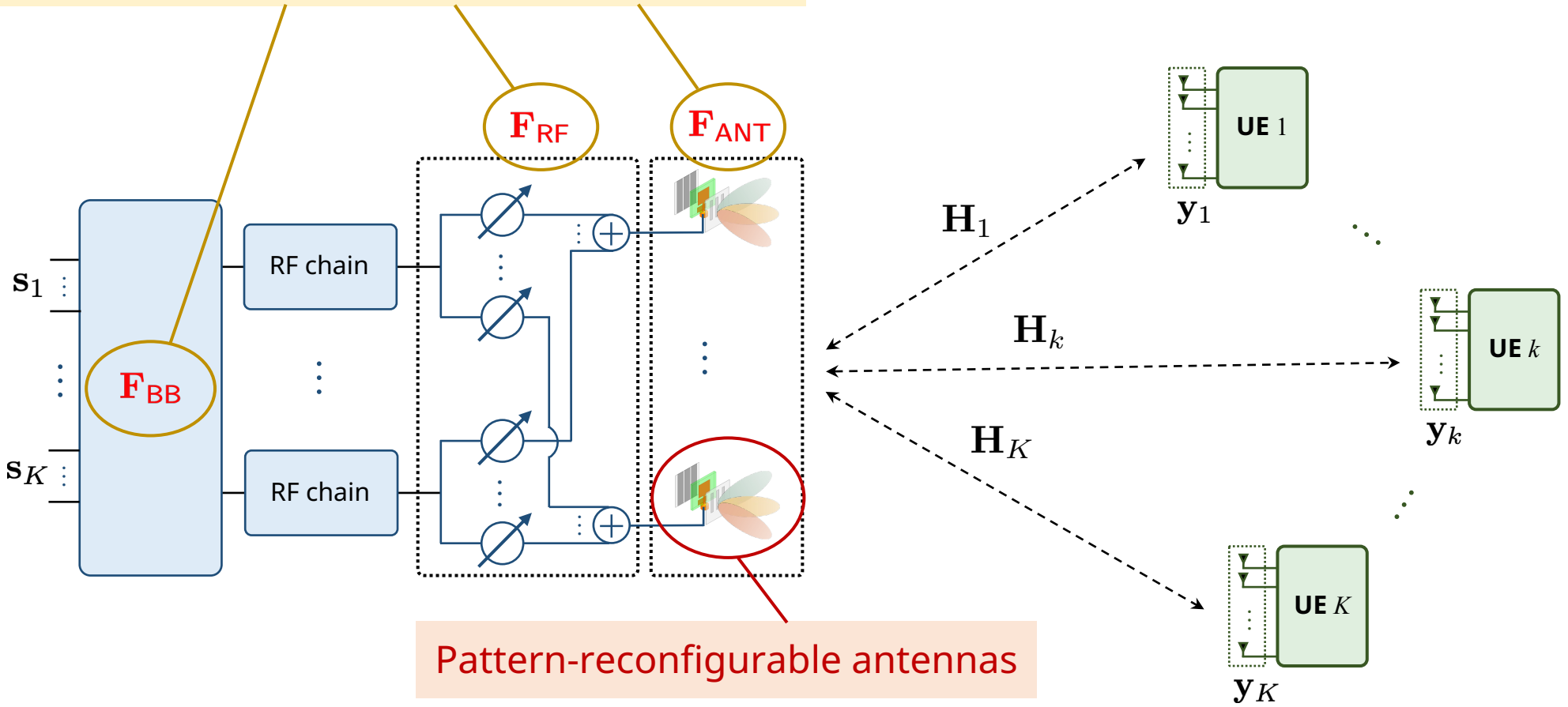
Different RA technology can be used here!

[1] P. Zheng, R. Wang, Y. Zhang, M. J. Hossain, A. Chaaban, A. Shamim, and T. Y. Al-Naffouri, "Reconfigurable Antennas for Next-Generation Wireless Communications: Technologies, Prototypes, Architectures, and Signal Processing," arXiv preprint arXiv:2506.00657, 2025.

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Tri-Hybrid Precoding with Pattern-Reconfigurable Antennas

How to design these **tri-domain precoders?**



[1] P. Zheng, Y. Zhang, T. Y. Al-Naffouri, M. J. Hossain, and A. Chaaban, "Tri-Hybrid Multi-User Precoding Using Pattern-Reconfigurable Antennas: Fundamental Models and Practical Algorithms," IEEE Transactions on Communications, vol. 74, pp. 11789–11804, 2026.

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How to Model Pattern Reconfigurability Mathematically?

$$\mathbf{H}_k = \sqrt{\frac{NM_k}{L_k}} \sum_{\ell=1}^{L_k} \alpha_{k,\ell} G_{\mathsf{UE}}(\vartheta_{k,\ell}, \varphi_{k,\ell}) G_{\mathsf{BS}}(\theta_{k,\ell}, \phi_{k,\ell}) \mathbf{a}_{\mathsf{UE}}(\vartheta_{k,\ell}, \varphi_{k,\ell}) \mathbf{a}_{\mathsf{BS}}^{\mathsf{H}}(\theta_{k,\ell}, \phi_{k,\ell})$$

Finite Pattern Selection

- Select a pattern from S candidates
- Align with how practical hardware works
- For the *n*-th antenna:

$$G_{(n)}^{\mathsf{BS}}(\theta, \phi) = \mathbf{g}^{\mathsf{T}}(\theta, \phi)\mathbf{b}_{(n)}$$

S candidate patterns

One-hot vector: $\mathbf{b}_{(n)} \in \{\mathbf{b} \in \{0,1\}^S : \|\mathbf{b}\|_0 = 1\}, \forall n$

- Define the **selection** precoder as [1]:

$$\mathbf{F}_{\mathsf{sel}} = \mathrm{blkdiag}\{\mathbf{b}_{(1)}, \mathbf{b}_{(2)}, \ldots, \mathbf{b}_{(N)}\}$$

Arbitrary Pattern Generation

- Assume we can generate any patterns
- Serve as a performance upper bound
- Use **spherical harmonics expression**:

$$G_{(n)}^{\mathsf{BS}}(\theta, \phi) \approx \sum_{u=0}^{U} \sum_{q=-u}^{u} c_{uq}^{(n)} Y_u^q(\theta, \phi) = \boldsymbol{\gamma}^{\mathsf{T}}(\theta, \phi)\mathbf{c}_{(n)}$$

Harmonic basis

Coefficient vector

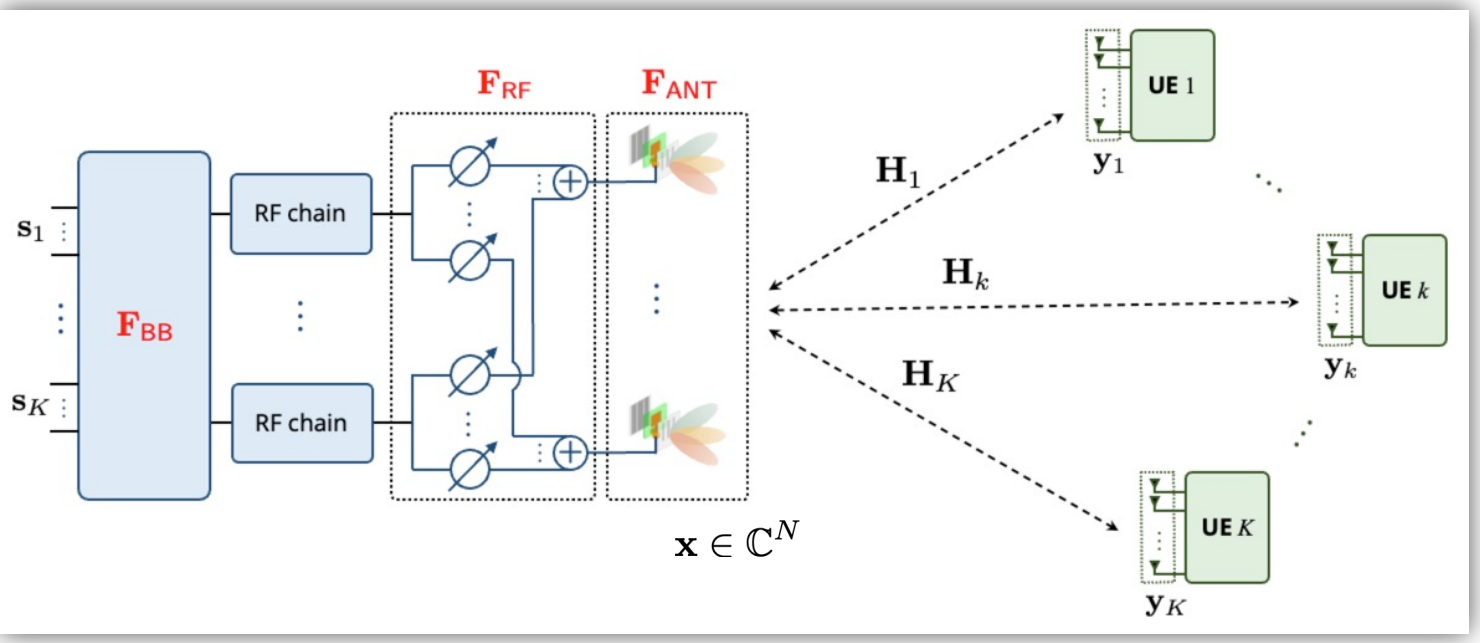
- Define the **coefficient** precoder as [1]:

$$\mathbf{F}_{\mathsf{cof}} = \mathrm{blkdiag}\{\mathbf{c}_{(1)}, \mathbf{c}_{(2)}, \ldots, \mathbf{c}_{(N)}\}$$

[1] P. Zheng, Y. Zhang, T. Y. Al-Naffouri, M. J. Hossain, and A. Chaaban, "Tri-Hybrid Multi-User Precoding Using Pattern-Reconfigurable Antennas: Fundamental Models and Practical Algorithms," IEEE Transactions on Communications, vol. 74, pp. 11789–11804, 2026.

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How to Formulate Precoder Optimization Problem?



Transmitted baseband symbol:

$$\mathbf{s} = [\mathbf{s}_1^{\mathsf{T}}, \mathbf{s}_2^{\mathsf{T}}, \ldots, \mathbf{s}_K^{\mathsf{T}}]^{\mathsf{T}}$$

Transmitted RF signal:

$$\mathbf{x} = \mathbf{F}_{\text{ANT}}\mathbf{F}_{\text{RF}}\mathbf{F}_{\text{BB}}\mathbf{s}$$

$$= \mathbf{F}_{\text{ANT}}\mathbf{F}_{\text{RF}} \left[\mathbf{F}_{\text{BB},1}, \ldots, \mathbf{F}_{\text{BB},K}\right] \begin{bmatrix} \mathbf{s}_1 \\ \vdots \\ \mathbf{s}_K \end{bmatrix}$$

$\mathbf{F}_{\text{ANT}} \in \{\mathbf{F}_{\text{sel}}, \mathbf{F}_{\text{cof}}\}$

Received signal at user k: $\mathbf{y}_k = \mathbf{H}_k\mathbf{x} = \mathbf{H}_k\mathbf{F}_{\text{ANT}}\mathbf{F}_{\text{RF}}\mathbf{F}_{\text{BB}}\mathbf{s}$

$$= \mathbf{H}_k\mathbf{F}_{\text{ANT}}\mathbf{F}_{\text{RF}}\mathbf{F}_{\text{BB},k}\mathbf{s}_k + \sum_{i \neq k} \mathbf{H}_k\mathbf{F}_{\text{ANT}}\mathbf{F}_{\text{RF}}\mathbf{F}_{\text{BB},i}\mathbf{s}_i + \mathbf{n}_k$$

Desired signal for user k | Interference | Noise

[1] P. Zheng, Y. Zhang, T. Y. Al-Naffouri, M. J. Hossain, and A. Chaaban, "Tri-Hybrid Multi-User Precoding Using Pattern-Reconfigurable Antennas: Fundamental Models and Practical Algorithms," IEEE Transactions on Communications, vol. 74, pp. 11789–11804, 2026.

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How to Formulate Precoder Optimization Problem?

Received signal at user k: $\mathbf{y}_k = \mathbf{H}_k\mathbf{x} = \mathbf{H}_k\mathbf{F}_{\text{ANT}}\mathbf{F}_{\text{RF}}\mathbf{F}_{\text{BB}}\mathbf{s}$

$$= \mathbf{H}_k\mathbf{F}_{\text{ANT}}\mathbf{F}_{\text{RF}}\mathbf{F}_{\text{BB},k}\mathbf{s}_k + \sum_{i\neq k}\mathbf{H}_k\mathbf{F}_{\text{ANT}}\mathbf{F}_{\text{RF}}\mathbf{F}_{\text{BB},i}\mathbf{s}_i + \mathbf{n}_k$$

Desired signal for user k | Interference | Noise

Let $\mathbf{F}_{\text{ANT}} = \mathbf{F}_{\text{sel}}$, we can formulate the **sum-rate maximization problem** [1]:

$$\max_{\mathbf{F}_{\text{sel}},\mathbf{F}_{\text{RF}},\mathbf{F}_{\text{BB}}} \sum_{k=1}^{K}\beta_k \log_2\det\left(\mathbf{I}_{M_k} + \mathbf{H}_k^{\text{sel}}\mathbf{F}_{\text{sel}}\mathbf{F}_{\text{RF}}\mathbf{F}_{\text{BB},k}\mathbf{F}_{\text{BB},k}^{\text{H}}\mathbf{F}_{\text{RF}}^{\text{H}}\mathbf{F}_{\text{sel}}^{\text{H}}\left(\mathbf{H}_k^{\text{sel}}\right)^{\text{H}}\right.$$

Power of desired signal

$$\left.\times\left(\sum_{i\neq k}\mathbf{H}_k^{\text{sel}}\mathbf{F}_{\text{sel}}\mathbf{F}_{\text{RF}}\mathbf{F}_{\text{BB},i}\mathbf{F}_{\text{BB},i}^{\text{H}}\mathbf{F}_{\text{RF}}^{\text{H}}\mathbf{F}_{\text{sel}}^{\text{H}}\left(\mathbf{H}_k^{\text{sel}}\right)^{\text{H}} + \sigma_k^2\mathbf{I}_{M_k}\right)^{-1}\right)$$

Power of interference & noise

$$\text{s.t.} \quad \left[\mathbf{F}_{\text{RF}}\mathbf{F}_{\text{BB}}\mathbf{F}_{\text{BB}}^{\text{H}}\mathbf{F}_{\text{RF}}^{\text{H}}\right]_{n,n} \leq P_n,\ \forall n,$$

$$\mathbf{F}_{\text{sel}} = \text{blkdiag}\left\{\mathbf{b}_{(1)},\mathbf{b}_{(2)},\ldots,\mathbf{b}_{(N)}\right\},$$

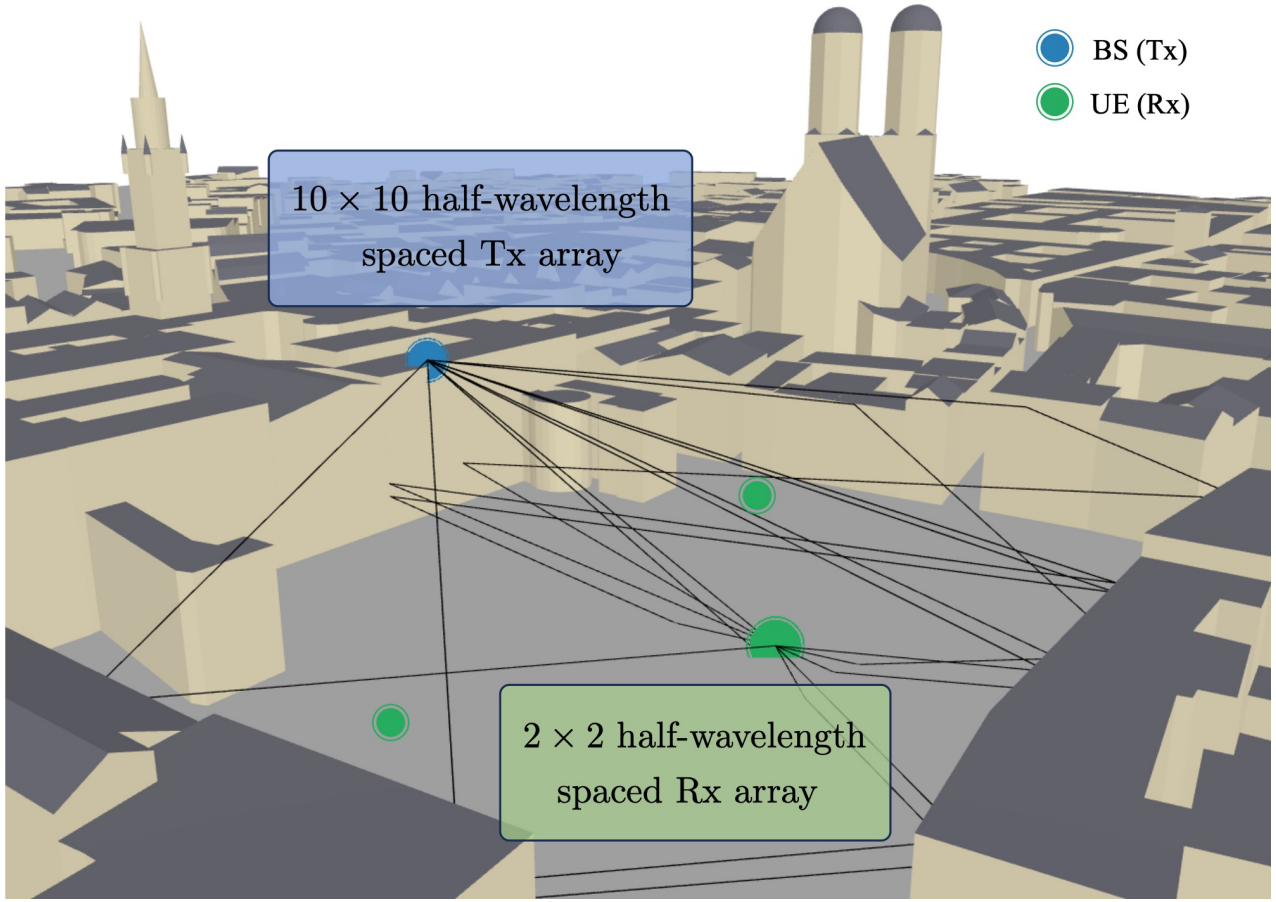
$$\mathbf{b}_{(n)} \in \left\{\mathbf{b}\in\{0,1\}^S \mid \|\mathbf{b}\|_0 = 1\right\},\ \forall n.$$

[1] P. Zheng, Y. Zhang, T. Y. Al-Naffouri, M. J. Hossain, and A. Chaaban, "Tri-Hybrid Multi-User Precoding Using Pattern-Reconfigurable Antennas: Fundamental Models and Practical Algorithms," IEEE Transactions on Communications, vol. 74, pp. 11789–11804, 2026.

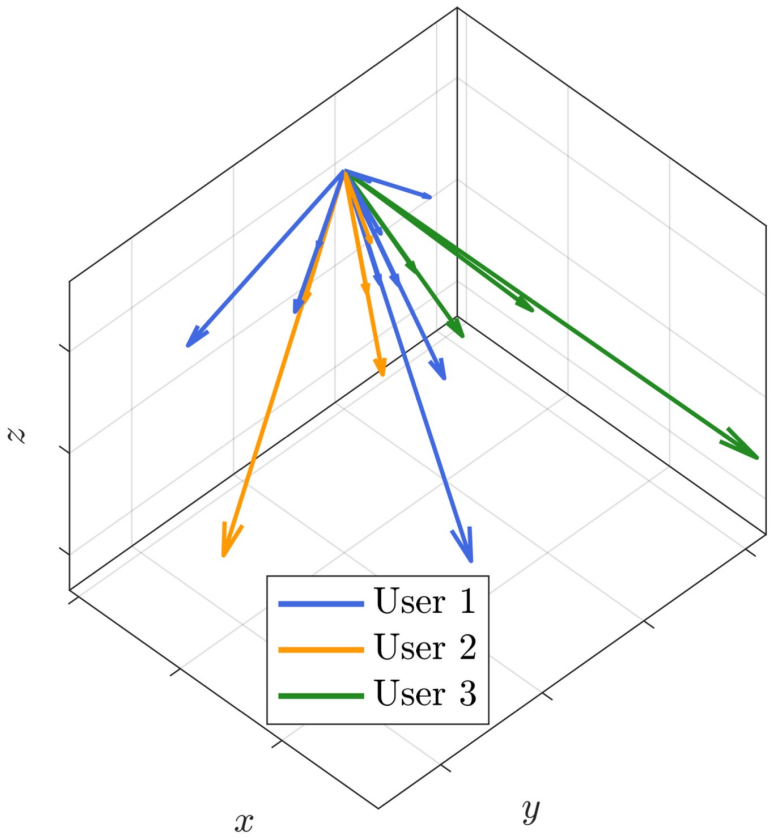
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Performance Evaluation

Ray-tracing channel simulation via Sionna RT



Multipath departure directions

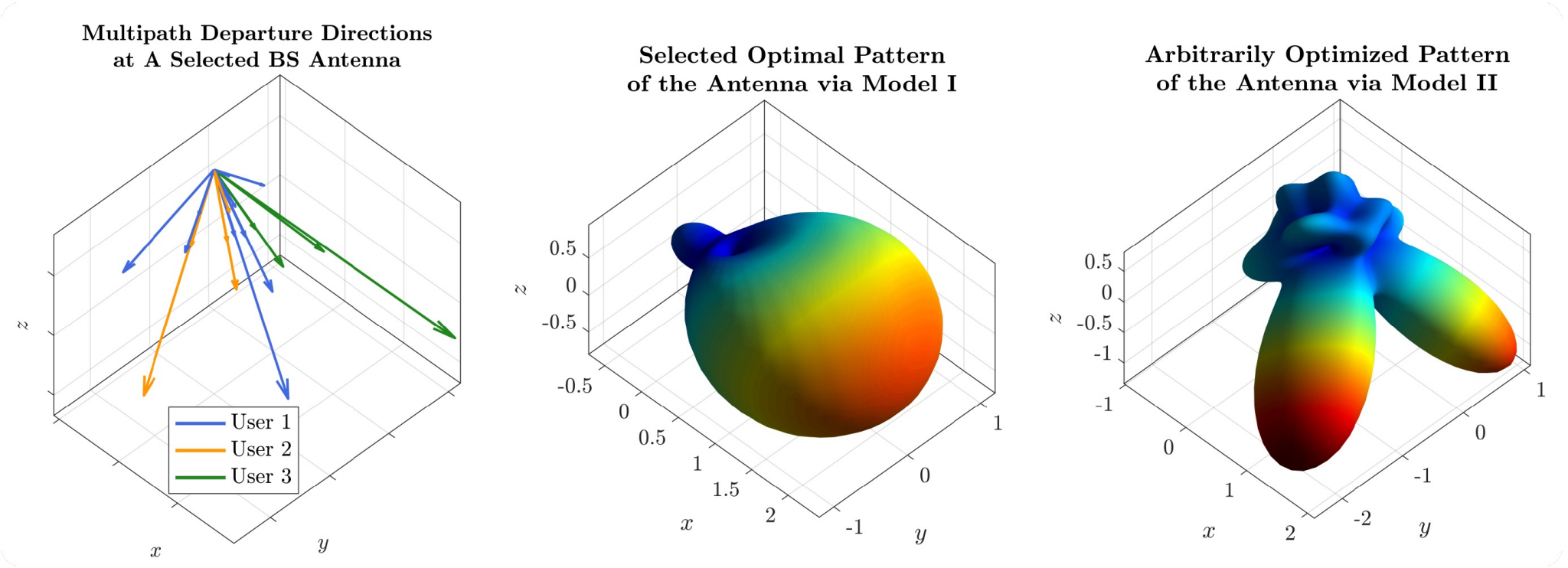


[1] P. Zheng, Y. Zhang, T. Y. Al-Naffouri, M. J. Hossain, and A. Chaaban, "Tri-Hybrid Multi-User Precoding Using Pattern-Reconfigurable Antennas: Fundamental Models and Practical Algorithms," IEEE Transactions on Communications, vol. 74, pp. 11789–11804, 2026.

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Performance Evaluation

Visualization of the optimized radiation pattern of a single antenna



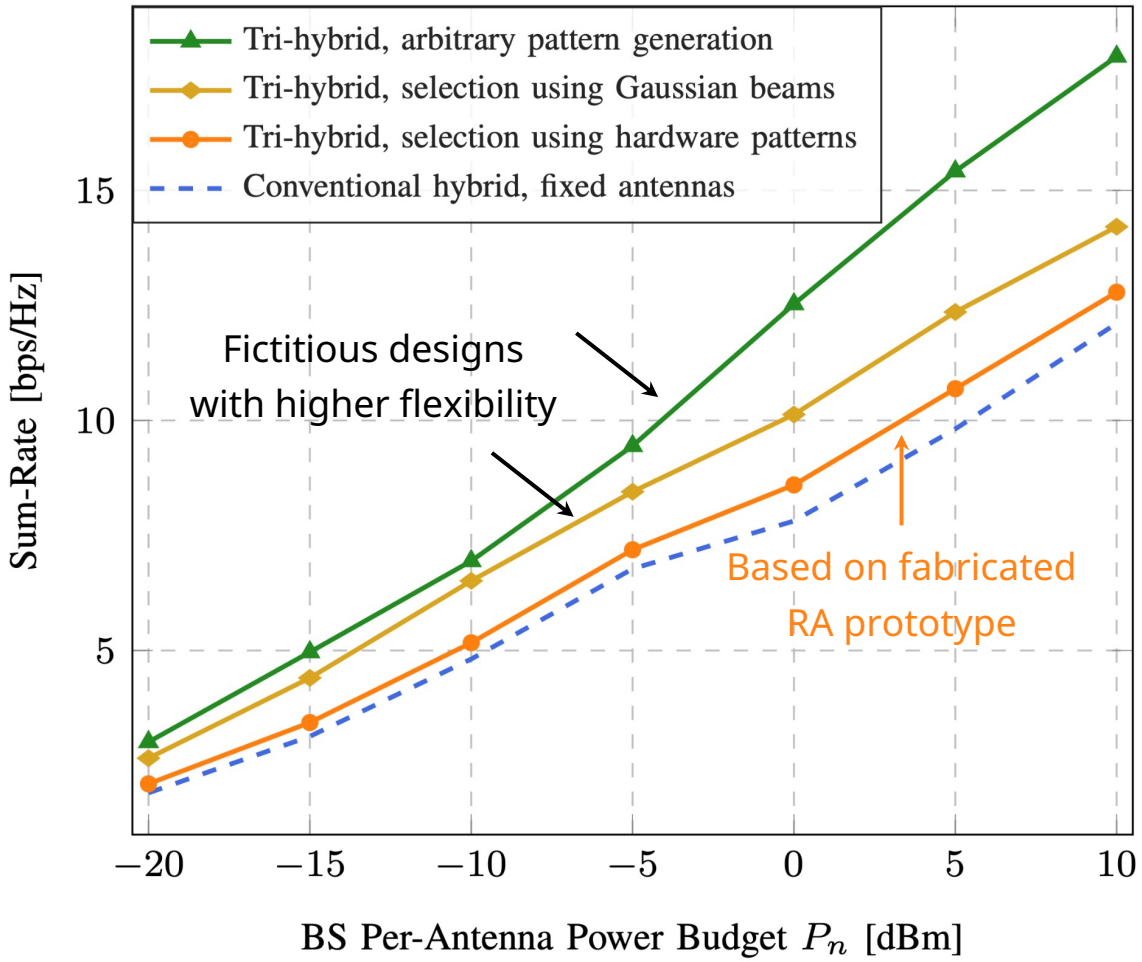
Finite pattern selection
(based on the fluid RA prototype)

Arbitrary pattern generation

[1] P. Zheng, Y. Zhang, T. Y. Al-Naffouri, M. J. Hossain, and A. Chaaban, "Tri-Hybrid Multi-User Precoding Using Pattern-Reconfigurable Antennas: Fundamental Models and Practical Algorithms," IEEE Transactions on Communications, vol. 74, pp. 11789–11804, 2026.

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Performance Evaluation

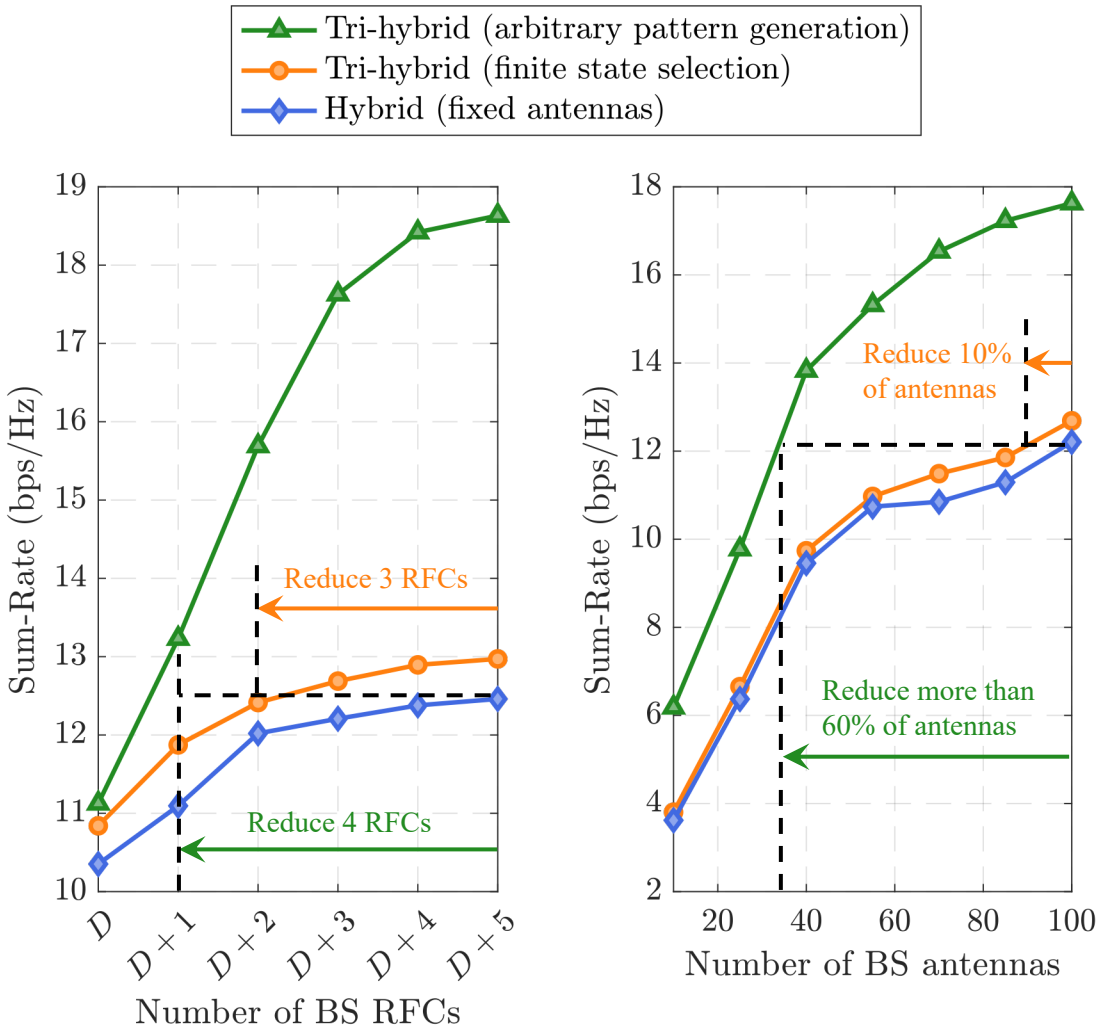


- ✓ The fabricated pattern-reconfigurable antennas provide limited performance gain.
- ✓ However, pattern-reconfigurable antennas still hold great potential when their radiation pattern can be more flexibly adjusted.
- ✓ We need more advanced reconfigurable antenna technologies!

[1] P. Zheng, Y. Zhang, T. Y. Al-Naffouri, M. J. Hossain, and A. Chaaban, "Tri-Hybrid Multi-User Precoding Using Pattern-Reconfigurable Antennas: Fundamental Models and Practical Algorithms," IEEE Transactions on Communications, vol. 74, pp. 11789–11804, 2026.

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Performance Evaluation



- ✓ D denotes the total number of data streams transmitted at the BS.
- ✓ Pattern-reconfigurable antennas can enhance hardware efficiency.

[1] P. Zheng, Y. Zhang, T. Y. Al-Naffouri, M. J. Hossain, and A. Chaaban, "Tri-Hybrid Multi-User Precoding Using Pattern-Reconfigurable Antennas: Fundamental Models and Practical Algorithms," IEEE Transactions on Communications, vol. 74, pp. 11789–11804, 2026.

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Tri-Hybrid Precoding with Pattern-Reconfigurable Antennas

Key Insights

- Tri-hybrid MIMO with reconfigurable antennas holds significant potential.
- Current hardware is not flexible enough to fully unleash this potential.
- Tri-hybrid MIMO is promising in enhancing hardware efficiency.

Unsolved Challenges

- The formulated optimization problem is very complex.
- Using iterative algorithm to solve it is very time-consuming and thus impractical.

[1] P. Zheng, Y. Zhang, T. Y. Al-Naffouri, M. J. Hossain, and A. Chaaban, “Tri-Hybrid Multi-User Precoding Using Pattern-Reconfigurable Antennas: Fundamental Models and Practical Algorithms,” IEEE Transactions on Communications, vol. 74, pp. 11789–11804, 2026.

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Iterative Algorithm for Solving Tri-Hybrid Precoding Problem

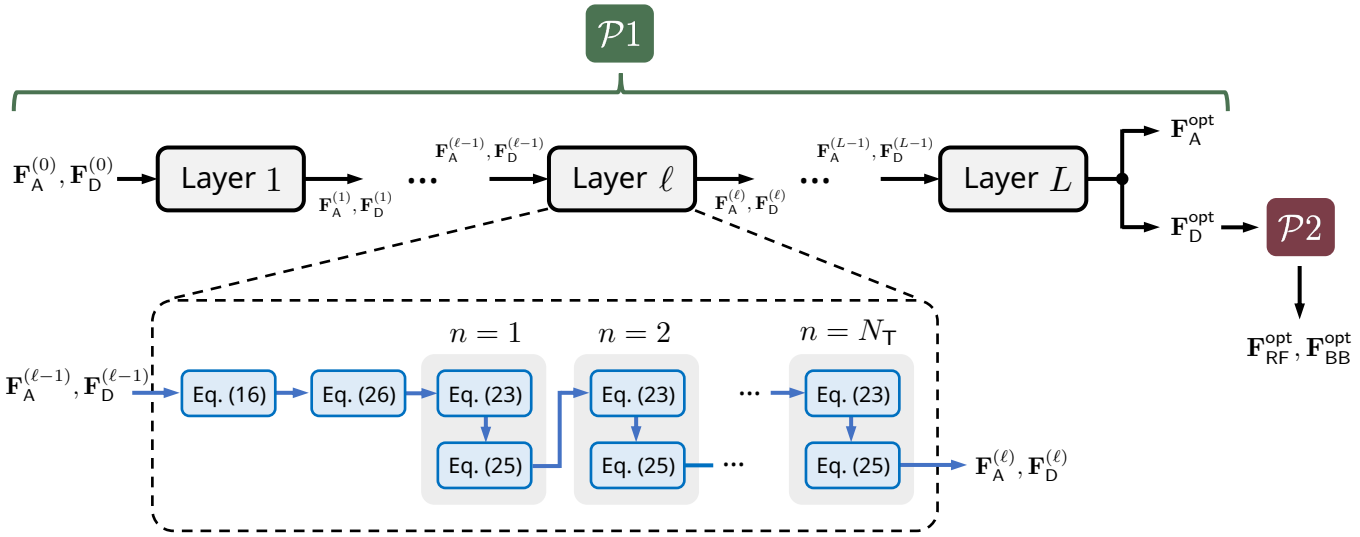
$$\max_{\mathbf{F}_{\text{sel}},\mathbf{F}_{\text{RF}},\mathbf{F}_{\text{BB}}} \sum_{k=1}^{K} \beta_k \log_2 \det \Big(\mathbf{I}_{M_k} + \mathbf{H}_k^{\text{sel}} \mathbf{F}_{\text{sel}} \mathbf{F}_{\text{RF}} \mathbf{F}_{\text{BB},k} \mathbf{F}_{\text{BB},k}^{\text{H}} \mathbf{F}_{\text{RF}}^{\text{H}} \mathbf{F}_{\text{sel}}^{\text{H}} \big(\mathbf{H}_k^{\text{sel}}\big)^{\text{H}} \times \Big(\sum_{i\neq k} \mathbf{H}_k^{\text{sel}} \mathbf{F}_{\text{sel}} \mathbf{F}_{\text{RF}} \mathbf{F}_{\text{BB},i} \mathbf{F}_{\text{BB},i}^{\text{H}} \mathbf{F}_{\text{RF}}^{\text{H}} \mathbf{F}_{\text{sel}}^{\text{H}} \big(\mathbf{H}_k^{\text{sel}}\big)^{\text{H}} + \sigma_k^2 \mathbf{I}_{M_k} \Big)^{-1} \Big)$$

$$\text{s.t.} \quad \big[\mathbf{F}_{\text{RF}} \mathbf{F}_{\text{BB}} \mathbf{F}_{\text{BB}}^{\text{H}} \mathbf{F}_{\text{RF}}^{\text{H}}\big]_{n,n} \le P_n, \ \forall n,$$

$$\mathbf{F}_{\text{sel}} = \text{blkdiag}\big\{\mathbf{b}_{(1)}, \mathbf{b}_{(2)}, \ldots, \mathbf{b}_{(N)}\big\},$$

$$\mathbf{b}_{(n)} \in \big\{\mathbf{b} \in \{0,1\}^S \mid \|\mathbf{b}\|_0 = 1\big\}, \ \forall n.$$

$\mathbf{F}_{\text{D}} \triangleq \mathbf{F}_{\text{RF}} \mathbf{F}_{\text{BB}}$



$\mathcal{P}1$

$$\max_{\mathbf{F}_{\text{A}},\mathbf{F}_{\text{D}}} \sum_{k=1}^{K} \beta_k \log_2 \det \Big(\mathbf{I} + \mathbf{H}_k \mathbf{F}_{\text{A}} \mathbf{F}_{\text{D},k} \mathbf{F}_{\text{D},k}^{\text{H}} \mathbf{F}_{\text{A}}^{\text{H}} \mathbf{H}_k^{\text{H}} \times \Big(\sum_{i\neq k} \mathbf{H}_k \mathbf{F}_{\text{A}} \mathbf{F}_{\text{D},i} \mathbf{F}_{\text{D},i}^{\text{H}} \mathbf{F}_{\text{A}}^{\text{H}} \mathbf{H}_k^{\text{H}} + \sigma_k^2 \mathbf{I} \Big)^{-1} \Big)$$

$$\text{s.t.} \quad [\mathbf{F}_{\text{D}} \mathbf{F}_{\text{D}}^{\text{H}}]_{n,n} \le P_n, \ \forall n,$$

$$\mathbf{F}_{\text{A}} = \text{blkdiag}\{\mathbf{b}_{(1)}, \mathbf{b}_{(2)}, \ldots, \mathbf{b}_{(N)},\}$$

$$\mathbf{b}_{(n)} \in \big\{\mathbf{b} \in \{0,1\}^S \mid \|\mathbf{b}\|_0 = 1\big\}, \ \forall n.$$

$\mathcal{P}2$

$$\min_{\mathbf{F}_{\text{RF}},\mathbf{F}_{\text{BB}}} \ \|\mathbf{F}_{\text{D}}^{\text{opt}} - \mathbf{F}_{\text{RF}} \mathbf{F}_{\text{BB}}\|_{\text{F}}^2$$

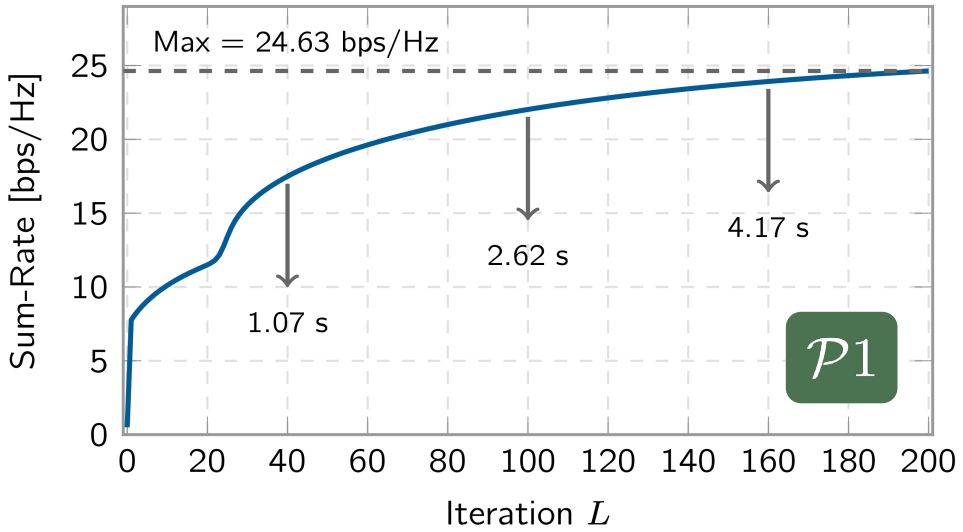
$$\text{s.t.} \quad |[\mathbf{F}_{\text{RF}}]_{i,j}|^2 = 1/N_{\text{T}}, \ \forall i,j,$$

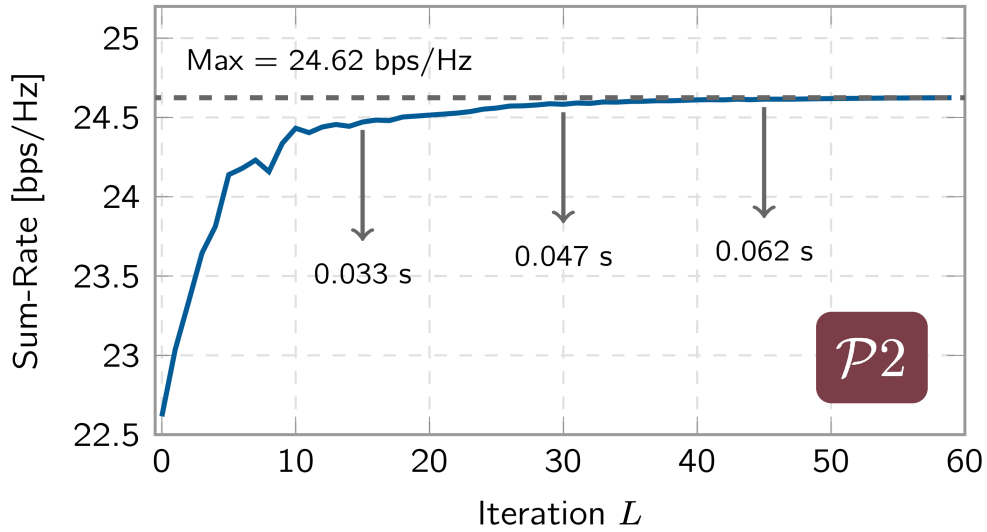
$$[\mathbf{F}_{\text{RF}} \mathbf{F}_{\text{BB}} \mathbf{F}_{\text{BB}}^{\text{H}} \mathbf{F}_{\text{RF}}^{\text{H}}]_{n,n} \le P_n, \ \forall n.$$

[1] P. Zheng, M. J. Hossain, and A. Chaaban, "Fast Tri-Hybrid Beamforming via Deep Unfolding," IEEE Transactions on Signal Processing, 2026, early access.

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Iterative Algorithm for Solving Tri-Hybrid Precoding Problem



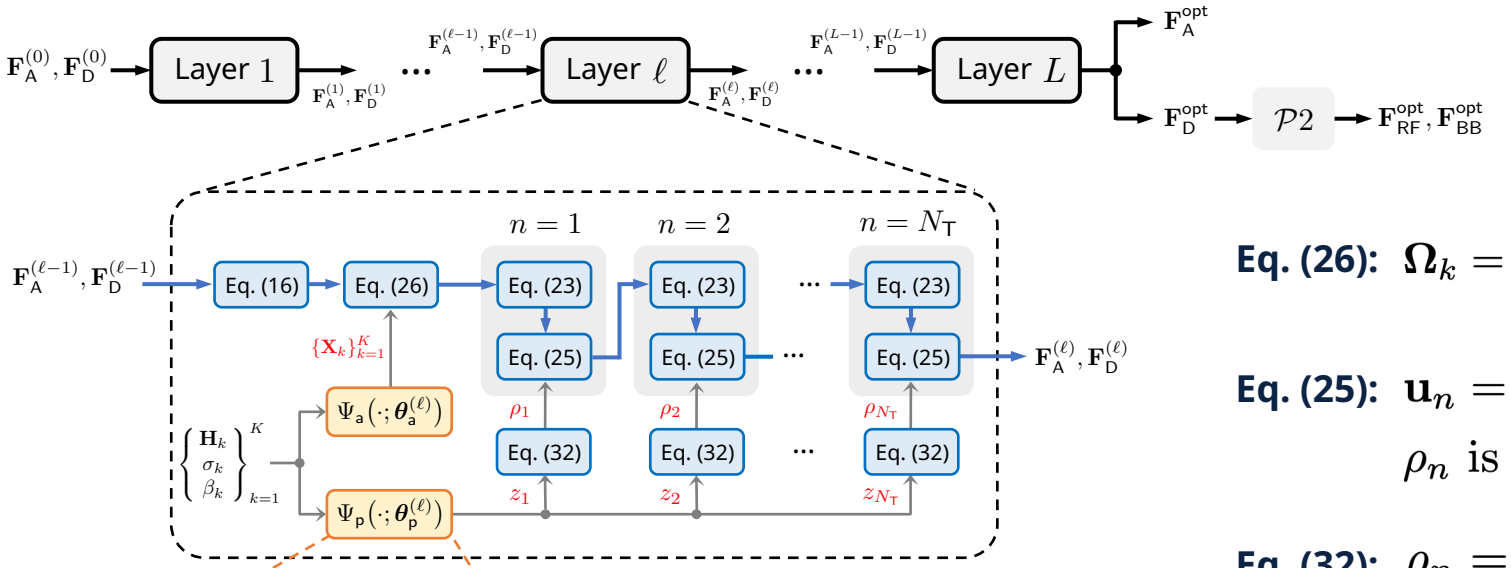


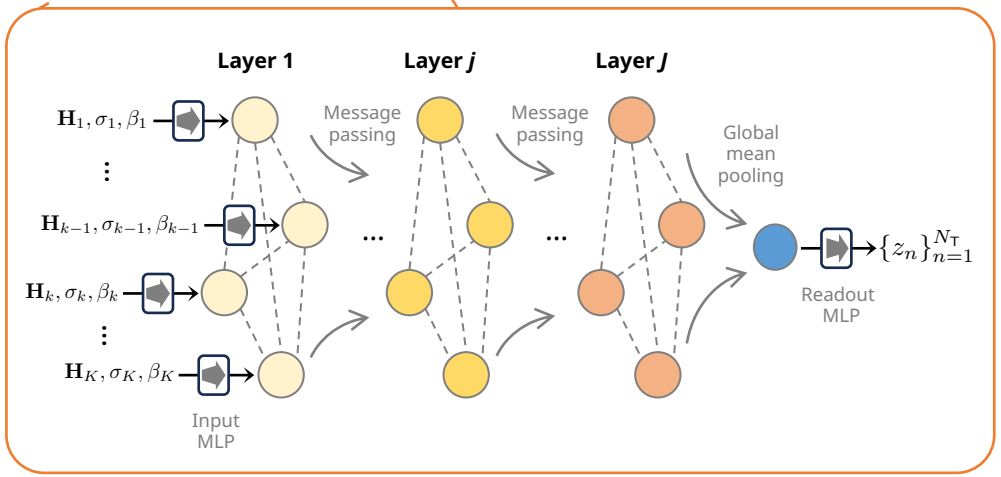
- P1 is the main bottleneck.
- The algorithm is too slow to be useful.

[1] P. Zheng, M. J. Hossain, and A. Chaaban, "Fast Tri-Hybrid Beamforming via Deep Unfolding," IEEE Transactions on Signal Processing, 2026, early access.

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Deep Algorithm Unfolding





An acceleration term

Eq. (26): $\boldsymbol{\Omega}_k = \left(\mathbf{I} - \boldsymbol{\Gamma}_k^{\mathsf{H}} \mathbf{H}_k \mathbf{F}_{\mathsf{A}} \mathbf{F}_{\mathsf{D},k}\right)^{-1} + \mathbf{X}_k + \mathbf{X}_k{}^{\mathsf{H}}, \ \forall k$

Eq. (25): $\mathbf{u}_n = e^{\mathrm{j}\arg\left((\rho_n \mathbf{I} - \mathbf{M}_n)\mathbf{u}_n - \frac{1}{2}\mathbf{b}_n\right)}$

ρ_n is a hyperparameter such that $\rho_n \geq \lambda_{\max}(\mathbf{M}_n)$

Eq. (32): $\rho_n = \lambda_{\max}(\mathbf{M}_n) + z_n$

Let NN decide!

Core idea:

- Full convergence is impractical under limited latency.
- We allow at most L iterations and train a neural network to help achieve the best possible performance within this budget.

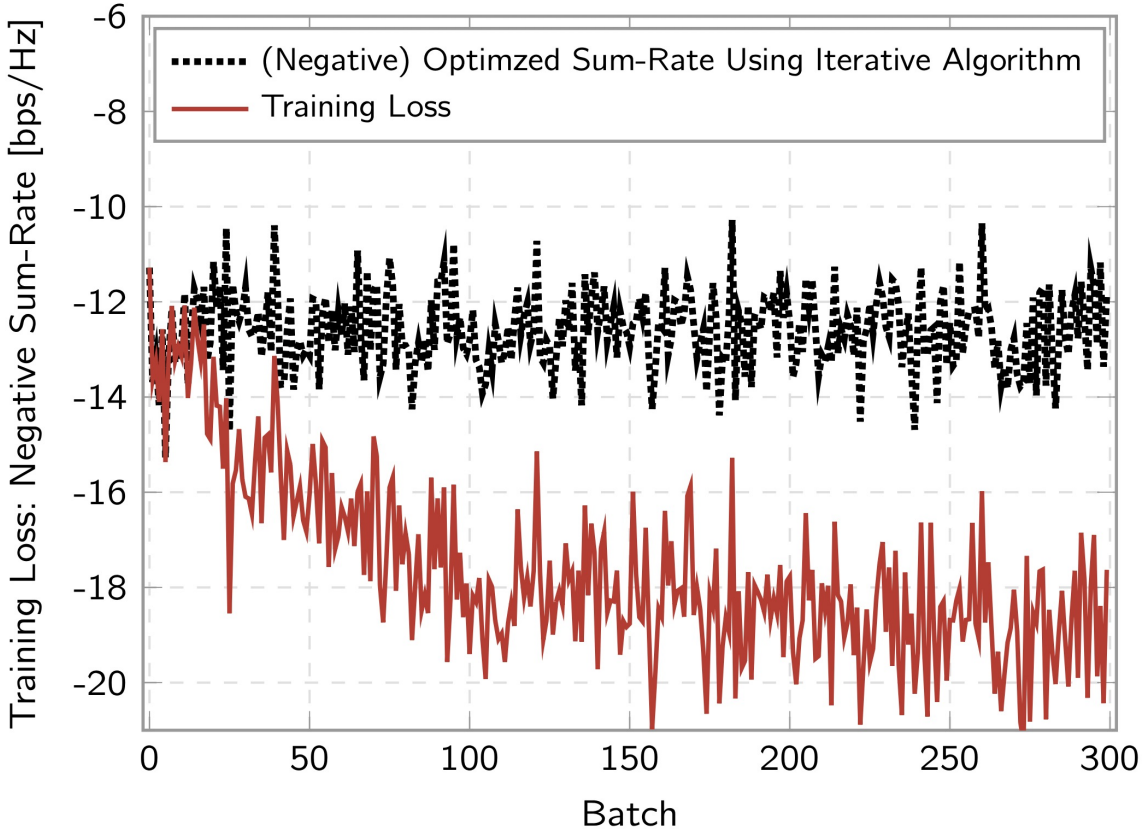
[1] P. Zheng, M. J. Hossain, and A. Chaaban, "Fast Tri-Hybrid Beamforming via Deep Unfolding," IEEE Transactions on Signal Processing, 2026, early access.

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Model Training

Module	Input MLP	GNN layers	Readout MLP
Ψ_a	$801 \to 406 \to 12$	$12 \to 12 \to 12$	$12 \to 10 \to 8$
Ψ_p	$801 \to 415 \to 30$	$30 \to 30 \to 30$	$30 \to 25 \to 20$

- DeepMIMO dataset [1].
- **Training data:** New York, Los Angeles, and Chicago (in total 28, 595 channel realizations).
- **Testing data:** Miami, Austin, Columbus, and Dallas.
- Varying user number $3 \leq K \leq 5$ [2].



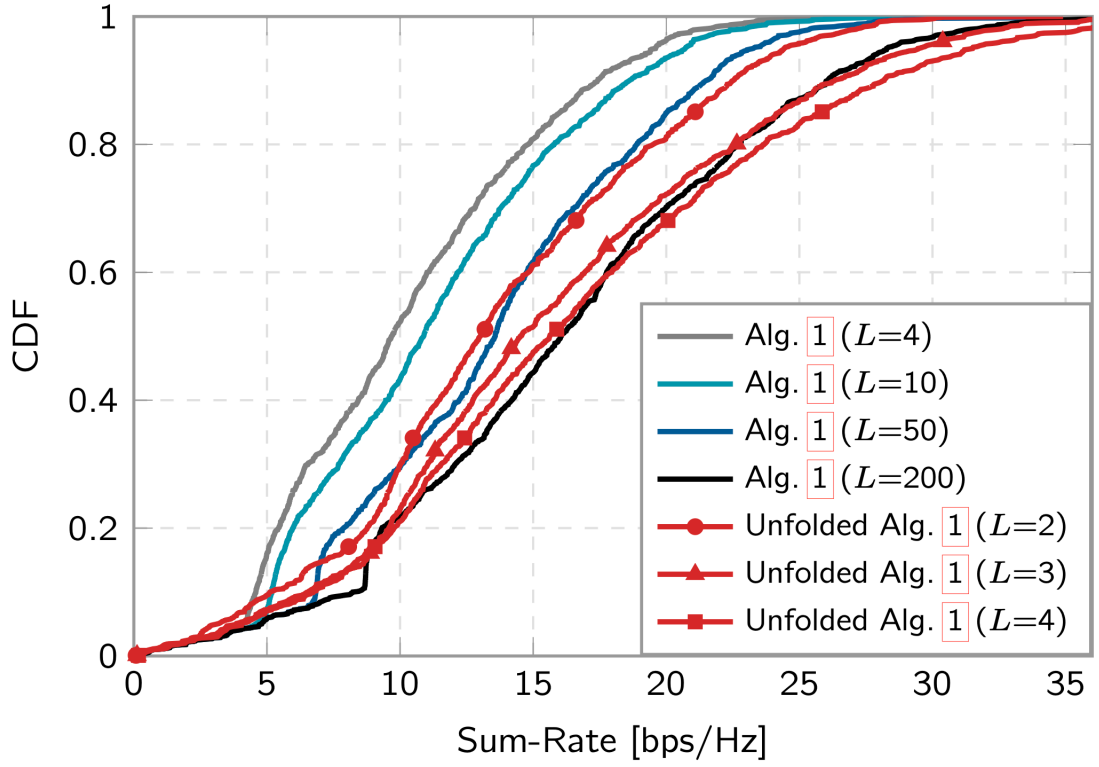
[1] A. Alkhateeb, "DeepMIMO: A generic deep learning dataset for millimeter wave and massive MIMO applications," in Proc. of Information Theory and Applications Workshop (ITA), San Diego, CA, Feb 2019, pp. 1–8.

[2] P. Zheng, M. J. Hossain, and A. Chaaban, "Fast Tri-Hybrid Beamforming via Deep Unfolding," IEEE Transactions on Signal Processing, 2026, early access.

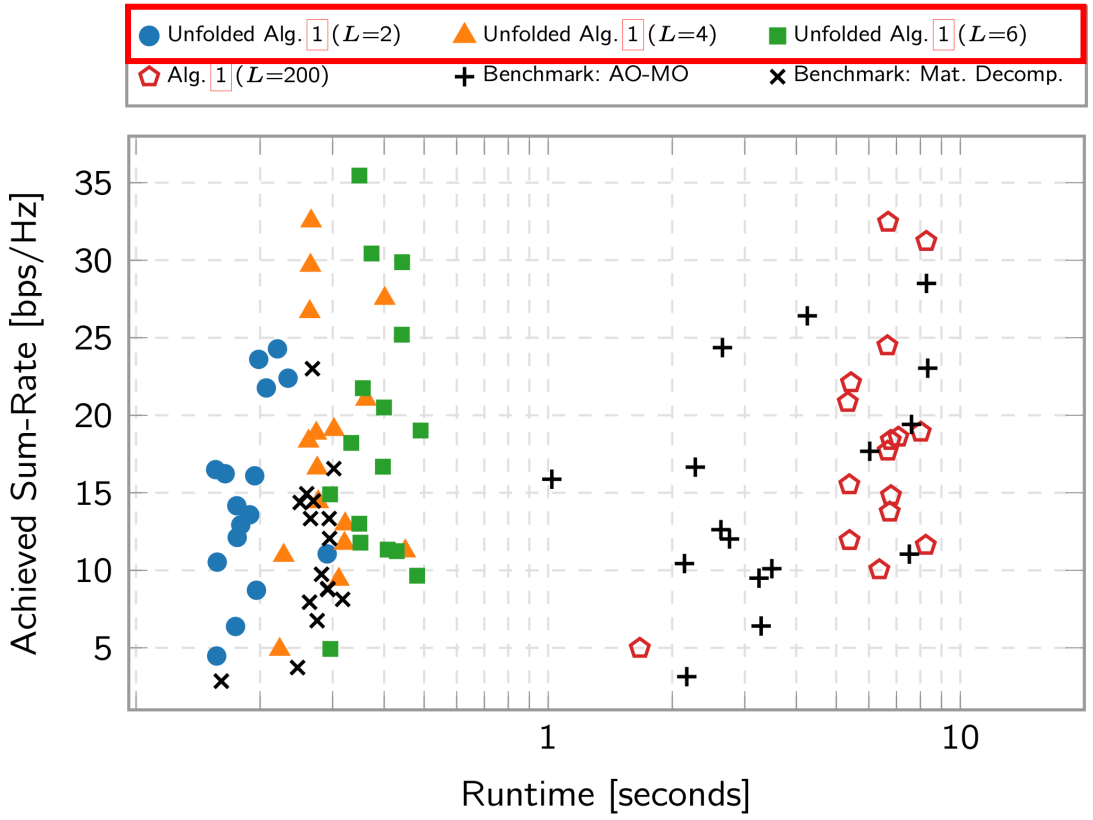
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Performance Evaluation

4 iterations are already enough!



Enjoy both **high sum-rate** & **short runtime**!

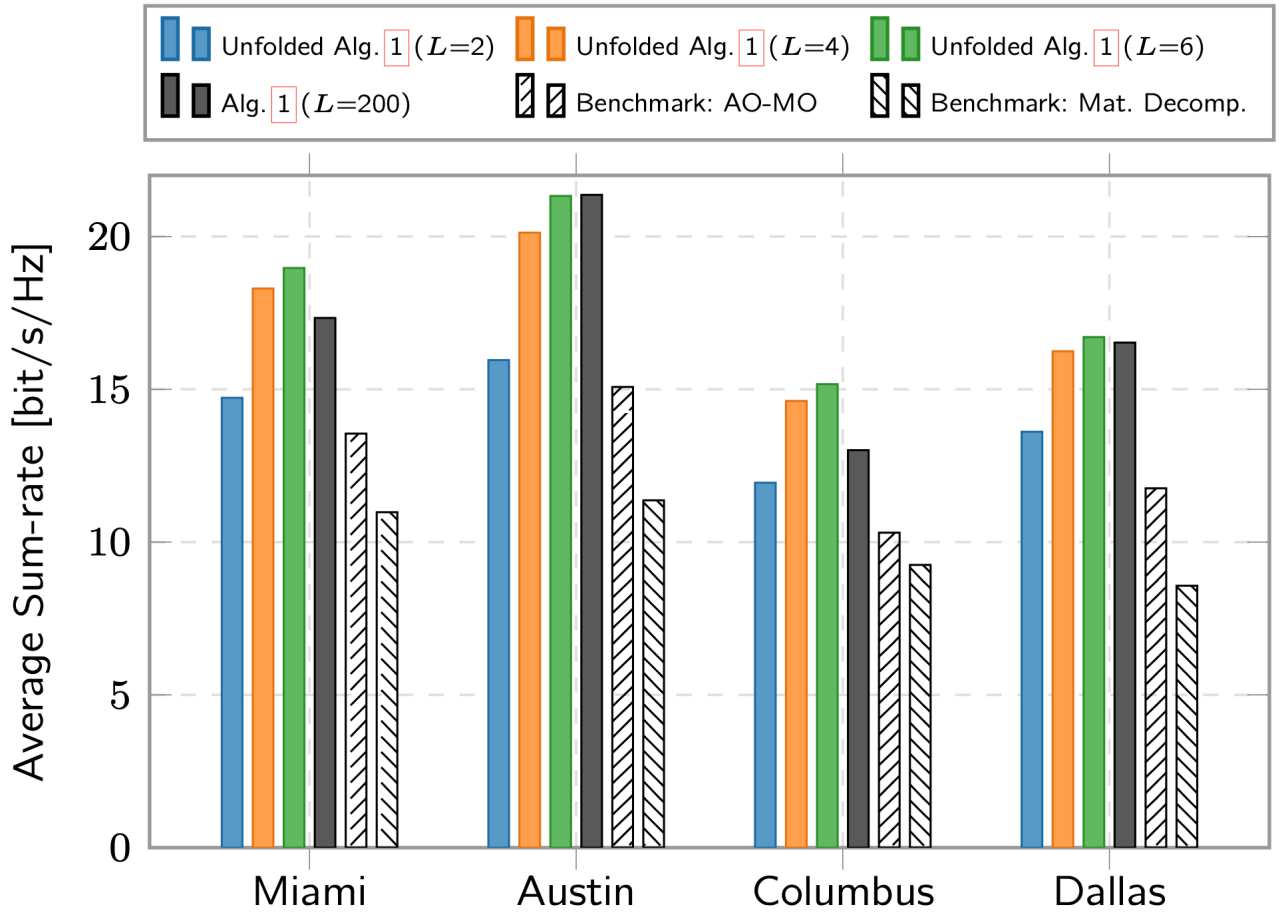


[1] P. Zheng, M. J. Hossain, and A. Chaaban, "Fast Tri-Hybrid Beamforming via Deep Unfolding," IEEE Transactions on Signal Processing, 2026, early access.

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Performance Evaluation

Strong generalization across various environments



[1] P. Zheng, M. J. Hossain, and A. Chaaban, “Fast Tri-Hybrid Beamforming via Deep Unfolding,” IEEE Transactions on Signal Processing, 2026, early access.

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More to Explore

- Channel estimation
- Sensing and ISAC
- Data-driven beam management
- More advanced antennas: pattern, frequency, polarization, metasurfaces…
- Hardware fabrication and experimental validation

…

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Thank You!

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OF BRITISH COLUMBIA
Okanagan Campus



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Tri-Hybrid Channel Modeling

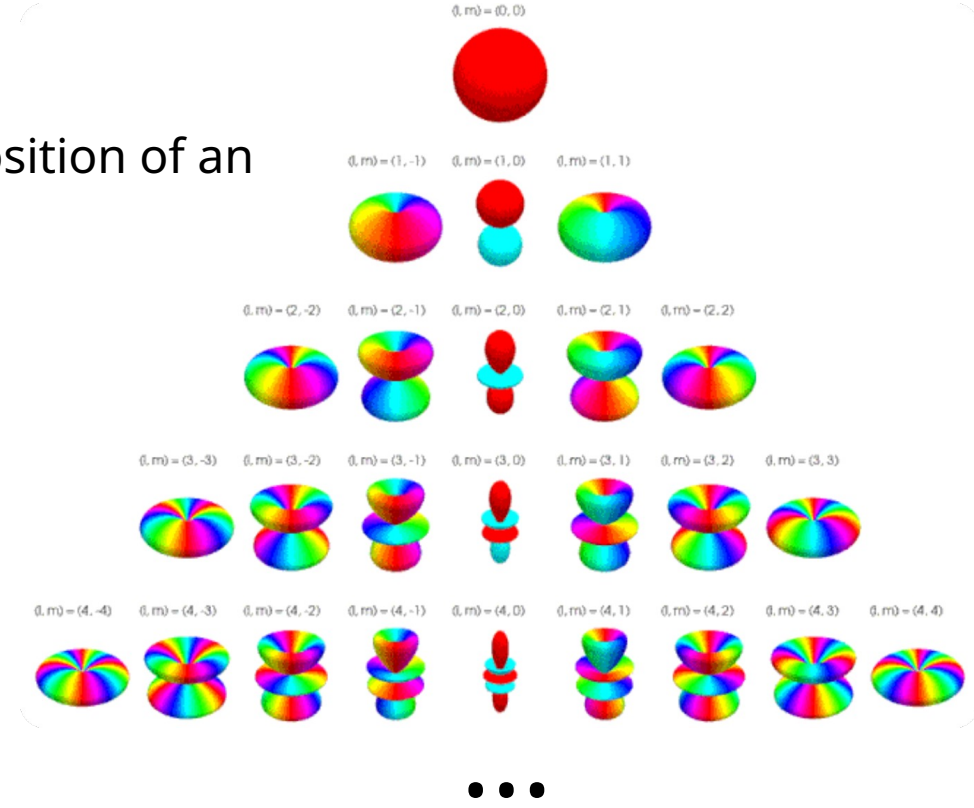
Model II: Arbitrary Radiation Pattern Generation

- Any spherical signal can be expressed as a superposition of an infinite series of spherical harmonics [1]:

$$G_{(n)}^{\mathrm{BS}}(\theta,\phi)=\sum_{u=0}^{+\infty}\sum_{q=-u}^{u}c_{uq}^{(n)}Y_u^q(\theta,\phi)$$

Coefficient

Spherical harmonics



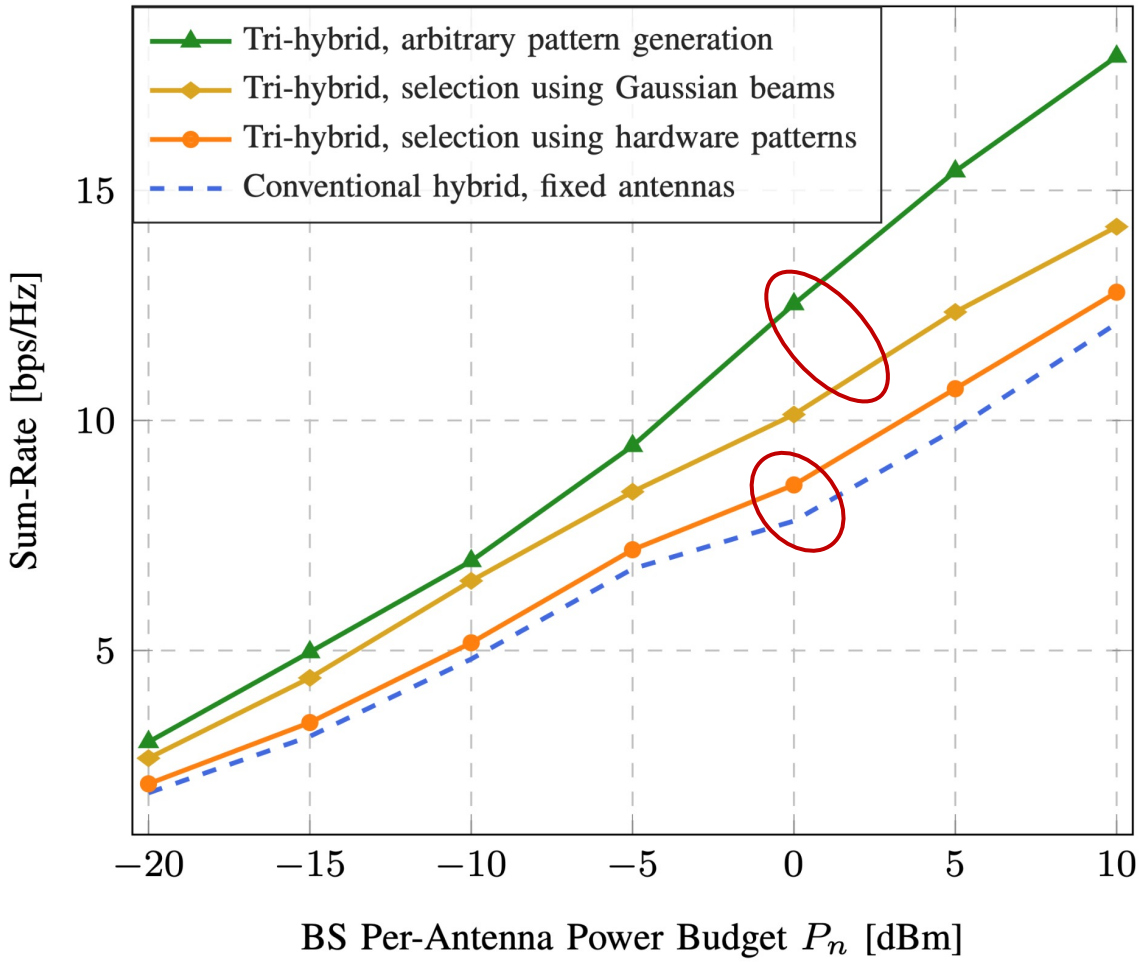
- Although it is an infinite series expansion, most radiation patterns are band-limited.

[1] I. Dokmanić and Y. M. Lu, "Sampling Sparse Signals on the Sphere: Algorithms and Applications," in IEEE Transactions on Signal Processing, vol. 64, no. 1, pp. 189-202, Jan.1, 2016.

[2] P. Zheng, Y. Zhang, T. Y. Al-Naffouri, M. J. Hossain, and A. Chaaban, “Tri-hybrid multi-user precoding using pattern-reconfigurable antennas: Fundamental models and practical algorithms,” 2025. [Online]. Available: https://arxiv.org/abs/2505.08938

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Performance Evaluation



- ✓ The fabricated pattern-reconfigurable antennas provide limited performance gain.
- ✓ However, pattern-reconfigurable antennas still hold great potential when their radiation pattern can be more flexibly adjusted.
- ✓ In particular, a set of better-designed available patterns can be promising.

Gaussian beams steered toward 64 directions uniformly distributed within $\theta \in [90^o, 180^o]$ and $\phi \in [-90^o, 90^o]$, each with a 3 dB beamwidth of 85^o.

[1] P. Zheng, Y. Zhang, T. Y. Al-Naffouri, M. J. Hossain, and A. Chaaban, "Tri-hybrid multi-user precoding using pattern-reconfigurable antennas: Fundamental models and practical algorithms," 2025. [Online]. Available: https://arxiv.org/abs/2505.08938.

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