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Massive Near-Field Spatial Multiplexing:

Higher Capacity Without More Bandwidth

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A special thanks to

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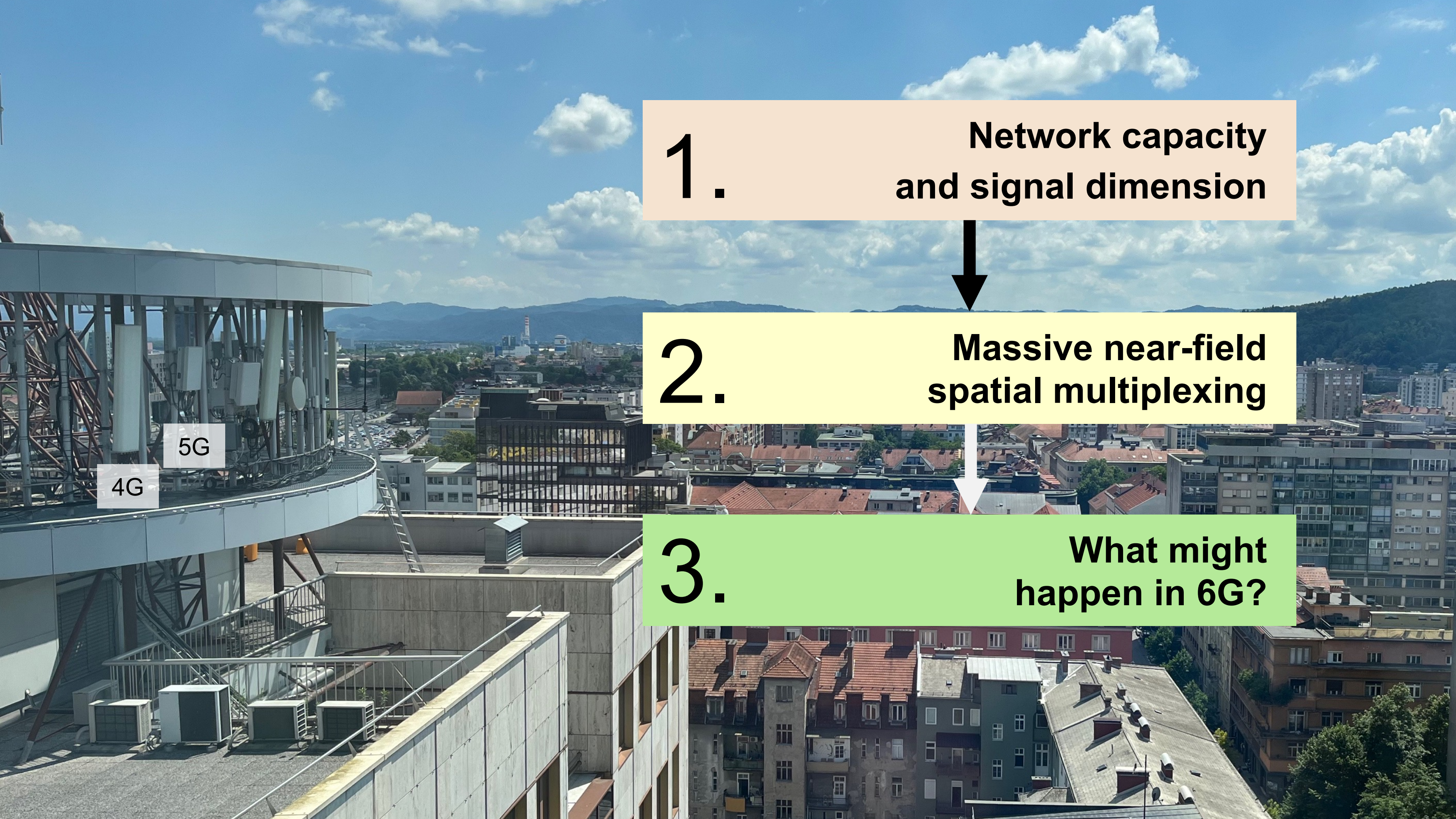
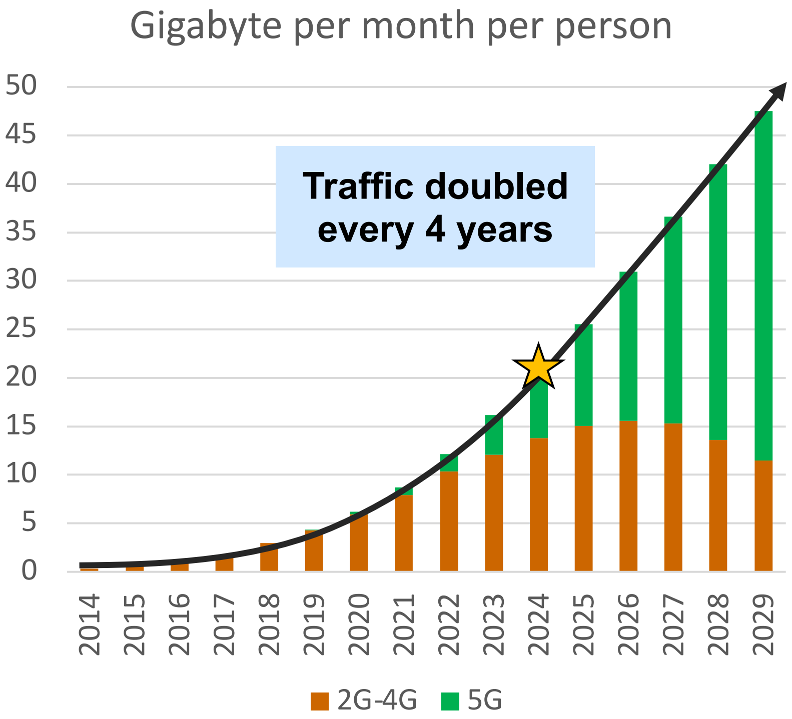


1. Network capacity and signal dimension
2. Massive near-field spatial multiplexing
3. What might happen in 6G?

Network Capacity in Mobile Networks

Demand



Traffic doubled every 4 years

Ericsson Mobility Report, 2024

Supply

Channel capacity (bit/s per access point):

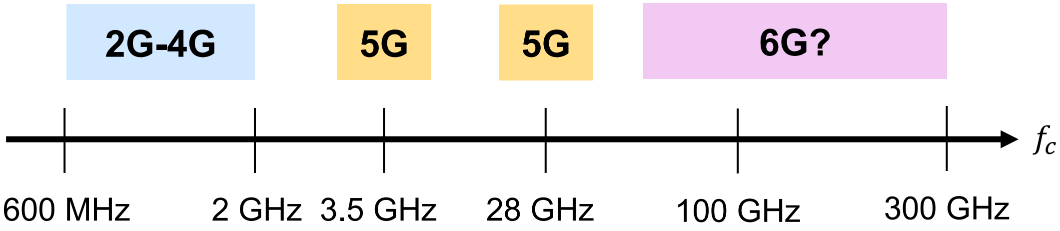
$$C = \text{Bandwidth} \cdot \text{Layers} \cdot \log_2(1 + \text{SNR})$$

We need more bandwidth?

The rise of mmWave…

…and fall?

Rule-of-thumb: Bandwidth $\propto f_c$



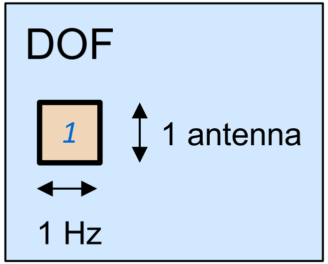
South Korea cancels SKT's 28 GHz 5G licence

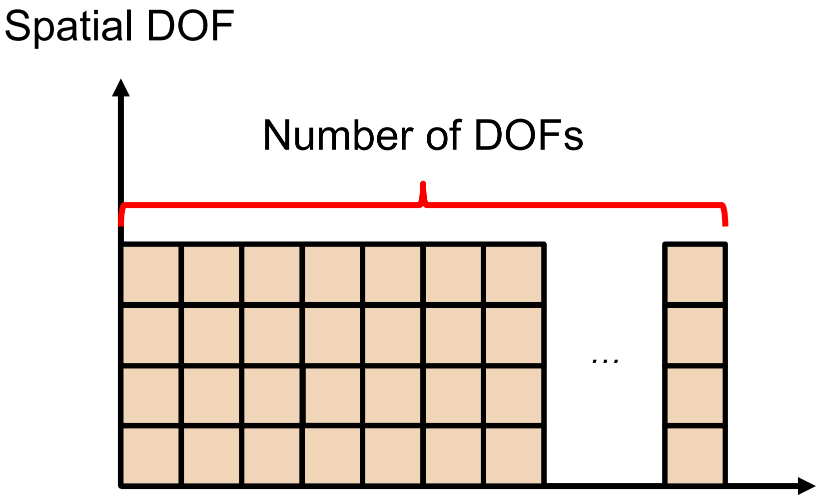
Written by Mary Lennighan 15 May 2023 @ 12:38

South Korea has withdrawn SK Telecom's licence to operate 5G services in the 28 GHz band, the telco having failed to meet its rollout requirements.

What Really Matters: Degrees-of-Freedom (DOF)

- **Bit rate formula:** $\text{bit/s} = \text{bit/DOF} \cdot \text{DOF/s}$





5G today

($f_c = 3.5$ GHz, $B = 100$ MHz)

8 spatial DOF

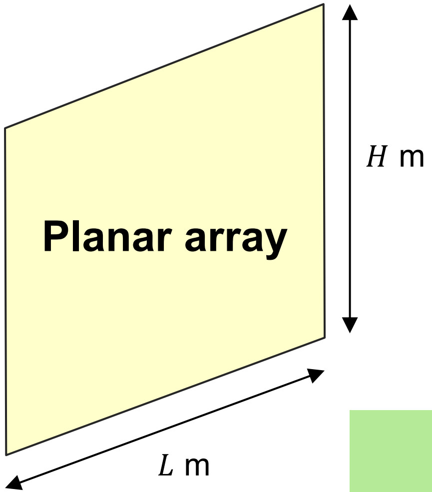
100 million bandwidth DOFs

10 bit/DOF (1024-QAM)

Theoretically up to 8 Gbps

Can we expand **spatial DOFs** in the future?

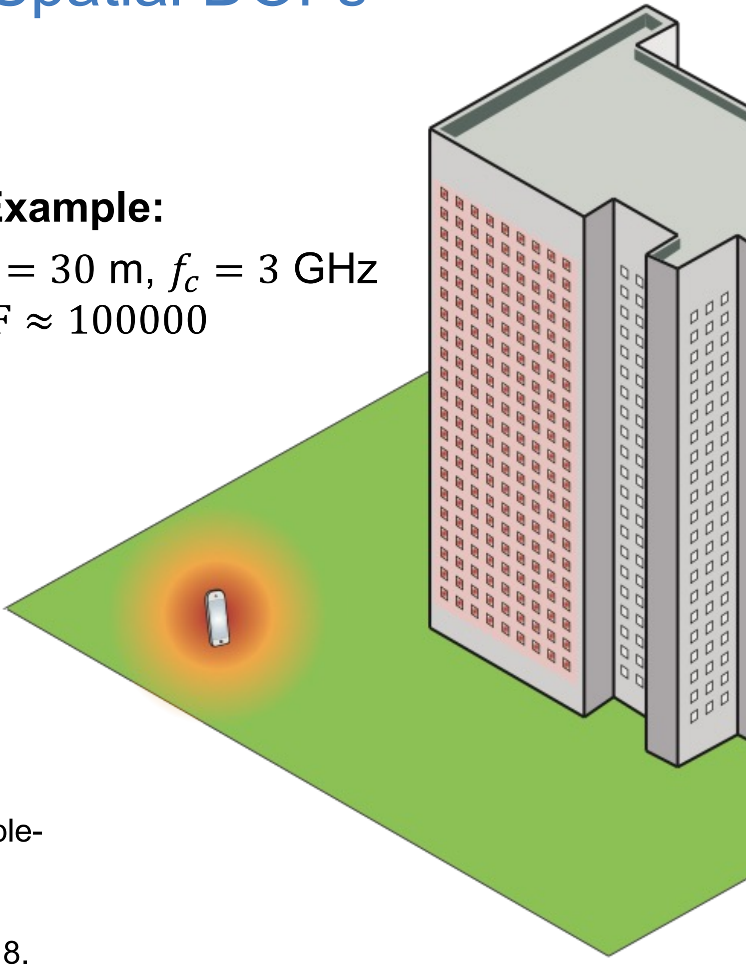
Quantifying the Theoretical Spatial DOFs



Example:

$L = 10$ m, $H = 30$ m, $f_c = 3$ GHz

$\mathrm{DOF} \approx 100000$



Maximum value:

$\mathrm{DOF} \approx \pi \frac{LH}{\lambda^2}$ spatial streams

Reference:

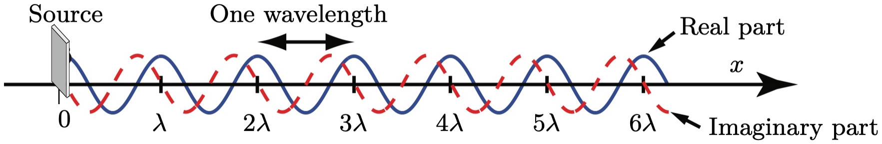
A. S. Y. Poon, R. W. Brodersen, and D. N. C. Tse, “Degrees of freedom in multiple-antenna channels: A signal space approach”, IEEE Trans. Inf. Theory, 2005.

S. Hu, F. Rusek, O. Edfors, “Beyond Massive MIMO: The Potential of Data Transmission with Large Intelligent Surfaces,” IEEE Trans. Signal Process., 2018.

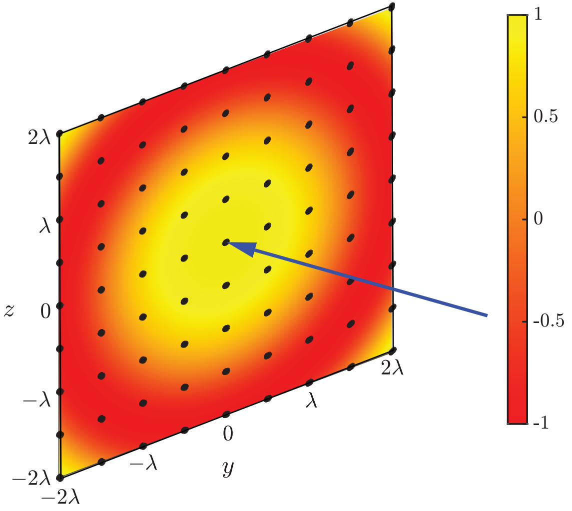
Uplink: The Array Samples the Impinging Waveform

Signal: $s \cdot e^{-j2\pi x/\lambda}$

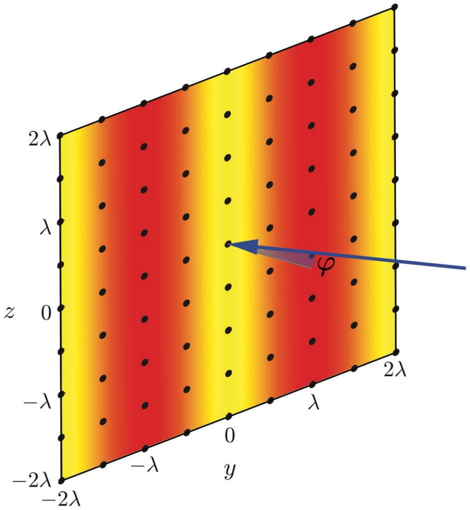
Data



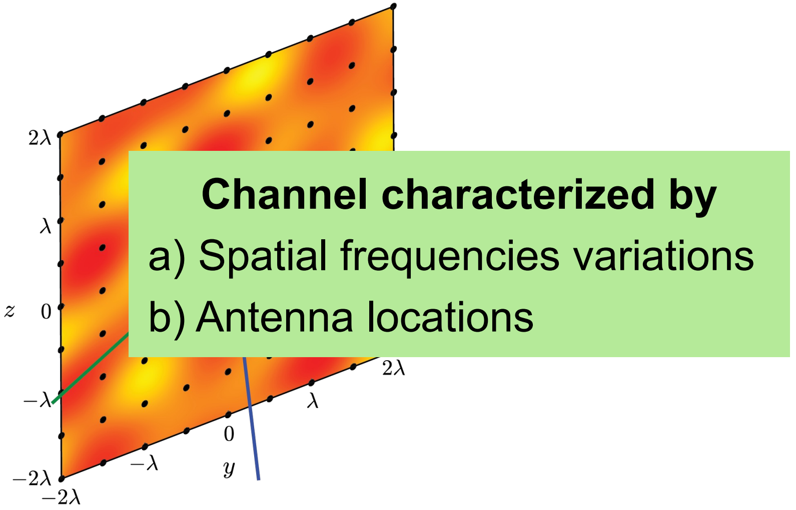
Spatial frequency: $\frac{1}{\lambda}$



User 1: near array in broadside ($d = 4\lambda$)



User 2: far from array, $\varphi = 30°$ azimuth angle



Channel characterized by

a) Spatial frequencies variations

b) Antenna locations

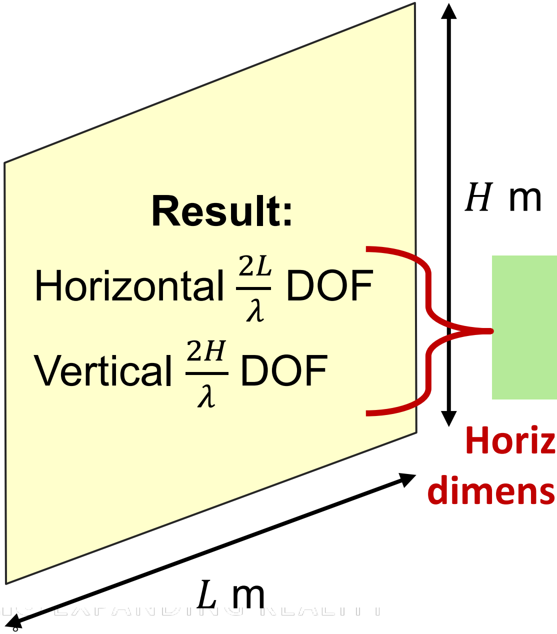
User 3: four far-field propagation paths

Nyquist Sampling Theorem

A complex-valued continuous-~~time~~ space signal ~~$g(t)$~~ $g(x)$

- Only contains frequencies in an interval smaller than ~~B~~ $2/\lambda$ Hz
- Entirely determined by samples spaced ~~$1/B$ seconds~~ $\lambda/2$ meters apart

→ Signal described by ~~B~~ $\mathrm{DOF/s}$ $2/\lambda\ \mathrm{DOF/m}$



Result:

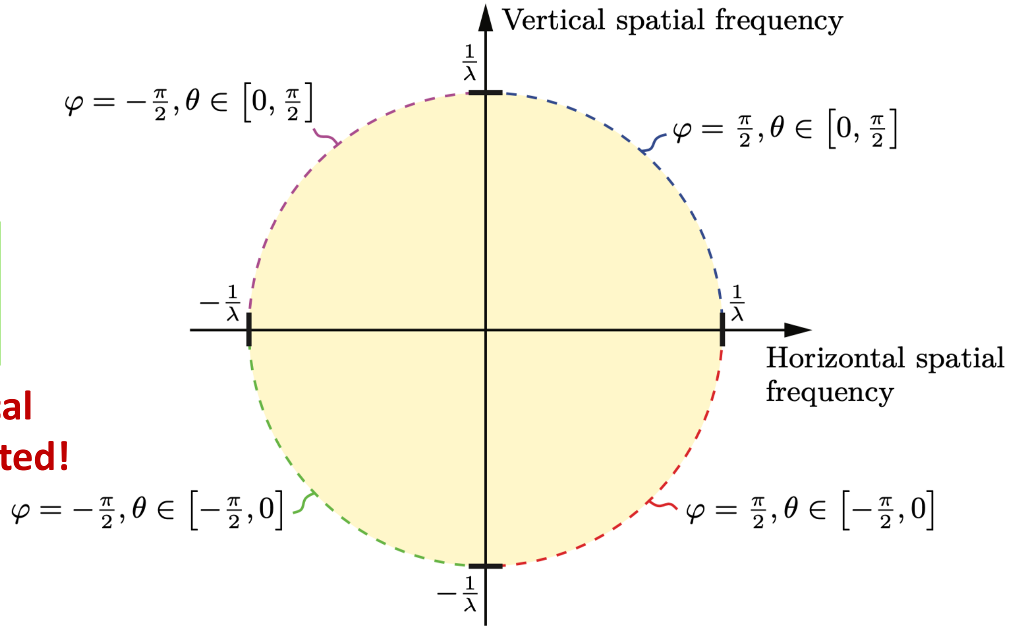
Horizontal $\frac{2L}{\lambda}$ DOF

Vertical $\frac{2H}{\lambda}$ DOF

Total DOFs

$$\frac{2L}{\lambda}\cdot\frac{2H}{\lambda}=\overset{\pi}{\cancel{4}}\frac{LH}{\lambda^2}$$

Horizontal and vertical dimensions are correlated!



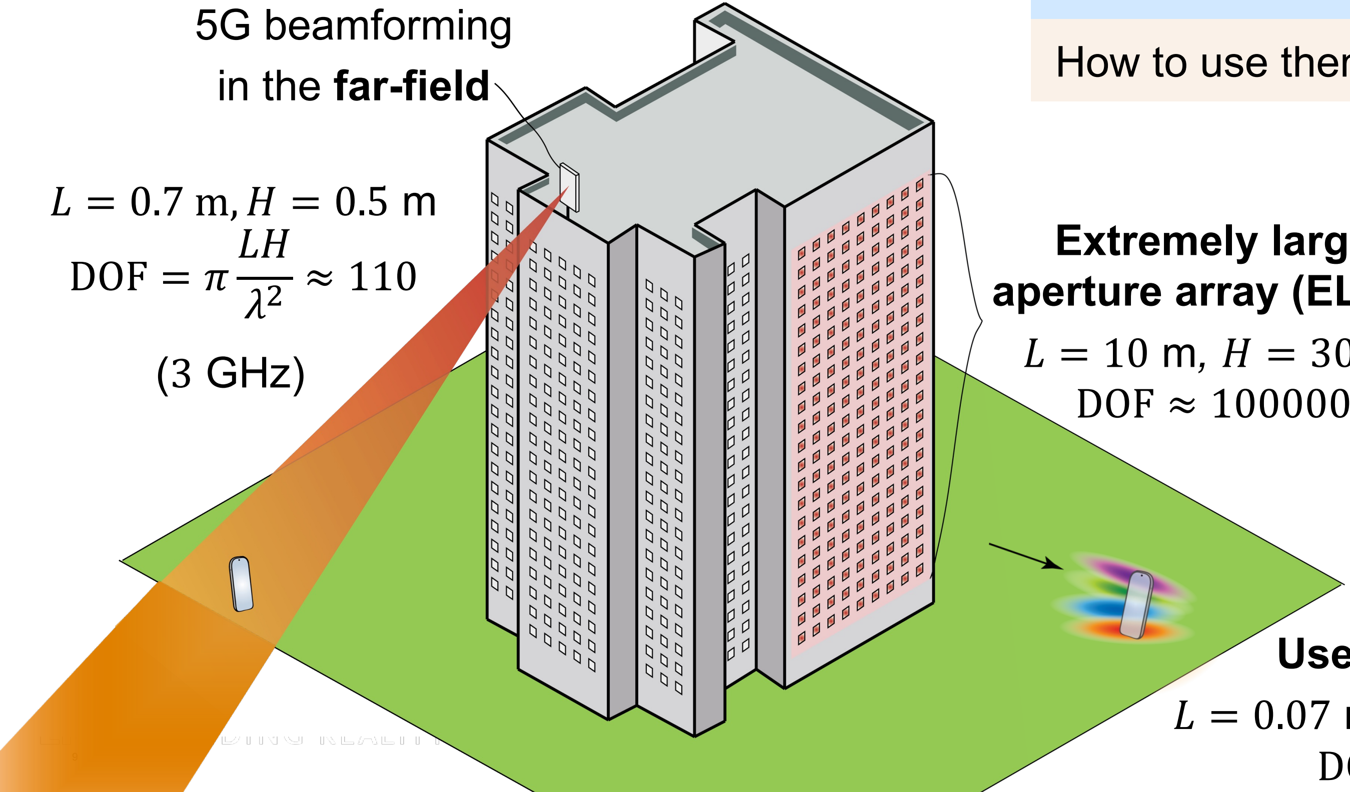
What are the Implications?

Can we get even more spatial DOFs?

Dual polarization: $2 \times$ DOFs

mmWave ($3 \rightarrow 30$ GHz):
$100\times$ more DOFs

How to use them for **spatial multiplexing?**



5G beamforming
in the **far-field**

$L = 0.7$ m, $H = 0.5$ m

$$\mathrm{DOF} = \pi \frac{LH}{\lambda^2} \approx 110$$

(3 GHz)

Extremely large aperture array (ELAA)

$L = 10$ m, $H = 30$ m

$\mathrm{DOF} \approx 100000$

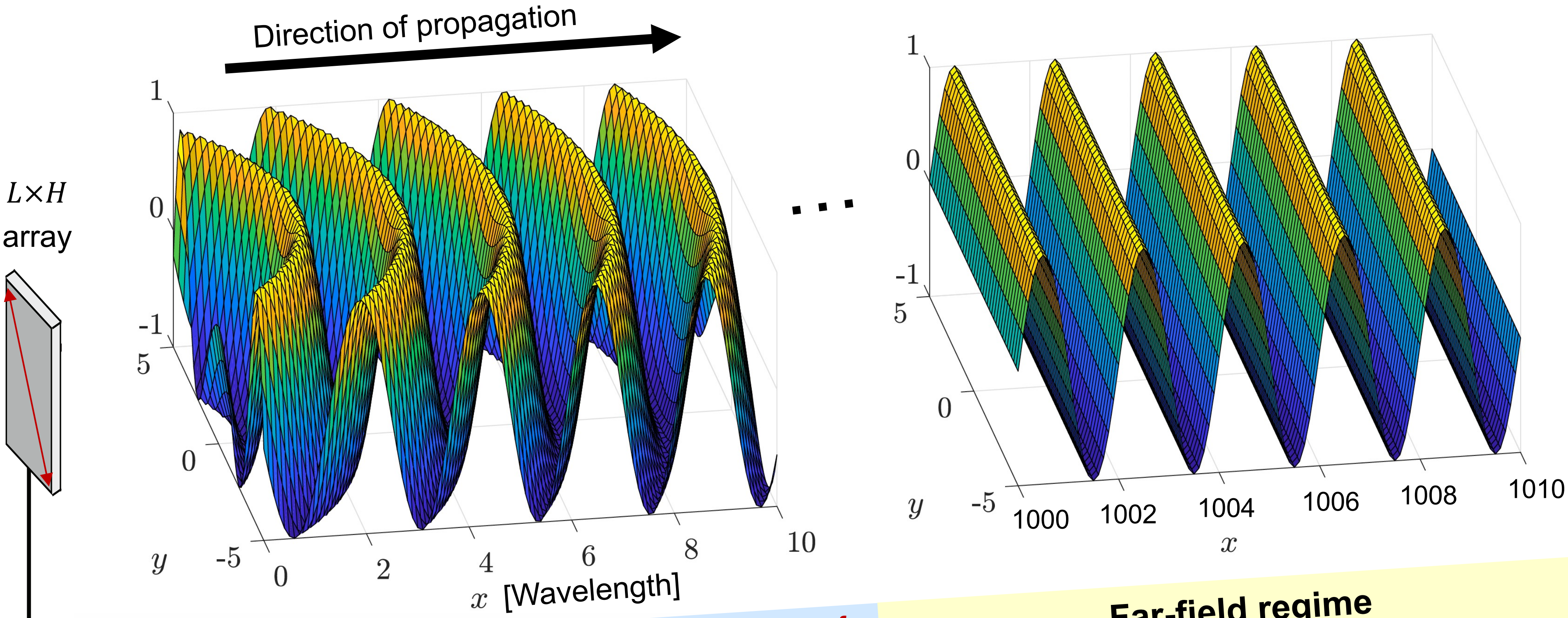
User device

$L = 0.07$ m, $H = 0.15$ m

$\mathrm{DOF} \approx 3$

MASSIVE NEAR-FIELD SPATIAL MULTIPLEXING

From **Spherical** Waves to **Approximately Planar** Waves



Reactive near-field

Radiative near-field

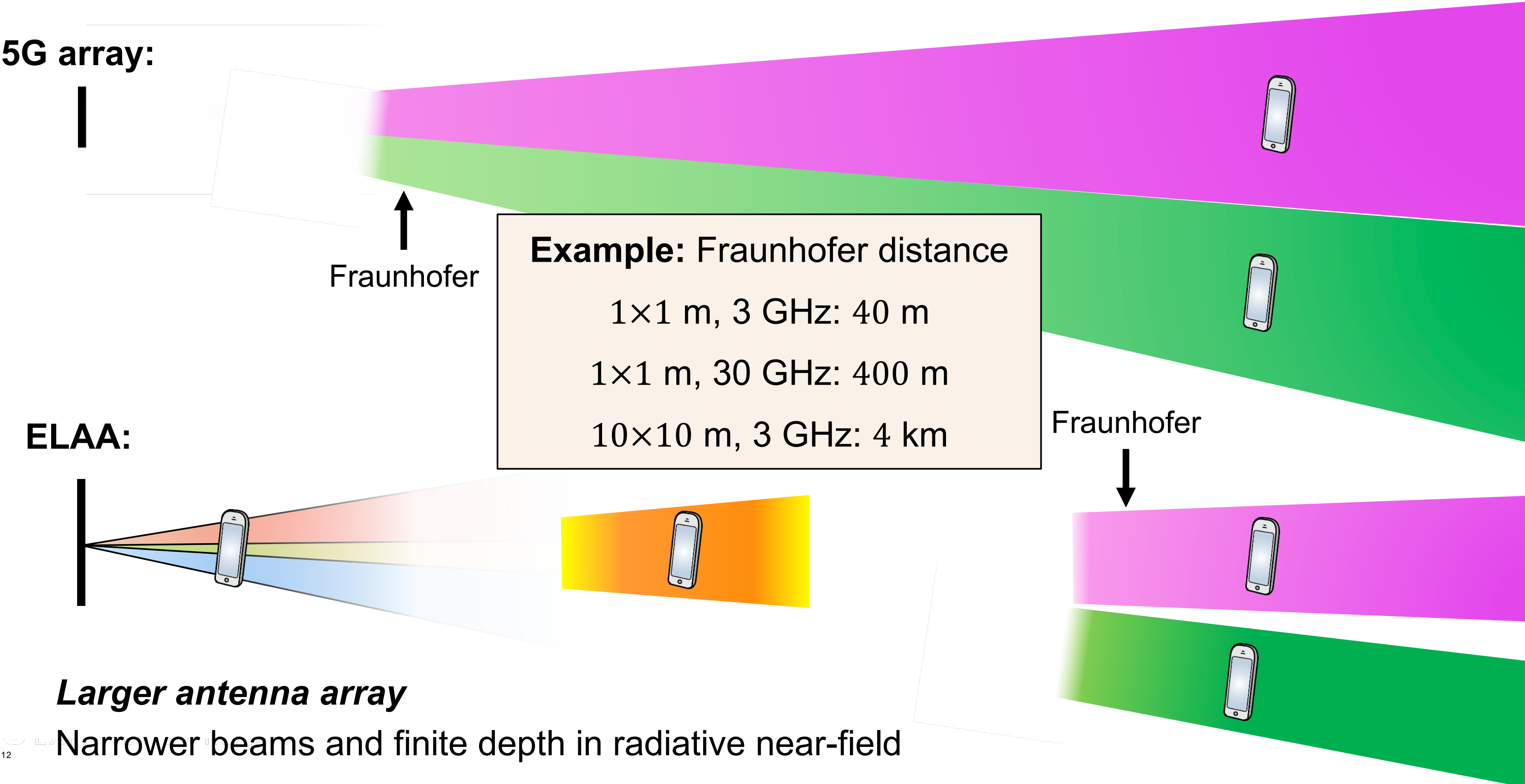
Fraunhofer distance

$$\text{User distance} < 2 \cdot \frac{L^2 + H^2}{\lambda}$$

Far-field regime

Traditional propagation scenario

Spatial Multiplexing in Both **Angle** and **Depth**



Example: Fraunhofer distance

1×1 m, 3 GHz: 40 m

1×1 m, 30 GHz: 400 m

10×10 m, 3 GHz: 4 km

Larger antenna array

Narrower beams and finite depth in radiative near-field

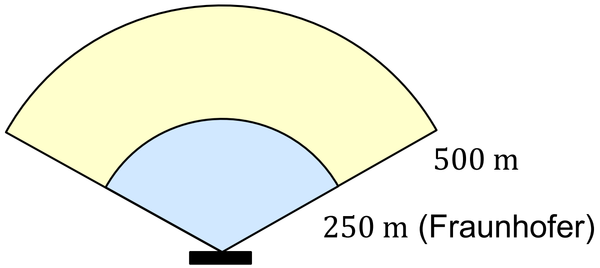
Exploiting Depth for Spatial Multiplexing of Many Users

Base station with N antennas

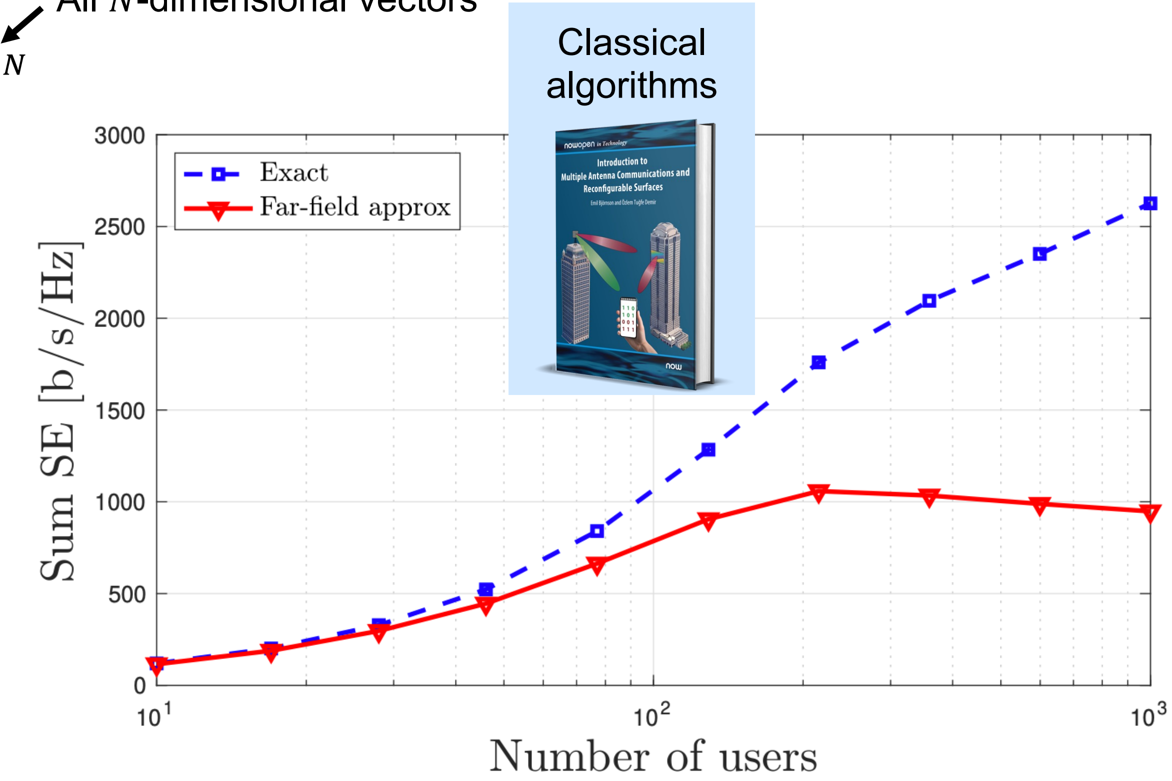
Channel vector, user k: $\boldsymbol{h}_k \in \mathcal{S} \subset \mathbb{C}^N$

All N-dimensional vectors

Subset of physically
possible vectors
(Dimension = DOF)



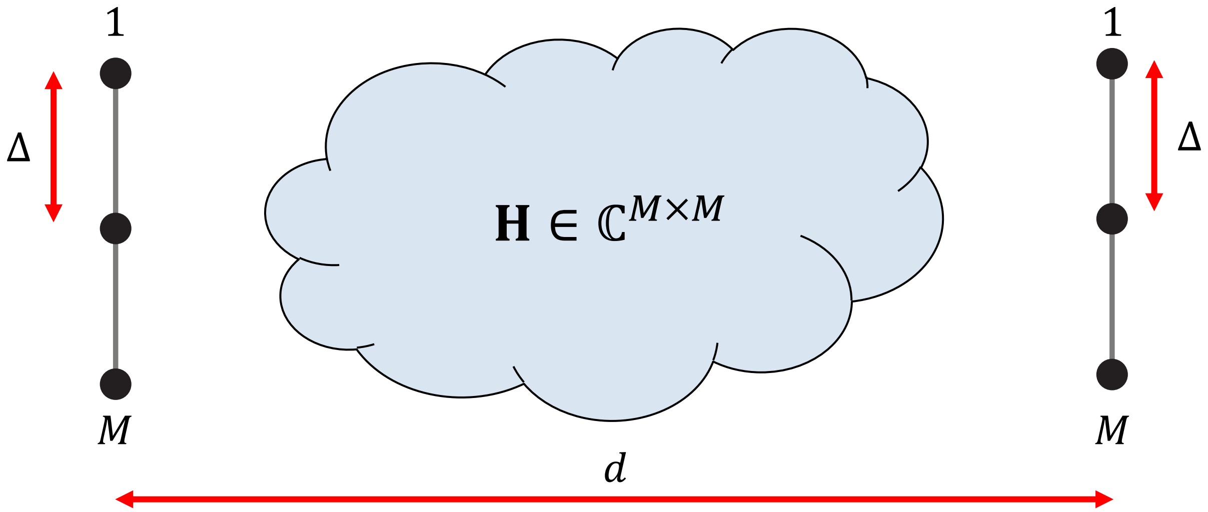
$N = 5000$ antennas
30 GHz, 1×0.5 m



"Towards 6G MIMO: Massive Spatial Multiplexing, Dense Arrays, and Interplay Between Electromagnetics and Processing," arXiv:2401.02844

Per Device: Line-of-Sight (LOS) Capacity Maximization

MIMO = Multiple Input Multiple Output



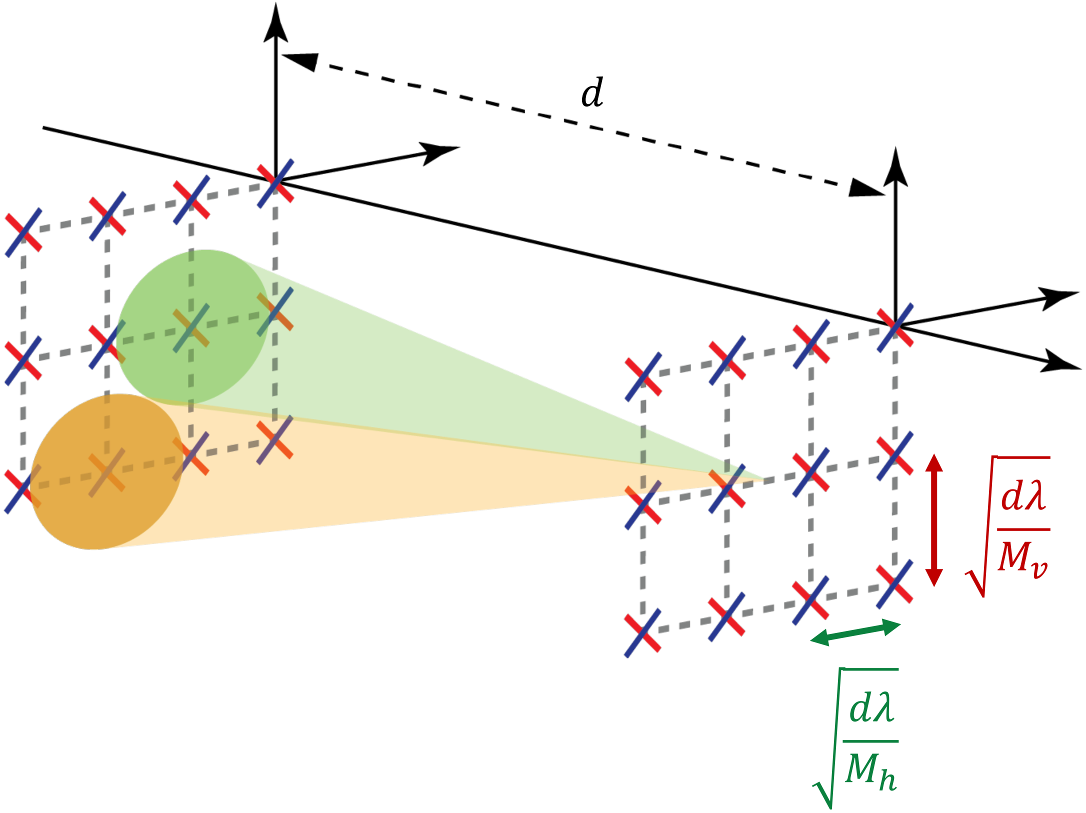
Problem: Optimize spacing Δ to maximize MIMO capacity

High SNR: M *equal singular values*

Solution: Apply parabolic approximation of spherical waves

Enforce that the columns of $\mathbf{H}$ are orthogonal

Optimized Planar Dual-Polarized $M_h \times M_v$ Arrays



$$\text{Area} = M_h \sqrt{\frac{d\lambda}{M_h}} M_v \sqrt{\frac{d\lambda}{M_v}} = d\lambda\sqrt{M}$$

with $M = M_h M_v$

Number of antennas in a fixed area:

$$M = \left(\frac{\text{Area}}{d\lambda}\right)^2$$

$2M$ DOFs with equal singular values
(Value independent of M)

Fraction of maximum DOF

$$\frac{\left(\frac{\text{Area}}{d\lambda}\right)^2}{\pi\frac{\text{Area}}{\lambda^2}} = \frac{\text{Area}}{\pi d^2} \ll 1$$

Reference: *A. Irshad, A. Kosasih, E. Björnson, L. Sanguinetti, "Optimal Dual-Polarized Arrays for Massive Capacity Over Point-to-Point MIMO Channels,"* arXiv:2312.02050

Scaling Law: Channel Capacity vs. Wavelength

Capacity formula [bit/s]:

$$C = B \cdot 2M \cdot \log_2\left(1 + \frac{P_r}{2BN_0}\right)$$

Received power per antenna

Bandwidth

Spatial DOFs

$$M = \left(\frac{\text{Area}}{d\lambda}\right)^2$$

Noise power

Isotropic antennas, area $A = \frac{\lambda^2}{4\pi}$

$$P_r = \frac{\lambda^2}{(4\pi d)^2} \cdot P_t$$

$$C \to \left(\frac{\text{Area}}{4\pi d^2}\right)^2 \frac{P_t}{N_0} \log_2(e) = \text{constant as } \lambda \to 0$$

Directive antennas

Antenna areas A_t and A_r with $A_r A_t \propto \lambda^{4-\rho}$

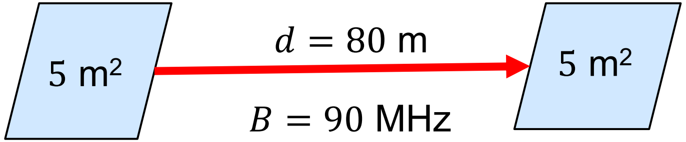
$$P_r = \frac{A_r A_t}{d^2 \lambda^2} \cdot P_t$$

$$C = O\left(\frac{1}{\lambda^{4-\rho}}\right) \to \infty \text{ as } \lambda \to 0 \text{ if } \rho \in (0,2]$$

Great Capacity Without More Bandwidth

Reference: *A. Irshad, A. Kosasih, E. Björnson, L. Sanguinetti, "Optimal Dual-Polarized Arrays for Massive Capacity Over Point-to-Point MIMO Channels,"* arXiv:2312.02050

Line-of-sight scenario:

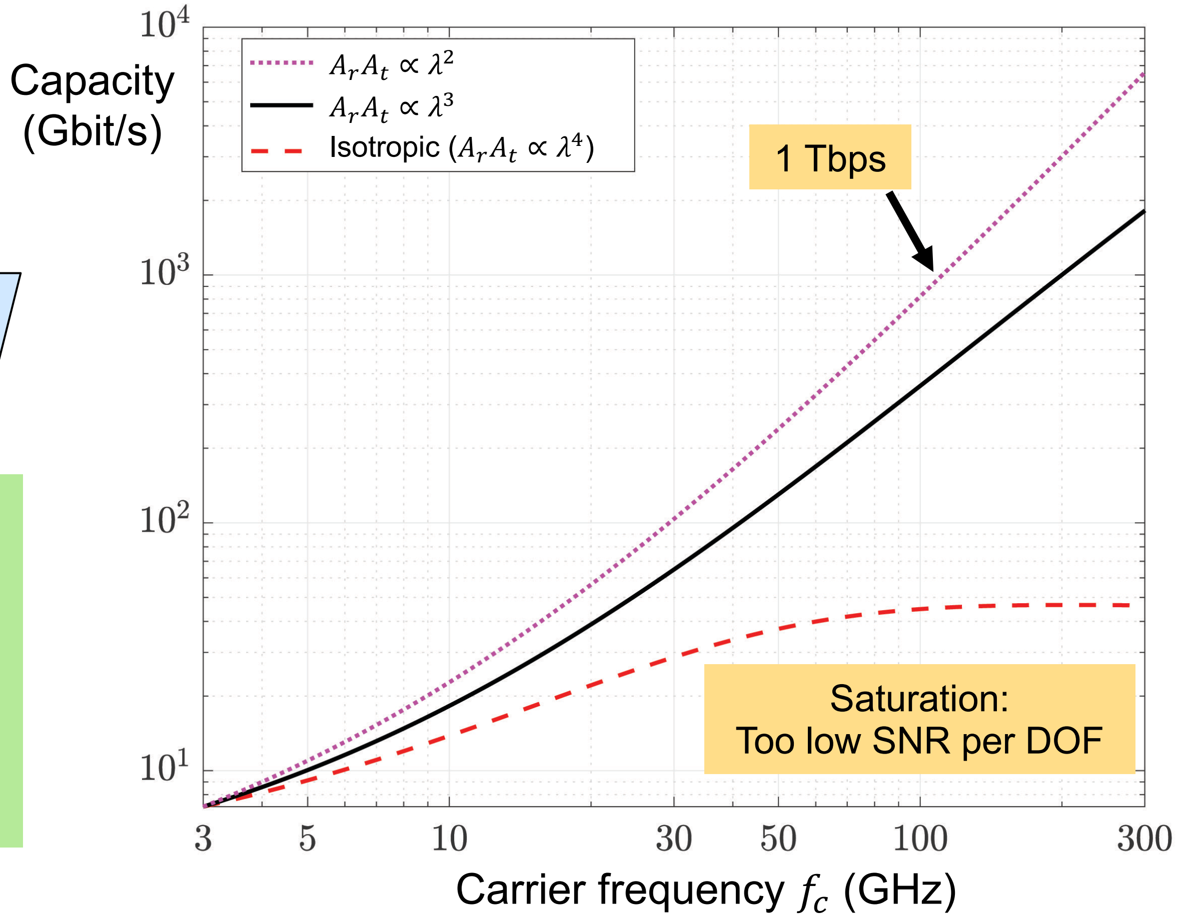


Slightly directive antennas

Area: $A_r = A_t \propto \lambda$,   Gain: $\propto 1/\lambda$

Spatial DOFs: $\left(\frac{\text{Area}}{d\lambda}\right)^2 = O(f_c^2)$

Capacity: $C = O(f_c^2)$

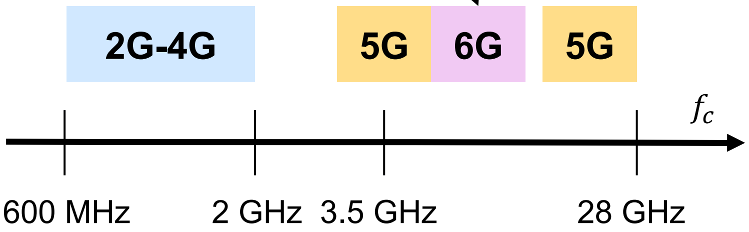


WHAT MIGHT HAPPEN IN 6G?

6G Frequency Bands…

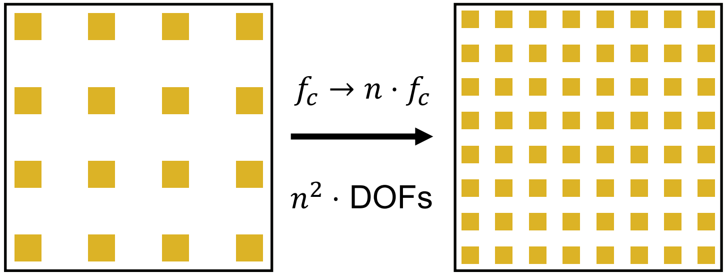
Frequency range 3 (FR3)

- 4.4-4.8 GHz
- 7.1-8.4 GHz
- 14.8-15.35 GHz



…and Implications

Number of spatial DOFs



Frequency band	**DOF scaling**
• 7.1-8.4 GHz	$n^2 = 5$
• 14.8-15.35 GHz	$n^2 = 18$

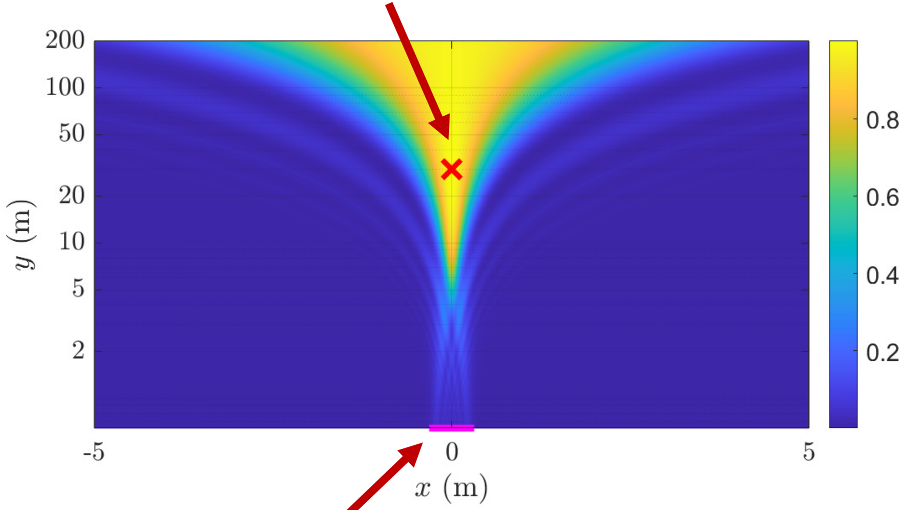
More DOFs in 6G!

2-3× more bandwidth DOFs

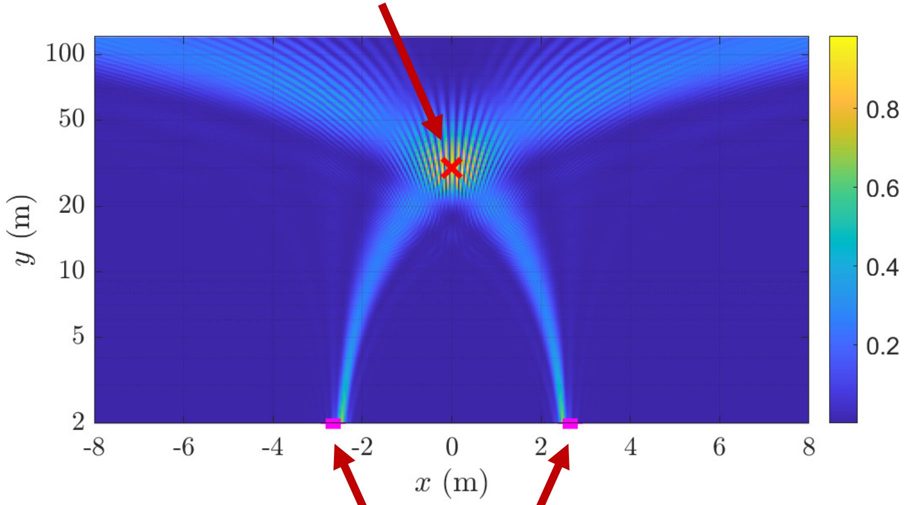
5-18× more spatial DOFs

Will Near-Field Effects Appear in 6G?

Receiver at 30 m (Fraunhofer = 40 m)



Uniform linear array (ULA)
64 antennas (64 cm) 15 GHz

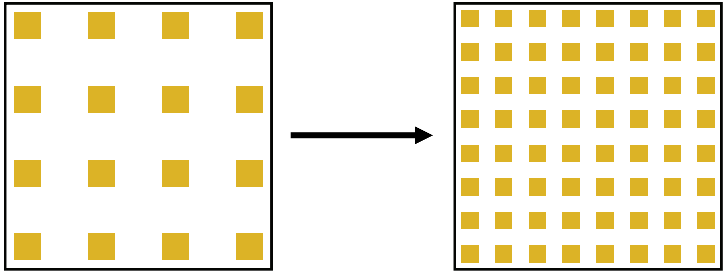


Two ULAs, 5 m apart

Yes, with distributed MIMO

Summary

Much Higher Capacity in 6G Without More Bandwidth

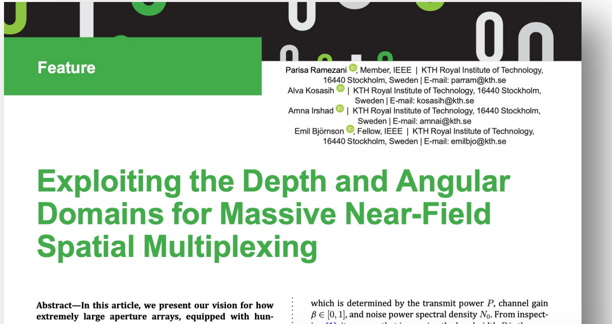


Capacity grows as f_c^2 thanks to MIMO

- Faster than $\mathcal{O}(f_c)$ with spectrum (Key in 6G!)
- Maximum DOFs ***and*** practically useful DOFs
- Array design essential to maintain the SNR

Near-field propagation effects

- Richer channels: Control both angle and depth



Feature

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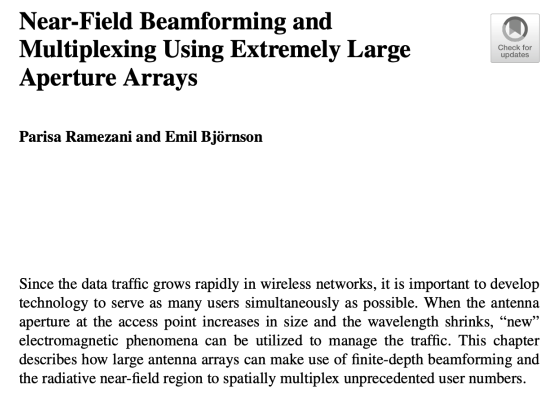
Exploiting the Depth and Angular Domains for Massive Near-Field Spatial Multiplexing

**Abstract—In this article, we present our vision for how extremely large aperture arrays, equipped with hundreds or thousands of antennas, can play a major role in future 6G networks by enabling a remarkable increase
in data rates through spatial multiplexing of a massiv
number of data streams to both a single user and man
simultaneous users. Specifically, with the quantum lea
in the array aperture size, the users will be in the so
called radiative near-field region of the array, wher
previously negligible physical phenomena dominate th
propagation conditions and give the channel matrice
more favorable properties. This article presents th
foundational properties of communication in the radia
tive near-field region and then exemplifies how thes
properties enable two unprecedented spatial multiplex**

which is determined by the transmit power P, channel gain $\beta \in [0,1]$, and noise power spectral density N_0. From inspecting (1), it appears that increasing the bandwidth B is the preferred way to enhance capacity. The signal-to-noise ratio



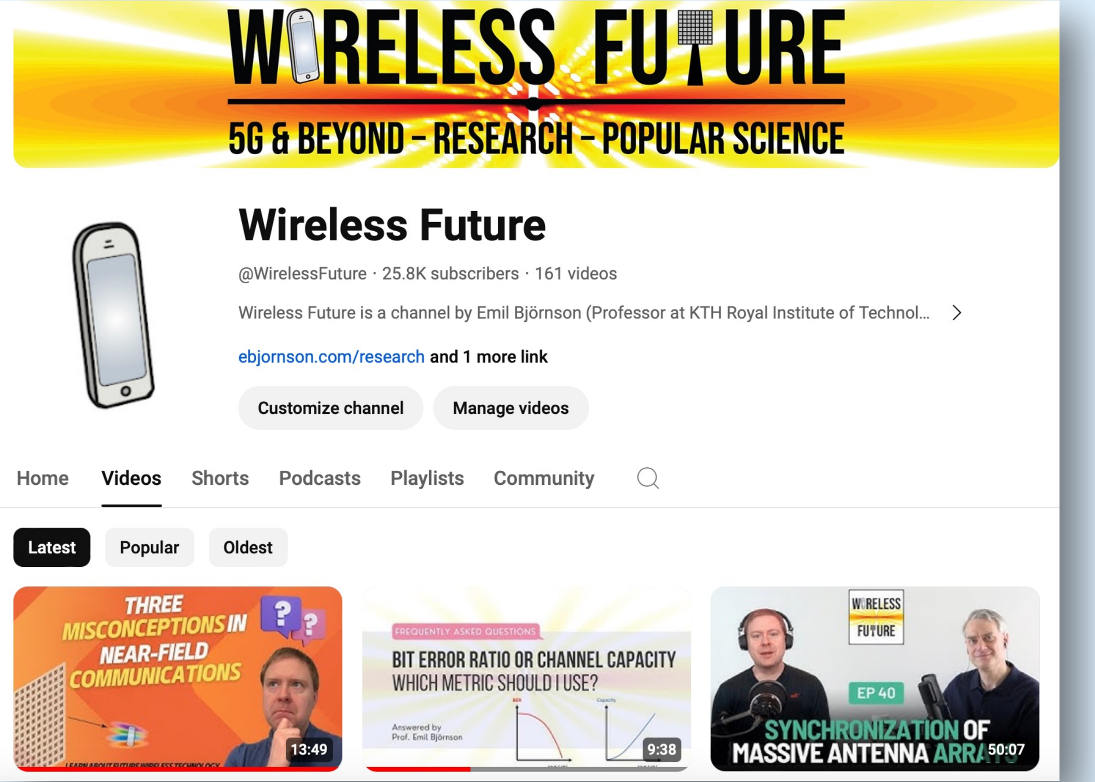
Near-Field Beamforming and Multiplexing Using Extremely Large Aperture Arrays

Check for updates

Parisa Ramezani and Emil Björnson

Since the data traffic grows rapidly in wireless networks, it is important to develop technology to serve as many users simultaneously as possible. When the antenna aperture at the access point increases in size and the wavelength shrinks, "new" electromagnetic phenomena can be utilized to manage the traffic. This chapter describes how large antenna arrays can make use of finite-depth beamforming and the radiative near-field region to spatially multiplex unprecedented user numbers.

Questions?



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