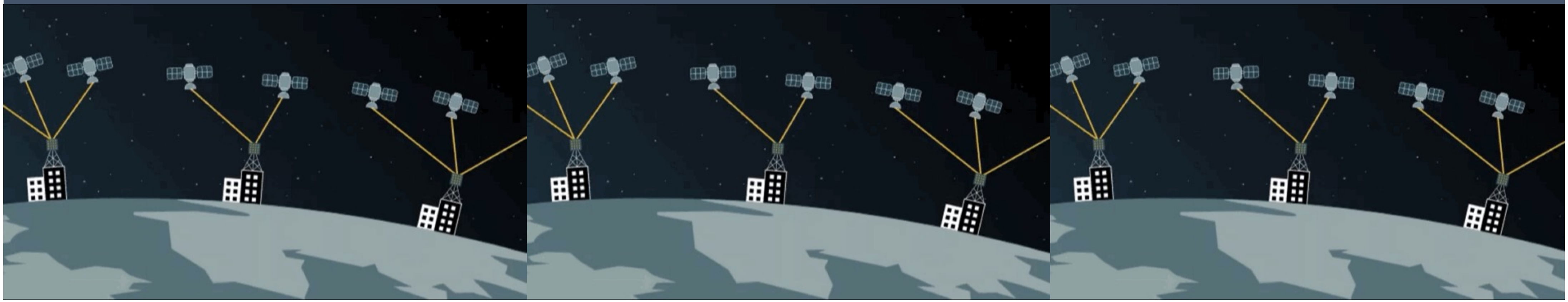
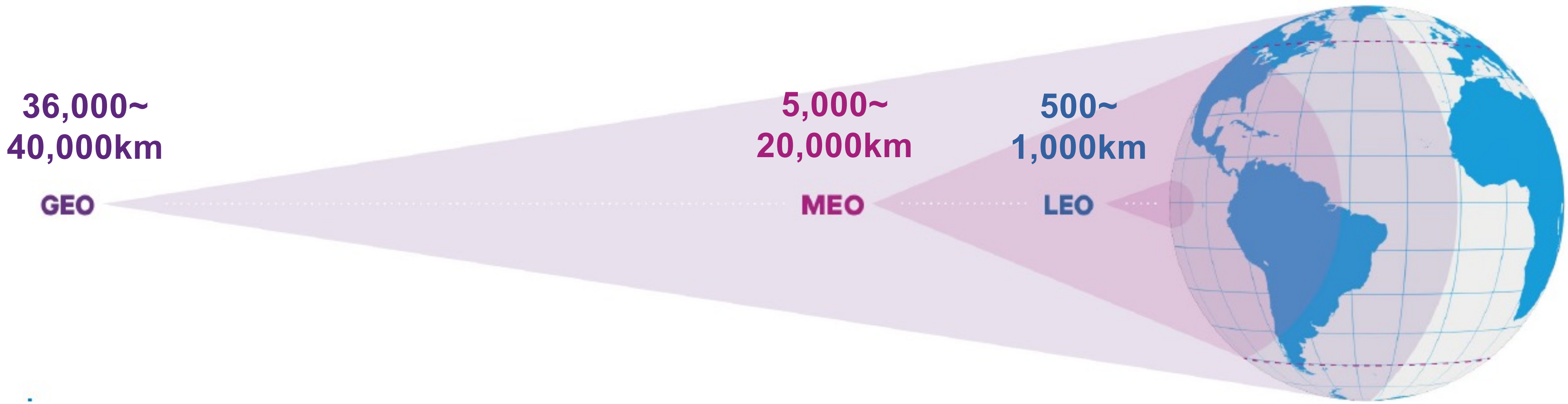
PMSat: Optimizing Passive Metasurface for Low Earth Orbit Satellite Communication

Hao Pan[1], Lili Qiu[1&2], Bei Ouyang[1],
Shicheng Zheng[1], Yongzhao Zhang[1&3], Yi-Chao Chen[1&3], Guangtao Xue[3]

[1]Microsoft Research Asia, [2]UT Austin, [3]Shanghai Jiao Tong University



Expanding Internet Access through and Space



SpaceX StarLink

Amazon Kuiper

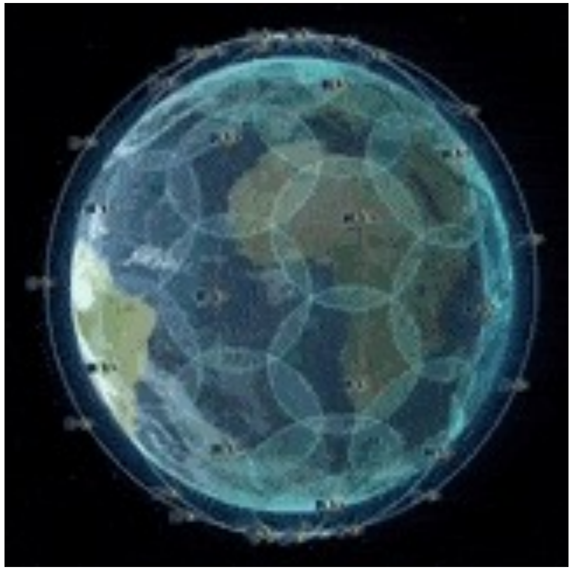
Airbus OneWeb

Advantages of LEO Satellite Communication

1. High Speed and Low latency

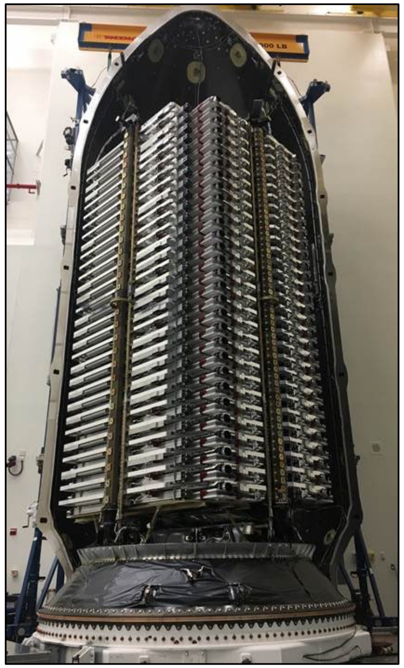
2. Easy to set up

3.Global Coverage



- ✓ SpaceX: 4408 LEO satellites
- ✓ OneWeb: 428 satellites
- • Kuiper: 3236 satellites (plan)

Low cost of launching nano LEO satellites



- ☐ Launch around 60 LEO satellites one time
- ☐ For each, cost $2000

Limitations of LEO satellite communication

Requirement of ground receiver terminal:

- mmWave experiences severe attenuation, requiring **high SNR** for high throughput
- Fast-moving satellites require **real-time tracking**

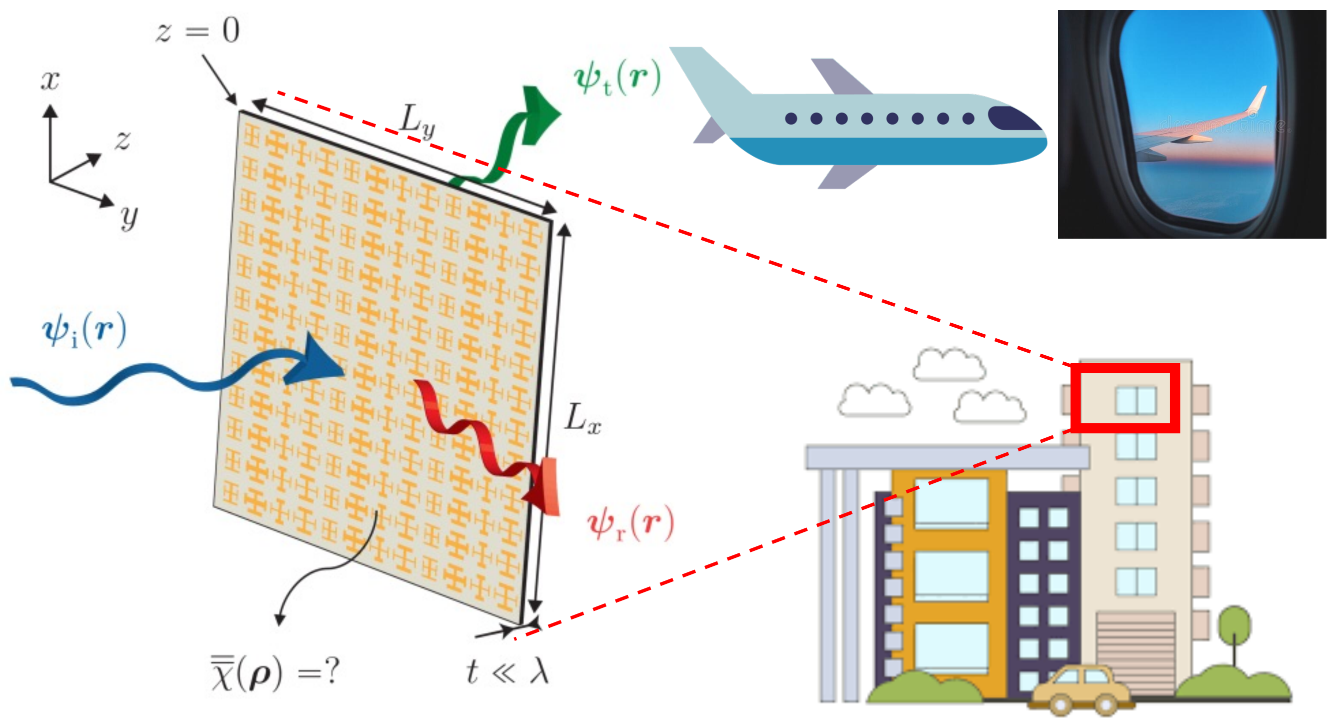
Challenges:

How to build a low-cost, space-saving, and high-performance ground station for LEO satellite communication?

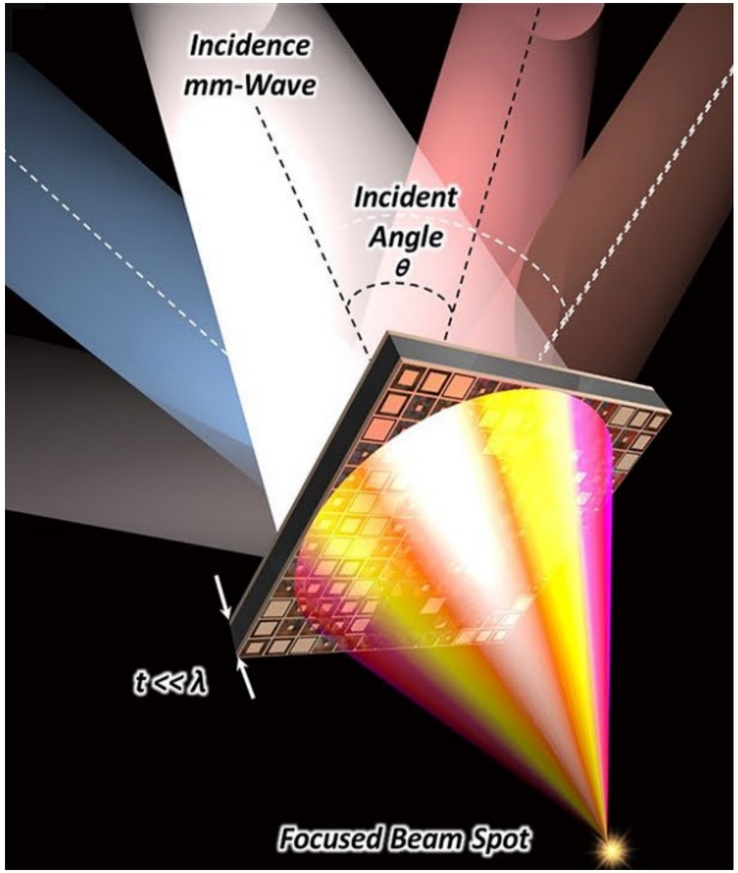
Equipment fee of ground antenna terminals: $599~2500 (for StarLink) [1]

[1] https://www.satelliteinternet.com/providers/starlink/

Passive EM metasurface provides a new solution!

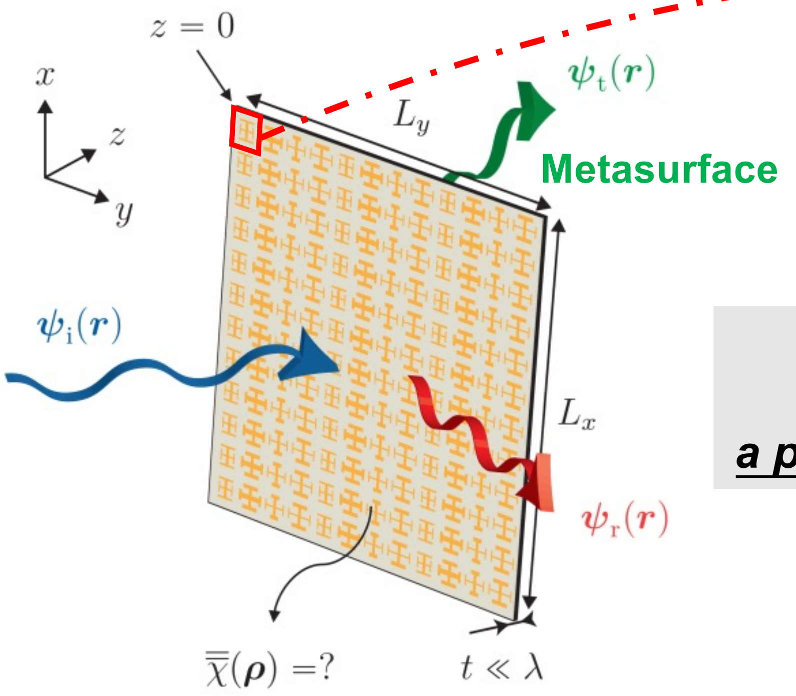


- **Passive** (no power needed)
- **2D** structure (negligible thickness)
- **Cheap** (Martial cost of metasurface< $20/m^2)

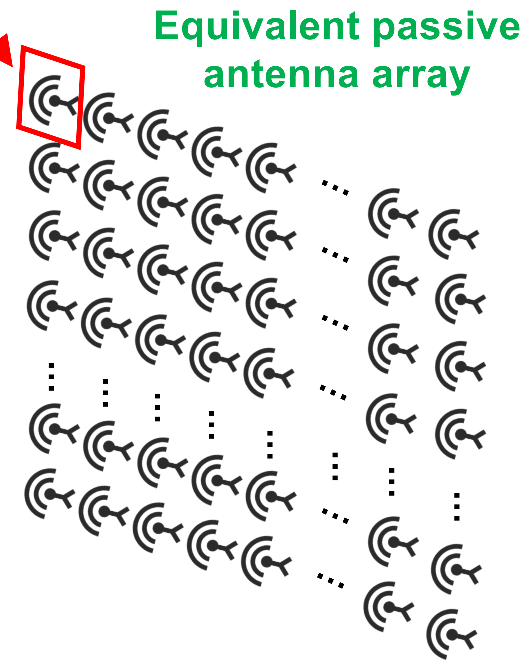


An example of EM metasurface for signal strength enhancement

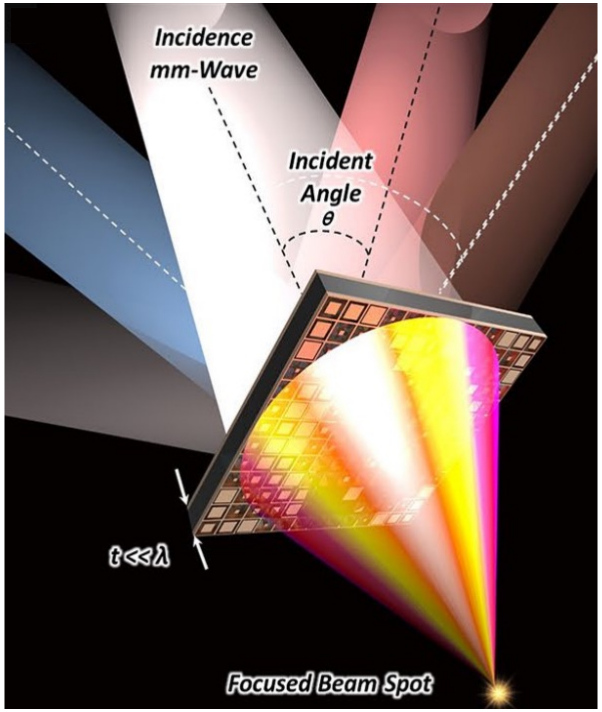
Metasurface equals to an antenna array



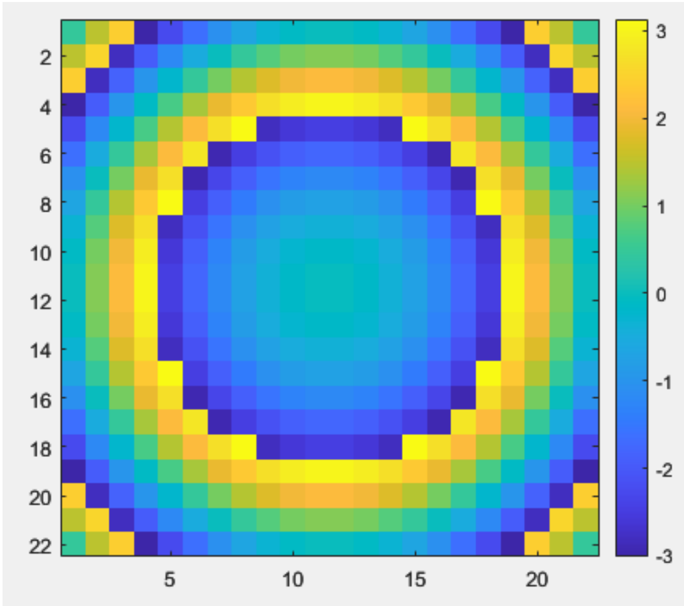
Each metasurface unit
can be equated to
a passive subwavelength antenna



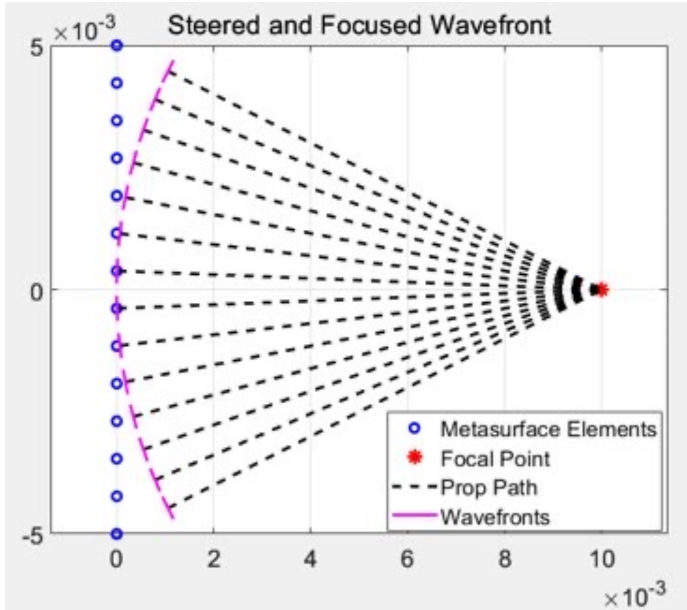
Case study: Focusing passive metasurface



Focusing metasurface: improve RSS



Metasurface's phase profile



Phase delay introduced by each unit can achieve the focusing effect.

Overview: How to design passive metasurface for LEO?

Q1: How to enable dynamic adaptation using passive metasurface?

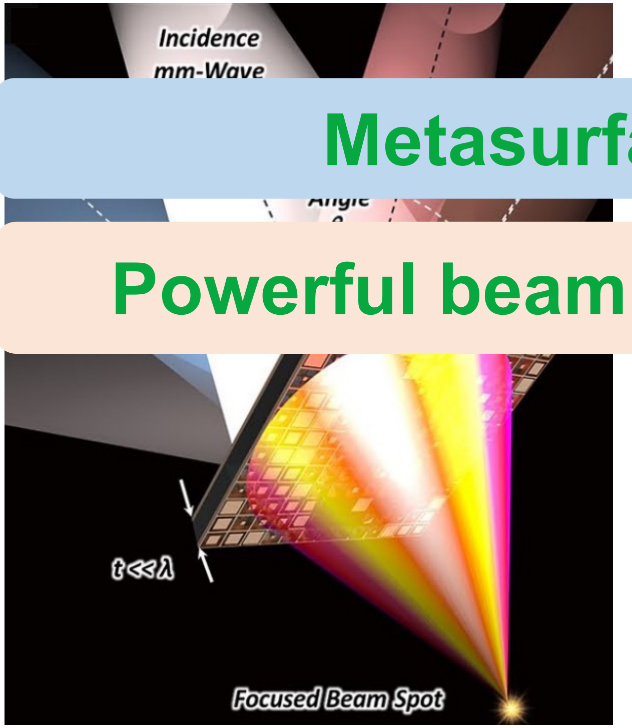
Q2: How to design phase profile of the metasurface?

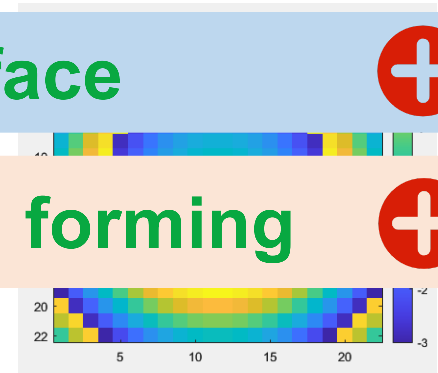
Q3: How to design the metasurface unit cell for LEO scenarios?

Our idea: A Passive Metasurface + A Small Phased Array

Passive Metasurface:

1. is cheap and has massive elements ☺
2. has a powerful capability of wavefront shaping ☺



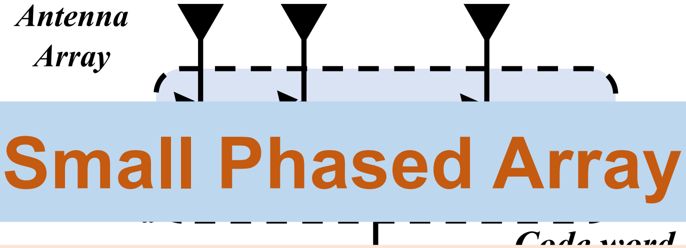


An example of EM metasurface for *FOCUSING*

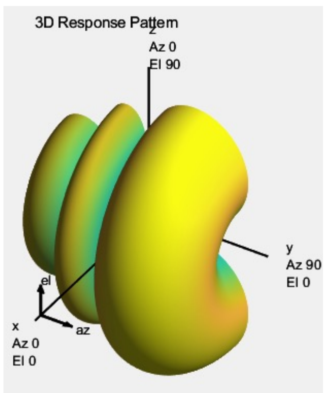
3. **cannot be reconfigurable once fabrication** ☹

Small Phased Array:

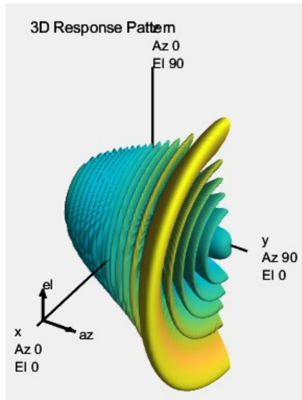
1. has **programmable** capability with digital phased shifters ☺



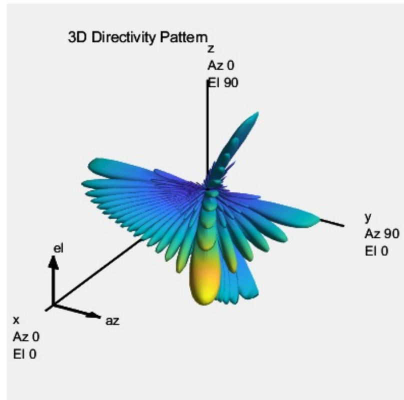
to the small scale



1x4 line PA



1x22 line PA



22x22 line PA

Metasurface ➕ Small Phased Array

Powerful beam forming ➕ Programmable beam steering

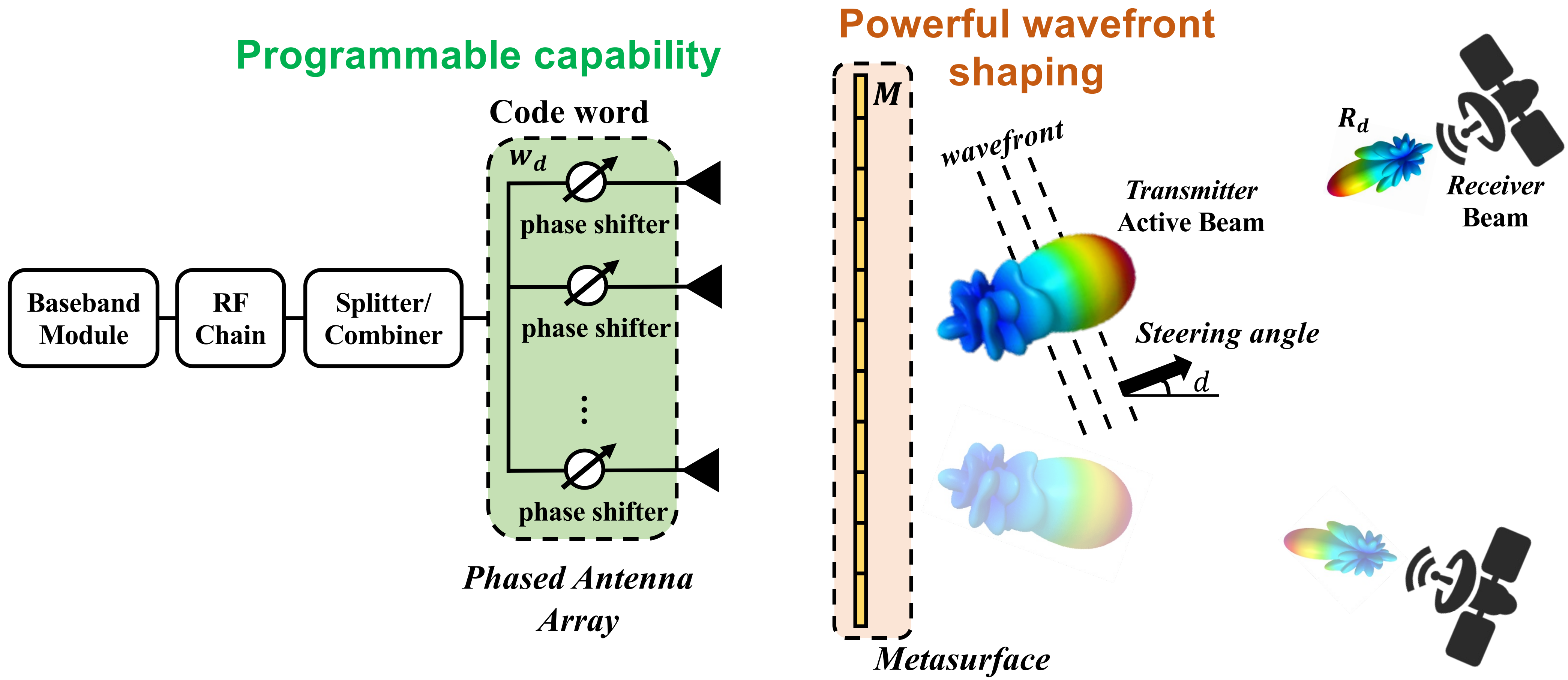
Overview: How to design passive metasurface for LEO?

Q1: How to enable dynamic adaptation using passive metasurface?

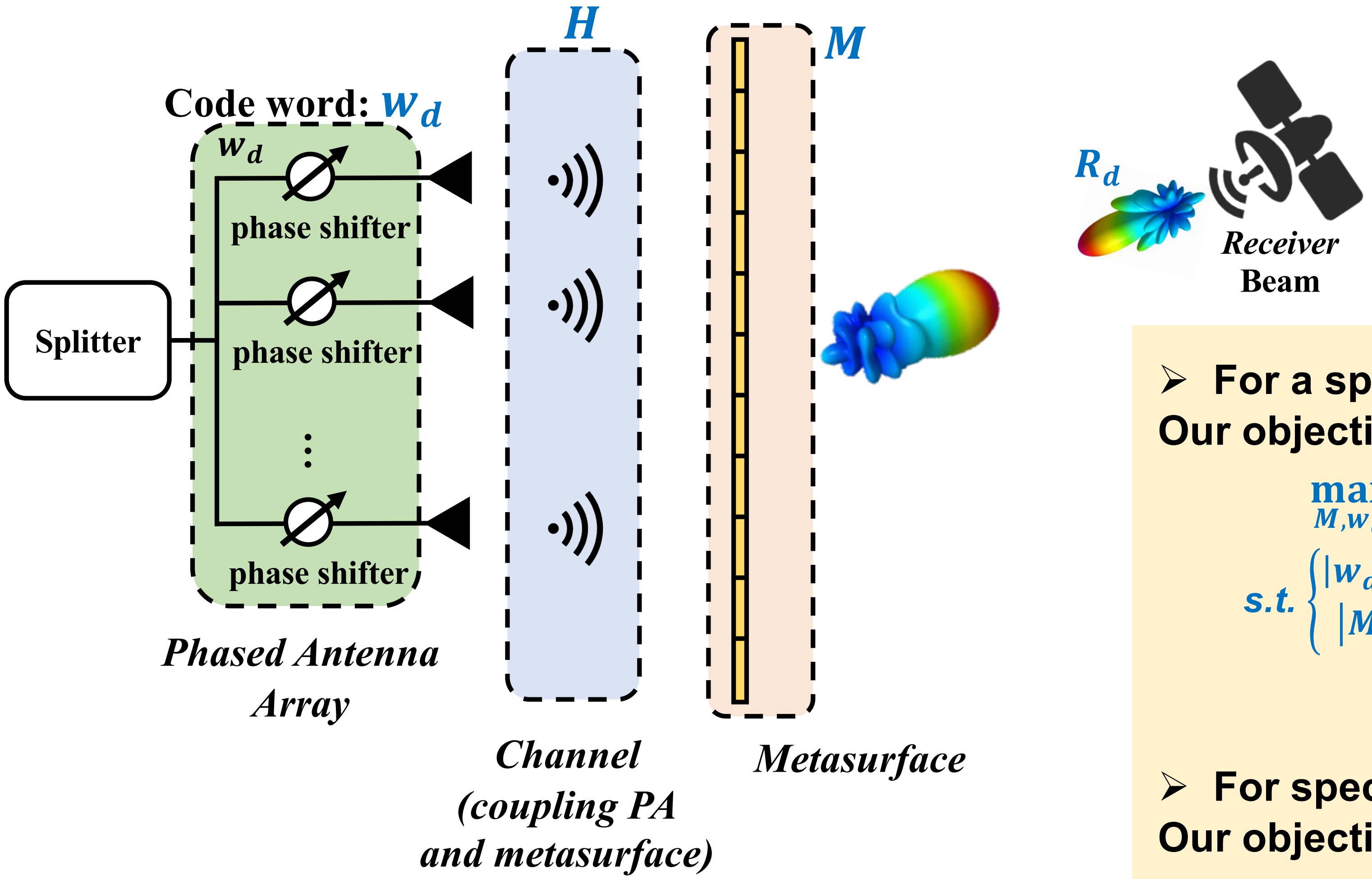
Q2: How to design phase profile of the metasurface?

Q3: How to design the metasurface unit cell for LEO scenarios?

Our idea: A Passive Metasurface + A Small Phased Array



Uplink Optimization Model



- For a specific steering direction, d.

Our objective is to:

$$\max_{M, w_d} F(w_d \, H \, M \, R_d)$$

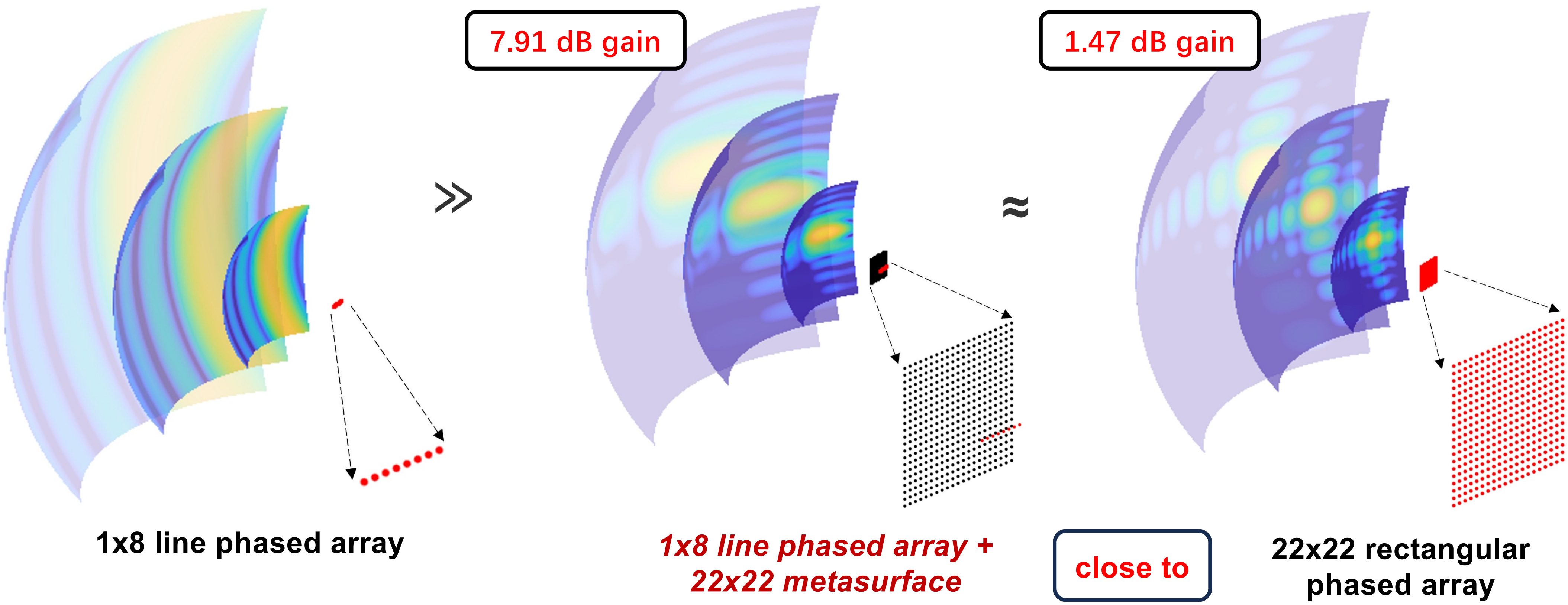
$$s.t. \begin{cases} |w_{d\_i}| = 1, \ (i = 1, 2, \ldots, N) \\ |M_j| = 1, \ (j = 1, 2, \ldots, L) \end{cases}$$

- For specific steering direction set, D.

Our objective is to: $\max_{M, W_D} F(W_D \, H \, M \, R_D)$

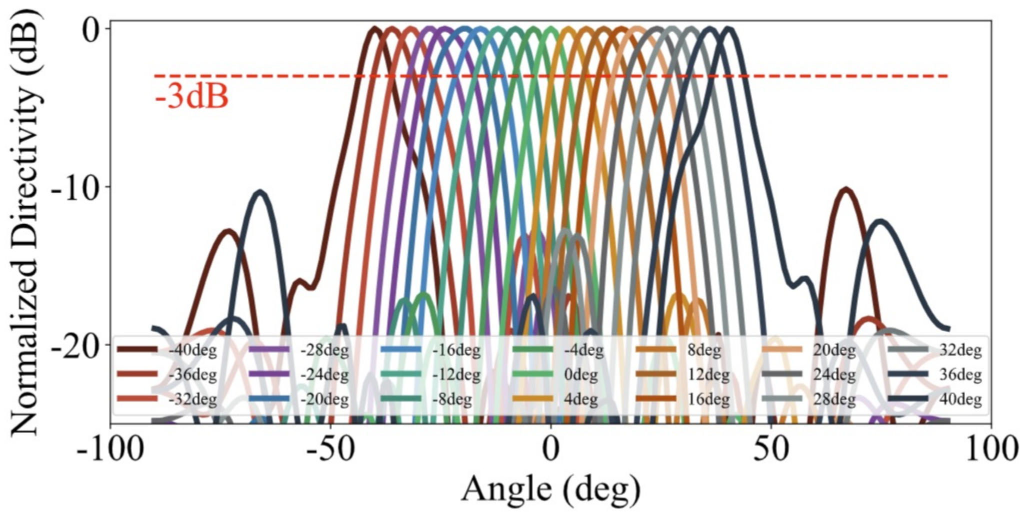
Uplink Performance: 1x8 PA + 21x21 HMS vs. PA

EM wave propagation in 3D space
Steering direction: azimuth = 20°, elevation = 0°



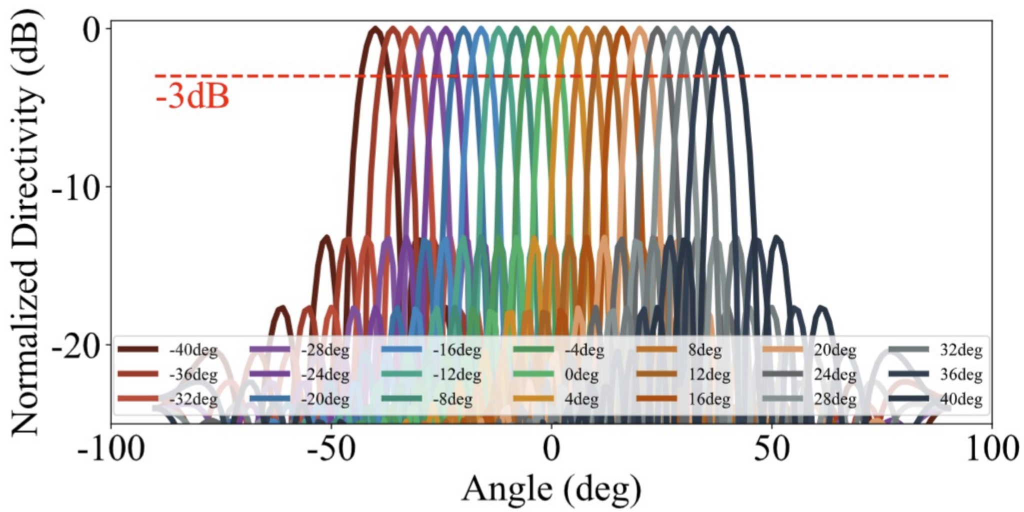
Uplink Performance: 1x8 PA + 21x21 HMS vs. PA

Beam patterns
Steering direction: azimuth: from -40° to 40 °, elevation = 0°



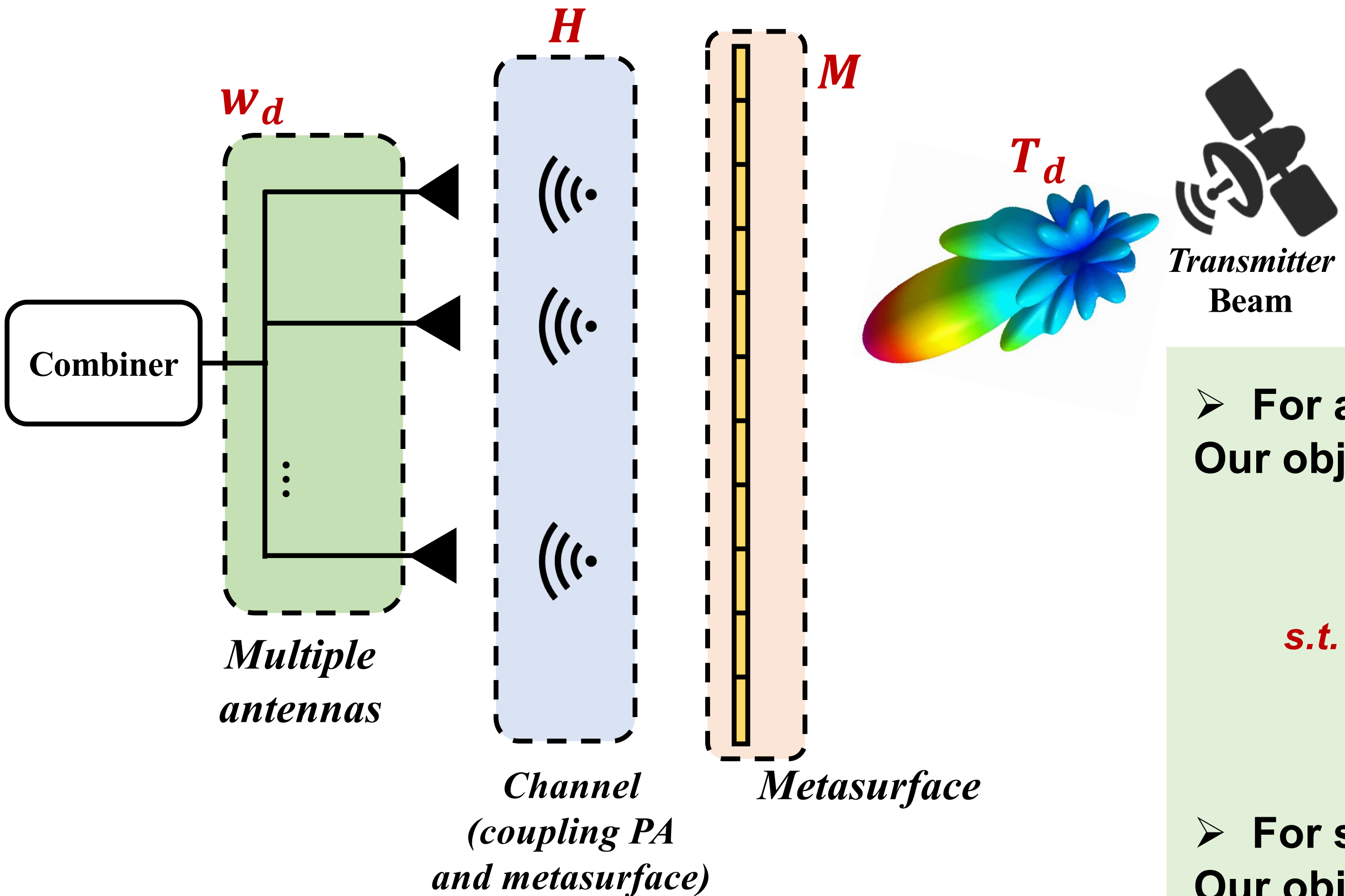
1x8 line phased array + 22x22 metasurface

close to



22x22 rectangular phased array

Downlink Optimization Model



- For a specific incident direction, d.

Our objective is to:

$$\max_{M, w_d} G(T_d\ M\ H\ w_d)$$

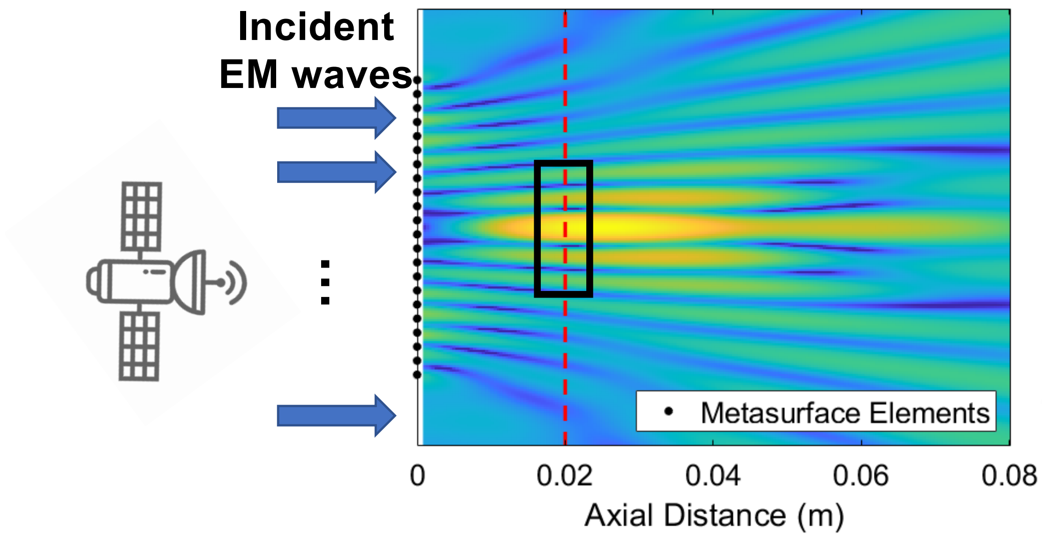
$$s.t. \begin{cases} w_{d,i} = 1, & (i = 1, 2, \dots, N) \\ |M_j| = 1, & (j = 1, 2, \dots, L) \end{cases}$$

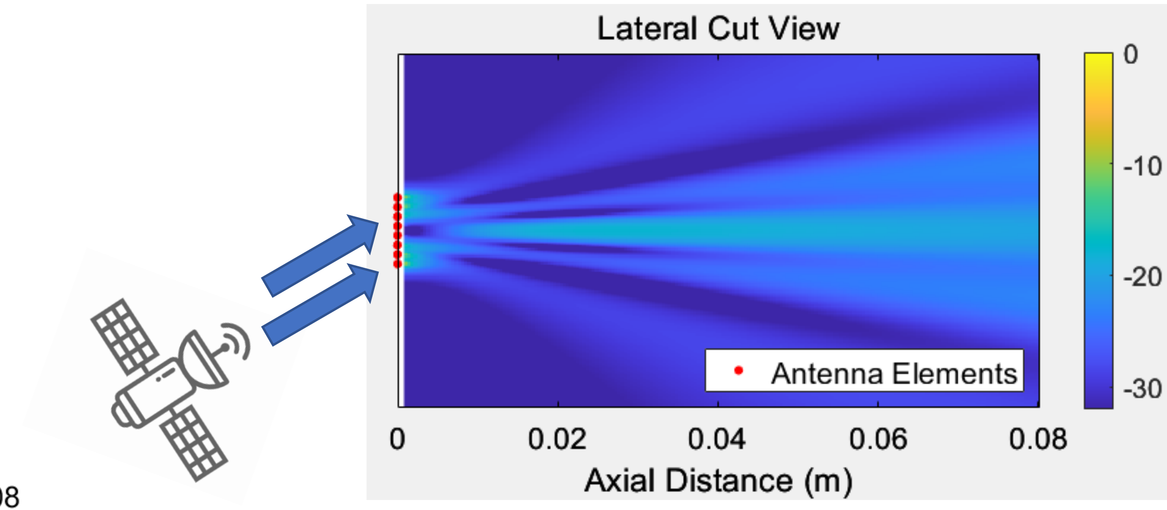
- For specific steering direction set, D.

Our objective is to: $\max_{M, W_D} G(T_D\ M\ H\ W_D)$

Downlink Performance: 1x8 PA + 22x22 HMS vs. 1x8 PA

EM wave focusing in lateral cut view





1x8 line phased array +
22x22 metasurface

11.76dB
gain

1x8 line phased array

Overview: How to design passive metasurface for LEO?

Q1: How to enable dynamic adaptation using passive metasurface?

Q2: How to design phase profile of the metasurface?

Q3: How to design the metasurface unit cell for LEO scenarios?

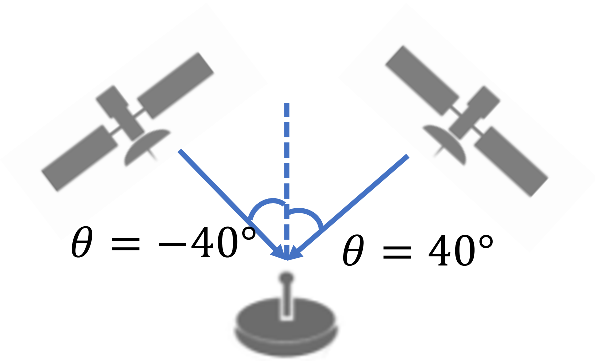
Microscopic design: Meta-atom for LEO scenarios

Requirements for TRANSMISSVE meta-atom design in LEO scenarios:

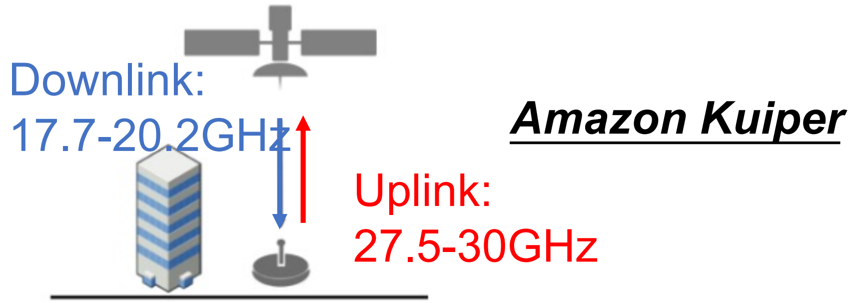
1. High transmission rate, e.g., >90%

2. 360° phase shift range for powerful wavefront control

3. **Wide incident angels**, [-40°, 40°]

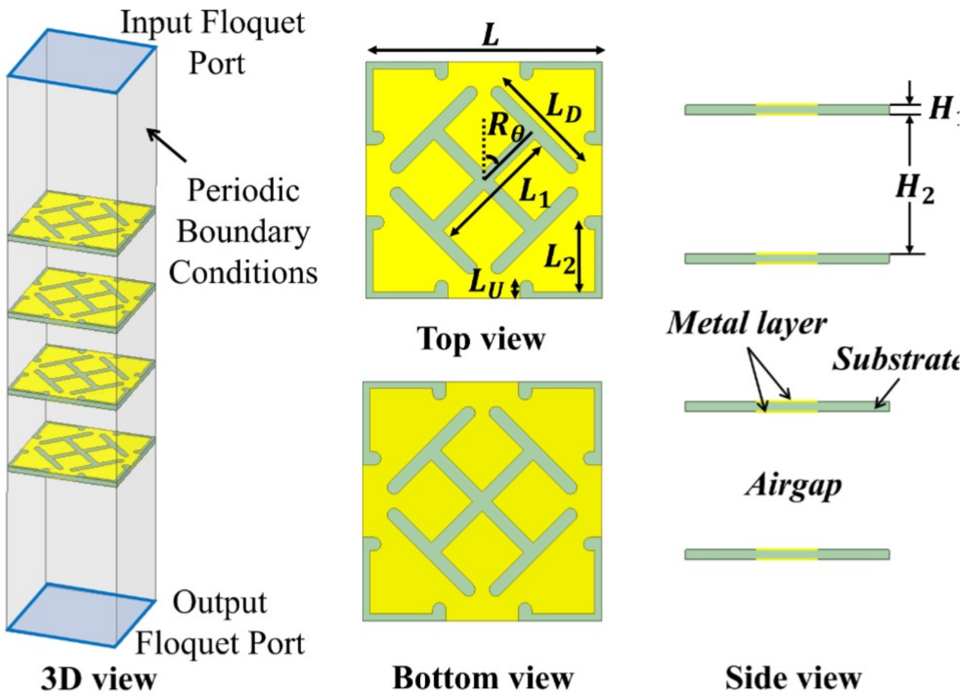


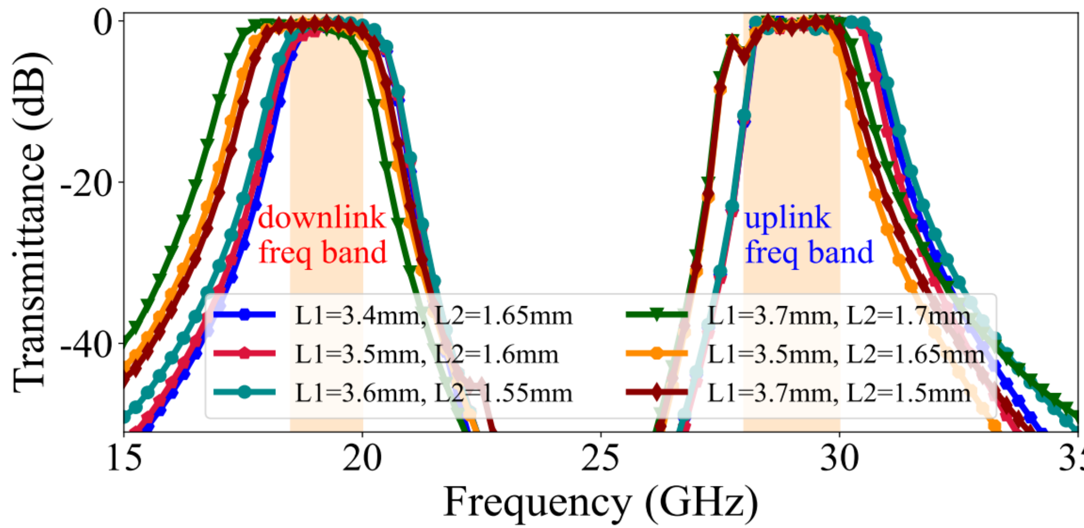
4. **Dual-band** support and wide frequency bands



Metasurface design: Meta-atom structure

Meta-atom structure design



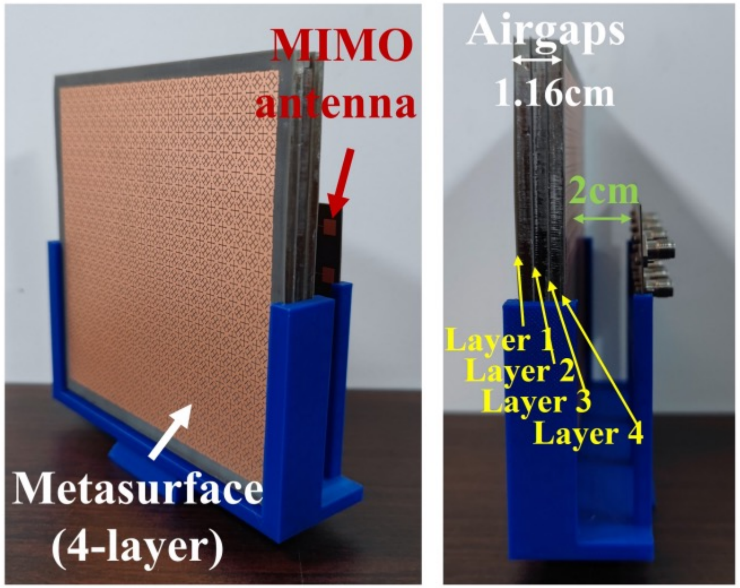


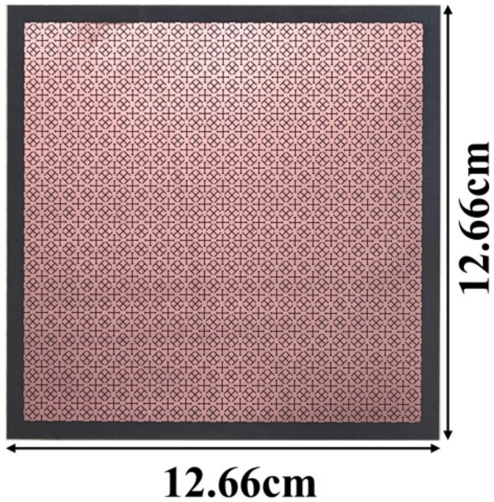
1. ***Metal-substrate-metal*** sandwich design
2. ***Two patterns*** are interlaced for dual bands
3. ***4-layers*** design for high transmission rate and 2π phase shift range

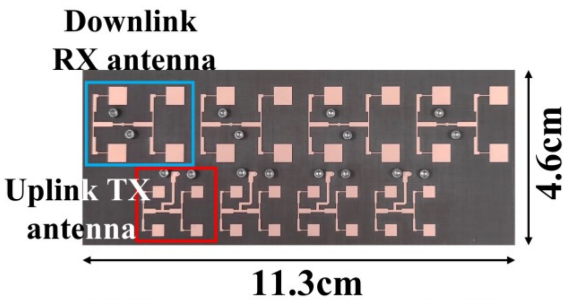
High transmission rates across wide frequency bands for uplink and downlink

Prototype of Our System

Metasurface + phased array

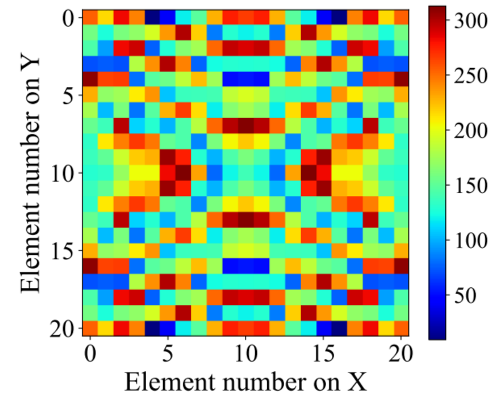




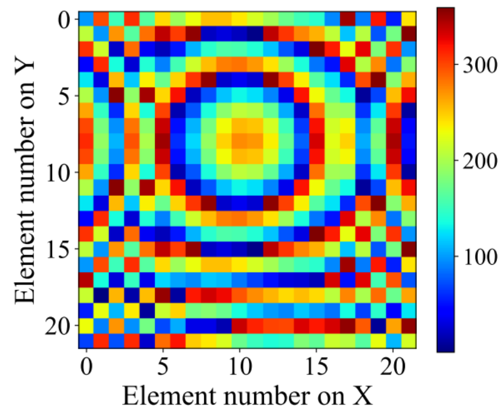


1x4 downlink antenna array
1x4 uplink phased array

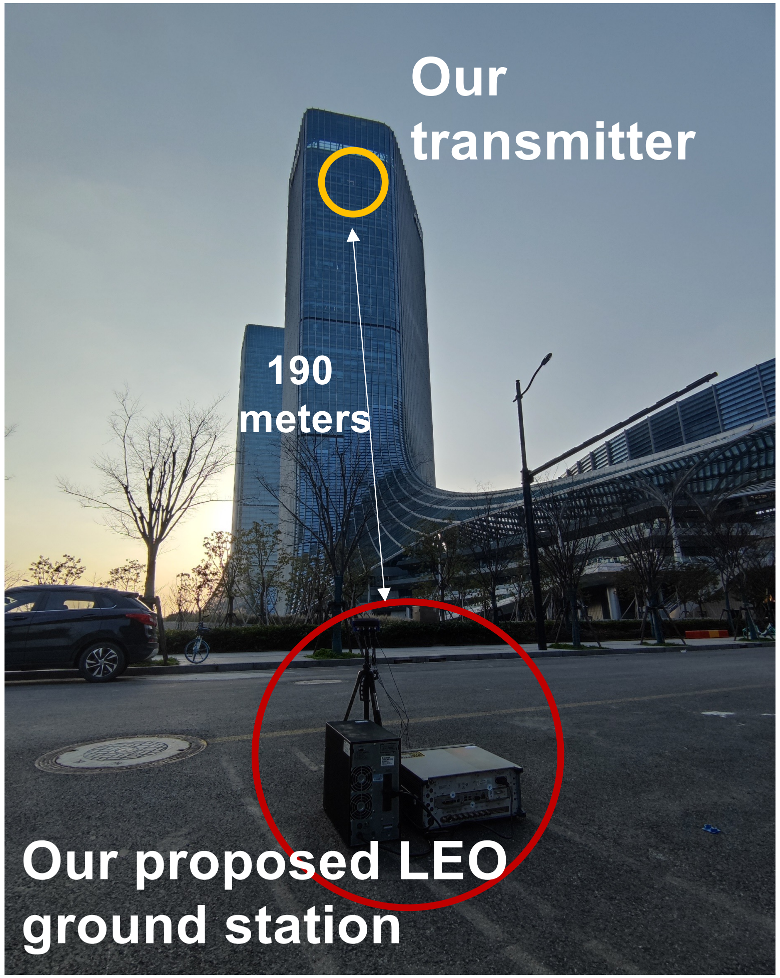
21x21 uplink metasurface



22x22 downlink metasurface



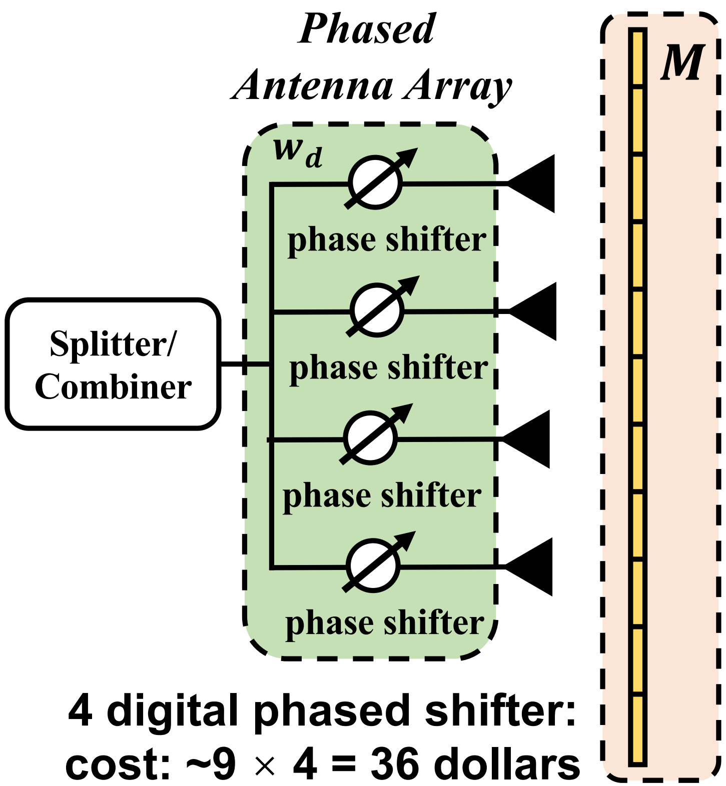
Real-world Experiment Setup



Uplink Gain:
8.32dB

Downlink Gain：
16.57dB

Performance of our prototyped system



4 digital phased shifter:
cost: ~9 × 4 = 36 dollars
1 × 4 phased array:
cost: ~10 dollars

Metasurface
cost: ~30 dollars

Total cost: ~76 dollars

Uplink performance comparison:

1x4 phased array + 21x21 metasurface → **8.32dB**

= 14x14 phased array for steering

Downlink performance comparison:

1x4 multiple antennas + 22x22 metasurface → **16.57dB**

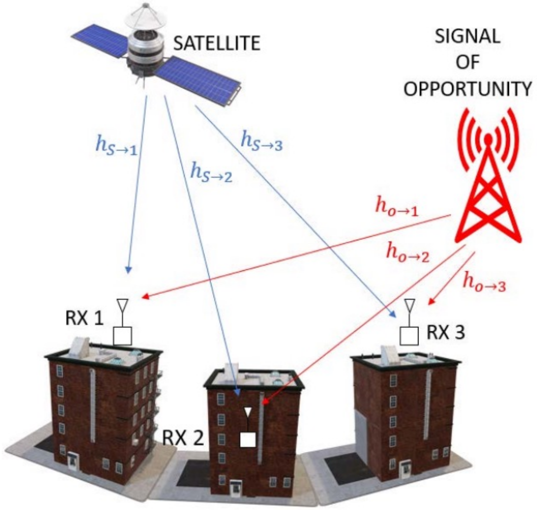
= 17x17 phased array for focusing

289 digital phased shifter:
Cost: ~9 × 289 = 2601 dollars
17 × 17 phased array:
Cost: ~200 dollars

Total cost: ~2800 dollars

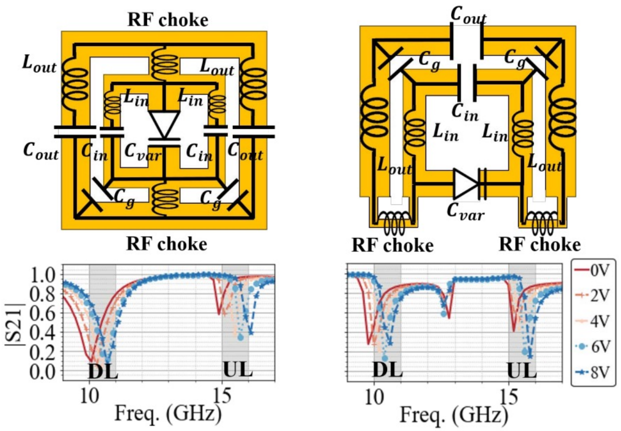
Related work

LEO ground station design



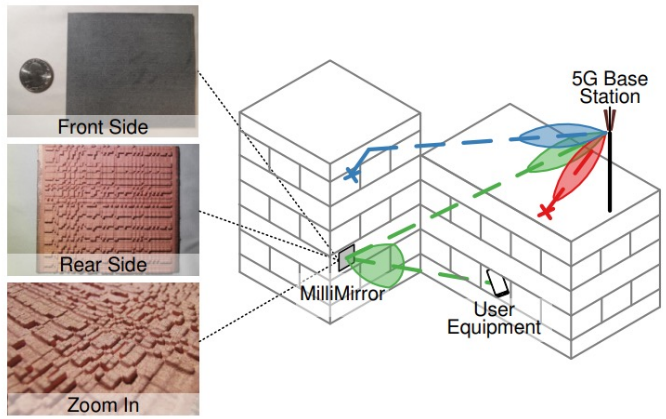
A Community-Driven Approach to Democratize Access to Satellite Ground Stations **[Mobicom'21]**

Active metasurface



Towards dual-band reconfigurable metasurfaces for satellite networking **[HotNets'22]**

Passive metasurface



MilliMirror: 3D Printed Reflecting Surface for Millimeter-Wave Coverage Expansion **[MobiCom'22]**

Our work: (1) joint design of passive metasurface and a small phased array
(2) novel metasurface unit cell design for LEO

Conclusion

- ✓ **We combine the passive metasurface and small phased array to achieve a low-cost high-performance LEO ground station.**
- ✓ **We joint optimize the metasurface's phase profile and phased array's code words in both uplink and downlink**
- ✓ **We design a meta-atom for LEO scenarios to satisfy high transmission rate, 2pi phase range, dual bands, and wide incident angles**

Microsoft

Thanks for listening!

How about discrete phase shifter?

Our system also supports non-continuous phase shifters, such as phase shifters that only support 16-level discrete phase modulation. Firstly, we assume that the phase shifter can still continuously modulate the phase, so that we can obtain an optimal metasurface phase map and the codeword information of the phased array antenna. Then, we update the codeword of the optimized phased array antenna based on the discrete phase of the phase shifter, and after that, we fine-tune the metasurface phase map according to the updated codeword. After two optimizations, we can make our metasurface support the settings of discrete phase shifters.

Other applications

Our system can not only be used in LEO scenarios but also has many other applications. Essentially, the system we proposed can utilize metasurfaces to help small phased arrays enhance their beam forming and steering capabilities. In other words, the optimized metasurface can transform a small phased array into a large phased array.

How to handle with dynamic environment

Although we use passive metasurfaces, our system can still handle dynamic wireless channel scenarios. Because we use a small phased array antenna system to provide programmability, our system can adapt to dynamic environments, such as indoor environments with many moving people. By changing the codewords of the phased array, our system can adapt to the dynamic environment and find the optimal codewords for communication.

3D beam steering

Our system can support 3D steering. The joint optimization framework of metasurface and phased array that we propose is not limited to 2D steering. When we configure the phased array as 2D, for example, setting it as a 4x4 square phased array, we can optimize a metasurface to work with the 2D phased array to achieve 3D steering.