Physically Large Antenna Arrays:
When the Near-Field Becomes Far-Reaching

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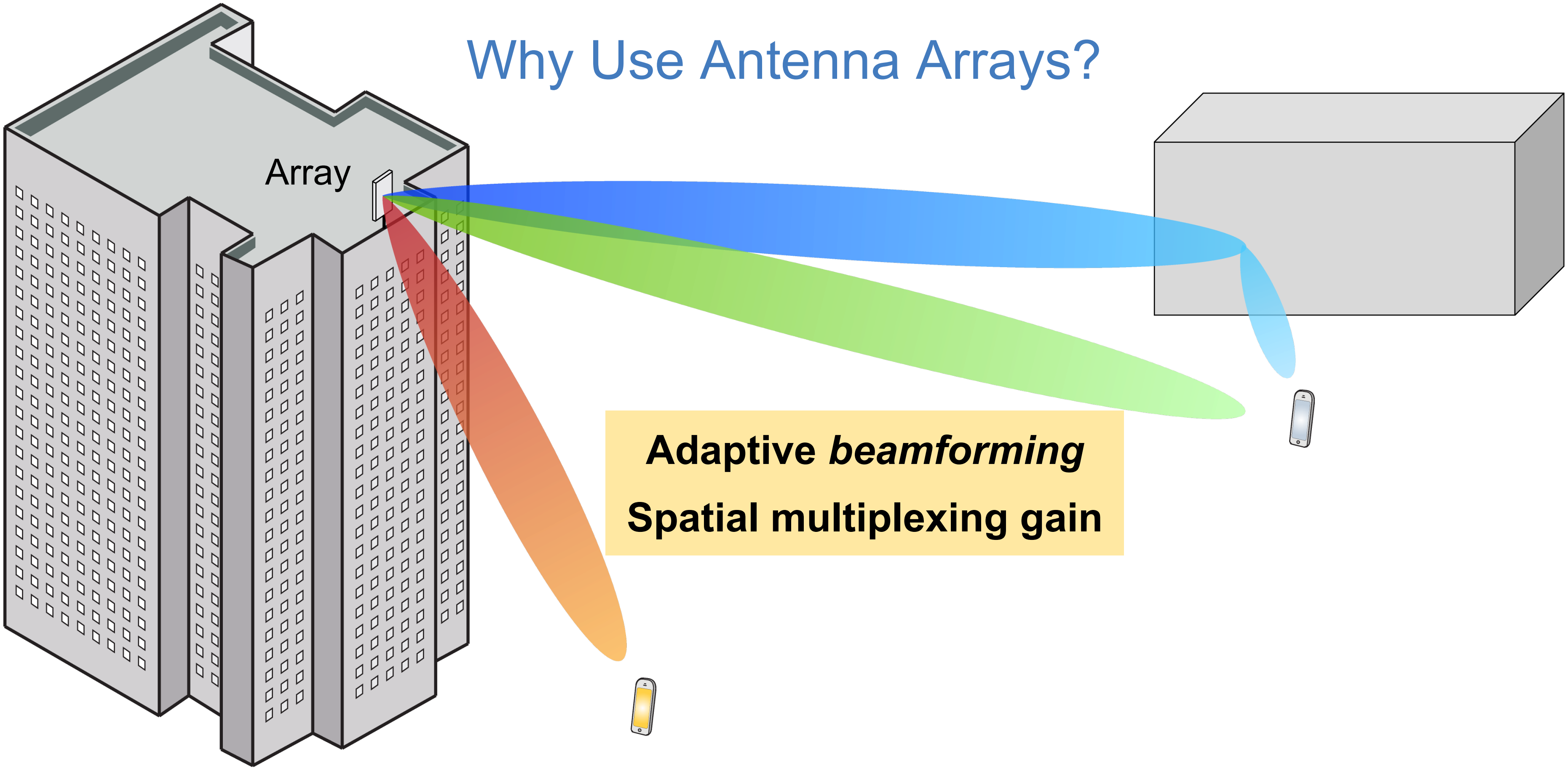
Why Use Antenna Arrays?

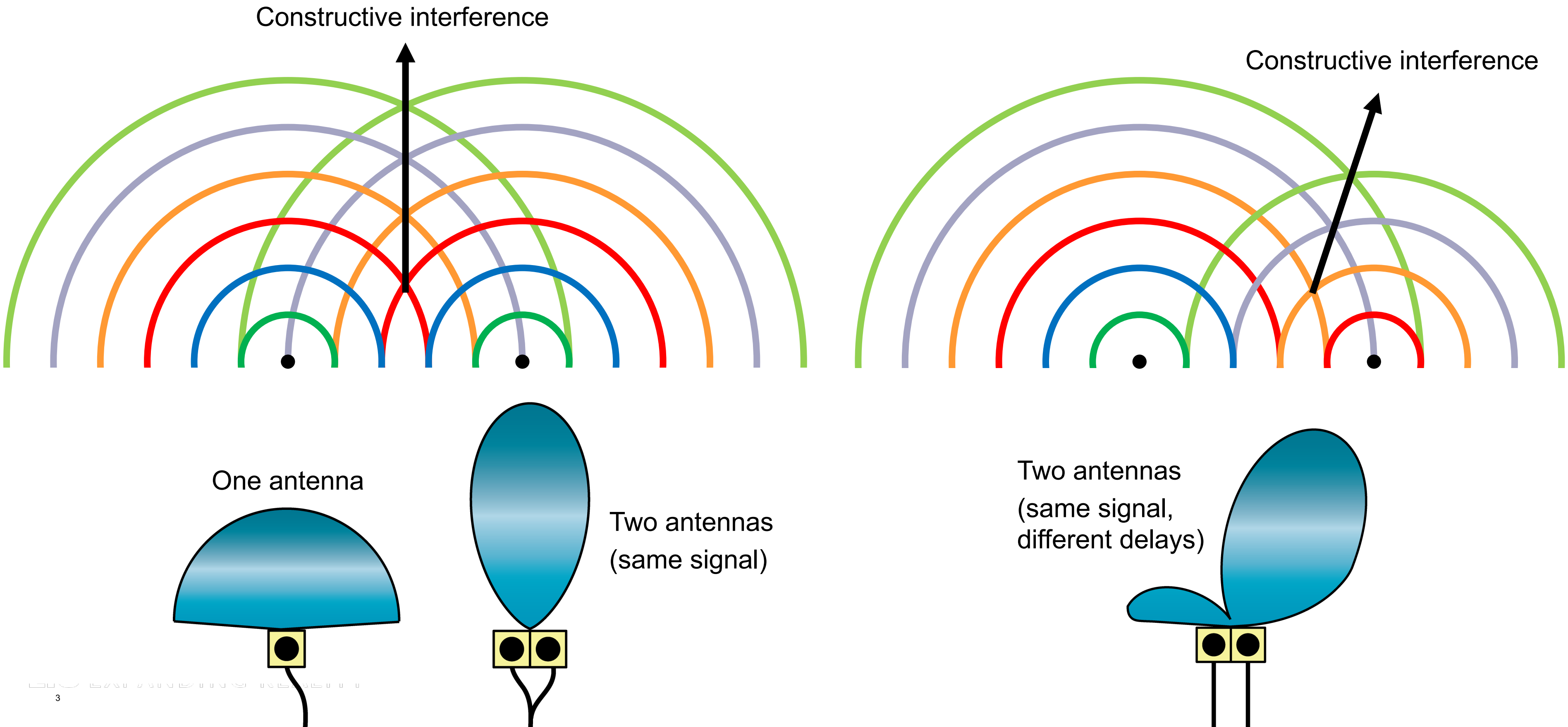


Adaptive *beamforming*

Spatial multiplexing gain

MIMO = Multiple input multiple output

Adaptive Beamforming in a Nutshell



What is **Massive** MIMO?

Definition of *massive*

1 : forming or consisting of a large mass:

- **a** : BULKY
  // *massive* furniture
- **b** : WEIGHTY, HEAVY
  // *massive* walls
  // a *massive* volume

Merriam-Webster®

2 **a** : large, solid, or heavy in structure
// *massive* jaw

b : large in scope or degree
// the feeling of frustration, of being ineffectual, is *massive*
— David Halberstam

AIR 3268

32 antennas (128 elements)

12 kg

200 W over 200 MHz in 3.5 GHz band

Integrated circuitry

Ericsson adds a 12 kg radio to Massive MIMO portfolio for easier 5G mid-band deployment

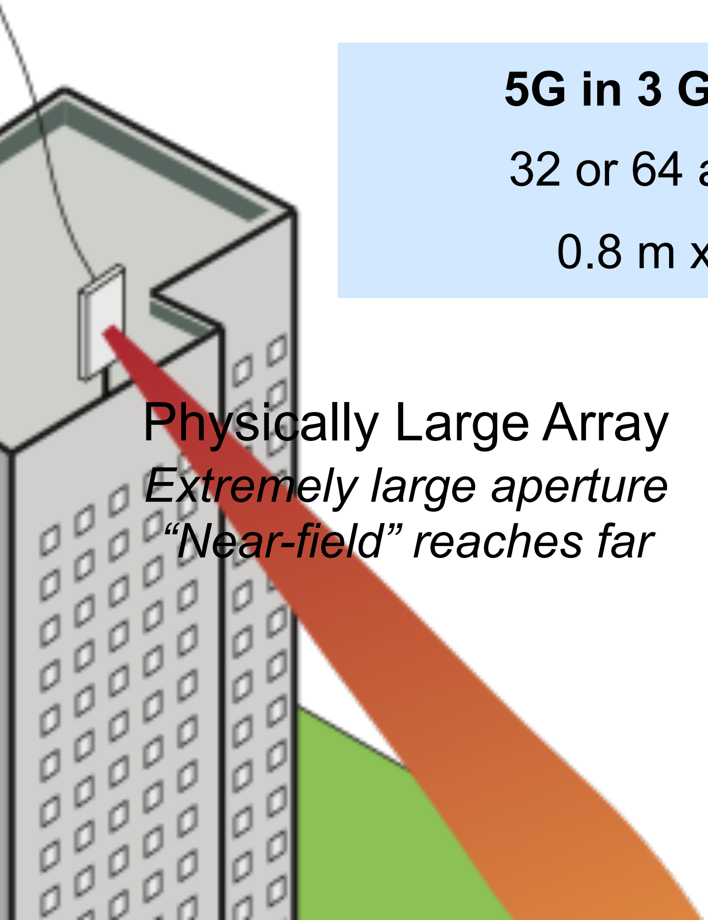
Available in English Français Español 日本語 繁體中文 Indonesia

Ericsson today unveils the latest addition to its Massive MIMO portfolio – the ultra-lightweight antenna-integrated radio AIR 3268 – for easier and efficient 5G mid-band deployments in dense urban and suburban areas.

News

Sep 21, 2021

Massive MIMO versus Physically Large Arrays



5G in 3 GHz band

32 or 64 antennas

0.8 m x 0.5 m

Massive MIMO array

Many antennas

Looks small

Physically Large Array

Extremely large aperture

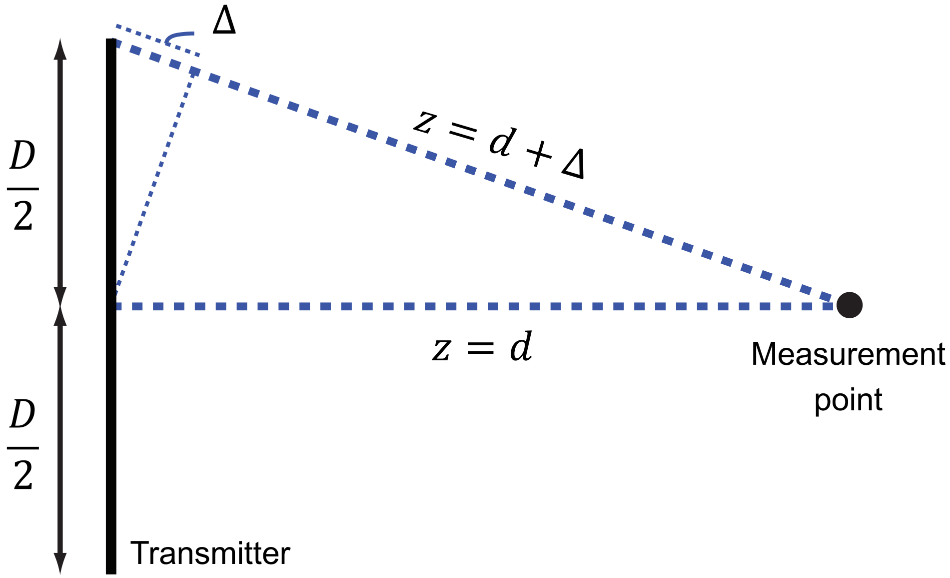
“Near-field” reaches far

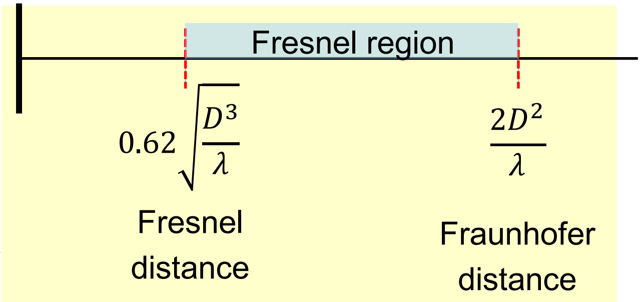
What are the benefits of this evolution?

PRELIMINARIES:

NEAR-FIELD OF A *PASSIVE* ANTENNA

Near-Field and Far-Field Regions (Electromagnetic Definition)





Electric field intensity proportional to

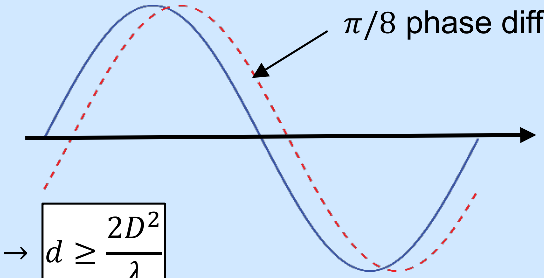
$$\int_{\text{Transmitter}} \frac{e^{-j\frac{2\pi}{\lambda}z}}{z}\left(1 + \underbrace{\frac{j}{2\pi z/\lambda} - \frac{1}{(2\pi z/\lambda)^2}}_{}\right) dz$$

Reactive near-field effect

(Negligible for $d > 0.62\sqrt{D^3/\lambda}$)

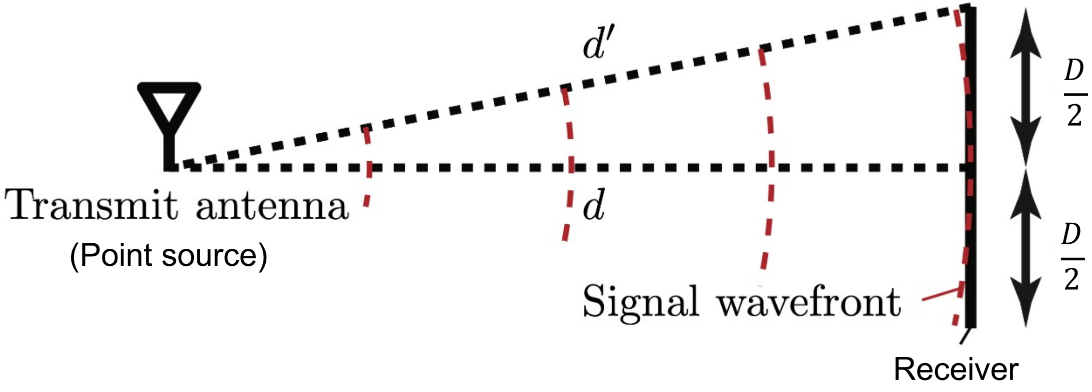
Radiative near-field

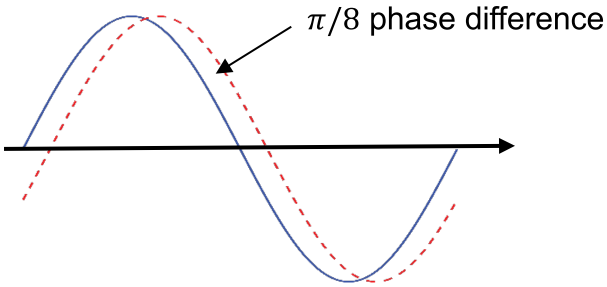
Path difference: $\Delta = \sqrt{d^2 + \left(\frac{D}{2}\right)^2} - d \approx \frac{D^2}{8d}$



$$\frac{\pi}{8} \geq \frac{2\pi}{\lambda}\frac{D^2}{8d} \rightarrow \boxed{d \geq \frac{2D^2}{\lambda}}$$

Near-Field and Far-Field Regions (Communication Perspective)





Amplitude difference d/d'

Less than $\cos(\pi/8) \approx 0.92$ if $d \geq 1.2D$

Example: 3 GHz, $D = \lambda = 0.1$ m

$1.2D = 0.12$ m

$$d_F = \frac{2D^2}{\lambda} = 2\lambda = 0.2 \text{ m}$$

Phase-shift difference less than $\pi/8$ if $d \geq d_F = \frac{2D^2}{\lambda}$

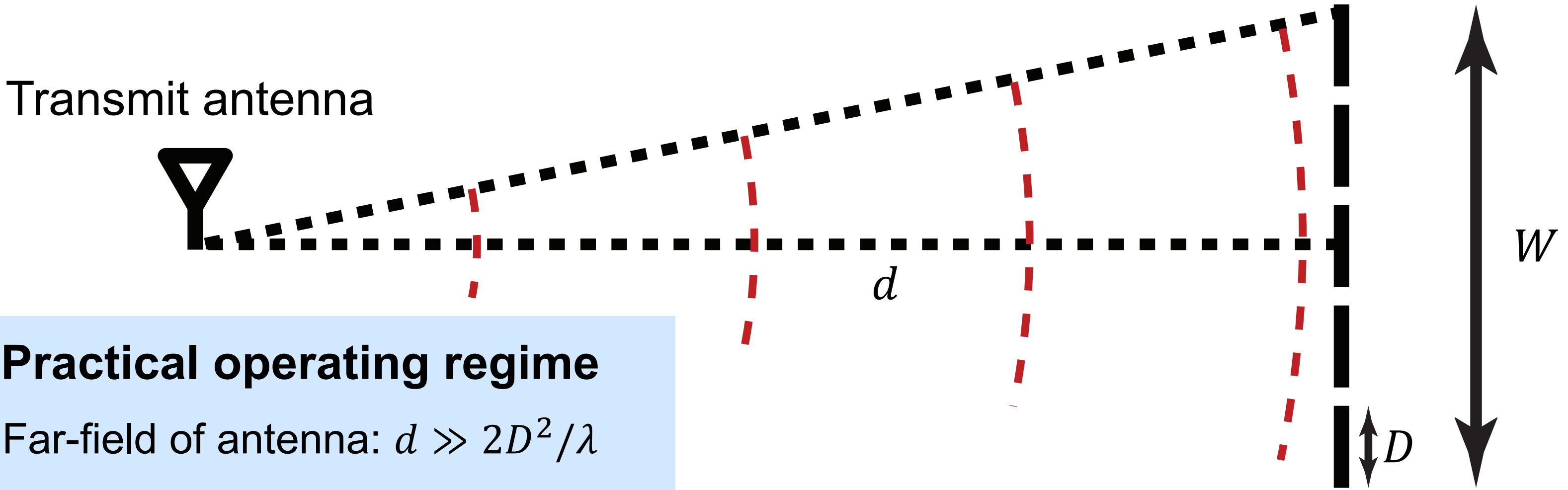
Fraunhofer distance

Locally plane wave over receiver aperture

NEAR-FIELD OF PHYSICALLY LARGE ARRAYS

Fraunhofer's Array Distance: d_{FA}

The distance after which the angular field distribution is essentially independent of the distance



Practical operating regime

Far-field of antenna: $d \gg 2D^2/\lambda$

Near-field of array if $d \leq 2W^2/\lambda$

Example: 3 GHz, $\lambda = 0.1$ m

$W = 10\lambda = 1$ m: $d_{FA} = \frac{2W^2}{\lambda} = 20$ m

$W = 100\lambda = 10$ m: $d_{FA} = \frac{2W^2}{\lambda} = 2$ km

Channel Modeling for Radiative Near-Field Phenomena

Near-field phenomena

1. Different distances to antennas
2. Different effective areas
3. Different polarization losses

Far-field channel gain

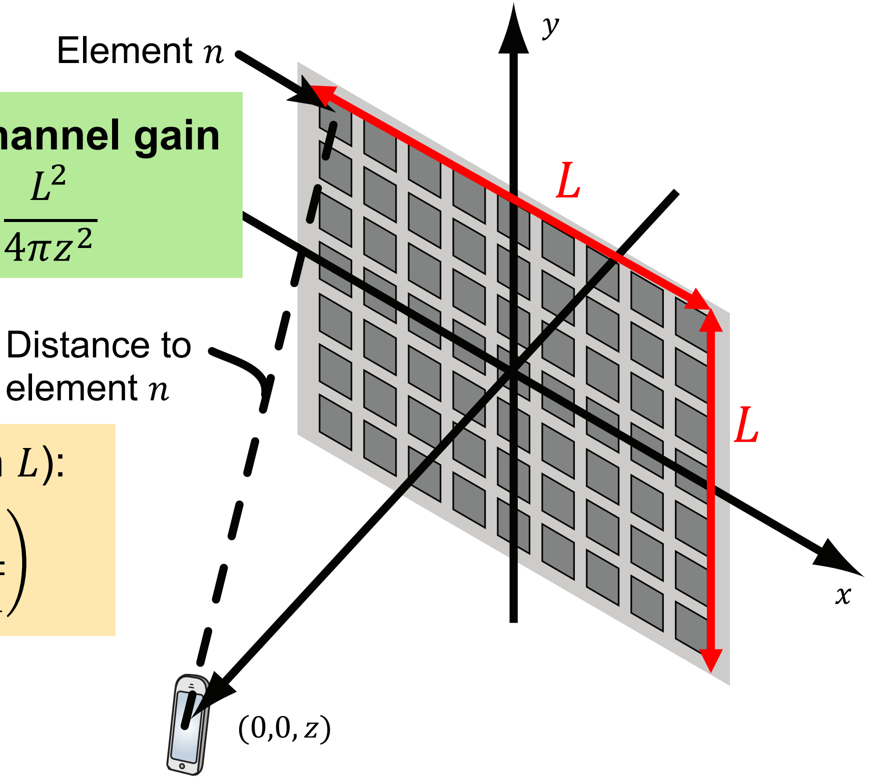
$$\beta_z = \frac{L^2}{4\pi z^2}$$

Free-space channel gain (distance z, width/length L):

$$\gamma_z = \frac{\beta_z}{3(\beta_z\pi + 1)\sqrt{2\beta_z\pi + 1}} + \frac{2}{3\pi}\tan^{-1}\left(\frac{\beta_z\pi}{\sqrt{2\beta_z\pi + 1}}\right)$$

Limits: $\gamma_z \approx \beta_z$ for $z \gg L$

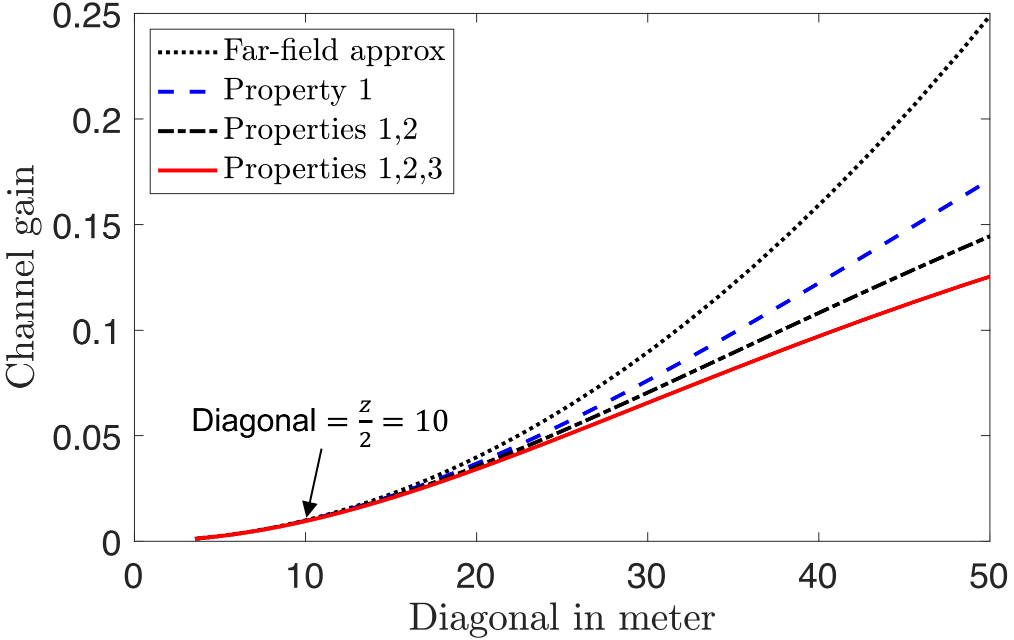
$\gamma_z \to \frac{1}{3}$ as $L \to \infty$



Reference: *E. Björnson, L. Sanguinetti, "Power Scaling Laws and Near-Field Behaviors of Massive MIMO and Intelligent Reflecting Surfaces," 2020*

When Are These Phenomena Appearing?

Distance to square array: $z = 20$ m



Björnson distance d_B

$2 \times$ Largest dimension = Distance to array

Near-field phenomena

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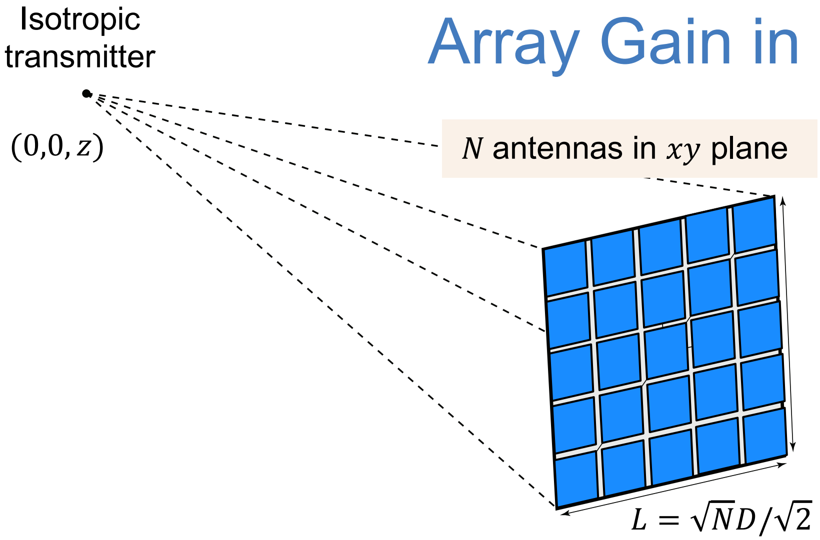
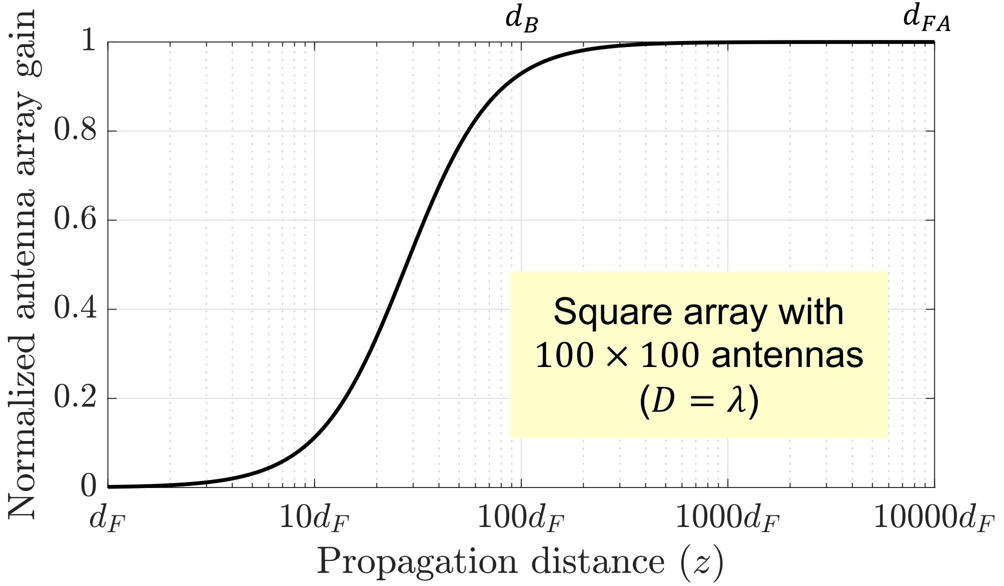
Array Gain in Radiative Near-Field





Normalized antenna array gain:

$$G_{\text{array}} = \frac{\text{Actual channel gain}}{\text{Far–field channel gain}}$$

Fraunhofer array distance:
$d_{FA} = 2ND^2/\lambda = Nd_F$

No evident impact on the gain

Björnson distance
$d_B = 2D\sqrt{N}$

Where at least 95% of gain is achieved

Beamforming in Fresnel Region ($d_B \leq z \leq d_{FA}$)

Fraunhofer array distance is still relevant:

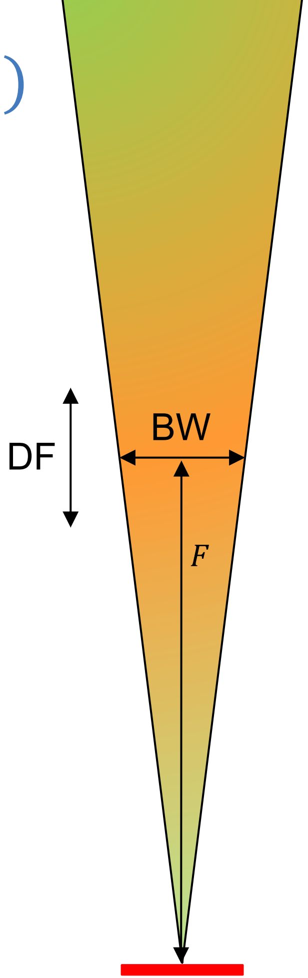
- For $z \geq d_{FA}$: *Use array response vector*
- For $z \leq d_{FA}$: *Use spherical curvature for beamforming*

Angular 3 dB beam-width (BW) is $\mathrm{BW}_{3\mathrm{dB}}^{\mathrm{ang}} \approx \frac{0.886\lambda}{D\sqrt{N/2}}$

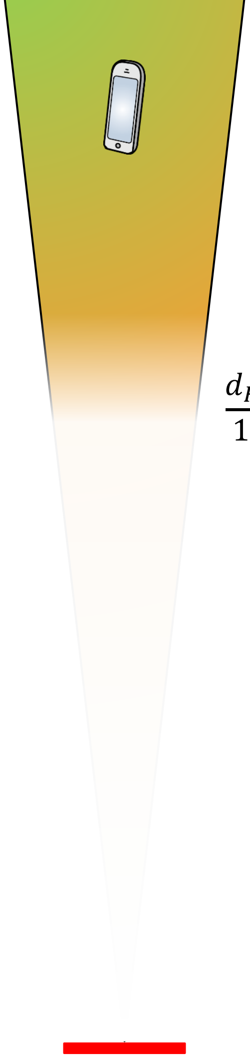
Theorem: Depth-of-focus (DF), where the array gain is at most 3 dB lower than the maximum, for focusing at $z = F$ is

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

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 2021, arXiv:2110.06661*

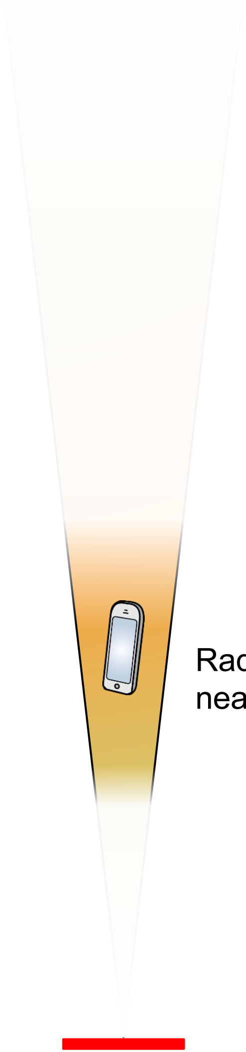


Far-Field vs. Near-Field Beamforming

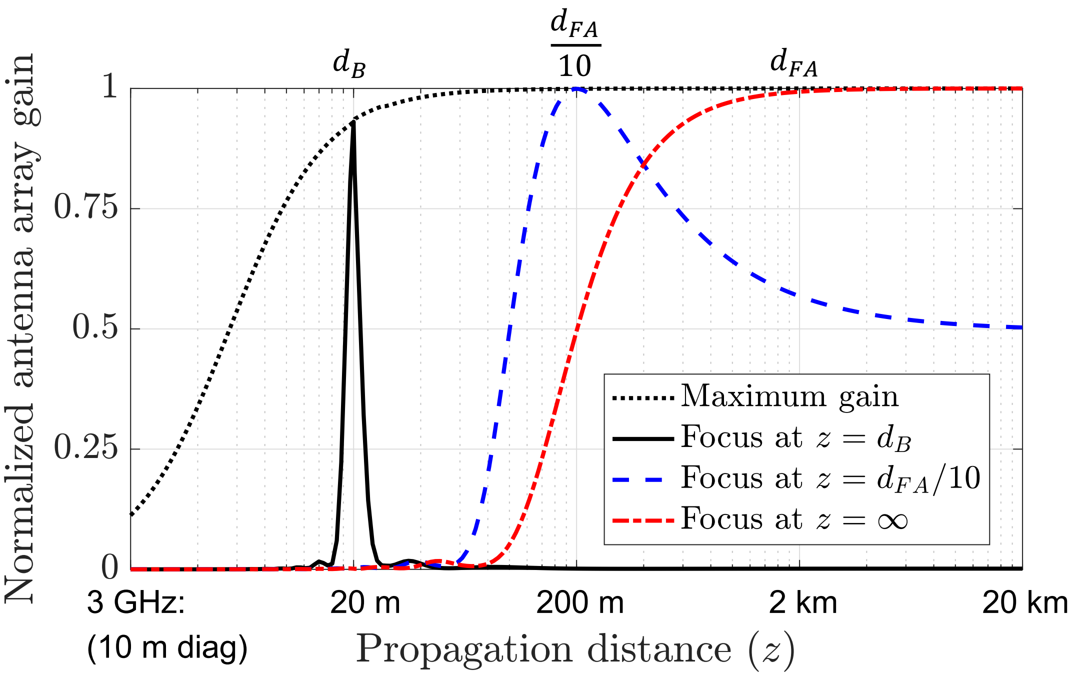
Impact of wavelength

Fixed array size: $d_{FA} \propto \lambda^{-1}$

Fixed number of elements: $d_{FA} \propto \lambda$



Near-Field **Finite-Depth** Beamforming



Fraunhofer array distance d_{FA}
Nothing special happens here

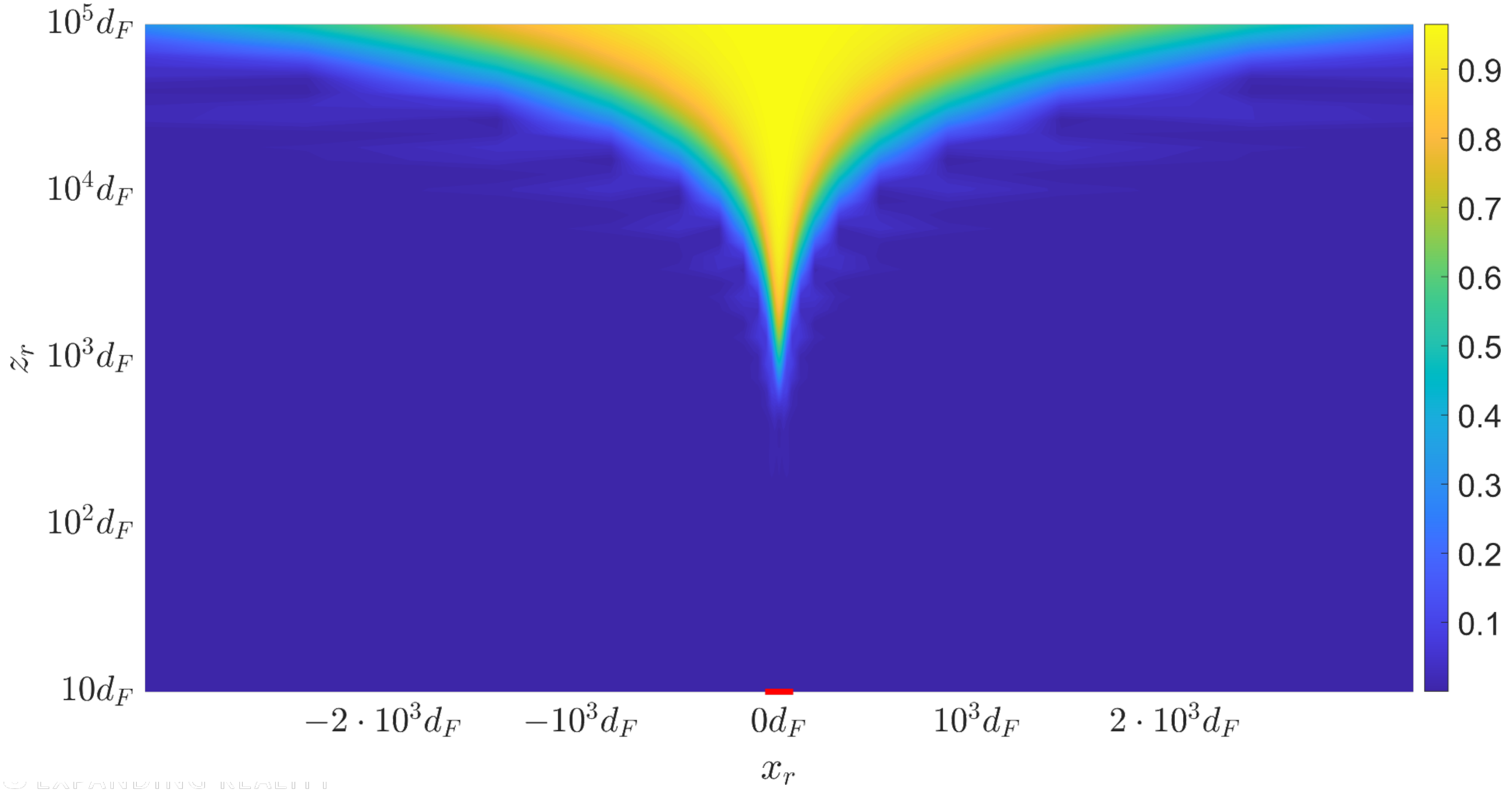
Finite-depth beamforming
closer than $d_{FA}/10$

Björnson distance:
Where the array gain tapers off

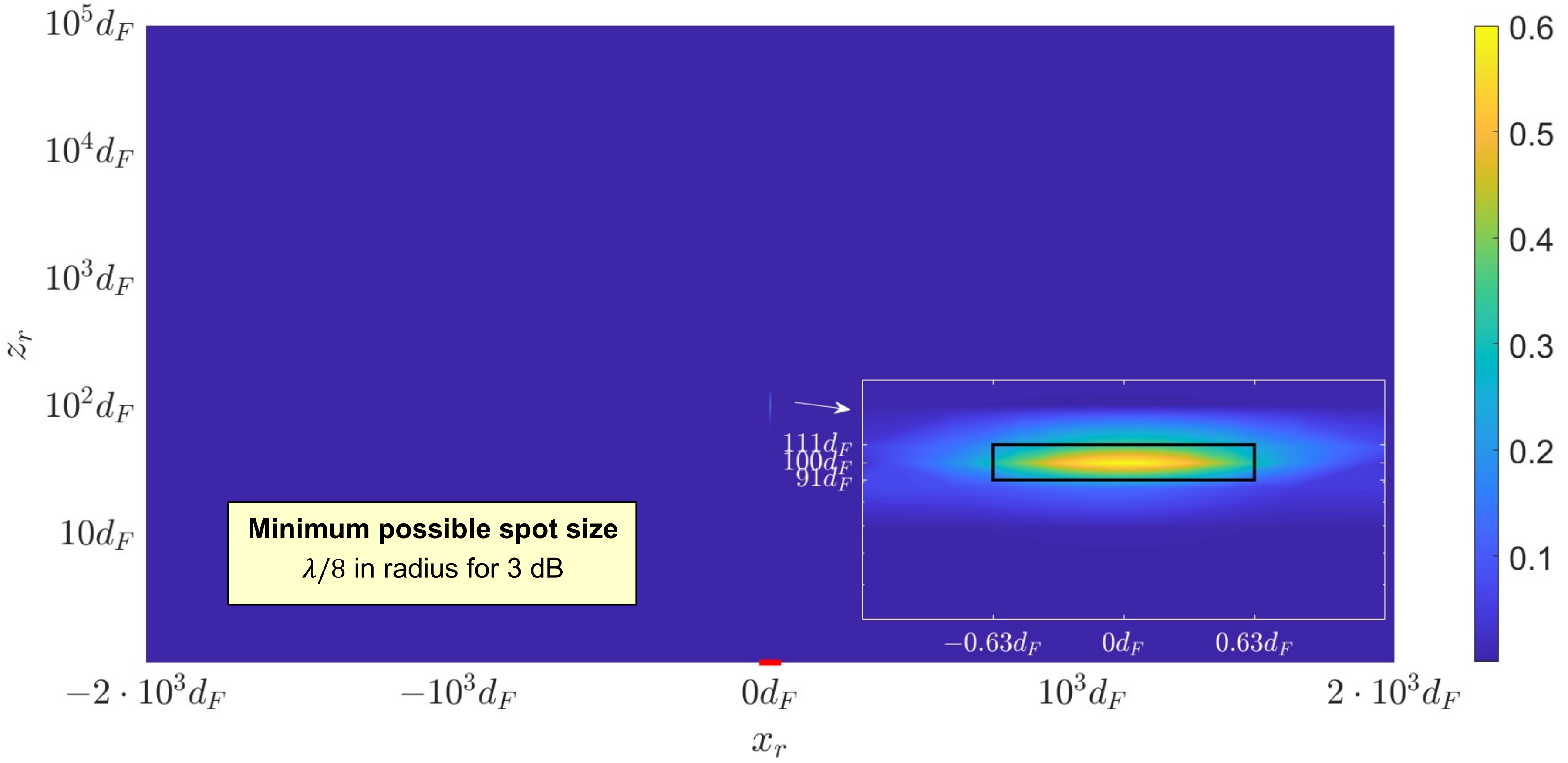
Setup: Square array with 100×100 antennas ($D = \lambda$)

Reference: *E. Björnson, Ö. T. Demir, L. Sanguinetti, "A Primer on Near-Field Beamforming for Arrays and Reconfigurable Intelligent Surfaces," Asilomar 2021, arXiv:2110.06661*

Conventional Far-Field Beamforming



Near-Field Beamforming

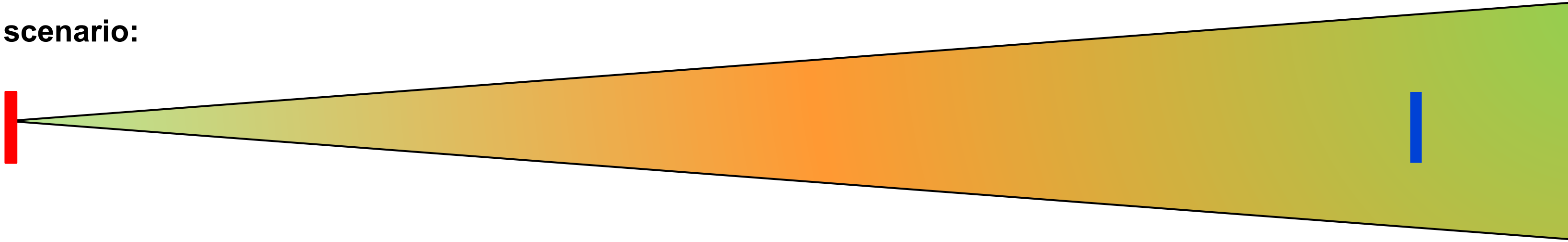


Reference: E. Björnson, L. Van der Perre, S. Buzzi, E. G. Larsson, " Massive MIMO in Sub-6 GHz and mmWave," 2019.

NEAR-FIELD MULTIPLEXING

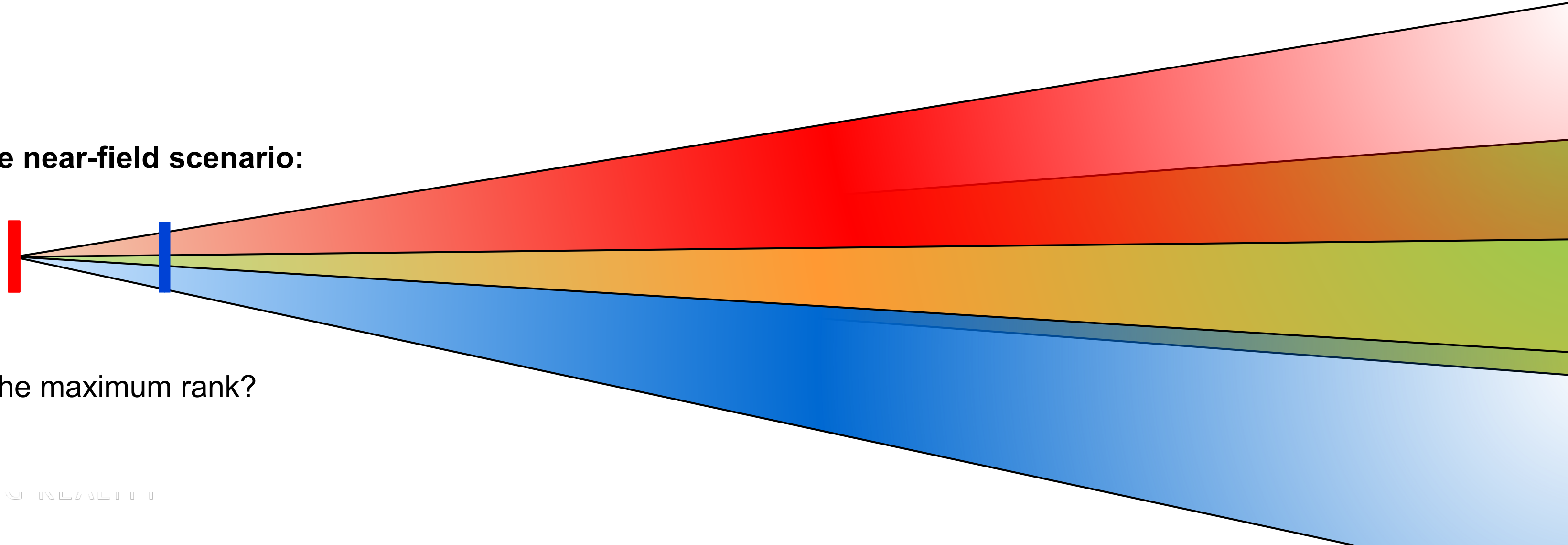
Rank of Channel in Line-of-Sight

Far-field scenario:



Maximum rank: 2 (One per polarization)

Radiative near-field scenario:



What is the maximum rank?

Fundamental Limit: Spatial Degrees-of-Freedom

Theorem

A large antenna array can resolve π signals for each segment of area λ^2

Planar array (length L, height H):

$$\eta \approx \pi \frac{LH}{\lambda^2}$$

We are very far from the limits!

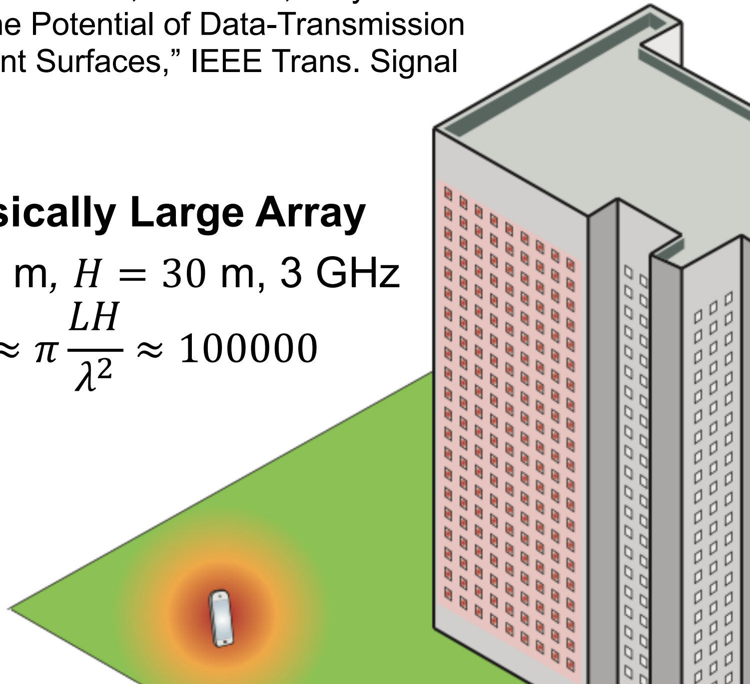
The richness of the channels is key

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

Physically Large Array

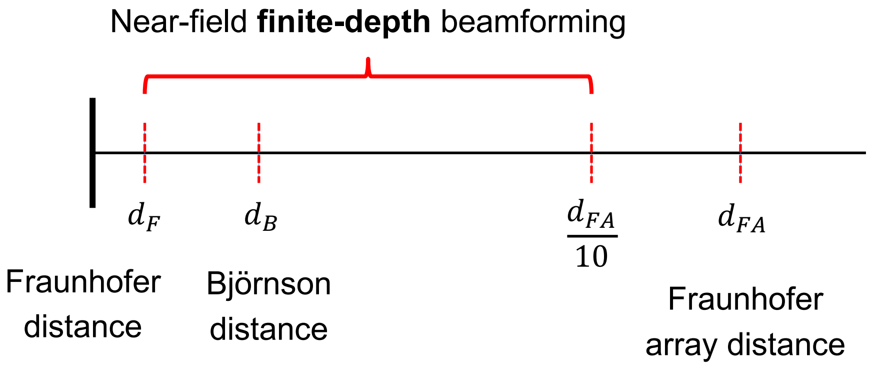
$L = 10$ m, $H = 30$ m, 3 GHz

$$\eta \approx \pi \frac{LH}{\lambda^2} \approx 100000$$



Conclusions

- Physically large arrays:
  - User in far-field of elements
    but maybe in near-field of the array



- Beamforming with finite depth and small width
  - Useful for spatial multiplexing
  - Maybe we don't need more bandwidth?

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