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Beyond Bandwidth

Phase-Coherent Distributed ISAC for 6G Positioning, Sensing, and Imaging

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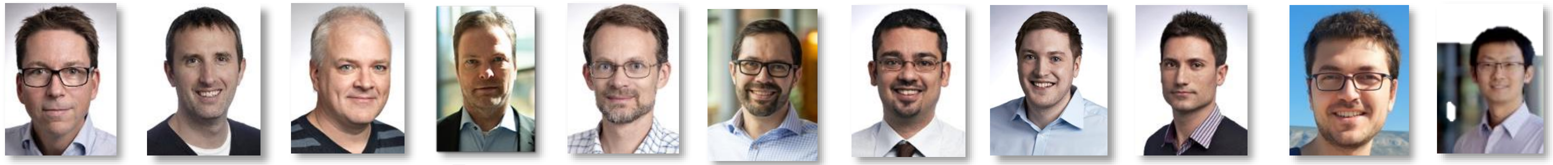
Chalmers and the CROSSNET group

- **Chalmers:** private foundation, established by William Chalmers in 1829, 300 professors, 11000 students



Erik Ström | Fredrik Brännström | Thomas Eriksson | Tommy Svensson | Erik Agrell | Henk Wymeersch | Giuseppe Durisi | Christian Häger | Alexandre Graell i Amat | M. Furkan Keskin | Hui Chen

- **CROSSNET group:** focus on radio localization and sensing. ~20 members, 3 permanent staff.
- **Our vision:** Repurpose developments in communication systems for positioning and sensing

WeChat

CROSSNET Group Spinoffs

- ISAC: https://www.radchat.tech

CEO: Prof. Simon HE
IEEE Senior Member
Changjiang Distinguished Professor, BIT

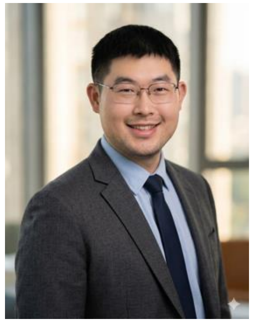
- Zero-energy devices: https://emickers.com

CEO: Dr. Navid Amani
PhD Chalmers and TU Eindhoven

- AI for fault monitoring: https://aiopt.se/

CEO: Jafar Banar

- Multi-modal sensing: https://raitech.se



CEO: Dr. Yu Ge
MIT

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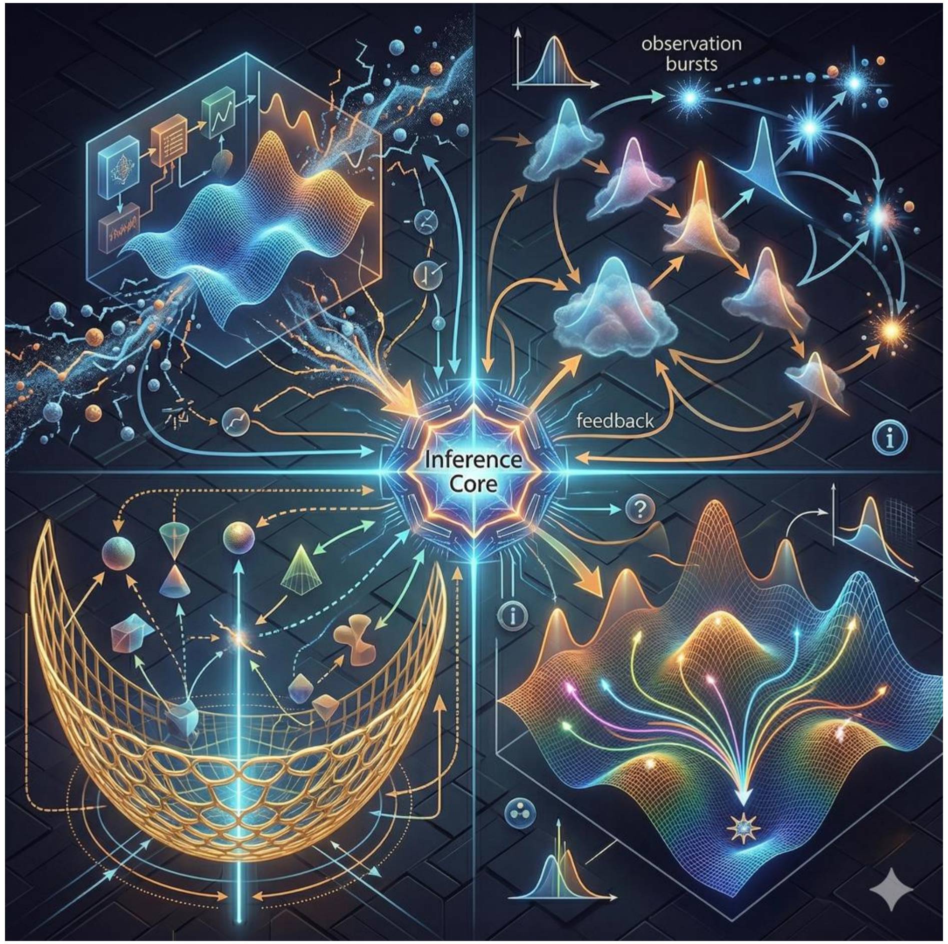
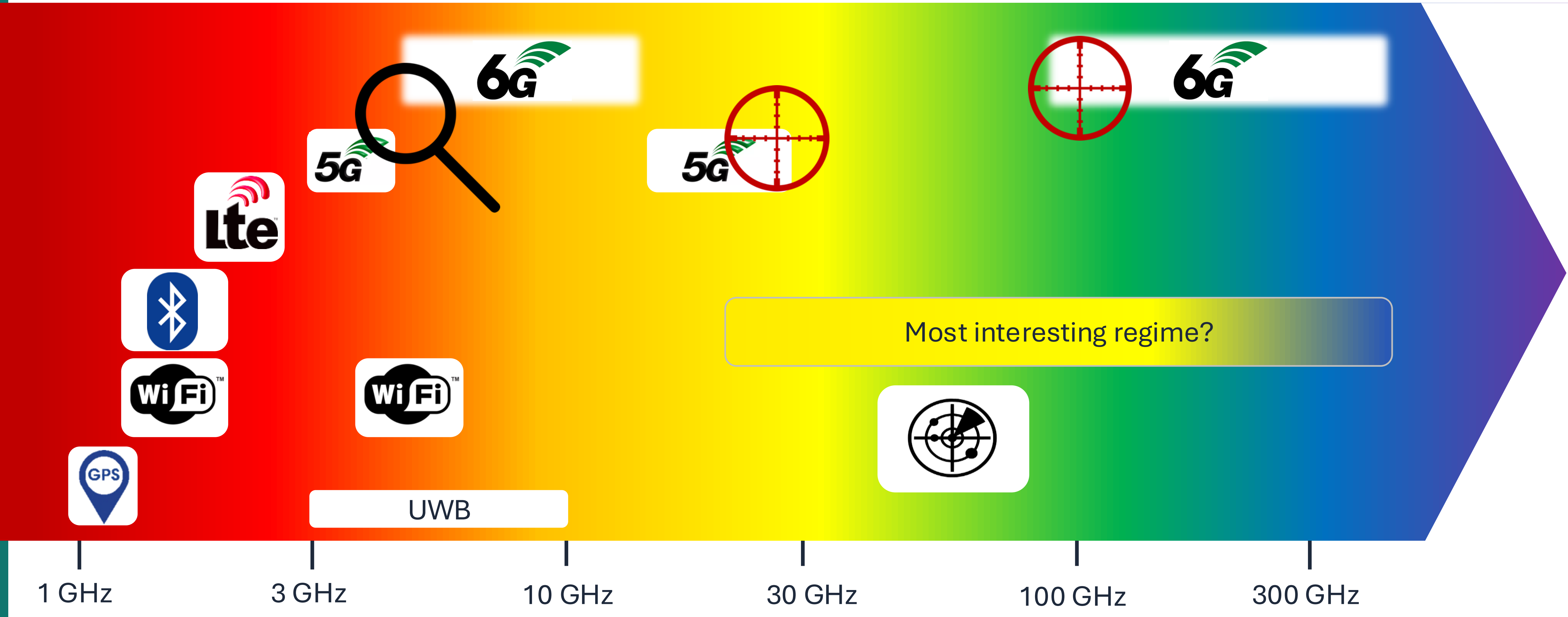
Our research: two paths



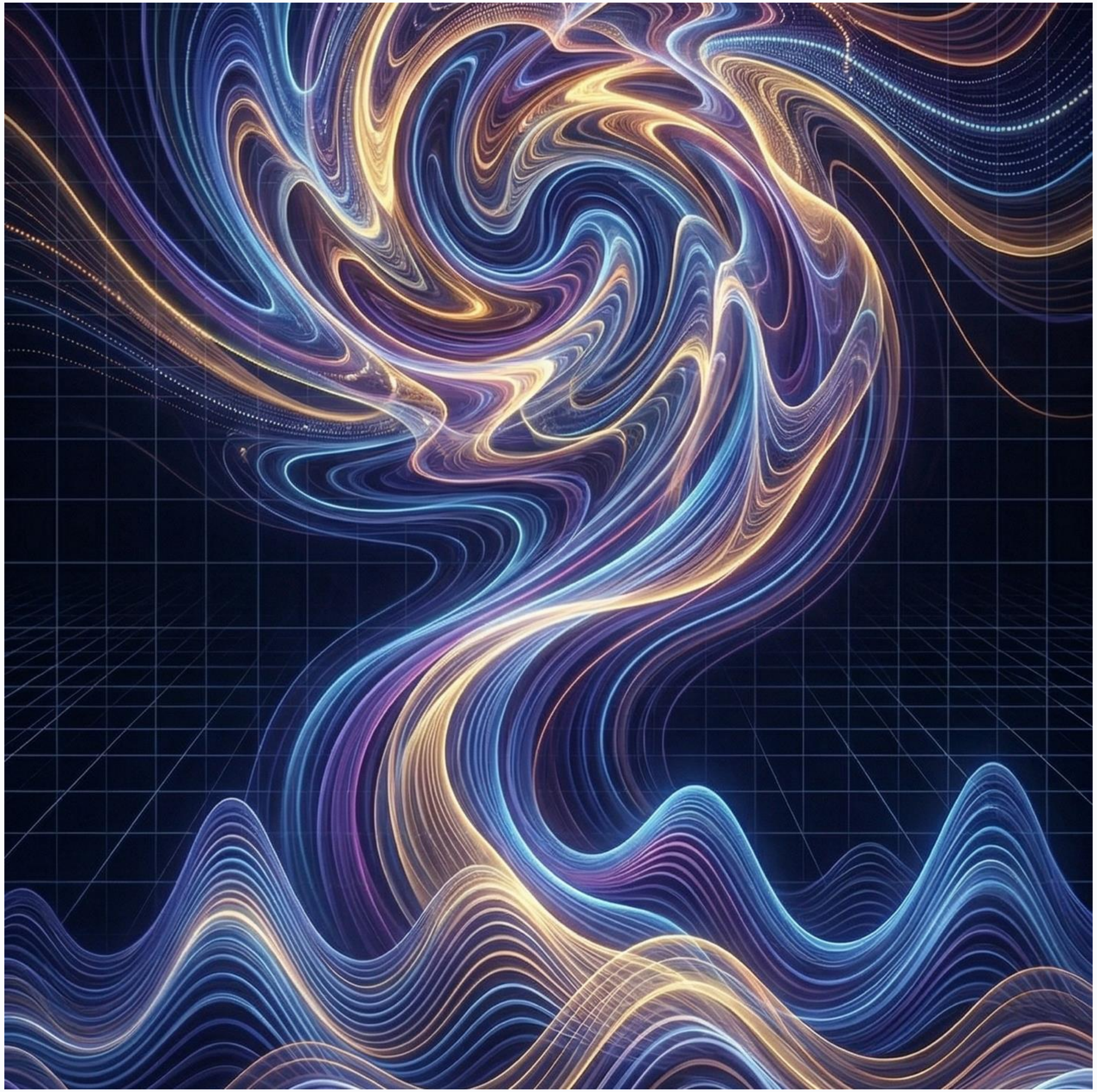
Model-based signal processing

Communication and sensing for 6G: all about bandwidth?



Outline

- Foundations of localization and sensing
- Phase-coherent deployments
- Accuracy, resolution, and ambiguity
- Beyond bandwidth localization
- Beyond bandwidth sensing and imaging
- Beyond bandwidth ISAC
- Conclusions
- References



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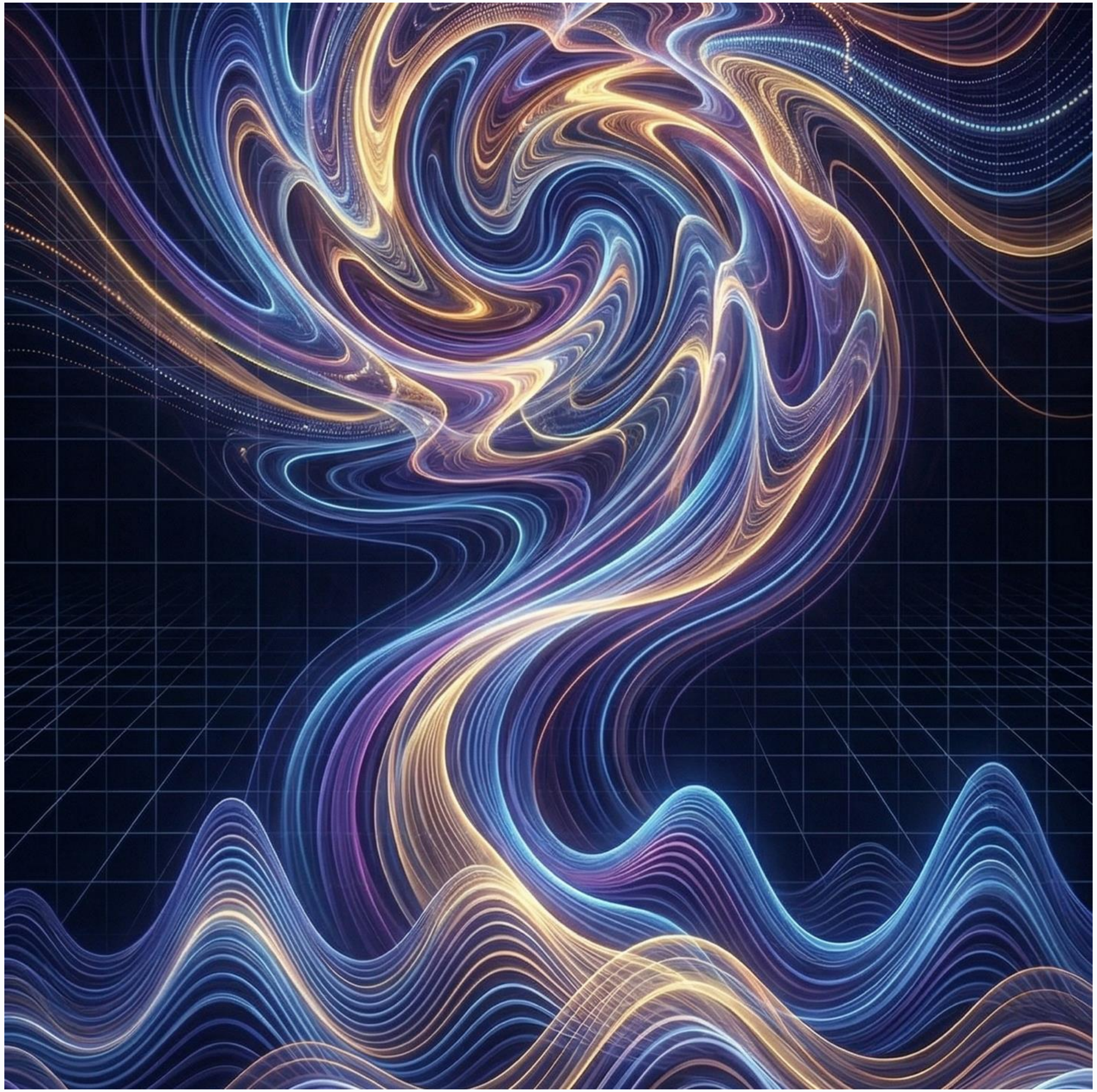
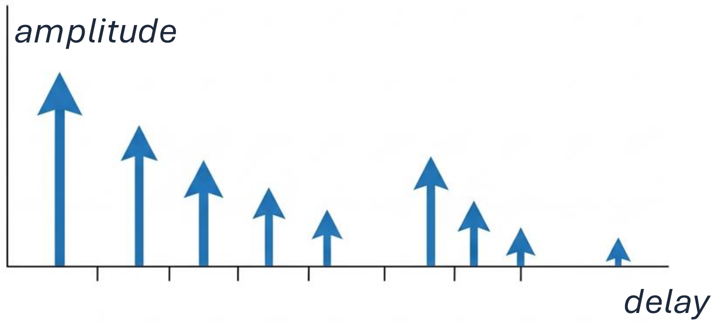


The wireless channel

- Communication channel models $\mathrm{vec}(\mathbf{H}) \sim \mathcal{CN}(\mathbf{0}, \sigma^2 \boldsymbol{I})$
- Rayleigh origin: many paths + central limit theorem
- At higher frequencies:
  - Severe shadowing: paths cannot penetrate objects
  - Objects appear rougher: less reflection
  - Overall fewer propagation paths
- Narrowband model:

$$\mathbf{H} = \sum_{\ell=1}^{N_\mathrm{p}} \alpha_\ell \mathbf{a}_\mathrm{R}(\theta_{\mathrm{R},\ell}) \mathbf{a}_\mathrm{T}^\top(\theta_{\mathrm{T},\ell})$$

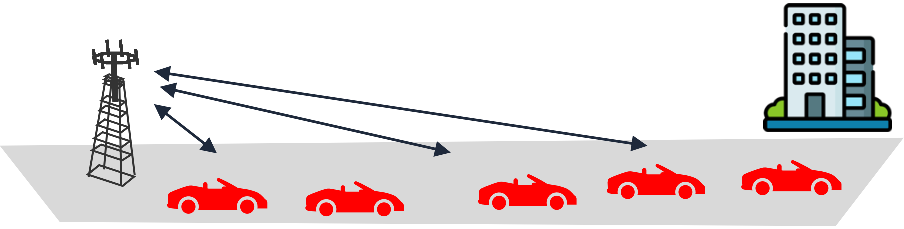


- Wideband model:

$$\mathbf{H}_k = \sum_{\ell=1}^{N_\mathrm{p}} \alpha_\ell \mathbf{a}_\mathrm{R}(\theta_{\mathrm{R},\ell}) \mathbf{a}_\mathrm{T}^\top(\theta_{\mathrm{T},\ell}) e^{-j2\pi k \Delta_f \tau_\ell}$$

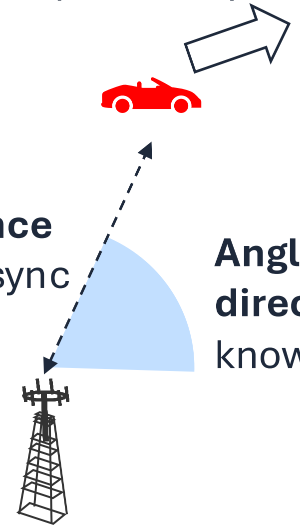
- Localization and sensing use the **same channel** as communication, so **same model**

Measurements from the channel



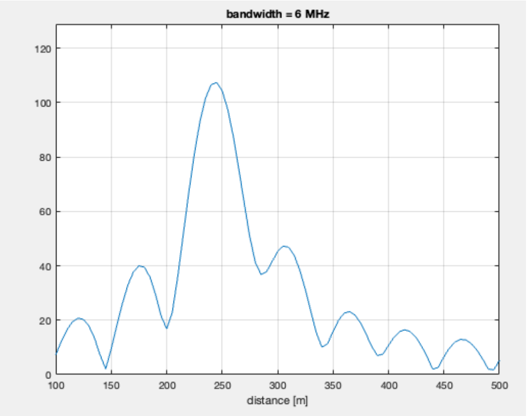
- Several domains available: angle-of-arrival or departure, time-of-arrival, Doppler
- Common model $y_n = \sum_{l=0}^{L} \alpha_l e^{jn\omega_l} + n_n$
- Interpretation of ω depends on *n*:
  - Observations over subcarriers $2\pi\tau_l\Delta_f$
  - Observations over antennas $\pi \sin\theta_l$
  - Observations over time $2\pi\nu_l T_s$
- Estimation is classical harmonic retrieval
- Resolution depends on aperture in frequency, space, time

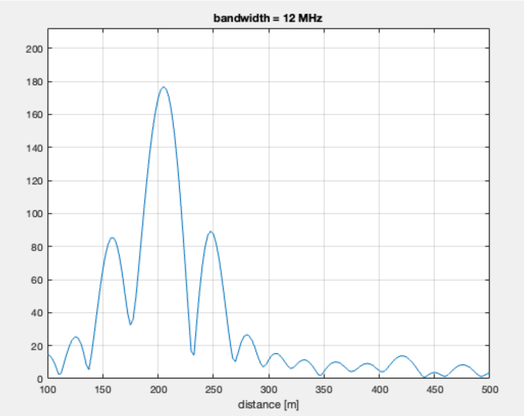
Doppler to (radial) velocity requires frequency sync

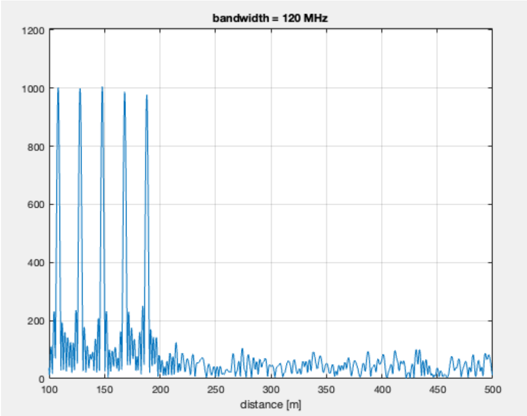


Time to distance requires time sync

Angle to direction requires known orientation







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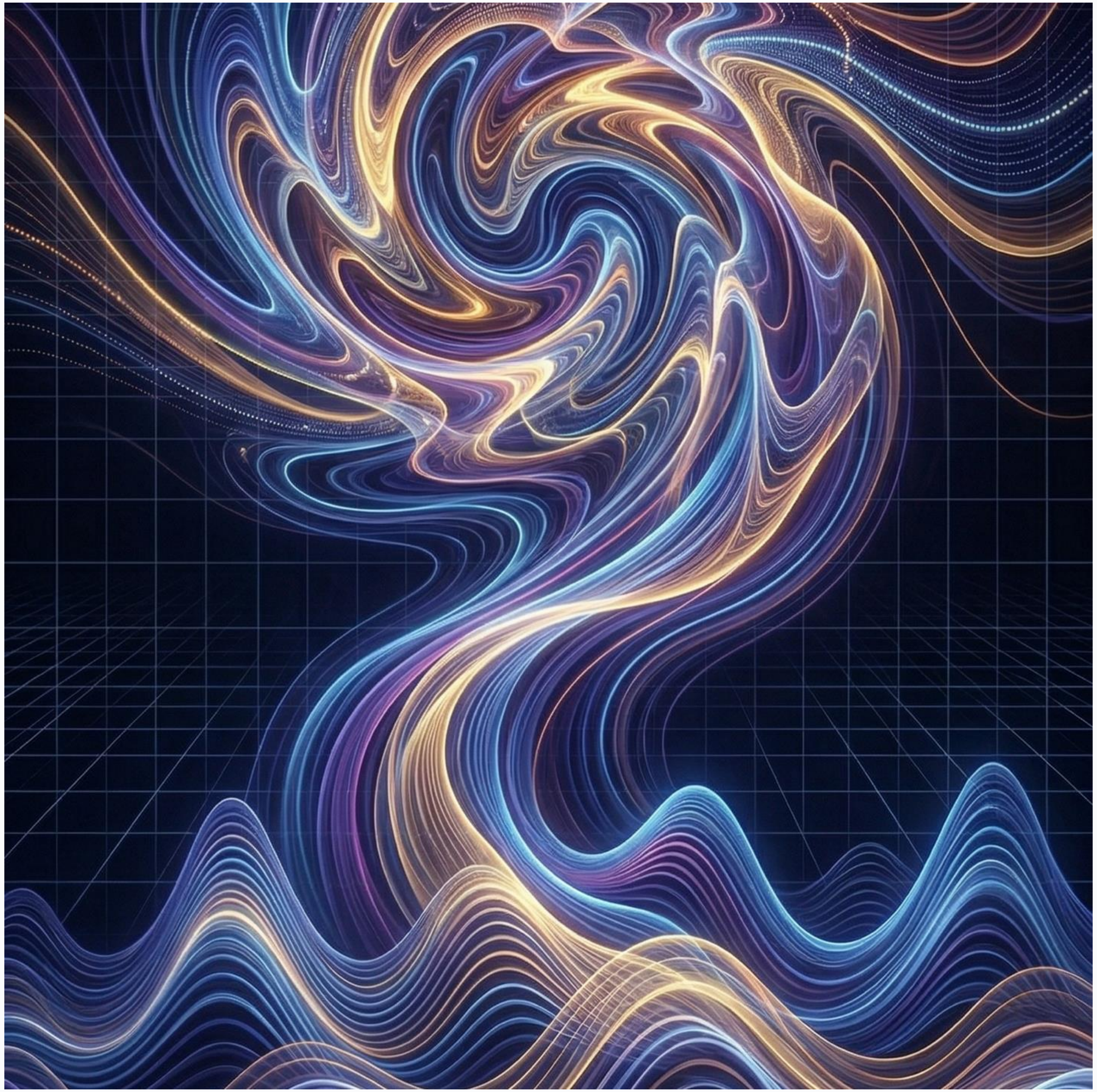


Phase-coherent deployments

- **Classical arrays** are phase coherent

$$\mathbf{r} = \alpha \mathbf{a}(\theta) + \mathbf{n}$$
$$\alpha = \rho \exp(\jmath \phi)$$
$$[\mathbf{a}(\theta)]_n = \exp(-\jmath \pi n \sin(\theta))$$

- **Extra-large arrays** are phase coherent

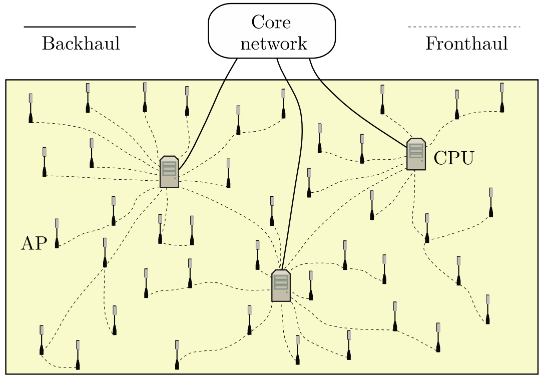
$$\mathbf{r} = \boldsymbol{\alpha} \odot \mathbf{a}(\mathbf{p}) + \mathbf{n}$$
$$[\boldsymbol{\alpha}]_n = \rho_n \exp(\jmath \phi)$$
$$[\mathbf{a}(\mathbf{p})]_n = \exp(-\jmath 2\pi (d_n - d_0)/\lambda)$$
$$d_n = \|\mathbf{p} - \mathbf{p}_n\|$$

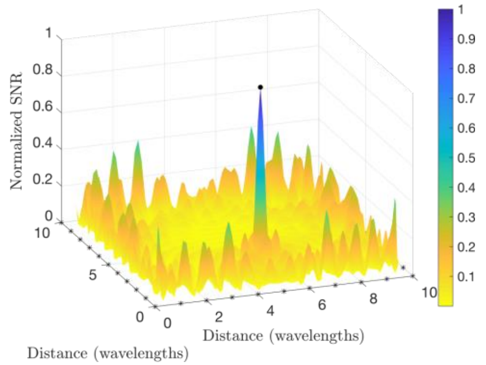
- **Cell-free systems** are phase coherent

- **RTK-GPS** is also phase coherent

- Main idea:
  observed phase relates to distance

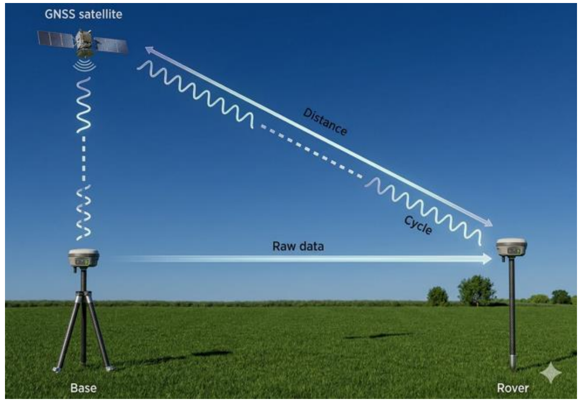
Chen, H., Keskin, M.F., Sakhnini, A., Decarli, N., Pollin, S., Dardari, D. and Wymeersch, H., 2024. 6G localization and sensing in the near field: Features, opportunities, and challenges. IEEE Wireless Communications, 31(4), pp.260-267.





(a) View with normalized SNR (between 0 and 1) on the vertical axis.

Özlem Tuğfe Demir, Emil Björnson and Luca Sanguinetti (2021), "Foundations of User-Centric Cell-Free Massive MIMO", Foundations and Trends® in Signal Processing: Vol. 14, No. 3-4, pp 162–472. DOI: 10.1561/2000000109.



Phase coherence: benefits and challenges

Benefits

- Phase observation provide distance measurement (up to wavelength)
- Widely distributed aperture in D-MIMO provide diverse geometric information

Challenges

- Requires fine synchronization (time, frequency, and phase)
- Requires fine geometric calibration
- Positioning, sensing computationally challenging

Solutions

- Reference nodes can relax sync requirements. Promising signal processing methods, including OTA sync
- In-situ calibration is possible at lower frequency bands
- Good problems for signal processing researchers ☺

Challenging but not impossible

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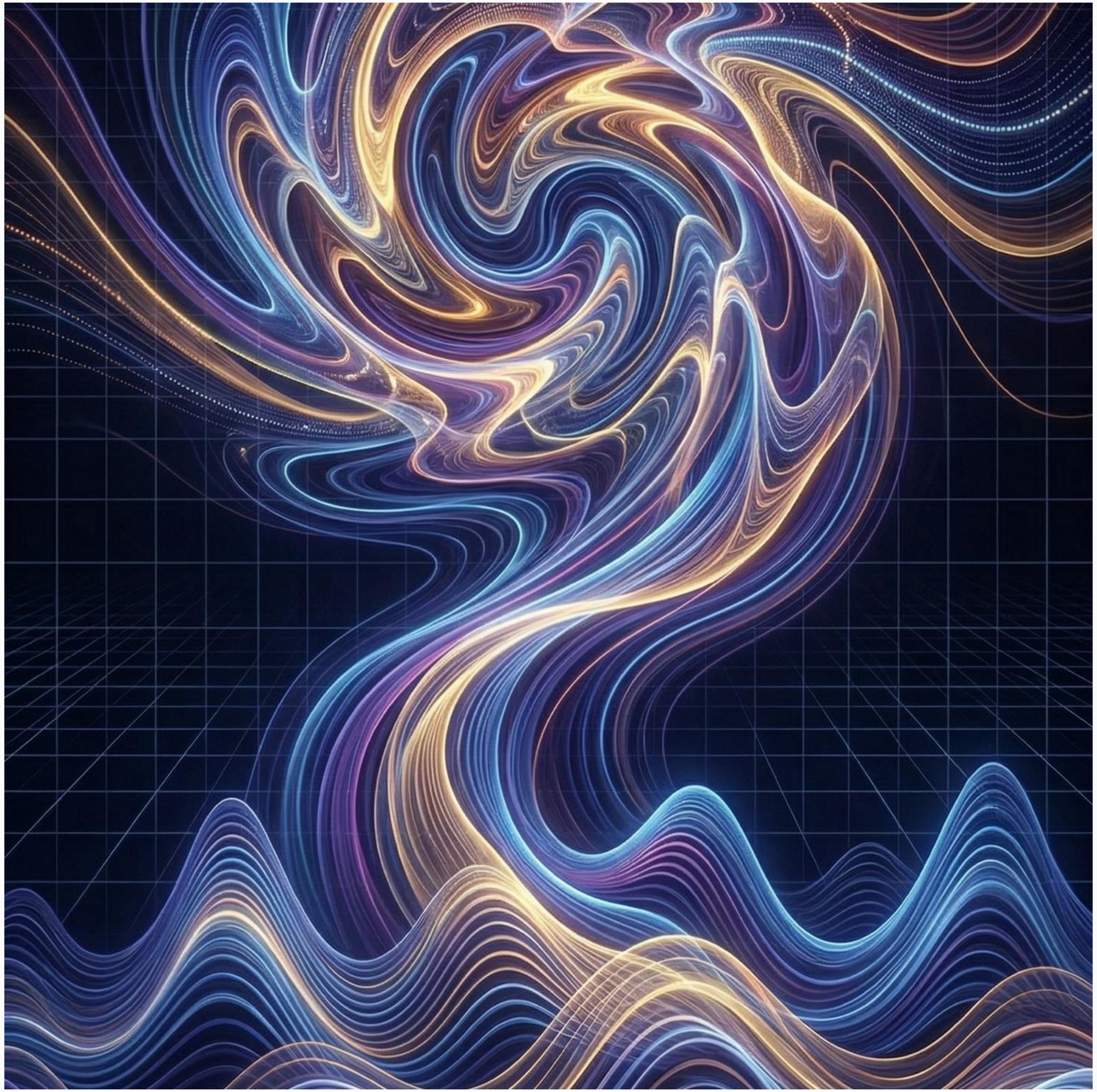


Classical array

Single source model:

$$\mathbf{r} = \alpha \mathbf{a}(\theta) + \mathbf{n}$$
$$\alpha = \rho \exp(\jmath \phi)$$
$$[\mathbf{a}(\theta)]_n = \exp(-\jmath \pi n \sin(\theta))$$

ML estimate:

$$\widehat{\theta}_{\mathrm{ML}} = \arg\max_{\theta} |\mathbf{a}^H(\theta)\mathbf{r}|^2$$

Normalized ambiguity function*:

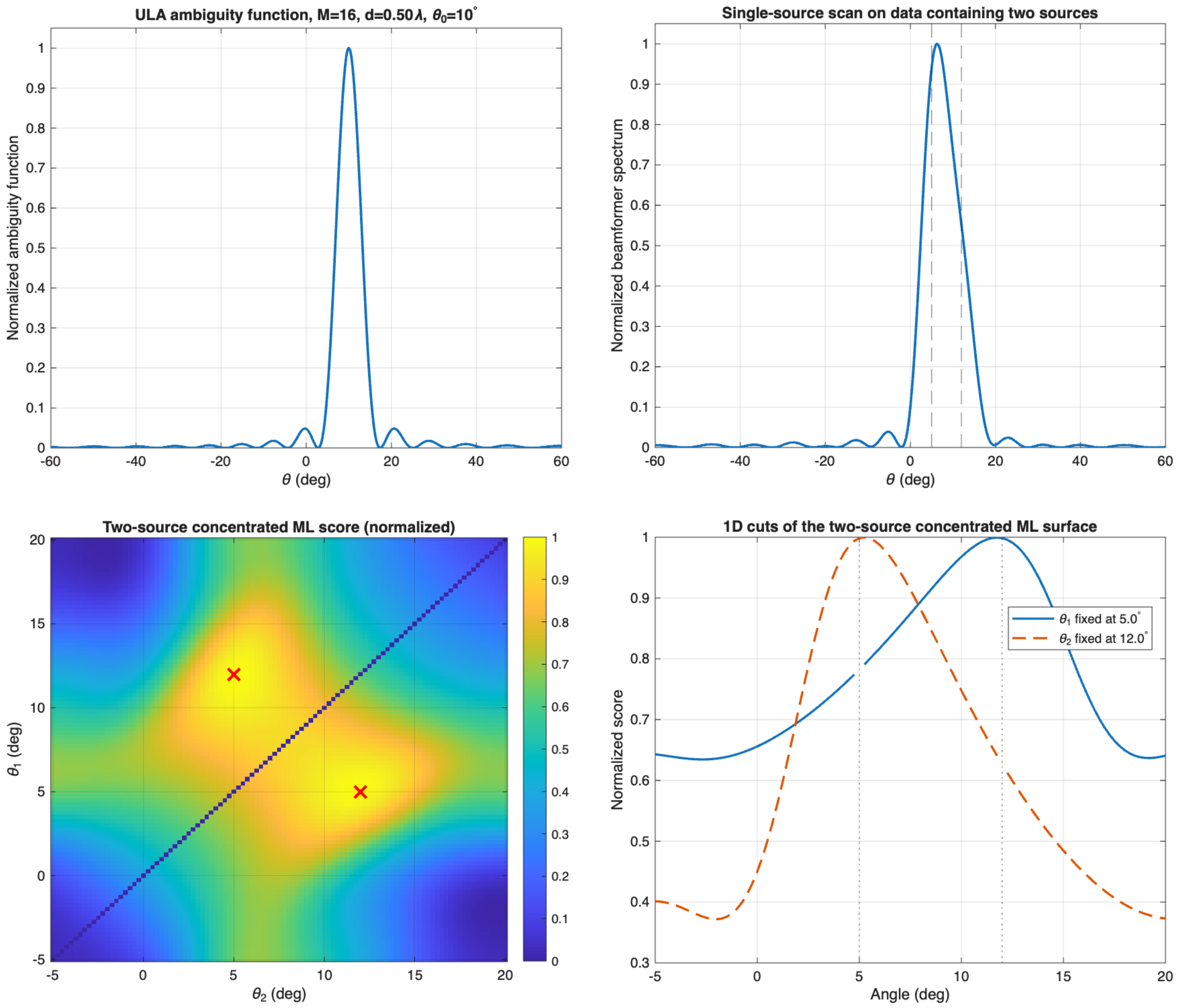
$$\chi(\theta, \theta_0) = \frac{|\mathbf{a}^H(\theta)\mathbf{a}(\theta_0)|^2}{\|\mathbf{a}(\theta)\|^2 \, \|\mathbf{a}(\theta_0)\|^2}$$
$$= \frac{1}{M^2}\left(\frac{\sin(M\psi/2)}{\sin(\psi/2)}\right)^2, \text{with } \psi = \pi\left(\sin\theta - \sin\theta_0\right)$$

Accuracy from Fisher information (curvature of AF)

$$J_{\mathrm{e}}(\theta) = \frac{\pi^2 \rho^2 \, M(M^2-1)\cos^2\theta}{6\sigma^2}$$

Properties:

- CRB does not account for entire AF
- AF is specific to the estimator's model



Everything smooth and well-behaved

*M. J. Rendas and J. M. F. Moura, "Ambiguity in radar and sonar," IEEE Trans. Signal Process., vol. 46, no. 2, pp. 294–305, Feb. 1998.

Widely distributed array

Single source model:

$$\mathbf{r} = \boldsymbol{\alpha} \odot \mathbf{a}(\mathbf{p}) + \mathbf{n}$$
$$[\boldsymbol{\alpha}]_n = \rho_n \exp(j\phi)$$
$$[\mathbf{a}(\mathbf{p})]_n = \exp(-j2\pi(d_n - d_0)/\lambda)$$
$$d_n = \|\mathbf{p} - \mathbf{p}_n\|$$

ML estimate (with $k = 2\pi/\lambda$)

$$\hat{\mathbf{p}}_{\text{ML}} = \arg\max_{\mathbf{p}} \left| \sum_{n=1}^{N} r_n^2 e^{j2k\|\mathbf{p}-\mathbf{p}_n\|} \right|$$

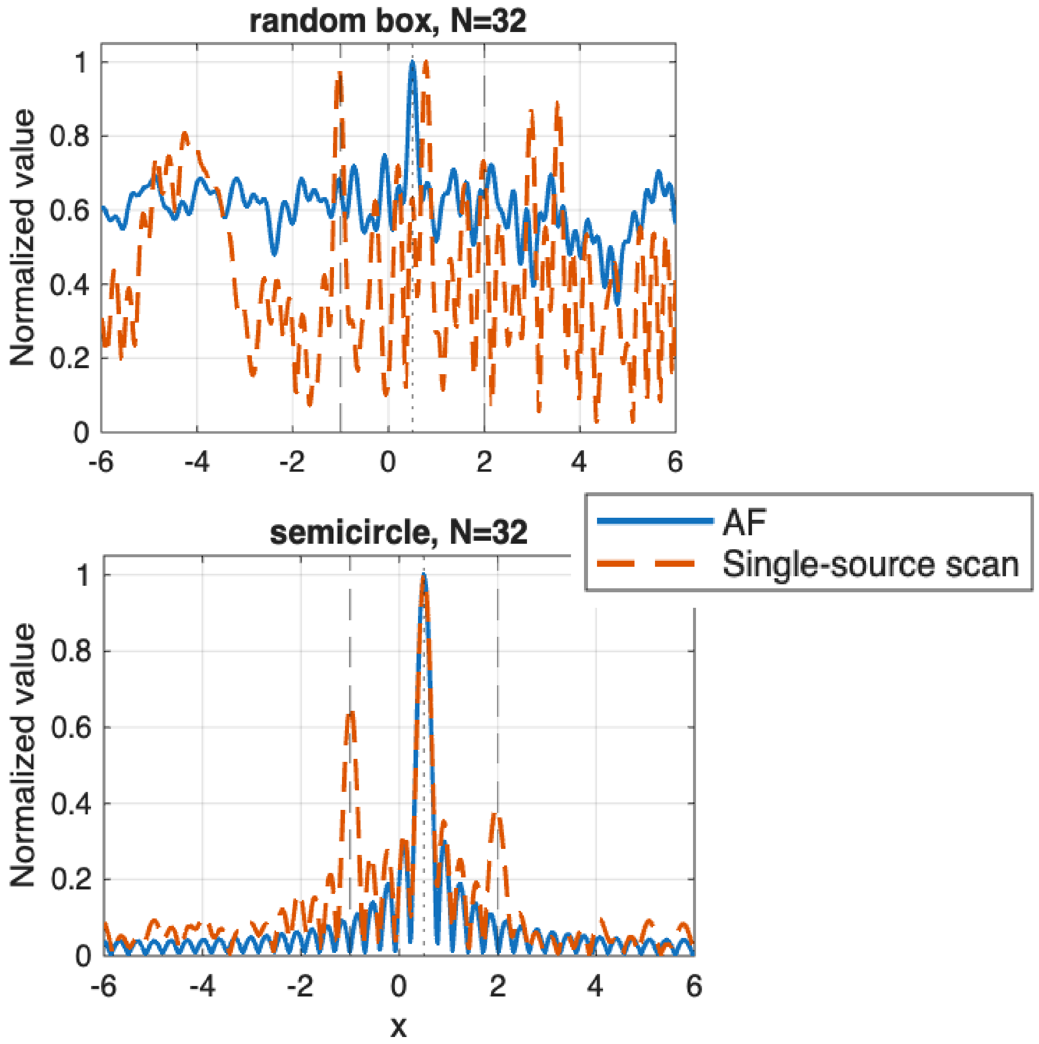
Normalized ambiguity function:

$$\chi(\mathbf{p};\mathbf{p}_0) = \frac{\left|\sum_{n=1}^{N} \rho_{0,n}^2 e^{j2k(\|\mathbf{p}-\mathbf{p}_n\| - \|\mathbf{p}_0-\mathbf{p}_n\|)}\right|}{\|\boldsymbol{\rho}\|^2}$$

Accuracy from Fisher information:

$$\mathbf{J}_{\text{e}}(\mathbf{p}) = \frac{2k^2}{\sigma^2} \sum_{n=1}^{N} \rho_n^2 (\mathbf{q}_n - \bar{\mathbf{q}})(\mathbf{q}_n - \bar{\mathbf{q}})^T$$

$$\bar{\mathbf{q}} = \frac{\sum_{n=1}^{N} \rho_n^2 \mathbf{q}_n}{\sum_{n=1}^{N} \rho_n^2}$$



Performance limited by ambiguities (CRB only at very high SNR)
Ambiguities limited by the deployment

Understanding the ambiguity function

- **Model:**

$$\mathbf{r} = \boldsymbol{\alpha} \odot \mathbf{a}(\mathbf{p}) + \mathbf{n}$$
$$[\boldsymbol{\alpha}]_n = \rho_n \exp(j\phi)$$
$$[\mathbf{a}(\mathbf{p})]_n = \exp(-j2\pi(d_n - d_0)/\lambda)$$
$$d_n = \|\mathbf{p} - \mathbf{p}_n\|$$

- **Nuisance-amplitude AF:**

$$\chi(\mathbf{p};\mathbf{p}_0) = \frac{\left|\sum_{n=1}^{N} \rho_{0,n}^2 e^{j2k(\|\mathbf{p}-\mathbf{p}_n\| - \|\mathbf{p}_0-\mathbf{p}_n\|)}\right|}{\|\boldsymbol{\rho}\|^2}$$

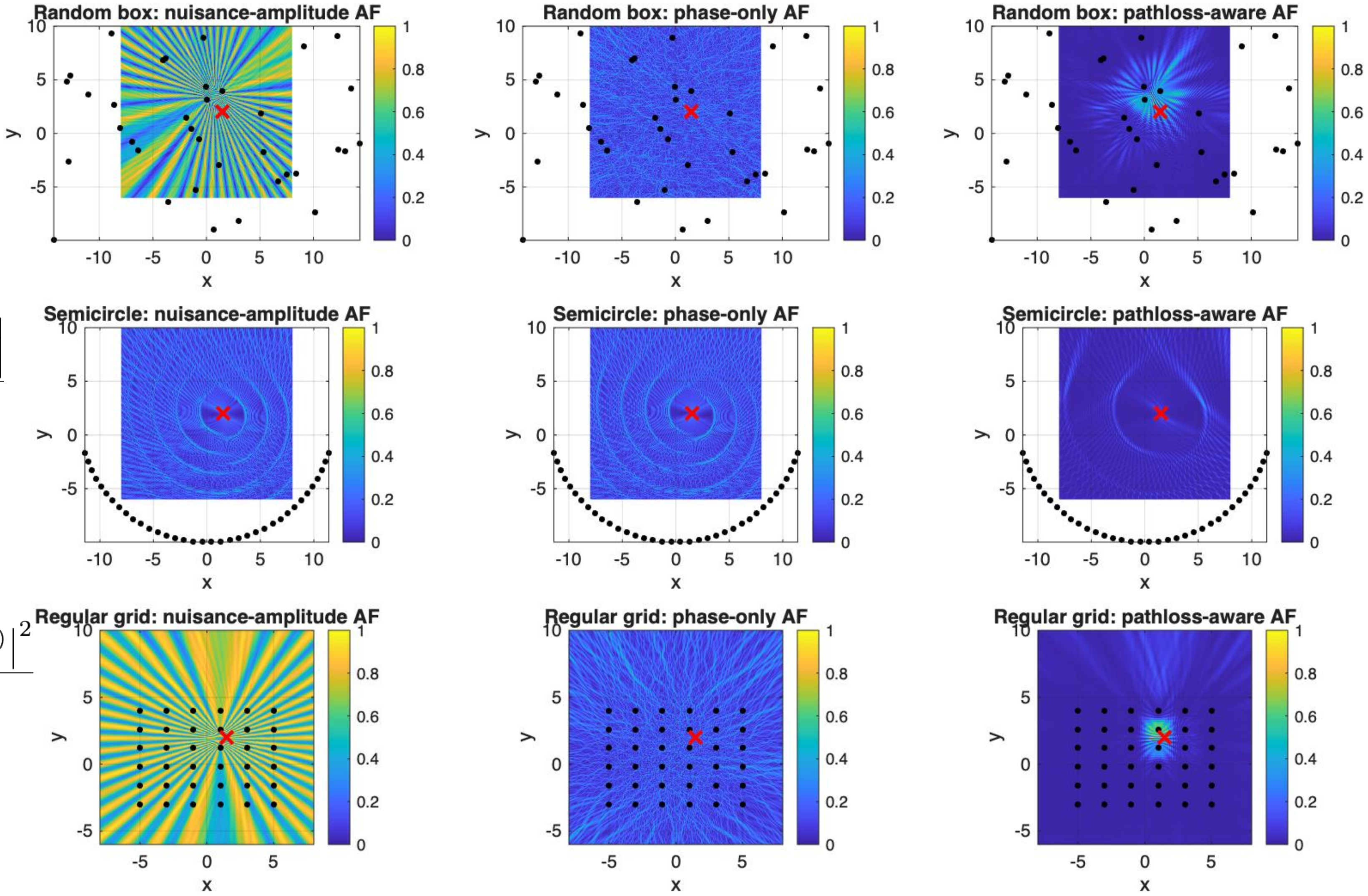
- **Phase-only AF (mismatched):**

$$\chi(\mathbf{p};\mathbf{p}_0) = \frac{\left|\mathbf{a}^H(\mathbf{p})\mathbf{a}(\mathbf{p}_0)\right|^2}{\|\mathbf{a}(\mathbf{p})\|^2\|\mathbf{a}(\mathbf{p}_0)\|^2}$$

- **Pathloss-aware AF:**

$$\chi(\mathbf{p};\mathbf{p}_0) = \frac{\left|\sum_n g_n(\mathbf{p}) g_n(\mathbf{p}_0) e^{jk(d_n(\mathbf{p}) - d_n(\mathbf{p}_0))}\right|^2}{\left(\sum_n g_n(\mathbf{p})^2\right)\left(\sum_n g_n(\mathbf{p}_0)^2\right)}$$

$$g_n(\mathbf{p}) = \frac{\beta}{d_n(\mathbf{p})^\gamma}$$



- **Improve AF:** deployment, frequency, antennas, bandwidth

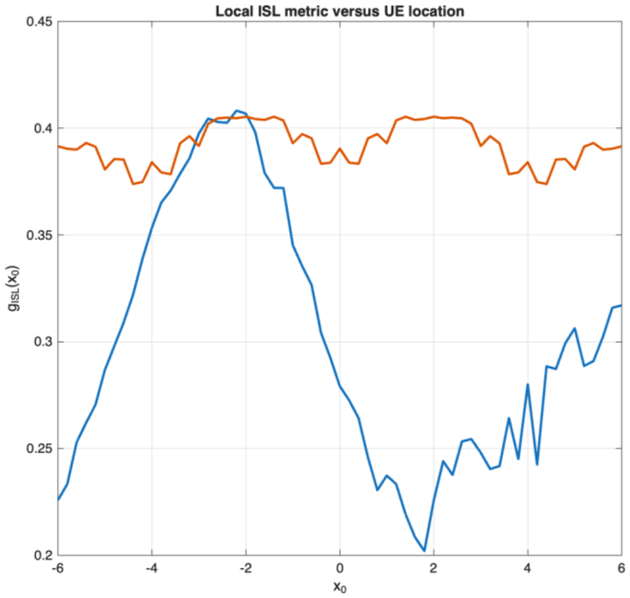
Improving the ambiguity function: metrics

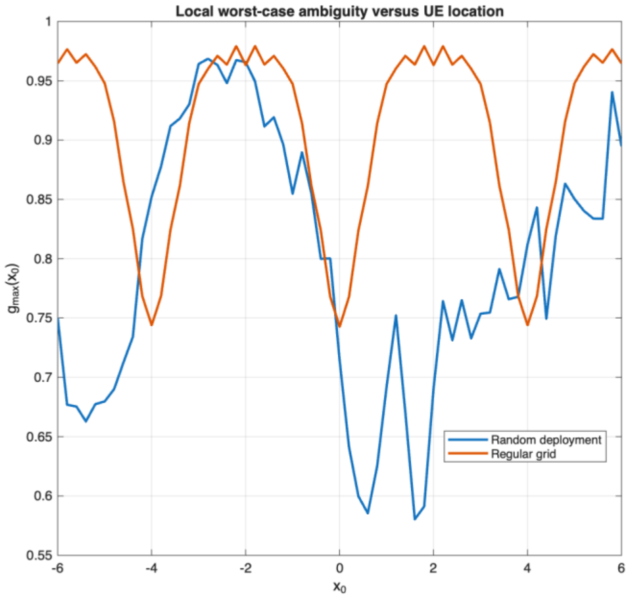
- AF preference: narrow main lobe and limited sidelobes
- Possible metrics
  - Integrated sidelobe level:

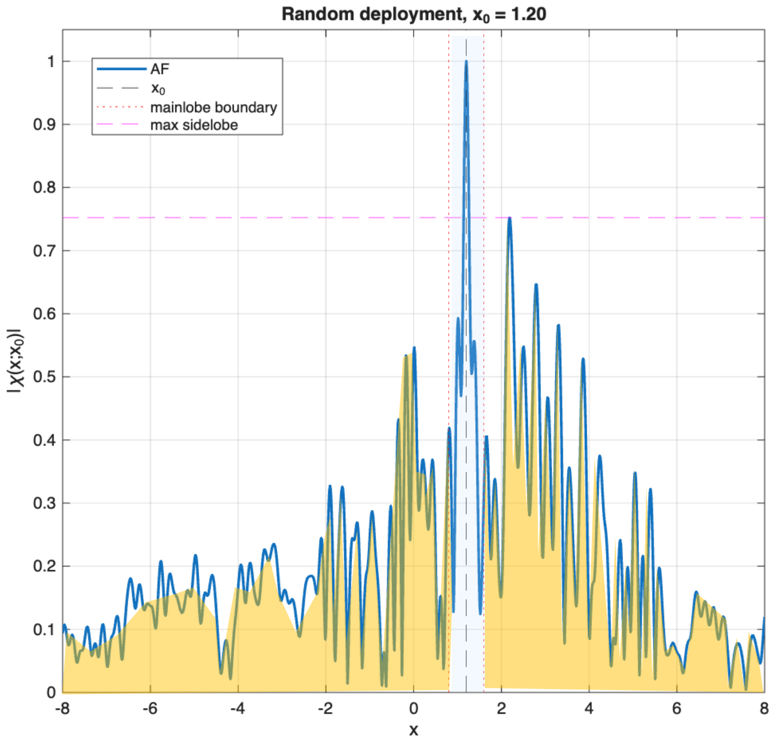
$$g_{\mathrm{ISL}}(\mathcal{R}) = \left(\mathrm{mean}_{\mathbf{p}_0 \in \mathcal{P}}\ \mathrm{mean}_{\mathbf{p} \in \mathcal{U}(\mathbf{p}_0)} |\chi(\mathbf{p}; \mathbf{p}_0)|^2\right)^{1/2}$$

  - Max. sidelobe level:

$$g_{\max}(\mathcal{R}) = \max_{\mathbf{p}_0 \in \mathcal{P},\ \mathbf{p} \in \mathcal{U}(\mathbf{p}_0)} |\chi(\mathbf{p}; \mathbf{p}_0)|$$







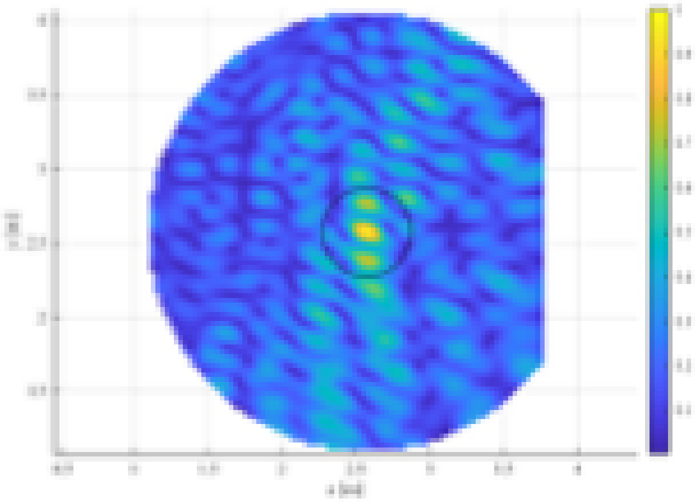
Metrics change slowly over space

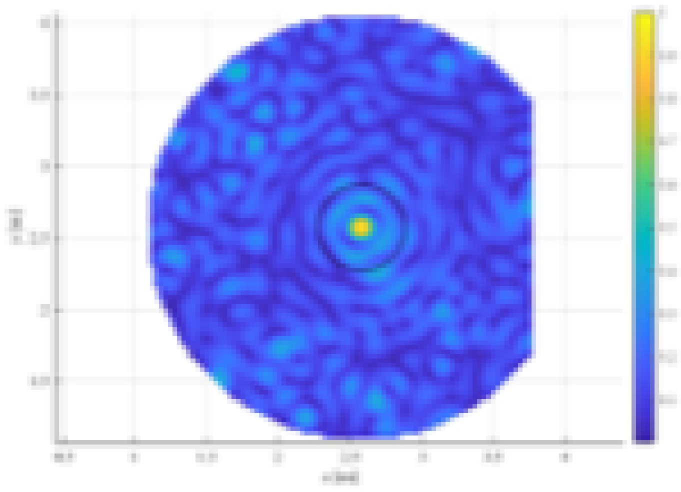
Improving the ambiguity function by *deployment optimization*

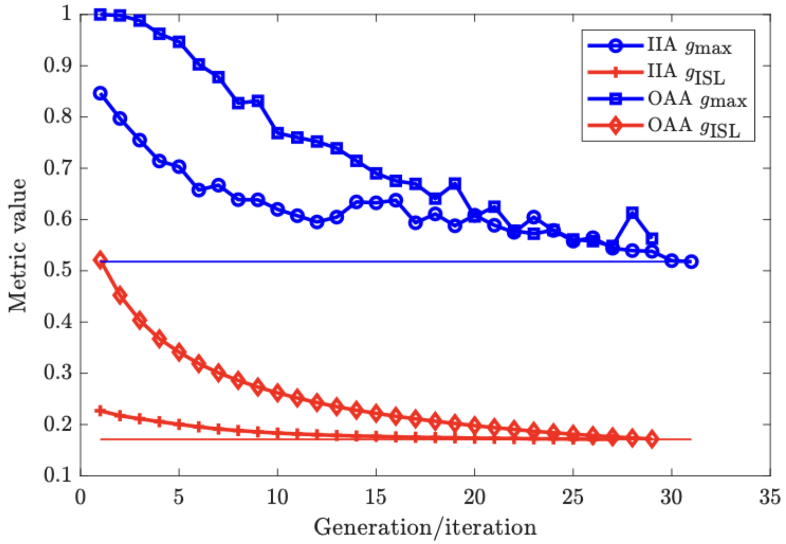
- Challenging non-convex, combinatorial problems

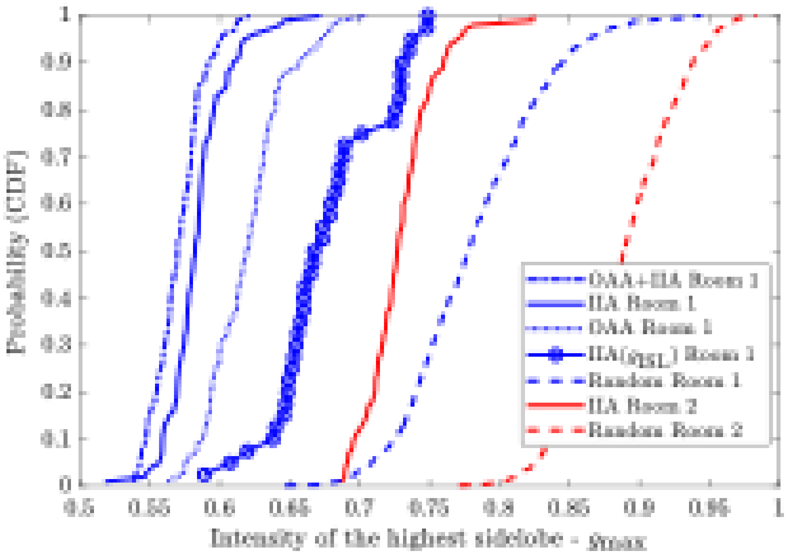
$$\min_{\mathcal{R}} \; g(\mathcal{R}) \qquad \min_{\mathcal{R}} \; |\mathcal{R}| \quad \text{s.t.} \quad g(\mathcal{R}) \leq \gamma$$

- Solved via heuristics (e.g., greedy methods)









Vukmirović, N., Erić, M., Wymeersch, H., Keskin, M.F., Ge, Y. and Djurić, P., 2026, January. Deployment Optimization for Uplink Phase-Coherent Localization. In 2026 IEEE 6th International Symposium on Joint Communications & Sensing (JC&S) (pp. 1-6). IEEE.

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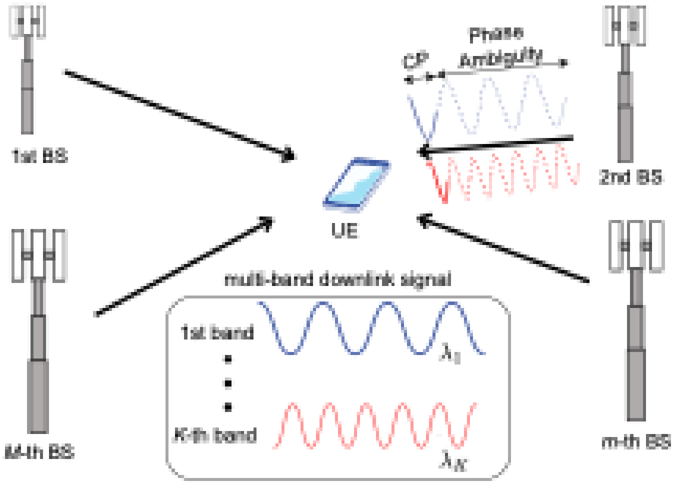
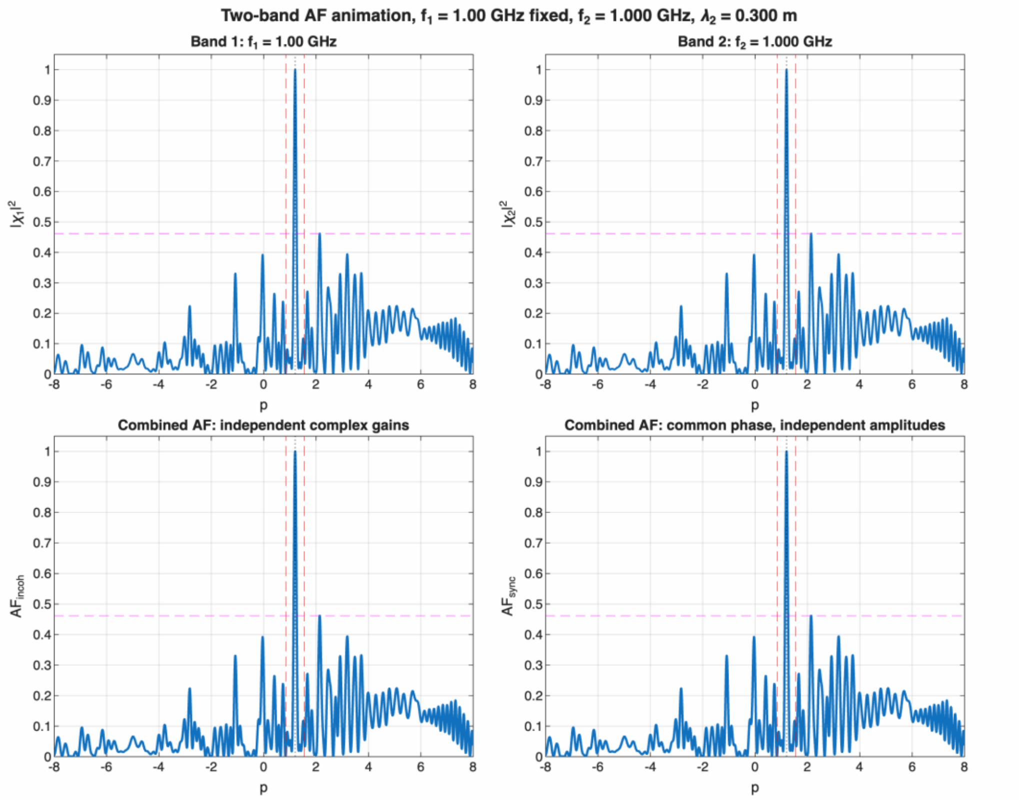
Improving the ambiguity function by *adding frequencies*



- Start with a few subcarriers, node *m*, band *k*:

$$\boldsymbol{y}_{m,k} = \sqrt{E_{s,k}}\alpha_{m,k}\boldsymbol{d}(\tau_{m,k}) + \boldsymbol{\omega}_{m,k},$$

- Each band has some finite bandwidth, provides initial estimate from time-of-arrival
- Ambiguities for different bands don't overlap



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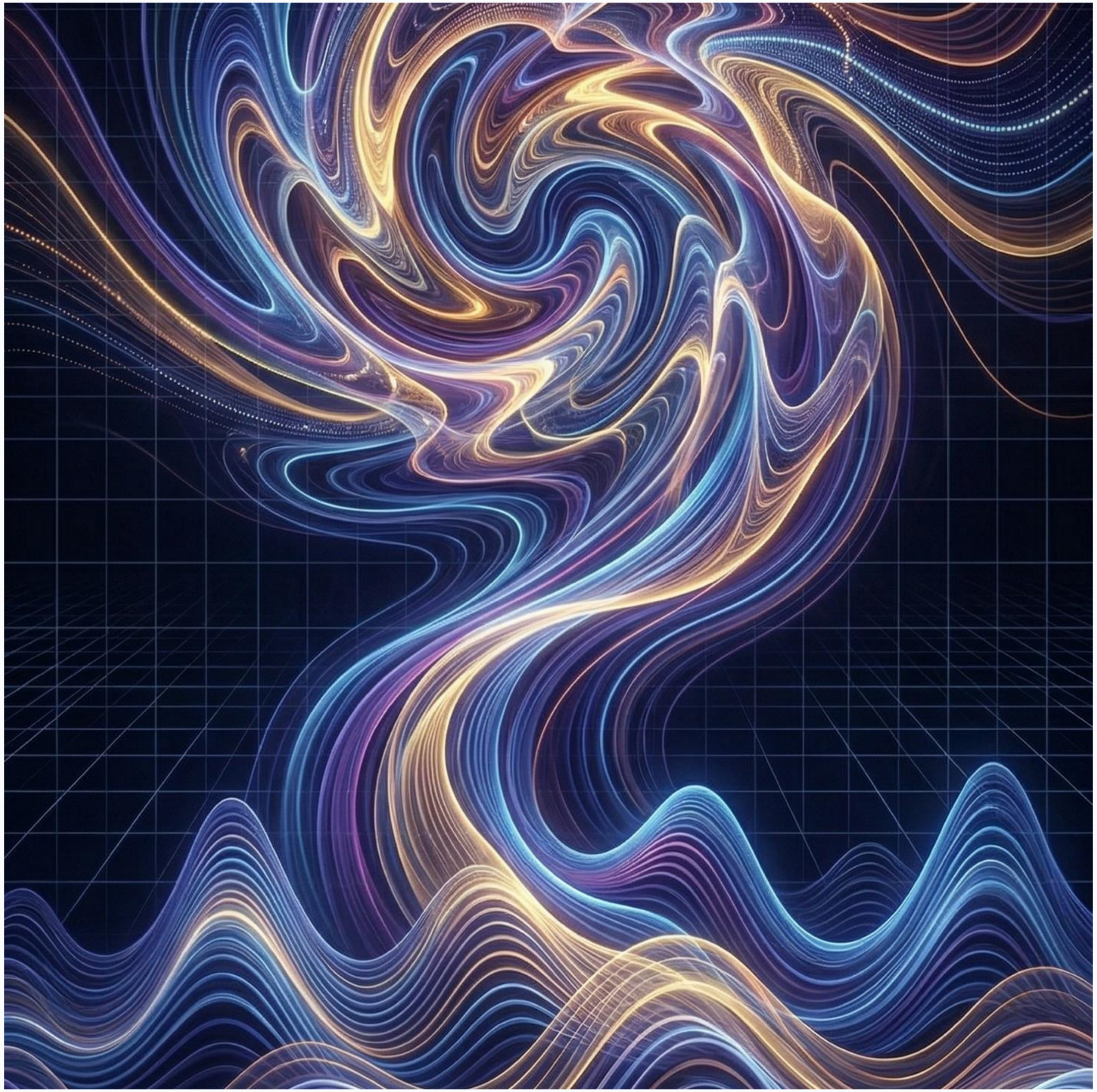


Localization under *negligible* bandwidth?

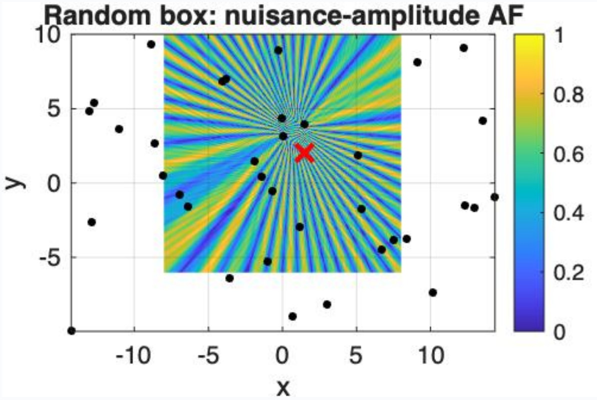
- Model under negligible bandwidth

$$\begin{aligned} \mathbf{r} &= \boldsymbol{\alpha} \odot \mathbf{a}(\mathbf{p}) + \mathbf{n} \\ [\boldsymbol{\alpha}]_n &= \rho_n \exp(j\phi) \\ [\mathbf{a}(\mathbf{p})]_n &= \exp(-j2\pi(d_n - d_0)/\lambda) \\ d_n &= \|\mathbf{p} - \mathbf{p}_n\| \end{aligned}$$

- Just one complex scalar per AP
- Transmit signal does not need to be known
- Estimator

$$\hat{\mathbf{p}}_{\mathrm{ML}} = \arg\max_{\mathbf{p}} \left| \sum_{n=1}^{N} r_n^2 e^{j2k\|\mathbf{p}-\mathbf{p}_n\|} \right|$$

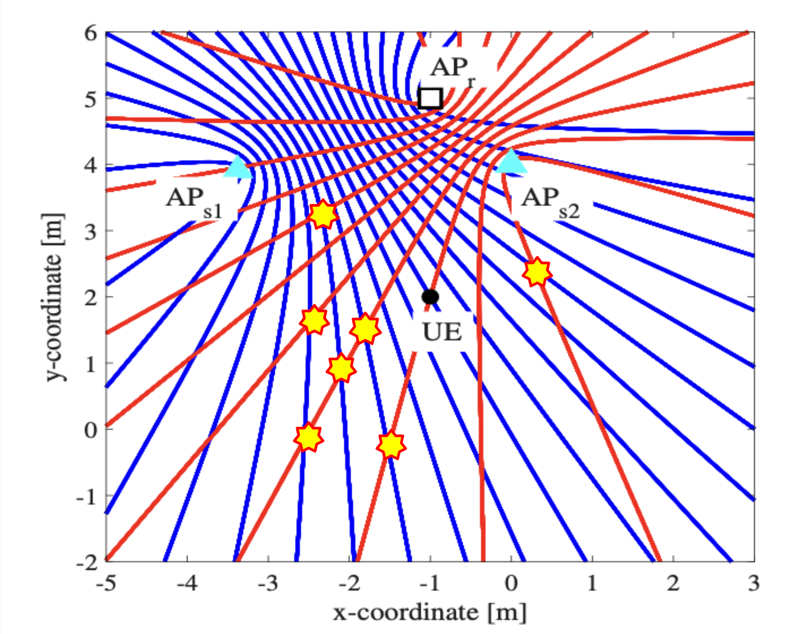
- AF may look random but has structure!



- For any pair of APs: differential phase measurement determines a family of hyperbola

$$\|\mathbf{p}_{s_1} - \mathbf{p}\| - \|\mathbf{p}_r - \mathbf{p}\| = \Delta r_{s_1} - z_{s_1}\lambda, z_{s_1} \in \mathbb{Z}$$

- A triplet of APs (common reference) determines a discrete set of points
- These points can be determined in closed form!



Insight: Number of candidate points scales with distance between APs.

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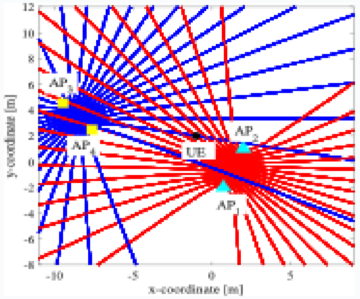
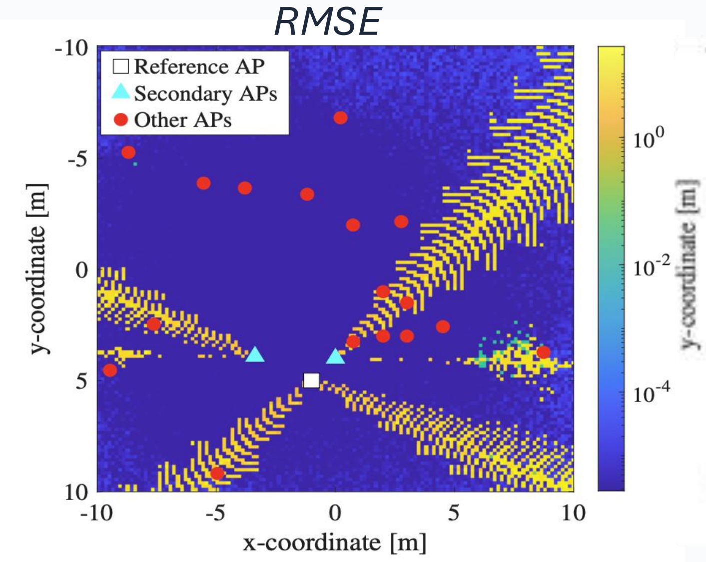
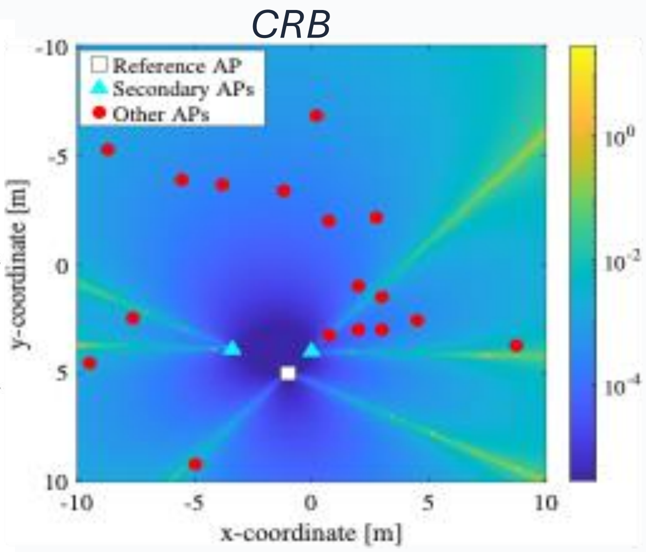
Phase-only localization (POLO)

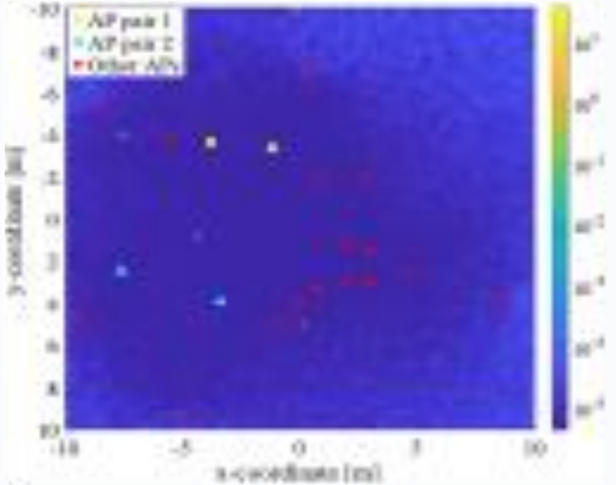
- Which APs to select?
- **POLO-I: at least 3 APs needed**
  - **Insight 1:** Number of candidate point scales with distance between APs. Use as an initial filter.
  - **Insight 2:** CRB considering 3 APs is correlated with RMSE from all APs (considering discrete locations from candidate APs). Use to select best APs
  - Regions with infinite CRB (coverage issue)
- **POLO-II: what about 4 APs?**
  - Select 4 APs to overcome coverage issue

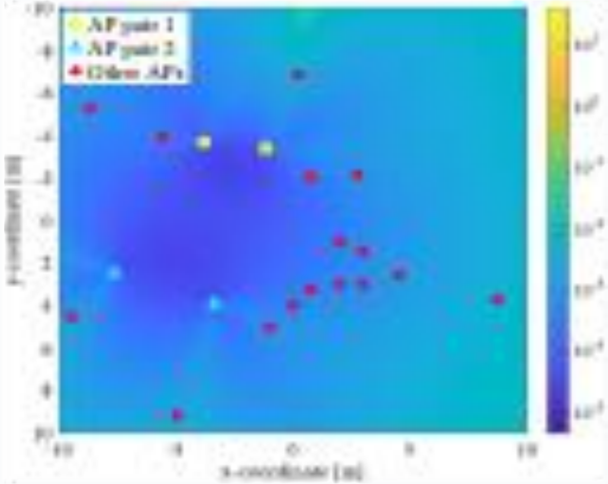


  - But no longer closed-form intersections



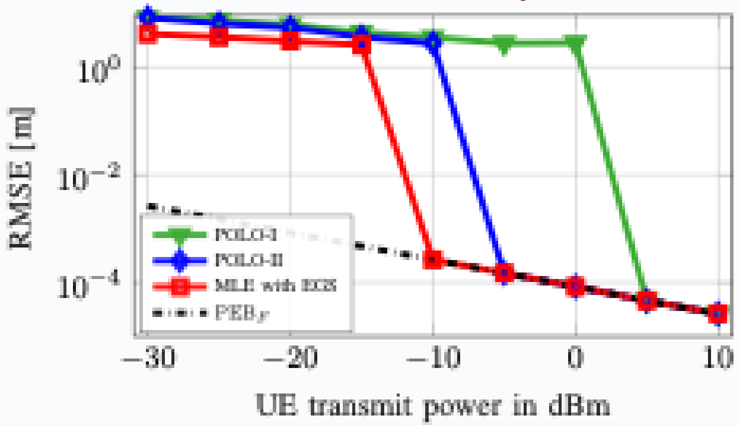




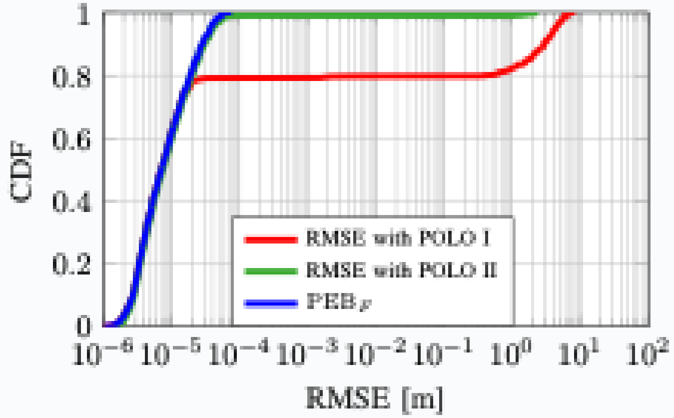


Beyond bandwidth localization: Performance

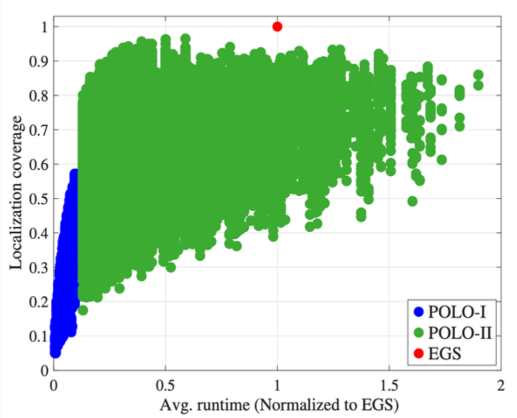
Accuracy



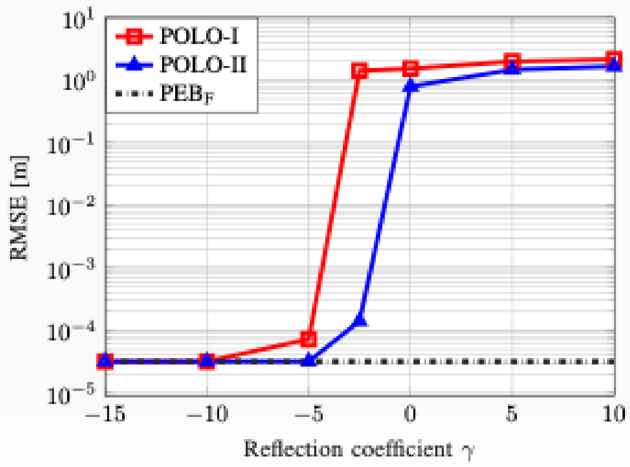
Coverage for 1 selection of APs



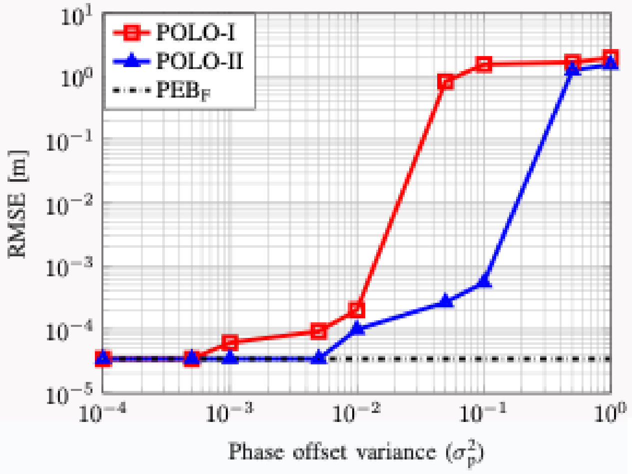
Complexity-performance

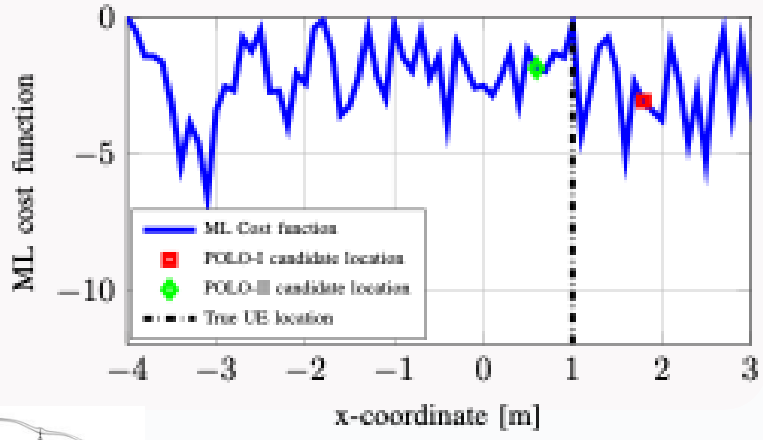


No robustness to multipath



Tight synchronization needed





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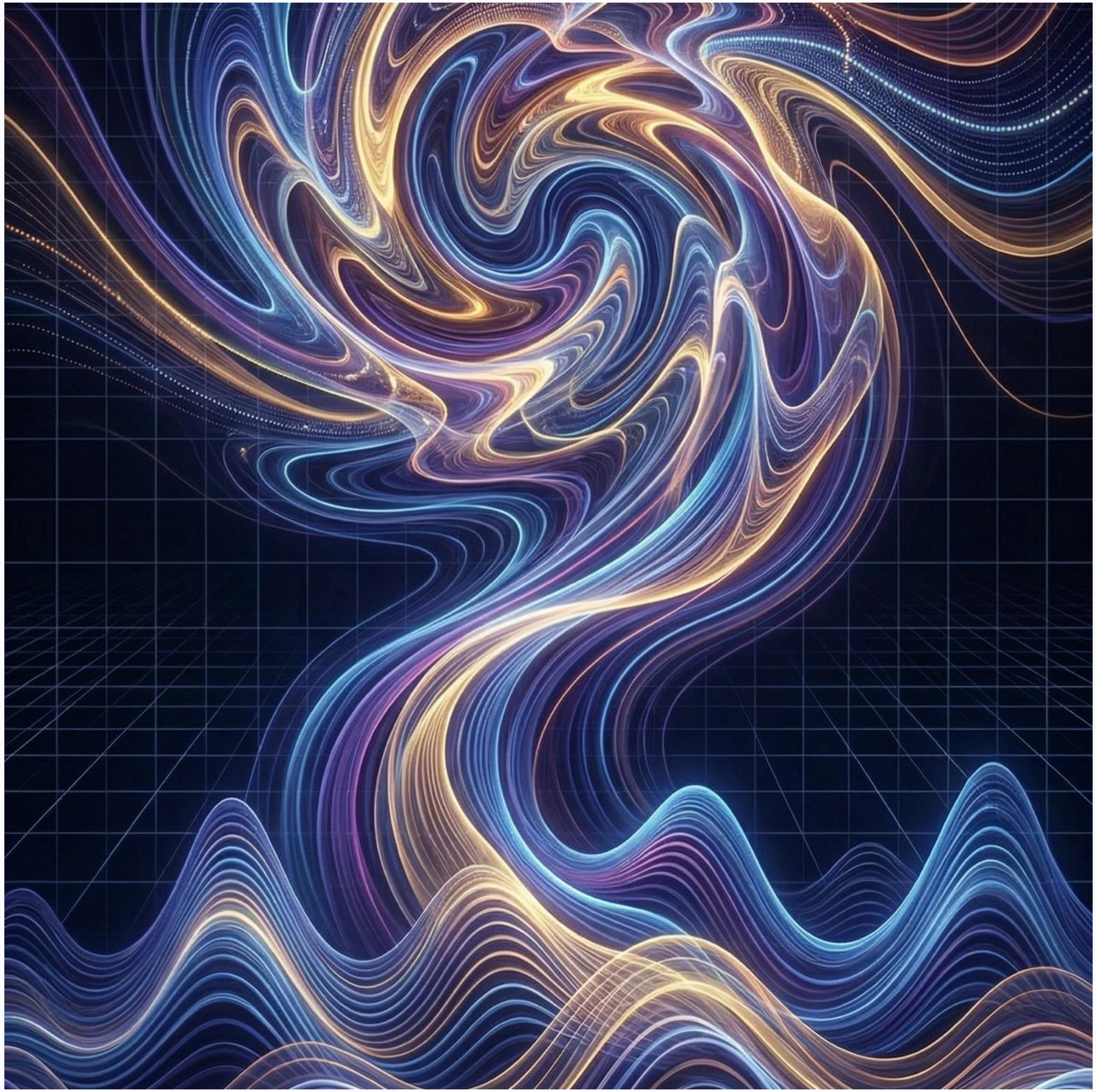
Outline

- Foundations of localization and sensing
- Phase-coherent deployments
- Accuracy, resolution, and ambiguity
- Beyond bandwidth localization
- **Beyond bandwidth sensing and imaging**
- Beyond bandwidth ISAC
- Conclusions
- References



~~Localization~~ Sensing under *negligible* bandwidth?

- In sensing, the multipath is of interest
- Requires a generative geometric model

$$y^n = \sqrt{E} \sum_{m=0}^{M} \rho^{m,n} e^{\jmath\theta^m} e^{-\jmath 2\pi f_c \tau^{m,n}} \zeta + w^n$$

- Several types of paths, e.g.:
  - LOS (calibrated UE):

$$\rho^{0,n} = \frac{\lambda}{4\pi \|\boldsymbol{x} - \boldsymbol{x}^n_{\mathrm{AP}}\|} \qquad \tau^{0,n} = \frac{\|\boldsymbol{x} - \boldsymbol{x}^n_{\mathrm{AP}}\|}{c}$$

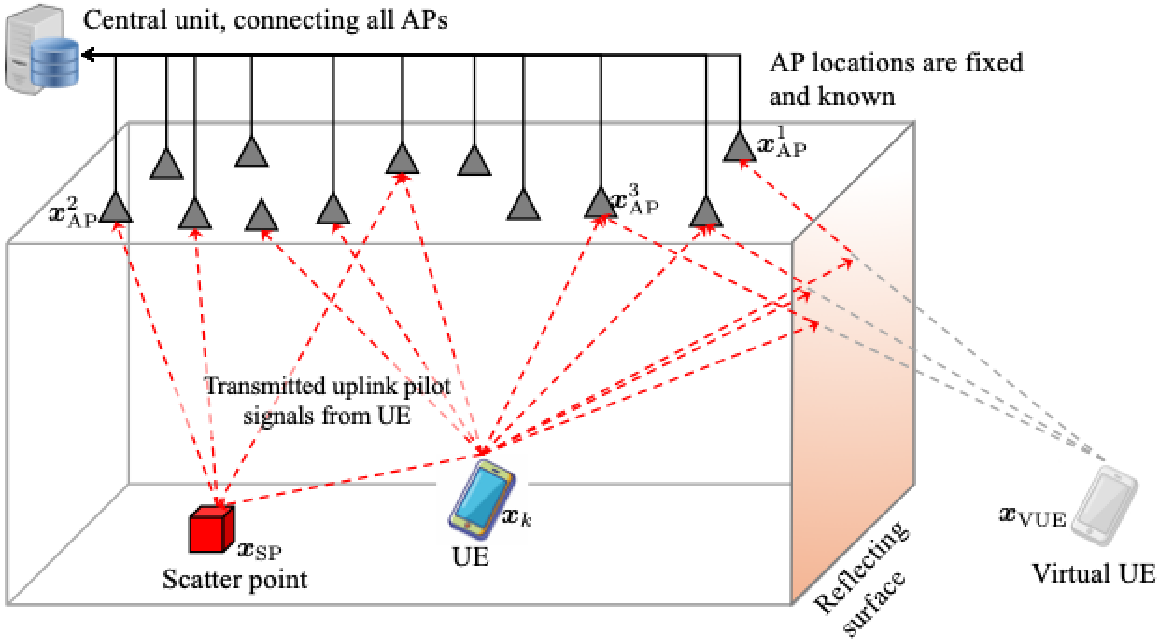
  - Scattering (isotropic!):

$$\rho^{m,n} = \frac{\lambda\beta}{(4\pi)^{3/2} \|\boldsymbol{x}^n_{\mathrm{AP}} - \boldsymbol{x}_{\mathrm{SP}}\| \|\boldsymbol{x} - \boldsymbol{x}_{\mathrm{SP}}\|}$$

$$\tau^{m,n} = \frac{\|\boldsymbol{x}^n_{\mathrm{AP}} - \boldsymbol{x}_{\mathrm{SP}}\| + \|\boldsymbol{x} - \boldsymbol{x}_{\mathrm{SP}}\|}{c}$$

  - Reflection:

$$\tau^{m,n} = \frac{\|\boldsymbol{x}^n_{\mathrm{AP}} - \boldsymbol{x}_{\mathrm{VUE}}\|}{c} \qquad \rho^{m,n} = \frac{\lambda\Gamma}{4\pi \|\boldsymbol{x}^n_{\mathrm{AP}} - \boldsymbol{x}_{\mathrm{VUE}}\|}$$



Insight: Unified geometric model under isotropic conditions

Sensing processing

- Aggregate observation:

$$\boldsymbol{y} = \zeta \sum_{m=0}^{M} \boldsymbol{\rho}^m \odot \boldsymbol{a}^m(\boldsymbol{x}, \boldsymbol{x}_{\mathrm{LM}}^m) + \boldsymbol{w}$$

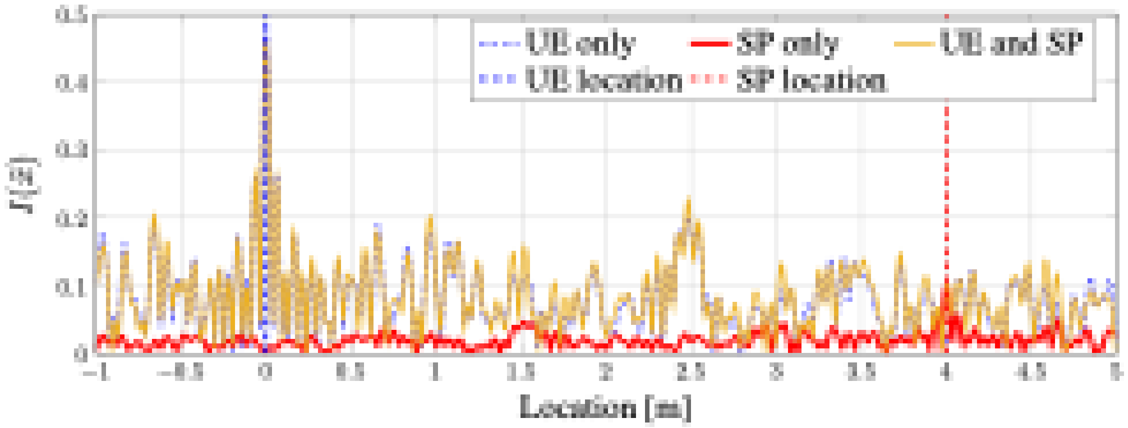
- Define steering vector:

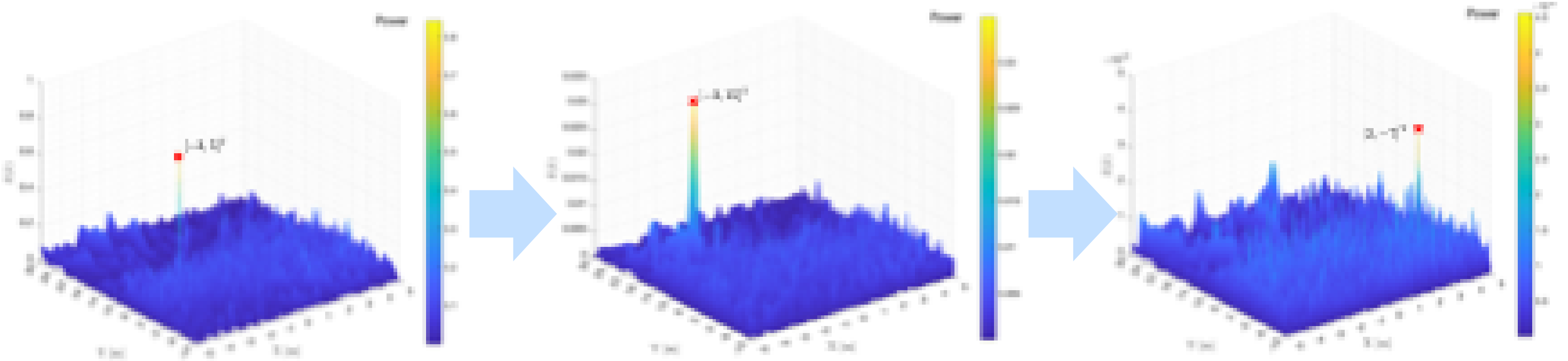
$$[\mathbf{a}(\tilde{\boldsymbol{x}})]_n = e^{-\jmath 2\pi f_c \tau^n(\tilde{\boldsymbol{x}})}$$

- Then an image can be formed as:

$$I(\tilde{\boldsymbol{x}}) = \left|H(\tilde{\boldsymbol{x}})\right|^2 = \left|\mathbf{a}^H(\tilde{\boldsymbol{x}})\boldsymbol{y}\right|^2$$

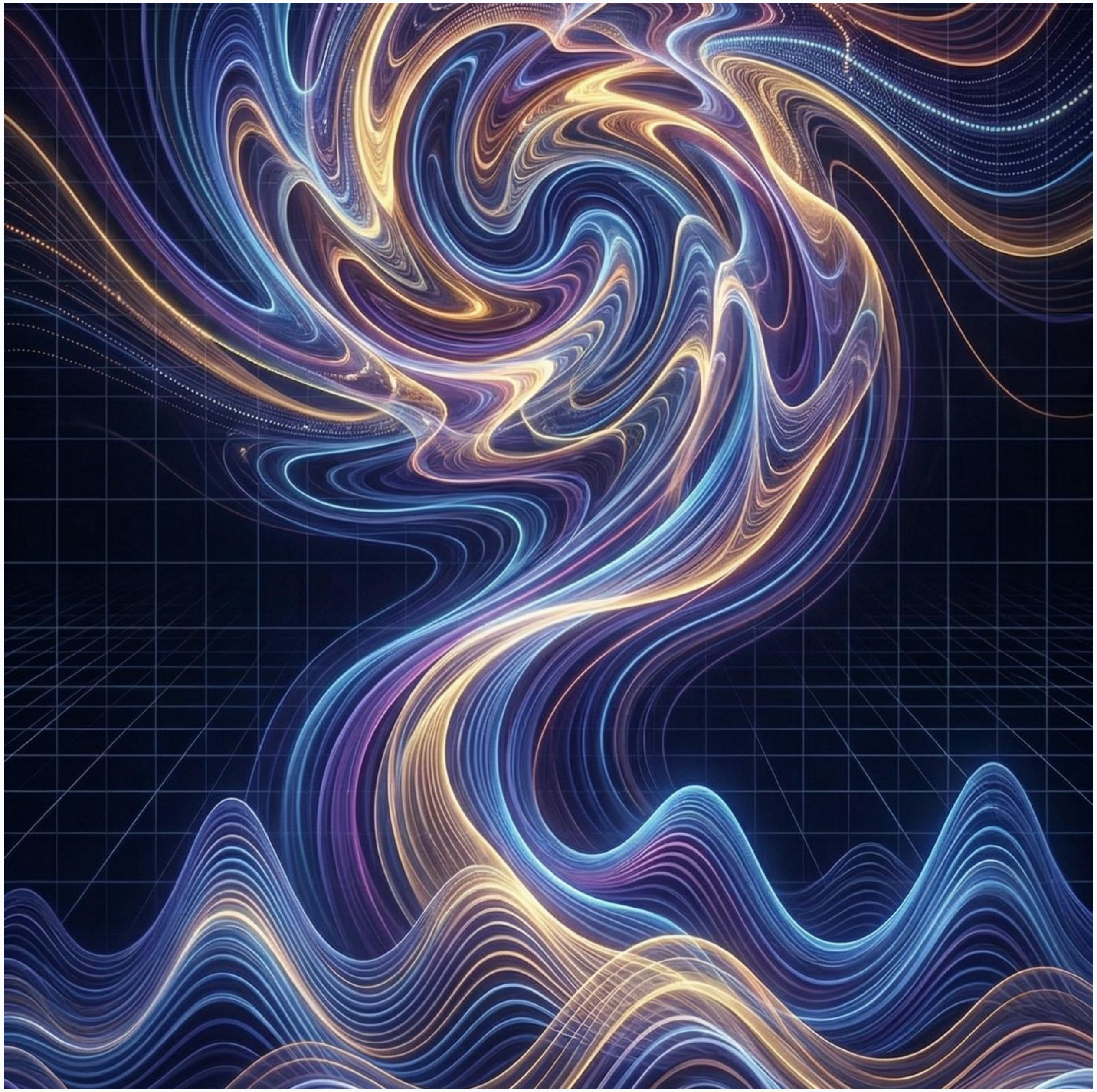
- Weak paths drown in sidelobes of strong paths
- Successive interference cancellation can be applied
- Considering path loss improves performance



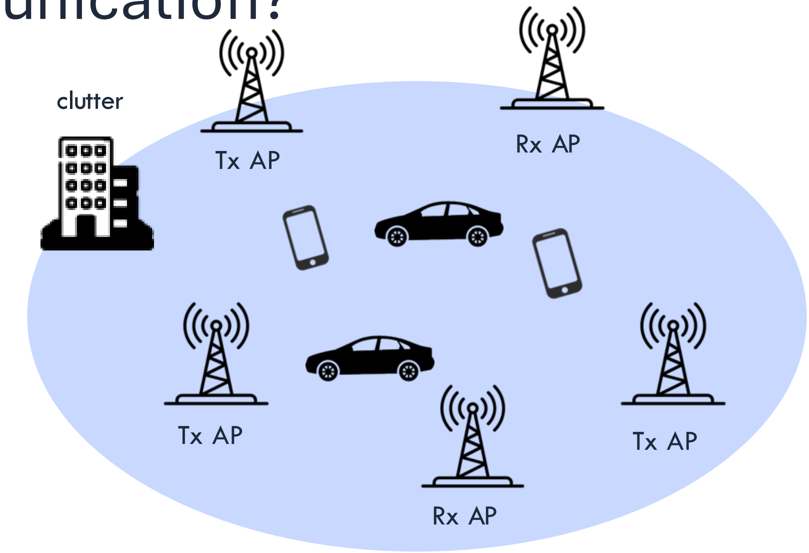


Yu Ge, Xin Tong, Nenad Vukmirovic, Musa Furkan Keskin, Miljko Eric, Petar Djuric, Henk Wymeersch, "Uplink Single-Snapshot Frugal SLAM in Phase-Coherent Distributed MIMO Systems", submitted to IEEE Globecom 2026.

Outline



Beyond bandwidth ISAC: How to co-exist with communication?



- *Scenario:*
  - Cell-free system, 1 antenna per AP, OFDM, downlink
- *Communication-centric operation:*
  - UL CSI acquired. DL precoders designed to maximize comm. Objective (e.g., sum-rate). Transmission by all APs on subcarrier s:

$$\mathbf{x}_{\text{com}}[s] = \sum_{k=1}^{K} \mathbf{f}_k[s] a_{k,\text{com}}[s] = \mathbf{F}_{\text{com}}[s] \mathbf{a}_{\text{com}}[s]$$

  - Reception across all UEs:

$$\mathbf{y}[s] = \mathbf{G}[s]\,\mathbf{F}_{\text{com}}[s]\,\mathbf{a}_{\text{com}}[s] + \mathbf{n}[s]$$

- *Sensing-centric operation:*
  - No CSI available. Assign some APs at TX, others RX. Each TX-AP uses orthogonal set of subcarriers

$$\mathbf{x}_{\text{sen}}[s] = \mathbf{a}_{\text{sen}}[s] \qquad \|\mathbf{a}_{\text{sen}}[s]\|_0 \leq 1$$

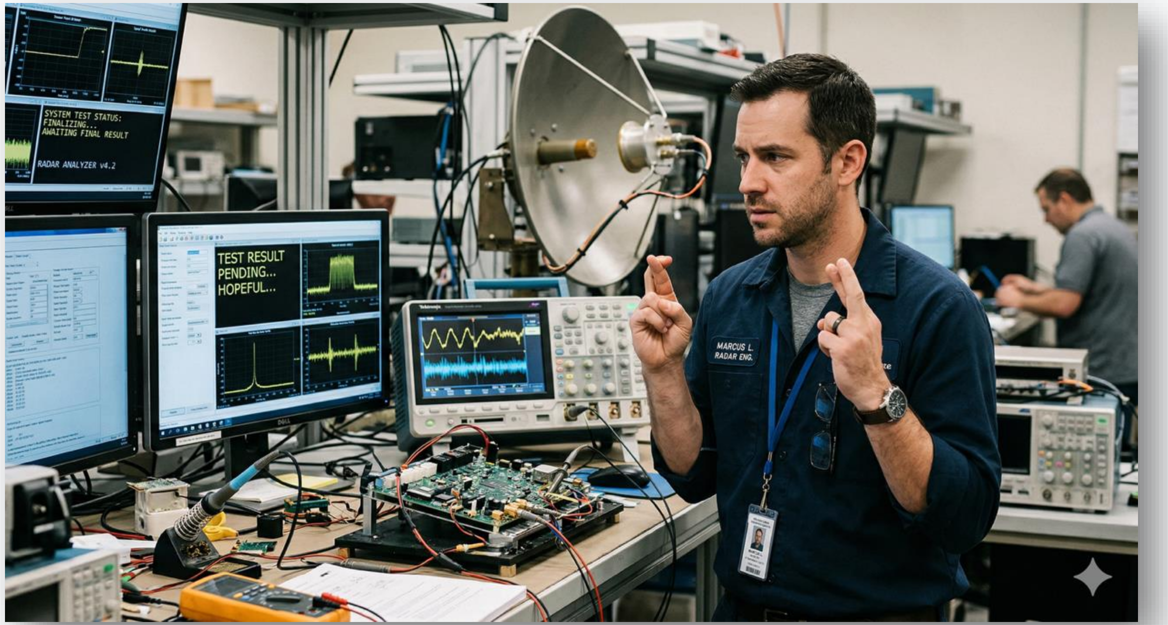
  - Receiver APs:

$$\mathbf{z}[s] = \mathbf{H}[s]\,\mathbf{a}_{\text{sen}}[s] + \mathbf{w}[s]$$

$$[\mathbf{H}[s]]_{mn} = \int \frac{\gamma[\mathbf{r}]\lambda_0 e^{-j\frac{2\pi}{c}(f_0 + s\Delta_f)(d(\mathbf{p}_n,\mathbf{r}) + d(\mathbf{r},\mathbf{p}_m))}}{(4\pi)^{\frac{3}{2}} d(\mathbf{p}_n,\mathbf{r}) d(\mathbf{r},\mathbf{p}_m)} \mathrm{d}\mathbf{r}$$

Combining communication and sensing

- Common approach
  - Component 1: superposition
  $w\mathbf{x}_{\text{com}}[s] + (1-w)\mathbf{x}_{\text{sen}}[s], w \in [0,1]$
  - Component 2:



Benefits

- Pure communication is a special case
- Pure sensing is a special case
- Flexible trade-off

Challenges

- “Fingers crossed” may not be optimal
- Limited by cross-functional interference

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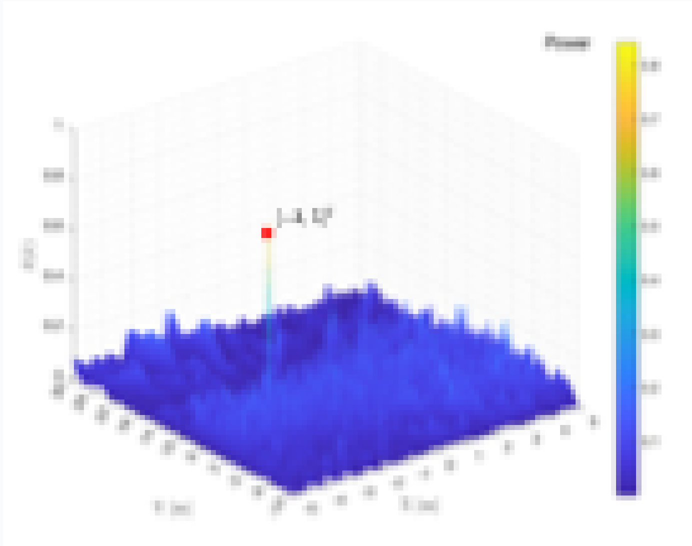
Beyond bandwidth ISAC: insights

- Positioning and sensing don't need much bandwidth
- We can reserve a small set of subcarriers for sensing (e.g., one subcarrier per TX AP) and a small subset of APs as sensing receivers
- Selection of APs, subcarriers subject to optimization
- Needs a sensing metric without a prior knowledge of target locations: **image or AF quality**

We want images/AFs with few narrow peaks



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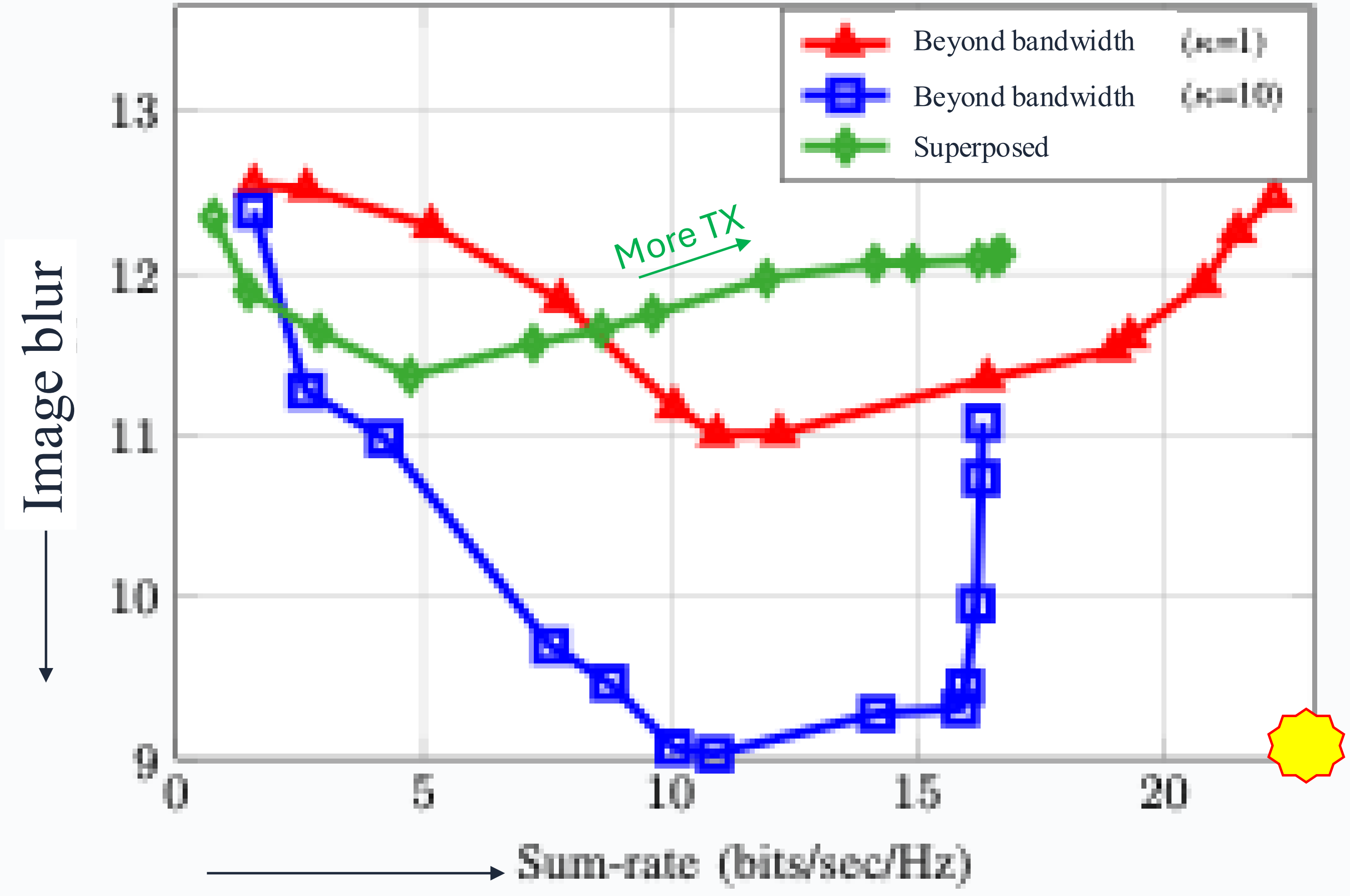
Beyond bandwidth ISAC: preliminary result



We want to be here!

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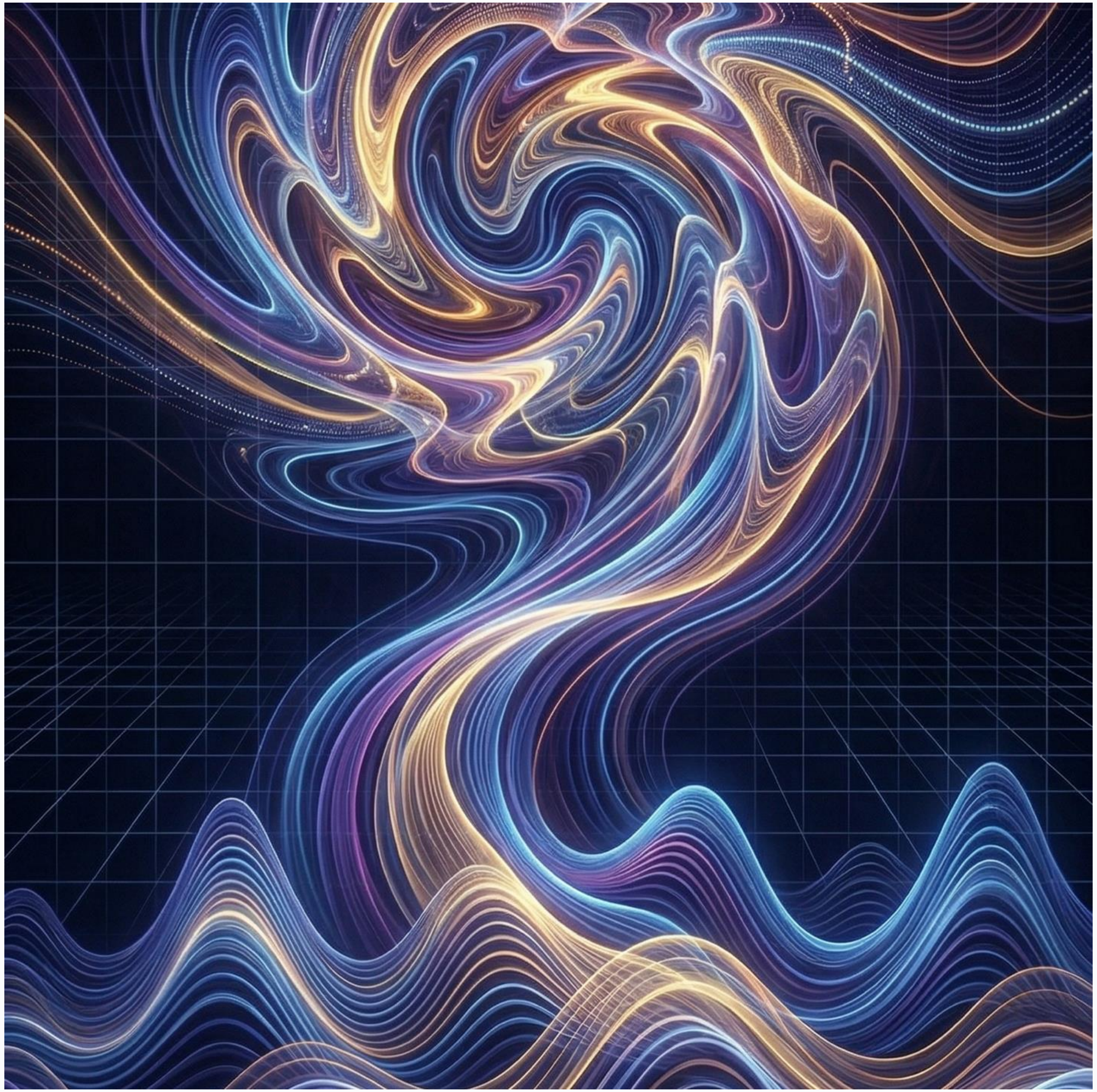

Conclusions and the road ahead

- Limited bandwidth is not a killer for high-accuracy sensing, localization, imaging
- Widely distributed arrays provide new resolution dimensions with extreme accuracy potential. Inspire new paradigms for ISAC
- Many challenges remain
  - Synchronization and calibration, wired or wireless
  - Coherence of nodes and targets across space and frequency
  - Cost of many APs: sweet spot of how many antennas per AP and how much bandwidth to be explored
  - (Distributed) super-resolution methods
  - AF shaping
  - Use of prior knowledge and data-driven methods
  - Combine with FR2 and sub-THz

5G FR2 will return

HORIZON 2020

WASP WALLENBERG AI, AUTONOMOUS SYSTEMS AND SOFTWARE PROGRAM

VINNOVA Sweden's Innovation Agency

Swedish Research Council

MARIE CURIE ACTIONS

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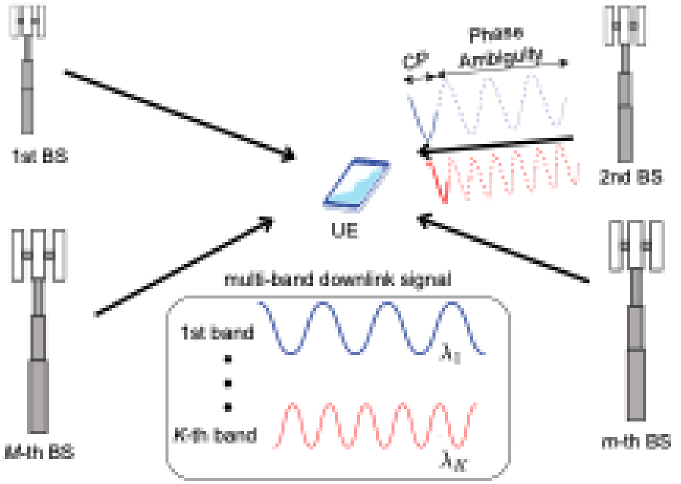
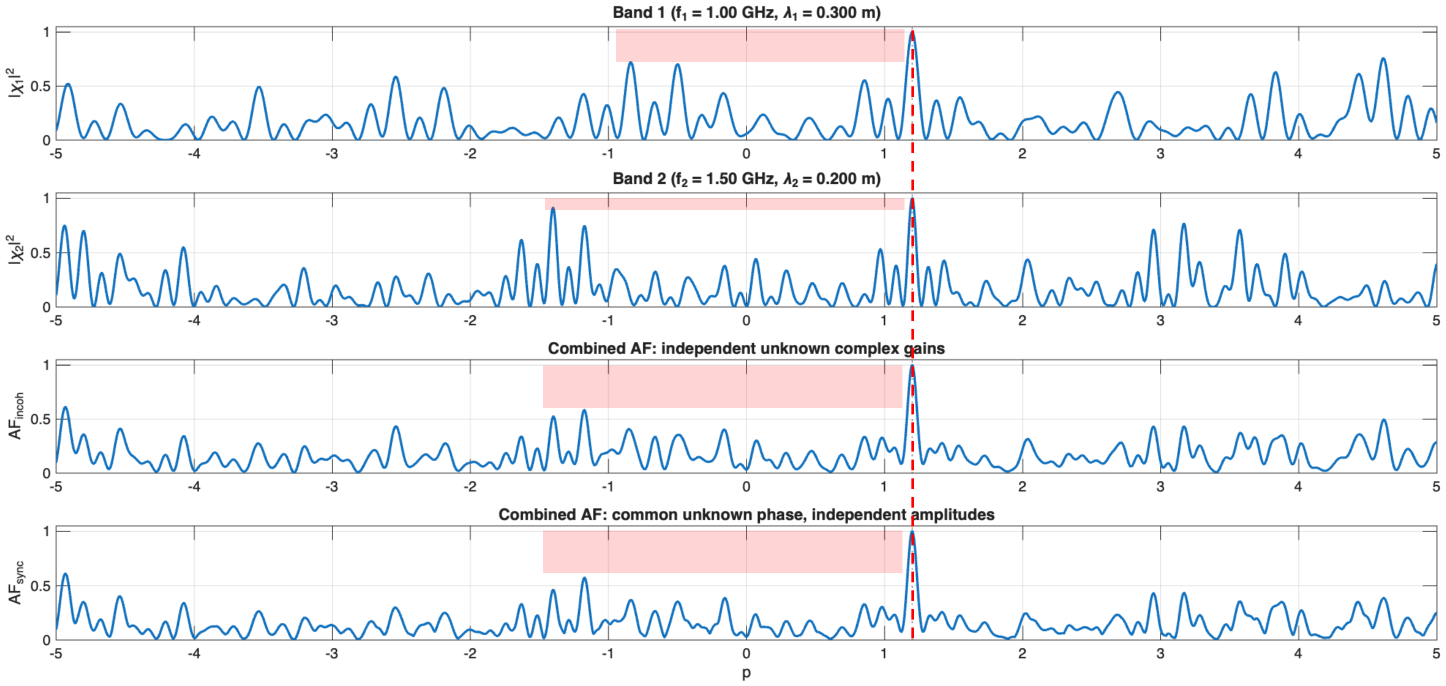
Localization under *limited* bandwidth



- Start with a few subcarriers, node *m*, band *k*:

$$\boldsymbol{y}_{m,k} = \sqrt{E_{s,k}}\alpha_{m,k}\boldsymbol{d}(\tau_{m,k}) + \boldsymbol{\omega}_{m,k},$$

- Each band has some finite bandwidth, provides initial estimate from time-of-arrival
- Ambiguities for different bands don't overlap



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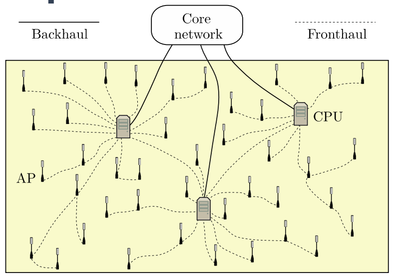
CRB and ambiguity function interplay

- **Carrier phase positioning example**

$$\boldsymbol{y}_{\mathrm{iq},m} = \sqrt{E_s}\alpha_m \boldsymbol{d}(\tau_m) + \boldsymbol{w}_m,$$

$$[\boldsymbol{d}(\tau)]_n = e^{-\jmath 2\pi n \Delta_f \tau}$$

$$\alpha_m = \rho_m e^{\jmath \vartheta_m}$$



- **Geometric information**

$$\tau_m = \frac{1}{c}\|\boldsymbol{x}_{\mathrm{bs},m} - \boldsymbol{x}_{\mathrm{ue}}\| + B_{\mathrm{ue}}$$

$$\vartheta_m = \frac{2\pi}{\lambda}\|\boldsymbol{x}_{\mathrm{bs},m} - \boldsymbol{x}_{\mathrm{ue}}\| + \phi_{\mathrm{ue}},$$

- **Convert to distances**

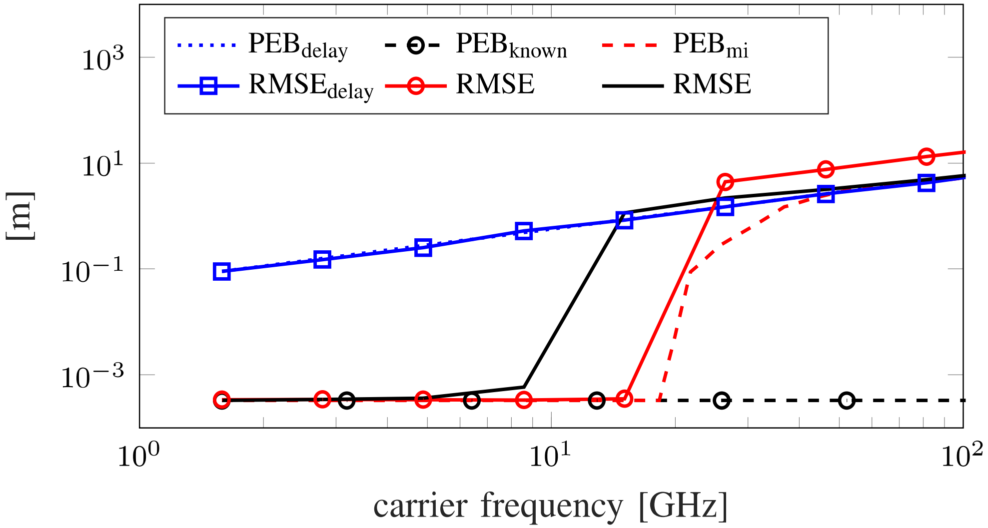
$$y_{\tau,m} = \|\boldsymbol{x}_{\mathrm{bs},m} - \boldsymbol{x}_{\mathrm{ue}}\| + B_{\mathrm{ue}}c + w_{\tau,m}$$

$$y_{\vartheta,m} = \|\boldsymbol{x}_{\mathrm{bs},m} - \boldsymbol{x}_{\mathrm{ue}}\| + z_m\lambda + \phi_{\mathrm{ue}}\frac{\lambda}{2\pi} + w_{\vartheta,m},$$

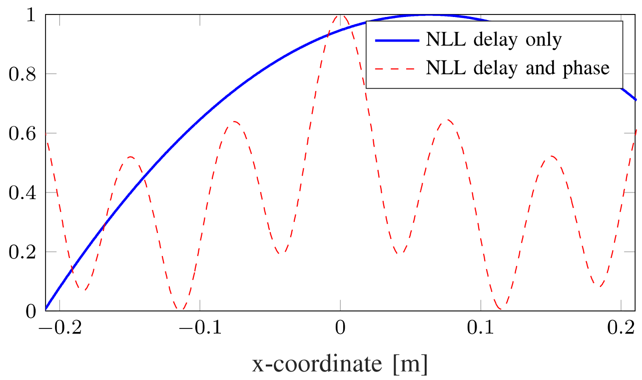
- **CRBs**

$$\mathbb{E}\{w_{\tau,m}^2\} \approx \left(\frac{2\,\mathrm{SNR}_m \pi^2 W^2}{3c^2}\right)^{-1} \sim \frac{c^2}{W^2}$$

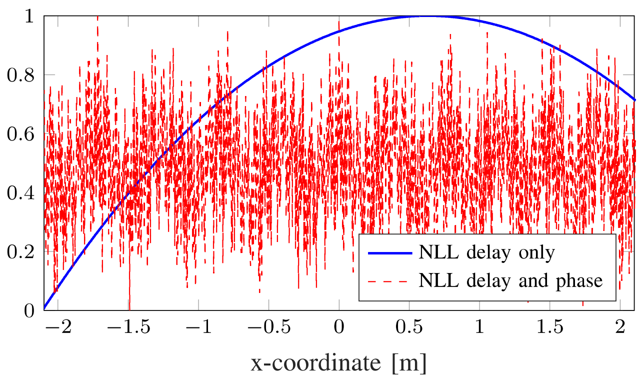
$$\mathbb{E}\{w_{\theta,m}^2\} = \left(\frac{8\,\mathrm{SNR}_m \pi^2}{\lambda^2}\right)^{-1} = \left(\frac{8\,\mathrm{SNR}_m \pi^2 f_c^2}{c^2}\right)^{-1} \sim \frac{c^2}{f_c^2}$$



3 GHz carrier



30 GHz carrier



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