RIT

6G Upper Midband Technology- Near-field Communication

EEEE.789

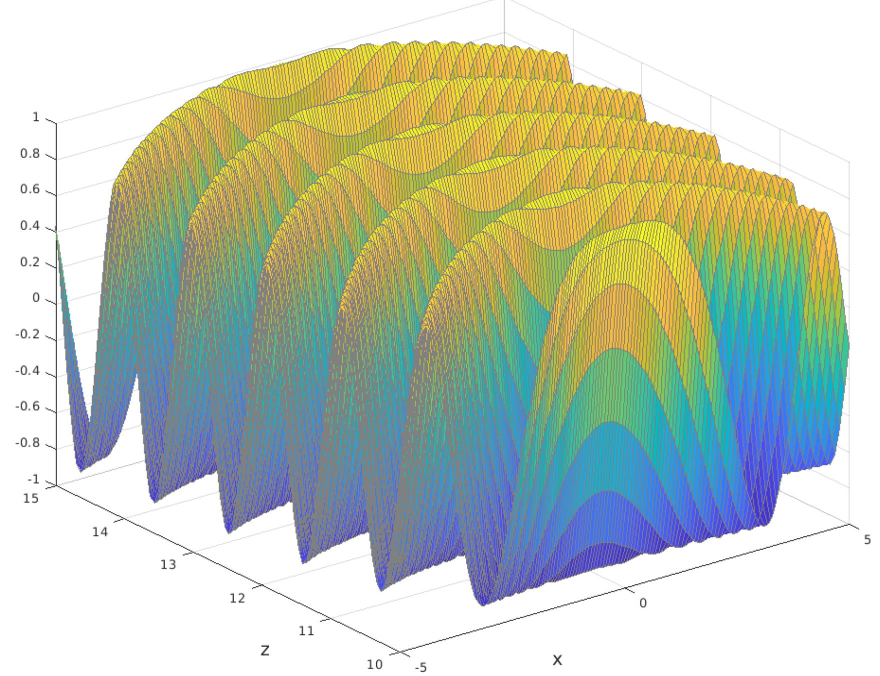
Shima Mashhadi

Jan 2025

Nearfield of the Antenna Array

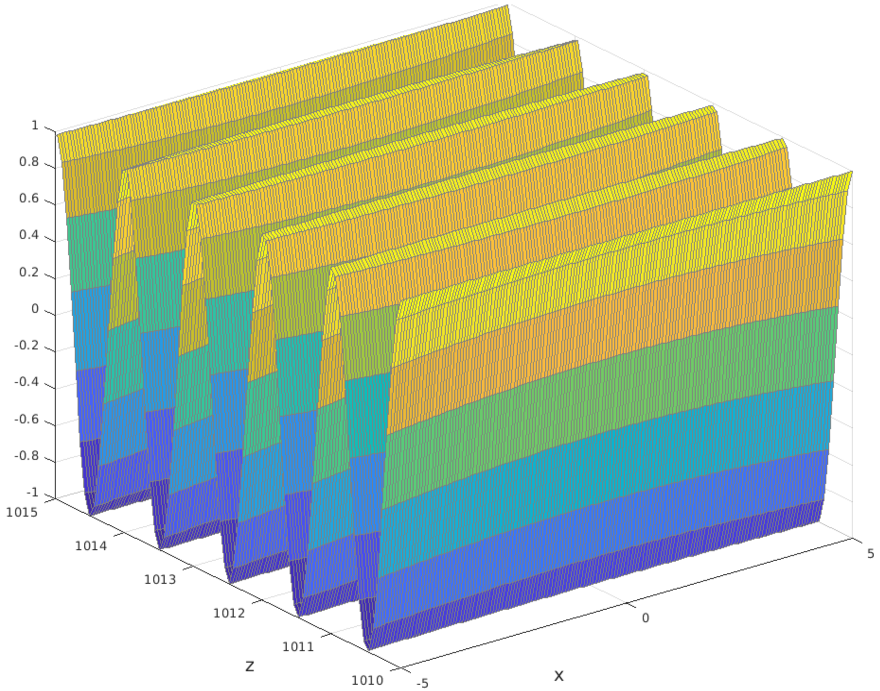
- Fresnel region is characterized by the fact that the amplitude variations can be neglected, but not the phase variations.

Curved wavefront



$$d_B < r < d_F$$

Planar wavefront

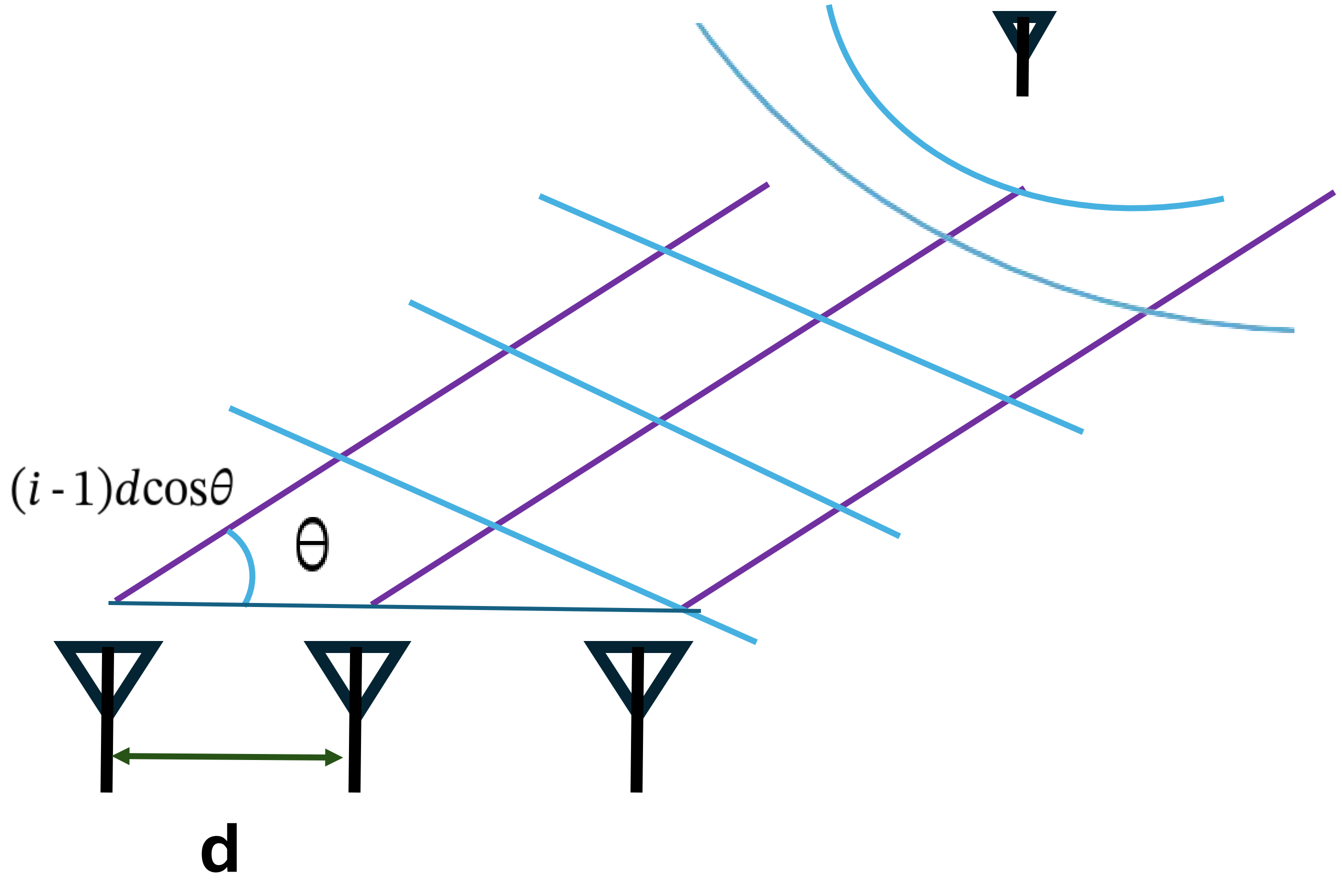


Example : Fraunhofer distance

0.5×0.5, 3 GHz = 10 m
1×1 m, 15 GHz = 200m
1×1 m, 30 GHz = 400 m

6G in the Upper Mid-Band: The Rise of Gigantic MIMO - YouTube

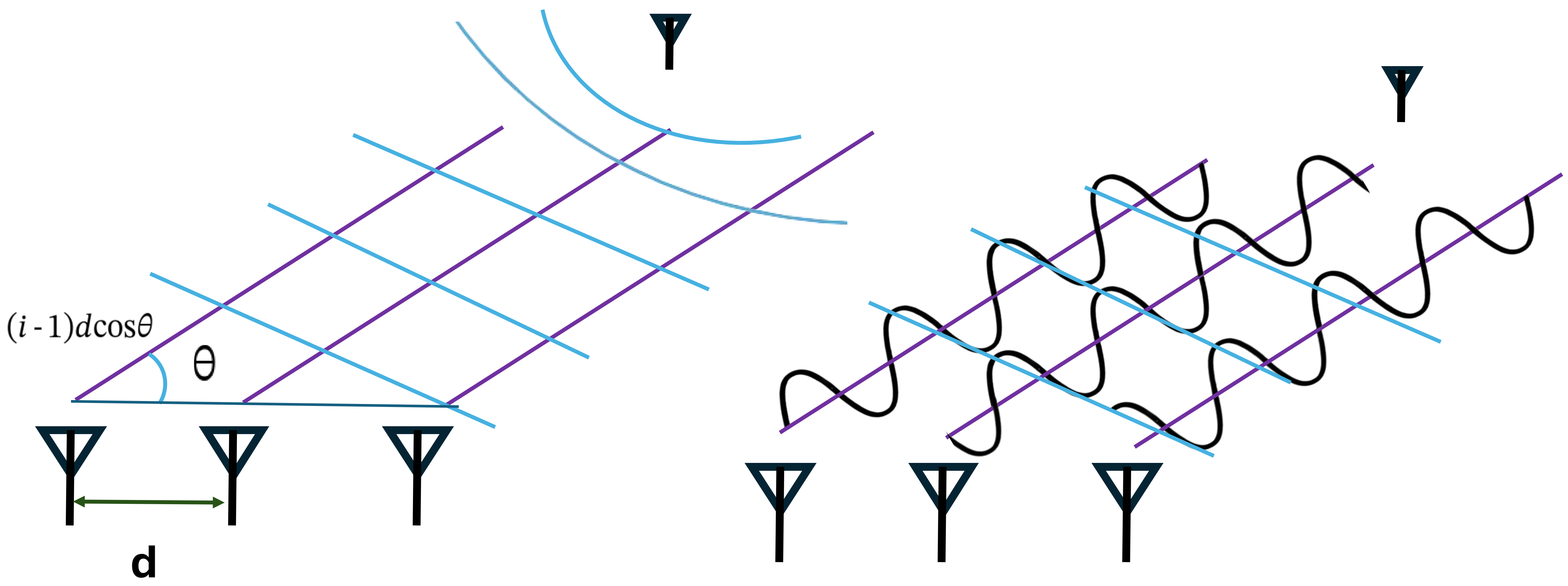
What is Beamforming ?



- Considering a simple SIMO
- Transmitter in the far-field

$$h_i = \frac{\lambda\sqrt{G}}{4\pi r} e^{-\left(j\frac{2\pi}{\lambda}(r-(i-1)d\cos\theta)\right)}$$

What is Beam Forming ?



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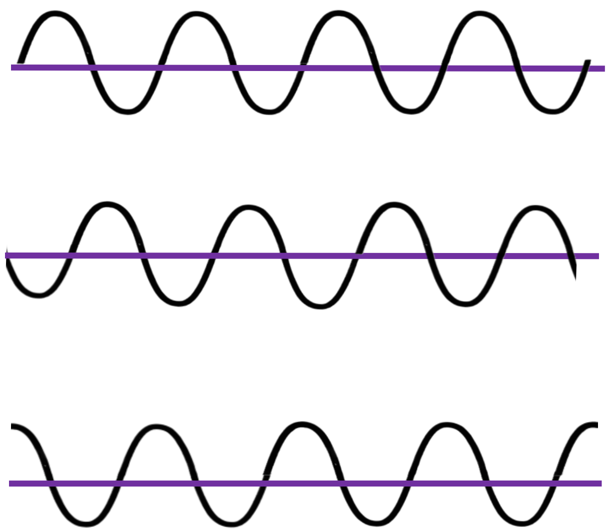
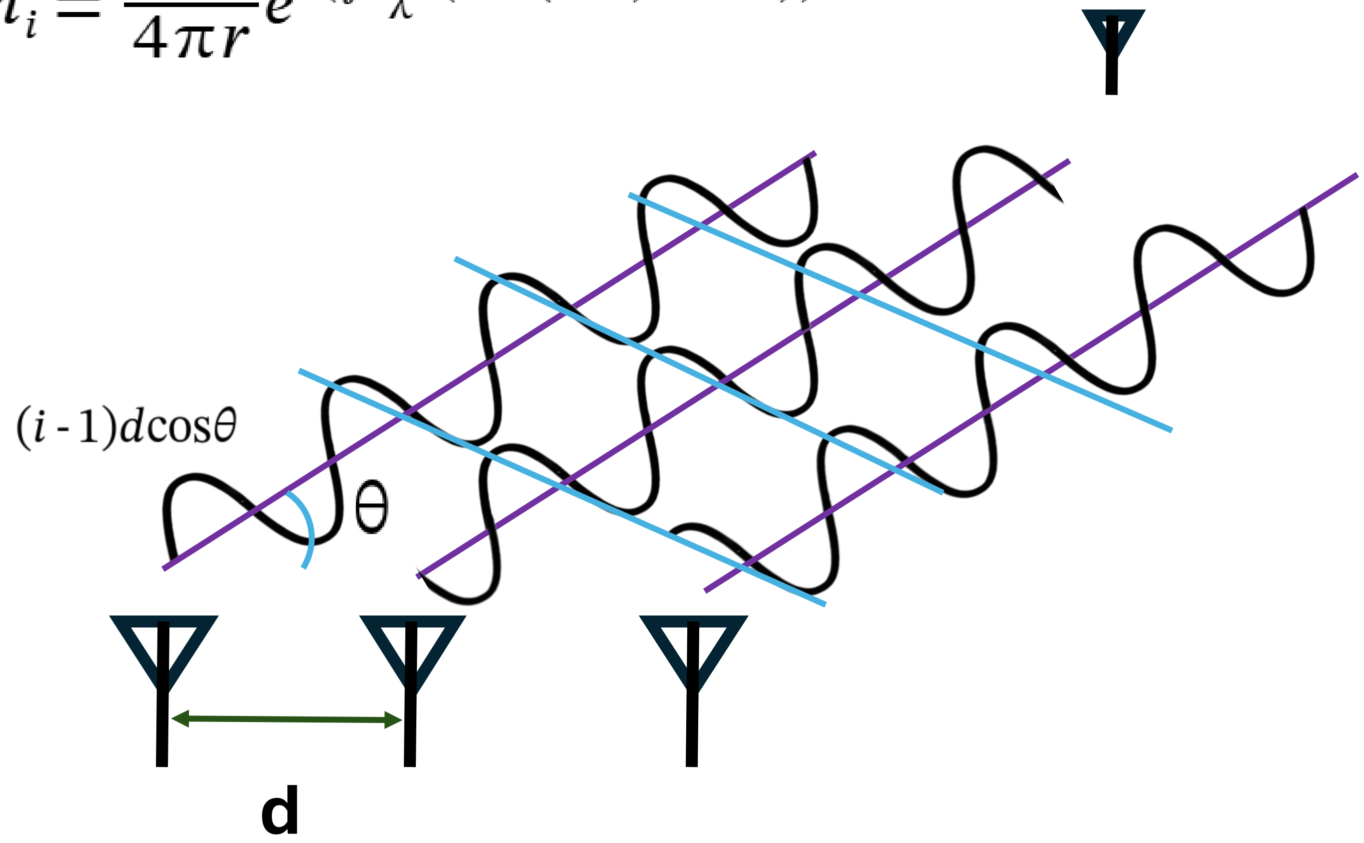


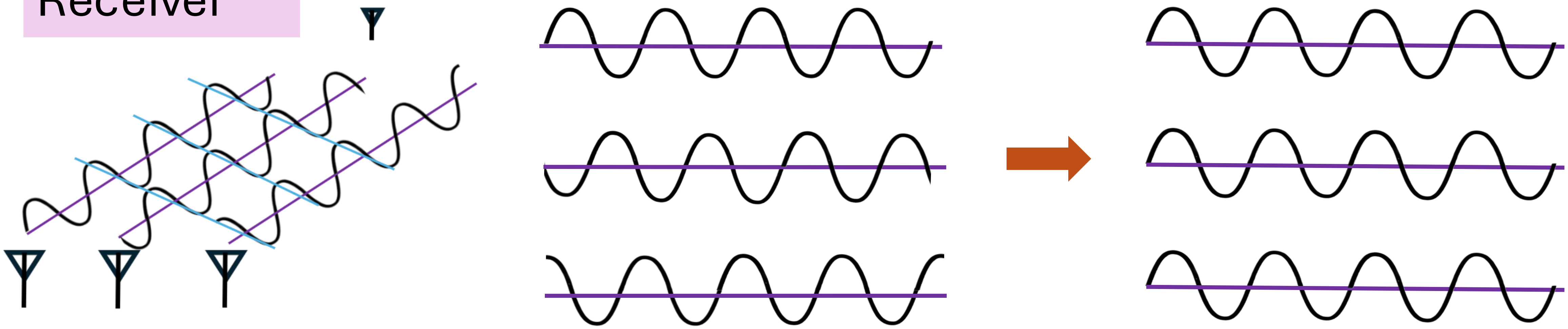
$$h_i = \frac{\lambda\sqrt{G}}{4\pi r} e^{-(j\frac{2\pi}{\lambda}(r+(i-1)d\cos\theta))}$$



[What is Beamforming? ("the best explanation I've ever heard") - YouTube](#)

What is Beam Forming ?

Receiver



$$h_i = \frac{\lambda\sqrt{G}}{4\pi r} e^{-(j\frac{2\pi}{\lambda}(r+(i-1)d\cos\theta))} \times e^{j\frac{2\pi}{\lambda}(i-1)d\cos\theta} \qquad r = \sum_{i=1}^{N} h_i e^{j\varphi_i} s + w$$

The received signal become M times larger

Achievable in LOS

What is Beamforming? ("the best explanation I've ever heard") - YouTube

RIT

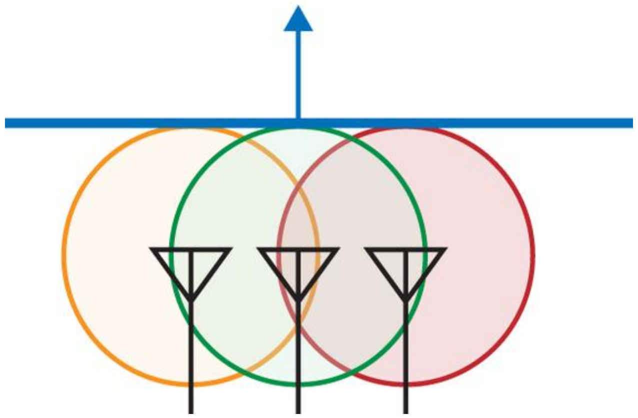
What is Beam Forming ?

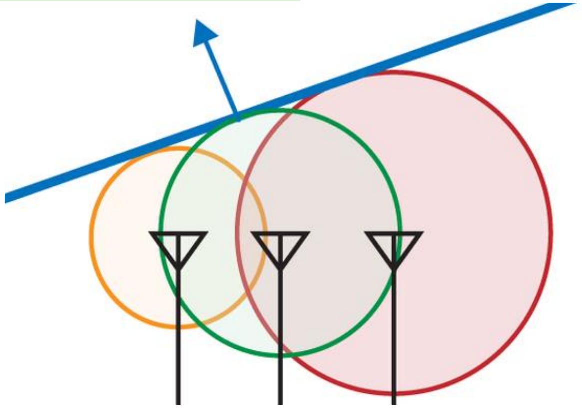
Transmitter

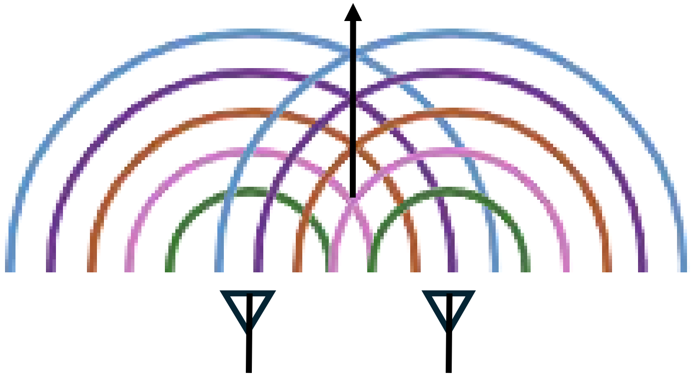
Antennas transmit the signal with the **phase-shift**

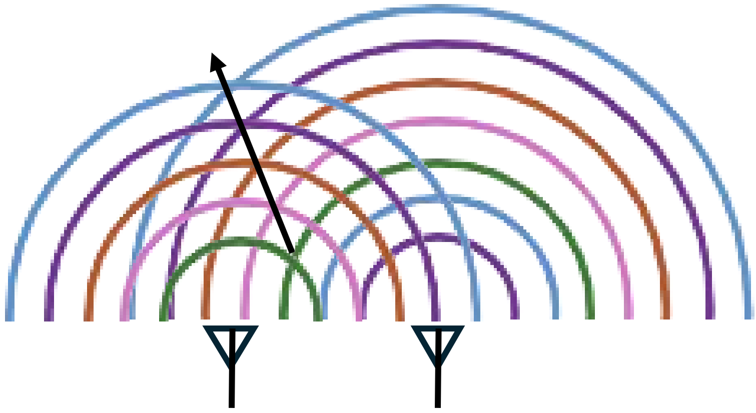
Send the radio energy preferentially in one direction

https://www.oreilly.com/library/view/80211ac-a-survival/9781449357702/ch04.html



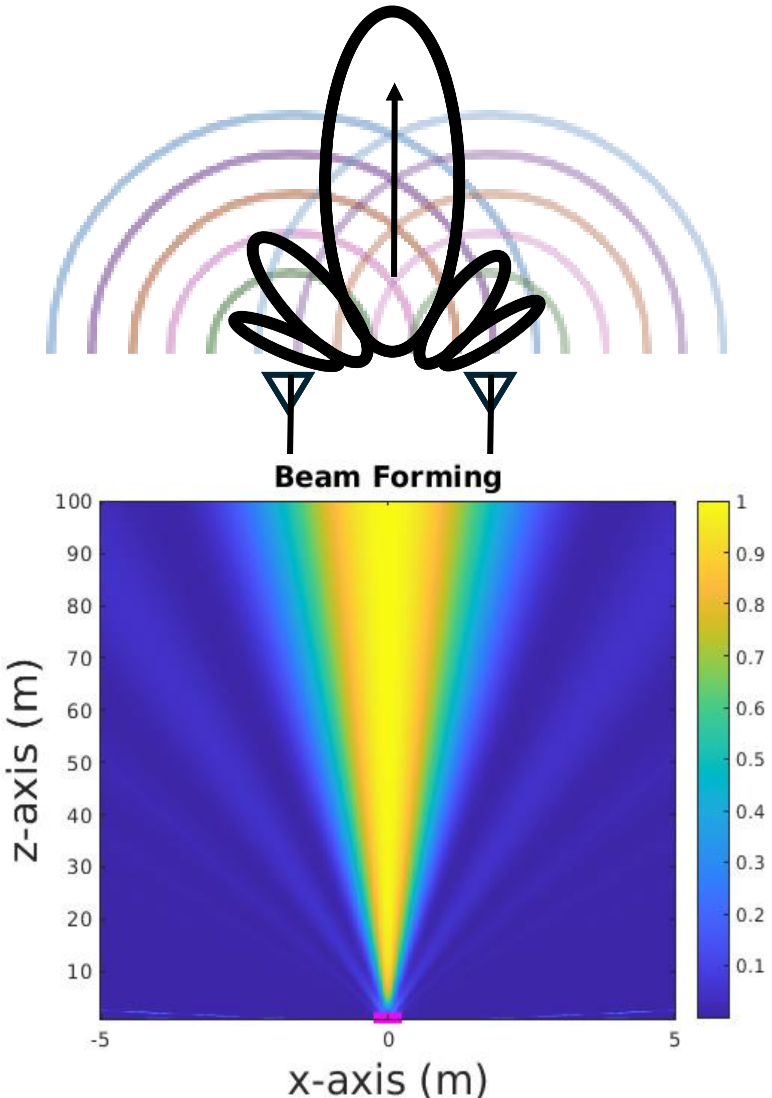


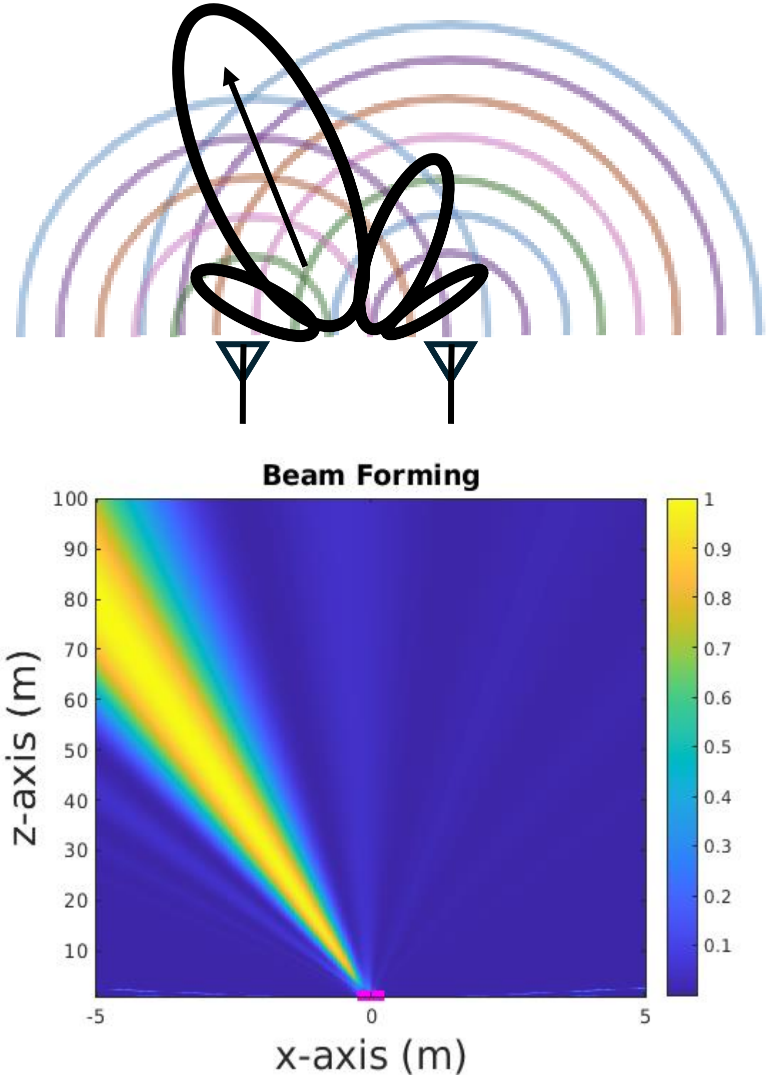




[Basics of Antennas and Beamforming - YouTube]()

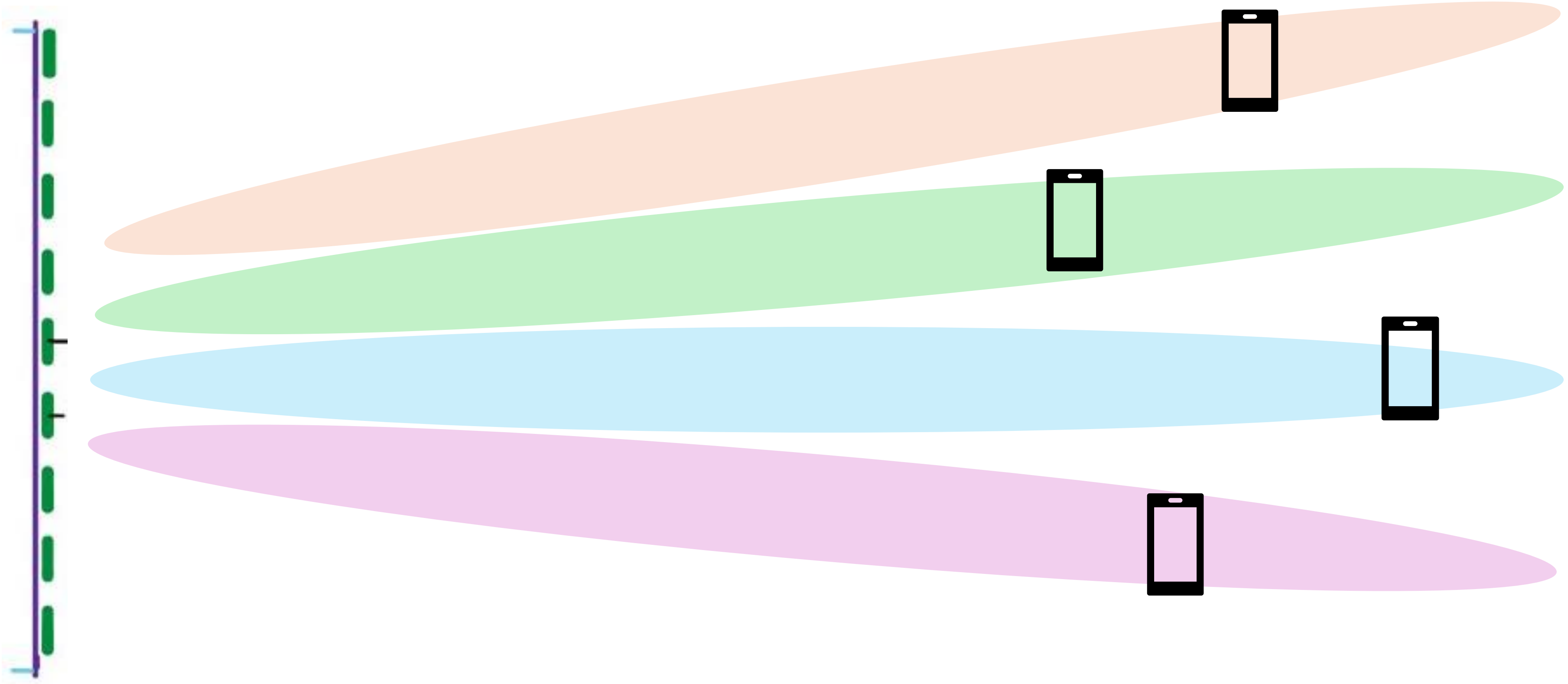
What is Beam Forming ?





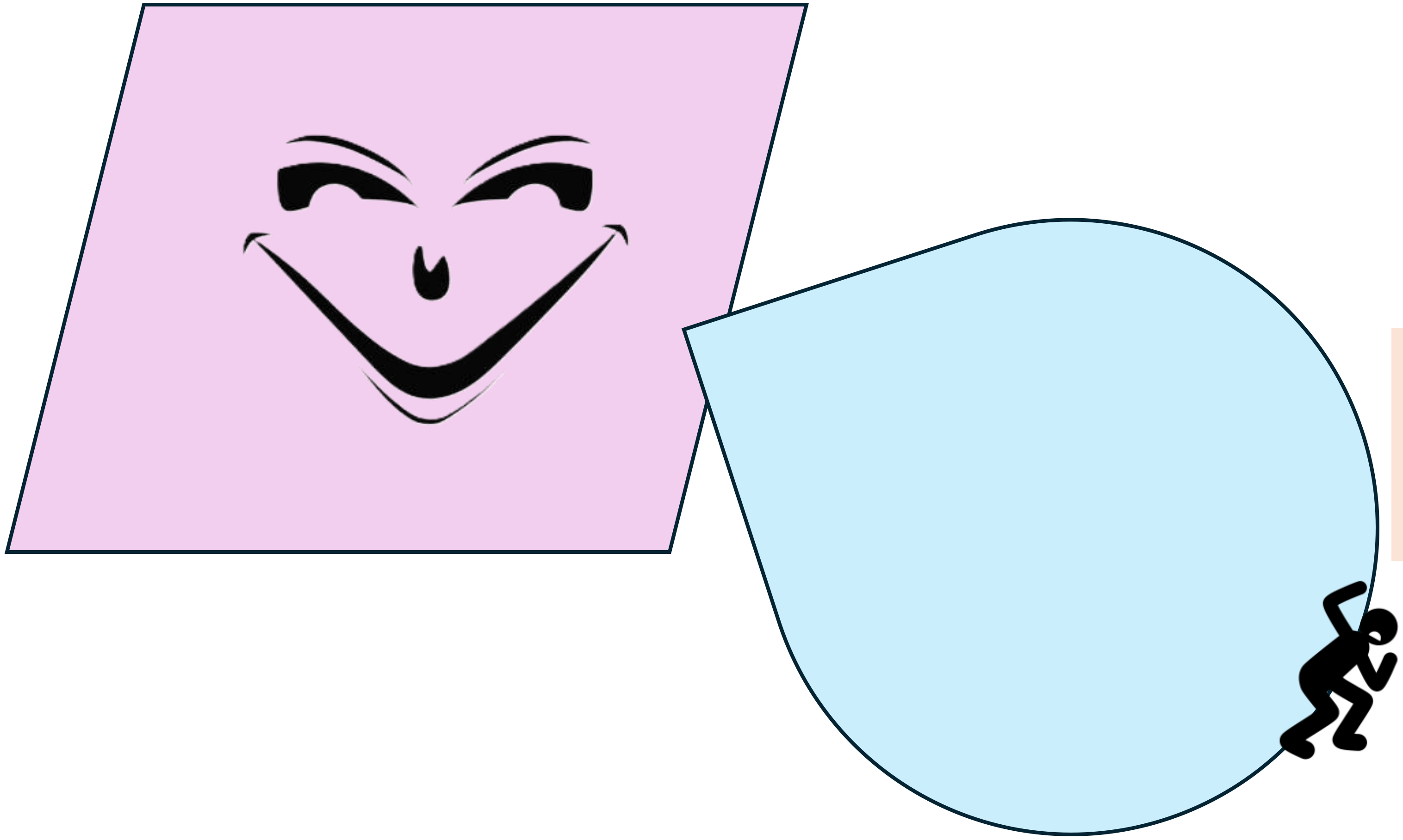
What is Beam Forming ?

What is the best thing we can do in the far-field?



Multi-user MIMO (MU-MIMO)

Beampattern in the Near-Field

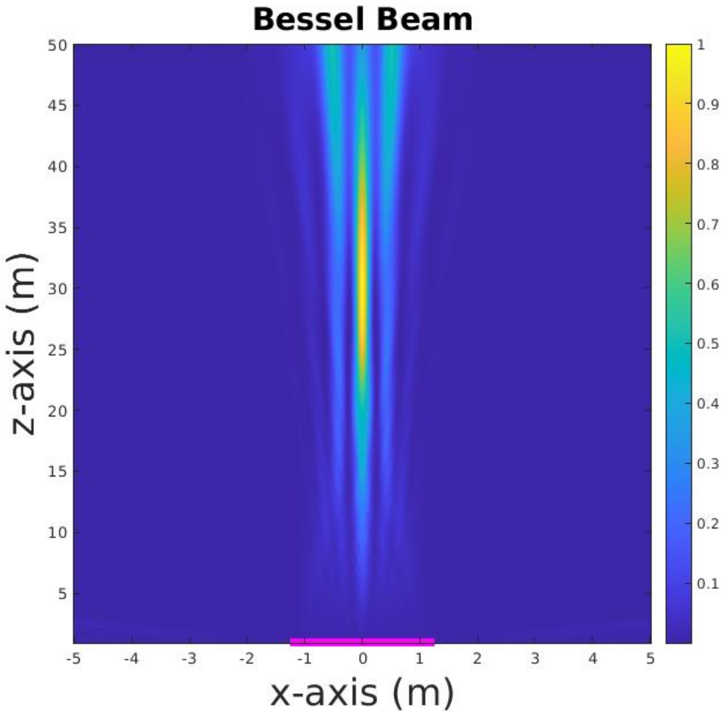


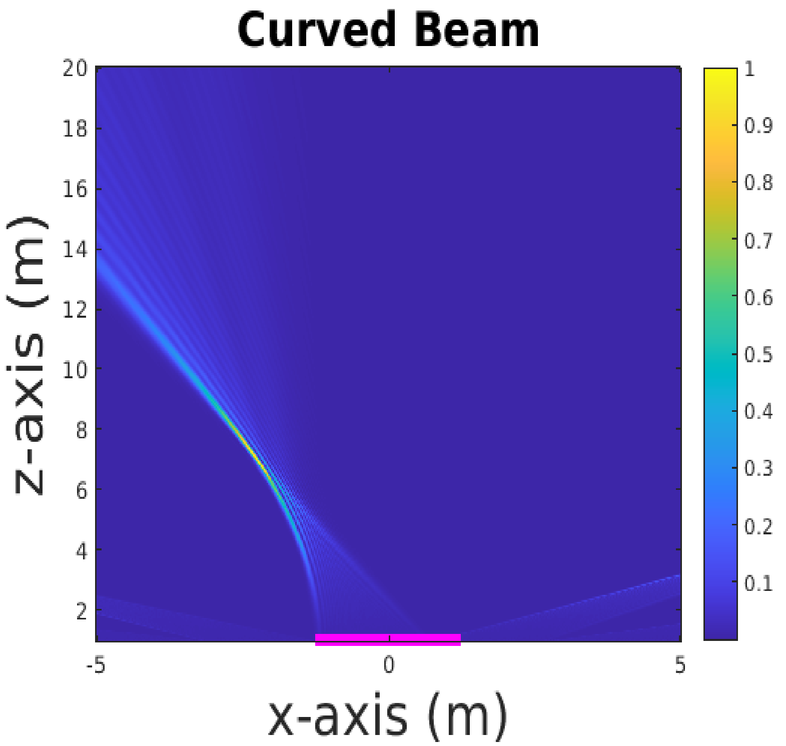
How about the shape of the beam in the Near-field?

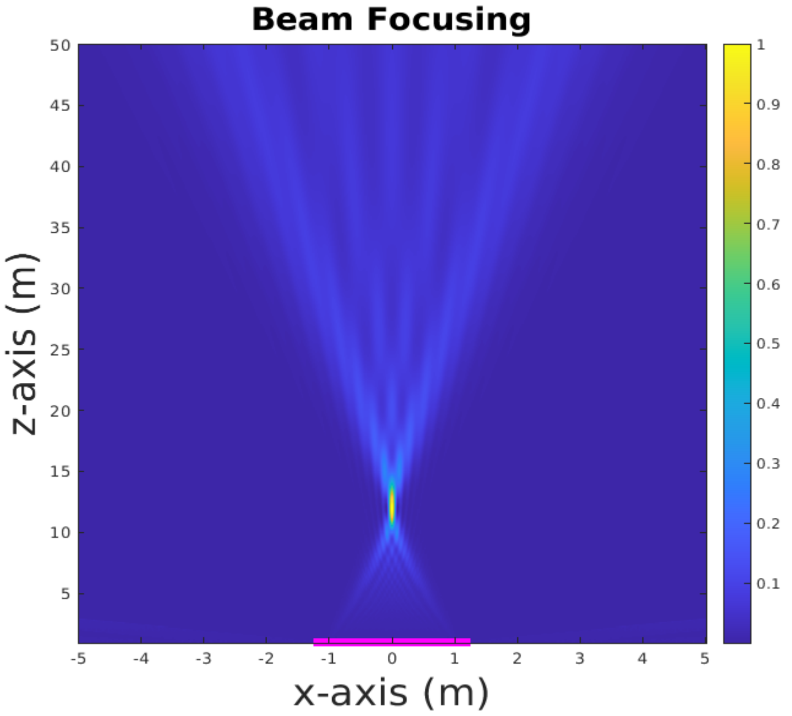
Near-field Beampatterns

- What happens if the user is located in the Fresnel region?

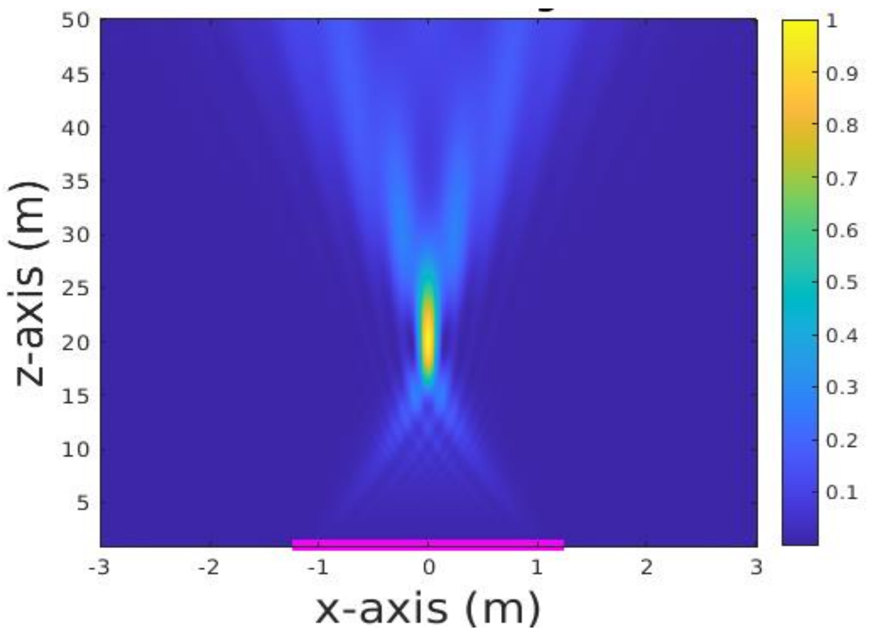
$$\boxed{d_B < r < d_F}$$







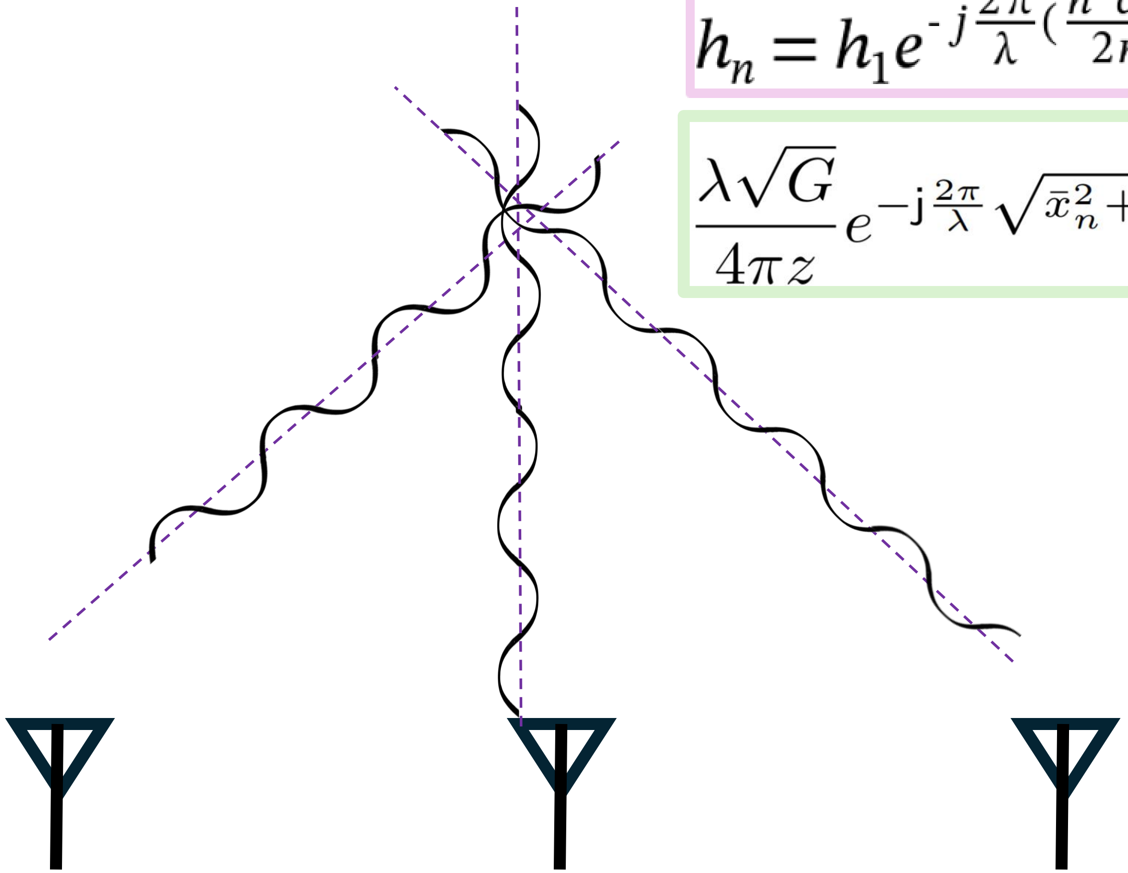
Beam Focusing



M = 250
F = 20 m

$$h_n = h_1 e^{-j\frac{2\pi}{\lambda}\left(\frac{n^2d^2}{2r} - nd\cos\theta\right)}$$

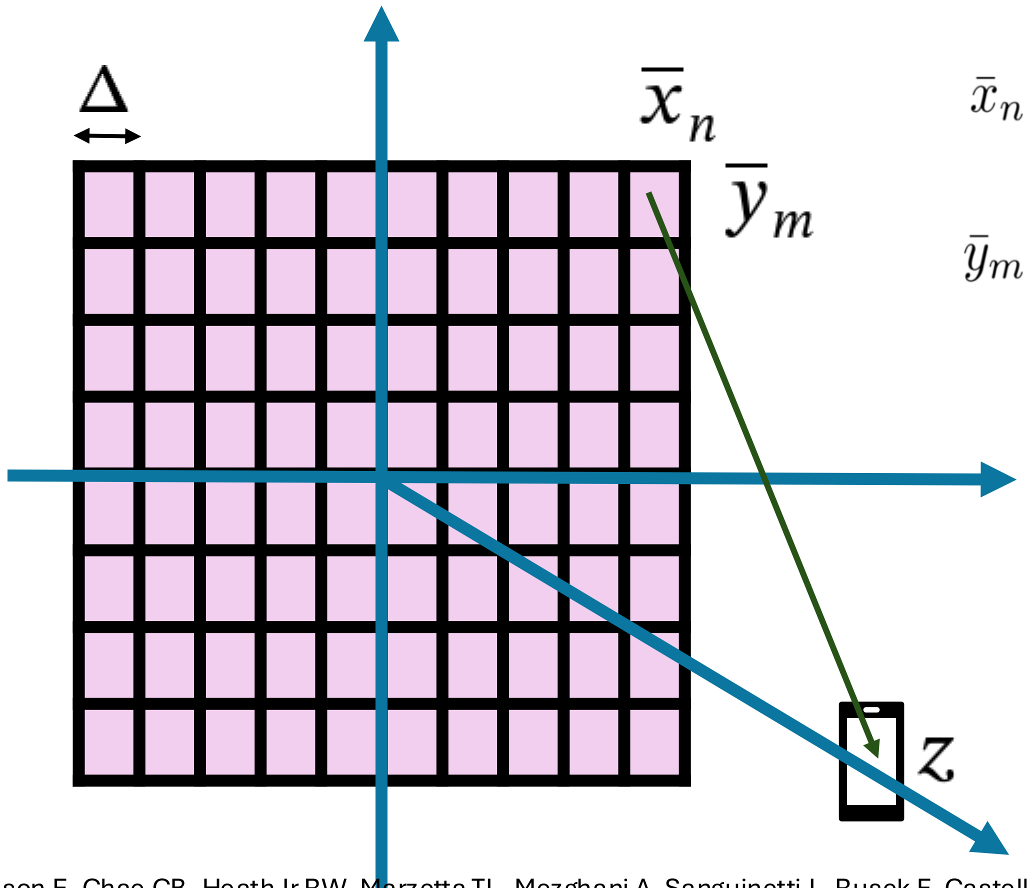
$$\frac{\lambda\sqrt{G}}{4\pi z} e^{-j\frac{2\pi}{\lambda}\sqrt{\bar{x}_n^2+\bar{y}_m^2+z^2}}$$



The gain is the same in the Far-Field and Near-Field

Beam Focusing in the Near-Field

- A uniform squared array with **M** antenna $N = \sqrt{M}$



$$\bar{x}_n = \left(n - \frac{N+1}{2}\right)\Delta,$$

$$\bar{y}_m = \left(m - \frac{N+1}{2}\right)\Delta.$$

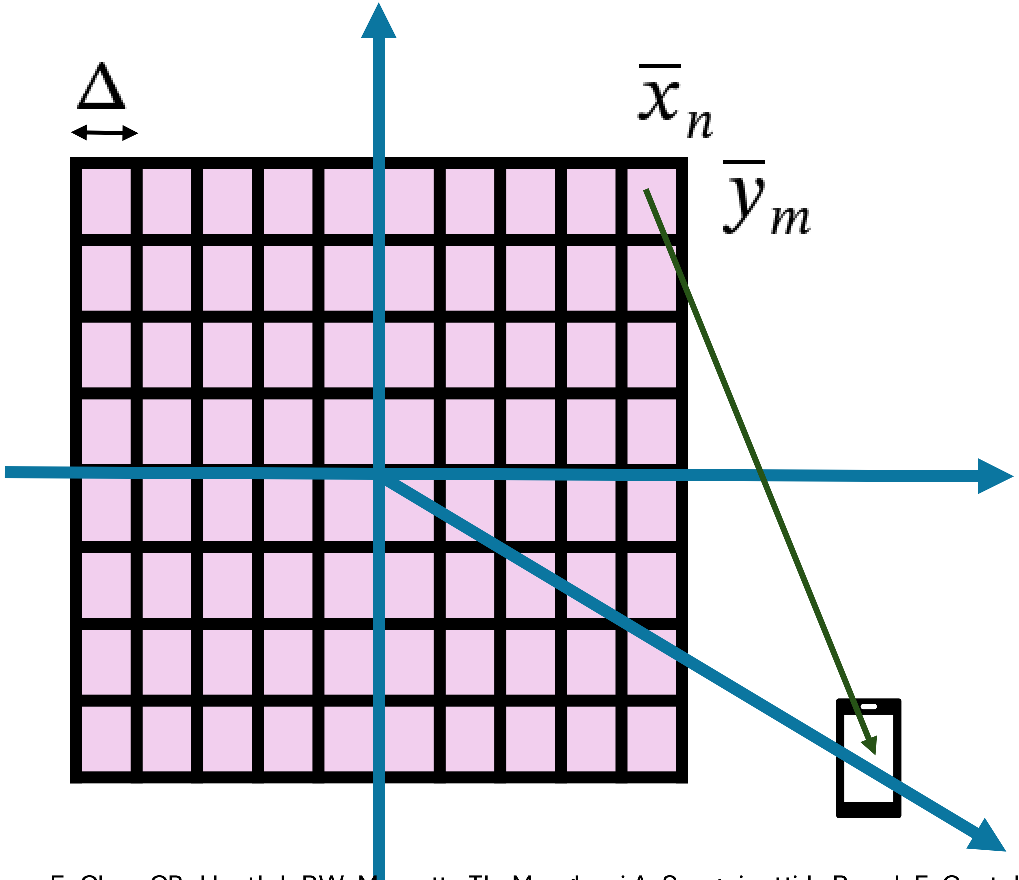
$$h_{n,m} = \frac{\lambda\sqrt{G}}{4\pi z} e^{-\mathrm{j}\frac{2\pi}{\lambda}\sqrt{\bar{x}_n^2+\bar{y}_m^2+z^2}}$$
$$\approx \frac{\lambda\sqrt{G}}{4\pi z} e^{-\mathrm{j}\frac{2\pi}{\lambda}\left(z+\frac{\bar{x}_n^2}{2z}+\frac{\bar{y}_m^2}{2z}\right)},$$

- Taylor approximation

Björnson E, Chae CB, Heath Jr RW, Marzetta TL, Mezghani A, Sanguinetti L, Rusek F, Castellanos MR, Jun D, Demir ÖT. Towards 6G MIMO: Massive spatial multiplexing, dense arrays, and interplay between electromagnetics and processing. arXiv preprint arXiv:2401.02844. 2024 Jan 5.

Beam Focusing in the Near-field

- A uniform squared array with **M** antenna



$$r = \sum_{n=1}^{N} \sum_{m=1}^{N} h_{n,m} \frac{e^{\mathrm{j}\psi_{n,m}}}{\sqrt{M}} s + w_{n,m},$$

Björnson E, Chae CB, Heath Jr RW, Marzetta TL, Mezghani A, Sanguinetti L, Rusek F, Castellanos MR, Jun D, Demir ÖT. Towards 6G MIMO: Massive spatial multiplexing, dense arrays, and interplay between electromagnetics and processing. arXiv preprint arXiv:2401.02844. 2024 Jan 5.

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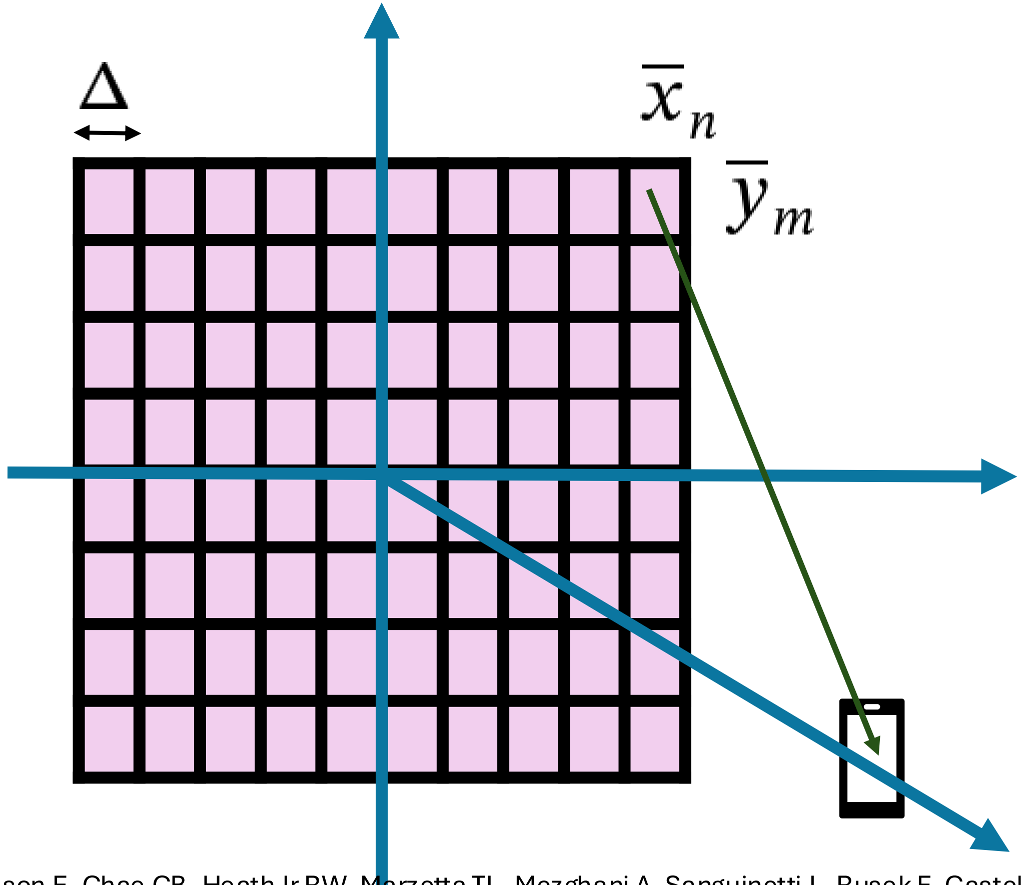

$$r = \sum_{n=1}^{N} \sum_{m=1}^{N} h_{n,m} \frac{e^{\mathrm{j}\psi_{n,m}}}{\sqrt{M}} s + w_{n,m},$$

$$\mathrm{SNR} = \frac{p}{\sigma^2} \left| \sum_{n=1}^{N} \sum_{m=1}^{N} h_{n,m} \frac{e^{\mathrm{j}\psi_{n,m}}}{\sqrt{M}} \right|^2$$

$$= \frac{p}{\sigma^2} \frac{\lambda^2 G}{(4\pi z)^2} \underbrace{\frac{1}{M} \left| \sum_{n=1}^{N} \sum_{m=1}^{N} e^{-\mathrm{j}\frac{2\pi}{\lambda}\sqrt{\bar{x}_n^2 + \bar{y}_m^2 + z^2}} e^{\mathrm{j}\psi_{n,m}} \right|^2}_{=\mathrm{AG}},$$

Array Gain

Björnson E, Chae CB, Heath Jr RW, Marzetta TL, Mezghani A, Sanguinetti L, Rusek F, Castellanos MR, Jun D, Demir ÖT. Towards 6G MIMO: Massive spatial multiplexing, dense arrays, and interplay between electromagnetics and processing. arXiv preprint arXiv:2401.02844. 2024 Jan 5.

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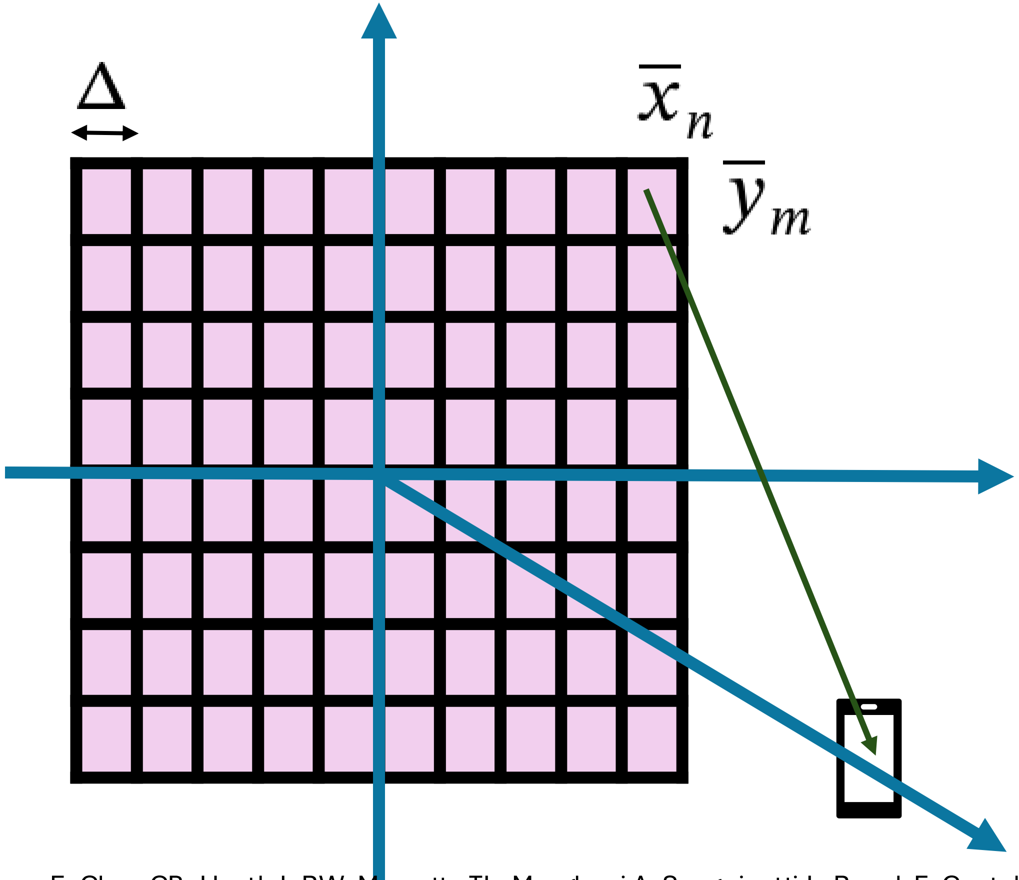


$$\mathrm{SNR} = \frac{p}{\sigma^2} \left| \sum_{n=1}^{N} \sum_{m=1}^{N} h_{n,m} \frac{e^{\mathrm{j}\psi_{n,m}}}{\sqrt{M}} \right|^2$$

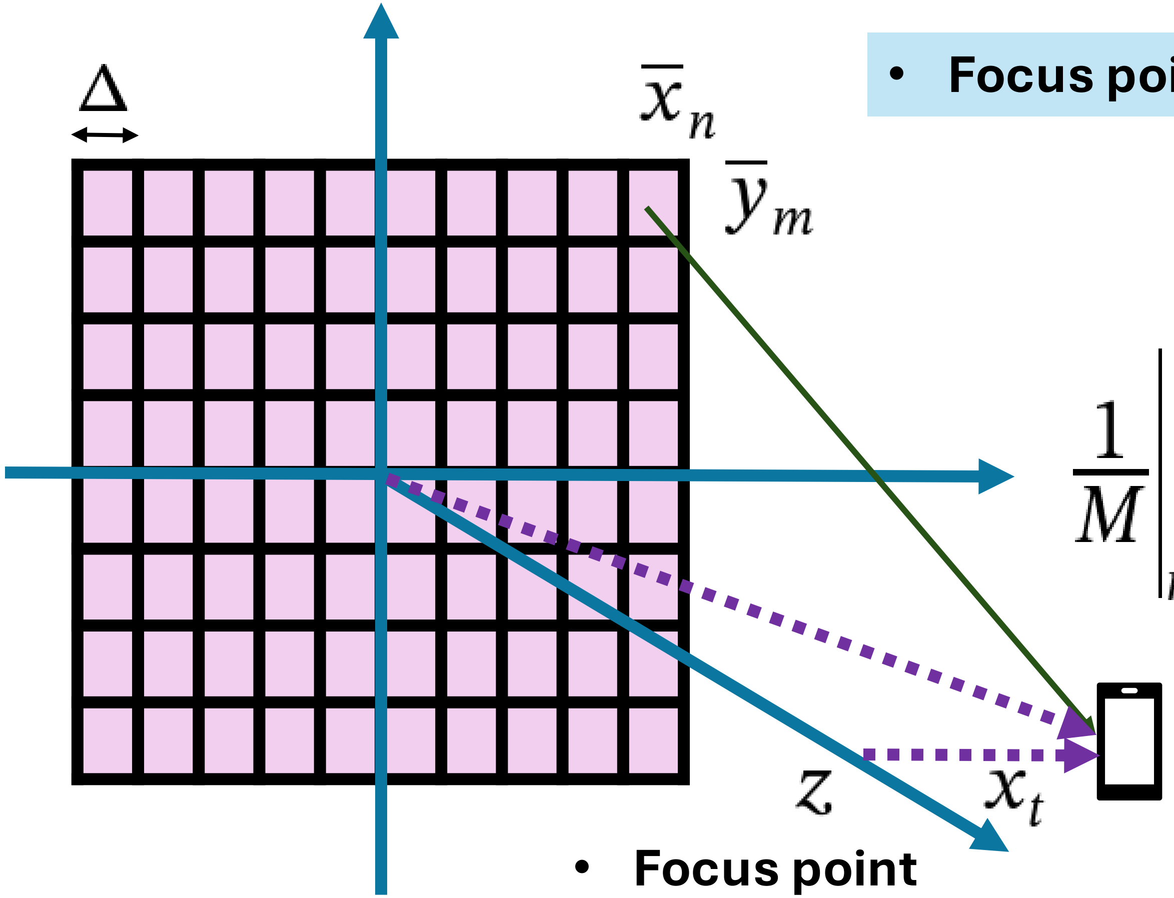
$$= \frac{p}{\sigma^2} \frac{\lambda^2 G}{(4\pi z)^2} \underbrace{\frac{1}{M} \left| \sum_{n=1}^{N} \sum_{m=1}^{N} e^{-\mathrm{j}\frac{2\pi}{\lambda}\sqrt{\bar{x}_n^2+\bar{y}_m^2+z^2}} e^{\mathrm{j}\psi_{n,m}} \right|^2}_{=\mathrm{AG}},$$

Array Gain

$$\psi_{n,m} = \frac{2\pi}{\lambda}\sqrt{\bar{x}_n^2 + \bar{y}_m^2 + z^2}$$

Björnson E, Chae CB, Heath Jr RW, Marzetta TL, Mezghani A, Sanguinetti L, Rusek F, Castellanos MR, Jun D, Demir ÖT. Towards 6G MIMO: Massive spatial multiplexing, dense arrays, and interplay between electromagnetics and processing. arXiv preprint arXiv:2401.02844. 2024 Jan 5.

Beamwidth in the nearfield



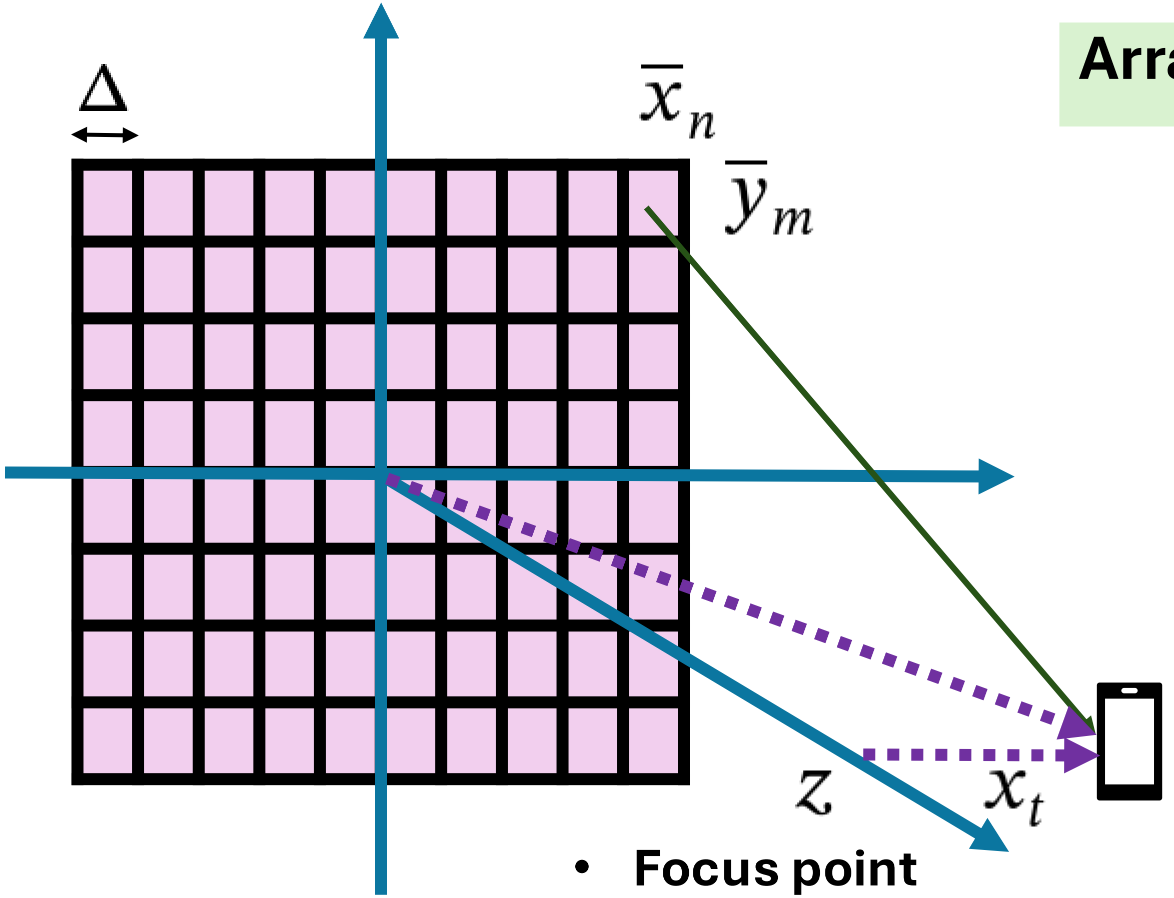
• **Focus point** $\psi_{n,m} = \frac{2\pi}{\lambda}\sqrt{\bar{x}_n^2 + \bar{y}_m^2 + z^2}$

Array Gain

$$\frac{1}{M}\left|\sum_{n=1}^{N}\sum_{m=1}^{N} e^{-j\frac{2\pi}{\lambda}\sqrt{(\bar{x}_n - x_t)^2 + \bar{y}_m^2 + z^2}}\, e^{j\frac{2\pi}{\lambda}\sqrt{\bar{x}_n^2 + \bar{y}_m^2 + z^2}}\right|^2$$

Kosasih A, Demir ÖT, Björnson E. Achieving Beamfocusing via Two Separated Uniform Linear Arrays. arXiv preprint arXiv:2412.03232. 2024 Dec 4.

Beamwidth in the nearfield



Array Gain

$$M\,\mathrm{sinc}^2\left(\frac{1}{\lambda} N \Delta \frac{x_t}{z}\right)$$

$$\mathrm{sinc}^2(0.443) \approx 0.5,$$

$$BW_{3dB} \approx \frac{0.886\lambda F}{N\Delta}$$

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Beamwidth in the Near-field

$$M\,sinc^2\left(\frac{1}{\lambda} N \Delta \frac{x_t}{z}\right)$$

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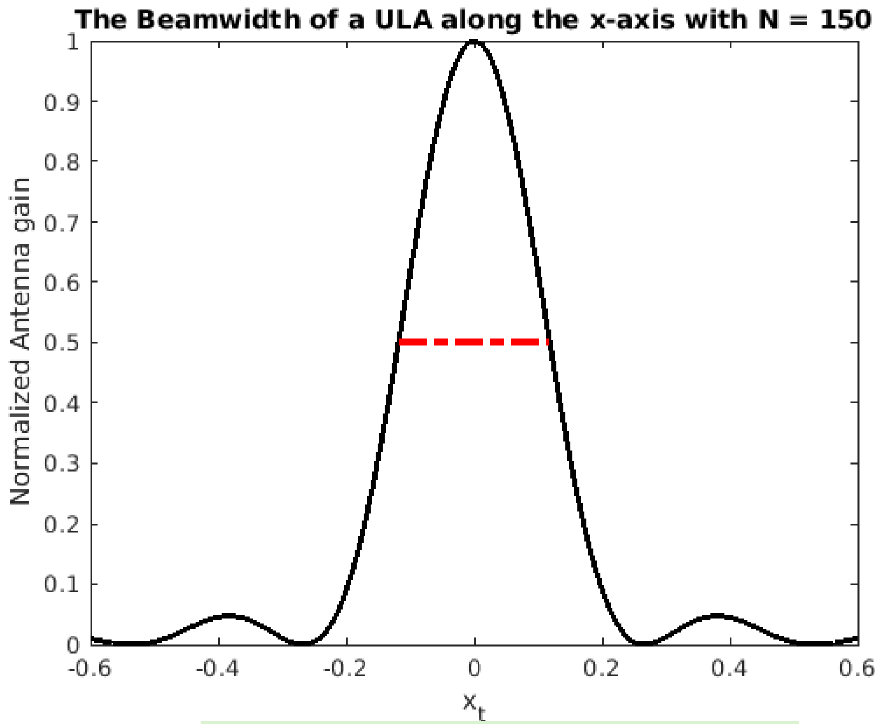
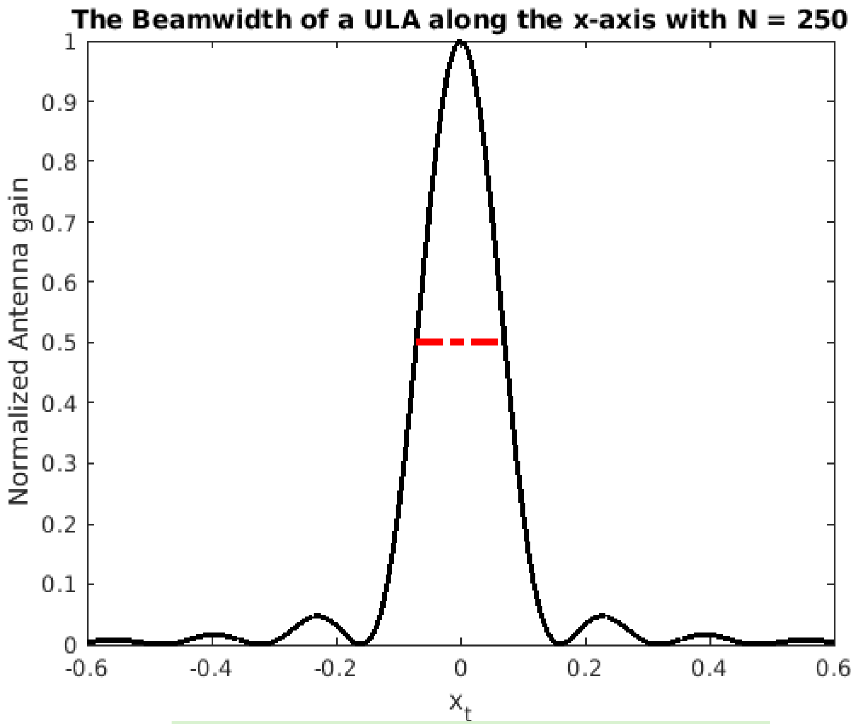


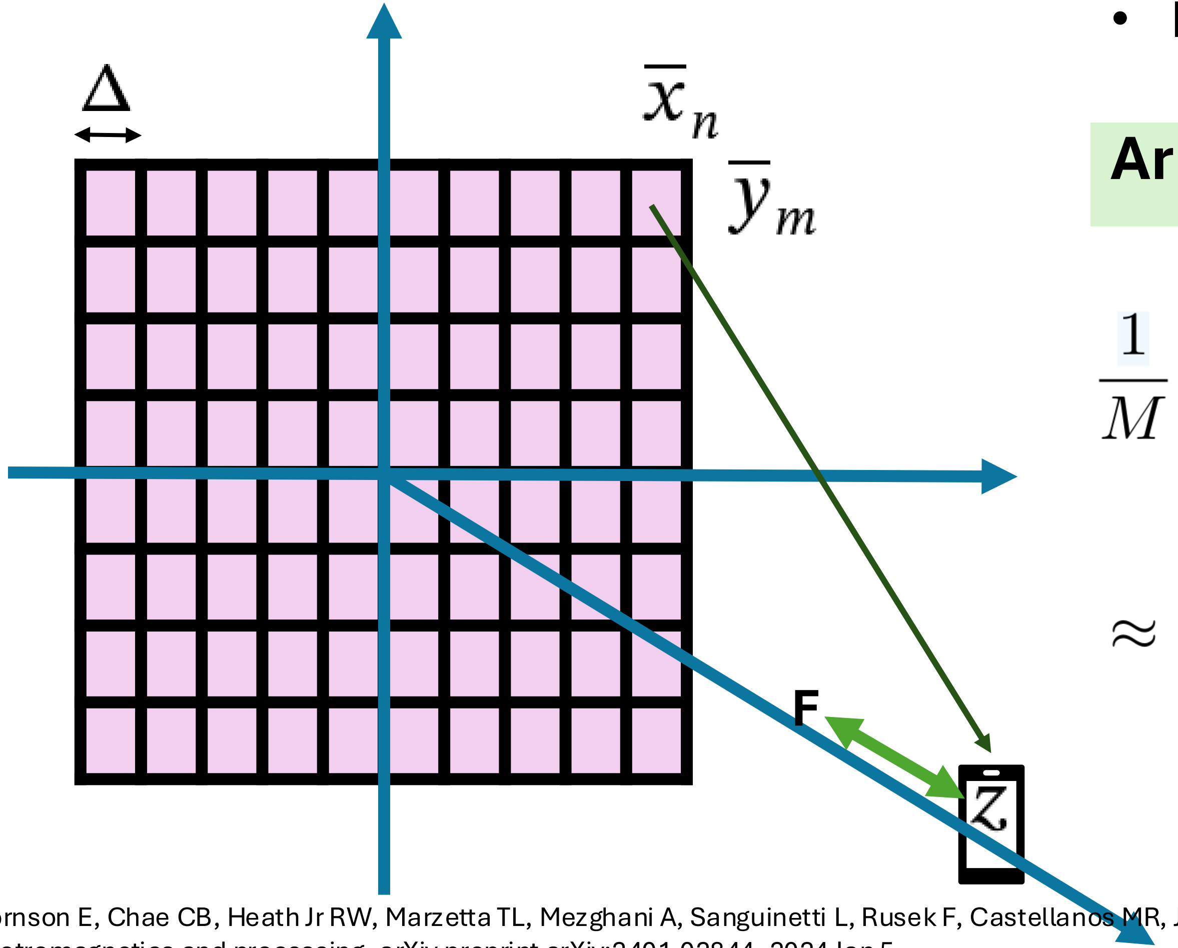
M = 150
F = 20 m
BW3dB = 0.236 m



M = 250
F = 20 m
BW3dB = 0.141 m

Kosasih A, Demir ÖT, Björnson E. Achieving Beamfocusing via Two Separated Uniform Linear Arrays. arXiv preprint arXiv:2412.03232. 2024 Dec 4.

Beamdepth in the Near-field



- **Focus point** $(0, 0, F)$ $\boxed{F \neq z}$

Array Gain

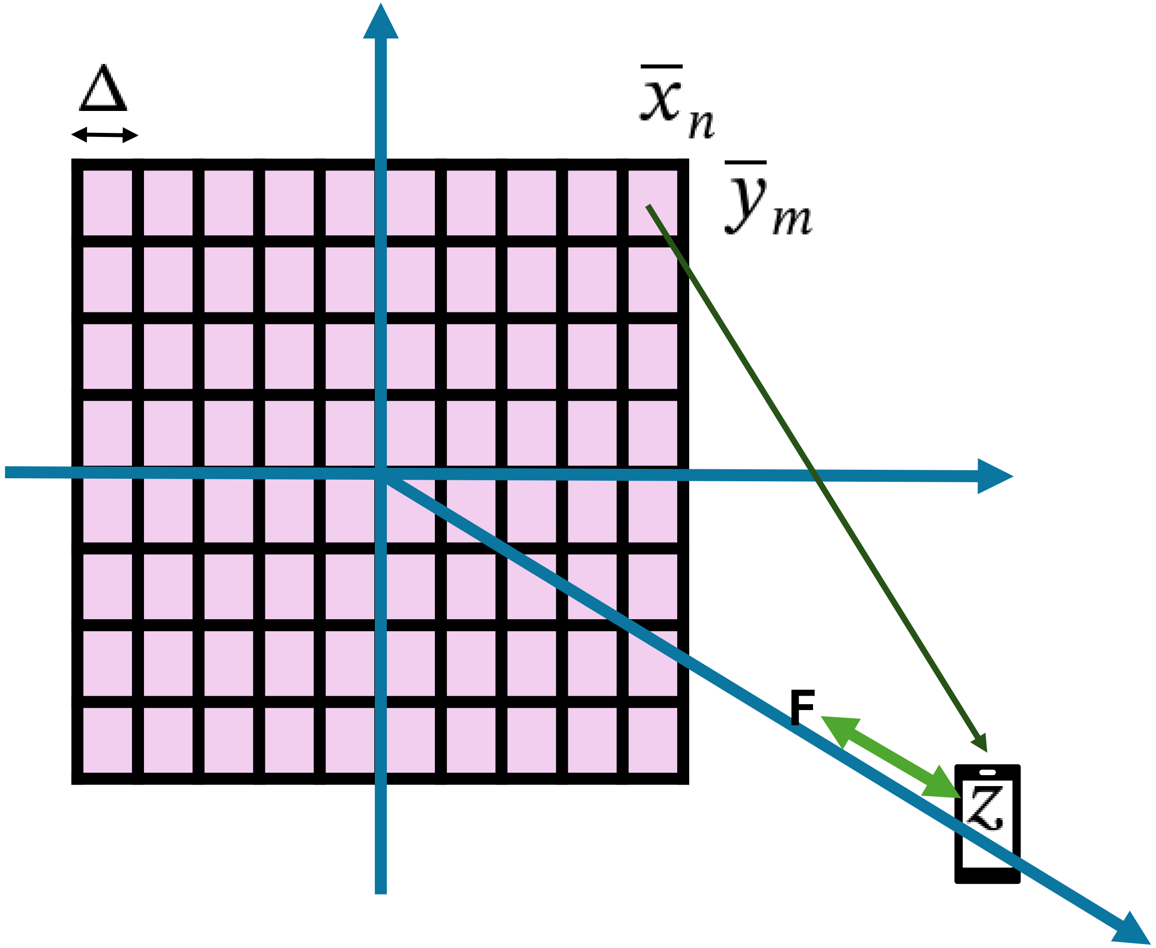
$$\frac{1}{M}\left|\sum_{n=1}^{N}\sum_{m=1}^{N} e^{-\mathrm{j}\frac{2\pi}{\lambda}\sqrt{\bar{x}_n^2+\bar{y}_m^2+z^2}} e^{\mathrm{j}\frac{2\pi}{\lambda}\sqrt{\bar{x}_n^2+\bar{y}_m^2+F^2}}\right|^2$$

$$\approx \frac{1}{M}\left|\sum_{n=1}^{N}\sum_{m=1}^{N} e^{-\mathrm{j}\frac{2\pi}{\lambda}\left(z+\frac{\bar{x}_n^2}{2z}+\frac{\bar{y}_m^2}{2z}\right)} e^{\mathrm{j}\frac{2\pi}{\lambda}\left(F+\frac{\bar{x}_n^2}{2F}+\frac{\bar{y}_m^2}{2F}\right)}\right|^2$$

Björnson E, Chae CB, Heath Jr RW, Marzetta TL, Mezghani A, Sanguinetti L, Rusek F, Castellanos MR, Jun D, Demir ÖT. Towards 6G MIMO: Massive spatial multiplexing, dense arrays, and interplay between electromagnetics and processing. arXiv preprint arXiv:2401.02844. 2024 Jan 5.

Ramezani P, Björnson E. Near-field beamforming and multiplexing using extremely large aperture arrays. In Fundamentals of 6G Communications and Networking 2023 Jul 10 (pp. 317-349).

Beamdepth in the Near-field



$$z_{\text{eff}} = \left| \frac{1}{F} - \frac{1}{z} \right|^{-1} = \frac{Fz}{|F-z|}$$

Array Gain

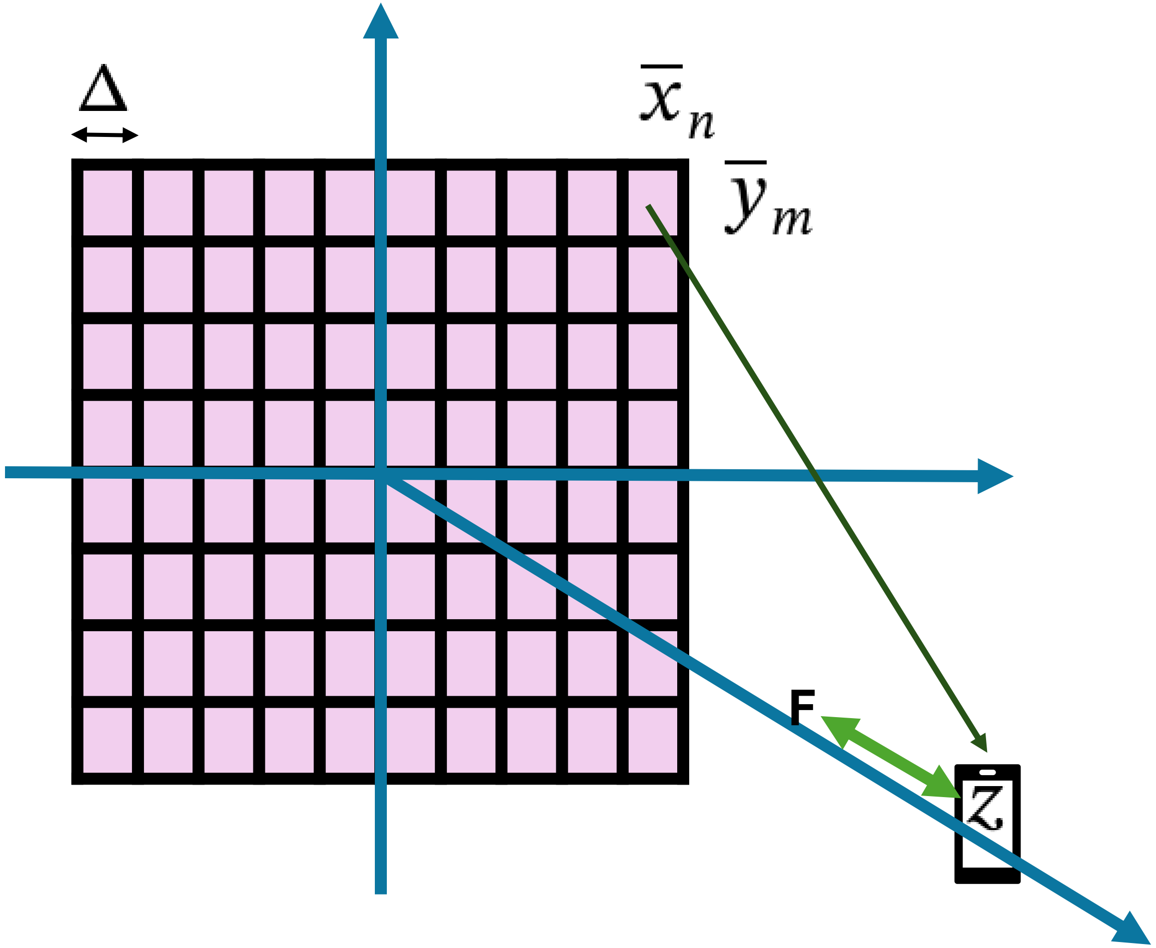
$$\approx \frac{1}{M} \left| \sum_{n=1}^{N} \sum_{m=1}^{N} e^{-\mathrm{j}\frac{2\pi}{\lambda}\left(z+\frac{\bar{x}_n^2}{2z}+\frac{\bar{y}_m^2}{2z}\right)} e^{\mathrm{j}\frac{2\pi}{\lambda}\left(F+\frac{\bar{x}_n^2}{2F}+\frac{\bar{y}_m^2}{2F}\right)} \right|^2$$

$$\approx \frac{1}{M} \left| \int_{-N/2}^{N/2} e^{\mathrm{j}\frac{\pi}{\lambda}\frac{n^2\Delta^2}{z_{\text{eff}}}} dn \int_{-N/2}^{N/2} e^{\mathrm{j}\frac{\pi}{\lambda}\frac{m^2\Delta^2}{z_{\text{eff}}}} dm \right|^2$$

$$= M \left(\frac{8z_{\text{eff}}}{d_{\text{F}}}\right)^2 \left(C^2\left(\sqrt{\frac{d_{\text{F}}}{8z_{\text{eff}}}}\right) + S^2\left(\sqrt{\frac{d_{\text{F}}}{8z_{\text{eff}}}}\right) \right)^2$$

Ramezani P, Björnson E. Near-field beamforming and multiplexing using extremely large aperture arrays. In Fundamentals of 6G Communications and Networking 2023 Jul 10 (pp. 317-349).
Polk C. Optical Fresnel-zone gain of a rectangular aperture. IRE Transactions on Antennas and Propagation. 1956 Jan;4(1):65-9.

Beamdepth in the Near-field



$$= M \left(\frac{8z_{\mathrm{eff}}}{d_{\mathrm{F}}}\right)^2 \left(C^2\left(\sqrt{\frac{d_{\mathrm{F}}}{8z_{\mathrm{eff}}}}\right) + S^2\left(\sqrt{\frac{d_{\mathrm{F}}}{8z_{\mathrm{eff}}}}\right)\right)^2$$

$$d_F = \frac{4N^2\Delta^2}{\lambda}$$

Fresnel integrals

$$C(x) = \int_0^x \cos\left(\frac{\pi t^2}{2}\right)\, dt$$

$$S(x) = \int_0^x \sin\left(\frac{\pi t^2}{2}\right)\, dt$$

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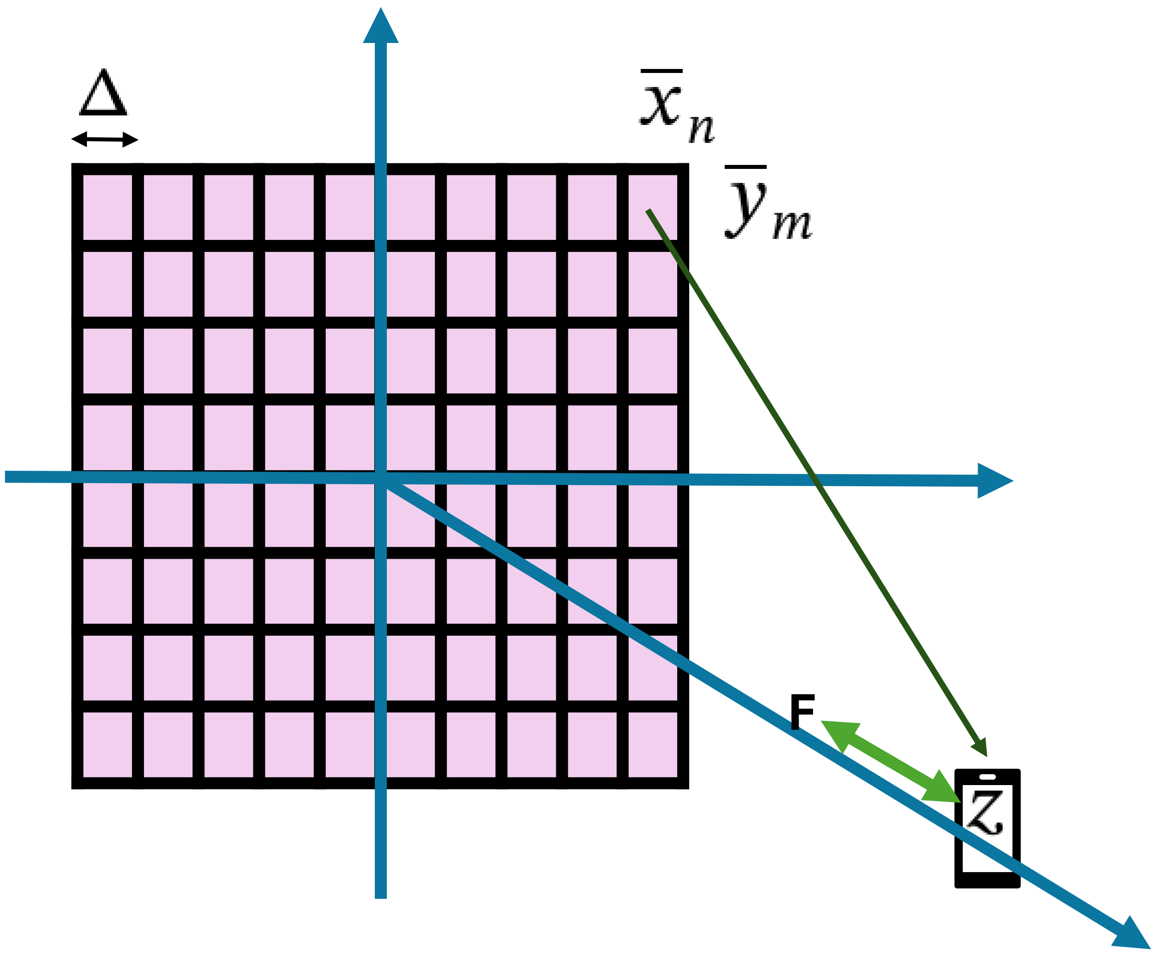
Beamdepth in the Near-field



$$= M \left(\frac{8z_{\mathrm{eff}}}{d_{\mathrm{F}}}\right)^2 \left(C^2 \left(\sqrt{\frac{d_{\mathrm{F}}}{8z_{\mathrm{eff}}}}\right) + S^2 \left(\sqrt{\frac{d_{\mathrm{F}}}{8z_{\mathrm{eff}}}}\right)\right)^2$$

$$\frac{\left(C^2(\sqrt{x}) + S^2(\sqrt{x})\right)^2}{x^2}$$

$$x = \frac{d_F}{8z_{eff}}$$

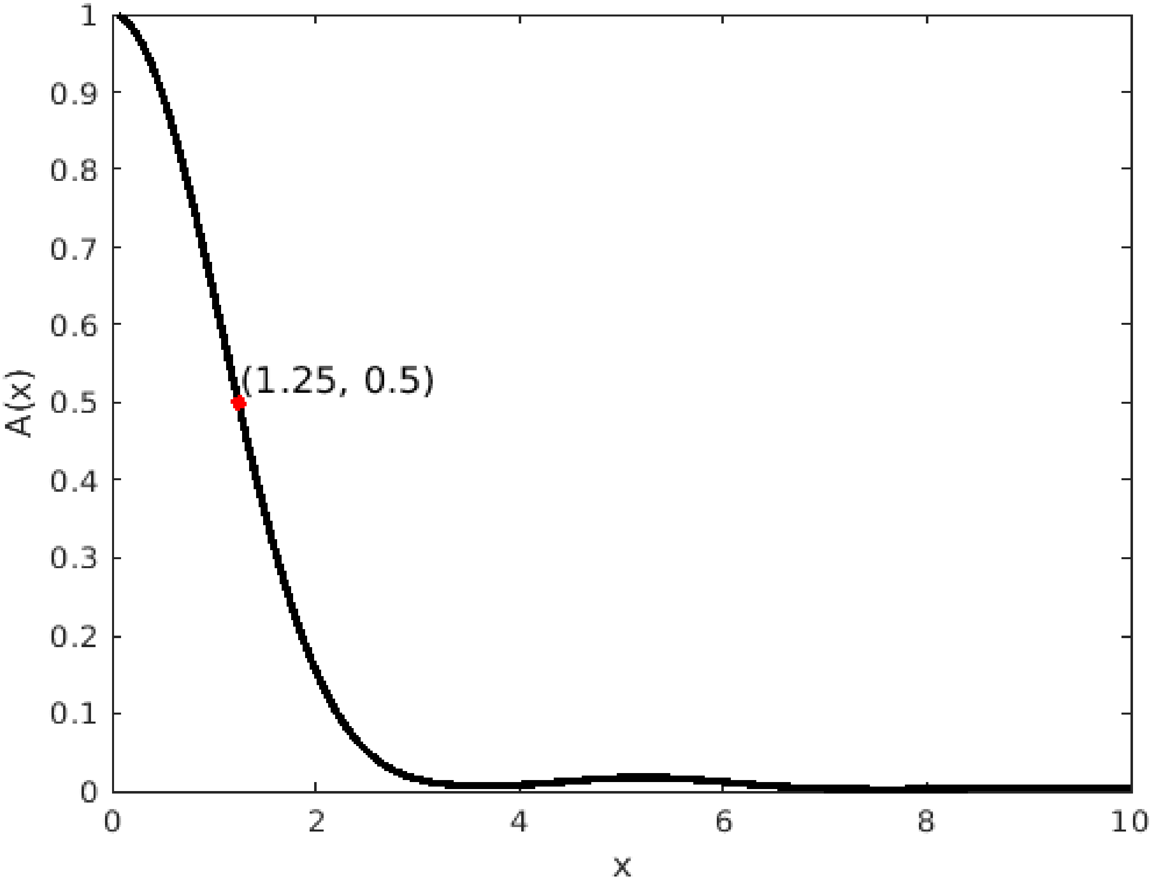
Björnson E, Chae CB, Heath Jr RW, Marzetta TL, Mezghani A, Sanguinetti L, Rusek F, Castellanos MR, Jun D, Demir ÖT. Towards 6G MIMO: Massive spatial multiplexing, dense arrays, and interplay between electromagnetics and processing. arXiv preprint arXiv:2401.02844. 2024 Jan 5.

Beamdepth in the Near-field

$$A(x) = \frac{\left(C^2(\sqrt{x}) + S^2(\sqrt{x})\right)^2}{x^2}$$

Decreasing function for $x = [0, 2]$

$$A(0) = 1, A(1.25) = 0.5$$



Beamdepth in the Near-field

$$A(x) = \frac{\left(C^2(\sqrt{x}) + S^2(\sqrt{x})\right)^2}{x^2} \Rightarrow$$

Decreasing function for $x = [0, 2]$

$$A(0) = 1, A(1.25) = 0.5$$

$$1.25 = \frac{d_{\mathrm{F}}}{8 z_{\mathrm{eff}}} = \frac{d_{\mathrm{F}}|F - z|}{8Fz} \rightarrow z = \frac{d_{\mathrm{F}} F}{d_{\mathrm{F}} \pm 10F}.$$

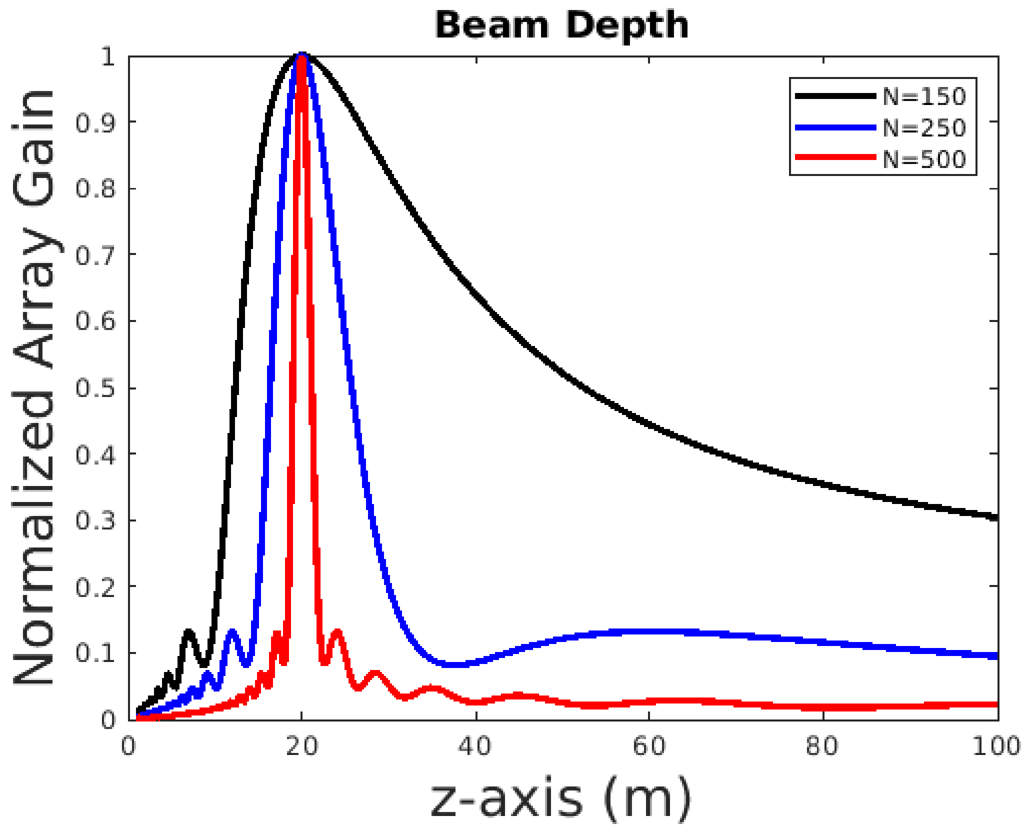
$$\mathrm{BD}_{3\,\mathrm{dB}} = \frac{d_{\mathrm{F}} F}{d_{\mathrm{F}} - 10F} - \frac{d_{\mathrm{F}} F}{d_{\mathrm{F}} + 10F} = \frac{20 d_{\mathrm{F}} F^2}{d_{\mathrm{F}}^2 - 100F^2}. \Rightarrow \boxed{F < \frac{d_F}{10}}$$

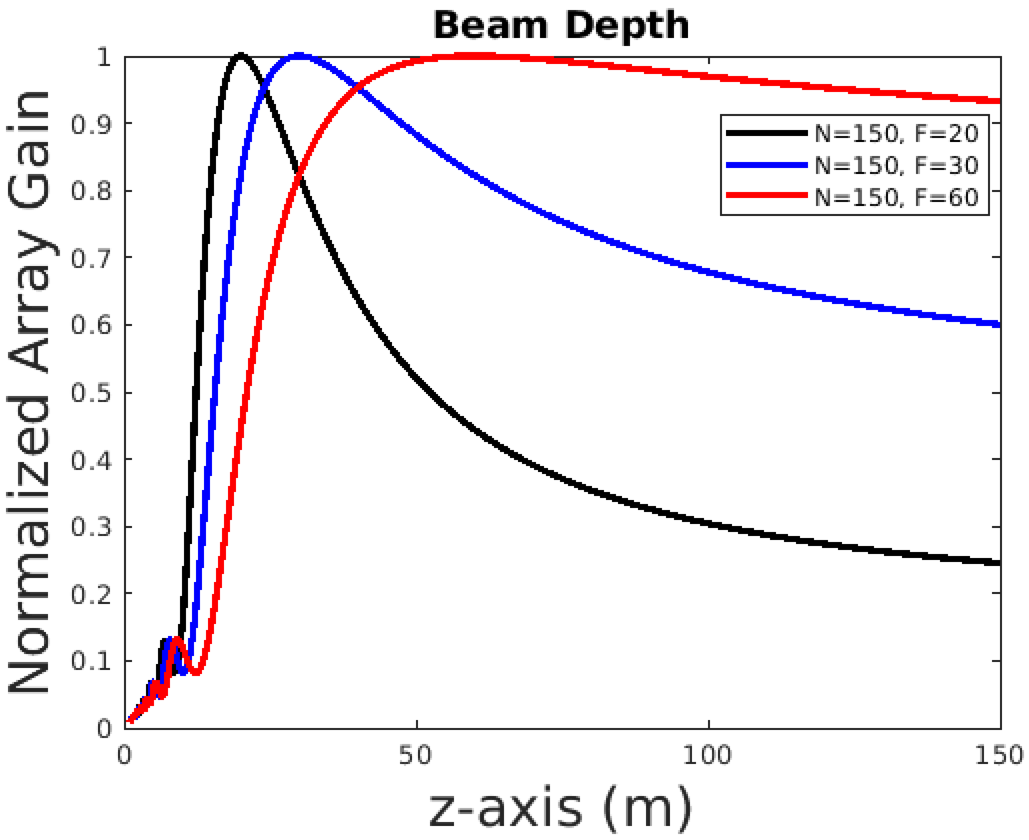
$$\boxed{d_B < r < d_F}$$

Björnson E, Chae CB, Heath Jr RW, Marzetta TL, Mezghani A, Sanguinetti L, Rusek F, Castellanos MR, Jun D, Demir ÖT. Towards 6G MIMO: Massive spatial multiplexing, dense arrays, and interplay between electromagnetics and processing. arXiv preprint arXiv:2401.02844. 2024 Jan 5.

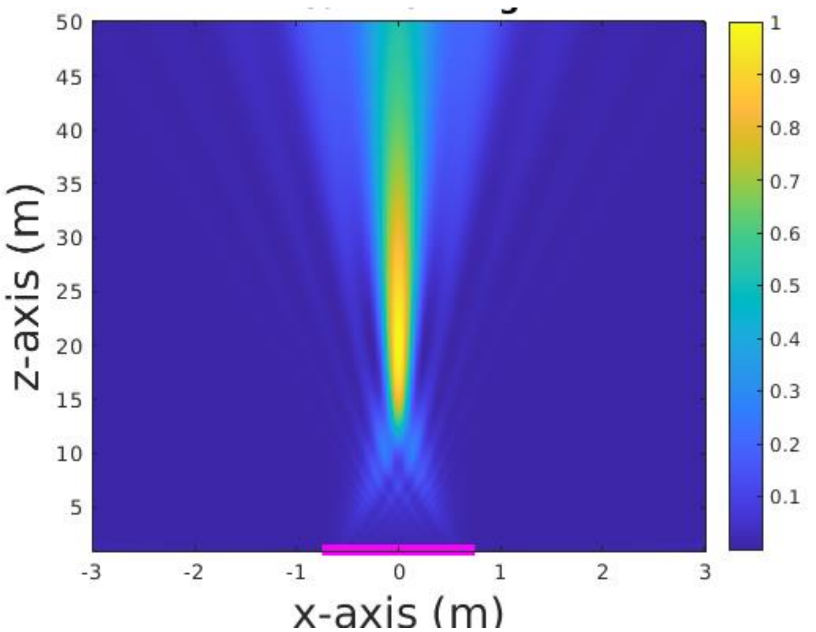
Beamdepth in the Near-field

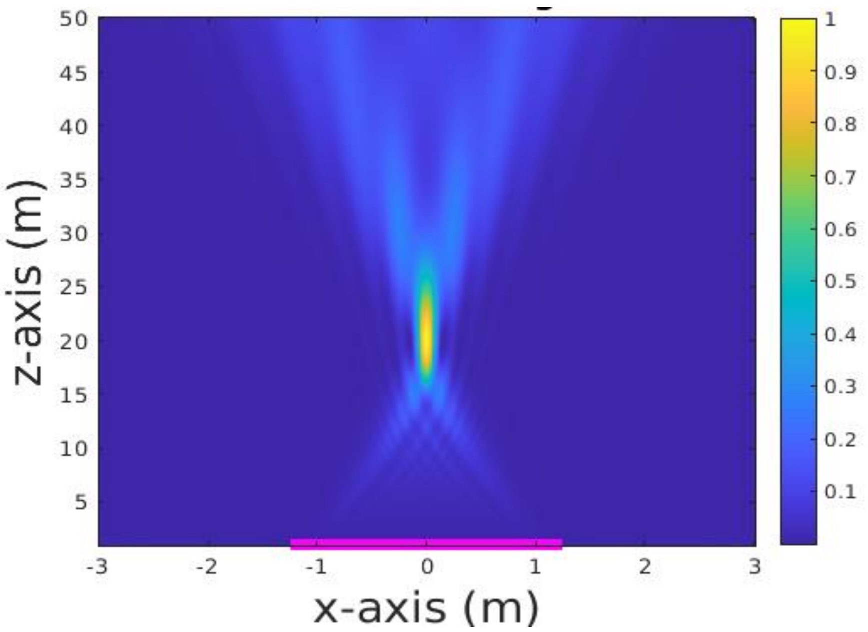
$$\mathrm{BD}_{3\,\mathrm{dB}} = \frac{d_{\mathrm{F}}F}{d_{\mathrm{F}} - 10F} - \frac{d_{\mathrm{F}}F}{d_{\mathrm{F}} + 10F} = \frac{20 d_{\mathrm{F}} F^2}{d_{\mathrm{F}}^2 - 100F^2}.$$

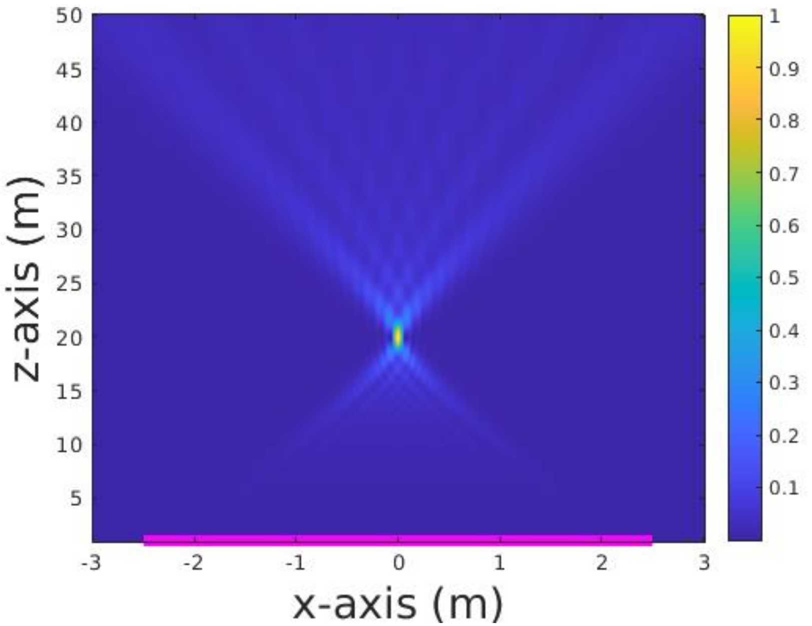




Beamdepth in the Near-field





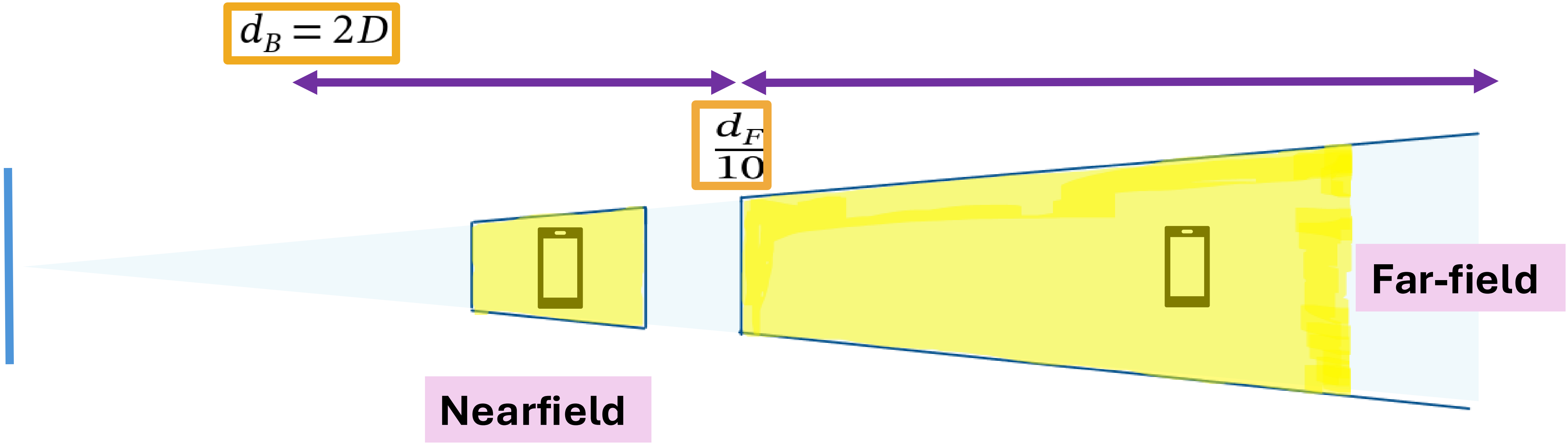


M = 150
F = 20 m
BW = 0.236 m
BD = 39.72m

M = 250
F = 20 m
BW = 0.141 m
BD = 9.26m

M = 500
F = 20 m
BW =0.0708m
BD= 3.226m

Nearfield spatial multiplexing

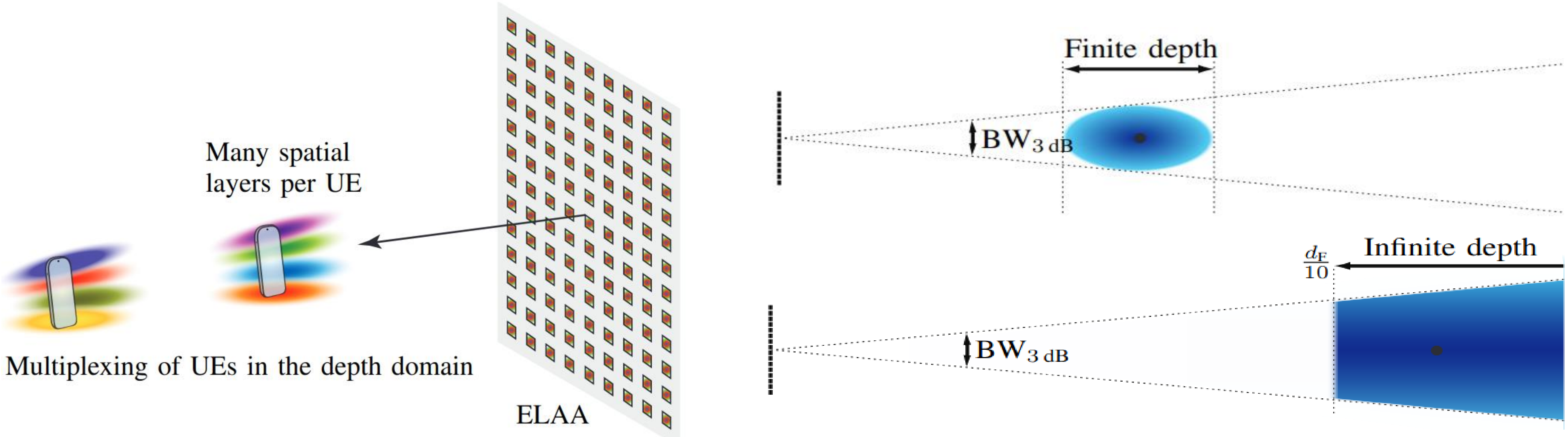


$$d_F = \frac{4N^2\Delta^2}{\lambda}$$

- **Impact of the wavelength**
- Fixed array size: $d_F \propto \lambda^{-1}$
- Fixed number of elements: $d_F \propto \lambda$

Nearfield spatial multiplexing

- Smaller focus area in **Nearfield**, both in **depth and width**.
- Reduce interference between concurrent signal transmission.
- Massive spatial multiplexing

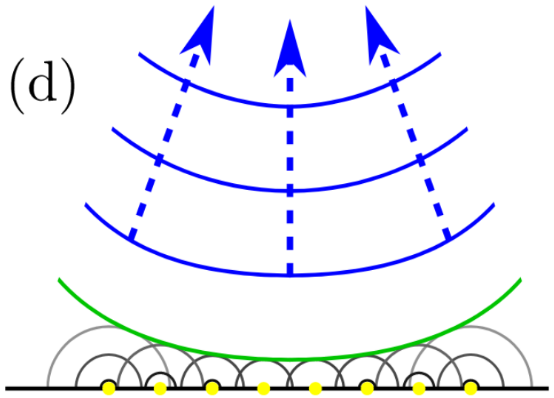


Ramezani P, Kosasih A, Irshad A, Björnson E. Exploiting the depth and angular domains for massive near-field spatial multiplexing. IEEE BITS the Information Theory Magazine. 2023 Oct 6;3(1):14-26.

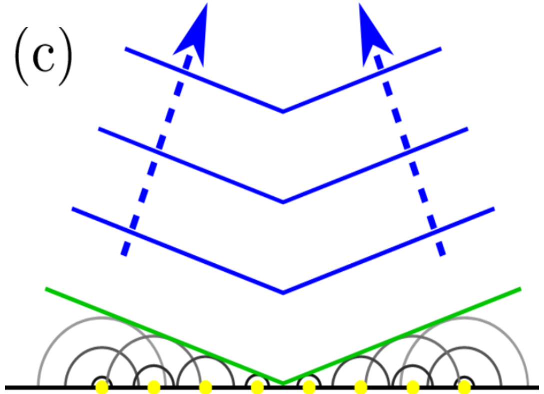
Bessel Beam

A long column of constructive interference can be seen along the z-axis.

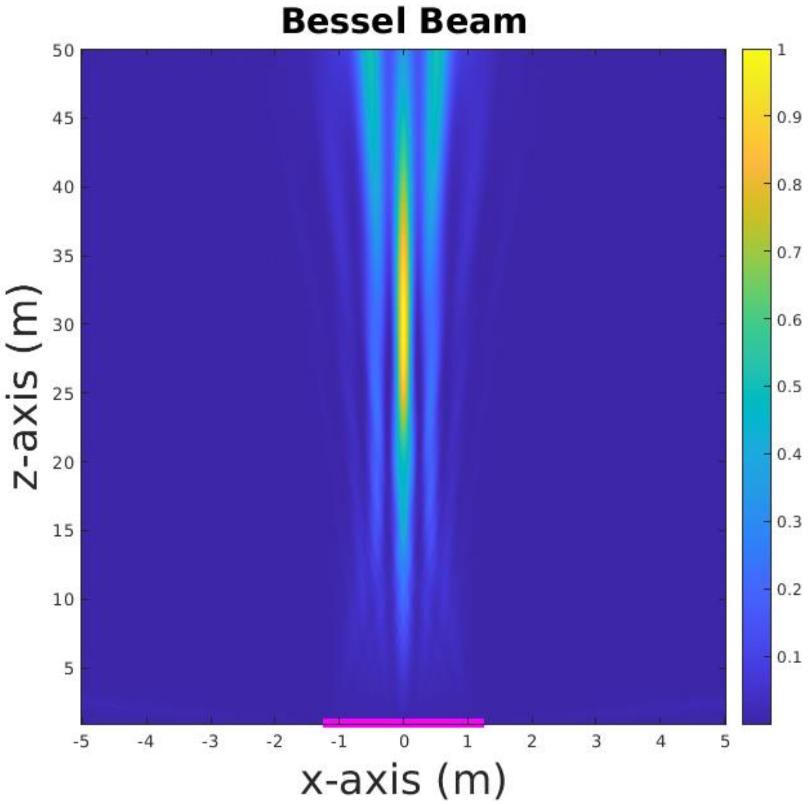
As the wave propagates, **the beam profile remains invariant.**



$$\varphi_{n,m} = \frac{2\pi}{\lambda}\sqrt{\bar{x}_n^2 + \bar{y}_m^2 + z^2}$$

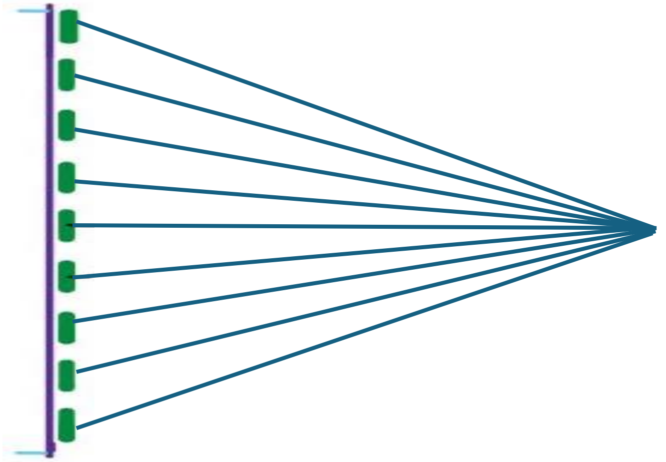


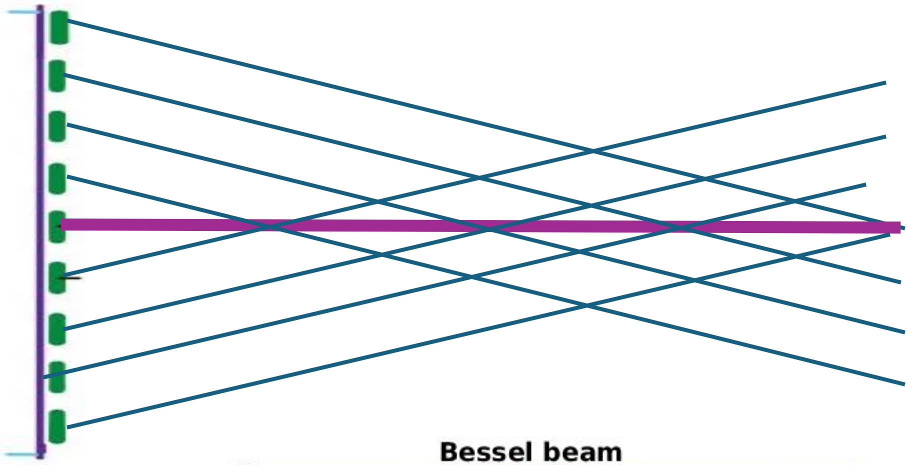
$$\varphi_{n,m} = \frac{2\pi}{\lambda}\left(\sqrt{\bar{x}_n^2 + \bar{y}_m^2}\right)\cos\theta$$

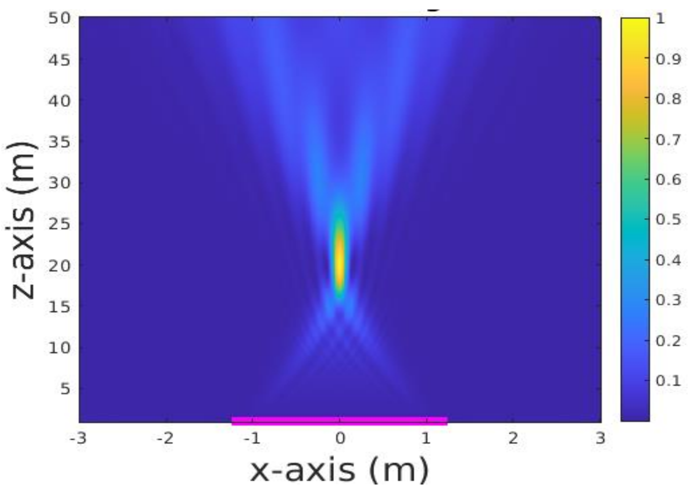


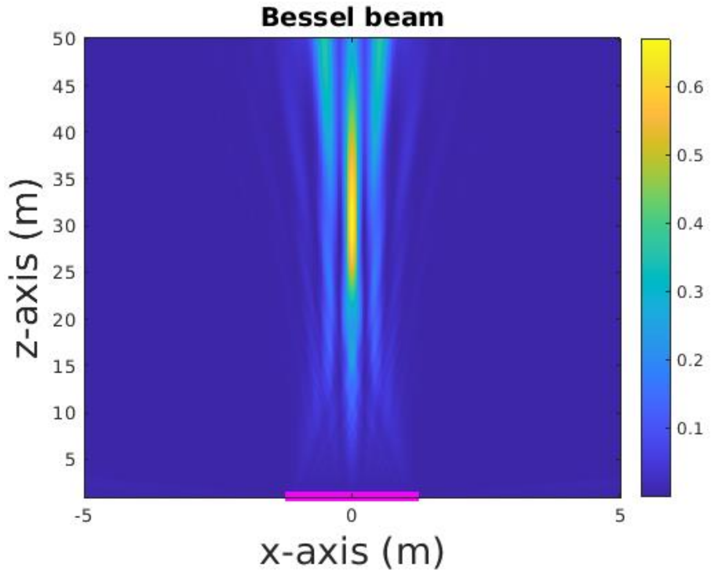
Headland D, Monnai Y, Abbott D, Fumeaux C, Withayachumnankul W. Tutorial: Terahertz beamforming, from concepts to realizations. Apl Photonics. 2018 May 1;3(5).

Bessel Beam





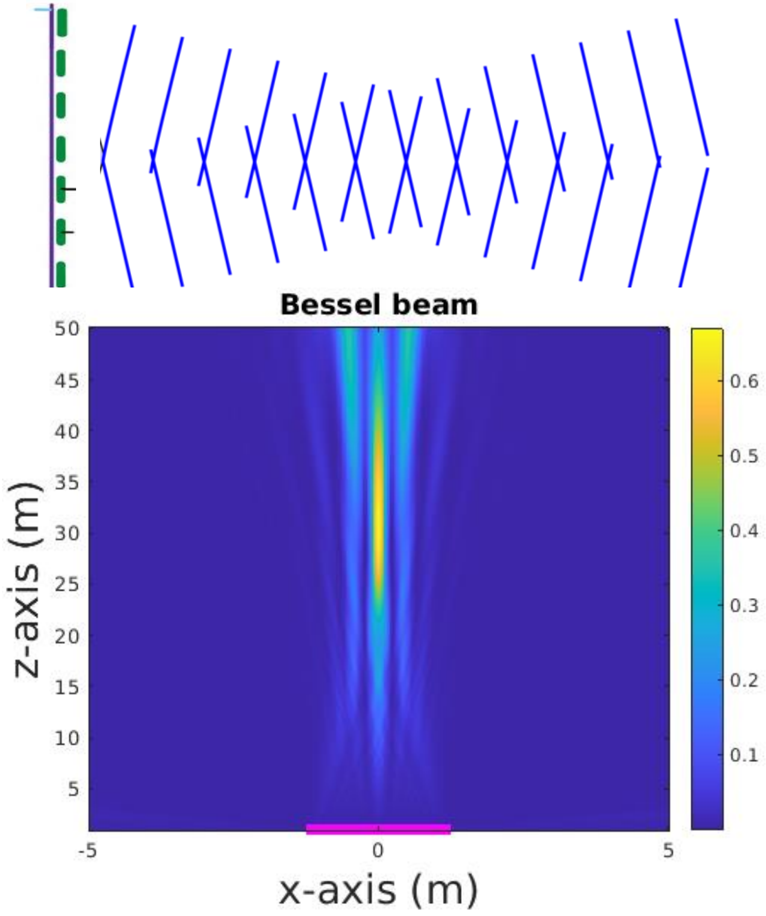


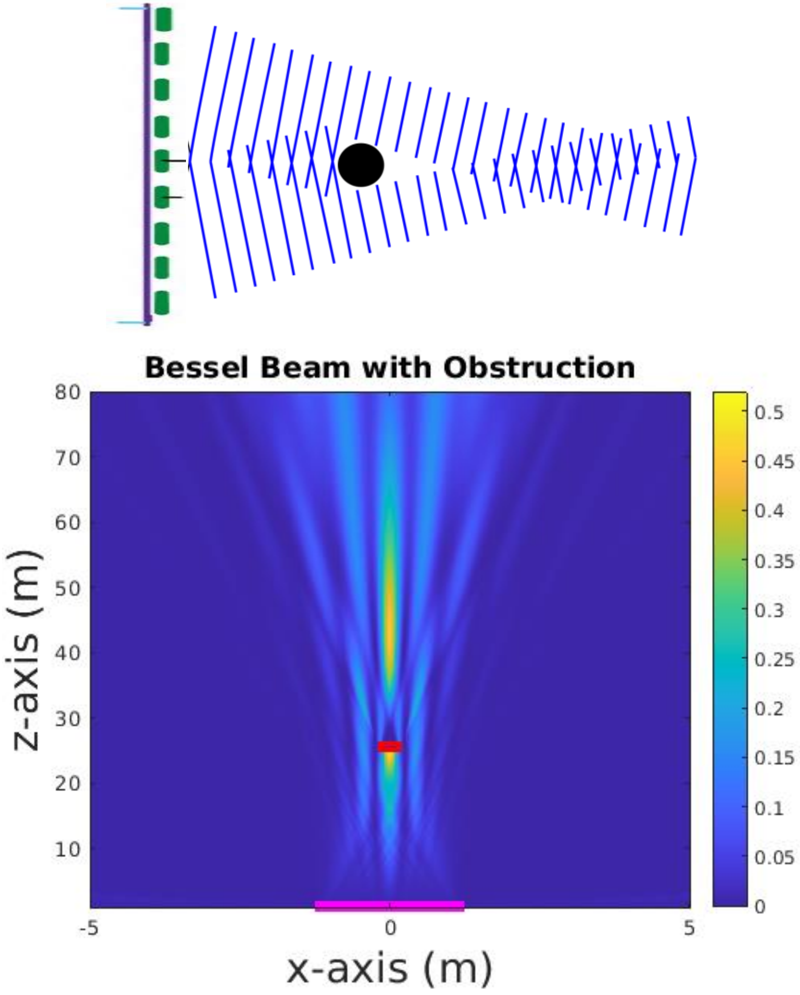


Headland D, Monnai Y, Abbott D, Fumeaux C, Withayachumnankul W. Tutorial: Terahertz beamforming, from concepts to realizations. Apl Photonics. 2018 May 1;3(5).

Bessel Beam

Bessel beams are ***self-healing***.



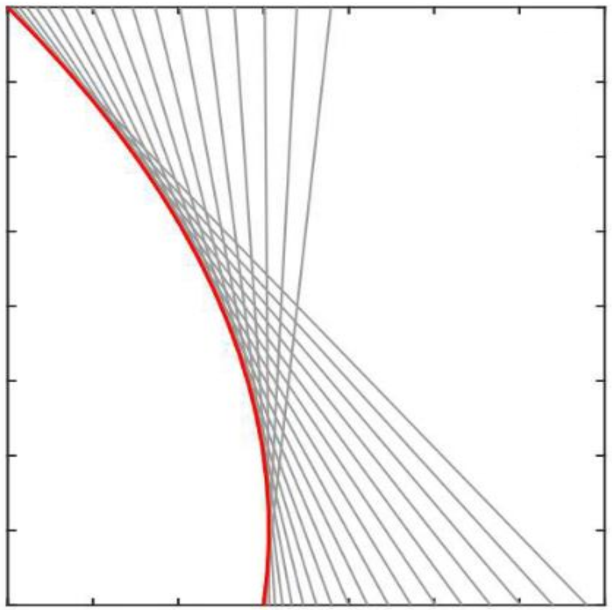


[Bessel beam - Wikipedia]
A. Singh et al., "Wavefront Engineering: Realizing Efficient Terahertz Band Communications in 6G and Beyond," in IEEE Wireless Communications, vol. 31, no. 3, pp. 133-139, June 2024.

Curved Beam

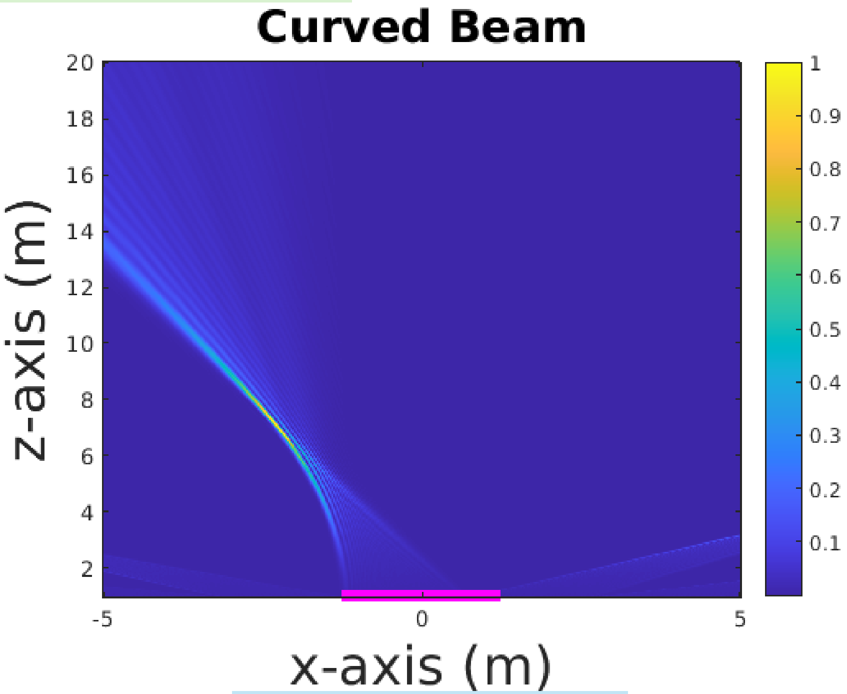
Follow arbitrary curved trajectories

Solve challenges associated to blockage.



$$g(z) = -0 \cdot 0125(z-1)^2 + .0025$$

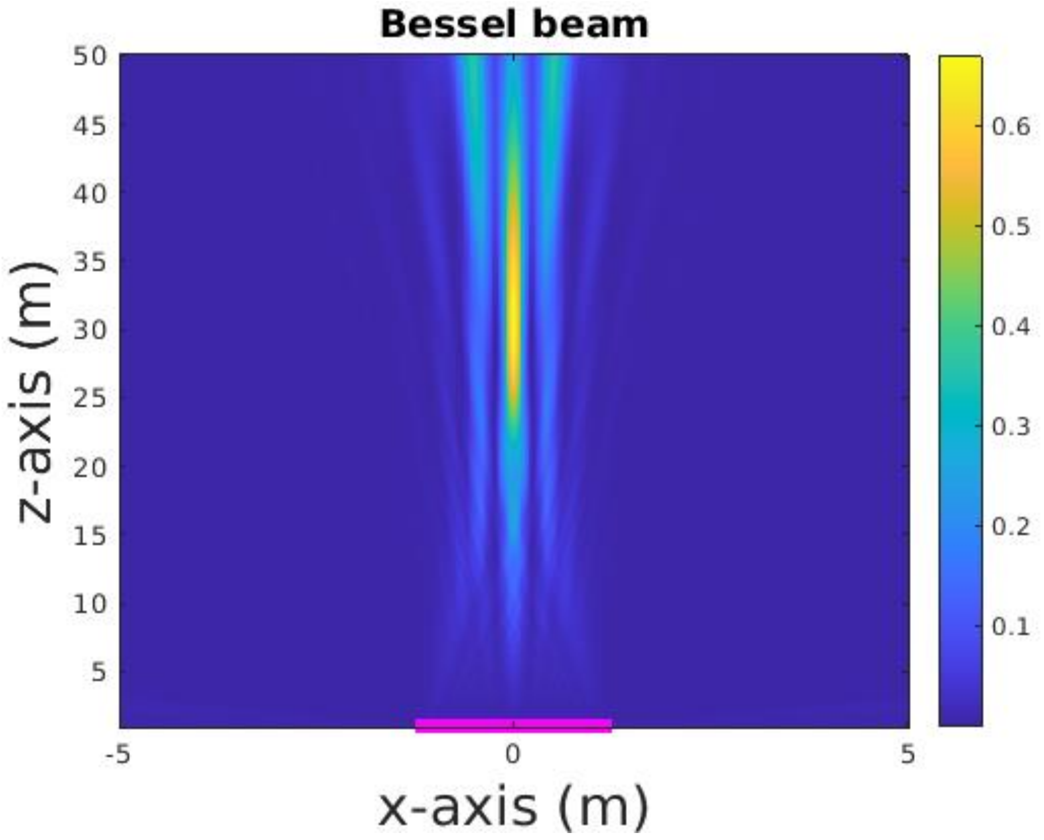
Trajectory

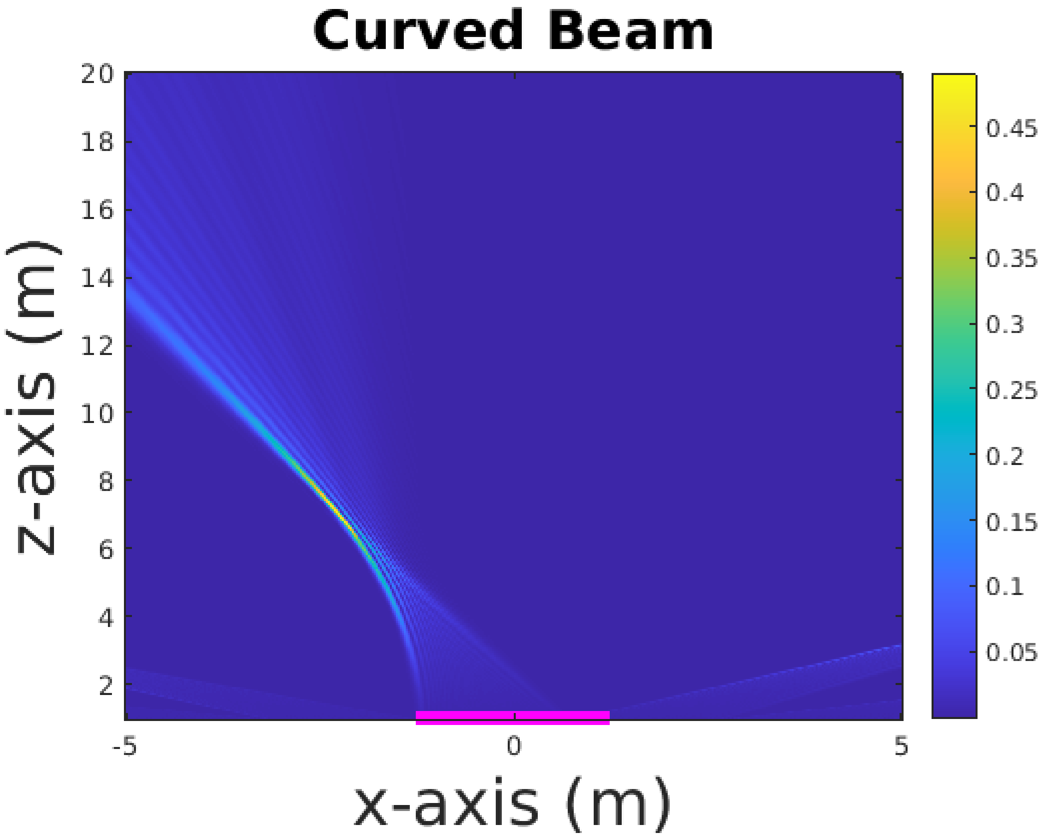


Result Beam

Guerboukha H, Zhao B, Fang Z, Knightly E, Mittleman DM. Curving THz Beams in the Near Field: A Framework to Compute Link Budgets. In2024 18th European Conference on Antennas and Propagation (EuCAP) 2024 Mar 17 (pp. 1-5). IEEE.

Bessel and Curved Beam





Will Near-Field Effects Appear in 6G?

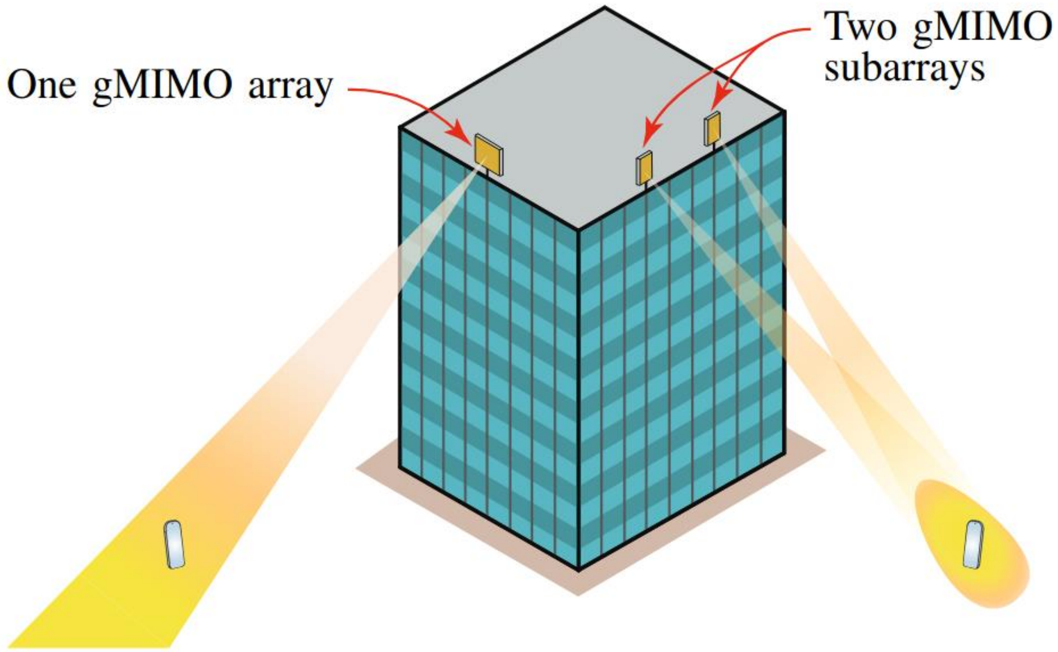
Example : $\boxed{F < \frac{d_F}{10}}$

0.5×0.5, 3 GHz = 1 m

1×1 m, 15 GHz = 20m

1×1 m, 30 GHz = 40 m

We need extremely large antenna array or very high frequency



Björnson E, Kara F, Kolomvakis N, Kosasih A, Ramezani P, Salman MB. Enabling 6G performance in the upper mid-band through gigantic MIMO. arXiv preprint arXiv:2407.05630. 2024 Jul.

Mini Matlab Project