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Reconfigurable Holographic Surfaces: A New Paradigm to Ultra-Massive MIMO for 6G

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IEEE ComSoc TCCN，Kuala Lumper, Dec. 5, 2023

Outline

1. Background

- 6G Communications and Challenges
- Reconfigurable Holographic Surface

2. RHS-aided Wireless Communications

- Holographic Beamforming
- Holographic-Pattern Division Multiple Access

3. RHS Prototype and Experiment Results

6G Communications

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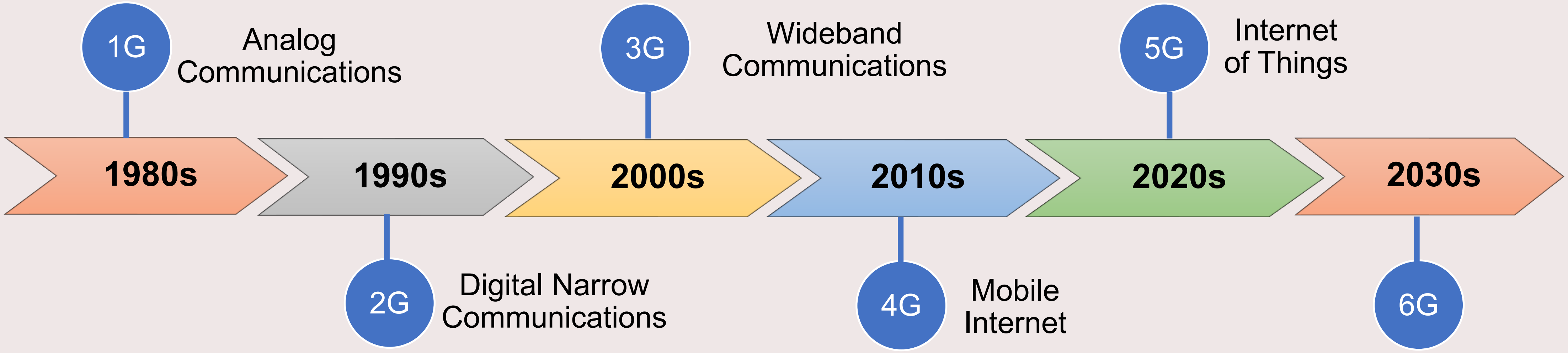


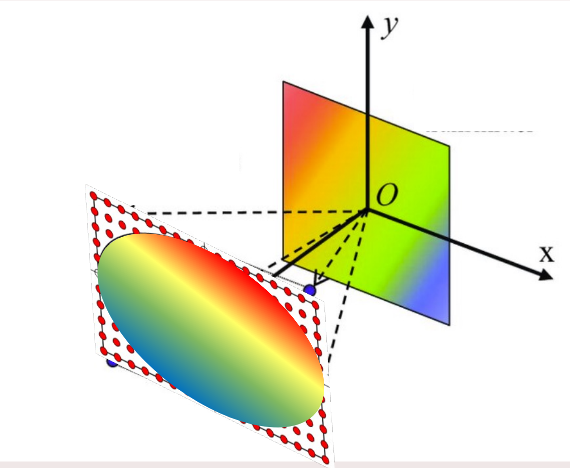
Wireless communication systems evolve every 10 years

6G KPIs

- **Peak data rate**: from 1Gbps to 50 Gbps
- **Energy efficiency**: 10 times of 5G
- **Area traffic capacity**: 10 Mbits/s/m^2 to 50 Mbits/s/m^2

Holographic MIMO/Communications

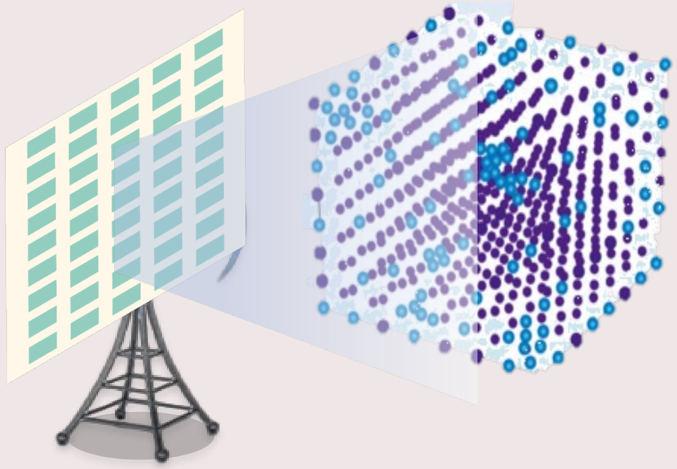
Three interpretations at different levels



ultimate degree of freedom

Continuous aperture packing
infinite number of antennas

Theoretical Bound



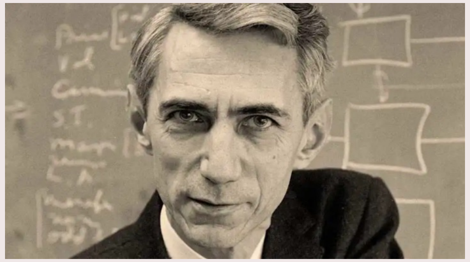
Ultra-high spatial resolution via
extremely large-scale antenna array

Enabling Technique

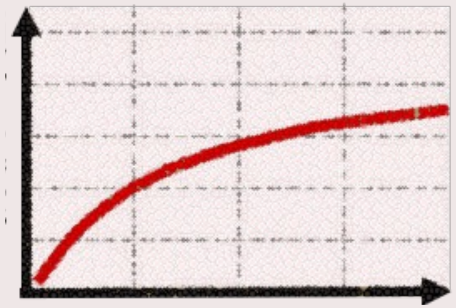
Fully immersive, real-time,
3D experiences

Application

Ultra-Massive MIMO



Claude Shannon



Data Rate ∝ Number of antennas

$$C = B\,log_2(1 + NP)$$

N : number of antennas

Ultra-massive MIMO: evolving towards mmWave band for high data rate, enabled by ultra large-scale multi-antenna technology

4G Multi-antennas
~10[1]

5G Massive MIMO
Scaling up MIMO by 10^2

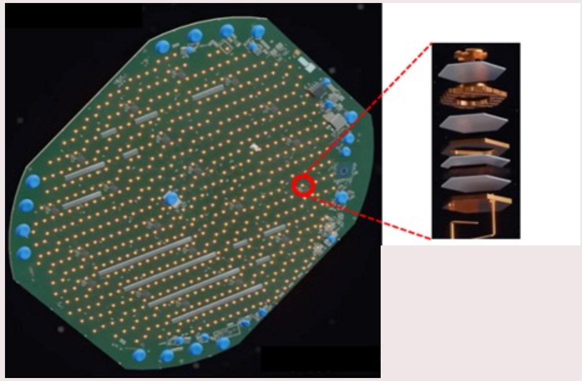
6G Ultra-massive MIMO
Scaling up MIMO by 10^3

Traditional Design Methods

Phase Arrays for 5G

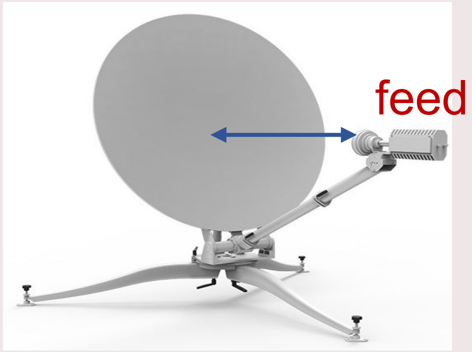
- **Costly hardware components**: numerous phase shifters
- **High power consumption**: complicated feeding network

Limiting the scale of the phased array



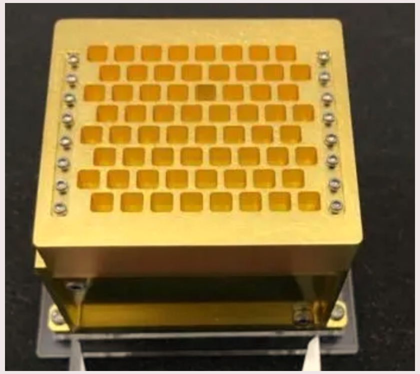
Reflecting Arrays for Satellites

- **Hard to integrate**: feed and antenna surface are separated → bulky structure
- **Limited flexibility**: mechanical manner for beam steering



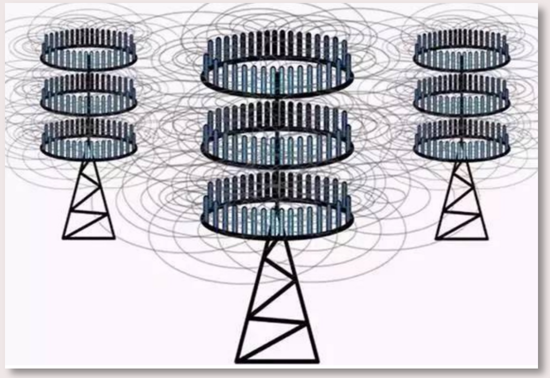
Challenges

Technical Barrier for Current Antenna Techniques



- **Limited Scale**： around the order of $\mathbf{10^2}$
- **High Energy Consumption**： complex feeding circuit
- **Unacceptable Cost**: expensive RF components

Urging new technology to serve as an alterative of the phase arrays



Large Scale

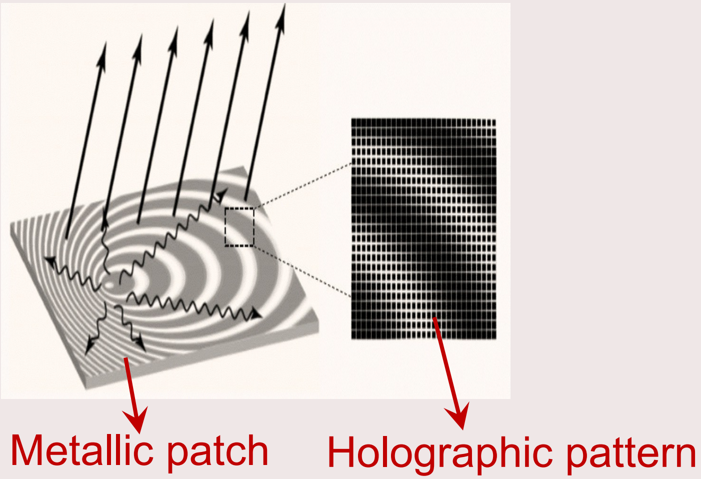
5G 6G

6GHz 24GHz 100GHz

High Frequency

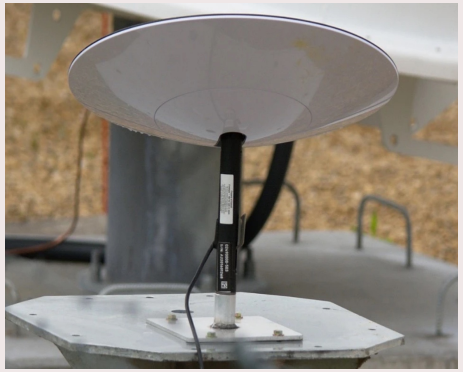
Low Cost

Holographic Antenna



Applying Hologram to Antenna Design

- **Large Scale**： numerous metallic patches
- **Low Cost**： PCB-level manufacturing
- **Low Power Consumption**: No complex phase-shifting circuits



Military Applications

- Satellites & terrestrial communications
- Radar detection for aircrafts

Emergency Communications

Working Principle

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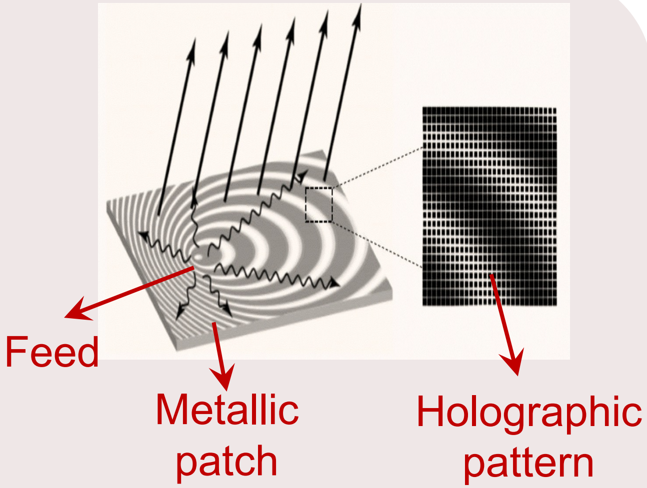
Hardware Structure: A Type of Leaky Wave Antenna

- The surface composes of numerous **metallic patches**
- The **feed** (which inputs the transmit signal) is embedded in the surface

Ultra-thin

- EM wave propagates along the surface and then emitted to the free space

Easy to be integrated



Key Concepts

- **Holographic pattern:** a specific geometric configuration of metallic patches designed by the holographic principle
- **Beamforming:** One holographic pattern refers to a **specific EM radiation pattern** in the free space, utilized to generate **directional beams**

Working Principle

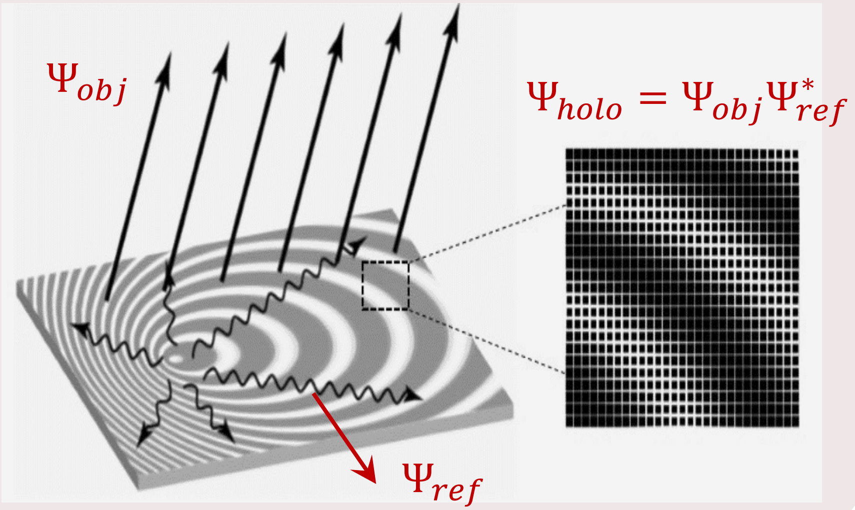
Definitions

- **Reference wave** Ψ_{ref} is the input of the feed, which carries the transmit signal, propagating along the surface
- **Objective wave** Ψ_{obj} is the directional beam that we aim to generate
- **Holographic pattern** $\Psi_{holo} = \Psi_{obj}\Psi_{ref}^*$ is the interference between reference and object waves

Step 1: Holographic Pattern Recording

- Record a holographic pattern Ψ_{holo} by placing the metallic patches on the surface in a specific manner such that adjacent patches can interfere with each other

$$\Psi_{holo} = \Psi_{obj}\Psi_{ref}^*$$



Working Principle

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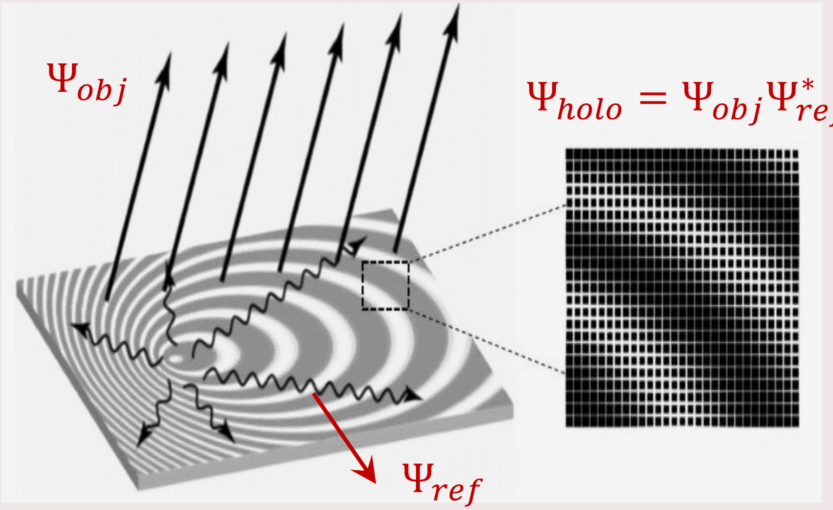
- **Holographic pattern** $\Psi_{holo} = \Psi_{obj}\Psi_{ref}^*$ is the interference between reference and object waves

Step 2: Holographic Beamforming

- When the reference wave Ψ_{ref} is fed to the surface, it interferes with the holographic pattern Ψ_{holo}

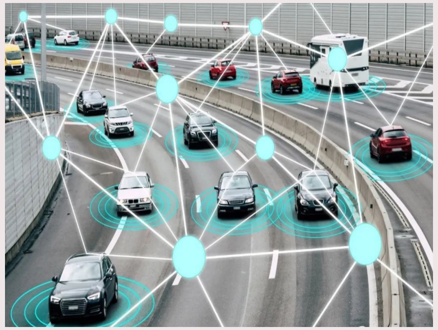
$$\Psi_{holo}\ \Psi_{ref} \propto \Psi_{obj}\ |\Psi_{ref}|^2$$

object wave is recovered   real-value



Problem and Solution

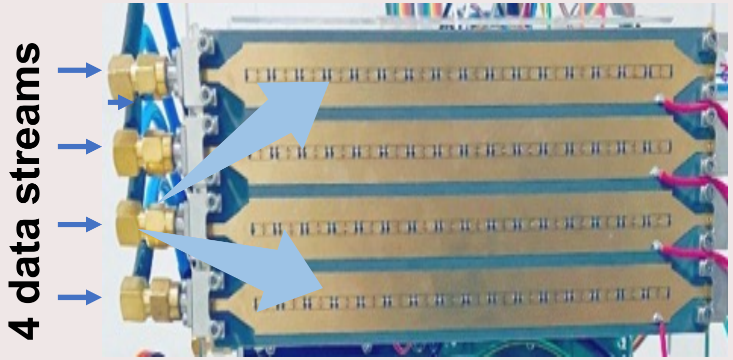
Limitation of Holographic Antenna



- Placement of metallic patches is fixed
- One holographic antenna only has a fixed beam pattern
- Unable to support the mobile scenarios

Reconfigurable Holographic Surface (RHS)

- Apply reconfigurable metasurface technique to holographic antenna design
- Holographic pattern can be reconfigured



Reconfigurable Metasurface Technique

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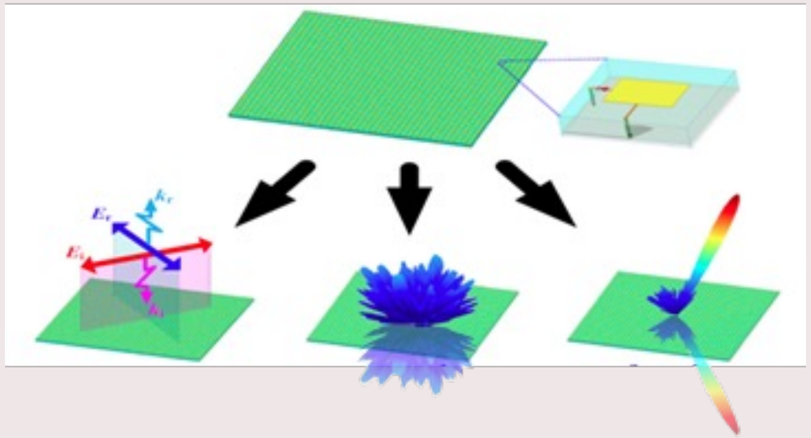
Metasurface

- Artificial structures that are non-existent in nature
- A thin surface composed of subwavelength elements



Reconfigurable Metasurface Element

- Active components: PIN diodes
- **Reconfiguration:** dynamic control for pointing of beams by biased voltages on PIN diodes

Benefits

- **Dynamic Beams:** Capable of controlling EM response of antenna elements
- **Low cost & energy consumption：** cheap PIN diodes and PCB techniques

RHS Working Principle

- **Metasurface:** a 2D planar structure with **ultra large number** of sub-wavelength elements
- **Reconfiguration:** by controlling each element, the EM amplitude response can be adjusted

1. **The feed** (RF chain) inputs the **reference wave** (transmit signal) to the surface

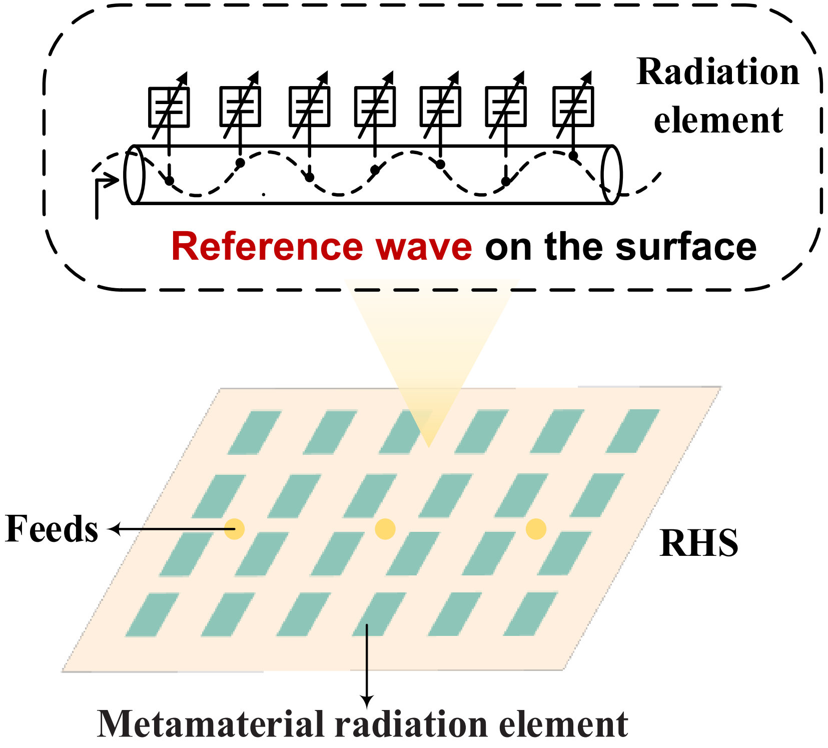
2. When reference wave arrives at RHS element, it interplays with **holographic pattern** and radiates energy into the space

   - Holographic pattern is recorded by **amplitude responses**

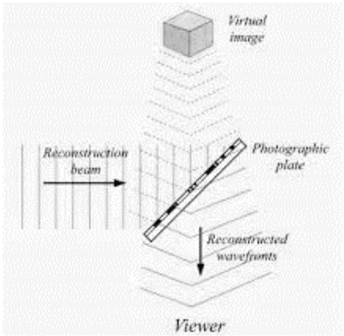
     dynamically controlled by diodes at each element

3. Reference waves turn into radiated signals in free space

   - Superimpose to form directional beams (**objective wave**)



Historical Development

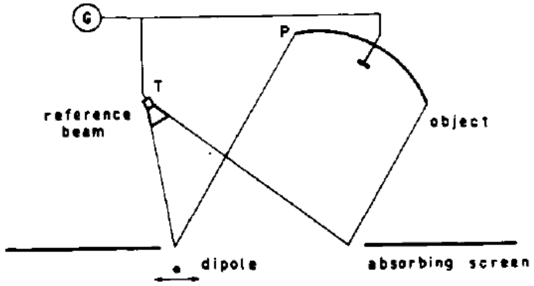


First proposal of holographic technology (D. Gabor)

1948

1967

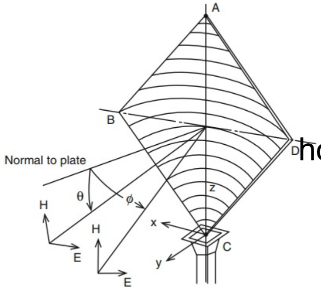
Holographic technology is first proposed in microwave band theoretically (G. A. Deschamps)



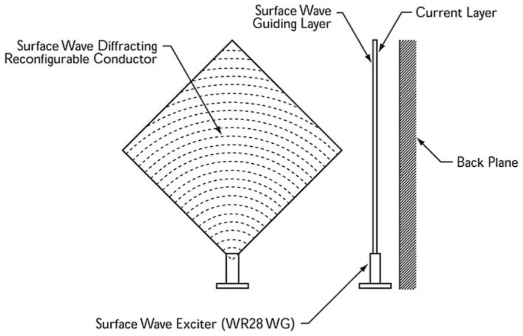
First proposal and design of holographic antennas (P. F. Checcacci)

1970

1975



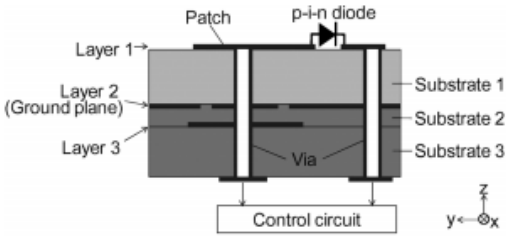
Volume-type holographic antenna (K. Lizuka)



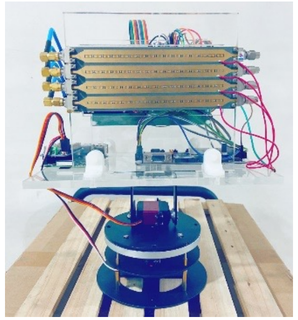
Introduction of surface wave theory (M. Elsherbiny)

2004

2010~2011



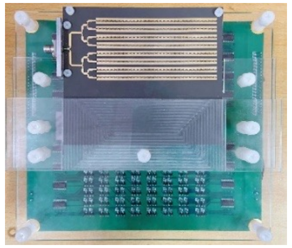
Generalized Snell's law and PIN diode based modulation（N. Yu, H. Kamoda etc.）



Ku-band RHS enabled point-to-point communication (Peking Univ.)

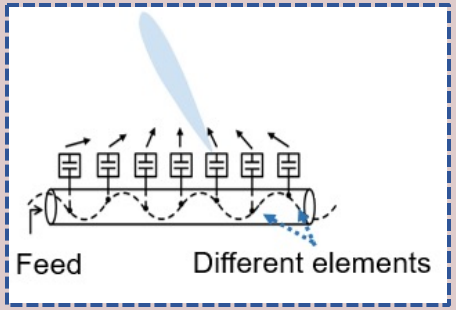
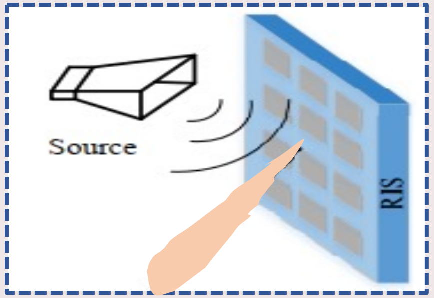
2021

2023



5G mmWave RHS prototype (Peking Univ.)

RHS VS RIS

Technology	Physical Structure	Operating Mechanism	Typical Applications
RHS	RF front end is **integrated** into the metasurface	① Leaky-wave antenna ② Serial feeding 	① Transmit/Receive antennas ② Mounted on mobile platforms ③ Sensing, microwave imaging
RIS	RF front end is **outside** of the metasurface	① Reflection antenna ② Parallel feeding  Simultaneous reflection	① Passive relays ② Deployed in the cell edge for coverage extension

RHS-enabled Communication System

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Goal: Implement a mmWave RHS-enabled communication system as an alternative to phase array

Key Design Parameters

- **Frequency:** above 26GHz
- **Bandwidth:** 800MHz
- **Polarization:** cross-polarization
- **Hardware architecture:** 4 pieces of RHS corresponding to 4 RF chains
- **Size:** $11.16 \times 9.65 \times 0.0873$ cm^3
- **Control:** 1 bit PIN diode amplitude control
- **Range:** horizontal $\pm 60^{\circ}$, vertical $\pm 15^{\circ}$
- **Switching speed:** 1 us (beam switching)

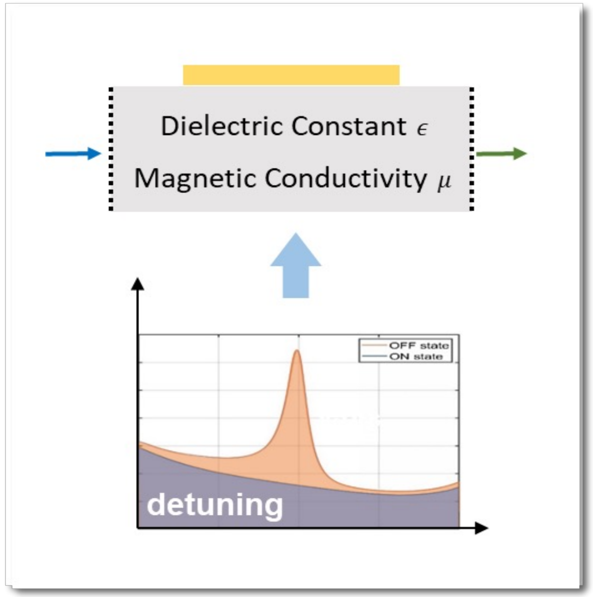
RHS Element Design

How an Element Works

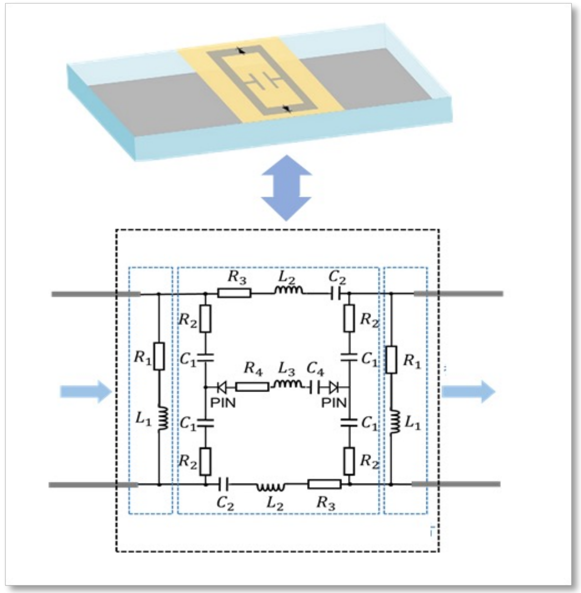
- By tuning the voltage imposed on the diode, the element resonance state is controlled, thus the EM wave is manipulated

Designing parameters

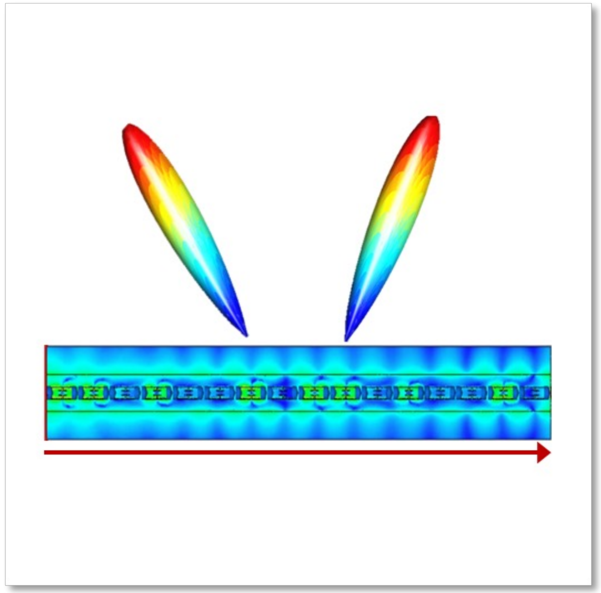
- Selection of dielectric material, geometric structure, diode equivalent circuit



Dielectric material selection

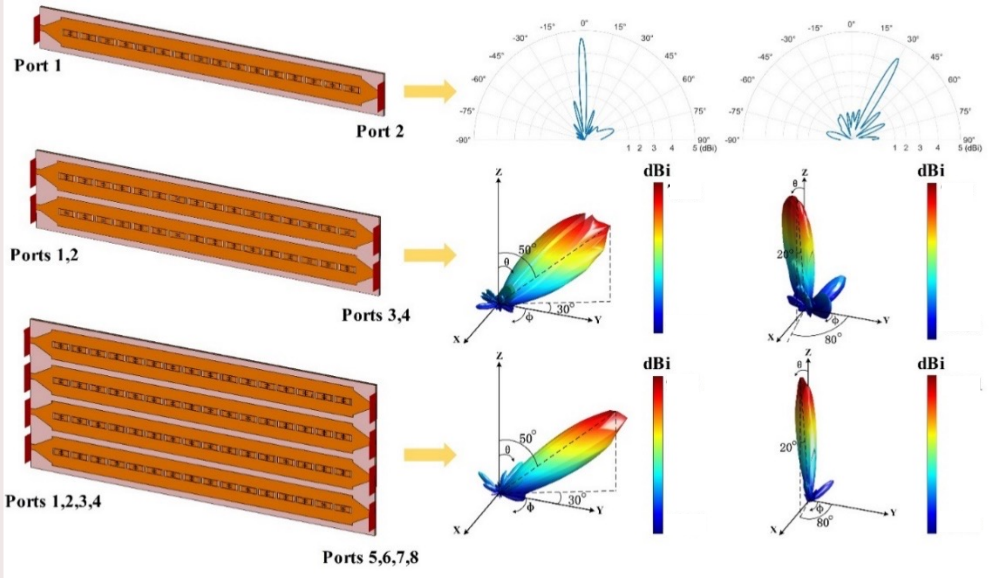


Element design



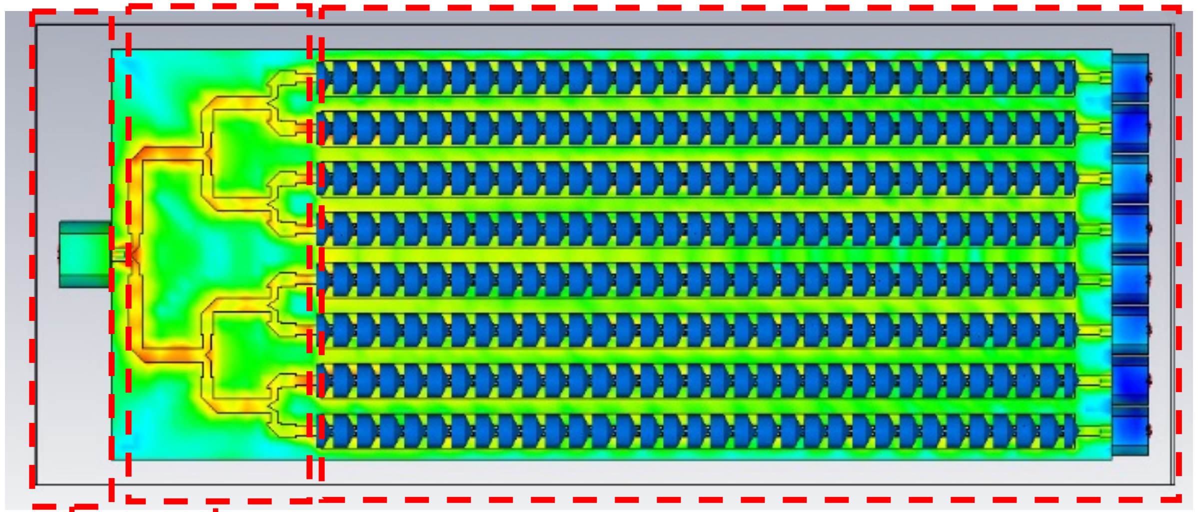
1D RHS array

RHS 2D Antenna Array Design



The antenna gain increases by 3dB when the size of RHS doubles

256 RHS elements



Feed: send the transmit signal (carried by the reference wave) to the surface

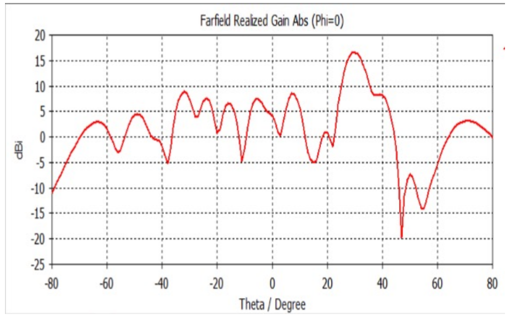
Micro strip power divider: deliver the reference wave to the whole surface

RHS Control Circuit and Integration

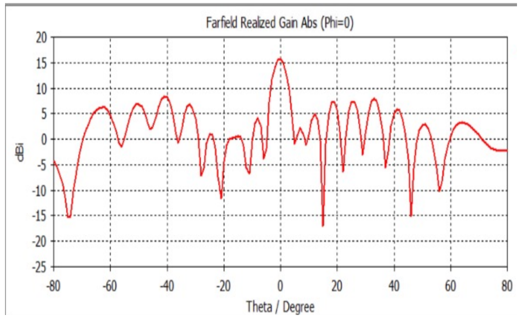
- **Control:** 1 bit PIN diode amplitude control
- **Range:** horizontal $\pm 60^{\circ}$, vertical $\pm 15^{\circ}$
- **Switching speed:**

  1 us (beam switching only)

  3 us (including control signaling)

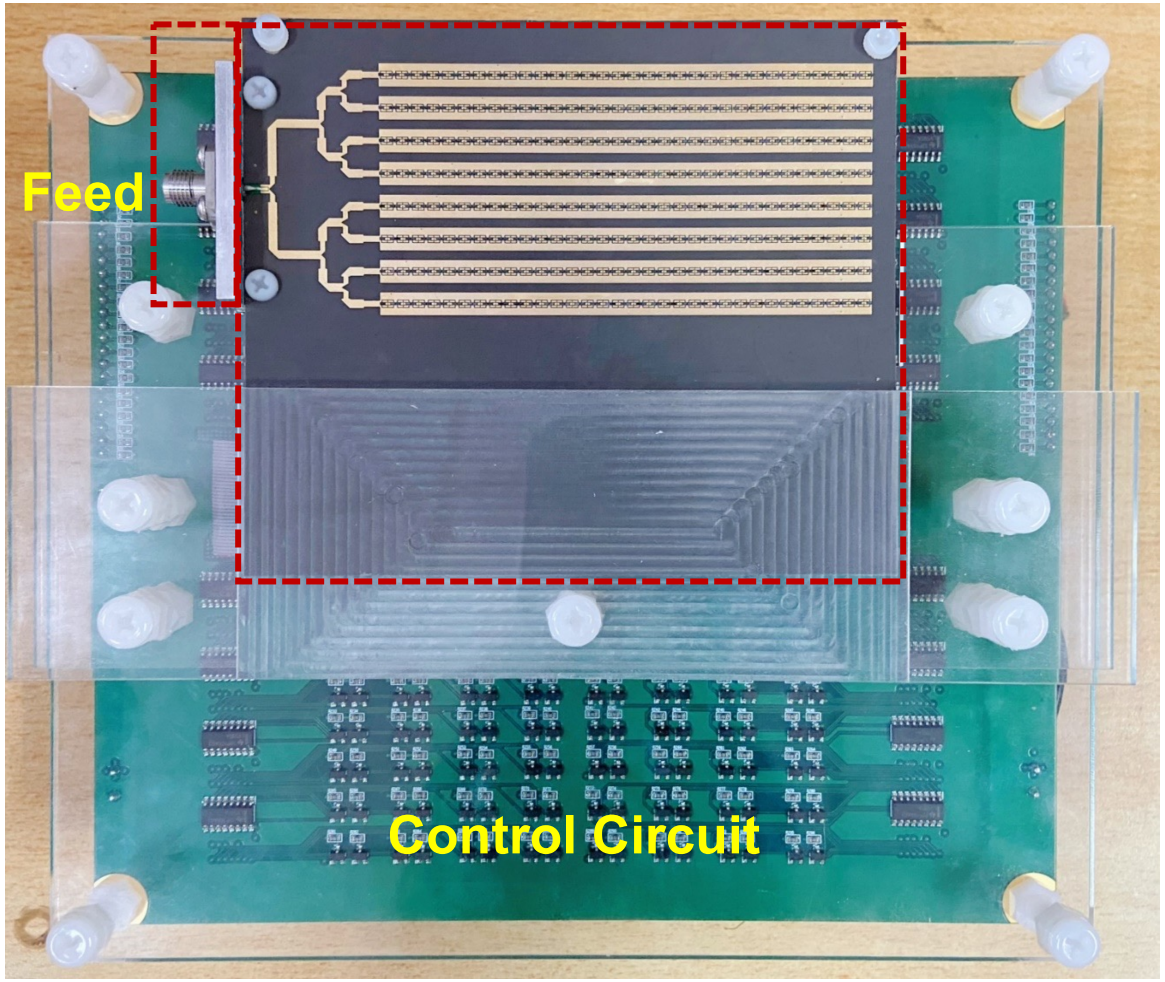


30° beam pattern



0° beam pattern

RHS



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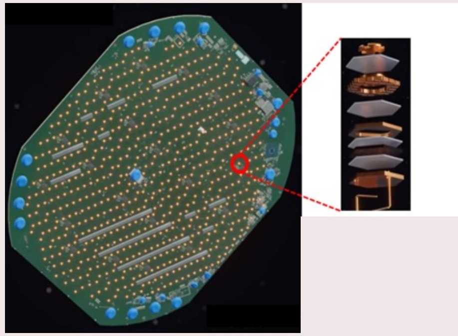
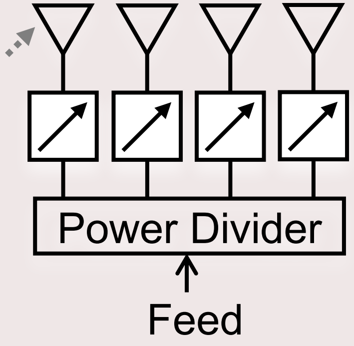
RHS Enabled Multi-Beam Transmission:

Amplitude-Controlled Holographic Beamforming

Ruoqi Deng, Boya Di, Hongliang Zhang, Yunhua Tan, and Lingyang Song, "*Reconfigurable holographic surface-enabled multi-user wireless communications: amplitude-controlled holographic beamforming*", IEEE Trans. Wireless Commun., vol. 21, no. 8, Aug. 2022.

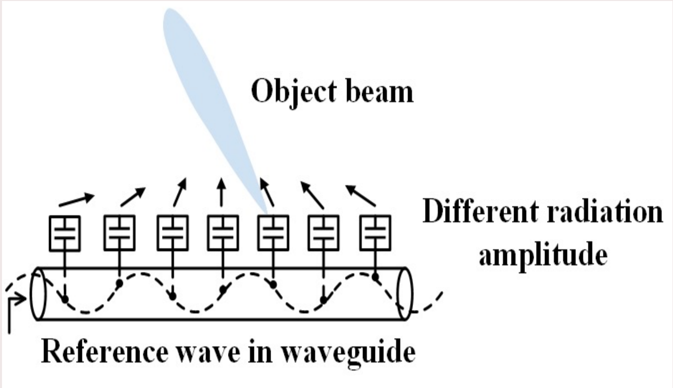
Research Challenges

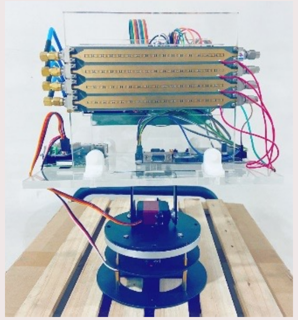




Parallel transmission
→ Serial transmission

Phase control
→ Amplitude control





Traditional phase arrays

RHS

1. **Serial feeding**:
   - signal propagates along the surface, urging new models
2. **Amplitude control**:
   - traditional phase-controlled beamforming does not apply

Transmission — Holographic beamforming for multiple beams

Multiple Access — Space-domain multiplexing via holographic pattern superposition

System Model

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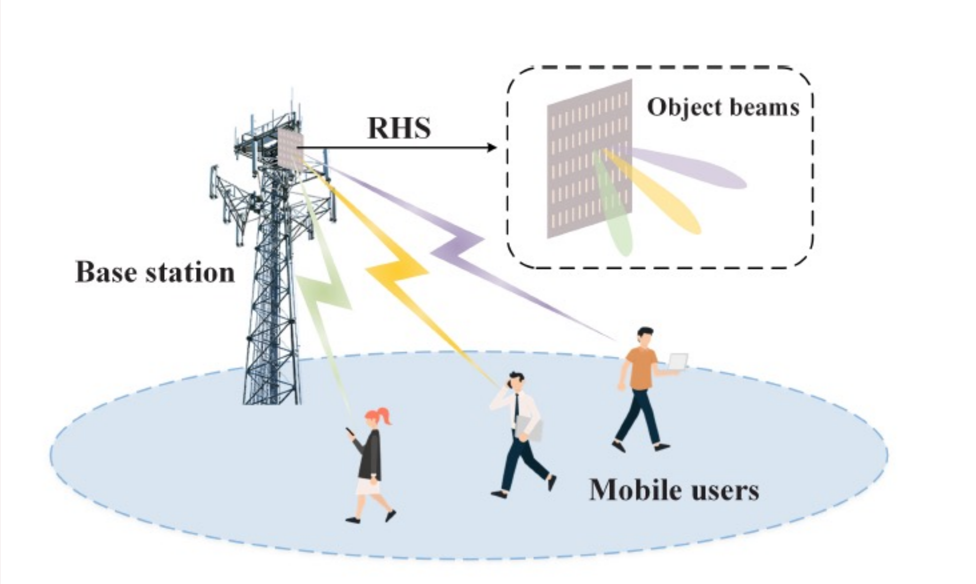
- **Key Questions**
  - How to model the signal propagation on the surface?
  - How to generate multiple beams via the RHS-enabled holographic beamforming?

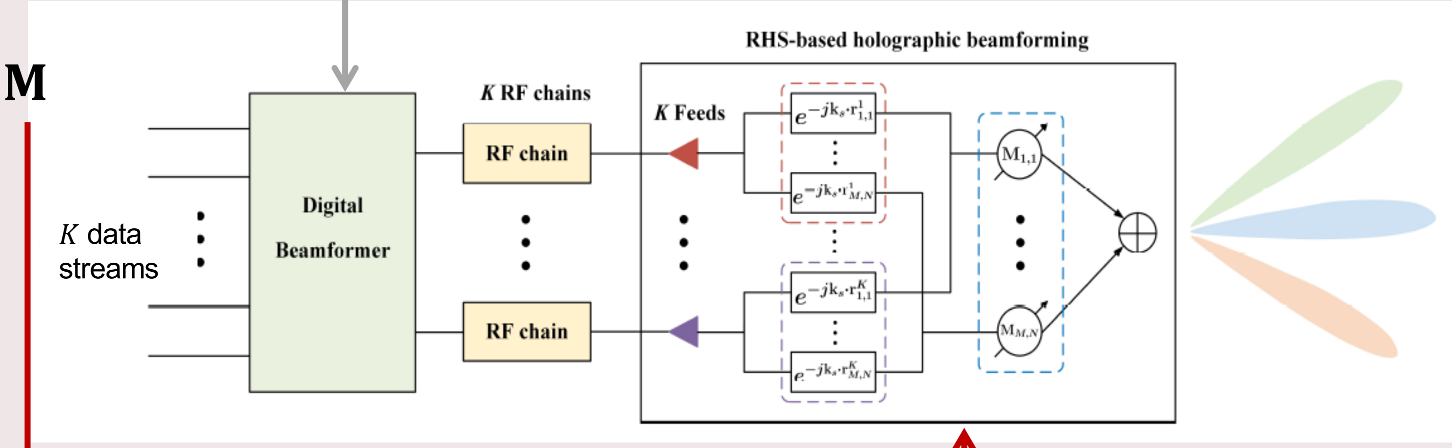
- **Scenario**
  - Downlink RHS-aided MU-MIMO system
    - One RHS BS and K users
    - User: single antenna
    - RHS: K feeds, $N_y \times N_z$ radiation elements



System Model

- **RHS-aided hybrid beamforming framework**
  - BS: Digital beamforming $\mathbf{V}$
  - RHS: Holographic beamforming $\mathbf{M}$

Enabling the function of traditional analog beamforming



Digital Beamformer

$$y_l = \mathbf{H}_l\mathbf{M}\mathbf{V}_l\mathbf{s}_l + \mathbf{H}_l\mathbf{M}\sum_{l'\neq l}\mathbf{V}_{l'}\mathbf{s}_{l'} + \mathbf{z}_l$$

Holographic Beamformer

Problem Formulation

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Achievable rate of each user

Channel matrix between RHS and user k

$$R_k = \log_2\left(1 + \frac{|\mathbf{H}_k \mathbf{M} \mathbf{V}_k|^2}{\sigma^2 + \sum_{l' \neq k} |\mathbf{H}_k \mathbf{M} \mathbf{V}_{l'}|^2}\right)$$

Sum rate maximization problem

$$\max_{\{\mathbf{V}, m_{n_y,n_z}\}} \sum_{k=1}^{K} R_k$$

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

Power constraint $\sum_{n_y,n_z} \eta \cdot m_{n_y,n_z}^2 \le 1,$

Amplitude constraint $0 \le m_{n_y,n_z} \le 1, \forall n_y, n_z.$

Problem Decomposition

Digital beamforming

$$\max_{\{\mathbf{V}\}} \sum_{k=1}^{K} R_k$$

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

Holographic beamforming

$$\max_{\{m_{n_y,n_z}\}} \sum_{k=1}^{K} R_k$$

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

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

Holographic Beamforming Model

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

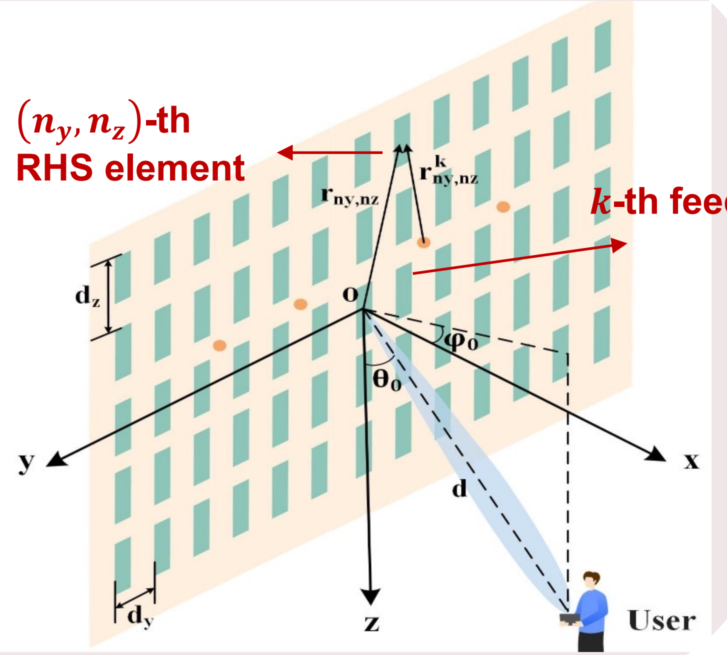
reference wave

$$M^k_{n_y,n_z} = \sqrt{\eta} \cdot m_{n_y,n_z} \cdot e^{-\alpha\left|\mathbf{r}^k_{n_y,n_z}\right|} \cdot e^{-j\mathbf{k}_s \cdot \mathbf{r}^k_{n_y,n_z}}$$

➡ Element-wise Ψ_{holo} Ψ_{ref}

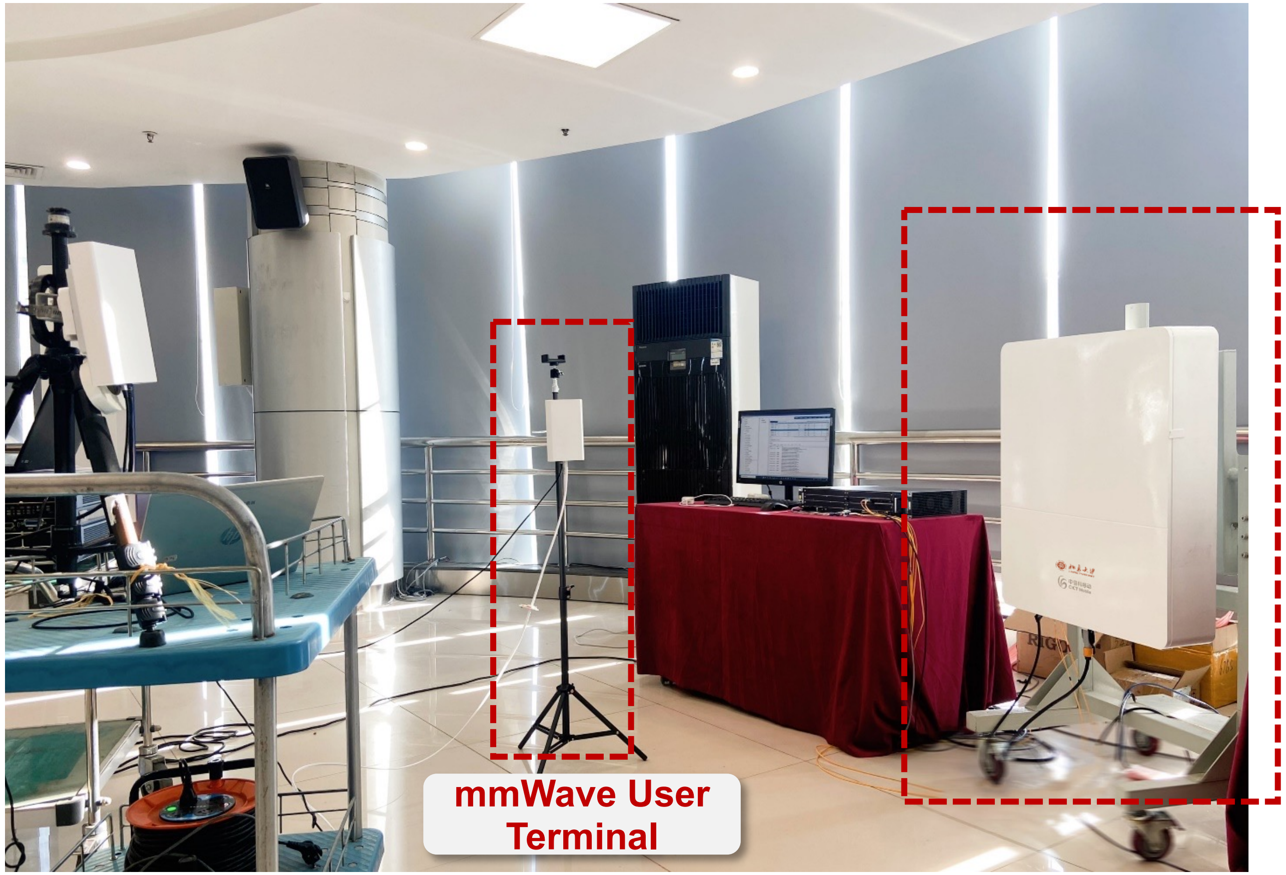
Holographic pattern: recorded via the amplitudes of all elements, i.e., $\{m_{n_y,n_z}\}$

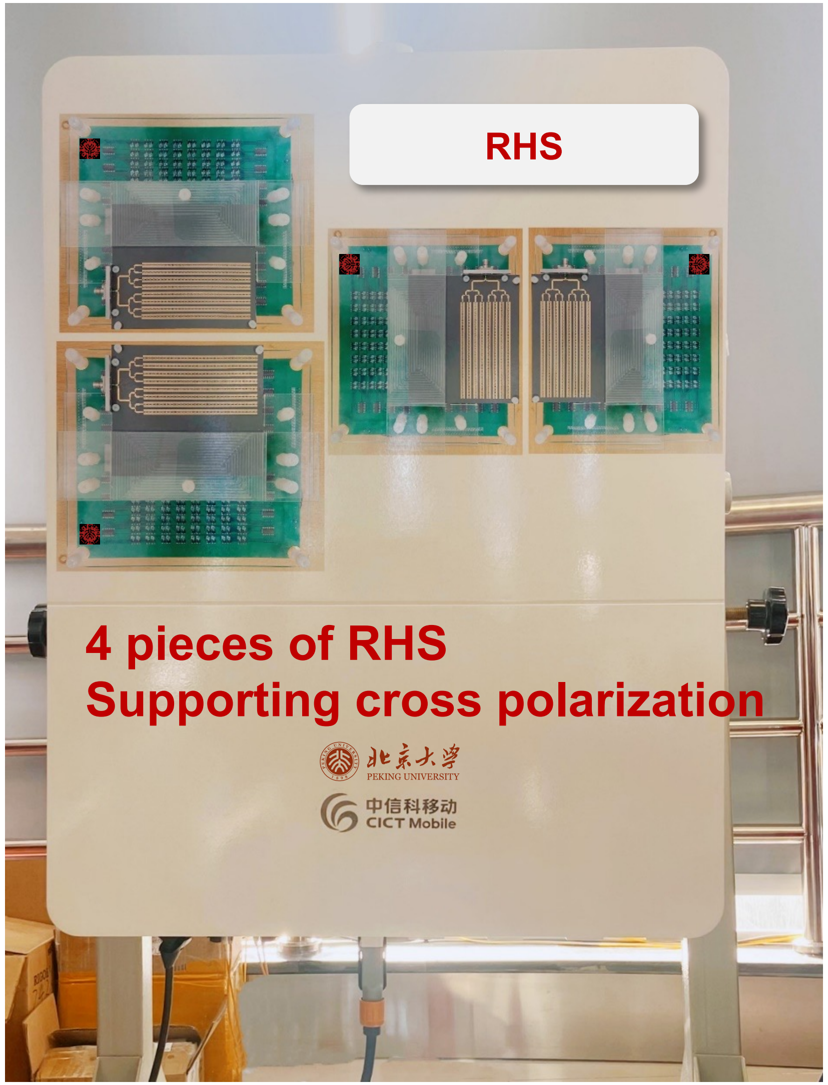
- $m_{n_y,n_z} \in [0,1]$: radiation amplitude response of the (n_y, n_z)-th RHS element, controlled via the diode
- $e^{-\alpha\left|\mathbf{r}^k_{n_y,n_z}\right|}$: surface propagation loss of reference wave
- $e^{-j\mathbf{k}_s \cdot \mathbf{r}^k_{n_y,n_z}}$: phase of the reference wave, and varies along its propagation



RHS-enabled Communication Prototype

One RHS-enabled transmitter sends to two mmWave user terminals





RHS Prototype (Peking Univ. and CICT)

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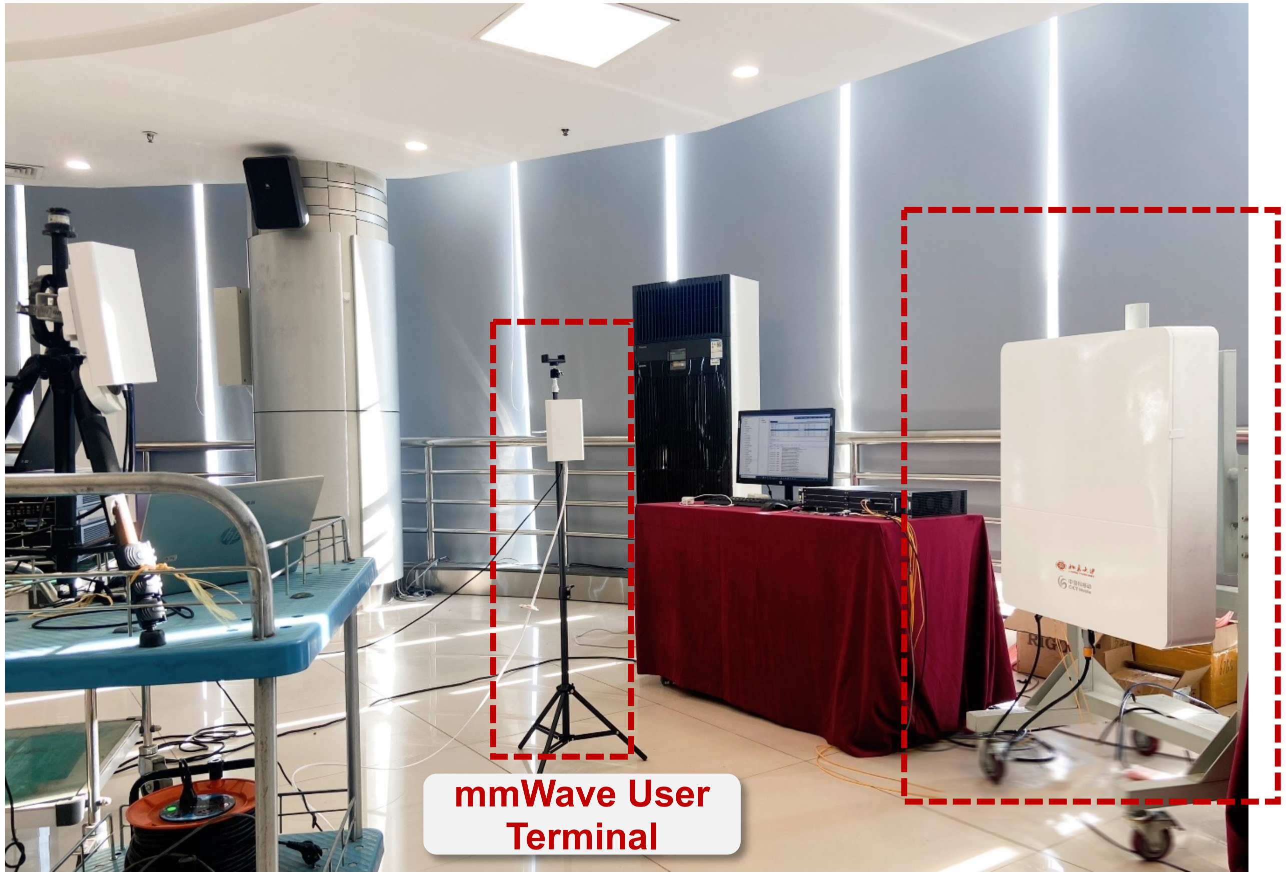
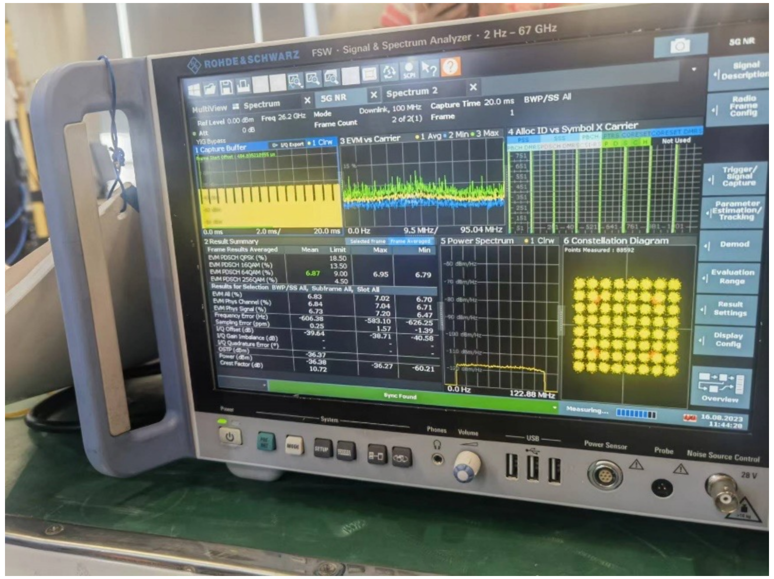
One RHS-enabled transmitter sends to two mmWave user terminals



- **64 QAM:** achieving EVM at 6.87% (lower than the threshold 8%)
- **Total throughput of two users: exceeding 4 Gbps**



Demonstration Video

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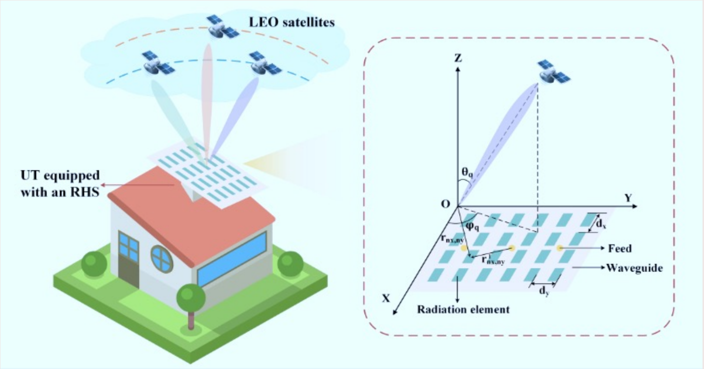
Applications: Communications



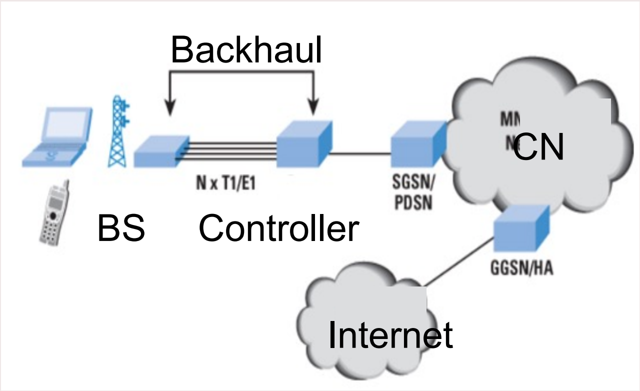
Sat User Terminal

UAV Terminal

Vehicular Terminal

Base Station

Emergency Comms Terminal



Backhauling

Publications

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1. RHS Proposal

"Reconfigurable holographic surface: Holographic beamforming for metasurface-aided wireless communications," ***IEEE TVT***

2. Multiple Access

"HDMA: Holographic-pattern division multiple access," ***IEEE JSAC***

3. Holographic BF

"Reconfigurable holographic surface enabled multi-user wireless communications: Amplitude-controlled holographic beamforming," ***IEEE TWC***

4. Holographic ISAC

"Holographic integrated sensing and communication," ***IEEE JSAC***

5. Satcoms

"Holographic MIMO for LEO Satellite Communications Aided by Reconfigurable Holographic Surfaces," ***IEEE JSAC***

6. Holographic Radar

"Holographic Radar: Target Detection Enabled by Reconfigurable Holographic Surfaces", ***IEEE CL***

7. 5G-A Implementation

"Reconfigurable Holographic Surfaces for Ultra-Massive MIMO in 6G: Practical Design, Optimization and Implementation", ***IEEE JSAC***

2019 — **Kick off**

2021-06

2022-04

2022-06

2022-07

2021-08

2023-01

2023-08

Thanks for your attention