Near-field sensing: opportunities and challenges

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Topics: mmW, terahertz, D-MIMO, semantics, very little about sensing

Motivation

The performance of communication and sensing systems is limited by:

- bandwidth – communications capacity, range resolution – wideband models and processing
- operating frequency – determines bandwidth, maximum range – FR3 frequency bands
- number of antennas – number of users (DoF), angular resolution – giantic MIMO, extremely large aperture arrays (ELAA), radiative near-field systems
- processing – coherent, noncoherent, L1, L2, L3 – low fronthaul or sequential processing

E. Björnson, F. Kara, N. Kolomvakis, A. Kosasih, P. Ramezani and M. B. Salman, "Enabling 6G Performance in the Upper Mid-Band by Transitioning From Massive to Gigantic MIMO," in *IEEE Open Journal of the Communications Society*, vol. 6, pp. 5450-5463, 2025, doi: 10.1109/OJCOMS.2025.3576931.

Motivation

- The increase in antenna array size and operating frequency extends the radiative near-field (NF) region of the aperture.
- The communication and sensing systems are becoming more distributed and sparse, the targets and users are often located within the NF region of the system.

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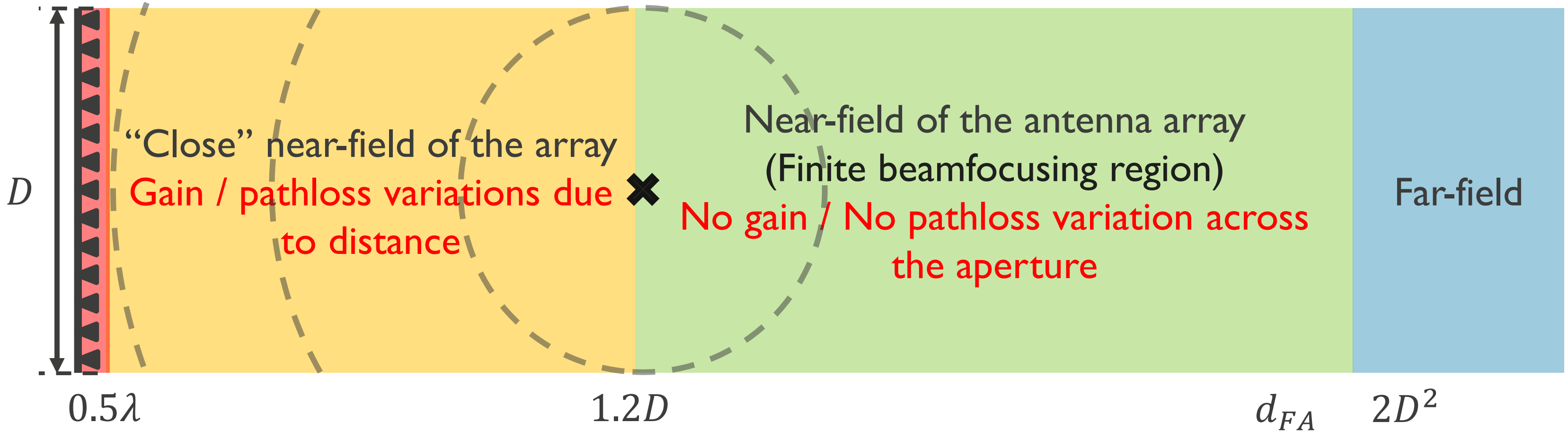
The radiative near-field region

- In the radiative near-field, the propagation distance is modeled based on spherical wave propagation. D – array aperture, λ – wavelength, α – scaling parameter dependent on the array geometry (≈5-10)



$$\frac{d_{FA}}{\alpha} = \frac{2D^2}{\alpha\lambda}$$

Near-field beamfocusing

- The nonlinear phase difference across antenna elements introduces additional phase diversity, making the array factor range dependent and facilitates beamfocusing – beamforming in the range domain.

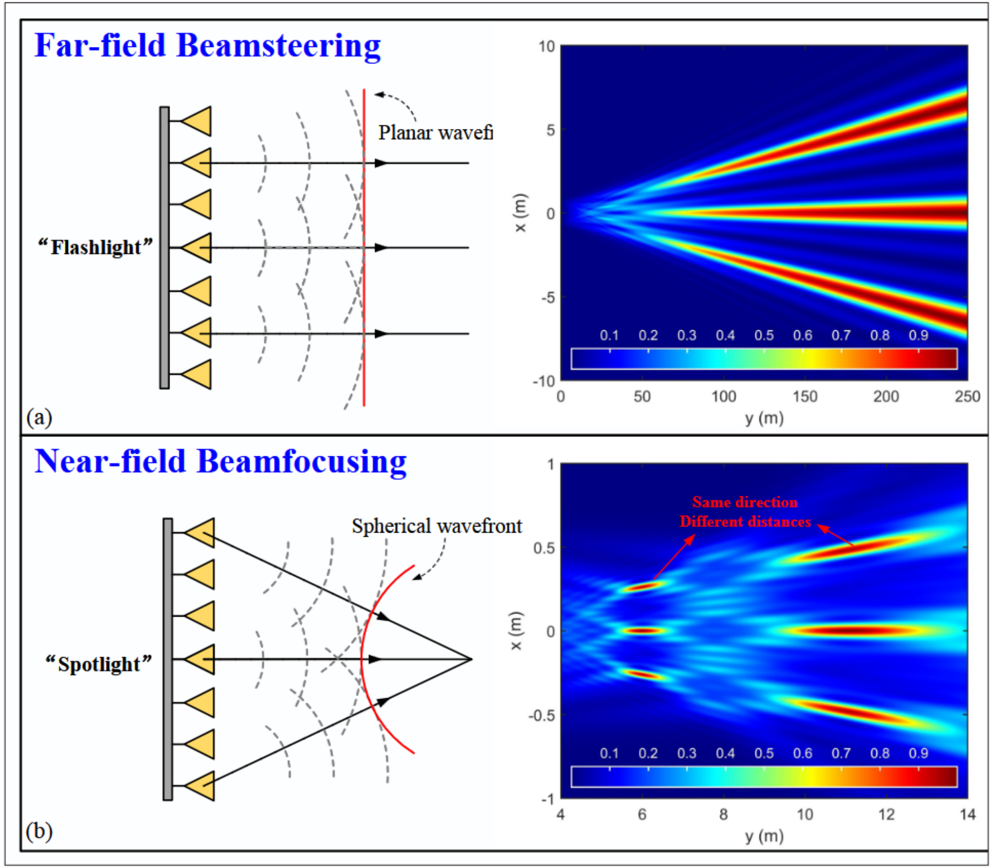


FIGURE 2. Beamforming in FFC and NFC. The beamsteering in FFC is like a "*flashlight*" emitting light with a plane wavefront, while the beamfocusing in NFC is like a "*spotlight*" emitting light with a spherical wavefront. The corresponding radiation patterns are illustrated on the right, where we consider a narrowband system with 256 antennas operating at a frequency of 28 GHz.

Y. Liu, J. Xu, Z. Wang, X. Mu and L. Hanzo, "Near-field Communications: What Will Be Different?," in IEEE Wireless Communications, vol. 32, no. 2, pp. 262-270, April 2025,
doi: 10.1109/MWC.001.2300588.

What does the near-field beamfocusing bring to <u>sensing</u> & communications?

Near-field array factor (AF)

Assume an arbitrary sensing geometry with M transmitters (TX) and N receivers (RX). The positions of the m-th transmitter and n-th receiver are given by

$$\mathbf{p}_m^{\text{tx}} = [x_m^{\text{tx}}, y_m^{\text{tx}}, z_m^{\text{tx}}]^{\text{T}}, \mathbf{p}_n^{\text{rx}} = [x_n^{\text{rx}}, y_n^{\text{rx}}, z_n^{\text{rx}}]^{\text{T}}.$$

Let $\mathbf{p} = [x, y, z]^{\text{T}}$ denote a point in space, the corresponding distances to the transmitter and receiver are defined as

$$d_m^{\text{tx}}(\mathbf{p}) = ||\mathbf{p} - \mathbf{p}_m||_2, \ d_n^{\text{rx}}(\mathbf{p}) = ||\mathbf{p} - \mathbf{p}_n||_2.$$

The bistatic distance is denoated by $d_{m,n}(\mathbf{p}) = d_m^{\text{tx}}(\mathbf{p}) + d_n^{\text{rx}}(\mathbf{p})$.

The channel simplifies to a distance-dependent phase shift (assuming coherence across the array or across target viewing angles)

$$h_{m,n}(\mathbf{p}) = e^{-j2\pi\frac{f_c}{c}d_{m,n}(\mathbf{p})}$$

where f_c is the center frequency and c is the speed of light.

Narrowband ambiguity function (single frequency)

The narrowband ambiguity function can be separated into a product of the transmit and receive array factors as follows

$$\mathcal{A}(\mathbf{p}',\mathbf{p}) = \underbrace{\frac{1}{\sqrt{M}} \sum_{m \in M} e^{-j2\pi \frac{f_c}{c} \Delta \mathrm{d}_m^{\mathrm{tx}}(\mathbf{p}',\mathbf{p})}}_{\mathrm{AF_{TX}}(\mathbf{p}',\mathbf{p})} \times \underbrace{\frac{1}{\sqrt{N}} \sum_{n \in N} e^{-j2\pi \frac{f_c}{c} \Delta \mathrm{d}_n^{\mathrm{rx}}(\mathbf{p}',\mathbf{p})}}_{\mathrm{AF_{RX}}(\mathbf{p}',\mathbf{p})},$$

where $\Delta d_m^{\mathrm{tx}}(\mathbf{p}',\mathbf{p}) = d_m^{\mathrm{tx}}(\mathbf{p}') - d_m^{\mathrm{tx}}(\mathbf{p})$ and $\Delta d_n^{\mathrm{rx}}(\mathbf{p}',\mathbf{p}) = d_n^{\mathrm{rx}}(\mathbf{p}') - d_n^{\mathrm{rx}}(\mathbf{p})$ is the distance difference between points $p'$and p for the m-th transmitter and n-th receiver.

Closed-form expressions of the AF

- The closed-form expression of the array factor can be obtained for selected geometries by approximating the sum as an integral and approximating the spherical distance difference as quadratic using 2nd order (quadratic) Taylor approximation.

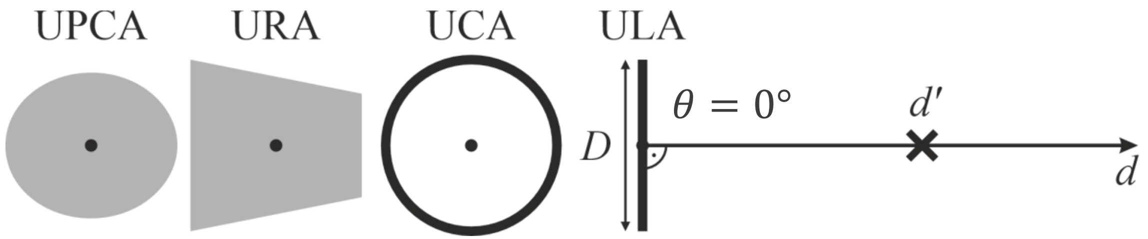
- For example, for a uniform linear antenna array (ULA)

$$d_m(\boldsymbol{p}) = d\sqrt{1 + \left(\frac{md_a}{d}\right)^2 - \frac{2md_a \sin(\theta)}{d}}$$

$$\sqrt{1+\mathrm{x}} \approx 1 + \frac{\mathrm{x}}{2} - \frac{\mathrm{x}^2}{8}$$

$$d_m(\boldsymbol{p}) \approx d \; - md_a \sin(\theta) + \frac{(md_a \cos(\theta))^2}{2d}$$

Array factor of the selected array geometries at the boresight



- **Uniform linear array (ULA)**

$$|\mathrm{AF}_{\mathrm{ULA}}(d',d)|^2 = M\frac{4}{d_{\mathrm{FA}}d_{\mathrm{ver}}}\left(C^2\left(\sqrt{\frac{d_{\mathrm{FA}}d_{\mathrm{ver}}}{4}}\right)+S^2\left(\sqrt{\frac{d_{\mathrm{FA}}d_{\mathrm{ver}}}{4}}\right)\right)$$

$d_{\mathrm{ver}} = \left|\frac{1}{d'}-\frac{1}{d}\right| = \frac{|d-d'|}{d'd}$ is the absolute value of the vergence difference.

$C(x) = \int_0^x \cos(\pi x^2/2)\ dx$ and $S(x) = \int_0^x \sin(\pi x^2/2)\ dx$ are Fresnel integrals.

Array factor of the considered antenna array geometries

- **Uniform circular array (UCA)**

$$\left|\mathrm{AF}_{\mathrm{UCA}}(d', d)\right|^2 = M \left| J_0\left(\frac{\pi d_{\mathrm{FA}} d_{\mathrm{ver}}}{16}\right)\right|^2,$$

where J_0 denotes the zero-order Bessel function of the first kind.

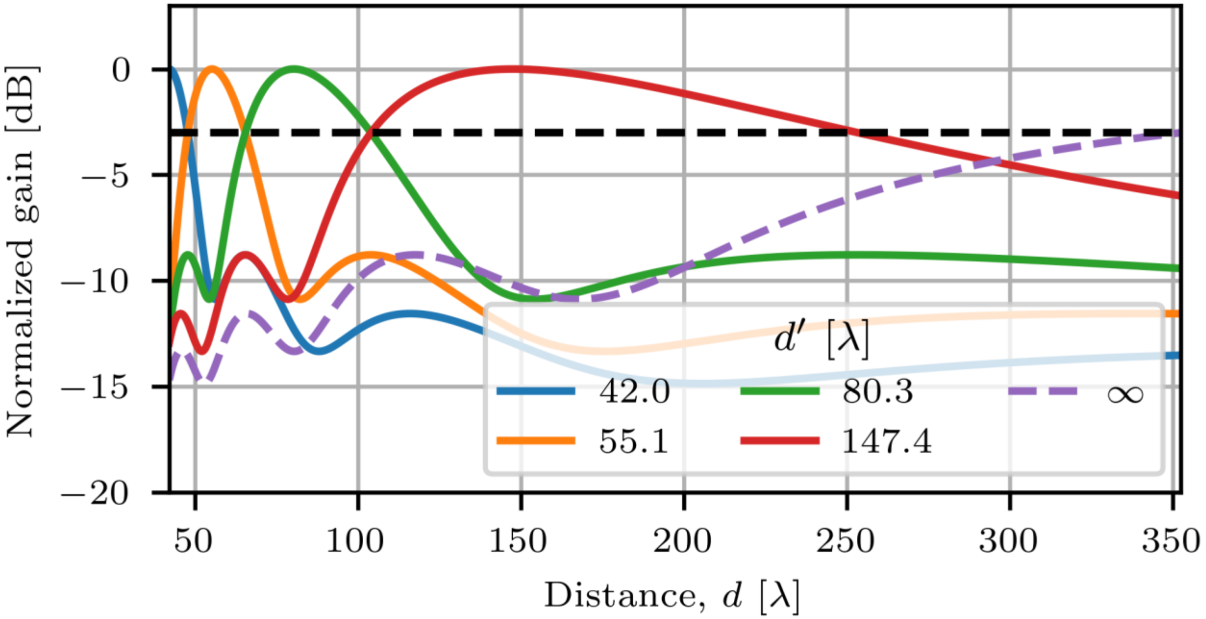
- **Uniform rectangular array (URA) (square)**

$$\left|\mathrm{AF}_{\mathrm{URA}}(d', d)\right|^2 = M \left(\frac{8}{d_{\mathrm{FA}} d_{\mathrm{ver}}}\right)^2 \left(C^2\left(\sqrt{\frac{d_{\mathrm{FA}} d_{\mathrm{ver}}}{8}}\right) + S^2\left(\sqrt{\frac{d_{\mathrm{FA}} d_{\mathrm{ver}}}{8}}\right)\right)$$

- **Uniform planar circular array (UPCA) (disk)**

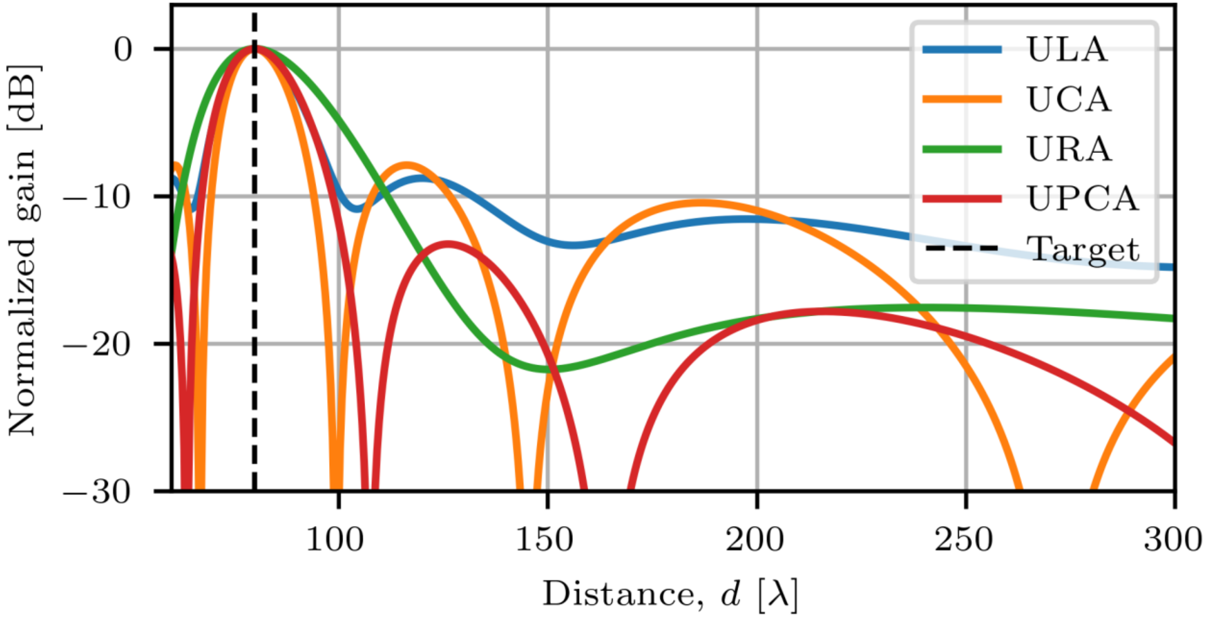
$$\left|\mathrm{AF}_{\mathrm{UPCA}}(d', d)\right|^2 = M \mathrm{sinc}^2\left(\frac{d_{\mathrm{FA}} d_{\mathrm{ver}}}{16}\right)$$

Array factor of ULA vs distance for a few beamfocusing positions d'



Array factor of the fitted 3 dB beamspots for $D = 35\,\lambda$. The black dashed line specifies the -3 dB. The purple dashed line denotes the array factor for a far-field point. The path loss is not included in the figure.

Array factor across different geometries



Array factor per geometry for $D = 50\,\lambda$ a target located at $80\,\lambda$.

Calculating the -3dB radial beamwidth (beamdepth)

Given the closed-form expressions of the array factor the -3dB beamdepth (BD) (radial resolution of a narrowband system) can be calculated as

$$\mathrm{BD}(D, d') = \begin{cases} \dfrac{2\alpha d_{\mathrm{FA}} d'^2}{d_{\mathrm{FA}}^2 - \alpha^2 d'^2}, & d' < \dfrac{d_{\mathrm{FA}}}{\alpha}, \\ \infty, & d' \geq \dfrac{d_{\mathrm{FA}}}{\alpha}. \end{cases}$$

The parameter α depends on the array geometry and configuration

Array geometry	$\alpha_{\mathrm{SIMO/MISO}}$	α_{MIMO}	α_{SAR}
ULA	6.952	4.969	3.476
UCA	5.737	4.148	2.868
URA	9.937	7.068	4.969
UPCA	7.087	5.103	3.544

Parameter α vs architecture and processing

The narrowband ambiguity function can be separated into a product of the transmit and receive array factors

$$\mathcal{A}(\mathbf{p}',\mathbf{p}) = \underbrace{\frac{1}{\sqrt{M}}\sum_{m\in M} e^{-j2\pi\frac{f_c}{c}\Delta \mathrm{d}_m^{\mathrm{tx}}(\mathbf{p}',\mathbf{p})}}_{\mathrm{AF_{TX}}(\mathbf{p}',\mathbf{p})} \times \underbrace{\frac{1}{\sqrt{N}}\sum_{n\in N} e^{-j2\pi\frac{f_c}{c}\Delta \mathrm{d}_n^{\mathrm{rx}}(\mathbf{p}',\mathbf{p})}}_{\mathrm{AF_{RX}}(\mathbf{p}',\mathbf{p})},$$

Different architectures/processing results in different ambiguity function

- Single aperture system

$$\mathcal{A}_{\mathrm{SIMO/MISO}}(\mathbf{p}',\mathbf{p}) = \mathrm{AF_{TX}}(\mathbf{p}',\mathbf{p}) = \mathrm{AF_{RX}}(\mathbf{p}',\mathbf{p})$$

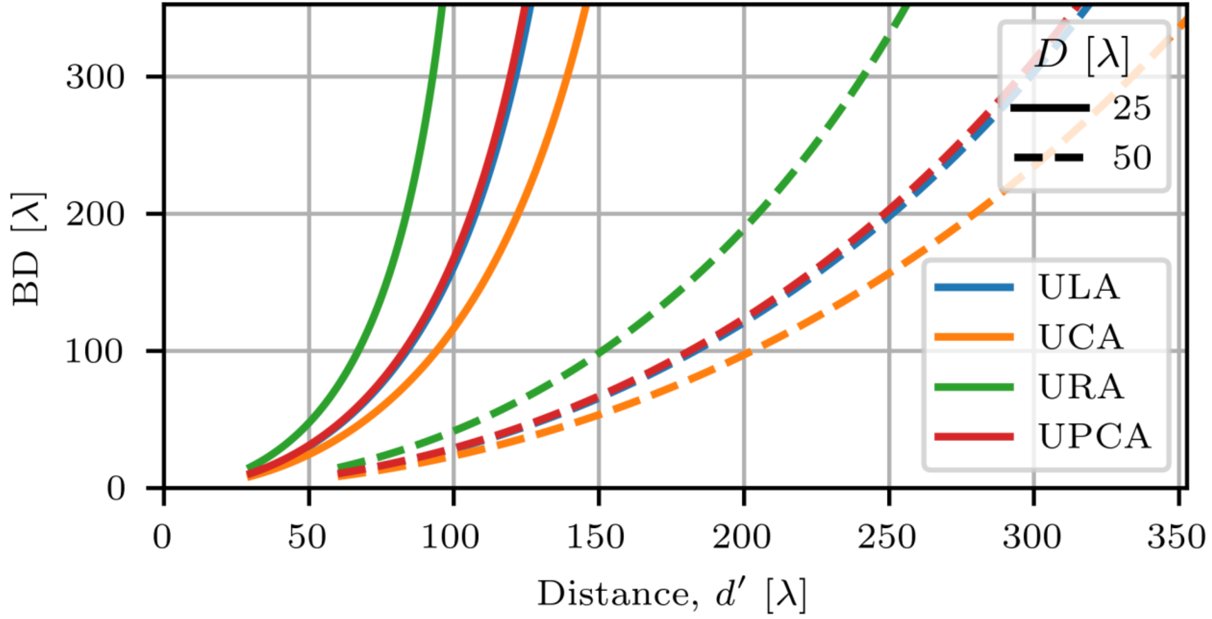
- Identical collocated TX and RX aperture (full MIMO)

$$\mathcal{A}_{\mathrm{MIMO}}(\mathbf{p}',\mathbf{p}) = \left(\mathrm{AF_{TX/RX}}(\mathbf{p}',\mathbf{p})\right)^2$$

- Synthetic aperture radar (single TX to collocated RX at given point in space)

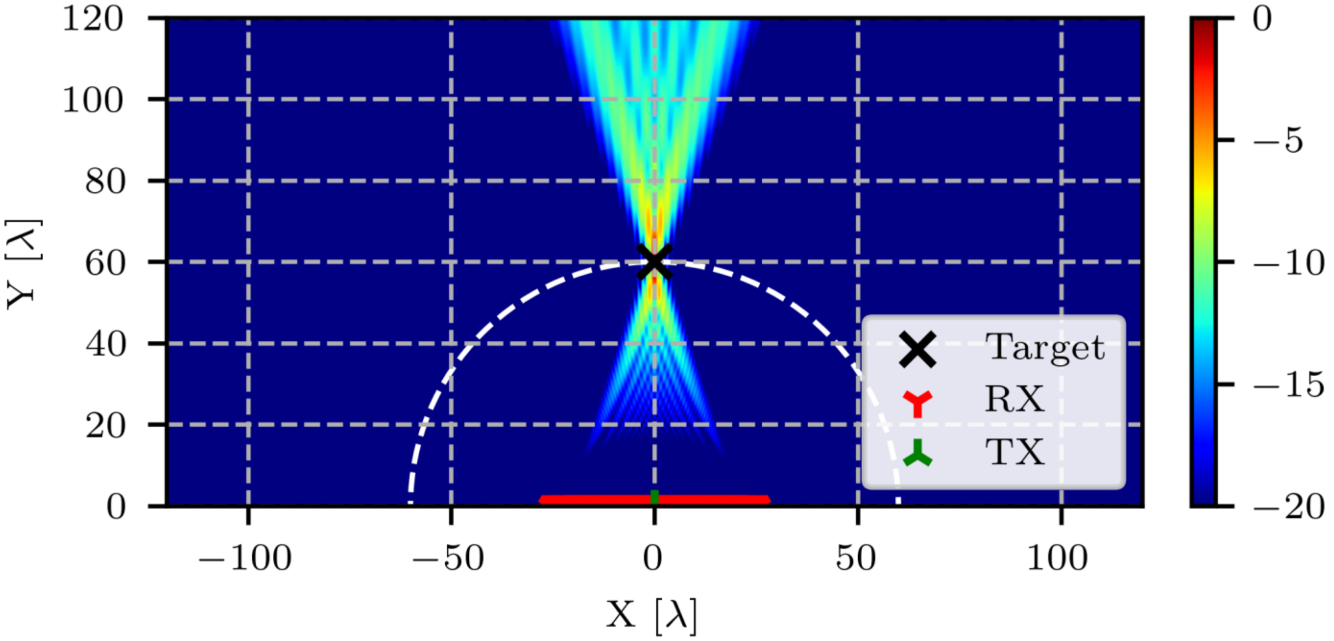
$$\mathcal{A}_{\mathrm{SAR}}(\mathbf{p}',\mathbf{p}) = \left(\mathrm{AF_{TX/RX}}(2\mathbf{p}',2\mathbf{p})\right)^2$$

Beamdepth vs distance for selected array geometries



Beamdepth as a function of distance for two array aperture sizes and selected array geometries.

2D beamfocusing pattern of ULA



Matched filter response for ULA, $D = 50\lambda$ and target / user at $d' = 120\lambda$.

Problems

- The near-field beamfocusing resolution and gains:
  - Require fully-digital or hybrid array architectures (requires 2D range&angle scanning)
  - Are only significant very close to the array
  - Requires coherence across the array and target/source viewing angles
  - Can be improved by extending the total aperture - problematic implementation
  - Requires scalable signal processing for coherent integration
- Benefits:
  - Lots of problems to solve
  - Updating the signal models and presenting the results in a new scenario - near-field

Approximation of the amb. func. in near-field systems with bandwidth

$$\mathcal{A}(\mathbf{p}',\mathbf{p}) = \frac{1}{\sqrt{MN}} \sum_{m\in\mathcal{M}} e^{-j2\pi \frac{f_c}{c}\Delta d_m^{\mathrm{tx}}(\mathbf{p}',\mathbf{p})} \times \sum_{n\in\mathcal{N}} e^{-j2\pi \frac{f_c}{c}\Delta d_n^{\mathrm{rx}}(\mathbf{p}',\mathbf{p})} \times \int_{-B/2}^{B/2} |S_m(f)|^2 e^{-j2\pi \frac{f}{c}\Delta d_{m,n}(\mathbf{p}',\mathbf{p})}\, df$$

TABLE II
BANDWIDTH-APERTURE PRODUCT CONSTRAINT FOR DIFFERENT ARRAY GEOMETRIES AND PROCESSING.

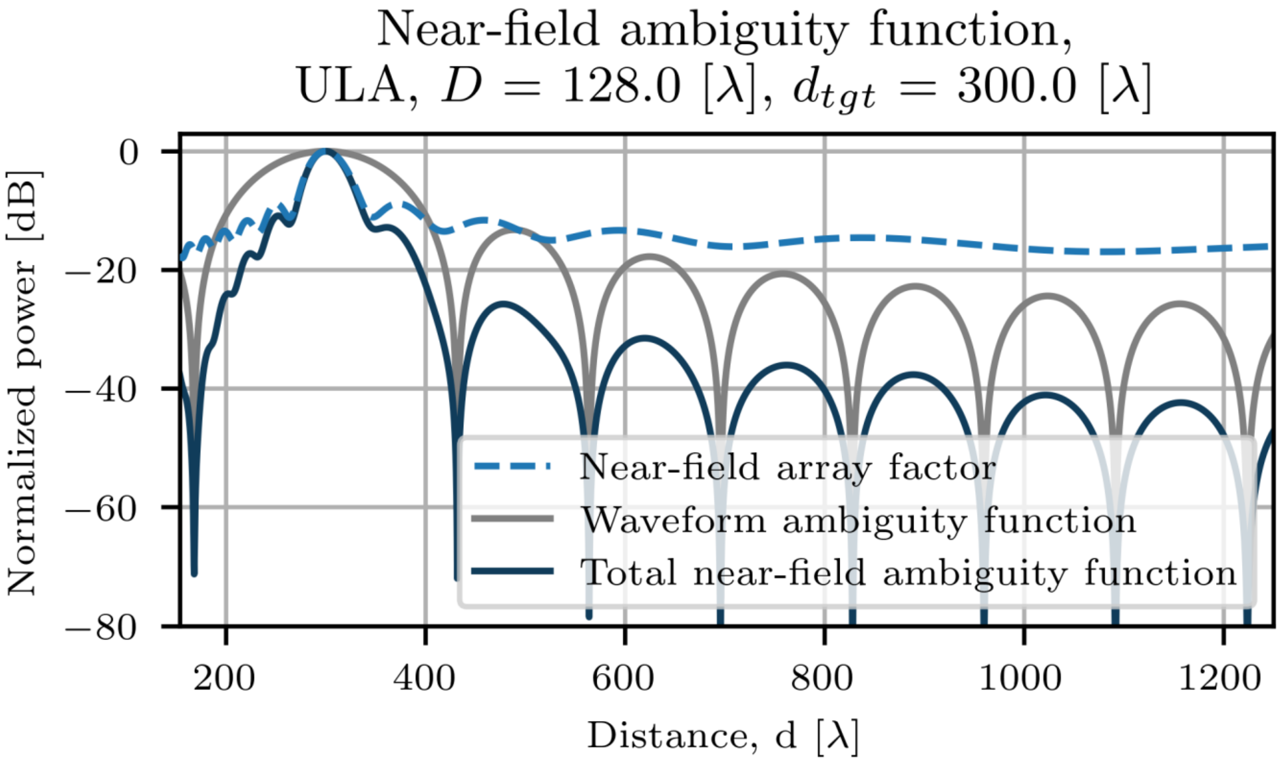
Array geometry	SIMO/MISO	MIMO
ULA, URA, UPCA	$B_f D_\lambda \ll 10$	$B_f D_\lambda \ll 5$
UCA	$B_f D_\lambda \ll 9.615$	$B_f D_\lambda \ll 4.808$

$$\mathcal{A}(\mathbf{p}',\mathbf{p}) \overset{A1}{\approx} \underbrace{R\left(-\frac{\Delta d_{0,0}(\mathbf{p}',\mathbf{p})}{c}\right)}_{\chi_B(\mathbf{p}',\mathbf{p})} \times \underbrace{\frac{1}{\sqrt{M}} \sum_{m\in\mathcal{M}} e^{-j2\pi \frac{f_c}{c}\Delta d_m^{\mathrm{tx}}(\mathbf{p}',\mathbf{p})}}_{\mathrm{AF}_{\mathcal{M}}(\mathbf{p}',\mathbf{p})} \times \underbrace{\frac{1}{\sqrt{N}} \sum_{n\in\mathcal{N}} e^{-j2\pi \frac{f_c}{c}\Delta d_n^{\mathrm{rx}}(\mathbf{p},\mathbf{p}')}}_{\mathrm{AF}_{\mathcal{N}}(\mathbf{p}',\mathbf{p})}.$$

$$\mathcal{A}(\mathbf{p}',\mathbf{p}) \overset{A1}{\approx} \chi_B(\mathbf{p}',\mathbf{p})\mathrm{AF}_{\mathcal{M}}(\mathbf{p}',\mathbf{p})\mathrm{AF}_{\mathcal{N}}(\mathbf{p}',\mathbf{p}).$$

[3] M. Wachowiak, A. Bourdoux and S. Pollin, "Approximation of the Range Ambiguity Function in Near-Field Sensing Systems," in *IEEE Transactions on Radar Systems*, vol. 4, pp. 430-442, 2026, doi: 10.1109/TRS.2026.3657154

Approximation of the amb. func. in near-field systems with bandwidth



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Outlook on the near-field

The near-field regime offers some improvements; however, they are limited

- NF of antenna array offers additional phase diversity, not extra DoF
- The near-field region is an add-on/extra region to existing systems
  (no NF-centric systems)
- The NF region with regular array geometries offers closed-form expressions of the performance vs exhaustive simulations (in CF-MIMO)

Conclusion

- The range-dependent beampattern can be used to resolve targets in range in the absence of bandwidth [1,2] and further improves the resolution and sidelobe performance of systems with bandwidth [3].
- Key challenges to limiting the adoption of near-field systems are
  - Cost-efficient and feasible implementation and architecture of large apertures:, e.g. sparse, irregular arrays
  - Synchronization of the large and distributed arrays, limited target coherence
  - Scalable signal processing

References

[1] M. Wachowiak, A. Bourdoux and S. Pollin, "Sizing Antenna Arrays for Near-Field Communication and Sensing," in *IEEE Wireless Communications Letters*, vol. 15, pp. 630-634, 2026, doi: 10.1109/LWC.2025.3635278

[2] M. Wachowiak, A. Bourdoux and S. Pollin, "Analysis of the range ambiguity function of narrowband near-field MIMO sensing," IEEE Radar Conference (RadarConf26), https://arxiv.org/abs/2505.10053

[3] M. Wachowiak, A. Bourdoux and S. Pollin, "Approximation of the Range Ambiguity Function in Near-Field Sensing Systems," in *IEEE Transactions on Radar Systems*, vol. 4, pp. 430-442, 2026, doi: 10.1109/TRS.2026.3657154