Massive Near-Field Spatial Multiplexing

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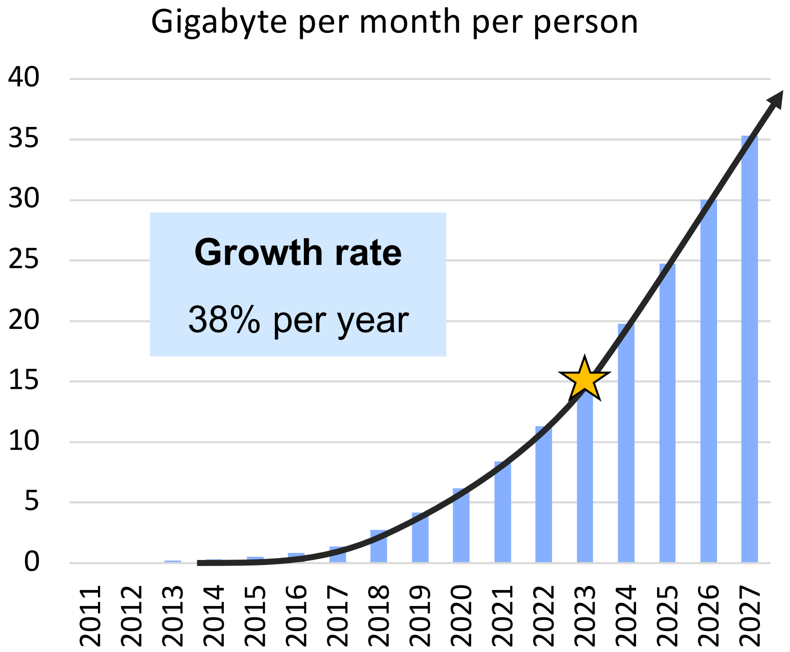
Network Capacity

Demand



Supply

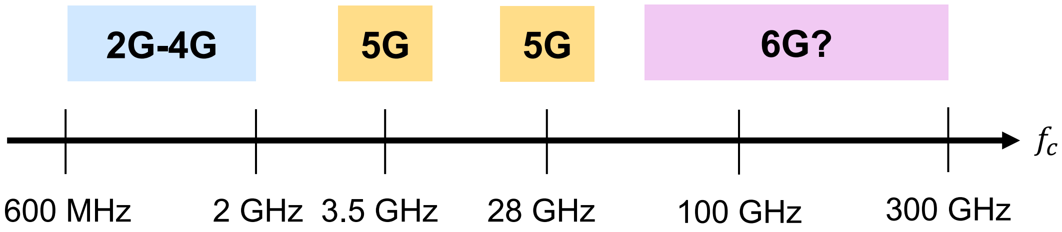
Channel capacity

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

We need more bandwidth?

The rise of mmWave…

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



…and fall?

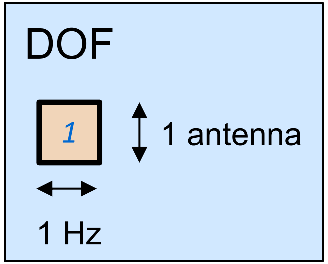
South Korea cancels SKT's 28 GHz 5G licence

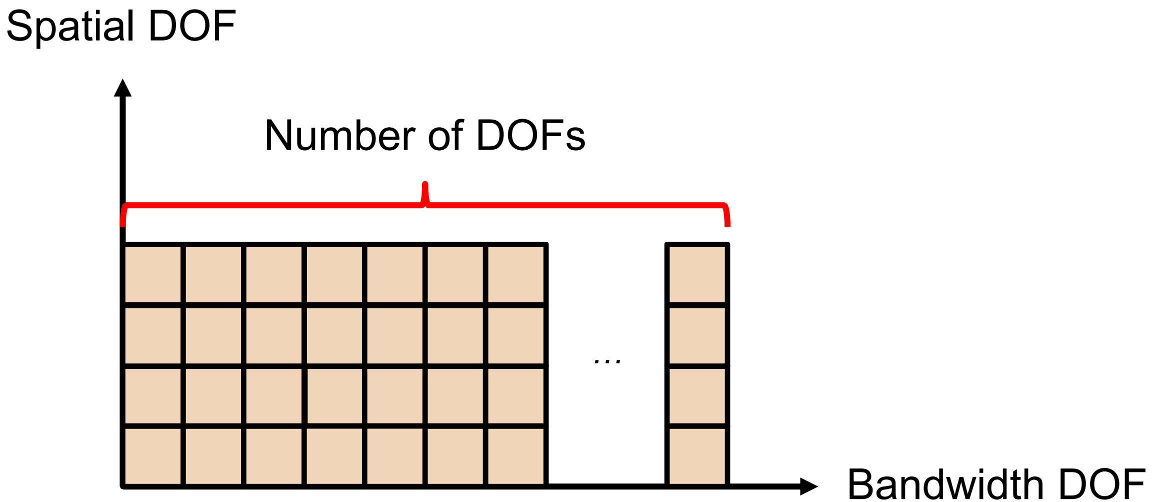
Written by Mary Lennighan 15 May 2023 @ 12:38

South Korea has withdrawn SK Telecom's licence to operate 5G services in the 28 GHz band, the telco having failed to meet its rollout requirements.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:** $\mathrm{bit/s} = \mathrm{bit/DOF} \cdot \mathrm{DOF/s}$





5G today

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

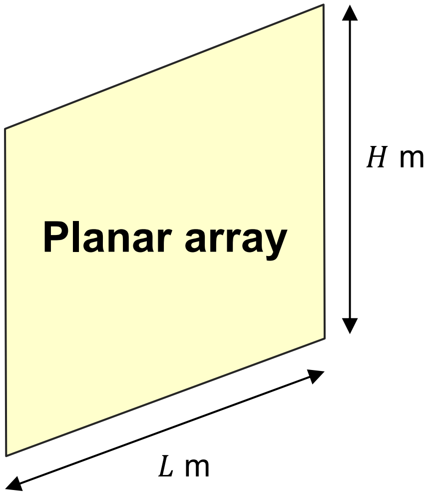
8 spatial DOF

100 million bandwidth DOFs

10 bit/DOF (1024-QAM)

Theoretically up to 8 Gbps

Quantifying the Spatial DOFs



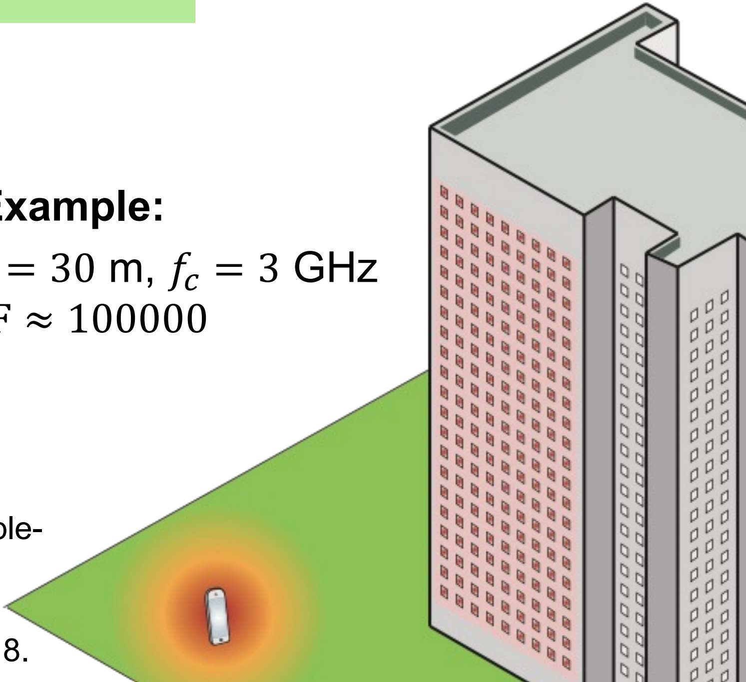
Maximum value:

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

Example:

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

$\mathrm{DOF} \approx 100000$



Reference:

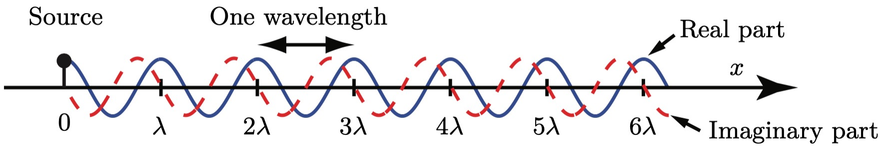
A. S. Y. Poon, R. W. Brodersen, and D. N. C. Tse, “Degrees of freedom in multiple-antenna channels: A signal space approach”, IEEE Trans. Inf. Theory, 2005.

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

Interpreting the Spatial DOF Formula

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

Data



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

Observation of aperture

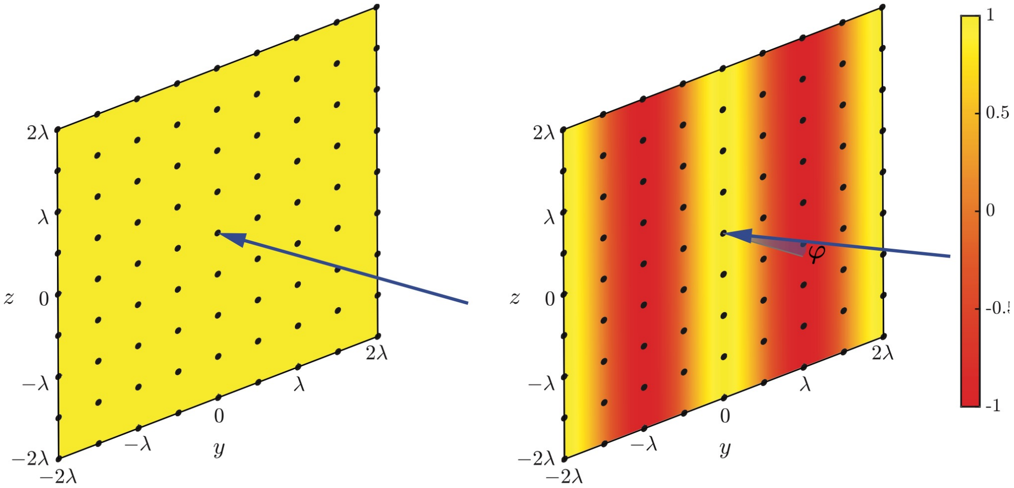
Signal with phase-shifts

Discrete antennas $\lambda/2$ apart

Take samples of phase-shifts

Channel characterized by

Horizontal/vertical spatial frequencies of incident signal



(a) Angle-of-arrival: $\varphi = 0$, $\theta = 0$.

(b) Angle-of-arrival: $\varphi = \pi/6$, $\theta = 0$.

Horizontal spatial freq: 0
Vertical spatial freq: 0

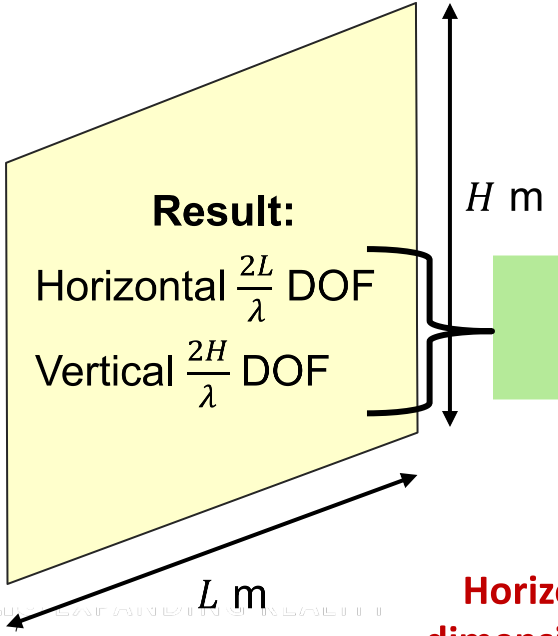
Horizontal spatial freq: $\frac{1}{2\lambda}$
Vertical spatial freq: 0

Sampling Theorem

A complex-valued continuous-~~time~~ space signal $\cancel{g(t)}$ $g(x)$

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

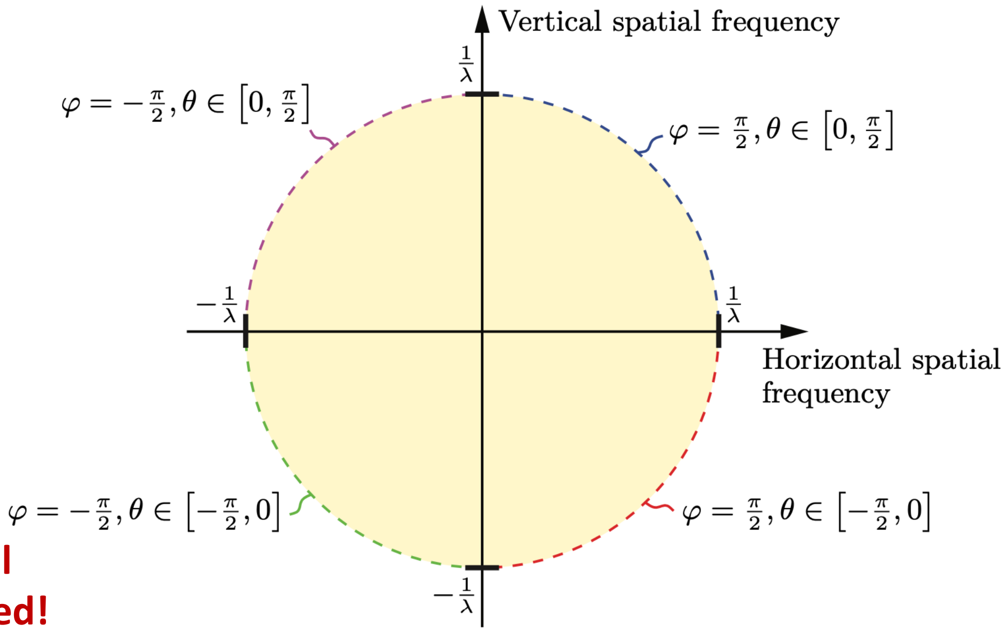
→ Signal described by $\cancel{B}$ $2/\lambda$ DOF/s DOF/m



Total DOFs

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

Horizontal and vertical dimensions are correlated!



What are the Implications?

Can we get more DOFs?

Dual polarization: $2\times$ more DOFs

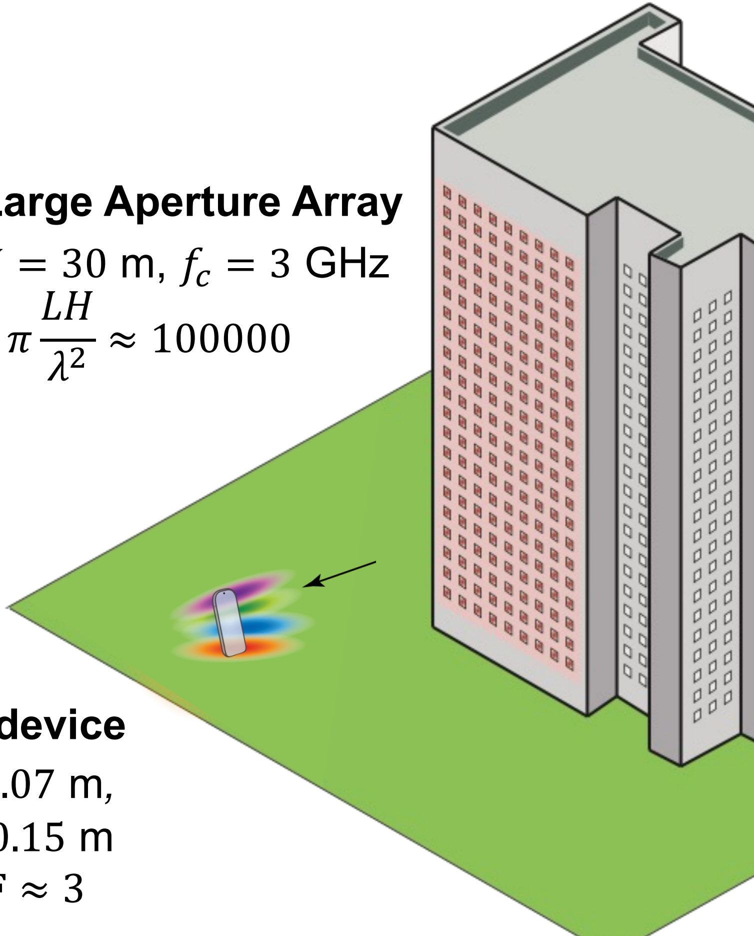
mmWave $100\times$ more DOFs

Can we make us of them all?

Extremely Large Aperture Array

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

$$\mathrm{DOF} = \pi \frac{LH}{\lambda^2} \approx 100000$$



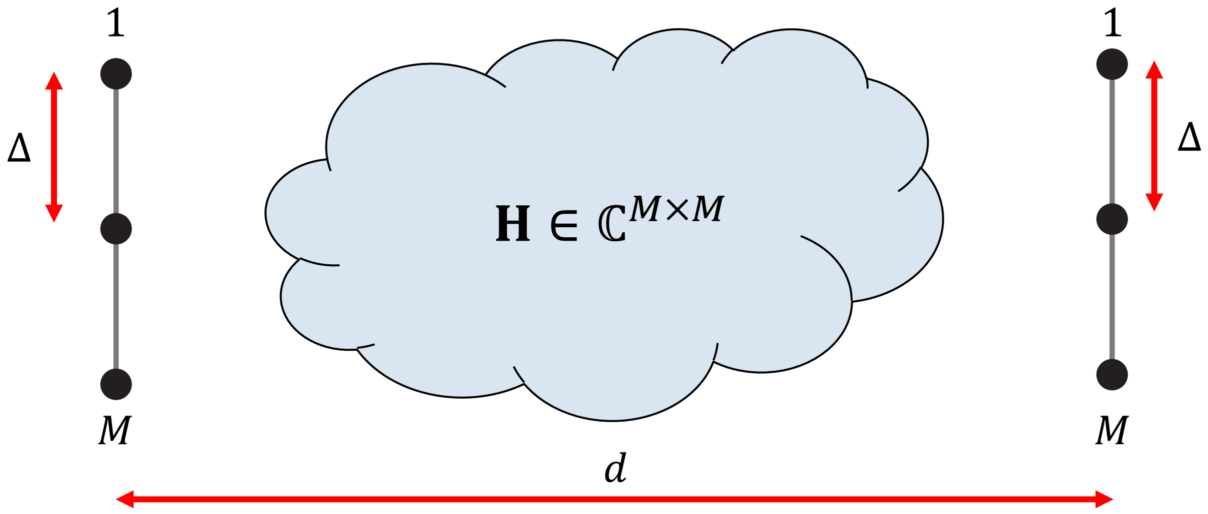
User device

$L = 0.07$ m,

$H = 0.15$ m

$\mathrm{DOF} \approx 3$

Line-of-Sight (LOS) Capacity Maximization



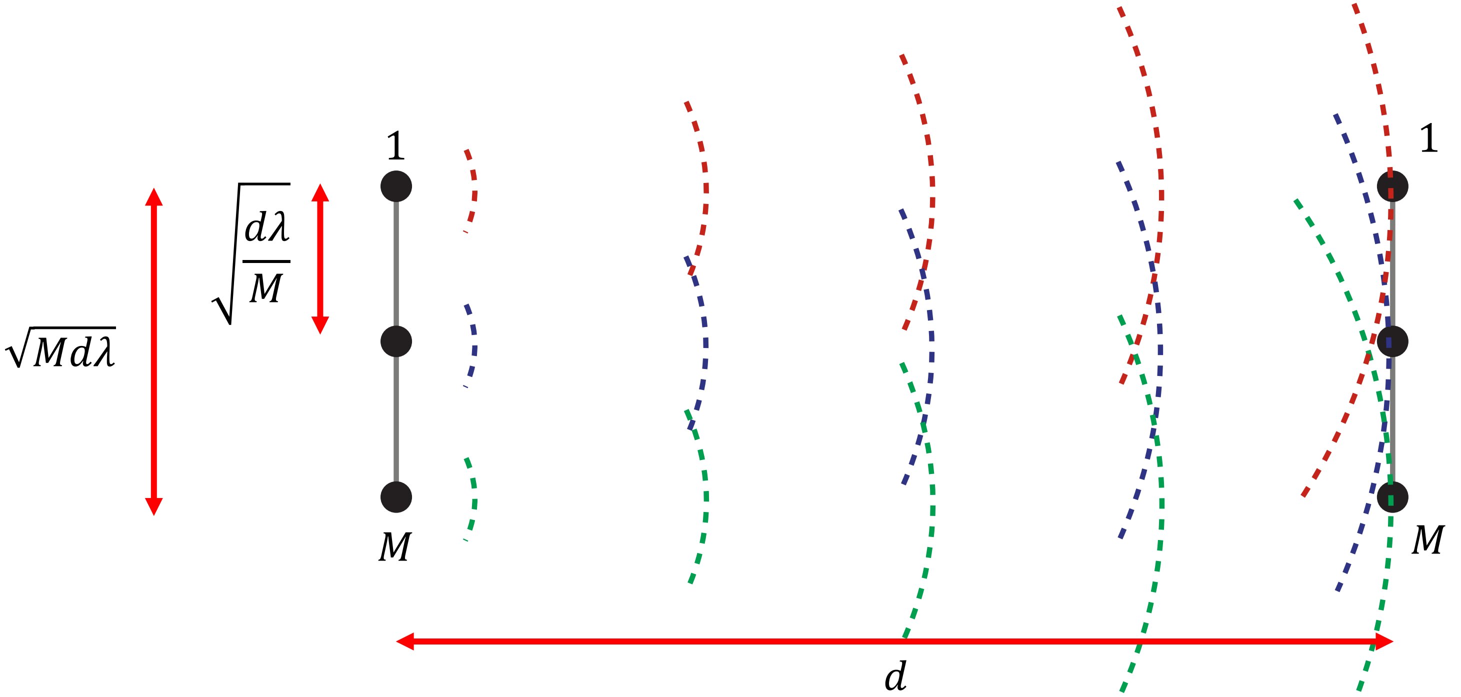
Problem: Optimize spacing Δ to maximize MIMO capacity

High SNR: M equal singular values

Solution: Apply parabolic approximation of spherical waves

Enforce that columns of $\mathbf{H}$ should be orthogonal

Optimal LOS MIMO Configuration

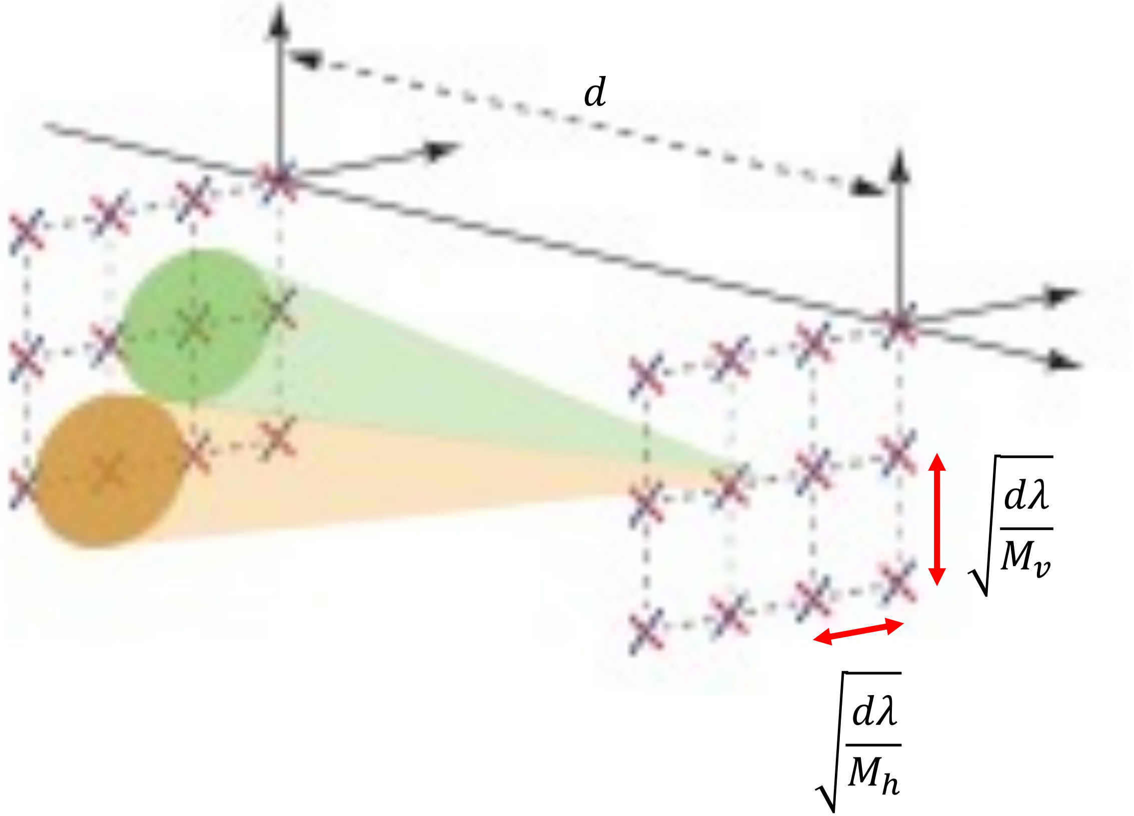


Fixed total width W

$$W = \sqrt{Md\lambda} \rightarrow M = W^2/(d\lambda)$$

Reference: *E. Torkildson, U. Madhow, and M. Rodwell, "Indoor millimeter wave MIMO: Feasibility and performance," IEEE Trans. Wireless Commun., 2011.*

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 $M = M_h M_v$

Antennas in fixed array area:

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

$2M$ DOFs with equal singular values

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,"*

Growing Capacity With Antenna Spacing

Example

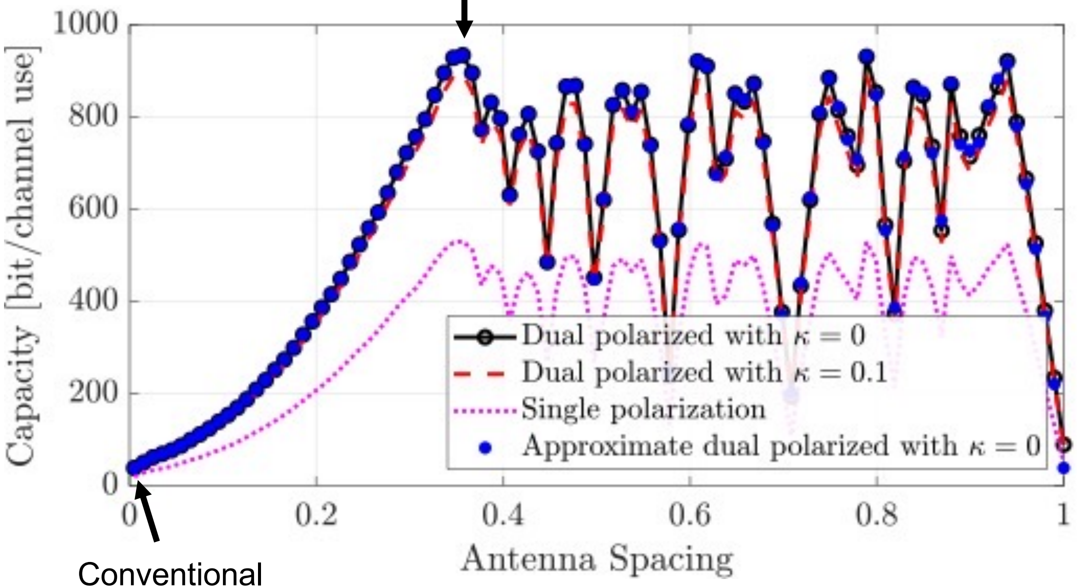
30 GHz, 100 m, 25 dB SNR

8×8 dual-polarized planar arrays

Leakage between polarizations: $\kappa \in [0,1]$

Optimal spacing:

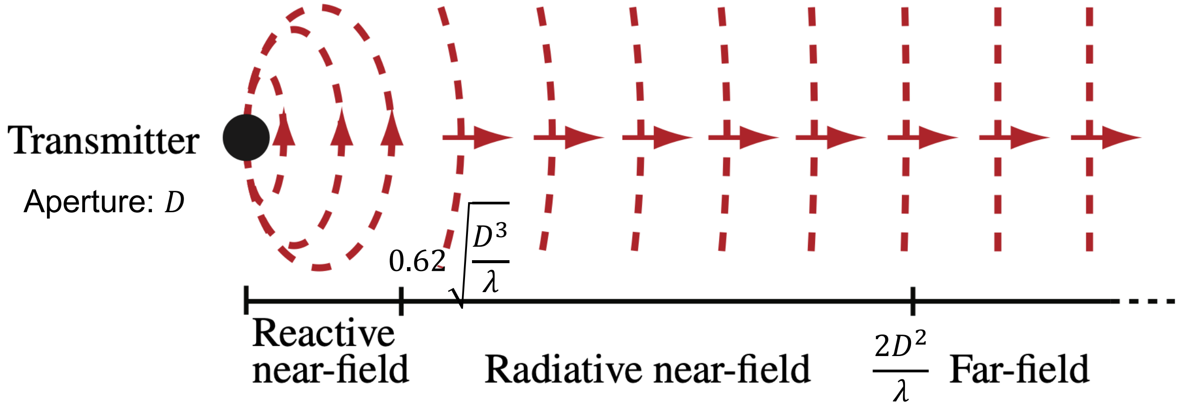
$\Delta = 0.35$ m $= 35\lambda$

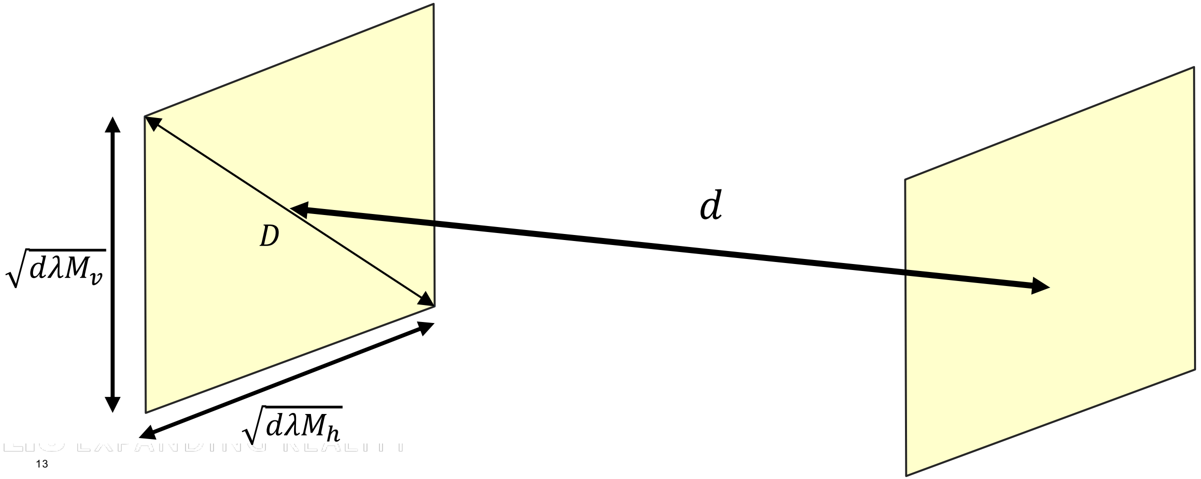


Conventional spacing:

$\Delta = \lambda/2$

Relation to Radiative Near-Field Communications





Fraunhofer array distance

$$d_{FA} = \frac{2D^2}{\lambda} = 2d(M_h + M_v) > d$$

Array design leads to near-field operation!

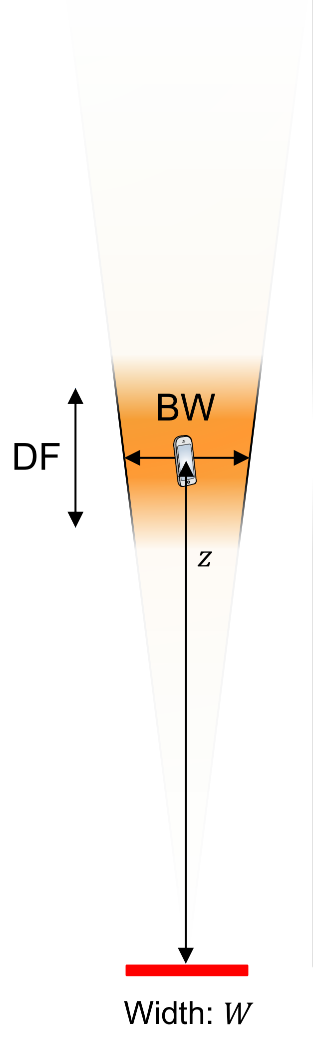
Beamforming: Width and Depth

Physical 3 dB beamwidth (BW) is $\mathrm{BW}_{3\mathrm{dB}} \approx \frac{2\pi\lambda}{5W} \cdot z$ meters

Depth-of-focus (DF), where the beamforming gain is at most 3 dB lower than the maximum, for focusing on distance z is

$$d \in \left[\frac{d_{FA} z}{d_{FA} + 10z}, \frac{d_{FA} z}{d_{FA} - 10z}\right]$$

Finite-depth beamforming closer than $d_{FA}/10$



Reference: *E. Björnson, Ö. T. Demir, L. Sanguinetti, "A Primer on Near-Field Beamforming for Arrays and Reconfigurable Intelligent Surfaces," Asilomar SSC 2021.*

Far-field

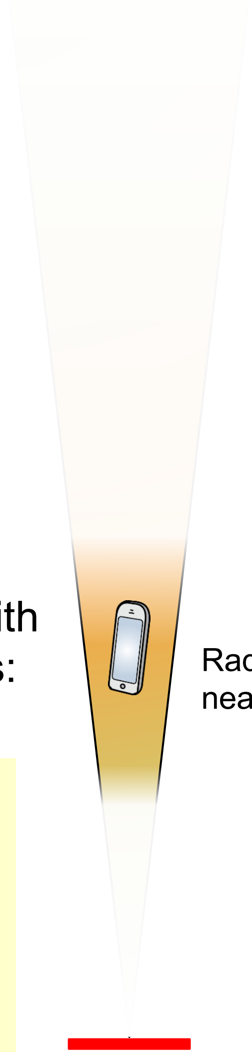
$\frac{d_{FA}}{10}$

Far-Field vs. Near-Field "Beamforming"

Impact of wavelength

$$d_{FA} = \frac{2W^2}{\lambda} \propto \lambda^{-1}$$

This is the situation with optimal MIMO arrays:



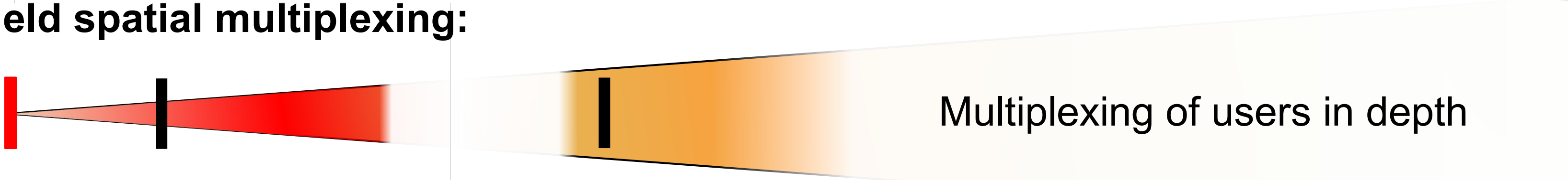
Radiative near-field

Example: 3 GHz, $\lambda = 0.1$ m	At 30 GHz
$W = 1$ m: $d_{FA} = \frac{2W^2}{\lambda} = 20$ m	$d_{FA} = \frac{2W^2}{\lambda} = 200$ m
$W = 10$ m: $d_{FA} = \frac{2W^2}{\lambda} = 2$ km	$d_{FA} = \frac{2W^2}{\lambda} = 20$ km

Near-Field Multi-User Multiplexing

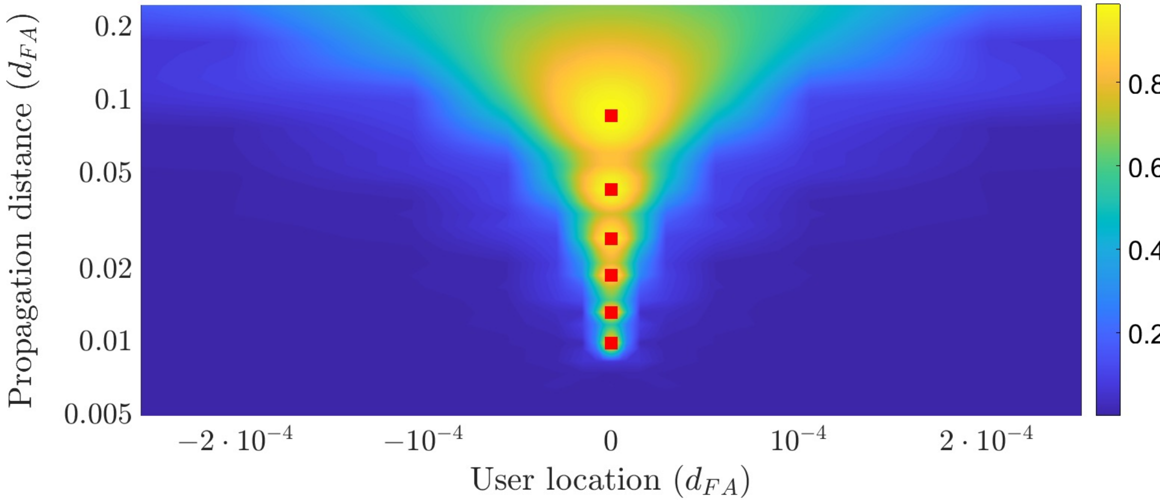
Far-field (Maximum rank 1):

Near-field spatial multiplexing:

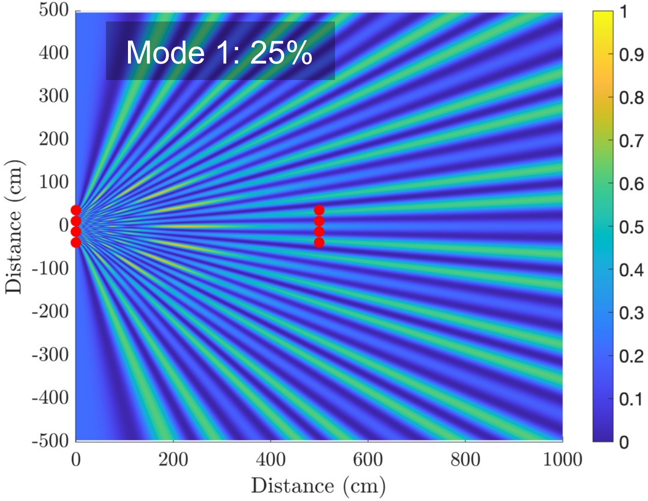


Same MIMO theory

Different channel matrix

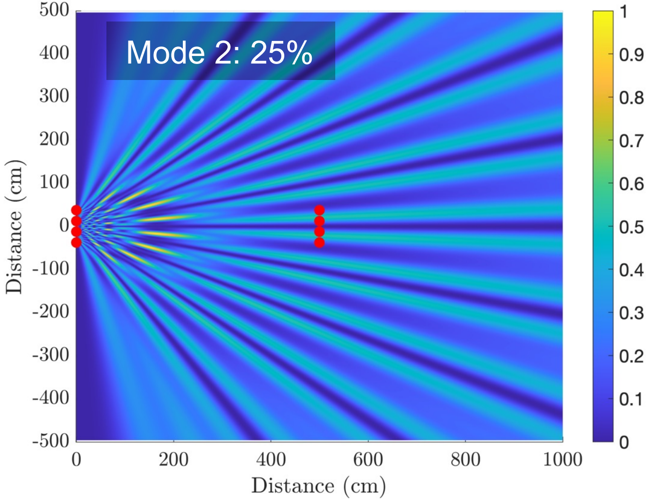


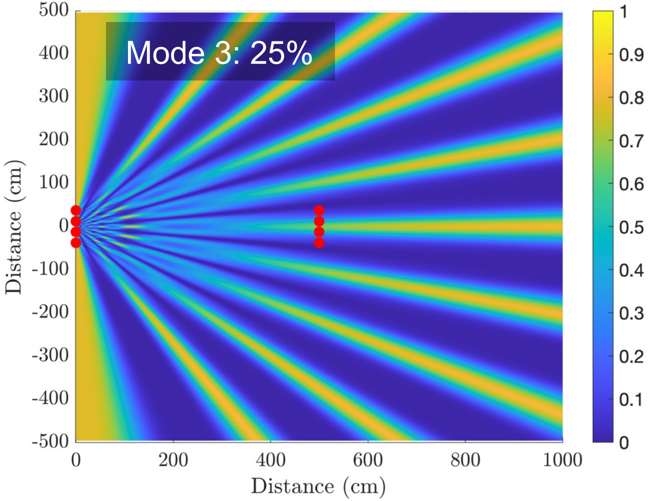
Point-to-Point
4×4 MIMO



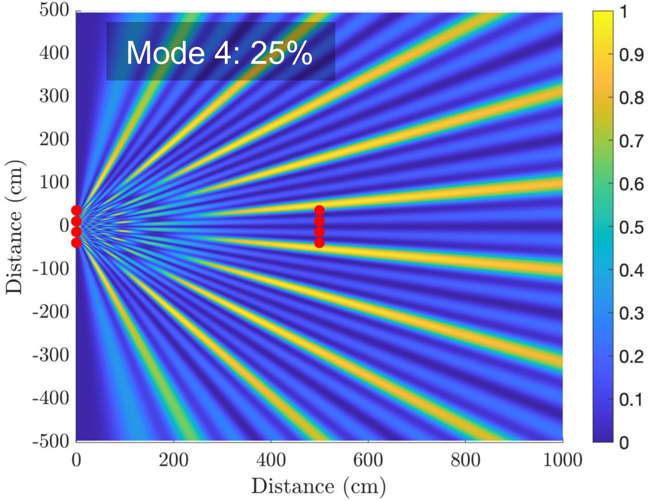
4x higher capacity than in far-field

Color = Fraction of maximum beamforming gain



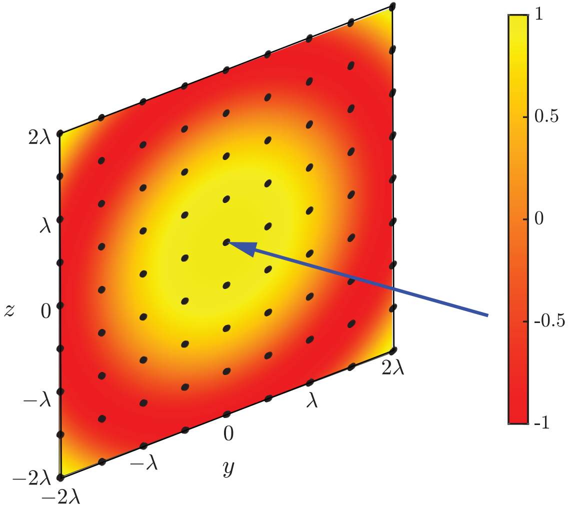


Grating lobes since larger than $\lambda/2$ spacing

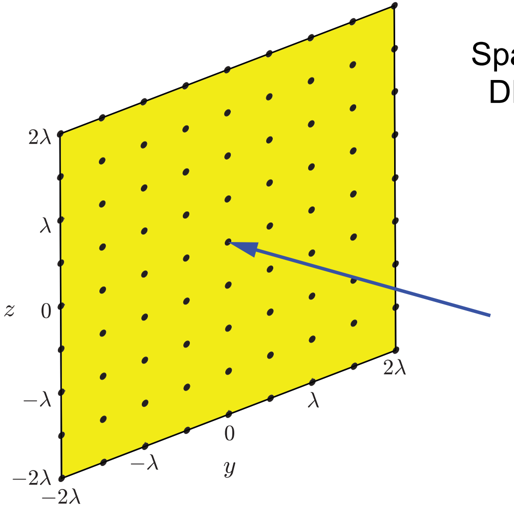


60 GHz band

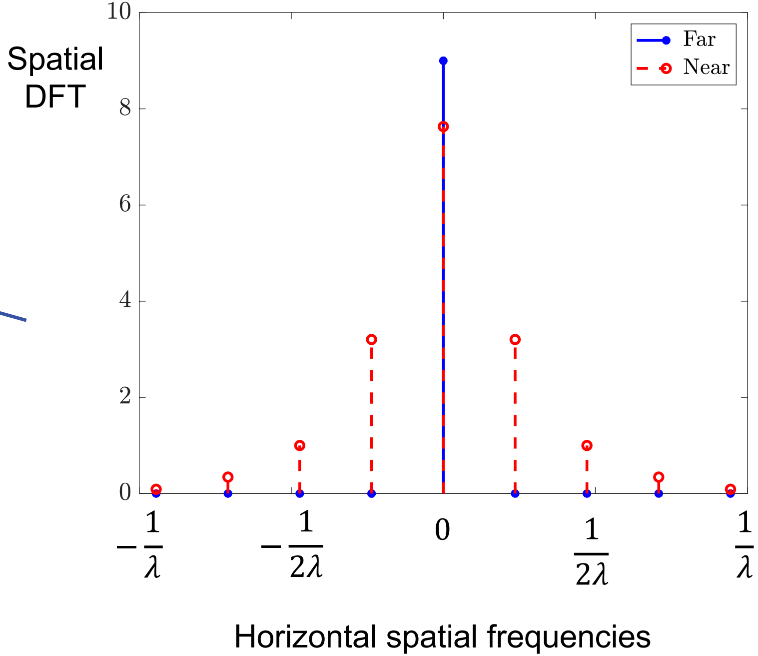
Are There More DOFs in the Near-Field?



User near the array
$(d = 4\lambda)$



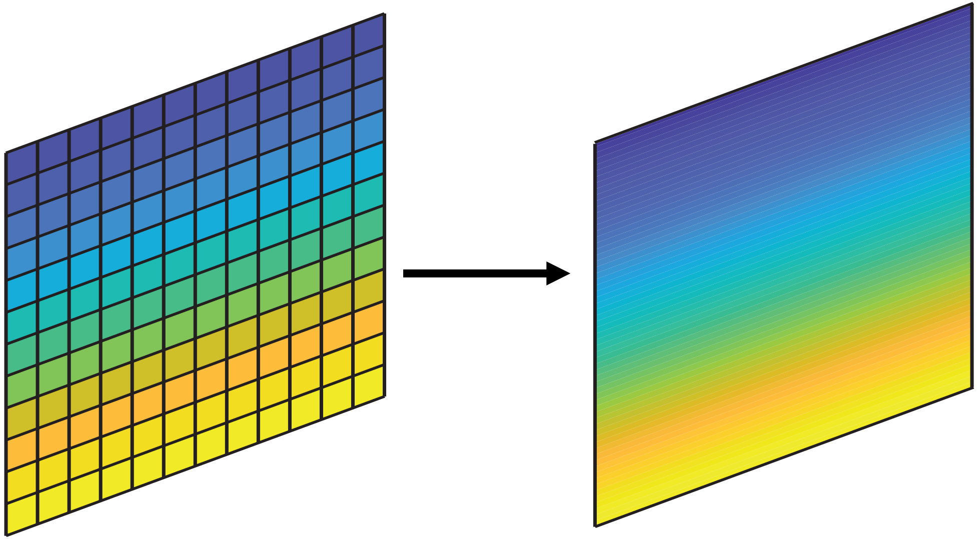
User far from the array
$(d \approx \infty)$



No, but can be used for angular and depth beamforming

But we typically have many antennas anyway…

Holographic MIMO



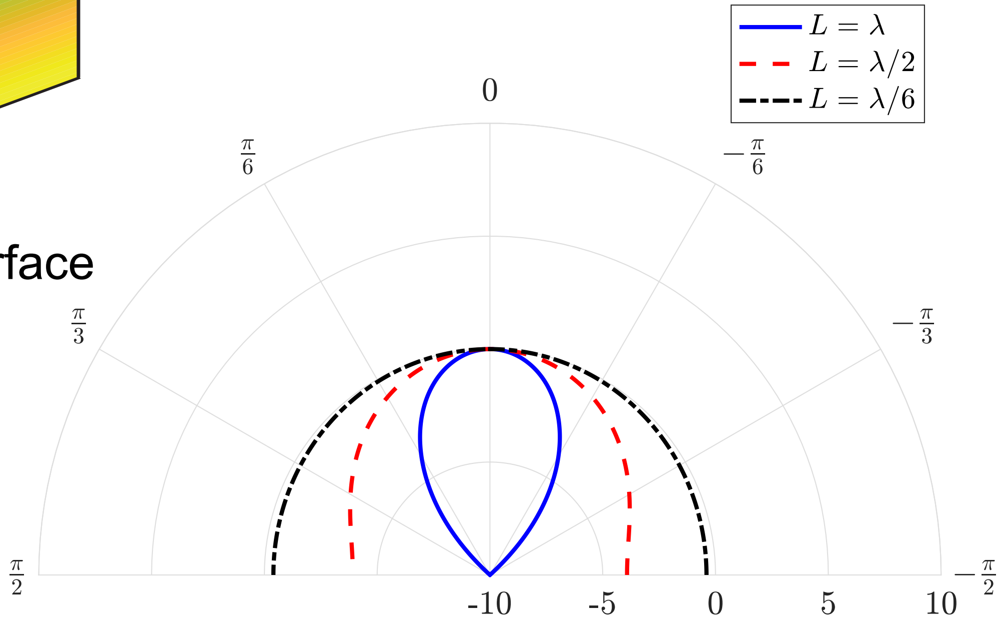
Discrete antennas

Continuous surface

Spatial oversampling

No new DOFs

More uniform radiation pattern?



Hologram

Phase-shift pattern on the surface

Described by spatial frequencies

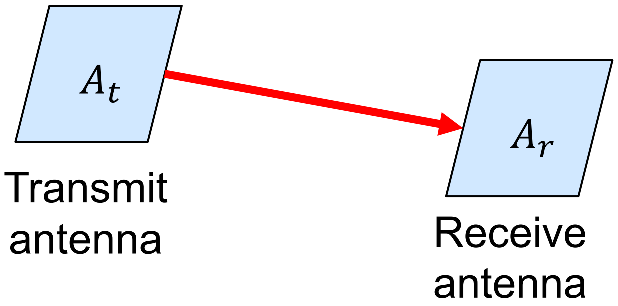
Revisiting Friis' Transmission Formula

Received power with isotropic antennas, having area $A = \frac{\lambda^2}{4\pi}$

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

Received power with aperture areas A_t and A_r:

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



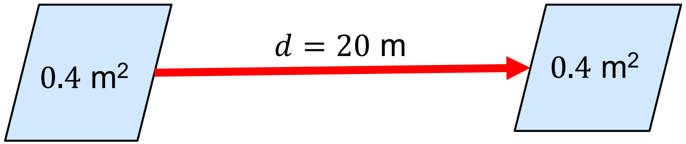
Cancel wavelength-dependence:

$A_t = A_r \propto \lambda$

Massive Spatial Multiplexing in mmWave Bands

- Reference case: $\text{Bandwidth} \cdot \log_2(1 + \text{SNR})$
- Extra degrees-of-freedom: $\text{Bandwidth} \cdot \text{DOF} \cdot \log_2(1 + \text{SNR}/\text{DOF})$

Line-of-sight scenario:

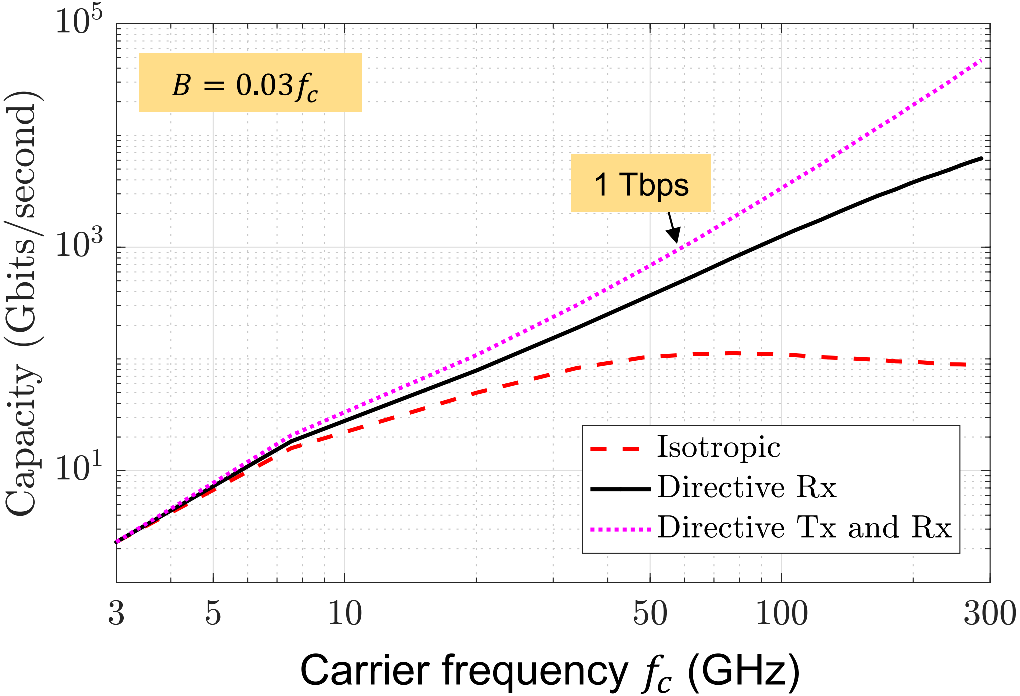


Increasing carrier frequency

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

$\text{SNR} \propto \{\lambda^2, 1, 1/\lambda^2\}$

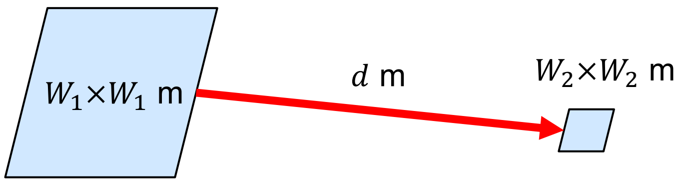
Capacity: $O(f_c^2)$ $O(f_c)$ $O(1)$



Great MIMO Capacity With Small Devices

Geometry requirement for maximum capacity:

$$W_1 \cdot W_2/d = \text{constant}$$



Example: $d = 50$ m

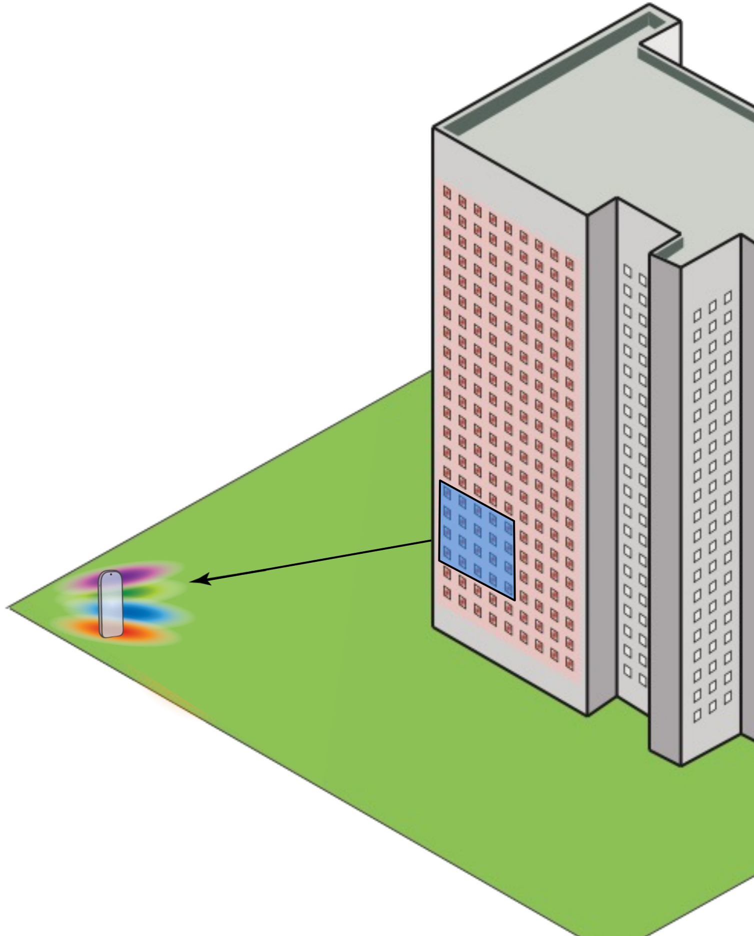
Base station: $W_1 = 6.75$ m

User device: $W_2 = 0.2$ m

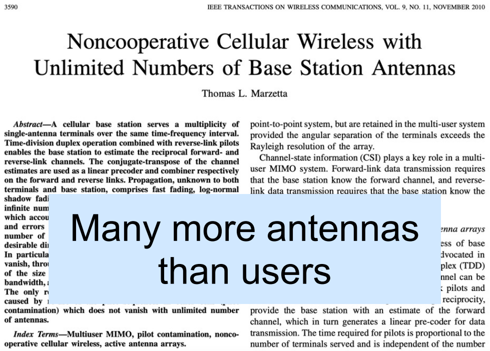
64 dual-polarized elements,
1 W/element

$B = 3$ GHz, $f_c = 100$ GHz

3.2 Tbps



From Science Fiction to Mainstream Technology



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Noncooperative Cellular Wireless with Unlimited Numbers of Base Station Antennas

Thomas L. Marzetta

Abstract—A cellular base station serves a multiplicity of single-antenna terminals over the same time-frequency interval. Time-division duplex operation combined with reverse-link pilots enables the base station to estimate the reciprocal forward- and reverse-link channels. The conjugate-transpose of the channel estimates are used as a linear precoder and combiner respectively on the forward and reverse links. Propagation, unknown to both terminals and base station, comprises fast fading, log-normal shadow fadi[…]

[…] contamination) which does not vanish with unlimited number of antennas.

Index Terms—Multiuser MIMO, pilot contamination, noncooperative cellular wireless, active antenna arrays.

point-to-point system, but are retained in the multi-user system provided the angular separation of the terminals exceeds the Rayleigh resolution of the array.

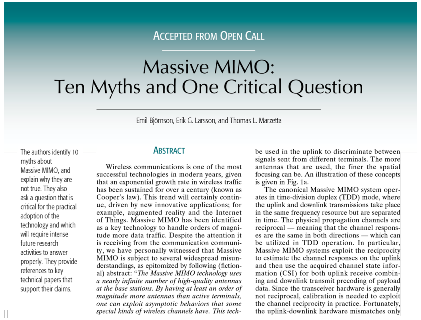
Channel-state information (CSI) plays a key role in a multi-user MIMO system. Forward-link data transmission requires that the base station know the forward channel, and reverse-link data transmission requires that the base station know the […]

[…] provide the base station with an estimate of the forward channel, which in turn generates a linear pre-coder for data transmission. The time required for pilots is proportional to the number of terminals served and is independent of the number

Many more antennas than users

Exponential data traffic growth

2010 2015 2020 2025 2030



ACCEPTED FROM OPEN CALL

Massive MIMO: Ten Myths and One Critical Question

Emil Björnson, Erik G. Larsson, and Thomas L. Marzetta

The authors identify 10 myths about Massive MIMO, and explain why they are not true. They also ask a question that is critical for the practical adoption of the technology and which will require intense future research activities to answer properly. They provide references to key technical papers that support their claims.

ABSTRACT

Wireless communications is one of the most successful technologies in modern years, given that an exponential growth rate in wireless traffic has been sustained for over a century (known as Cooper's law). This trend will certainly continue, driven by new innovative applications; for example, augmented reality and the Internet of Things. Massive MIMO has been identified as a key technology to handle orders of magnitude more data traffic. Despite the attention it is receiving from the communication community, we have personally witnessed that Massive MIMO is subject to several widespread misunderstandings, as epitomized by following (fictional) abstract: "*The Massive MIMO technology uses a nearly infinite number of high-quality antennas at the base stations. By having at least an order of magnitude more antennas than active terminals, one can exploit asymptotic behaviors that some special kinds of wireless channels have. This tech-*

be used in the uplink to discriminate between signals sent from different terminals. The more antennas that are used, the finer the spatial focusing can be. An illustration of these concepts is given in Fig. 1a.

The canonical Massive MIMO system operates in time-division duplex (TDD) mode, where the uplink and downlink transmissions take place in the same frequency resource but are separated in time. The physical propagation channels are reciprocal — meaning that the channel responses are the same in both directions — which can be utilized in TDD operation. In particular, Massive MIMO systems exploit the reciprocity to estimate the channel responses on the uplink and then use the acquired channel state information (CSI) for both uplink receive combining and downlink transmit precoding of payload data. Since the transceiver hardware is generally not reciprocal, calibration is needed to exploit the channel reciprocity in practice. Fortunately, the uplink-downlink hardware mismatches only

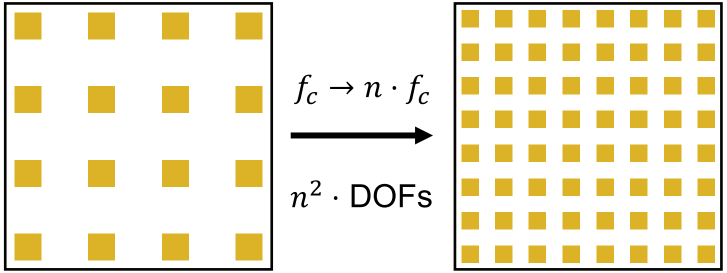
Massive Near-Field Spatial Multiplexing

Many spatial streams

?

- Power consumption?
- Hardware imperfections?
- Cost?

Massive Spatial Multiplexing:
The Way to Raise Capacity in the Future?



- Capacity grows as f_c^2 due to MIMO
  - Faster than f_c-scaling due to spectrum
  - Maximum DOFs ***and*** practically useful
  - **Near-field:** Control both angle and depth

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

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QUESTIONS?