KTH VETENSKAP OCH KONST

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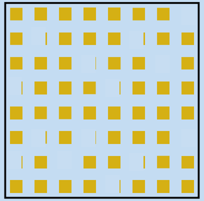
Swedish Wireless Innovation Network

Asymmetric Antenna Arrays



Emil Björnson

Professor of Wireless Communication

Department of Communication Systems (COS)

KTH Royal Institute of Technology, Stockholm, Sweden

A special thanks to

Murat Babek Salman
Nikolaos Kolomvakis
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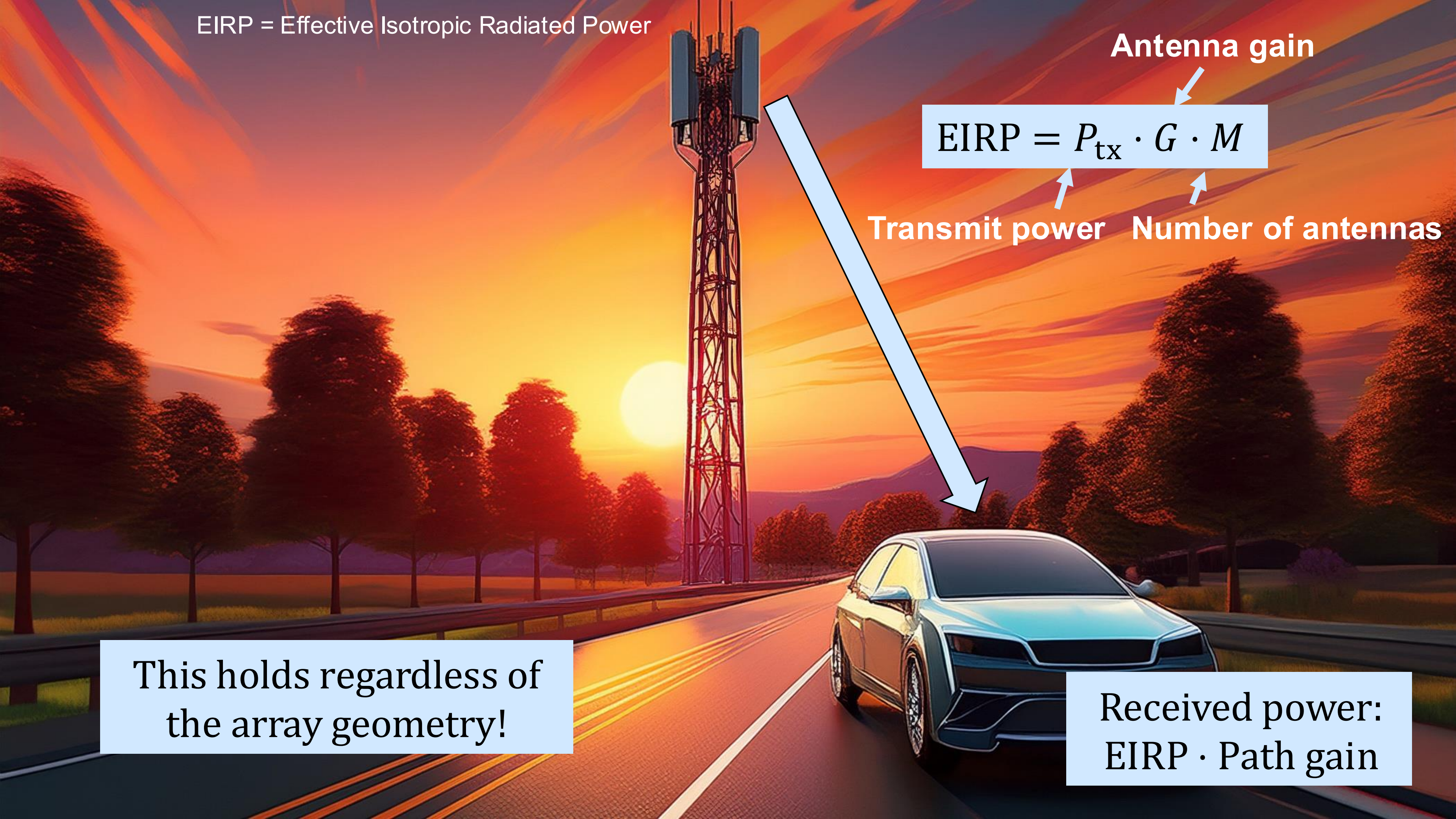
SSF

Knut and Alice Wallenberg Foundation

Swedish Research Council

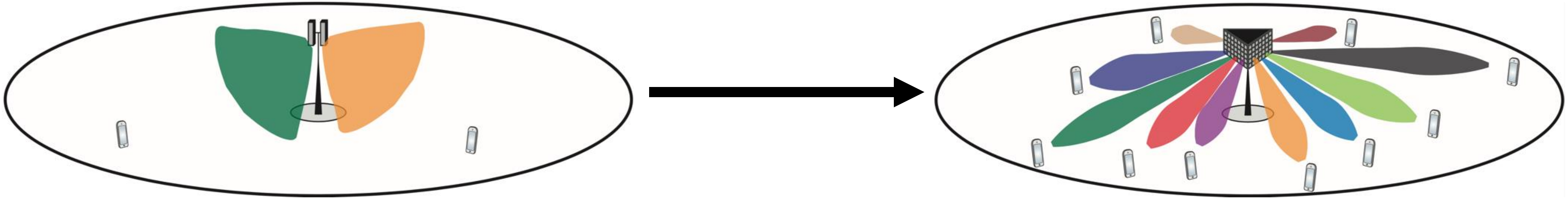
What I want you to remember:

- Larger antenna arrays are essential for 6G
- We should rethink the array geometry
- The role that movable antennas might play

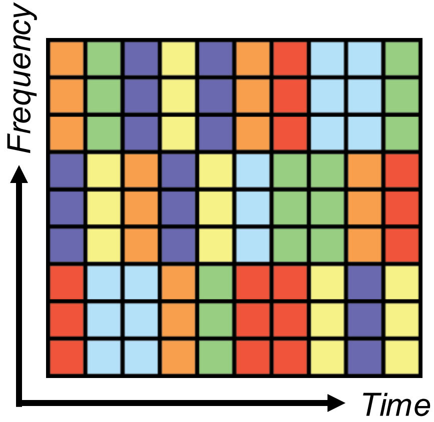

EIRP = Effective Isotropic Radiated Power
Antenna gain
$\text{EIRP} = P_{\text{tx}} \cdot G \cdot M$
Transmit power
Number of antennas
This holds regardless of the array geometry!
Received power:
EIRP · Path gain

Evolution in Multiple Access

1. Sectorization and frequency reuse → 2. Multi-user MIMO (multiple-input multiple-output)



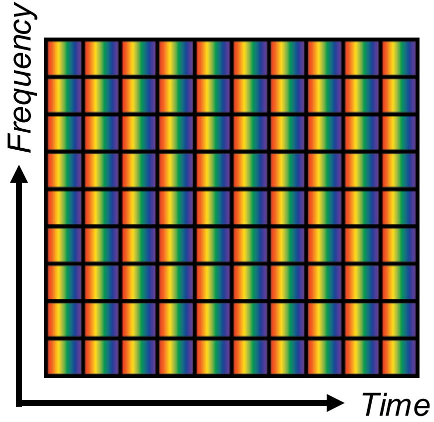
Time-frequency scheduling



Beamforming:
Higher SNR
Channel hardening

Spatial multiplexing:
Higher cell capacity

User-separation by beamforming

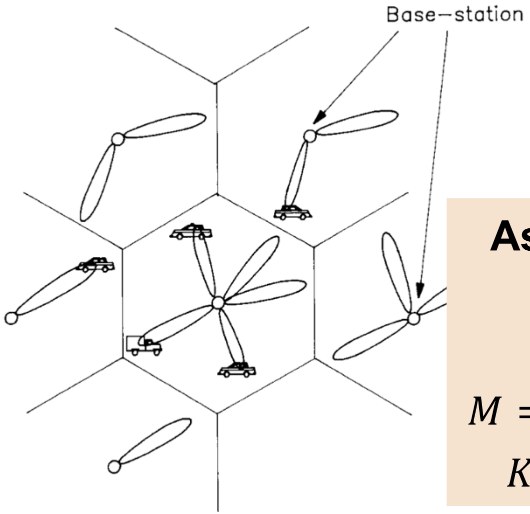


From **SDMA** to **Massive MIMO**

Space-division multiple access

Concept from late 80s, early 90s

Information theory in 00s



Assumption

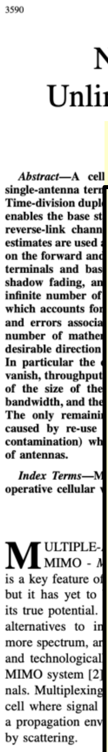
$M \approx K$

M = #antennas

K = #users

Reference: Swales, Beach, Edwards, McGeehan, "The Performance Enhancement of Multibeam Adaptive Base-Station Antennas for Cellular…," IEEE TVT 1990.

Marzetta's "Massive" MIMO (2010)

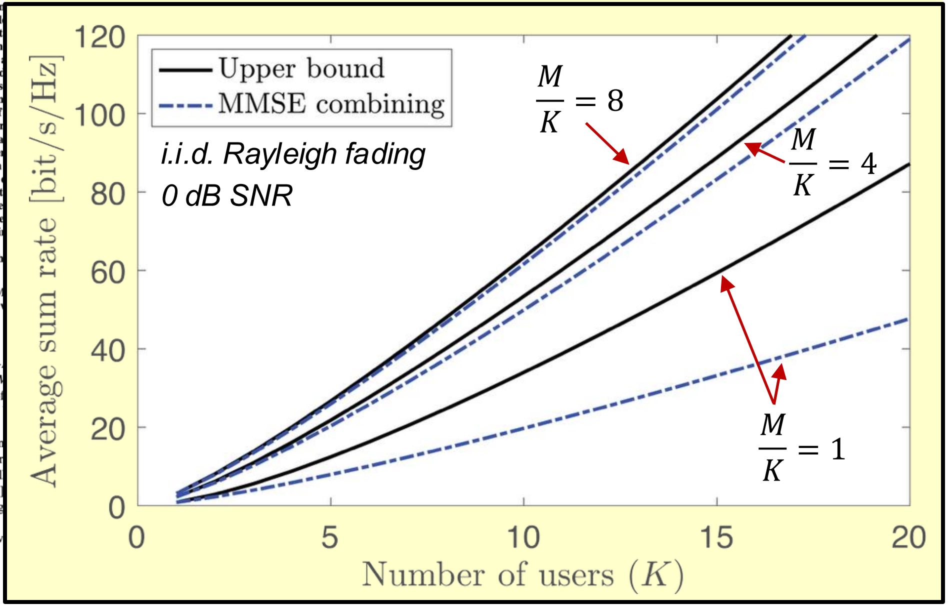

3590 IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, VOL. 9, NO. 11, NOVEMBER 2010

Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas

Assumption

$M \gg K$

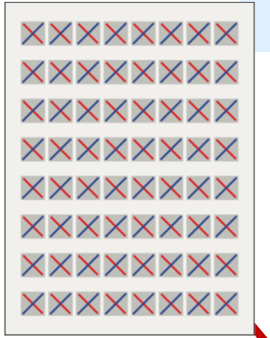
Abundance of antennas → "Favorable propagation"



Massive MIMO in 5G

n78 band: 3.3-3.8 GHz

100 MHz bandwidth



64 antennas

One device: 710 Mbps (average)

MU-MIMO with 8 user devices

- 16 spatial layers, 2 layers/user
- 650 Mbps per device (average)
- 5.2 Gbps in total (52 bit/s/Hz)

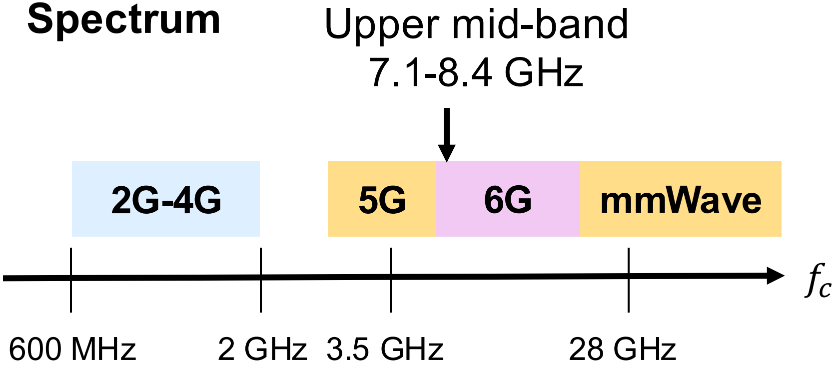
$$\frac{M}{K} = 4$$

4 antennas

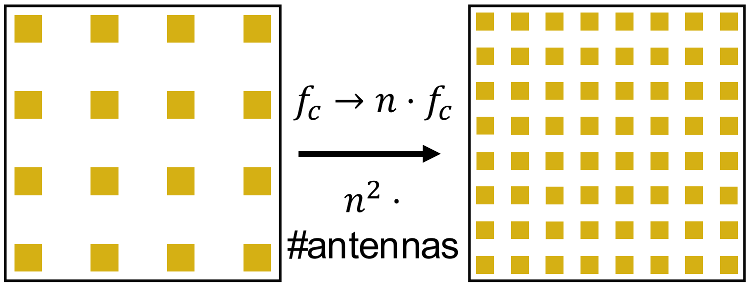
Reference: Signals Research Group, "The Industry's First Independent Benchmark Study of 5G NR MU-MIMO," 2020

Spectrum and Antenna Numbers in 6G

Spectrum



Antennas fitting in the aperture



Example: $(7.8/3.5)^2 \approx 5$

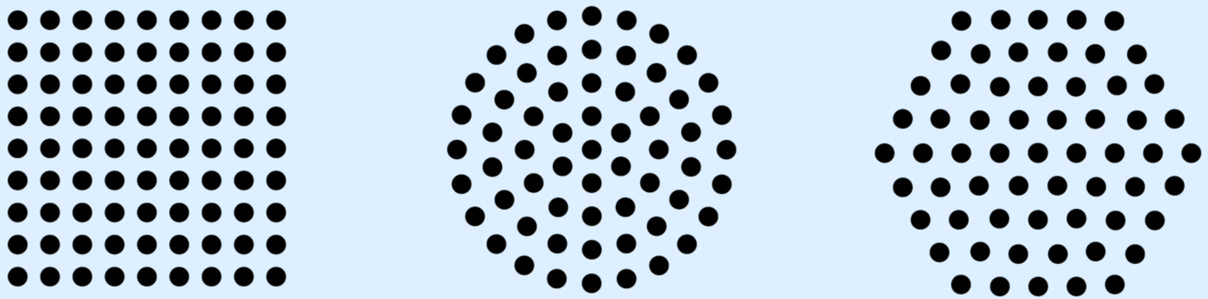
4G		5G		6G
20 MHz	$5\times$ →	100 MHz	$2\times$ →	200 MHz
4 antennas	$16\times$ →	64 antennas	$5\times$ →	320 antennas

Capacity growth mainly achieved by ***bigger MIMO***!

Challenge: Very many antennas if we keep $M \gg K$

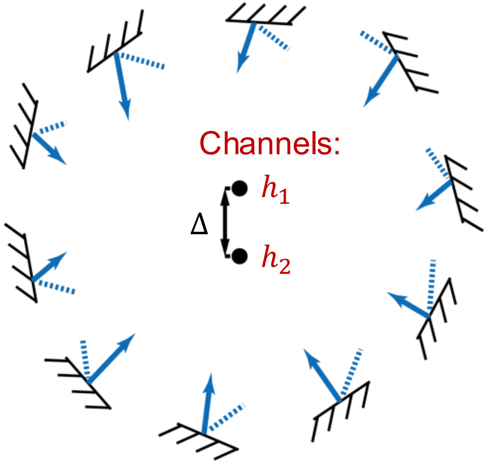
Can we avoid the antenna abundance by smarter array design?

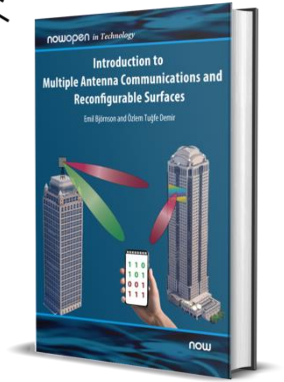
WHAT IS A GOOD ANTENNA ARRAY GEOMETRY?



Classical Motivations for $\lambda/2$-Spacing

Isotropic 3D scattering environment



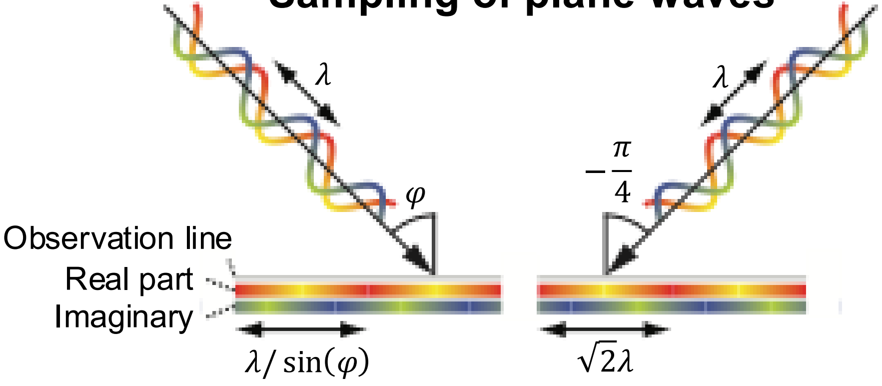


$$E\{h_1 h_2^*\} = \cdots = \beta \cdot \text{sinc}\left(\frac{\Delta}{\lambda/2}\right)$$

Nulls at $\Delta = \frac{\lambda}{2} \cdot \text{integer}$ (except 0)

→ Place antennas $\lambda/2$ apart!

Sampling of plane waves



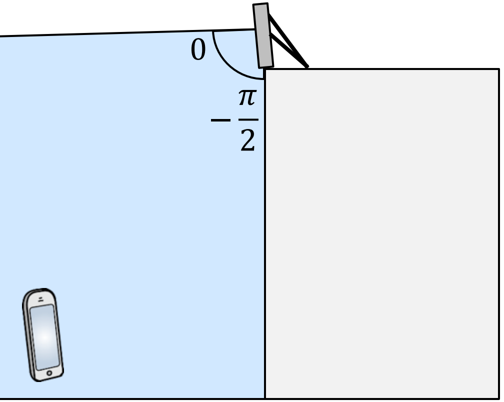
Arbitrary plane waves: $\varphi \in [-\pi/2, \pi/2]$

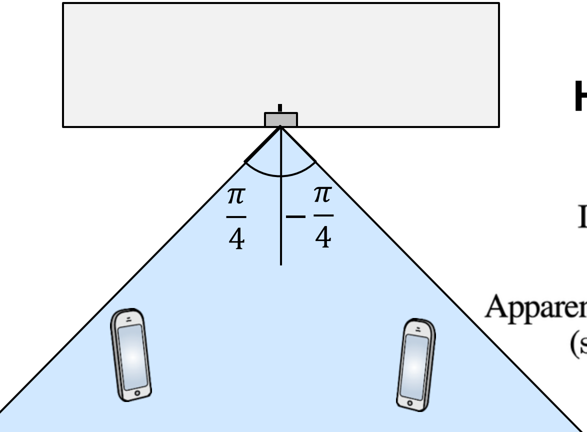
→ Spatial frequencies: $\sin(\varphi)/\lambda \in [-1/\lambda, 1/\lambda]$

→ Spatial bandwidth $2/\lambda$

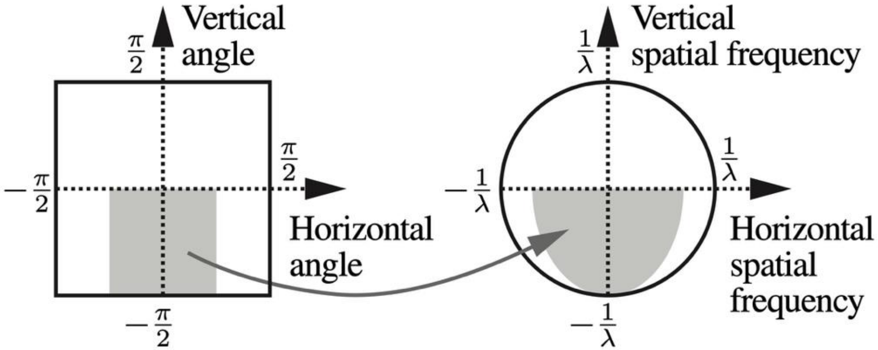
Sampling theorem (complex signal):
Place antennas to take samples $\lambda/2$ apart!

Practical Deployments are Different

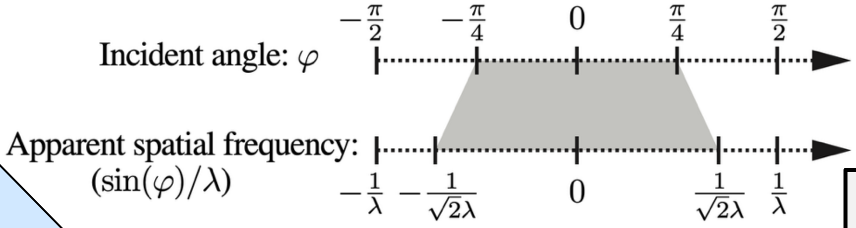




Joint horizontal and vertical coverage:

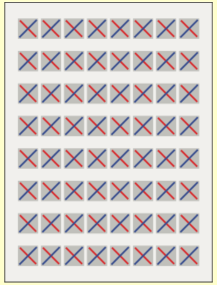


Horizontal coverage sector:



Use spacing:
$\sqrt{2}\lambda/2$ horizontally
λ vertically

Vertical spacing 0.7λ



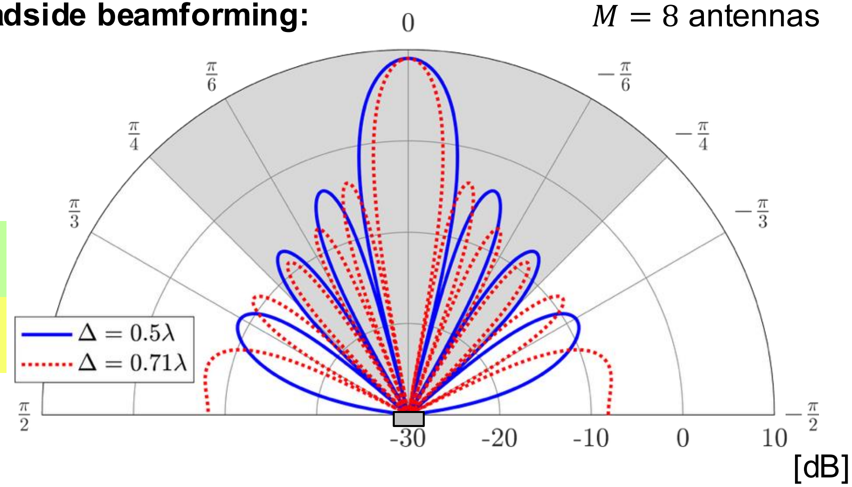
64 antennas

Place antennas $\sqrt{2}\lambda/2$ apart!

Sparse Uniform Arrays: What is the Catch?

Broadside beamforming:

$M = 8$ antennas



+ Narrower beam!

Different sidelobes

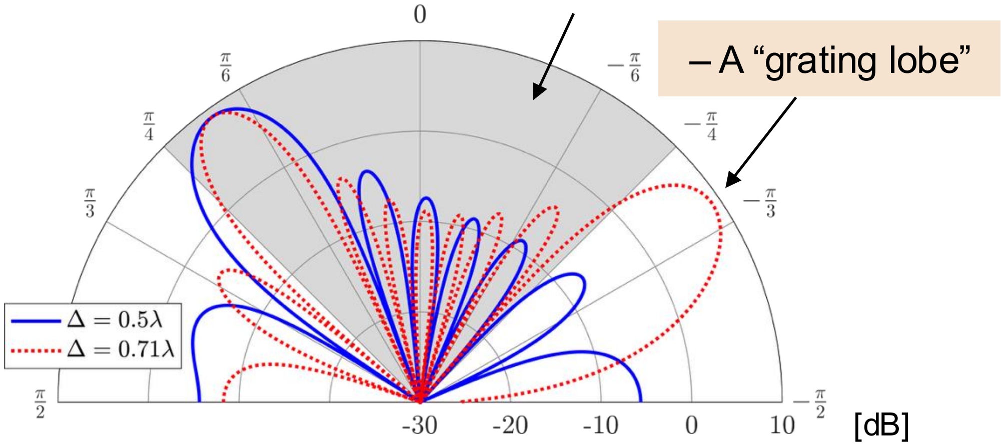
Are grating lobes
a **real issue?**

Yes, for localization and
interference to others

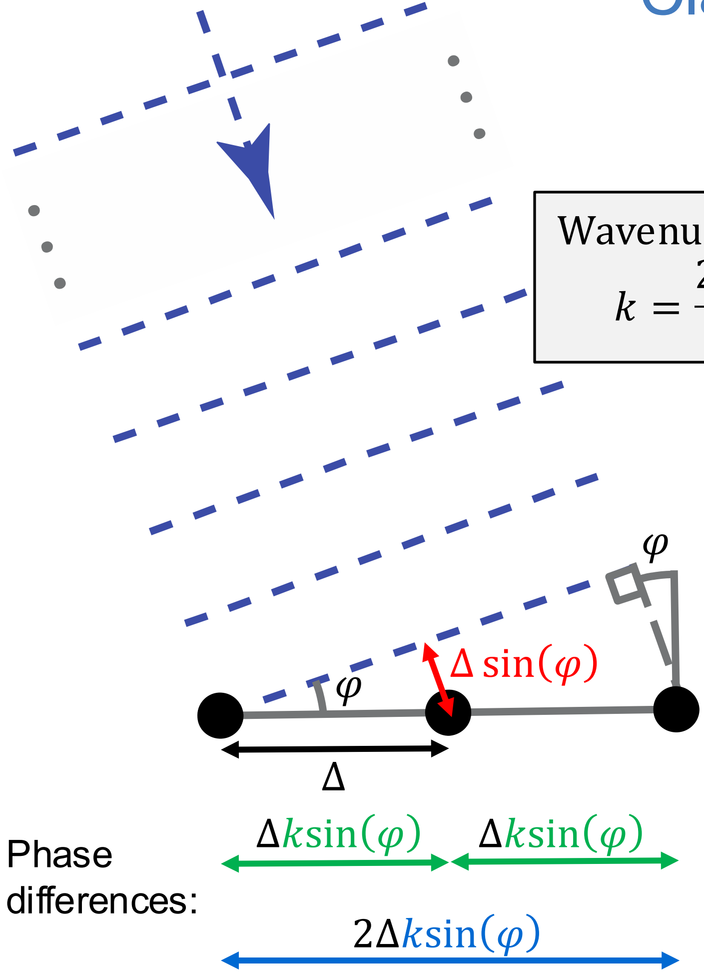
But…

Leads to better beam resolution
in the coverage region

Beamforming toward $\pi/5$:



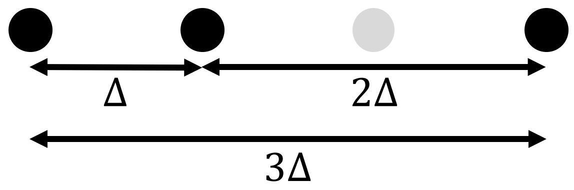
Classical **Structured Non-Uniform** Arrays



Phase differences:

Wavenumber
$k = \frac{2\pi}{\lambda}$

Minimum-redundancy array (MRA):



Three unique separations:

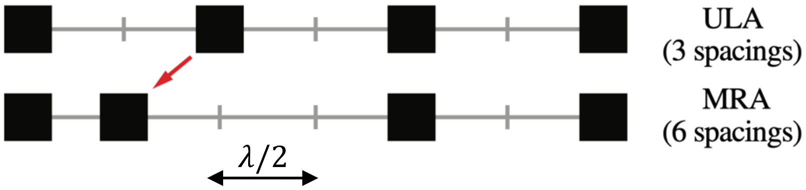
Maximum number of phase differences!

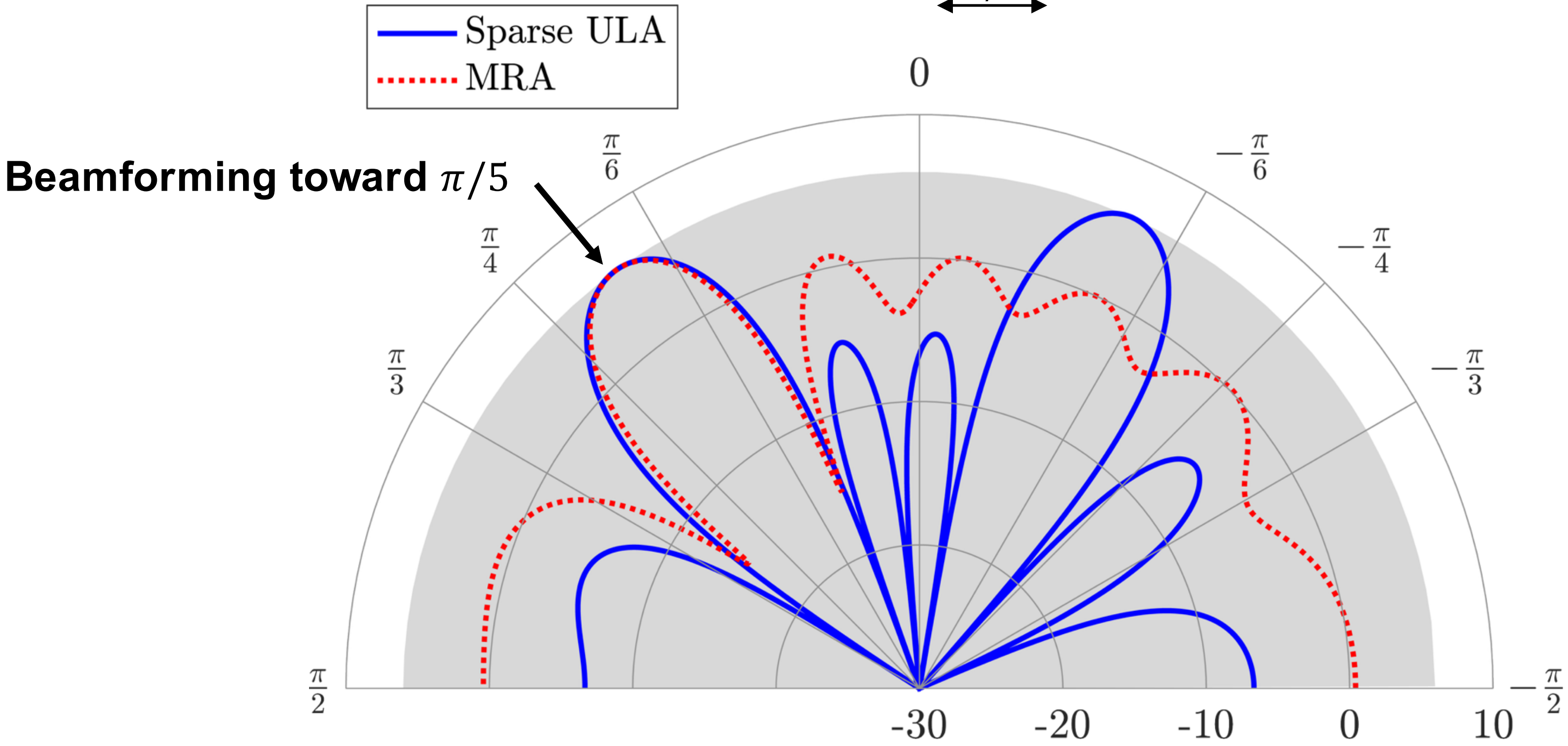
M-antennas arrays can generate up to $\binom{M}{2} = \frac{M(M-1)}{2}$ phase differences

Detect $\approx M^2/2$ sources using M antennas

Reference: Moffet, “Minimum-redundancy linear arrays,” IEEE TAP,1968

What Happens to the Beam Pattern?





Are Non-Uniform Arrays **Useful for Communications**?

Channel estimation: Yes

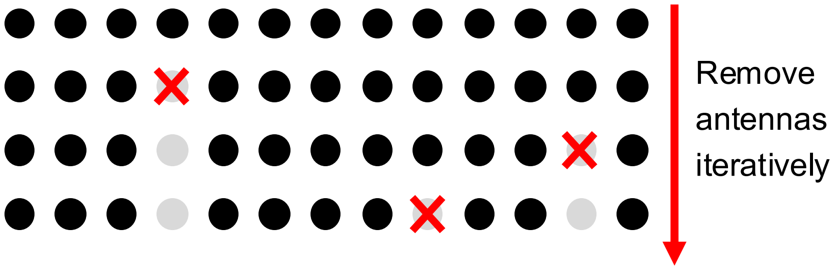
For sparse channels (identify $M^2/2$ paths)

Beamformed data transmission: Unsure

M-length channels: At most M orthogonal beams

Mainlobe size ∝ 1/(array length)

Approach 1: **Thinned array**

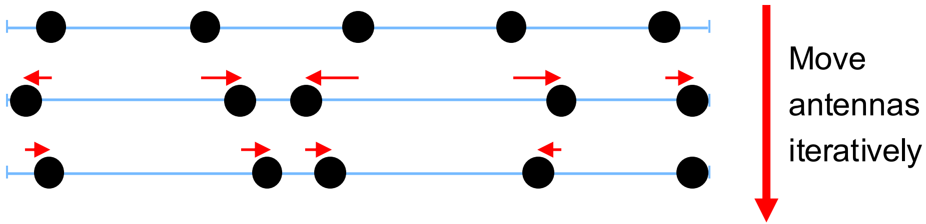


Maximize communication performance

Example: Maintain average sum rate

Reference: Skolnik, Sherman, "Planar arrays with unequally spaced elements," Radio and Electronic Engineer, vol. 28, pp. 173–184, 1964.

Approach 2: **Pre-optimized Irregular Array (PIA)**

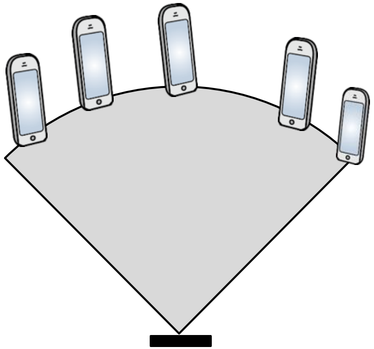


Use *particle swarm optimization (PSO)* or similar method

Arbitrary spacings, but $\geq \lambda/2$ to avoid coupling

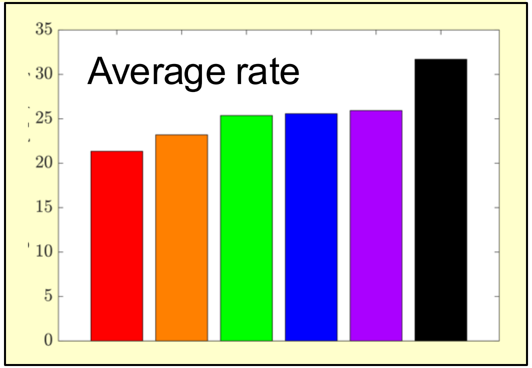
Reference: Irshad, Kosasih, Petrov, Björnson, "Pre-Optimized Irregular Arrays versus Movable Antennas in Multi-User MIMO Systems," IEEE WCL, 2025

Uplink Example: $M = 8$ antennas, $K = 5$ users



Non-uniform arrays are best!

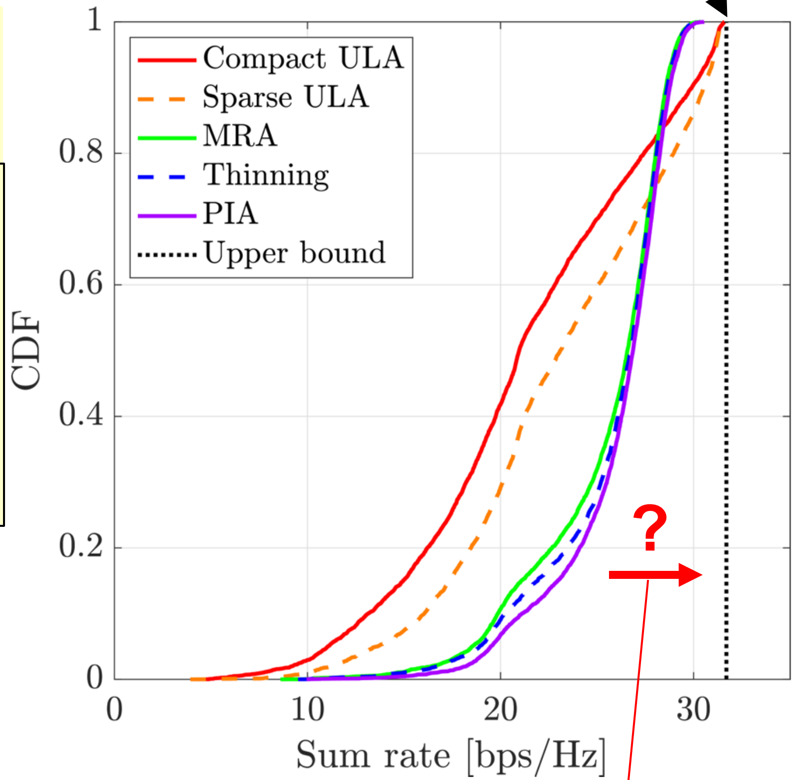
PIA a little better than MRA/thinning

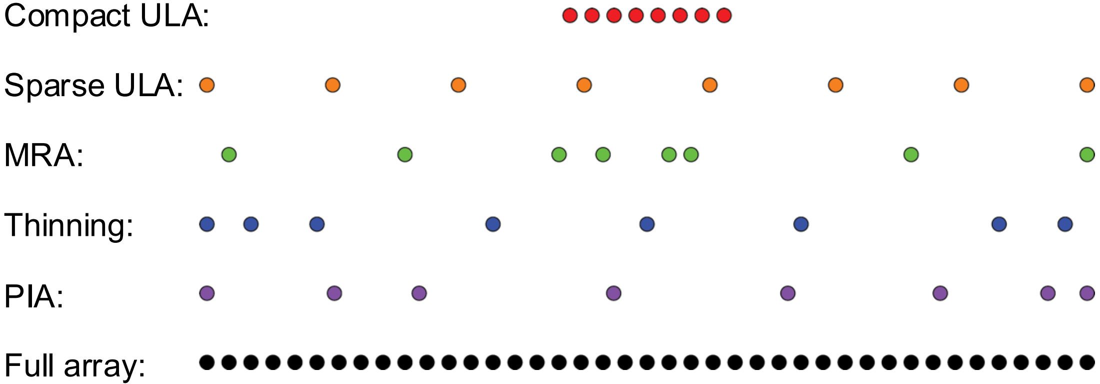


Linear aperture: Length 20λ

- Line-of-sight, 10 dB SNR
- Random angles (10^4 user drops)

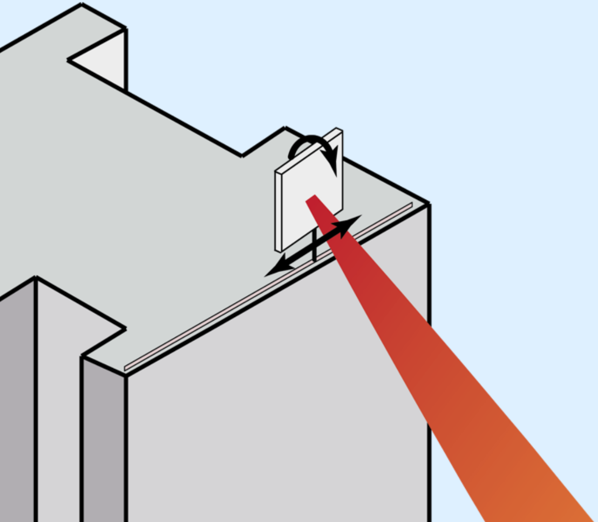
No interference





Can we do anything more?

REAL-TIME MOVABLE ANTENNAS:
IS THAT A THING?



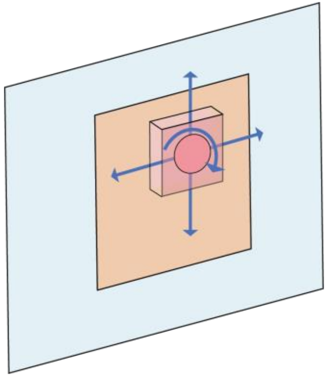
"…for a fixed array, there are certain things that cannot be done in the digital domain. […] To deal with such problems, an interesting avenue for future research is the study of arrays with flexible geometry that could optimally position themselves or their elements with some degrees of freedom."

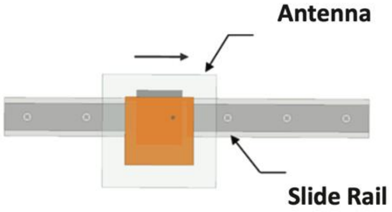
Björnson, Sanguinetti, Wymeersch, Hoydis, Marzetta, "Massive MIMO is a Reality—What is Next?", DSP, 2019

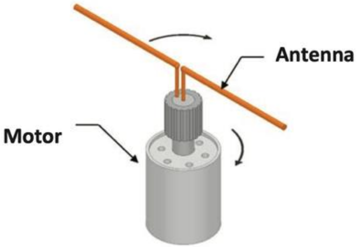
Hardware for Movable Antennas

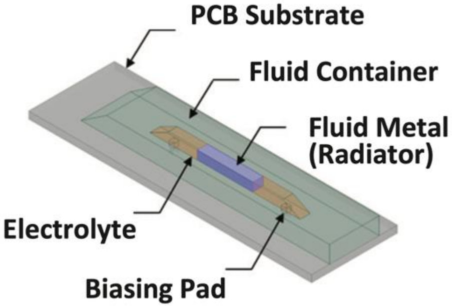
Element-level

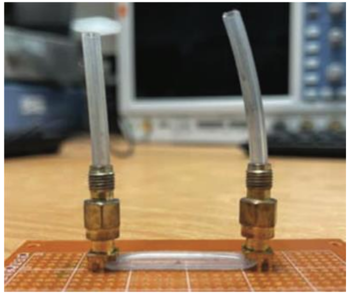
Shift and rotate



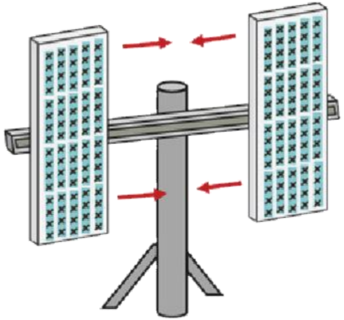


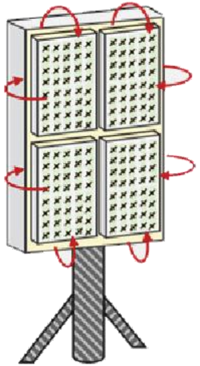






Array-level





Hardware-based terminologies

1999: MEMS reconfigurable antenna

2007: Mechanically movable antenna

2008: Electrolytic fluid antenna

MIMO-related concepts

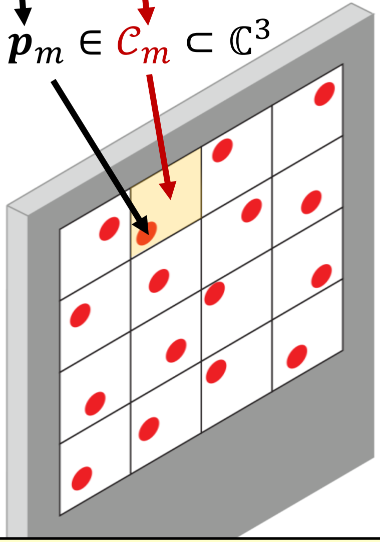
2019: Intelligent Massive MIMO

2020: Fluid antenna system

2022: Movable antenna system

Original sources cited in: Ning, Yang, Wu, Wang, Mei, Yuen, Björnson, “Antenna-Enhanced Wireless Communications: General Architectures and Implementation Methods,” IEEE Wireless Communications, 2025.

Optimizing Antenna Positions



Problem formulation:

$$\underset{\mathbf{p}_1,\ldots,\mathbf{p}_M}{\text{maximize}} \quad R_\Sigma(\mathbf{p}_1,\ldots,\mathbf{p}_M)$$ ← Sum rate (or another metric)

$$\text{subject to} \quad \mathbf{p}_m \in \mathcal{C}_m, \; m = 1,\ldots,M$$ ← Movable area

$$\|\mathbf{p}_m - \mathbf{p}_j\| \geq \lambda/2, \; m \neq j$$ ← Avoid mutual coupling

Use parametrized channel:

$$\boldsymbol{h} = \sum_i c_i \boldsymbol{a}(\mathbf{p}_1,\ldots,\mathbf{p}_M,\varphi_i,\theta_i,)$$

Coefficient; Array response; Angles

Key challenges:

1. Acquire channel knowledge (*evaluate many* $R_\Sigma(\mathbf{p}_1,\ldots,\mathbf{p}_M)$)
2. Calculate the desired antenna locations (*solve problem above*)
3. Move the antennas quickly (*faster than channel coherence*)

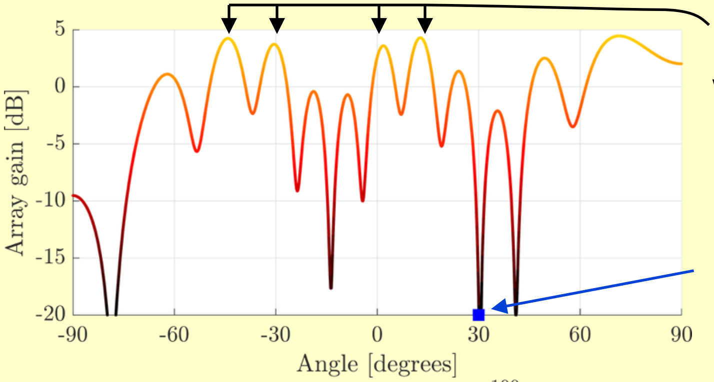
PSO or something else

No real-time experiments?

Reference: Irshad, Kosasih, Petrov, Björnson, "Pre-Optimized Irregular Arrays versus Movable Antennas in Multi-User MIMO Systems," 2025

Uplink Example (continued)

Where is the *extra* gain coming from?

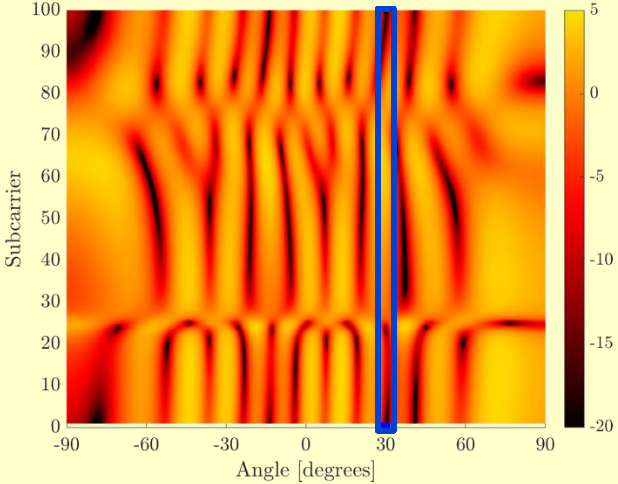


Beam pattern to *User 1* with four multipaths

Example: $M = 3, K = 2$

Null at angle to *User 2* (LOS-only channel)

We orthogonalize user channels!

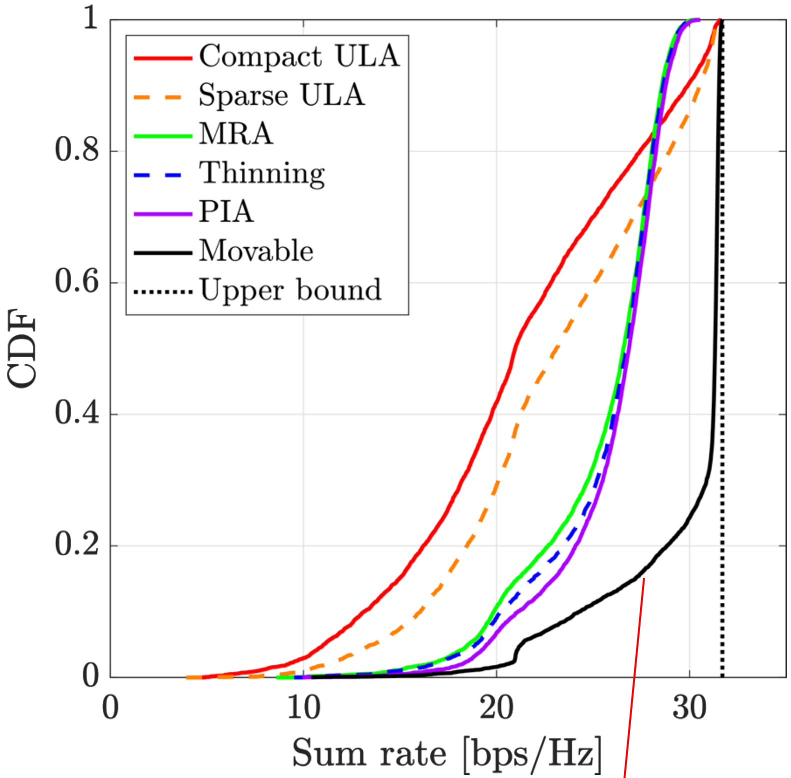


Practical limitation:

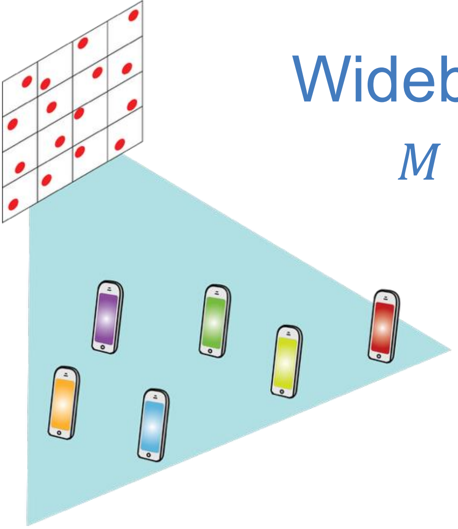
Different channels on each subcarrier!

Linear aperture: Length 20λ

$M = 8$ antennas, $K = 5$ users



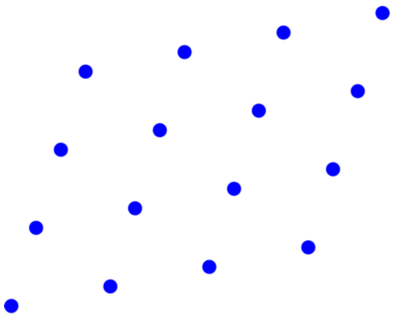
Movable antennas achieve upper bound in 75% of setups



Wideband Example

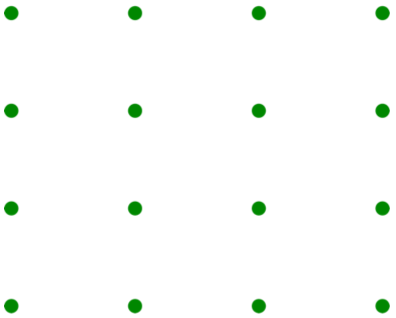
$M = 16, K = 10$

Shifted UPA:

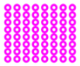


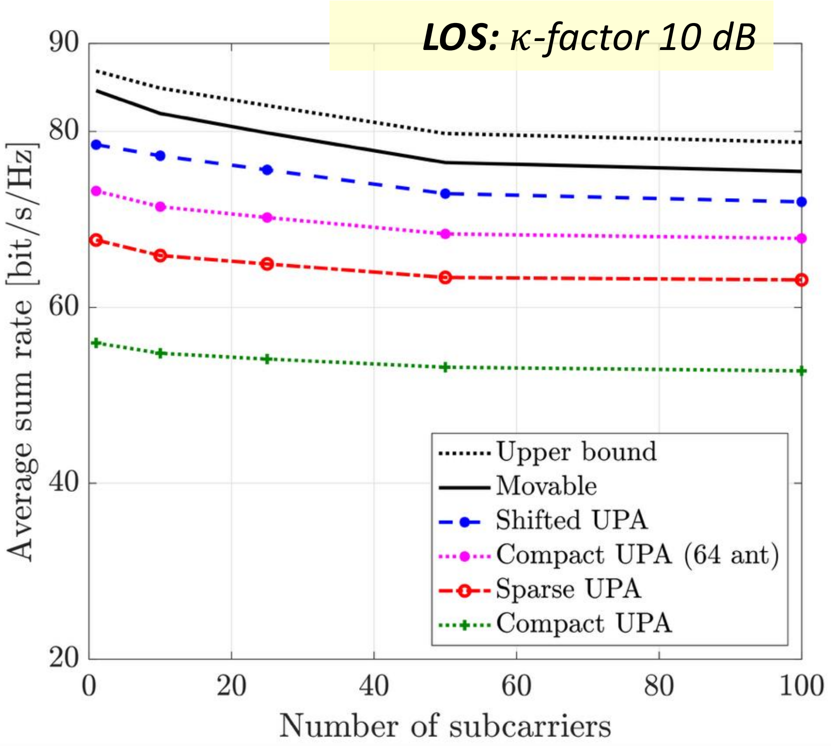
Compact UPA

Sparse UPA:



Compact UPA
(64 antennas)





Observations

Movable antennas consistently perform best

Shifted UPA only 6% worse

Both outperform 64-antenna UPA (same EIRP)

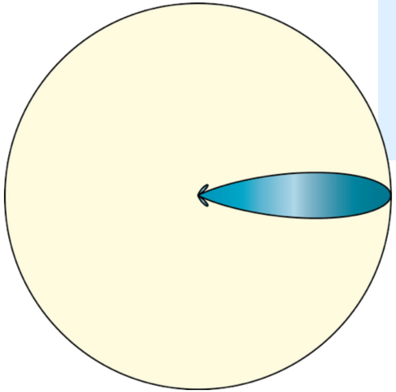
Maintaining the EIRP (Effective Isotropic Radiated Power)

Antenna gain

$$\mathrm{EIRP} = P_{\mathrm{tx}} \cdot G \cdot M$$

Transmit power

Number of antennas

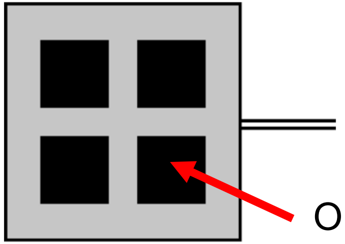


Fewer antennas

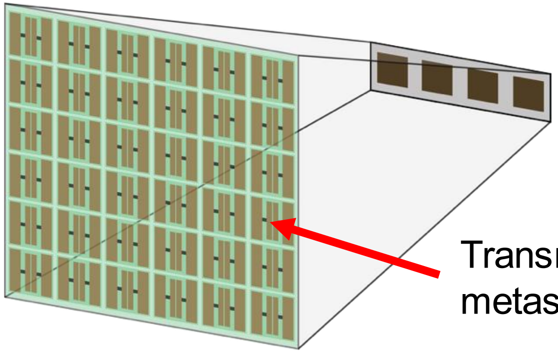
Larger gain to maintain EIRP

Option 1: Antennas with multiple elements

One “antenna port”



Option 2: RIS-Integrated antenna array



Reference: Demir, Björnson, “User-Centric Cell-Free Massive MIMO With RIS-Integrated Antenna Arrays,” IEEE SPAWC 2024.

Summary: **From Antenna Abundance to Antenna Intelligence**

We need more spatial multiplexing in 6G bands

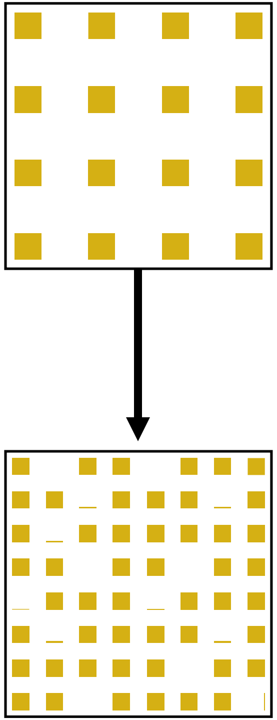
- Larger M (antennas) and K (users)

We can scale M more slowly (reduced M/K) using

- Non-uniform array tailored for the coverage area
- Tweak antenna gains to maintain EIRP

Real-time movable antennas

- Only useful in LOS scenarios
- Gains are only large compared to “wrong” benchmarks



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