Holographic Radio: A New Paradigm for Ultra-Massive MIMO

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Outline

Background

- 6G Communications and Requirements
- Reconfigurable Holographic Surface (RHS) Basics

RHS-aided Wireless Communications

- RHS-aided Holographic Beamforming
- HDMA: Holographic-Pattern Division Multiple Access

Physical Implementations and Prototypes

- Implementation of RHS
- RHS-aided Communication Platform

Future Research Directions

Conclusion

Sixth Generation--6G

- A number of 6G projects have been started around the world.

2019.9, Huawei (Canada)

Started research on future 6G mobile technology

2018.7, ITU-T

Established a focus group called *Technologies for Network 2030*

2019, Finland

The Oulu university published the first *white paper* for 6G

2020.5, US

The president announced the start of several 6G research programs

2019.11, China

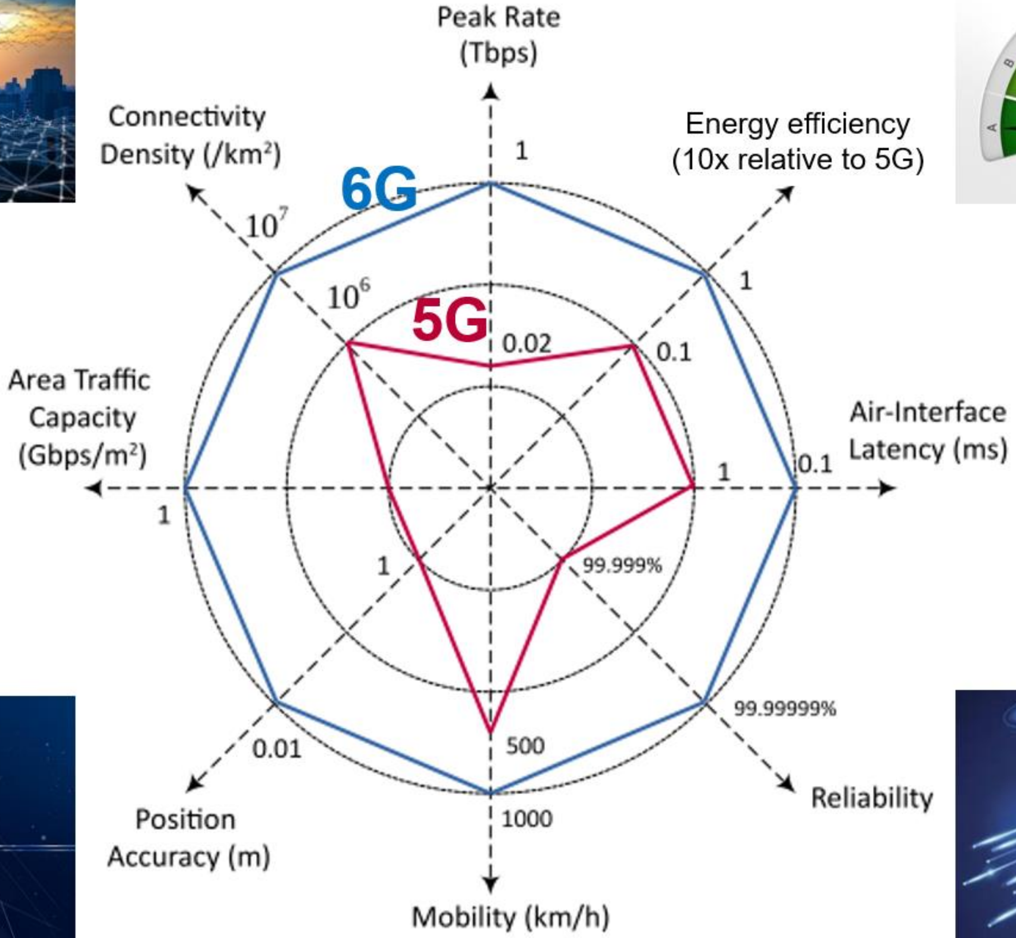
The country's Ministry of Science and Technology officially announced the start of work to create a 6G network

[1] L. U. Khan, I. Yaqoob, M. Imran, Z. Han and C. S. Hong, "6G Wireless Systems: A Vision, Architectural Elements, and Future Directions," *IEEE Access*, vol. 8, pp. 147029-147044, Aug. 2020.

General 6G KPI Targets

Peak spectral efficiency 3x

Peak data rate 50x



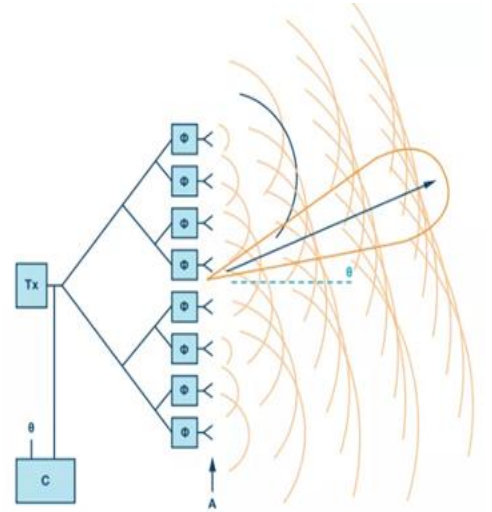
[1] W. Jiang, B. Han, M. A. Habibi and H. D. Schotten, "The Road Towards 6G: A Comprehensive Survey," *IEEE Open J. Commun. Society*, vol. 2, pp. 334-366, Feb. 2021

Current Technology

Multiple input multiple output (MIMO)

- Phase-controlled beamforming achieved by phased array
- Exploit spatial diversity/multiplexing through highly directional bea

- **MIMO → Massive MIMO →Ultra-massive MIMO**
  - Scaling up MIMO and size of phased array for significant capacity enhancement and massive connectivity



4G MIMO

From single-antenna system to multi-antenna system

5G Massive MIMO

Scaling up MIMO by orders of magnitude

6G Ultra-massive MIMO

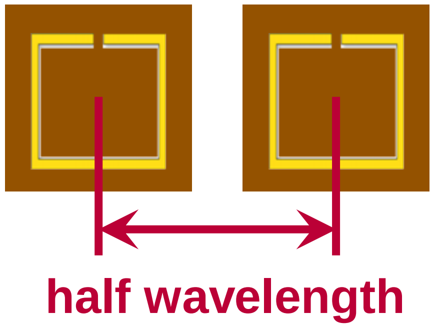
To meet the explosively increasing mobile data demands in 6G era

Dilemma in Conventional Massive MIMO

Ultra-massive MIMO with phased array is hard to realize in practice

- Large element spacing: Half wavelength → Restrict directive gain for a given physical dimension
- Costly hardware components and high power consumption

Novel antenna technologies are required to meet the 6G KPI target.



Large element spacing

Costly components

High power consumption

Solution: Reconfigurable Metamaterial-Based Antenna

Compact element deployment

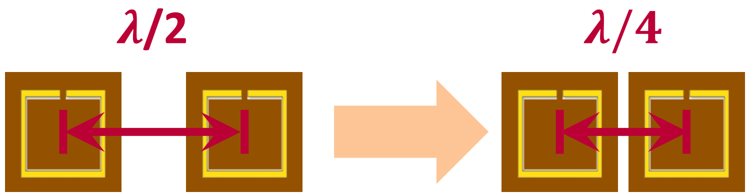
- Element spacing $<$ One quarter wavelength[1]

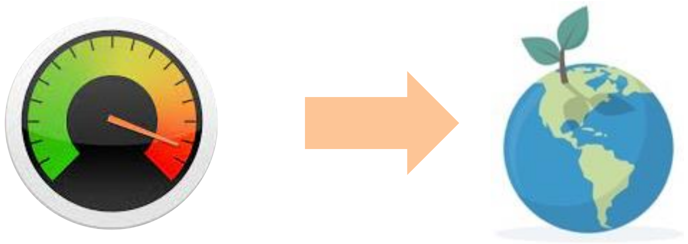
Low hardware cost

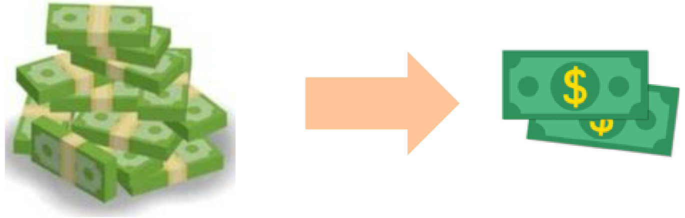
- Regulate electromagnetic waves via software instead of costly hardware components

Low power consumption

- No active amplification internally and complex phase-shifting circuits







Reconfigurable metamaterial-based antenna is a promising solution to realize ultra-massive MIMO

[1] According to the effective medium theory.

Reconfigurable Metamaterial Based Antennas

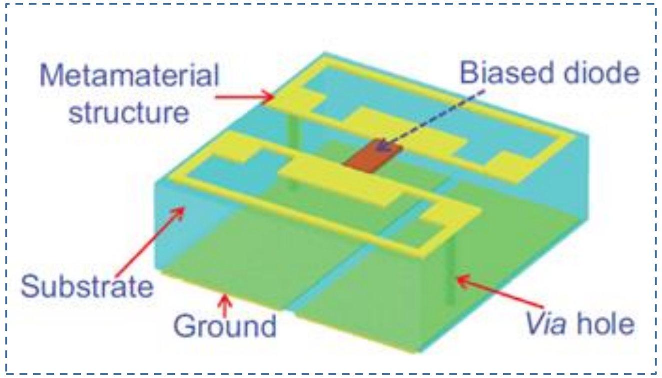
Metamaterials

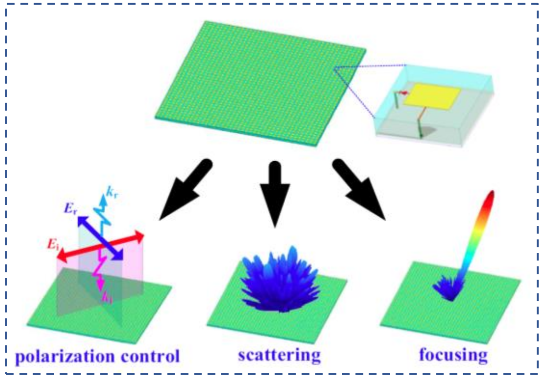
- Metamaterials are artificial structures that are non-existent in natureTwo studying metamaterials – Optics and Microwave

Reconfigurable metamaterials based antennas

- Element spacing can be far less than half-wavelength due to the unique structure
- Powerful electromagnetic (EM) wave control capability by controlling the biased voltage applied to the diodes
  - Dynamic control for polarization, scattering, and pointing of beams

Example of a programmable metamaterial element





Reconfigurable Holographic Surface (RHS)

Ultra-thin reconfigurable metamaterial-based antennas integrated with transceivers

① **The feed** inputs the **reference wave** to antennas, each feed is connected to an RF chain

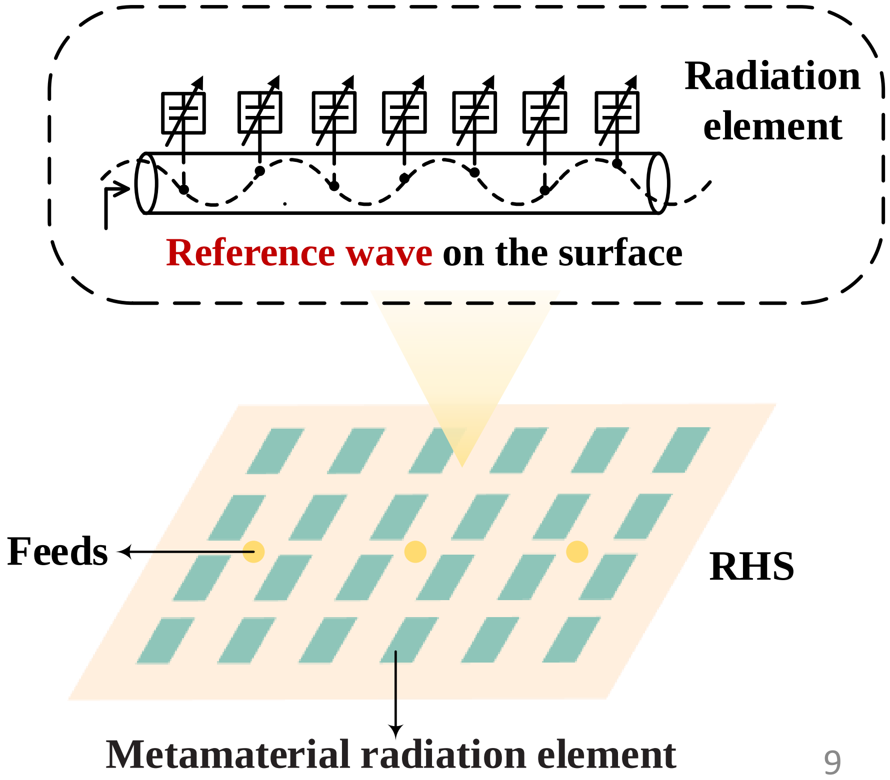
- The reference wave carries the transmit signal

② The reference wave propagates on the surface

③ When the reference wave arrives at each RHS element, it radiates part of energy into the space (i.e., EM response)

- The reference wave is radiated in the free space
- The phase/amplitude response at each RHS element can be controlled by the diode embedded in each element

④ The radiated signals from multiple RHS elements superpose in the free space and form a directional beam



Working Principle

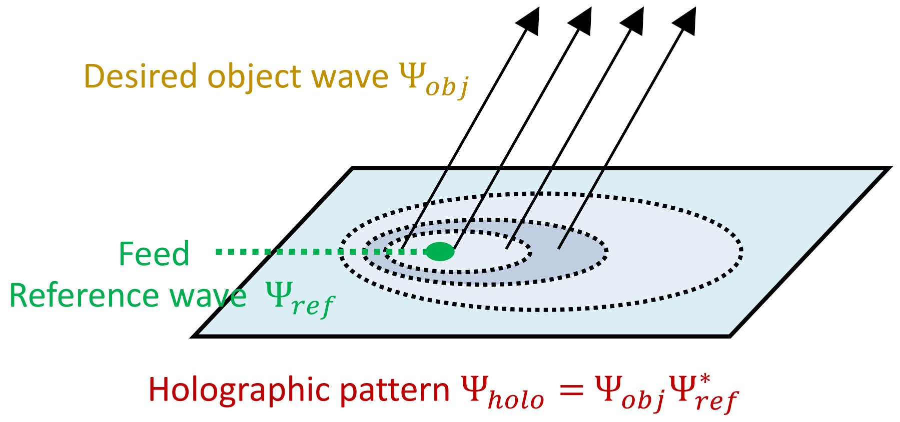
- The feed inputs the reference wave Ψ_{ref} to the surface
- Goal: to generate an objective wave Ψ_{obj} projecting towards the desired direction
- When propagating along the surface, the reference wave interplays with the pre-constructed holographic pattern on the surface, i.e., holographic beamforming is performed.

$$\boxed{\text{Holographic pattern } \Psi_{intf} = \Psi_{obj}\Psi_{ref}^{*}}$$

- After the holographic beamforming, the reference wave turns into the objective wave, projected towards the target direction

$$\boxed{\Psi_{intf}\ \Psi_{ref} \propto \Psi_{obj}|\Psi_{ref}|^{2}}$$

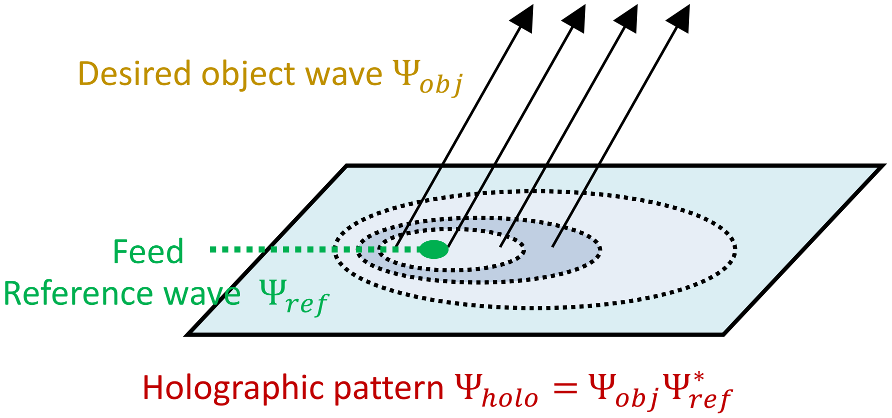
The objective wave is generated



Details of the Working Principle

1. Holographic pattern construction

Reference wave	$\Psi_{ref}\left(\mathbf{r}^{k}_{n_y,n_z}\right) = \exp\left(-j\mathbf{k}_s \cdot \mathbf{r}^{k}_{n_y,n_z}\right)$ Propagation vector of the reference wave ($\mathbf{k}_s$); The distance vector from feed k to the element ($\mathbf{r}^{k}_{n_y,n_z}$)
Objective wave	$\Psi_{obj}\left(\mathbf{r}_{n_y,n_z}, \theta_0, \varphi_0\right) = \exp\left(-j\mathbf{k}_f \cdot \mathbf{r}_{n_y,n_z}\right)$ Propagation vector in free space ($\mathbf{k}_f$); Position of the element ($\mathbf{r}_{n_y,n_z}$)
Holographic pattern	$\Psi_{holo}\left(\mathbf{r}^{k}_{n_y,n_z}, \theta_0, \varphi_0\right) = \Psi_{obj}\Psi^{*}_{ref}$



- The real part of holographic pattern: $\mathrm{Re}[\Psi_{holo}(\mathbf{r}^{k}_{n_y,n_z}, \theta_0, \varphi_0)] = \cos(\boldsymbol{k_s} \cdot \mathbf{r}^{k}_{n_y,n_z} - \boldsymbol{k_f} \cdot \mathbf{r}_{n_y,n_z})$

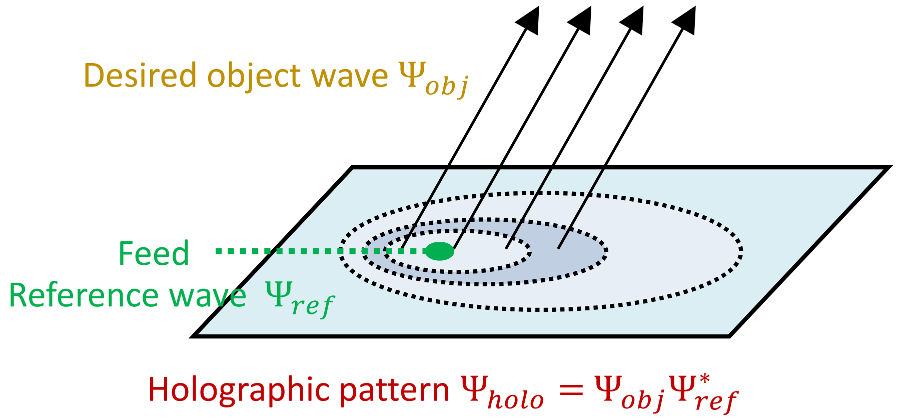
The real part can be used to record such a holographic pattern via the surface

Details of the Working Principle

- To construct the holographic pattern, we record its real-part information using the amplitude response of the element, which can adjusted by the embedded diode:

$$m\left(\mathbf{r}_{n_y,n_z}^{k},\theta_0,\varphi_0\right)=\frac{Re\left[\Psi_{holo}\left(\mathbf{r}_{n_y,n_z}^{k},\theta_0,\varphi_0\right)\right]+1}{2}$$

Key idea: when the phase shift of the transmit signal at an element is different from that of the target signal, the element is detuned and radiates little energy into free space (small amplitude). Otherwise, the element is tuned to radiate much energy (large amplitude).



Details of the Working Principle

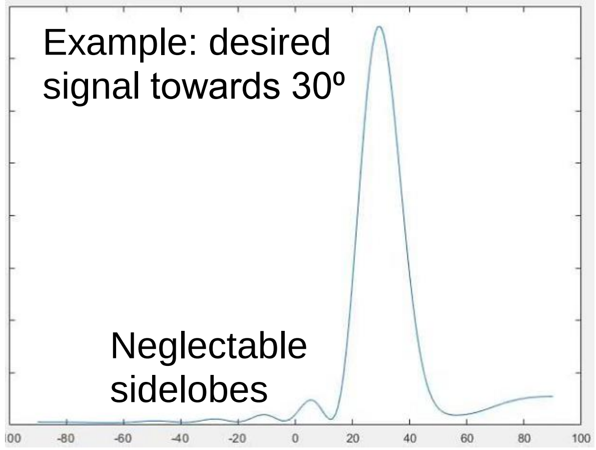
2. Holographic beamforming: generate the objective wave towards the target direction

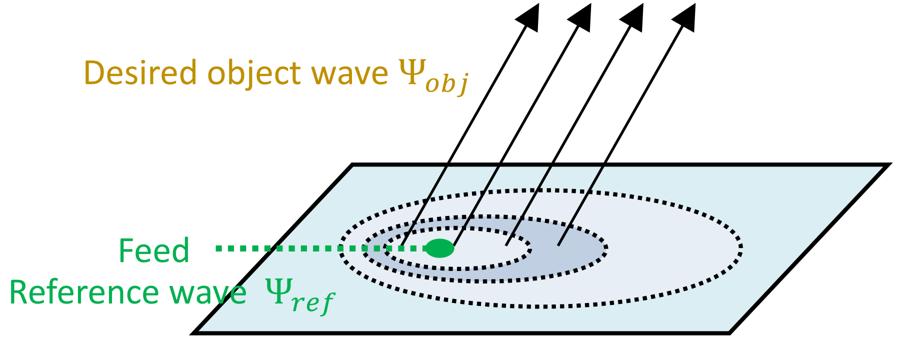
- The reference wave Ψ_{ref} interferes with the holographic pattern ($\mathbf{r}^k_{n_y,n_z}$ is omitted for convenience)

$$
\begin{aligned}
m(\theta_0,\varphi_0)\cdot\Psi_{ref} &= \frac{\mathrm{Re}[\Psi_{holo}(\theta_0,\varphi_0)]+1}{2}\cdot\Psi_{ref} \\
&= \frac{1}{4}\Psi_{obj}(\theta_0,\varphi_0)\left|\Psi_{ref}\right|^2 + \frac{1}{4}\Psi^*_{obj}(\theta_0,\varphi_0)\Psi^2_{ref} + \frac{1}{2}\Psi_{ref} \\
&= \frac{1}{4}\left|\Psi_{ref}\right|^2\Psi_{obj} + \Psi_{obj}\left[\frac{1}{4}\left(\bar{\Psi}_{obj}\Psi_{ref}\right)^2 + \frac{1}{2}\bar{\Psi}_{obj}\Psi_{ref}\right] \\
&= \frac{1}{4}\left(\Psi_{obj}(\theta_0,\varphi_0)\right)\left[\left|\Psi_{ref}\right|^2 + C\right]
\end{aligned}
$$

The desired signal is projected towards the target direction

Neglectable sidelobe item





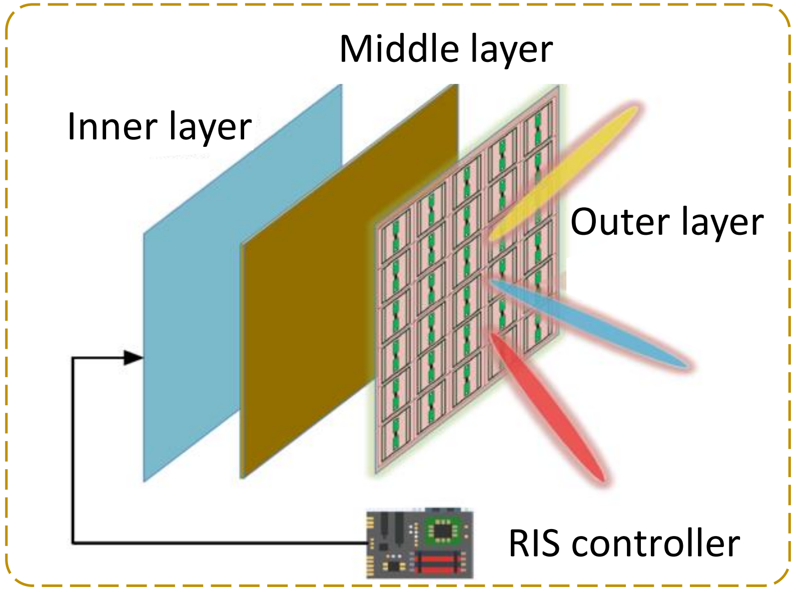
Holographic pattern $\Psi_{holo} = \Psi_{obj}\Psi^*_{ref}$

Differences Between RHS and RIS

Reconfigurable intelligent surface (RIS)

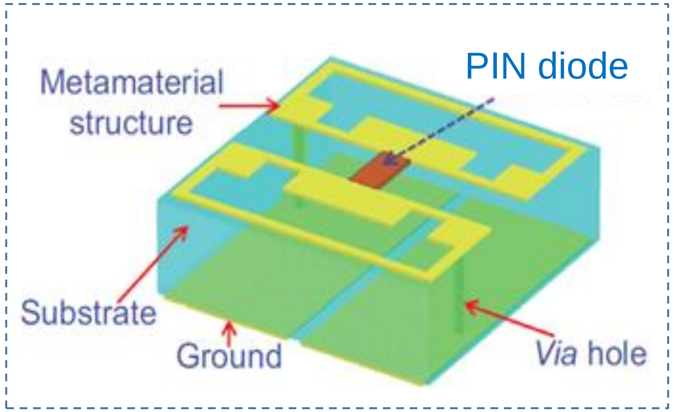
—— An ultra-thin metasurface composed of multiple layers

- **Outer layer**: A 2D-array of RIS elements which directly interacts with incident signals
- **Middle layer**: A copper plate which prevents the signal energy leakage
- **Inner layer**: A printed circuit which connects the RIS elements to the RIS controller



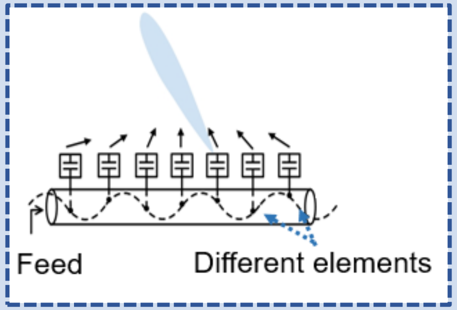
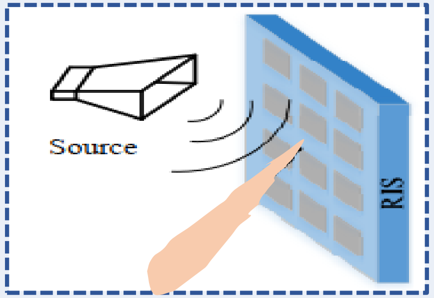
RIS element

- Low-cost sub-wavelength programmable metamaterial particle
- Reflect incident RF signals and impose a controllable phase shift



RIS element

Differences Between RHS and RIS

Technology	Physical Structure	Operating Mechanism	Typical Applications
RHS	① RF front end is integrated into a PCB ② No extra control link	① Leaky-wave antenna ② Series feeding 	① Transmit/Receive antennas ② Mounted on mobile platforms ③ Sensing, microwave imaging
RIS	① RF front end is on the outside of the meta-surface ② Extra control link	① Reflection antenna ② Parallel feeding  Simultaneous reflection	① Passive relays ② Deployed in the cell edge for cell-edge users' performance improvement

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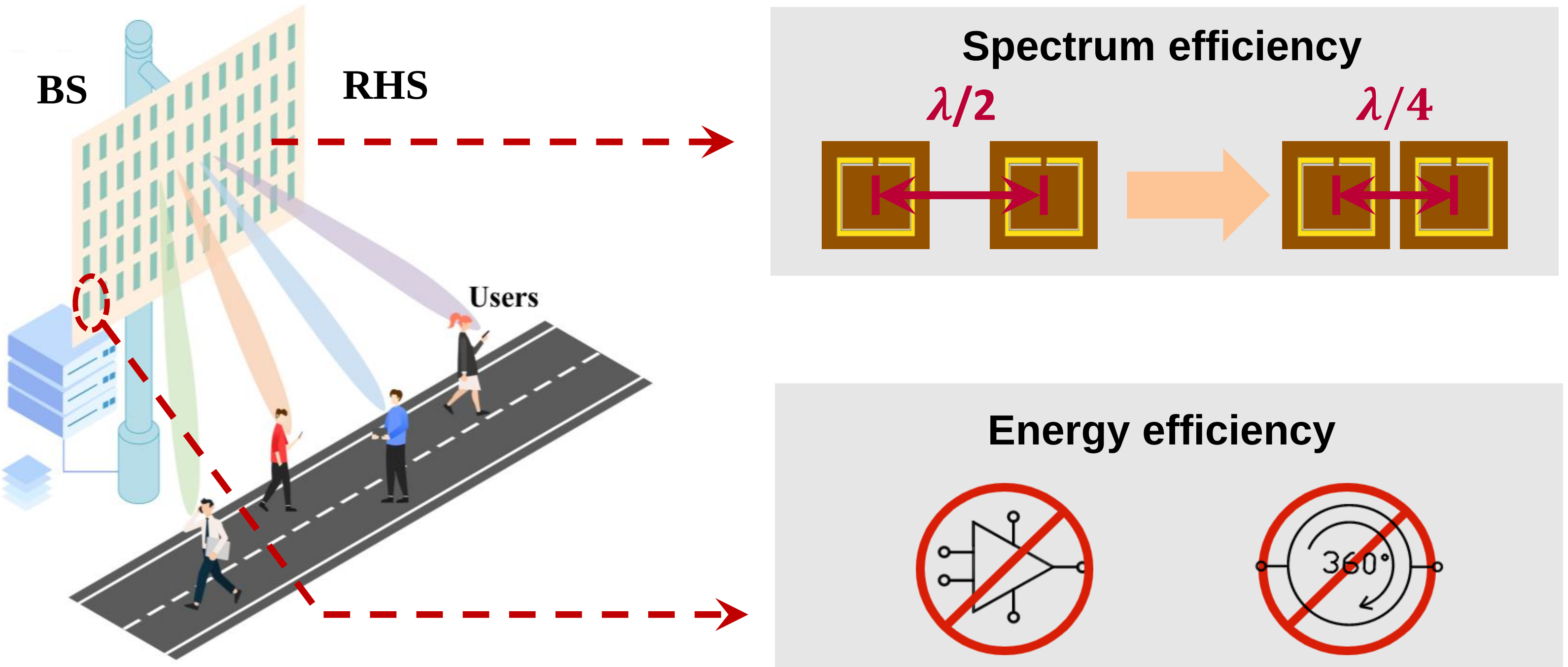
RHS-aided Wireless Communications

Spectrum efficiency enhancement

- Compact element deployment of RHS provides higher spatial diversity gain

Energy efficiency improvement

- RHS has no active amplification internally and complex phase-shifting circuits



Case Study I: RHS-aided Holographic Beamforming

RHS Enabled Multi-User Wireless Communications:

Amplitude-Controlled Holographic Beamforming

① R. Deng, B. Di, H. Zhang, Y. Tan, and L. Song, “Reconfigurable holographic surface: Holographic beamforming for metasurface-aided wireless communications,” IEEE Trans. Veh. Tech., vol. 70, no. 6, pp. 6255-6259, June 2021.

② R. Deng, B. Di, H. Zhang, Y. Tan, and L. Song, “Reconfigurable holographic surface enabled multi-user wireless communications: Amplitude-controlled holographic beamforming,” *IEEE Trans. Wireless Commun.*, early access.

Motivations and Contributions

Motivations

- RHSs provide a promising alternative to traditional large-scale antennas
- Most research only demonstrates the viability of the RHS to achieve multi-beam steering
- It is worthwhile to study the influence of holographic beamforming on system performance improvement in wireless communications

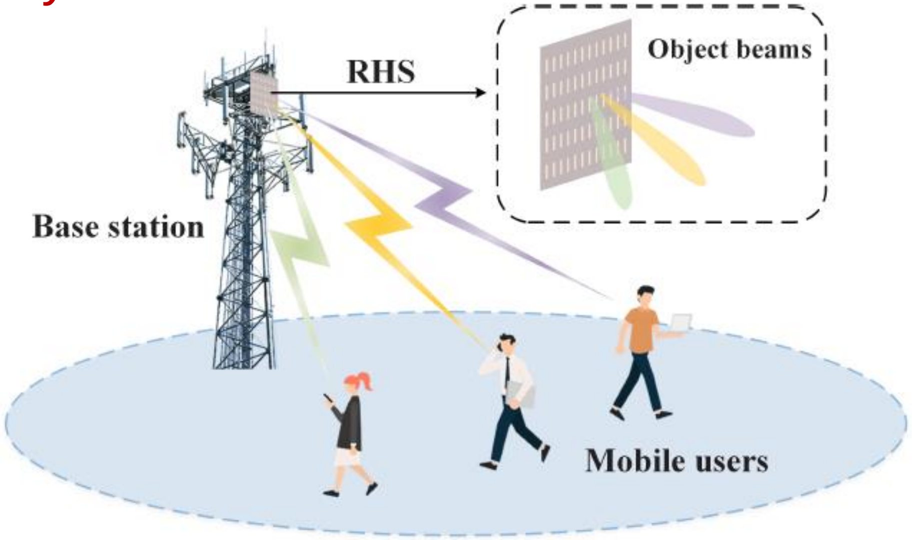
Contributions

- We propose a hybrid beamforming scheme in a downlink RHS-aided multi-user system
    - The BS performs digital beamforming
    - The RHS performs holographic beamforming by leveraging the holographic technique
    - Each user conducts receive combining
- We develop a sum rate maximization algorithm by jointly optimizing the digital beamformer, holographic beamformer, and receive combiner
- Simulation results show that the RHS can achieve a higher sum-rate than a phased array of the same physical dimension

System Model

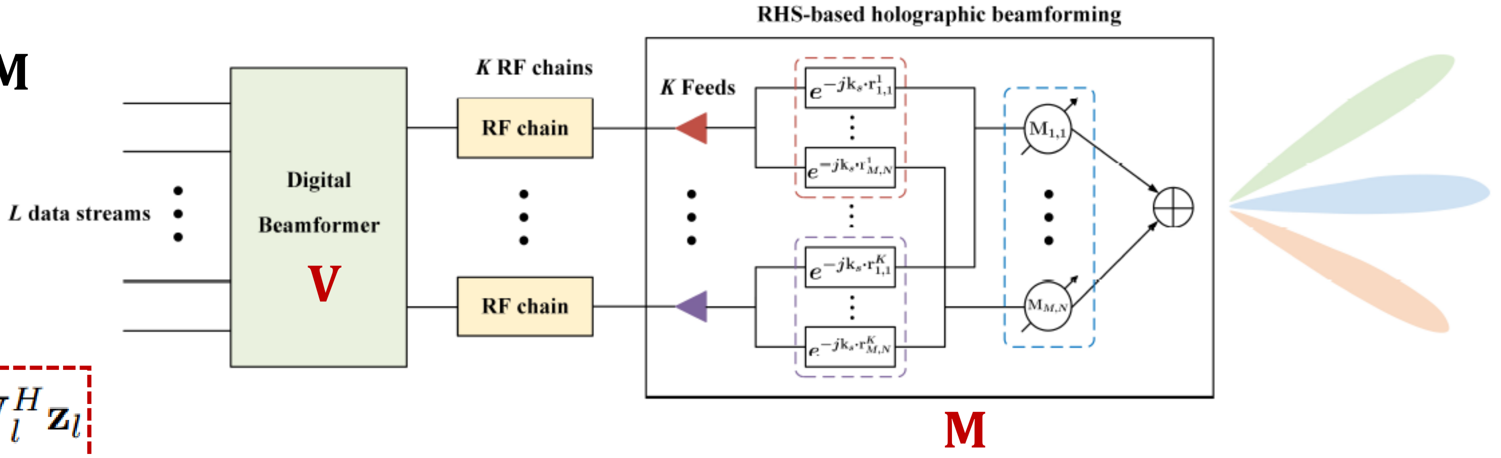
Scenario: downlink RHS-aided multi-user communication system

- A BS equipped with an RHS transmits to L users
- Each user requires a single data stream
- RHS: K feeds, $N_y \times N_z$ radiation elements
- User: J receive antennas



RHS-aided hybrid beamforming

- BS: Digital beamforming $\mathbf{V}$
- RHS: Holographic beamforming $\mathbf{M}$
- User: Receive combiner $\mathbf{W}$



$$y_l = \mathbf{W}_l^H \mathbf{H}_l \mathbf{M} \mathbf{V}_l \overset{\text{Transmit signal}}{\mathbf{s}_l} + \overbrace{\boxed{\mathbf{W}_l^H \mathbf{H}_l \mathbf{M} \sum_{l' \neq l} \mathbf{V}_{l'} \mathbf{s}_{l'}}}^{\text{Interference}} + \underbrace{\boxed{\mathbf{W}_l^H \mathbf{z}_l}}_{\text{Noise}}$$

Problem Formulation

Achievable rate of each user

Channel matrix between RHS and user l

$$R_l = \log_2\left(1 + \frac{|\mathbf{W}_l^H \mathbf{H}_l \mathbf{M} \mathbf{V}_l|^2}{J\sigma^2 + \sum_{l' \neq l} |\mathbf{W}_l^H \mathbf{H}_l \mathbf{M} \mathbf{V}_{l'}|^2}\right)$$

Sum rate maximization problem

$$\max_{\{\mathbf{W}, \mathbf{V}, m_{n_y,n_z}\}} \sum_{l=1}^{L} R_l$$

$$s.t. \quad |\mathbf{W}_l(j)|^2 = 1,$$

$$\mathrm{Tr}(\mathbf{V}\mathbf{V}^H) \leq P_T,$$

$$\sum_{n_y=1}^{N_y} \sum_{n_z=1}^{N_z} \eta \cdot m_{n_x,n_y}^2 \leq 1.$$

$$0 \leq m_{n_y,n_z} \leq 1, \forall n_y, n_z,$$

Problem

Decomposition

$$\max_{\{\mathbf{W}\}} \sum_{l=1}^{L} R_l$$

$$s.t. \quad |\mathbf{W}_l(j)|^2 = 1$$

RF combiner design

$$\max_{\{\mathbf{V}\}} \sum_{l=1}^{L} R_l$$

$$s.t. \quad \mathrm{Tr}(\mathbf{V}^H\mathbf{V}) \leq P_T$$

Digital beamforming

$$\max_{\{m_{n_y,n_z}\}} \sum_{l=1}^{L} R_l$$

Holographic beamforming

$$s.t. \quad \sum_{n_y=1}^{N_y} \sum_{n_z=1}^{N_z} \eta \cdot m_{n_x,n_y}^2 \leq 1$$

$$0 \leq m_{n_y,n_z} \leq 1, \forall n_y, n_z,$$

(To be explained on next page)

Holographic Beamforming

Holographic beamformer: $\mathbf{M} \in \mathbb{C}^{N_y N_z \times K}$

$$M_{n_y,n_z}^k = \sqrt{\eta} \cdot m_{n_y,n_z} \cdot e^{-\alpha|\mathbf{r}_{n_y,n_z}^k|} \cdot e^{-j\mathbf{k}_s \cdot \mathbf{r}_{n_y,n_z}^k}$$

- $e^{-j\mathbf{k}_s \cdot \mathbf{r}_{n_y,n_z}^k}$: Phase of the reference wave (the reference wave carries the transmit signal)
- $e^{-\alpha|\mathbf{r}_{n_y,n_z}^k|}$: Amplitude attenuation of the reference wave during its propagation process

Energy conservation constraint

- Define the ratio of the power accepted by the RHS element P_a to the total power P_t: $\eta = \frac{P_a}{P_t}$
- Since the radiation amplitude of each RHS element: m_{n_y,n_z}
- We present the radiated power from each RHS element as: $\eta P_t m_{n_y,n_z}^2$
- The sum of the radiated power from each RHS element should be no larger than P_t

$$\sum_{n_y=1}^{N_y} \sum_{n_z=1}^{N_z} \eta P_t \cdot m_{n_y,n_z}^2 \le P_t \quad \Rightarrow \quad \sum_{n_y=1}^{N_y} \sum_{n_z=1}^{N_z} \eta \cdot m_{n_x,n_y}^2 \le 1$$

Sum Rate Maximization Algorithm

Overall iterative algorithm

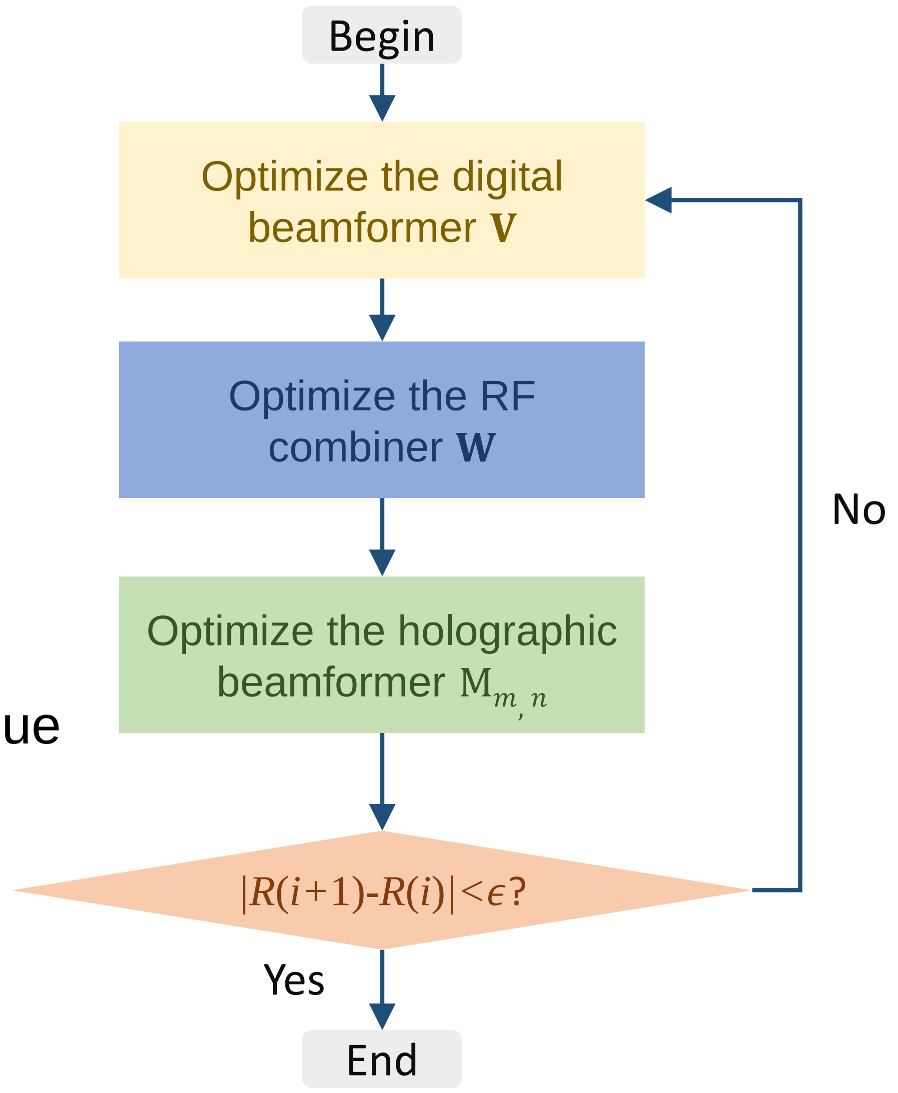
- The three subproblems will be solved alternatively
- Until the difference of the sum rate R between two adjacent iterations (i and i+1) is less than a predefined threshold ϵ

Solutions to sub-problems

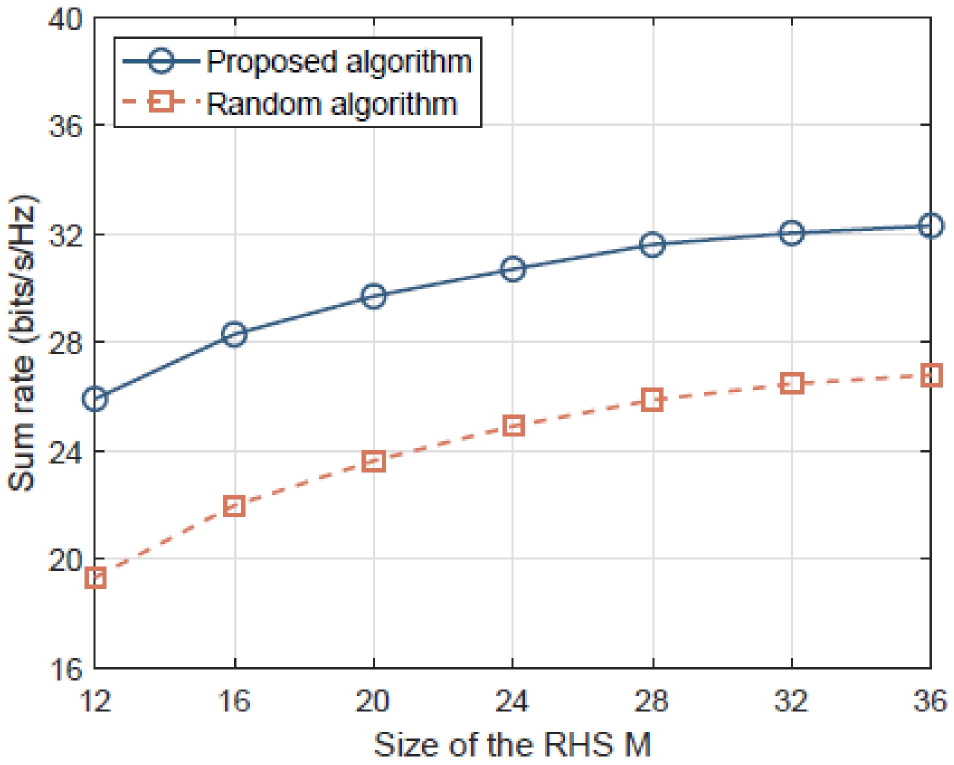
- Digital beamforming: Zero-forcing+ Power allocation
- RF combiner: Iterative coordinate descent algorithm
- Holographic beamforming: Fractional programming technique
  - Eliminate the non-convex ratio $\frac{|\mathbf{W}_l^H \mathbf{H}_l \mathbf{M} \mathbf{V}_l|^2}{J\sigma^2 + \sum_{l' \neq l} |\mathbf{W}_l^H \mathbf{H}_l \mathbf{M} \mathbf{V}_{l'}|^2}$ in R_l and recast R_l into the maxima of a concave function

$$\max_{x} \frac{A(x)}{B(x)}, \quad s.t.\, x \in X$$

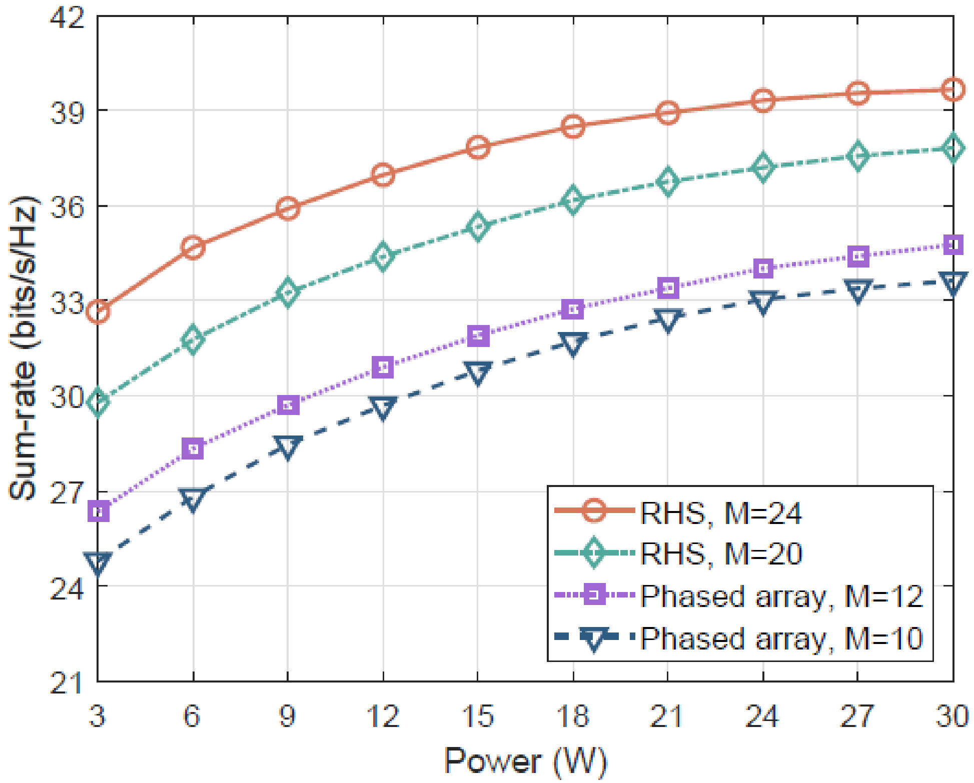
$$\max_{x,y} 2y\sqrt{A(x)} - y^2 B(x), \quad s.t.\, x \in X$$



Simulation Results



- The sum rate grows rapidly with a small size of RHS and gradually flattens as the size of RHS continues to increase.



- The RHS can achieve a higher sum-rate than a phased array of the same physical dimension.

Case Study II: Multiple Access Technology Based on RHS

HDMA:

Holographic-Pattern Division Multiple Access

R. Deng, B. Di, H. Zhang, and L. Song, “HDMA: Holographic-pattern division multiple access,” *IEEE J. Sel. Areas Commun.*, vol. 40, no. 4, pp. 1317-1332, Apr. 2022.

Motivations and Contributions

Motivations

- The optimization for the holographic beamformer is with high complexity
  - The number of optimization variables is equal to the number of RHS elements
- The RHS provides a new multiple access method through the superposition of holographic patterns corresponding to different users with low complexity

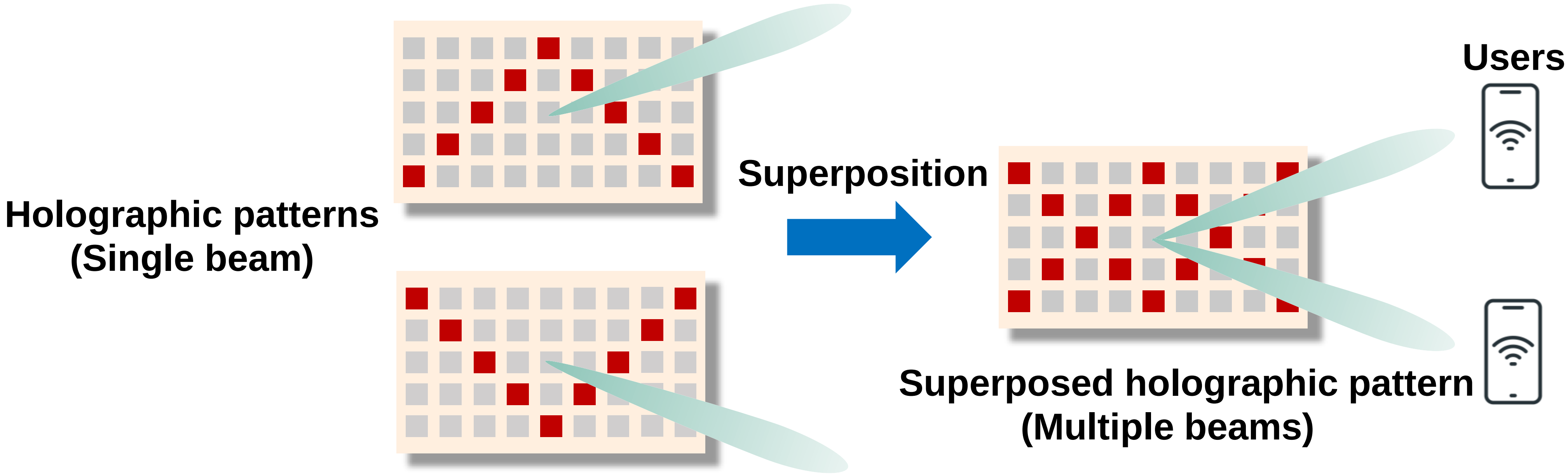
Contributions

- We propose a novel multiple access technique based on the superposition of holographic patterns, called holographic-pattern division multiple access (HDMA)
- With the same element spacing, the HDMA provides a more cost-effective solution for pursuing high data rate compared with traditional SDMA
- Due to the compact element spacing of the RHS, the HDMA has great potential in capacity improvement and enhancing massive connectivity

Holographic-Pattern Division Multiple Access

Principle of HDMA

- Map the transmitted data onto a single holographic pattern utilizing the superposition of the holographic patterns corresponding a single beam
- Based on the superposed holographic pattern, the RHS can control the radiation amplitude of the leaky wave at each element to generate multiple desired beams



Holographic Pattern Superposition

Holographic pattern corresponding to a single directional beam

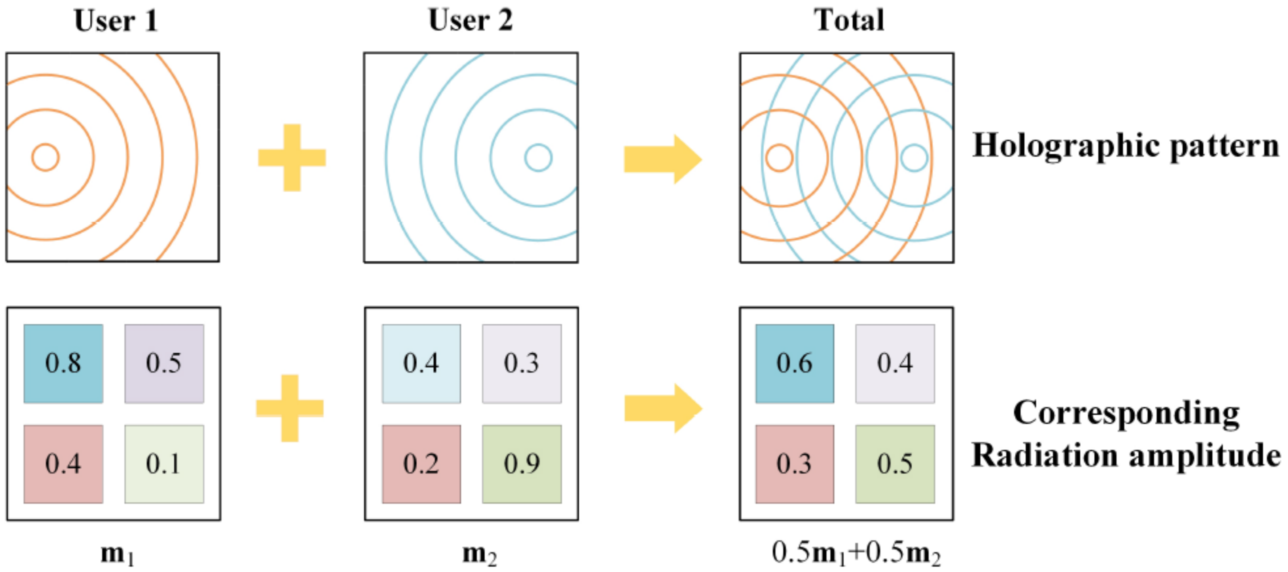
$$m(\mathbf{r}^k_{n_y,n_z}, \theta_0, \varphi_0) = \frac{\mathrm{Re}[\Psi_{intf}(\mathbf{r}^k_{n_y,n_z}, \theta_0, \varphi_0)] + 1}{2}$$

The **superposed holographic pattern** is a weighted summation of the radiation amplitude distribution corresponding to each object beam

$$m_{n_y,n_z} = \sum_{l=1}^{L}\sum_{k=1}^{K} a_{l,k} m(\mathbf{r}^k_{n_y,n_z}, \theta_l, \varphi_l)$$

Amplitude ratio for the beam pointing to user l from feed k

Direction of the l-th user



HDMA System Performance

System capacity can be rewritten as

$$C = \sum_{l=1}^{L} \log_2 \left(1 + \frac{P_l \lambda^2 G_l A \eta d_l^2}{\sigma^2 \pi^2 d_y^2 d_z^2} \sum_{k=1}^{K} a_{l,k}^2 f(S) \right)$$

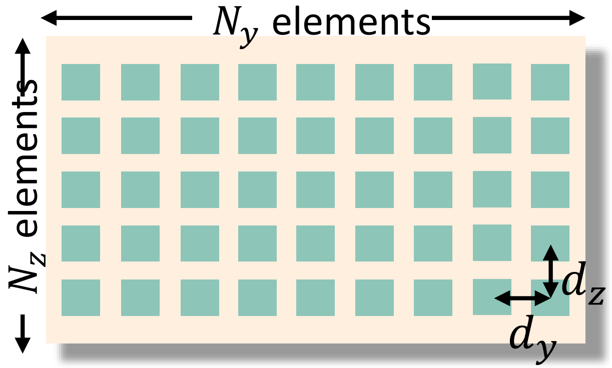
Physical dimension of the RHS: $N_y d_y \times N_z d_z$

$f(S)$ is a function of the physical dimension, which is independent of the element spacing

The relation between system capacity and number of RHS elements

- When the physical dimension $N_y d_y \times N_z d_z$ is fixed $\rightarrow f(S)$ is a constant

$$C \propto \log_2 (d_y d_z)^{-1} \quad \xleftrightarrow{N \propto (d_y d_z)^{-1}} \quad C \propto \log_2 N$$



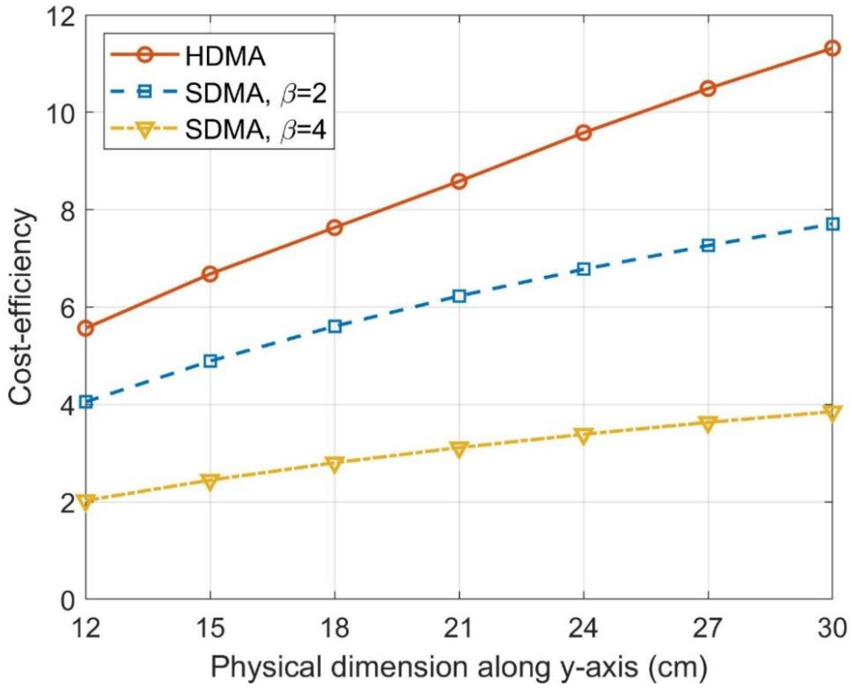
$\boldsymbol{N = N_y N_z}$

Comparison Between HDMA and SDMA

Cost efficiency: the ratio of the sum rate to the hardware cost

- Cost ratio of the phased array to RHS given the same element number is about 2~10
  - Cost ratio: $\beta = \frac{\text{Hardware cost of a phased array with N elements}}{\text{Hardware cost of an RHS with N elements}}$
- The physical dimension as well as the element spacing of the phased array and those of the RHS is set as the same

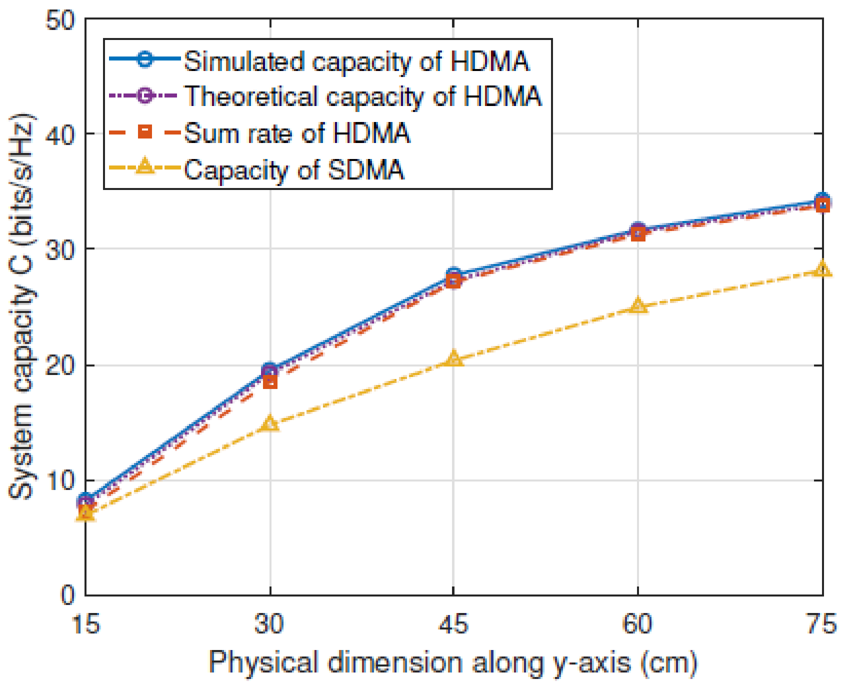
The superiority of the HDMA scheme in cost savings becomes clearer with the number of elements N and the cost ratio β.

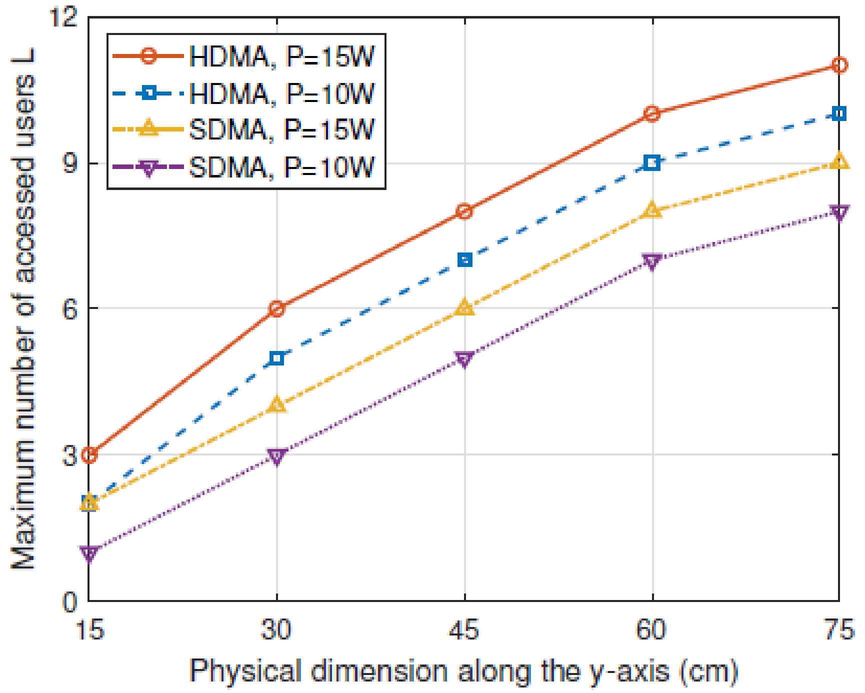


Comparison Between HDMA and SDMA

Performance metrics: capacity and number of accessed users

- The element spacing of the phased array is half wavelength, while that of the RHS is one quarter wavelength





Due to the compact element spacing, the HDMA scheme outperforms the SDMA scheme in terms of capacity and number of accessed users

Outline

Background

- 6G Communications and Requirements
- Reconfigurable Holographic Surface (RHS) Basics

RHS-aided Wireless Communications

- RHS-aided Holographic Beamforming
- HDMA: Holographic-Pattern Division Multiple Access

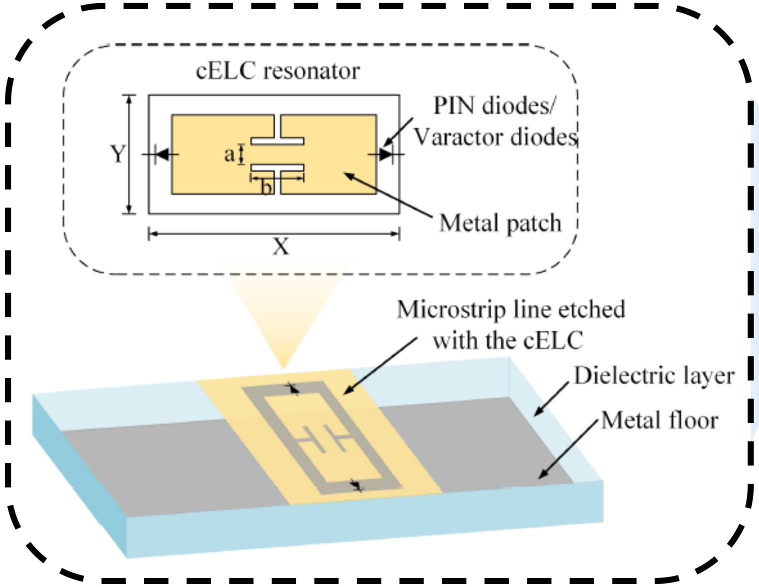
Physical Implementations and Prototypes

- Implementation of RHS
- RHS-aided Communication Platform

Future Research Directions

Conclusion

Physical Implementation



RHS element structure

RHS element design

RHS antenna array design

- Design the space between two adjacent elements
- Impedance matching

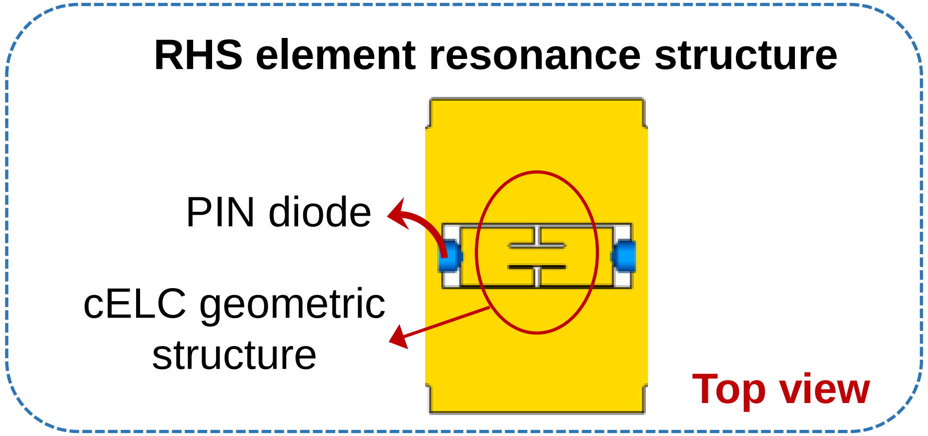
Amplitude control based holographic beamforming

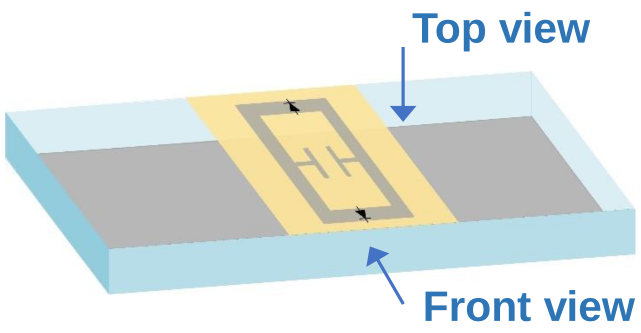
- Adjust biased voltage applied to the diodes
- Radiation amplitude of the element changes

RHS Element Design

RHS element resonance structure

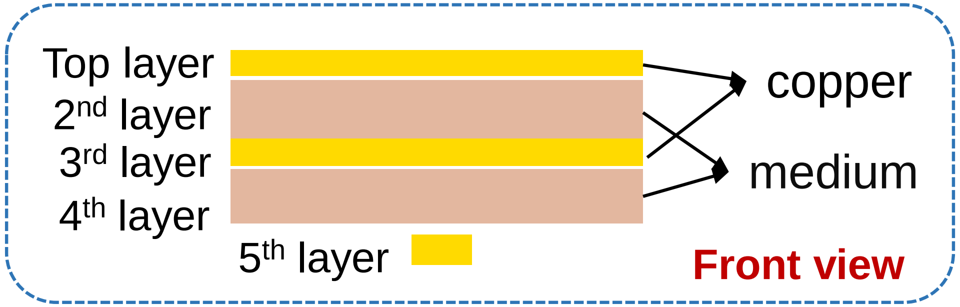
- We adopt the cELC geometric structure, which has multiple geometric parameters for flexible design
- The PIN diode is embedded in the resonance structure, controlled by the DC feed on the fifth layer





Each RHS element consists of five layers

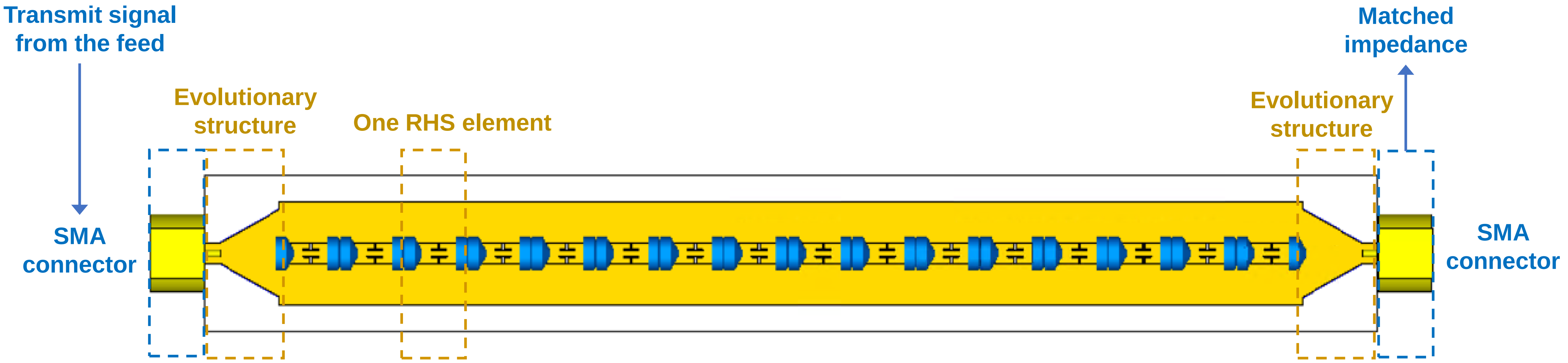
- From top to bottom are copper, medium (F4B), ground (copper), medium (F4B), and DC feed (copper) which provides biased voltage for PIN diodes



RHS Antenna Array

The RHS antenna array consists of multiple elements, two SMA connectors, and two symmetric evolutionary structures

- SMA connector: connects to the feed which sends the transmit signals
- Evolutionary structure: designed for impedance matching



Holographic Beamforming

Binary amplitude control

- PIN diodes OFF at each RHS element: Radiate much energy into free space → State “1”
- PIN diodes ON at each RHS element: Radiate little energy into free space → State “0”

Holographic beamforming: control the ON/OFF state of each RHS element

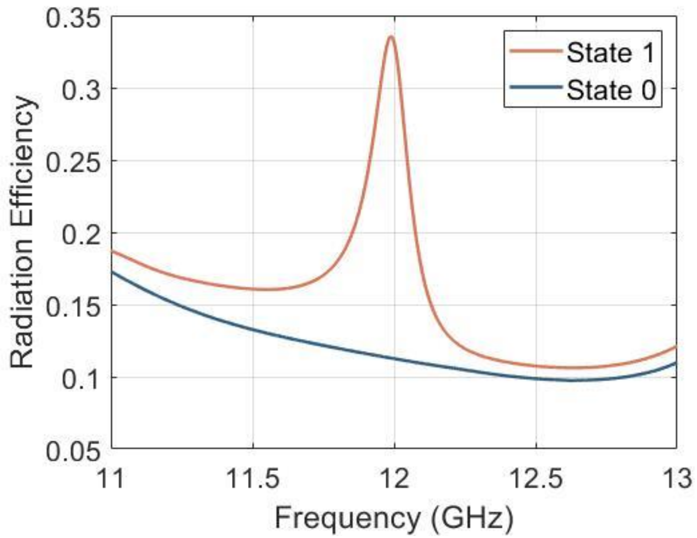
- The radiation amplitude of an RHS element at position (n_y, n_z) is

$$m\left(\mathbf{r}_{n_y,n_z}, \theta_0, \varphi_0\right) = \frac{Re\left[\Psi_{holo}\left(\mathbf{r}^k_{n_y,n_z}, \theta_0, \varphi_0\right)\right] + 1}{2}$$

Discretization

$$\widehat{m}_{n_y,n_z} = \begin{cases} 1 & m_{n_y,n_z} \geq 0.5 \\ 0 & m_{n_y,n_z} < 0.5 \end{cases}$$

- The radiation efficiency varies at different states, verifying the effectiveness of amplitude control



Full-Wave Analyses

Full-wave analyses of RHSs with different sizes

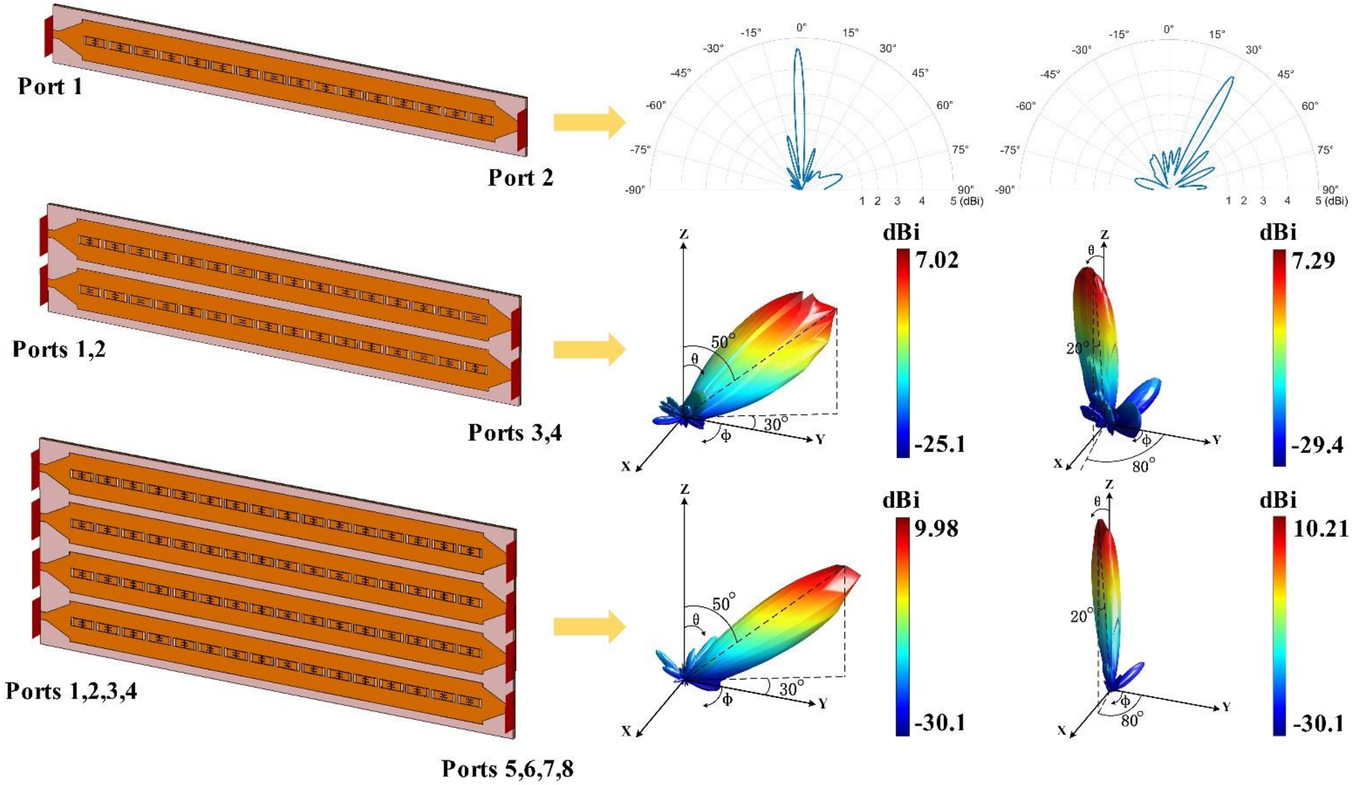
- One-dimensional RHS with 16 elements: Target angle 0°, 30°
- Two-dimensional RHSs with 32 and 64 elements: Target angle (330°, 50°), (80°, 20°)

elevation angle

azimuth angle

Simulated results

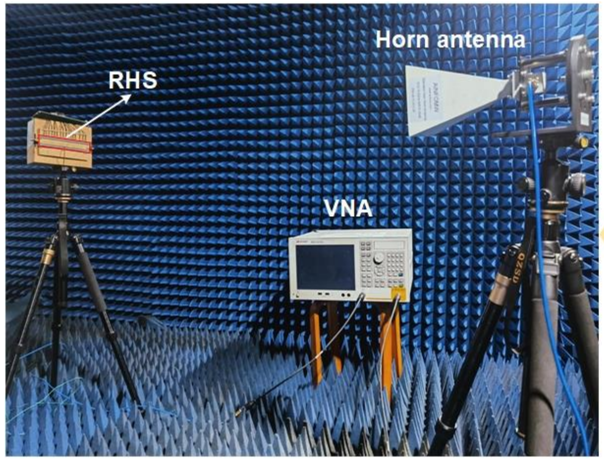
- The direction of main-lobe matches the theoretical target angle
- RHS with more elements can generate a main-lobe with narrower beam-width
- When the number of RHS elements doubles, the antenna gain increases about 3 dB

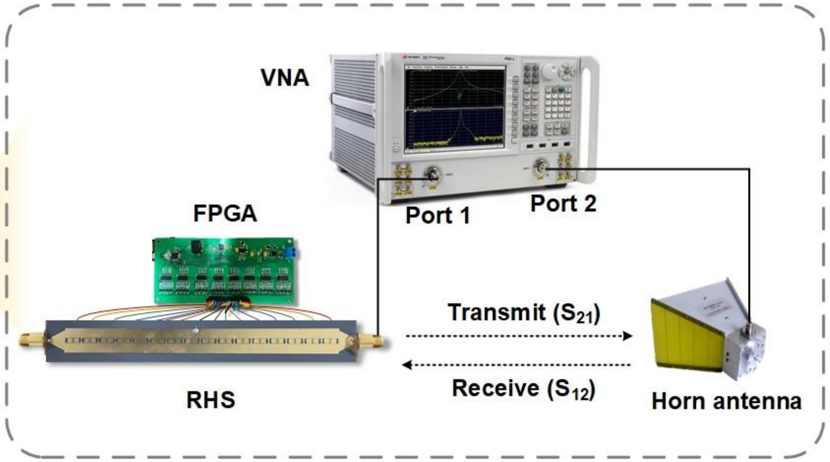


Prototype of the RHS

RHS beam pattern measurement

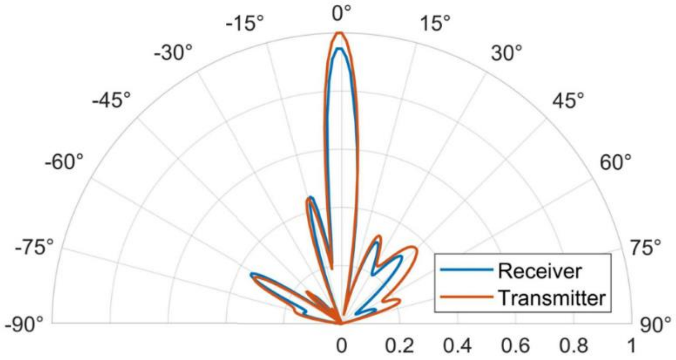
- Control circuit (FPGA) for PIN diodes state control
- Vector network analyzer (VNA) for measurement
- Standard horn antenna



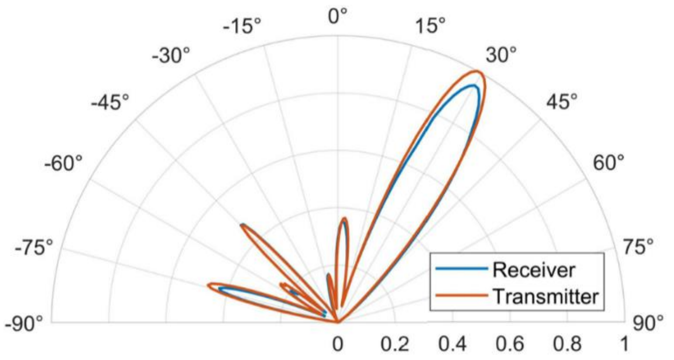


Experimental results of one-dimensional RHS

- Good agreement between the experiment and the full-wave analysis
- Transmit and receive beam patterns are almost the same
  → Transceiver reciprocity



Theoretical angle: 0°

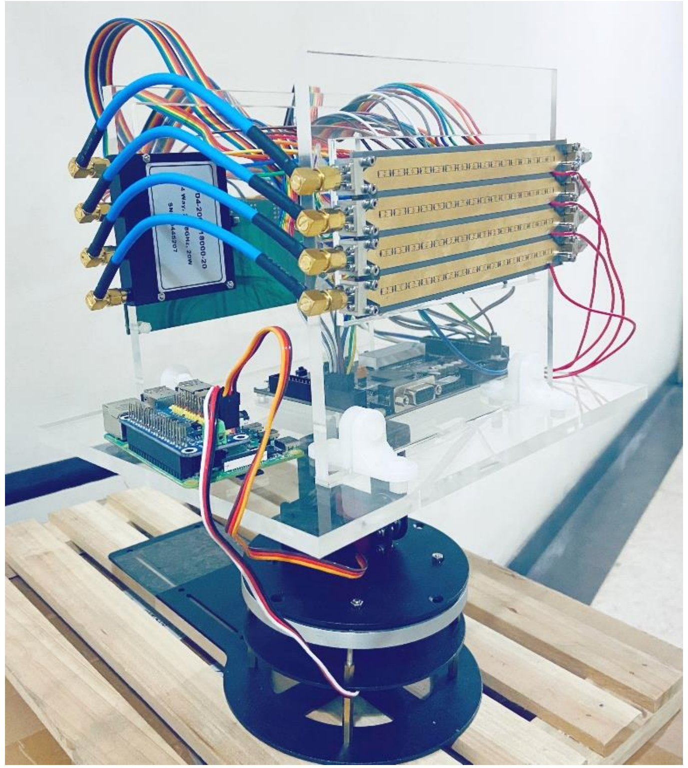


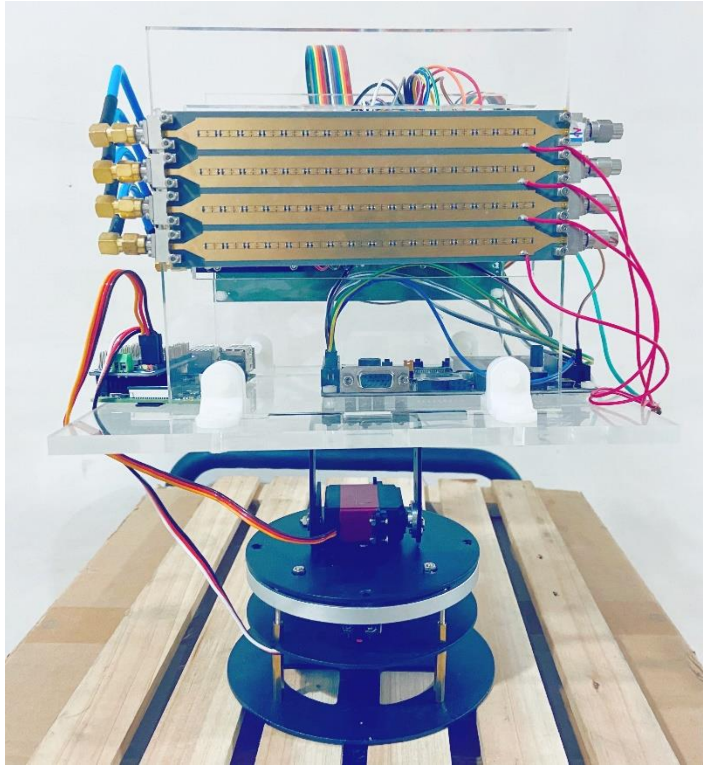
Theoretical angle: 30°

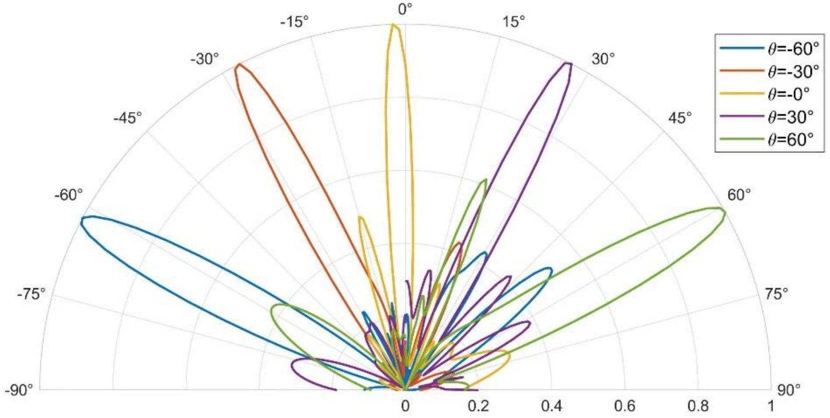
Prototype of the RHS

Experimental results of two-dimensional RHS

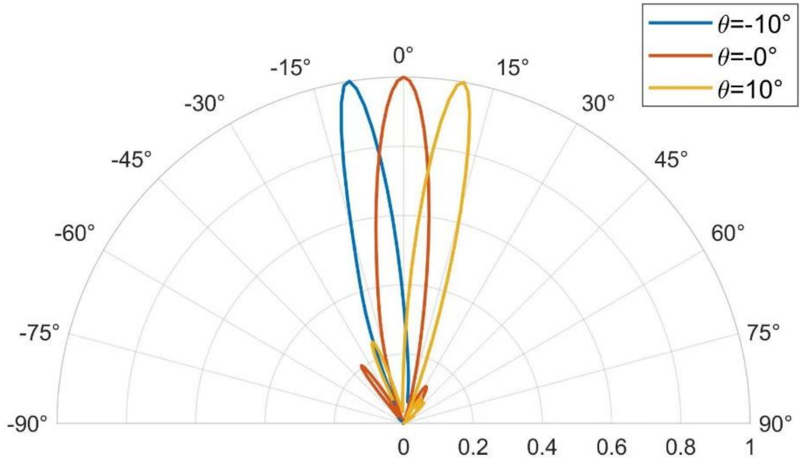
- We show the beam pattern obtained by the three-dimensional holographic beamforming





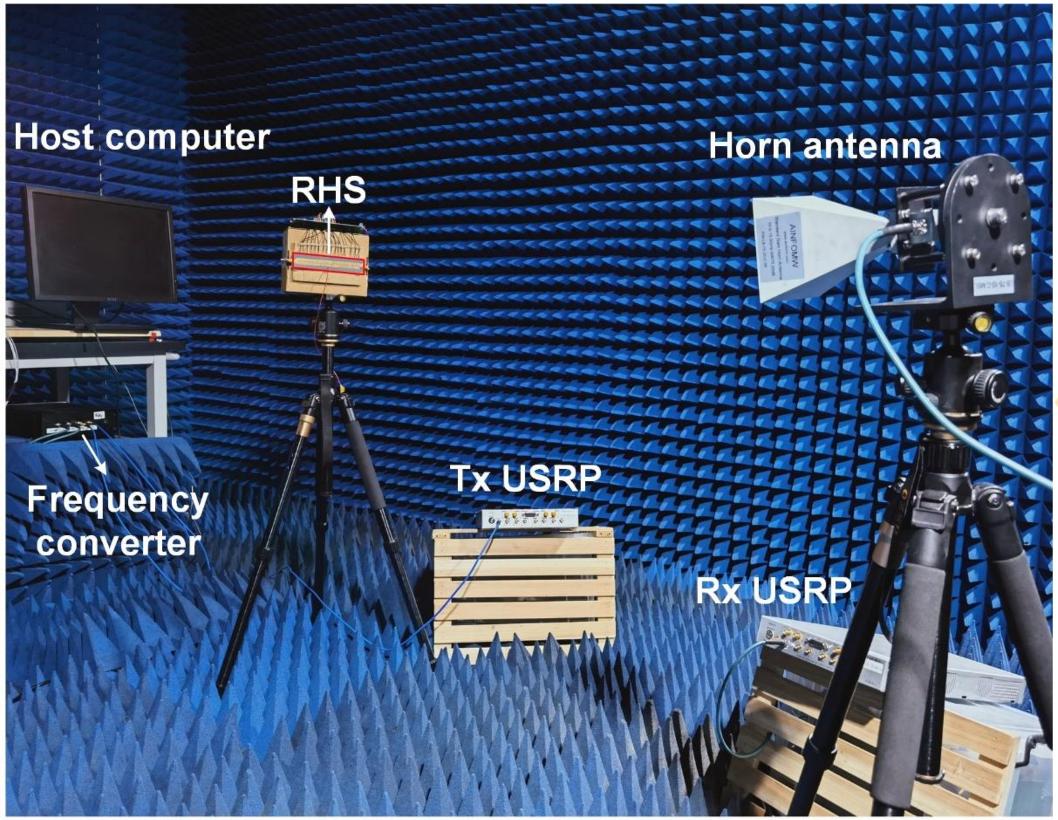


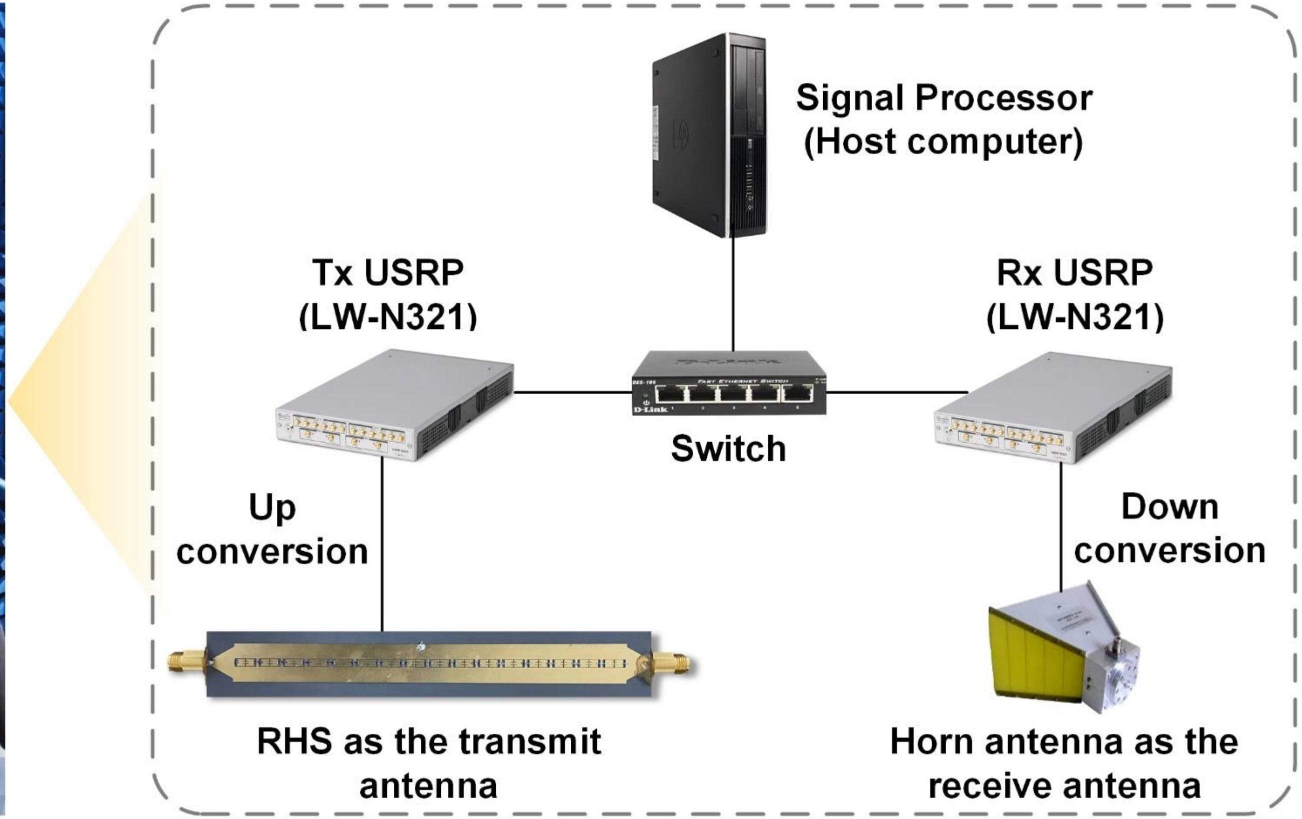
E-plane pattern



H-plane pattern

RHS-Aided Communication Platform

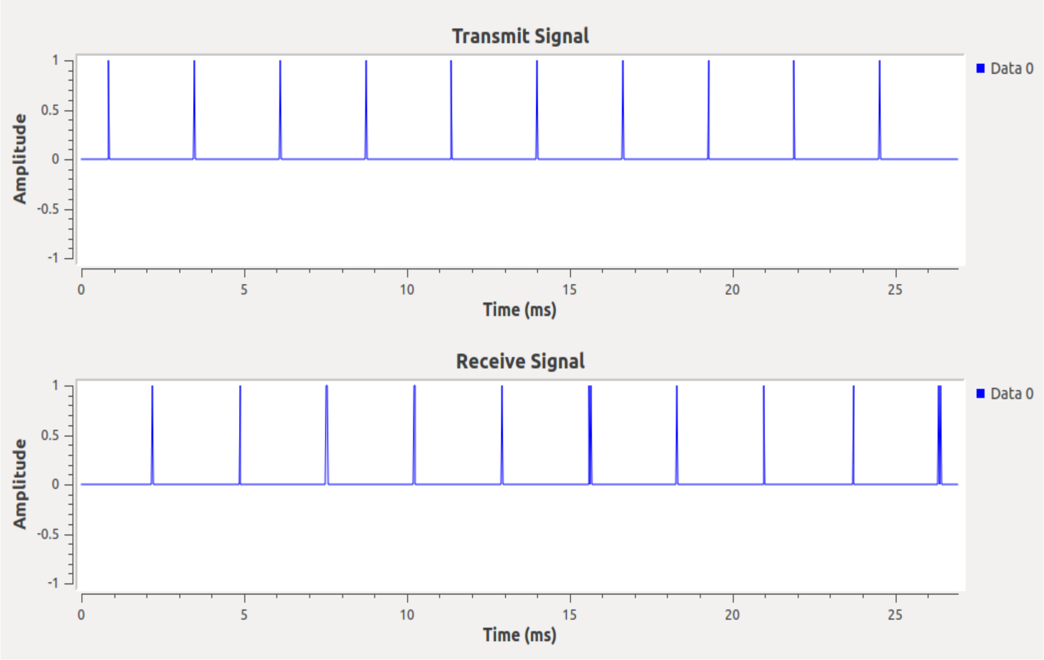




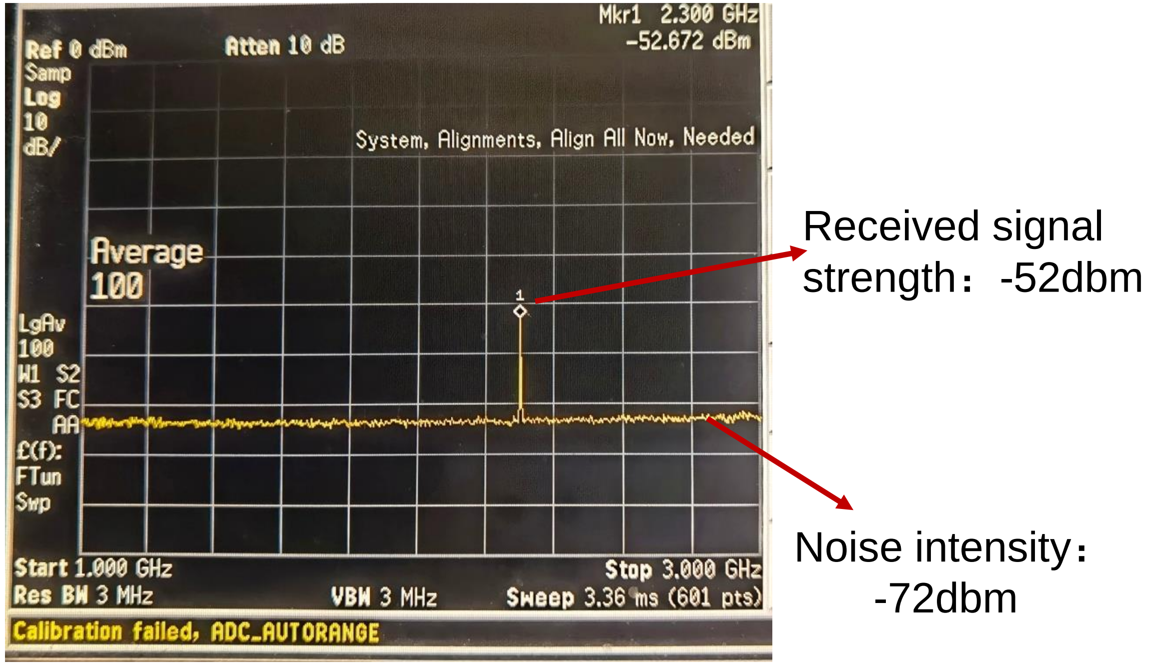
- **Experimental environment**：Microwave anechoic chamber
- **Experimental equipment**: Tx/Rx USRP (RF modulation/demodulation, baseband signal processing), Frequency converter, Ethernet switch, RHS, Horn antenna (LB-75-20-C-SF)

* Photo shows the actual metasurface prototype used as the testbed in PKU lab.

Experimental Results



Visual interface of Tx and Rx signals



Spectrum analyzer at Rx USRP

- The RHS-aided point-to-point communication platform supports real-time data transmission
- Under the experimental environment, SNR = 20dB， Data rate = 6.65bits/s/Hz

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Future Direction

- **Key Techniques**
  - RHS size design
  - Element spacing design
  - Channel estimation
  - Resource management
- **Applications**
  - Satellite communications: beam tracking
  - Vehicle networks: mobility and doppler effect
  - Localization: coupled with position estimation

Publication

1. B. Di, “Reconfigurable holographic metasurface aided wideband OFDM communications against beam squint,” *IEEE Trans. Veh. Tech.*, vol. 70, no. 5, pp. 5099-5103, May 2021.
2. R. Deng, B. Di, H. Zhang, Y. Tan, and L. Song, “Reconfigurable holographic surface: Holographic beamforming for metasurface-aided wireless communications,” *IEEE Trans. Veh. Tech.*, vol. 70, no. 6, pp. 6255-6259, June 2021.
3. R. Deng, B. Di, H. Zhang, D. Niyato, Z. Han, H. V. Poor, and L. Song, “Reconfigurable holographic surfaces for future wireless communications,” *IEEE Wireless Commun.*, vol. 28, no. 6, pp. 126-131, Dec. 2021.
4. R. Deng, B. Di, H. Zhang, and L. Song, “HDMA: Holographic-pattern division multiple access,” *IEEE J. Sel. Areas Commun*., vol. 40, no. 4, pp. 1317-1332, Apr. 2022.
5. R. Deng, B. Di, H. Zhang, Y. Tan, and L. Song, “Reconfigurable holographic surface enabled multi-user wireless communications: Amplitude-controlled holographic beamforming,” *IEEE Trans. Wireless Commun.*, early access.
6. H. Zhang, H. Zhang, B. Di, M. Di Renzo, Z. Han, H. V. Poor, and L. Song, “Holographic integrated sensing and communication,” *IEEE J. Sel. Areas Commun.*, vol. 40, no. 7, pp. 2114-2130, Jul. 2022.
7. X. Hu, R. Deng, B. Di, H. Zhang, and L. Song, “Holographic beamforming for ultra massive MIMO with limited radiation amplitudes: How many quantized bits do we need?” *IEEE Commun. Lett.*, vol. 26, no. 6, pp. 1403-1407, Jun. 2022.
8. R. Deng, B. Di, H. Zhang, H. V. Poor, and L. Song, “Holographic satellite communications by reconfigurable metasurfaces,” *IEEE J. Sel. Areas Commun.*, to appear.
9. X. Zhang, H. Zhang, H. Zhang, and B. Di, "Holographic Radar: Target Detection Enabled by Reconfigurable Holographic Surfaces," *IEEE Commun. Lett*., under revision.
10. R. Deng, Y. Zhang, H. Zhang, B. Di, H. Zhang, and L. Song, “Reconfigurable Holographic Surface: A New Paradigm to Implement Holographic Radio,” *IEEE Veh. Technol. Mag.,* submitted.
11. H. Zhang, H. Zhang, B. Di, and L. Song, “Holographic Integrated Sensing and Communications: Principles, Technology, and Implementation”, *IEEE Wireless Commun.,* submitted.

Conclusion

RHS provides a promising alternative to traditional large-scale antennas

- An ultra-thin, lightweight metamaterial antenna
- A more cost-effective solution for pursing high data rates
- A great potential in capacity improvement and enhancing massive connectivity

We explore different aspects related to RHS-aided communications

- Amplitude-controlled holographic beamforming design
- A novel multiple access technique: HDMA
- Implementation of an RHS-aided communication platform supporting real-time transmission

Future Applications

- Satellite communications: beam tracking
- Vehicle networks: mobility and doppler effect
- Localization: coupled with position estimation

Upcoming Tutorials

- **Lingyang Song, Zhu Han, Boya Di, and Hongliang Zhang, "Holographic Radio: A New Paradigm for Ultra-Massive MIMO", IEEE GLOBECOM, Rio de Janeiro, Brazil, Dec. 4th, 2022.**

- **Boya Di, Hongliang Zhang, Lingyang Song "Holographic Radio: A New Paradigm for Ultra-Massive MIMO", IEEE ICCC, Foshan, Aug. 11th, 2022.**

Background

- 6G Communications and Requirements
- Reconfigurable Holographic Surface (RHS) Basics

RHS-aided Wireless Communications

- RHS-aided Holographic Beamforming
- A Limited Number of Radiation Amplitudes
- HDMA: Holographic-Pattern Division Multiple Access
- RHS-aided Satellite Communications

RHS-aided Sensing

- RHS Radar: Target Detection + Parameter Estimation
- Holographic Integrated Sensing and Communication

Physical Implementations and Prototypes

- RHS Implementation (both 1D and 2D)
- RHS-aided Communication and Sensing Platform

Future Research Directions

Conclusion

Thanks for your attention