Spatial Multiplexing in the Radiative Near-Field

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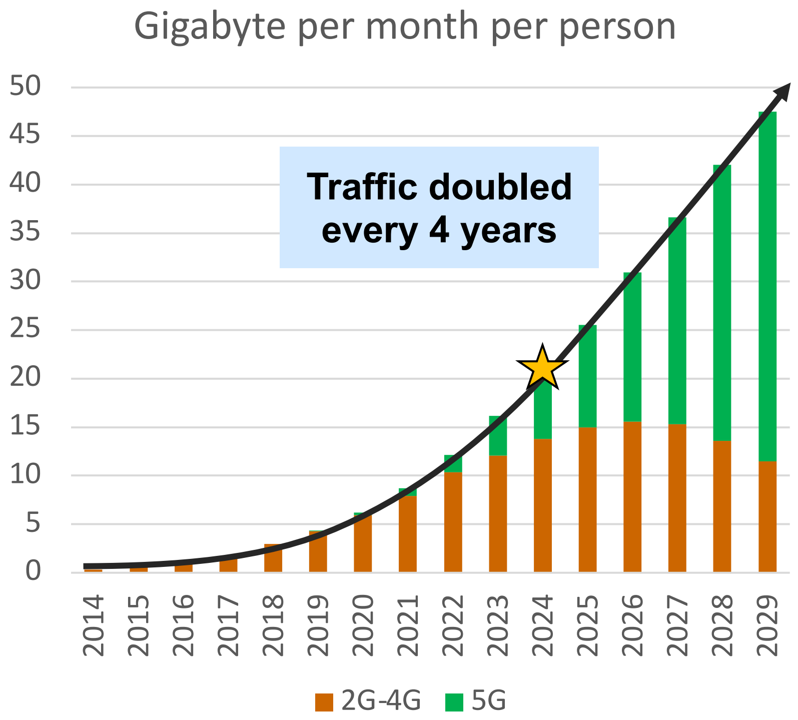
Network Capacity in Mobile Networks

Demand



Ericsson Mobility Report, 2024

Supply

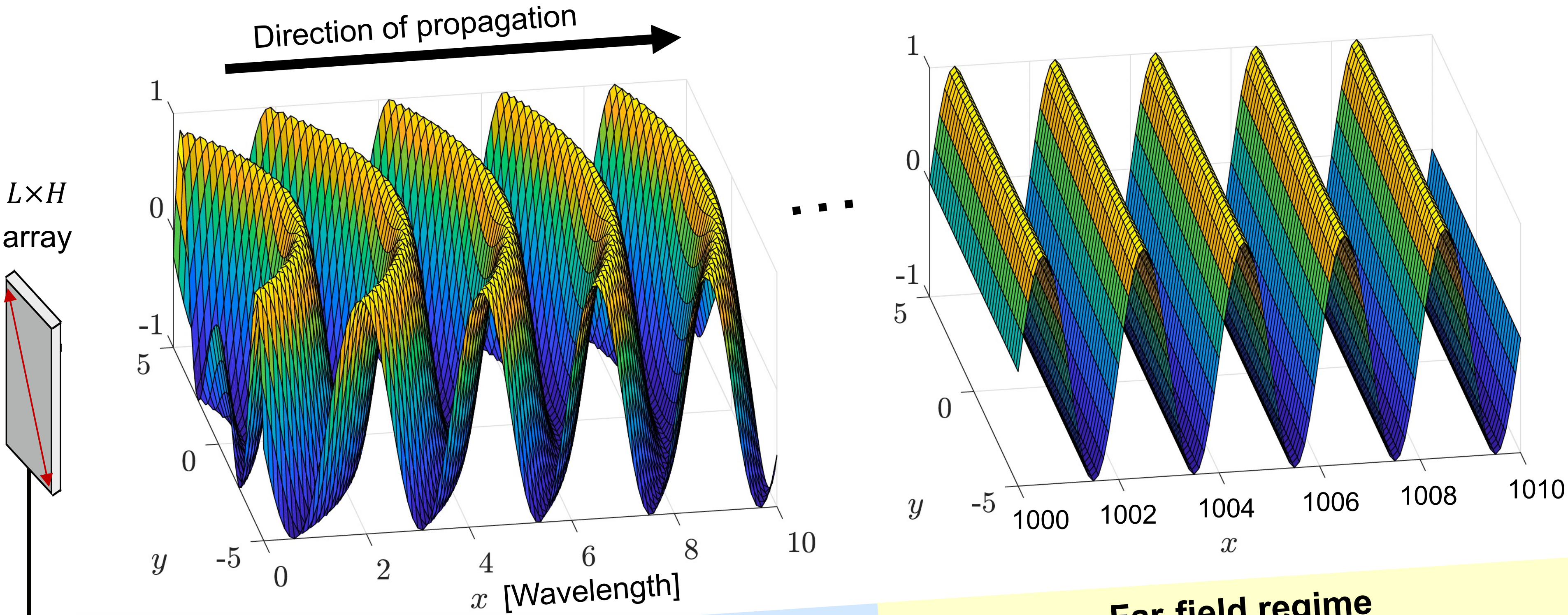
Channel capacity (bit/s per access point):

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

6G: More bandwidth?

6G: Bigger MIMO?

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



Reactive near-field

Radiative near-field

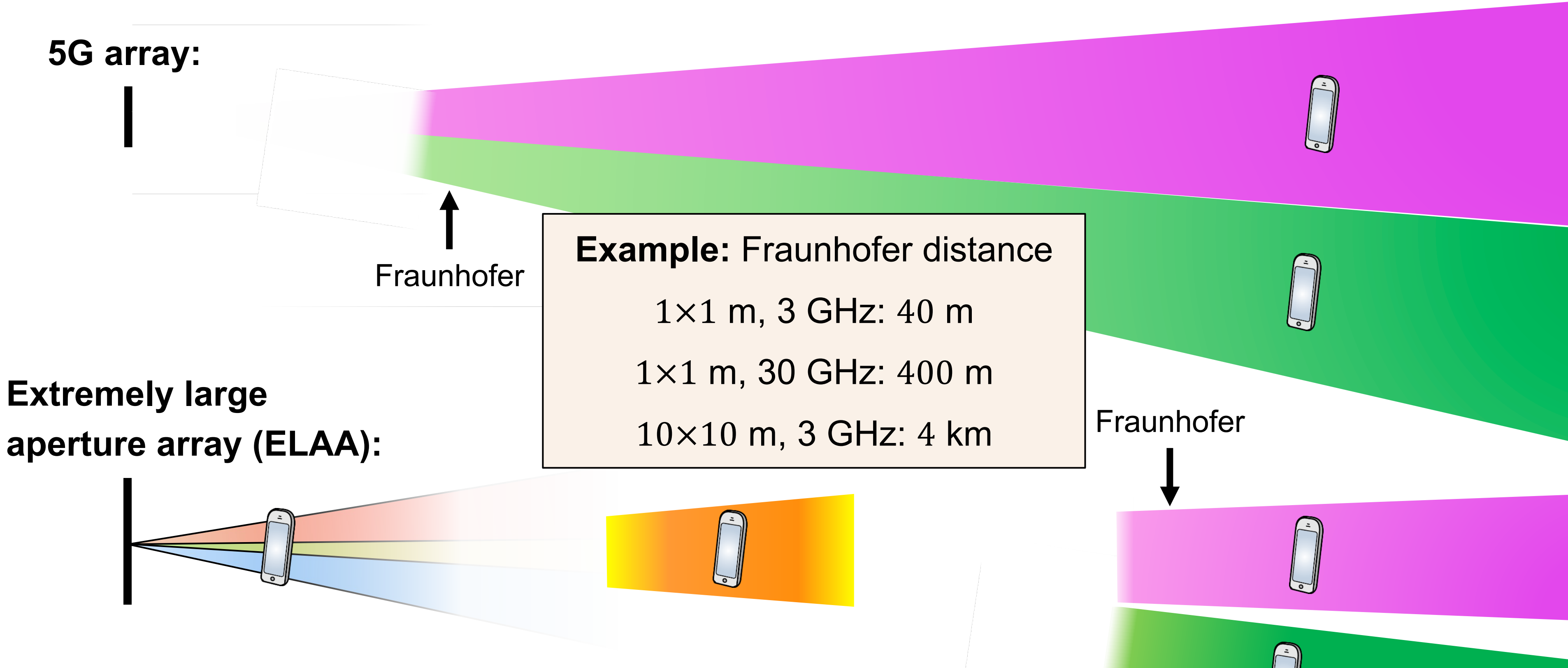
Fraunhofer distance

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

Far-field regime

Traditional propagation scenario

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



Larger antenna array

Narrower beams and finite depth in radiative near-field

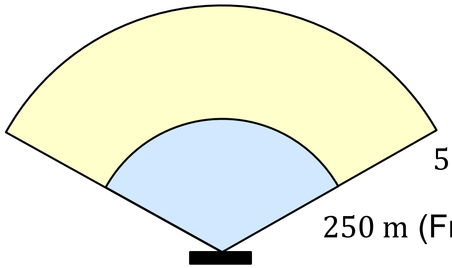
Exploiting Depth for Spatial Multiplexing of Many Users

Base station with N antennas

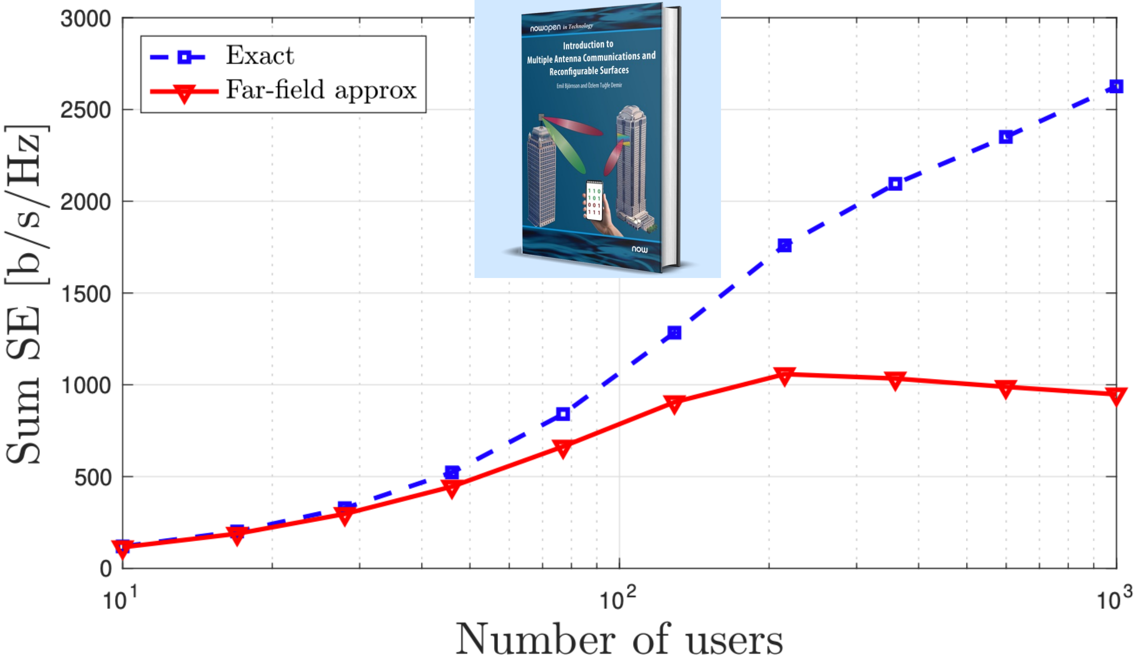
Channel vector, user k: $\boldsymbol{h}_k \in \mathcal{S} \subset \mathbb{C}^N$

All N-dimensional vectors

Subset of physically possible vectors (Dimension = DOF)



$N = 5000$ antennas
30 GHz, 1×0.5 m



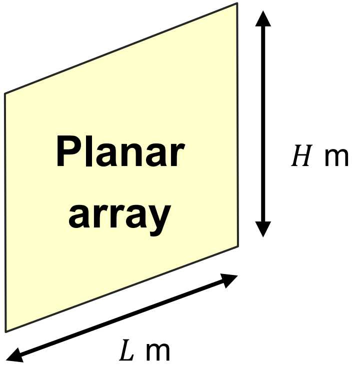
“Towards 6G MIMO: Massive Spatial Multiplexing, Dense Arrays, and Interplay Between Electromagnetics and Processing,” arXiv:2401.02844

Theoretical Spatial Degrees-of-Freedom (DoF)

Reference: *S. Hu, et al., "Beyond Massive MIMO: The Potential of Data Transmission with Large Intelligent Surfaces," 2018*

Maximum layers

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

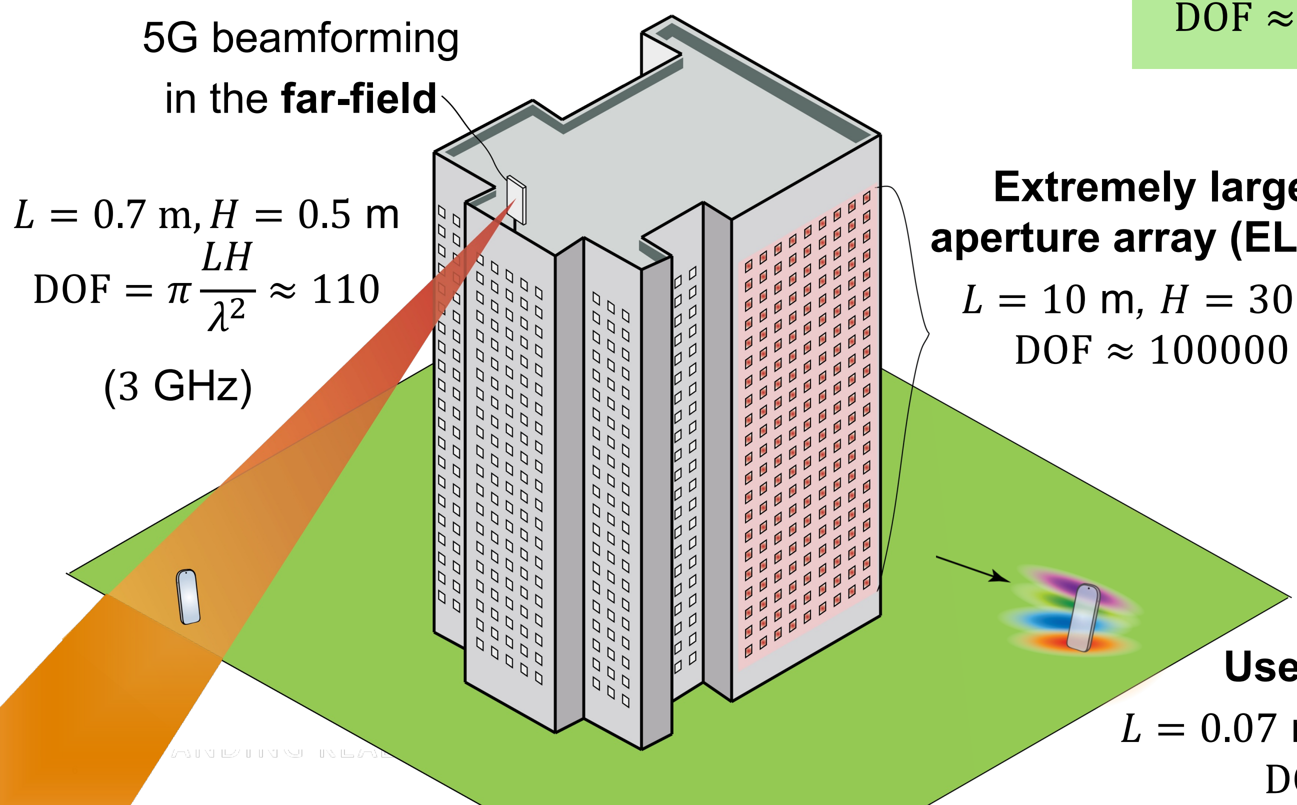


5G beamforming in the **far-field**

$L = 0.7$ 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

$\mathrm{DOF} \approx 3$

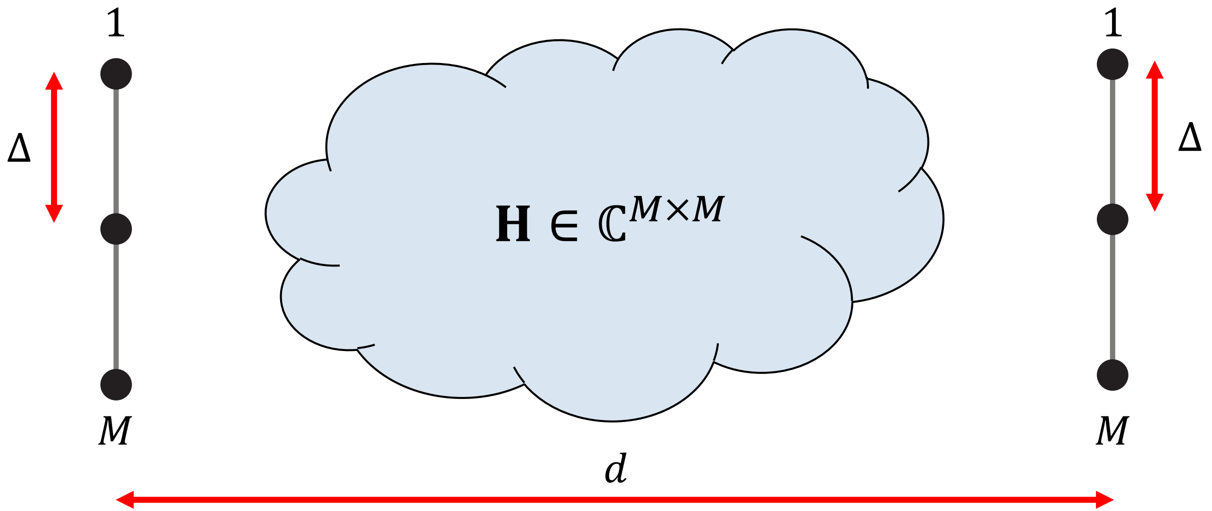
Can we get even more?

Dual polarization: $2 \times$ DOFs

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

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

MIMO = Multiple Input Multiple Output



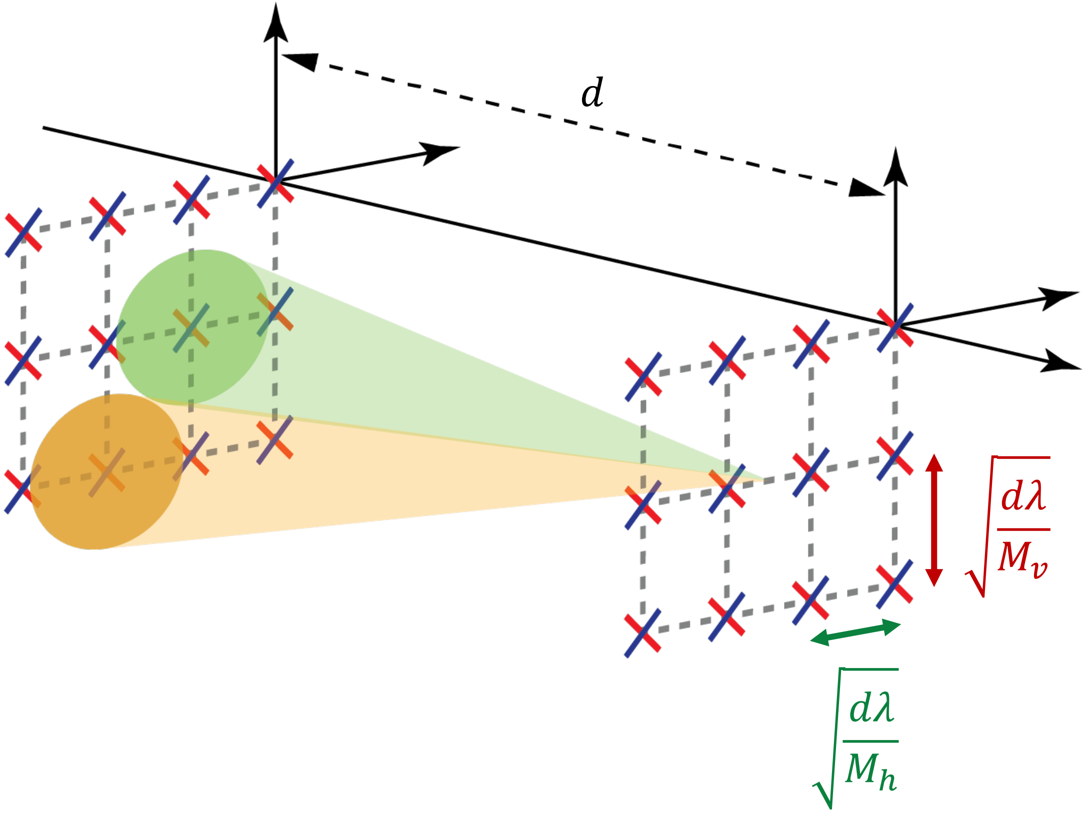
Problem: Optimize spacing Δ to maximize MIMO capacity

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]:

Received power per antenna

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

Bandwidth

Spatial DOFs

Noise power

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

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

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

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

Directive antennas

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

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

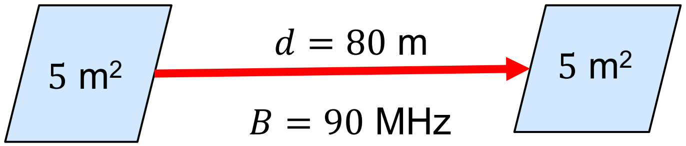
$$C = O\left(\frac{1}{\lambda^{4-\rho}}\right) \rightarrow \infty \text{ as } \lambda \rightarrow 0 \text{ if } \rho \in (0,2]$$

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

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:

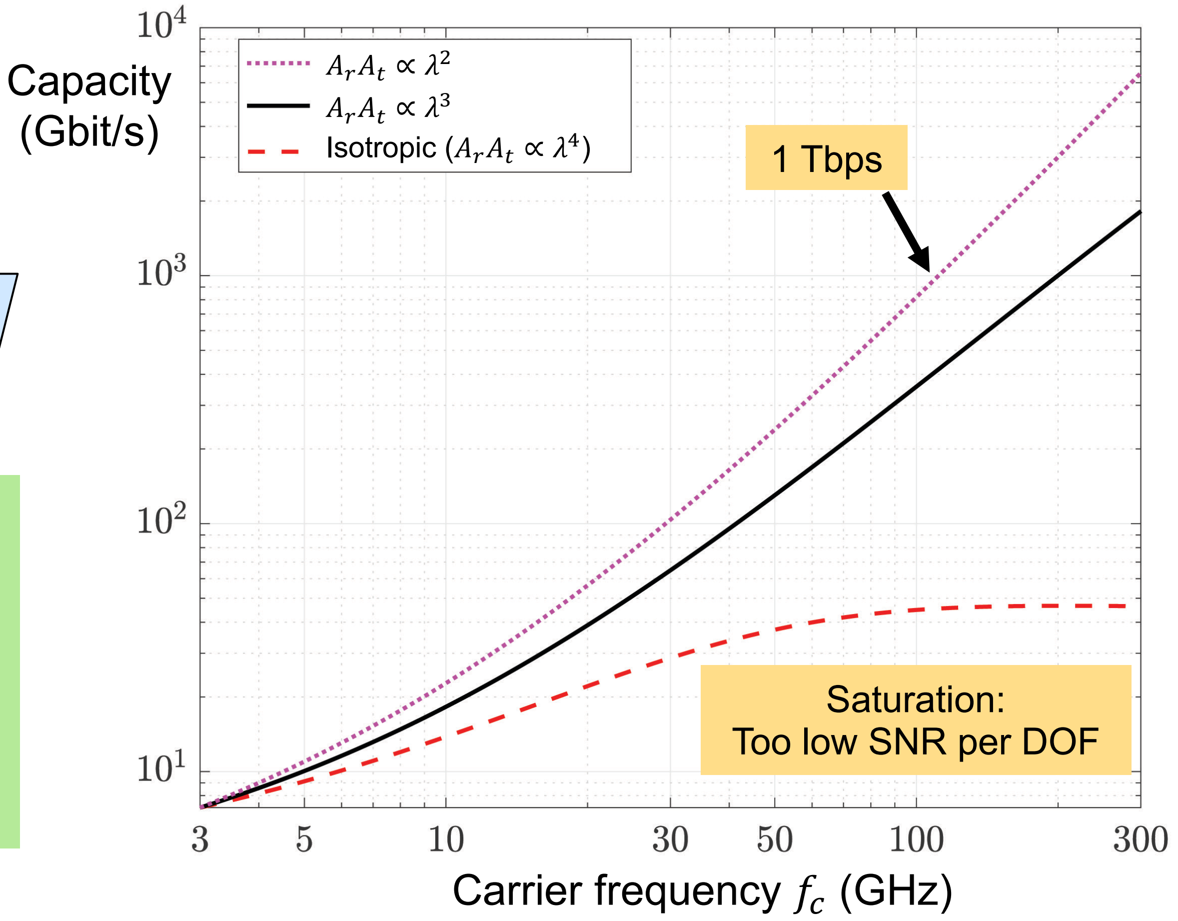


Slightly directive antennas

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

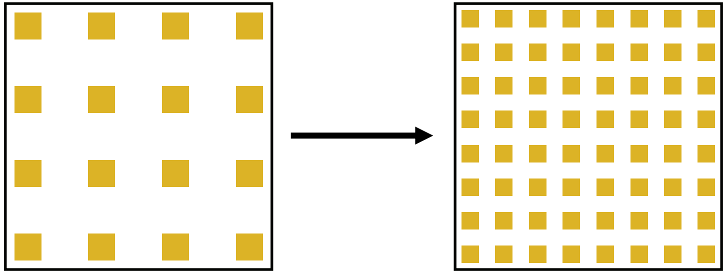
Spatial DOFs: $\left(\frac{\text{Area}}{d\lambda}\right)^2 = O(f_c^2)$

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



Summary

Much Higher Capacity in 6G Without More Bandwidth

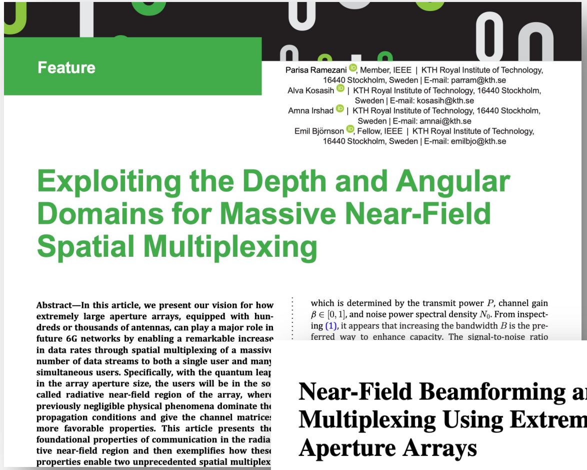


Capacity grows as f_c^2 thanks to MIMO

- Faster than $\mathcal{O}(f_c)$ with spectrum
- 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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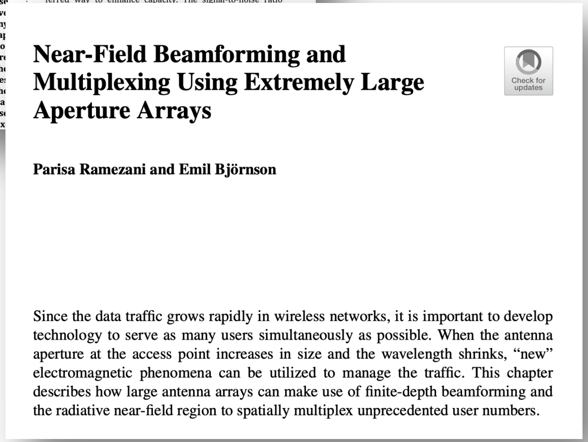
Exploiting the Depth and Angular Domains for Massive Near-Field Spatial Multiplexing

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 massive number of data streams to both a single user and many simultaneous users. Specifically, with the quantum leap in the array aperture size, the users will be in the so called radiative near-field region of the array, where previously negligible physical phenomena dominate the propagation conditions and give the channel matrices more favorable properties. This article presents the foundational properties of communication in the radia tive near-field region and then exemplifies how these 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.