KU LEUVEN

Massive
Data-driven
Integrated Sensing and Communication

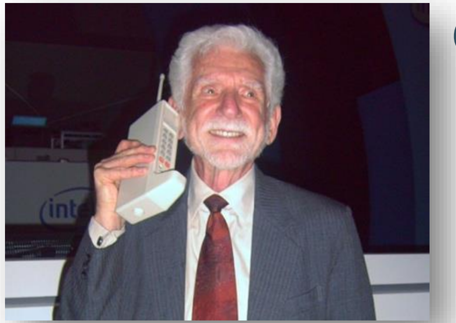
Sofie Pollin

ELLIT Focus Period – Linkoping – April 21-23 2026

Joint work with Robbert Beerten, Haoqiu Xiong, Sibren De Bast, Adham Sakhnini, Andre Bourdoux, Marcin Wachowiak, Jialun Kou, Zhuangzhuang Cui

WAVECORE NETWORKED SYSTEMS imec

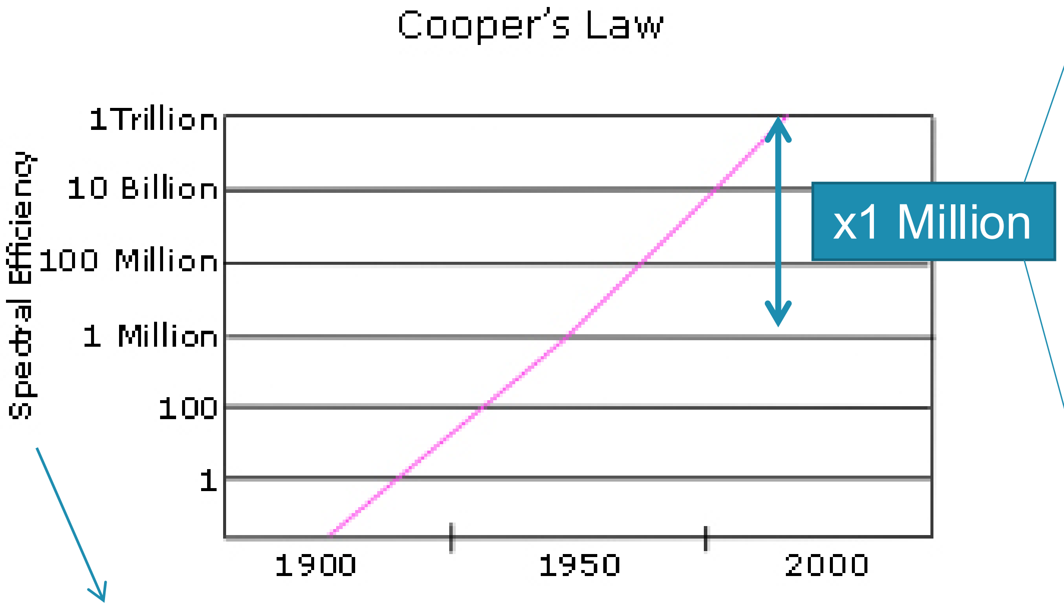
6G takes shape. Same as usual?



Cooper's law

The spectrum utilization has <u>doubled every 30 months</u> over the last 104 years

Factor 1.000.000 in 50 years



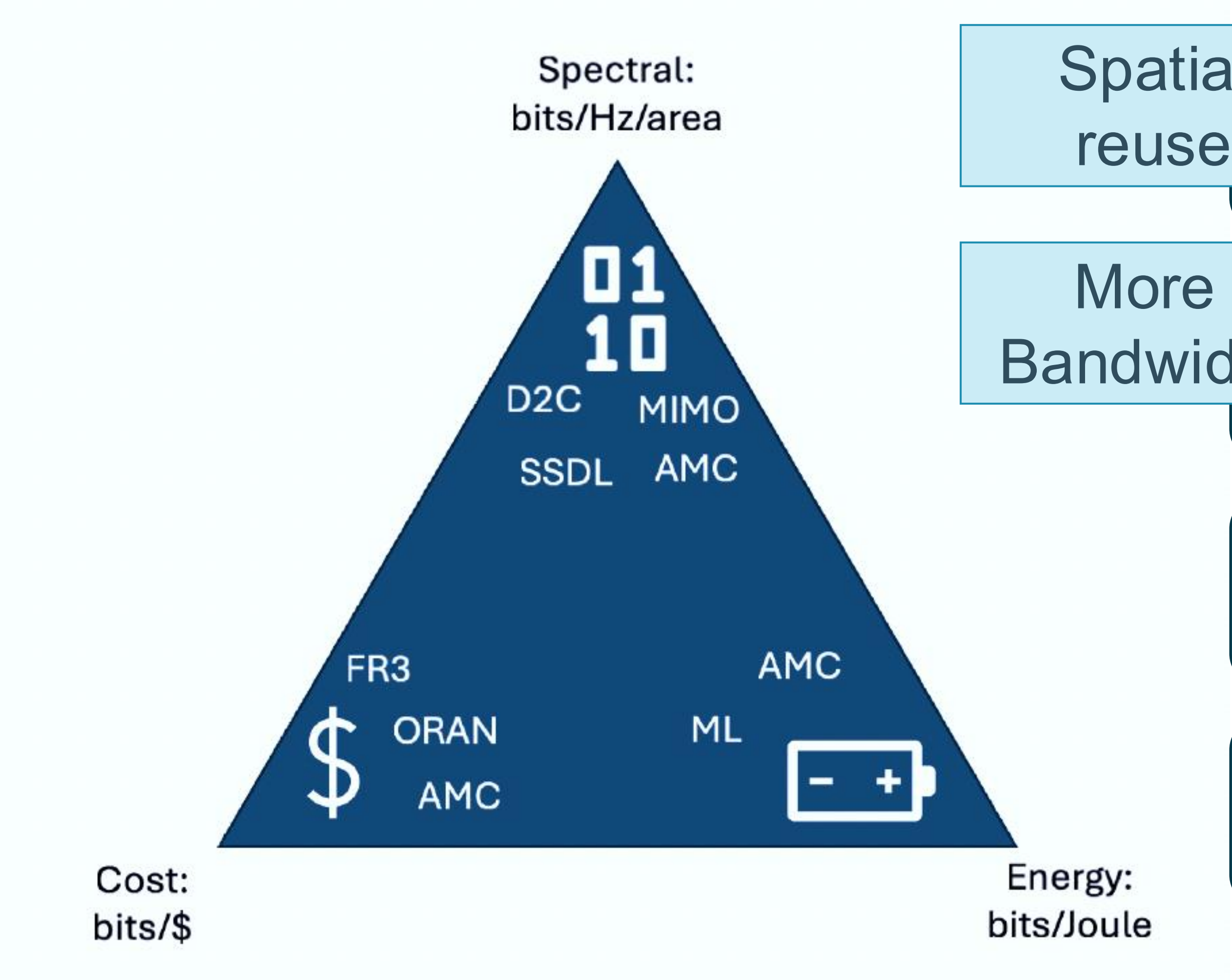
Conversations/spectrum
(instead of bits/sec/Hz)

In 5G bandwidth was much
Larger than usual

PHY algorithms	5X
More bandwidth	25X
Spatial reuse	1600X
Better slicing	5X

[Zander, Jens & Mähönen, Petri. (2013). Riding the Data Tsunami in the Cloud :
Myths and Challenges in Future Wireless Access. IEEE Communications Magazine.]

Baseline requirements for 6G: efficiency



Spatial reuse → MIMO

More Bandwidth → FR3

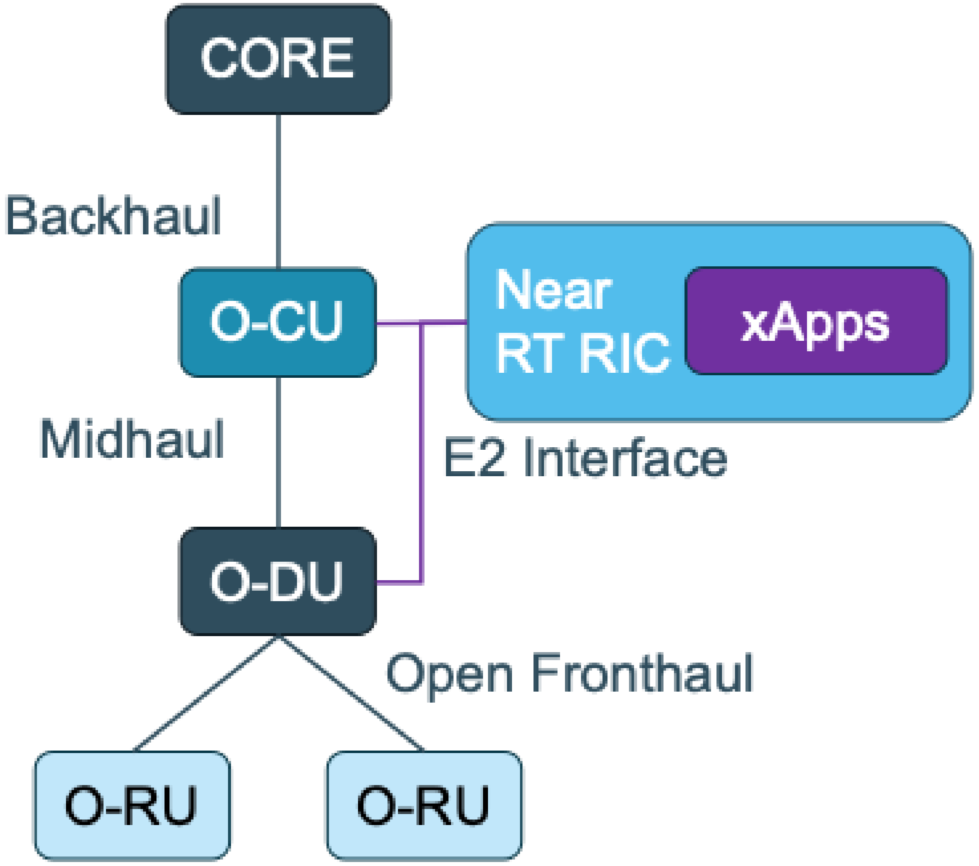
O-RAN

ML

 [J. G. Andrews, T. E. Humphreys and T. Ji, "6G Takes Shape," in *IEEE BITS the Information Theory Magazine]*

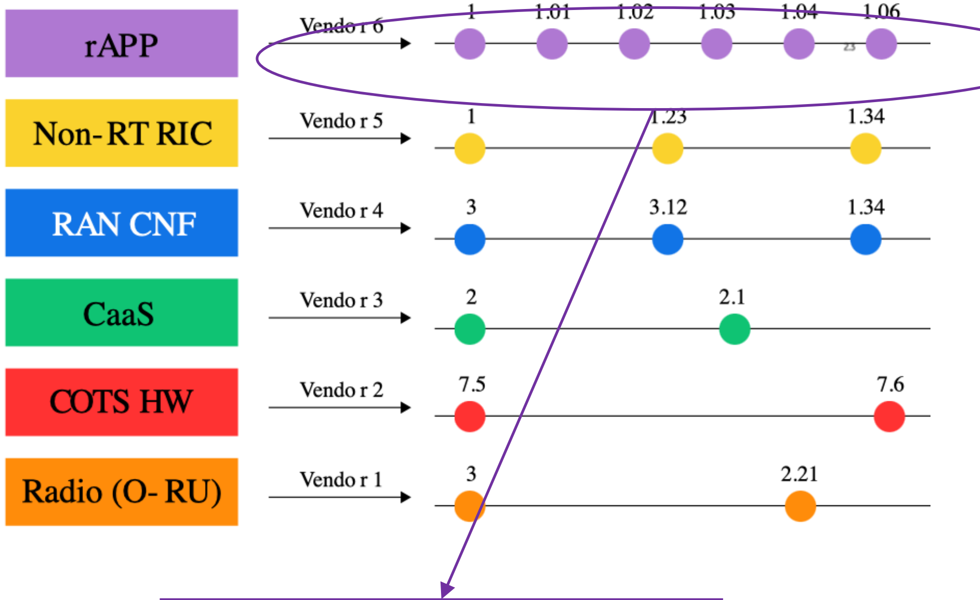
O-RAN: Open, intelligent, disaggregated RAN

Disaggregation



Integration of AI

Separation of HW and SW



Are there limits to the speed of innovation?

[https://www.ericsson.com/en/blog/2024/6/automated-testing-enables-open-ran-deployment]

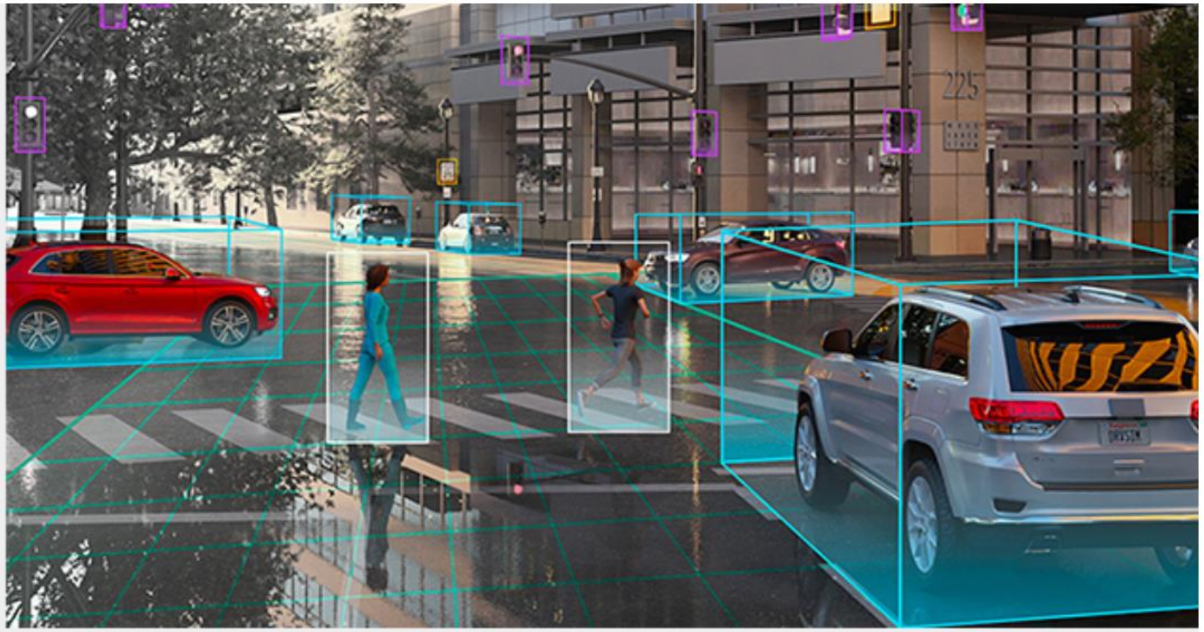
ISAC applications

Source: *https://www.qualcomm.com/news/onq/2024/09/when-wireless-sensing-meets-communications-what-new-efficiencies-and-experiences-can-you-expect-in-the-6g-era*

NVIDIA Unveils Open Physical AI Dataset to Advance Robotics and Autonomous Vehicle Development

Expected to become the world's largest such dataset, the initial release of standardized synthetic data is now available to robotics developers as open source.

March 18, 2025 by Katie Washabaugh



Robot-integrated sensors

Advantages:

- Autonomy → Functions everywhere
- Mobility → Free to move

Disadvantages:

- Limited range
- Power consumption
- Complexity & cost
- No cooperation

🚀 **Use Cases:**



Infrastructure-integrated sensors

Advantages:

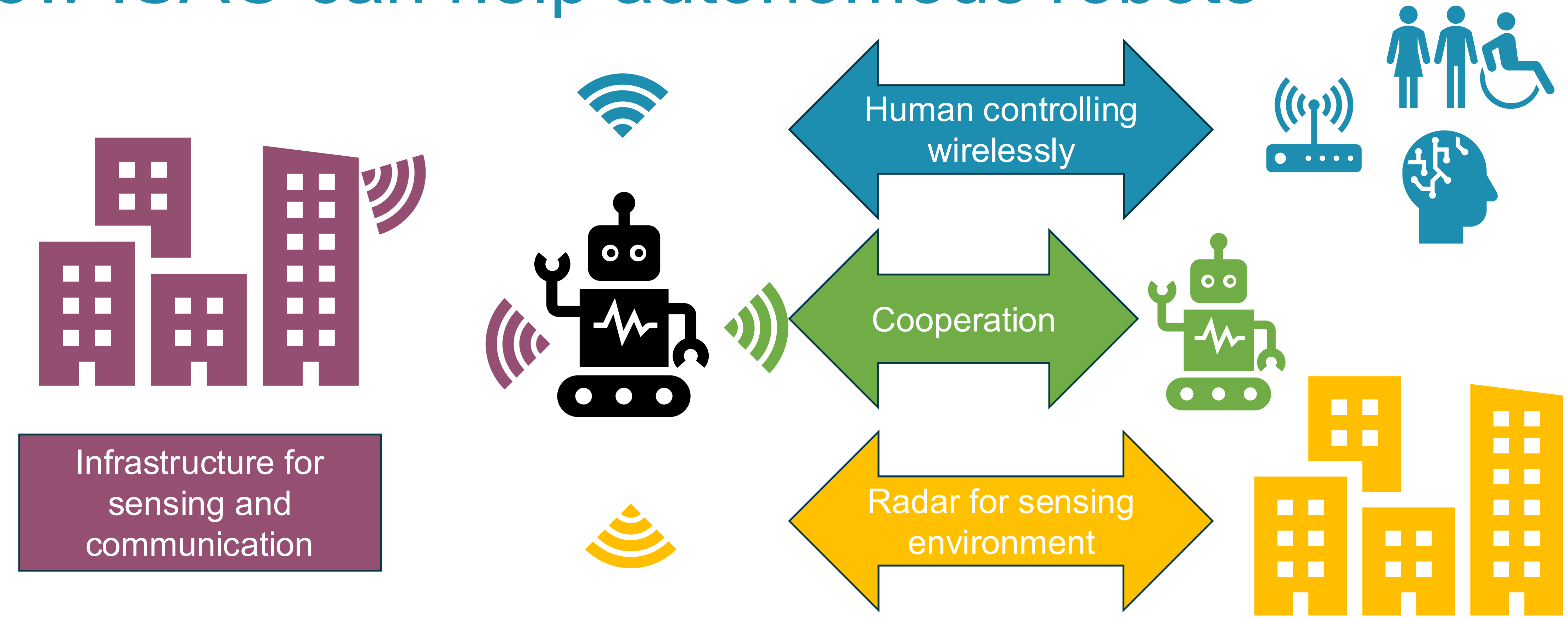
- Reduced processing load
- Scalability & cooperation → Multiple robots
- Improved sensing range

Disadvantages:

- High initial infrastructure cost
- Lack of mobility (only where coverage)
- Communication challenges

Use Cases:


How ISAC can help autonomous robots



The opportunity and the use case are there. How to accelerate?

Multiple bands (non-contiguous)

Distributed Radios

Data & AI

Humans & Robots

How to accelerate?

Outline

1. Basics (cell-free) sensing
2. Near-field range resolution
3. Non-contiguous bandwidth
4. Cell-free vital sign sensing
5. Sensing for communication
6. Call for more data and frictionless reproducability

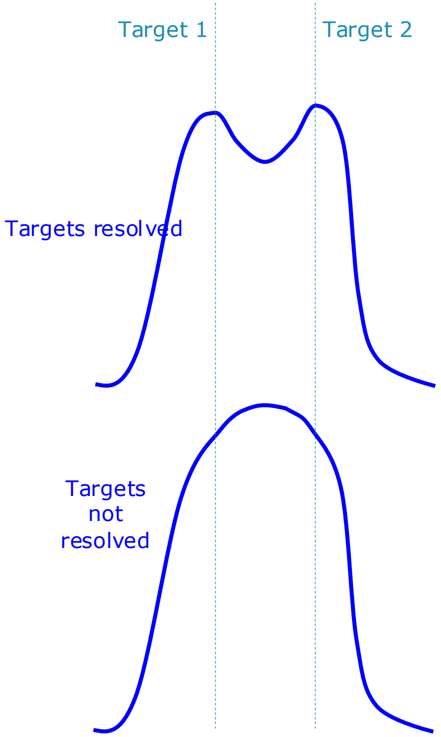
Resolution and ambiguity … and accuracy

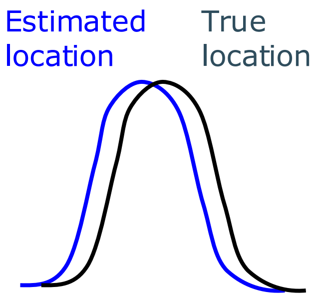
- Resolution quantifies the capability to discriminate **two** targets
- Resolutions depend on radar parameters

	Range	Doppler	Angle
Resolution	$\Delta_R = \frac{c}{2B}$	$\Delta_v = \frac{\lambda}{2T_{PRI}}$	$\Delta_\theta = \frac{1.22\lambda}{D_{ant}}$
Ambiguity	$R_{amb} = \frac{cT_{PRI}}{2}$	$v_{amb} = \frac{\lambda}{2NT_{PRI}}$	Depends on element spacing (phased array, MIMO) No ambiguity if $\text{Spacing} \leq \frac{\lambda}{2}$

- Accuracy quantifies how accurately the position of **one** target is estimated
- Accuracies depend on resolution and on SNR
- Cramér-Rao lower bound

	Range	Doppler	Angle
Accuracy	$R_{acc} = \frac{\Delta_R}{\sqrt{2 \cdot SNR}}$	$v_{acc} = \frac{\Delta_v}{\sqrt{2 \cdot SNR}}$	$\theta_{acc} = \frac{\Delta_\theta}{\sqrt{2 \cdot SNR}}$





[courtesy: A. Bourdoux]

More about (spatial) sensing resolution

- Range resolution: $R_{res} \approx \frac{c}{2 \cdot BW}$
  - 2GHz → **7.5cm**
- Angular or Cross-range resolution: $CR_{res} \approx R \cdot \theta_{res}$
  - 10 degree at 10m → **1.75 m**!

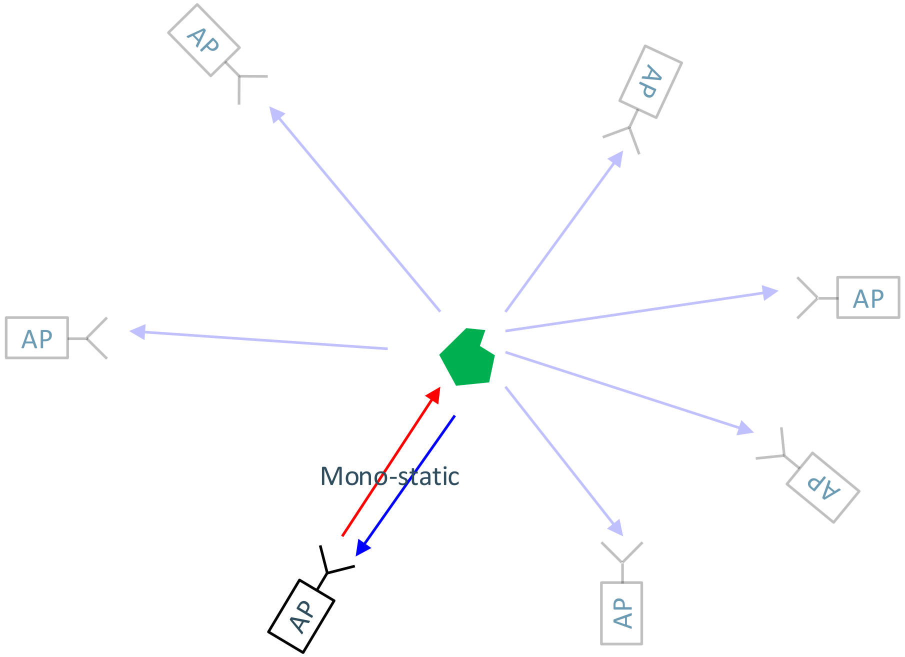
High angular /cross-range resolution is often difficult to achieve!

- Desired angular performance
  - Same resolution in cross-range as in range (depth)
  - As high as possible for imaging
  - This is a HUGE challenge

How to increase the angular resolution in sensing?

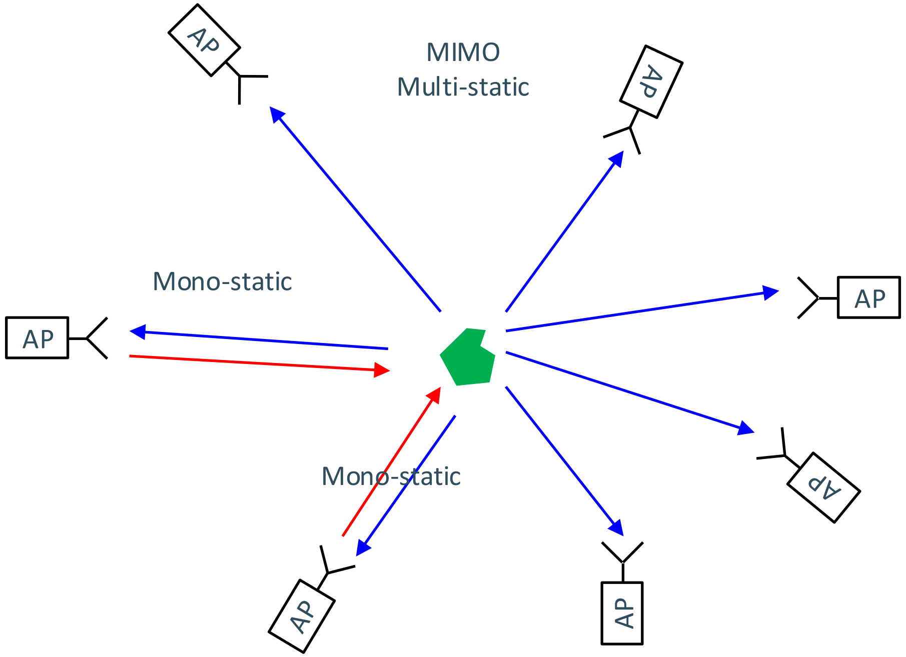
- Larger antennas: $\theta_{res} \approx \frac{\lambda}{D}$
  - More antenna elements (€ € €)
  - Sparse arrays
- MIMO (MIMO radar ≠ MIMO communications)
  - $N_{virtual} = N_{TX}\ N_{RX}$
- Distributed or cell-free MIMO
  - Large mono-static and/or multi-static network
  - Mix of coherent processing and/or non-coherent processing (also triangulation and trilateration)

Spatial resolution with a distributed architecture



SISO mono-static range resolution:

- $R_{res} \approx \frac{c}{2 \cdot BW}$
- 18MHz → 8.33 to 16.67 m!



Distributed, multi-static x-y resolution:

- $R_{res,X}$ = ?
- $R_{res,Y}$ = ?

Spatial resolution with a distributed architecture

Distributed or cell-free MIMO

- Target in seen from *many* different angles
- Target is in the *near-field* of the distributed array

Imaging processing options, including Doppler

- Full back-projection:
  - Range-Doppler processing + Coherent combining
  - Combining: $\mathcal{O}(XY\dot{X}\dot{Y}MN)$
  - Best performance, highest complexity
- Non-coherent back-projection
  - Neglect Doppler
  - Non-coherent combining of images from each puls~
  - Combining: $\mathcal{O}(XYLMN)$

$$r_{mn}^{(r)}(d,l) = \frac{1}{K}\sum_{k=1}^{K} r_{mn}(k,l) f(d,k) \quad \text{(Range)}$$

$$r_{mn}^{(rd)}(d,\dot{d}) = \frac{1}{L}\sum_{l=1}^{L} r_{mn}^{(r)}(d,l) g(\dot{d},l) \quad \text{(Doppler)}$$

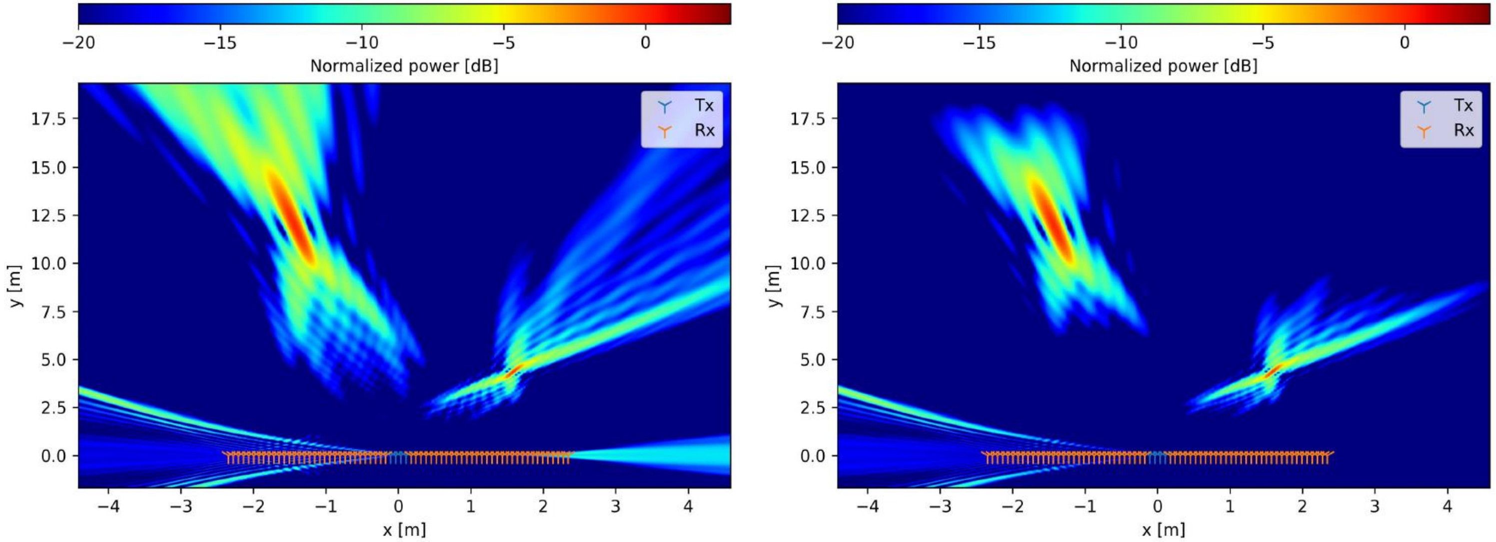
$$r^{(fb)}(x,y,\dot{x},\dot{y}) = \left| \sum_{m=1}^{M}\sum_{n=1}^{N} r_{mn}^{(rd)}(x,y,\dot{x},\dot{y}) \overline{v}_{mn}(x,y) \right|^2$$

$$r^{(ncb)}(x,y) = \frac{1}{L}\sum_{l=1}^{L} \left| \sum_{m=1}^{M}\sum_{n=1}^{N} r_{mn}^{(r)}(x,y,l) \overline{v}_{mn}(x,y)) \right|^2$$

[A. Sakhnini, S. De Bast, M. Guenach, A. Bourdoux, H. Sahli and S. Pollin, "Near-Field Coherent Radar Sensing Using a Massive MIMO Communication Testbed ", IEEE Trans on Wireless Comm, 2022]

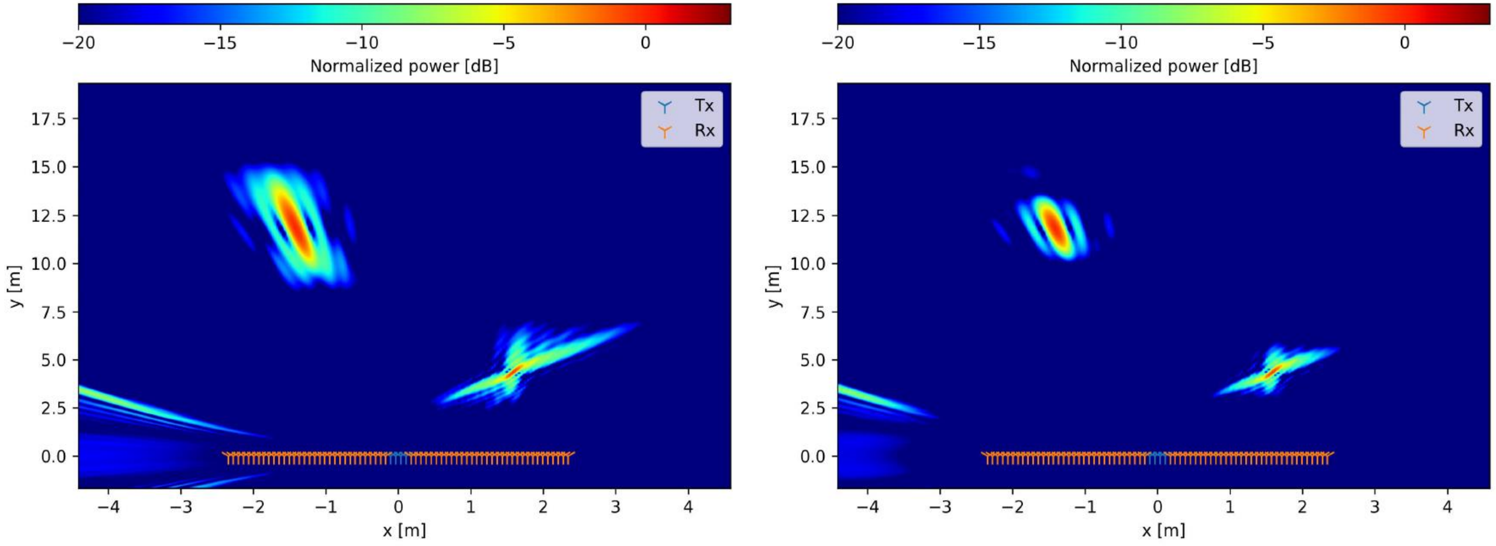
Simulation

- Spatial ambiguity function for two scatterers located at
  - (x, y) = (1.6, 4.3)
  - (x, y) = (−1.4, 11.8)
- Array resolution gain dominates at short distances (near-field)
- Signal bandwidth dominates at long distance (far-field)
- But: increasing the bandwidth increases the dynamic range as indicated by the reduction in the skirts around the main lobes.



(a) 1 subcarrier

(b) 100 subcarriers (18 MHz bandwidth)



(c) 200 subcarriers (36 MHz bandwidth)

(d) 400 subcarriers (72 MHz bandwidth)

Nobody trusts models, except the people who model

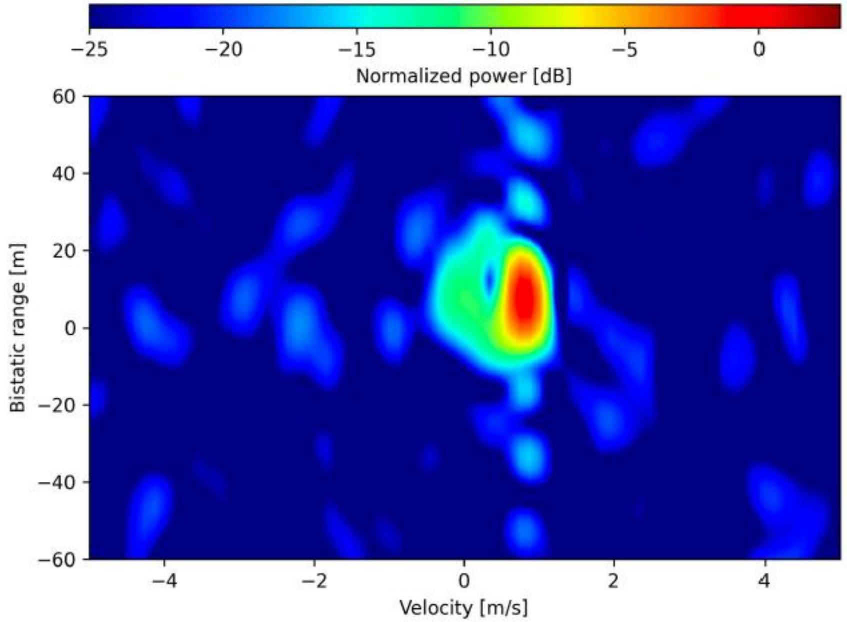
Everybody trusts measurements except the people who measure

Massive multi-static radar

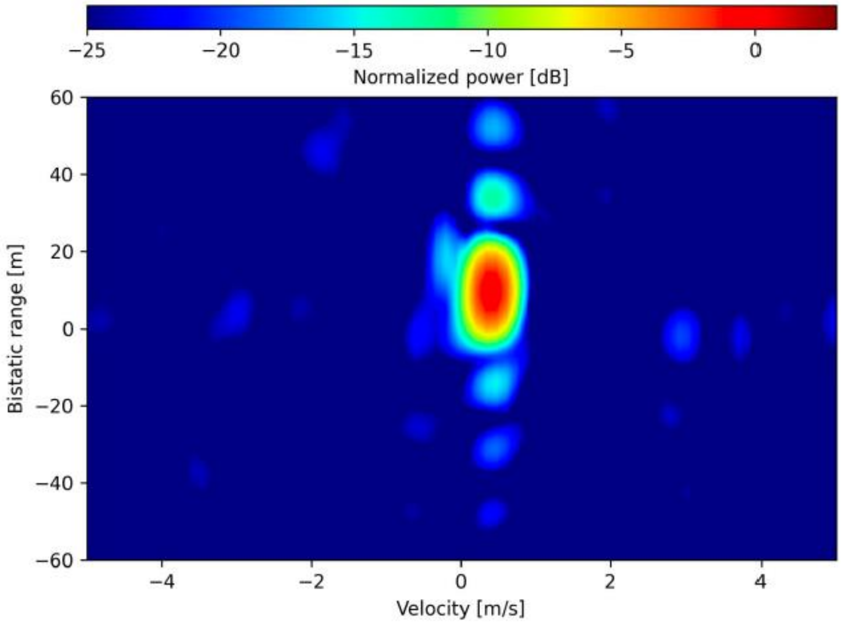
Single link performance metrics	
Bistatic range resolution	16.67 m
Bistatic Doppler resolution	1.34 m/s
Maximum unambiguous bistatic range	1667 m
Maximum unambiguous bistatic Doppler	85.7 m/s
CRLB in bistatic range in 20 dB SNR	0.94m
CRLB in bistatic Doppler at 20 dB SNR	0.08 m/s

A. Sakhnini, S. De Bast, M. Guenach, A. Bourdoux, H. Sahli and S. Pollin, "Near-Field Coherent Radar Sensing Using a Massive MIMO Communication Testbed," in IEEE Transactions on Wireless Communications, vol. 21, no. 8, pp. 6256-6270, Aug. 2022

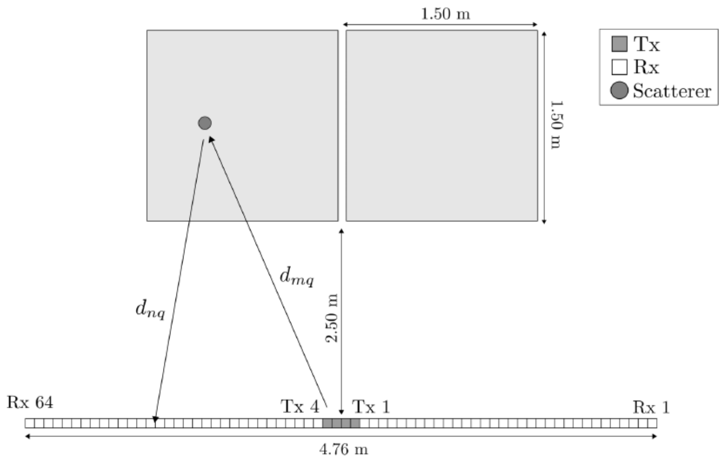
Range – Doppler maps



(b) Receiver 64, transmitter 1



(a) Receiver 1, transmitter 1



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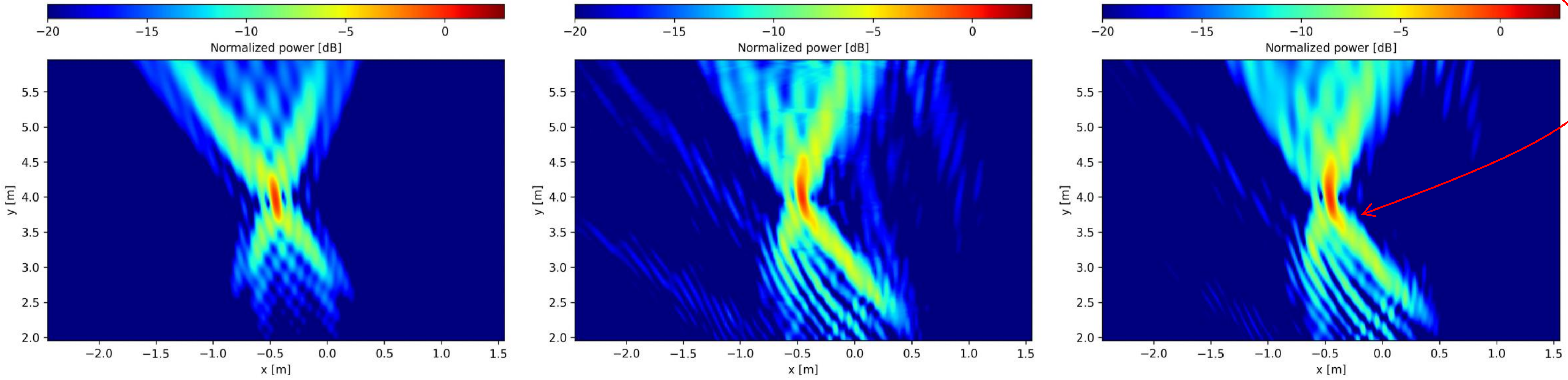
Measurement with Massive MIMO testbed

- **Bandwidth is not always needed for high resolution in the near-field of massive MIMO arrays**
- A distributed MIMO radar enables high X-Y resolution at lower frequencies where bandwidth is scarse
- Resolution is <u>much better than the range resolution</u> $c/(2 \cdot Bw)$

~5x30 centimeter resolution with ≥ 8 m bistatic range resolution!

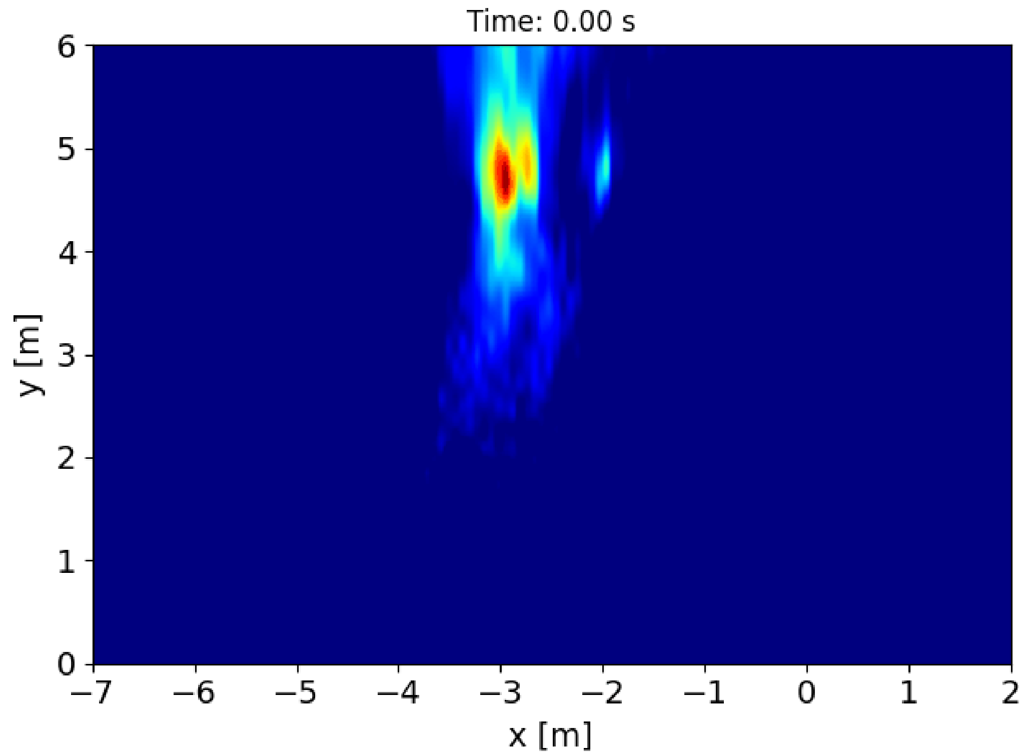


(a) Theoretical ambiguity function (b) Non-coherent backprojection (c) Constant-Doppler backprojection

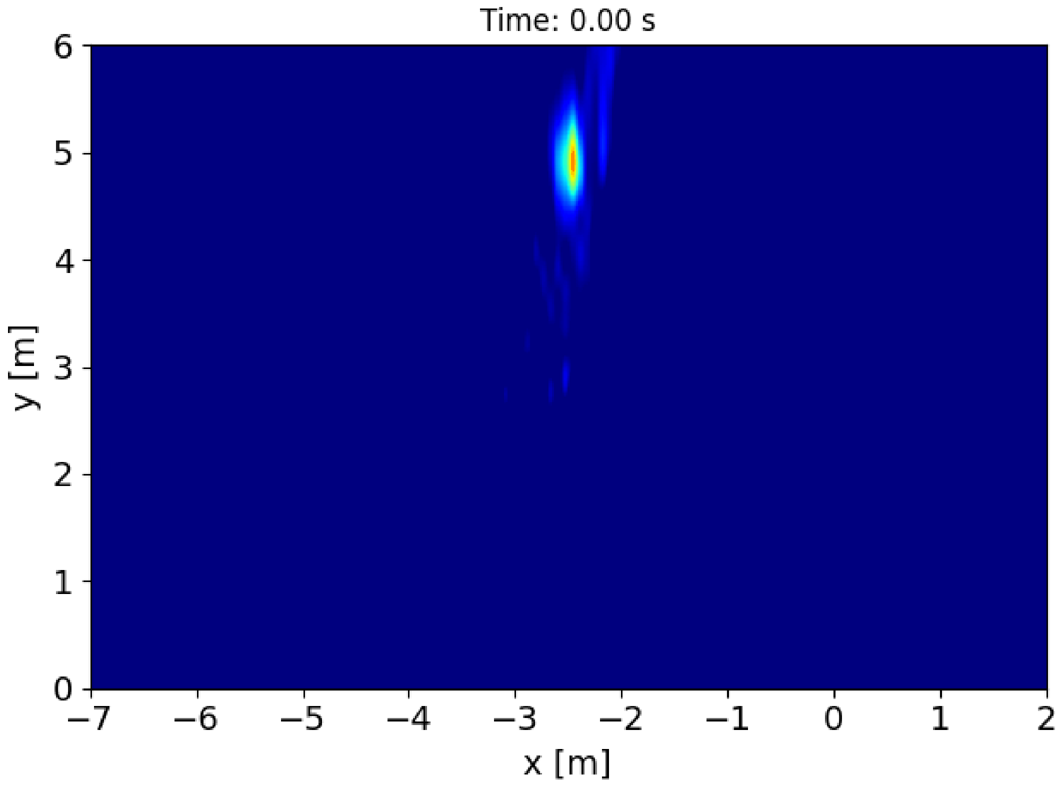
A. Sakhnini, S. De Bast, M. Guenach, A. Bourdoux, H. Sahli and S. Pollin, "Near-Field Coherent Radar Sensing Using a Massive MIMO Communication Testbed," in IEEE Transactions on Wireless Communications, vol. 21, no. 8, pp. 6256-6270, Aug. 2022

Example: Near-field sensing with extremely large arrays

Tracking two persons with 18 MHz of bandwidth

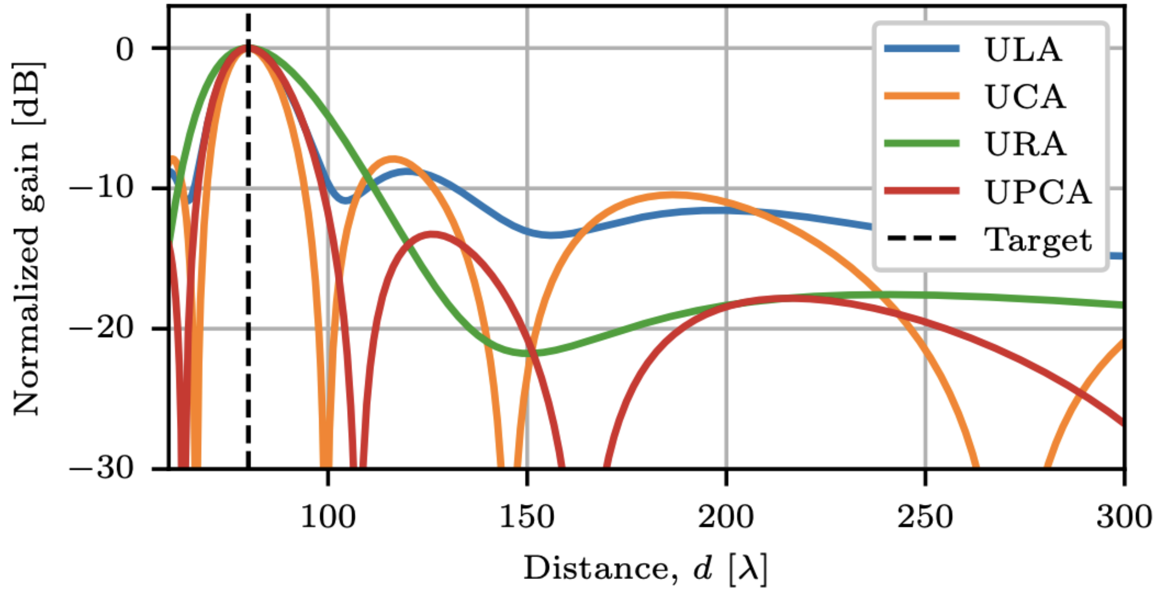


Tracking three persons with 18 MHz of bandwidth

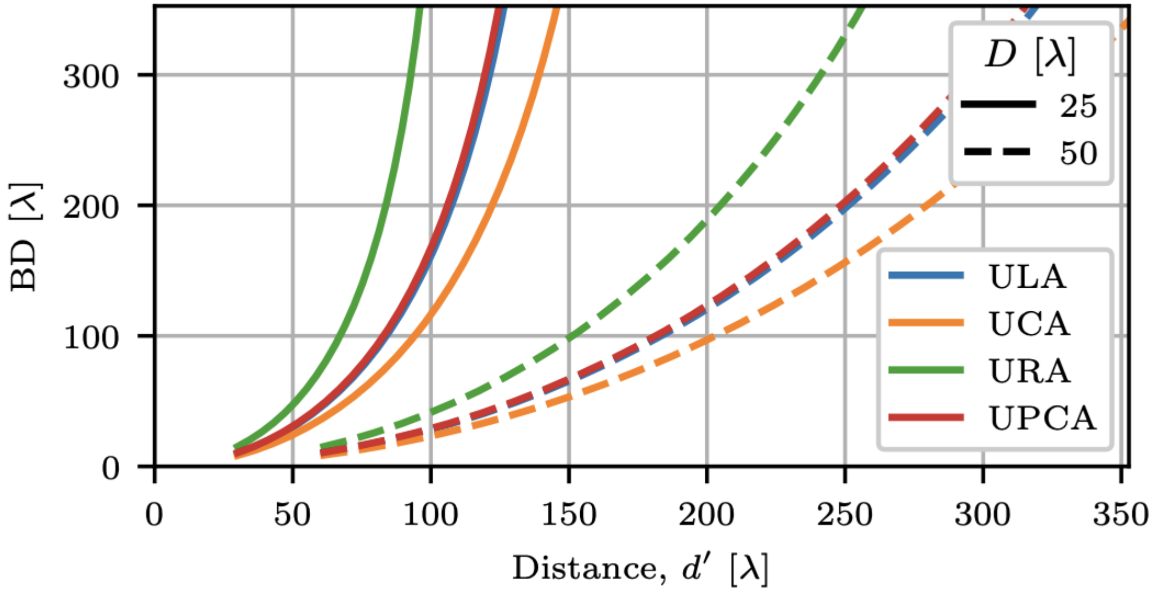


Approximation of the range ambiguity function in near-field sensing systems

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



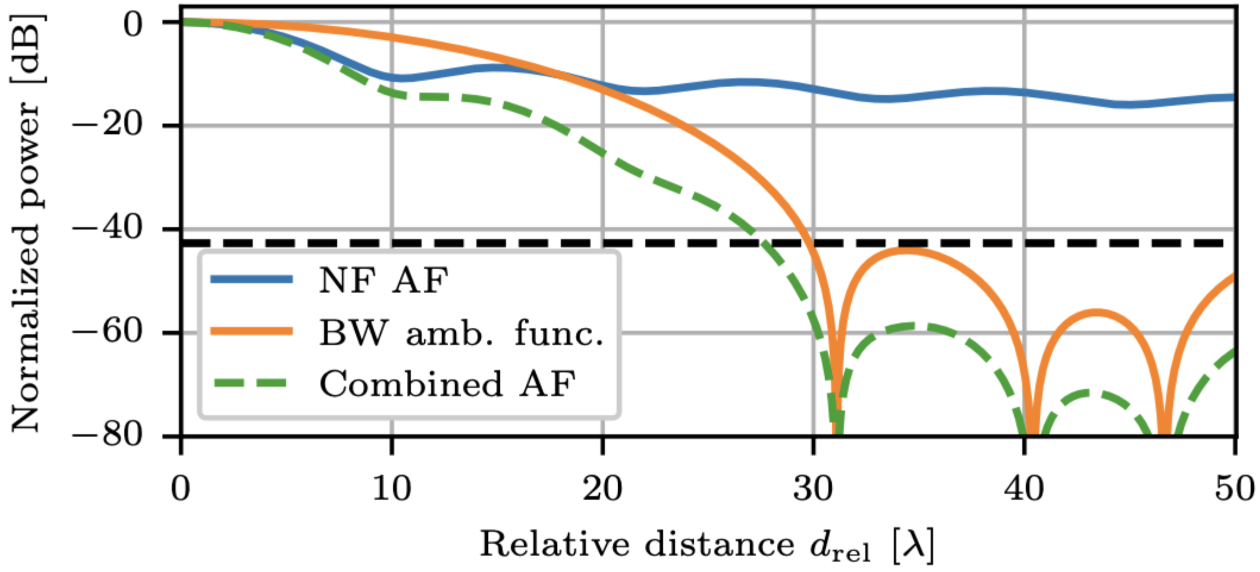
Beamdepth as function of aperture D and beamdepth d'



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

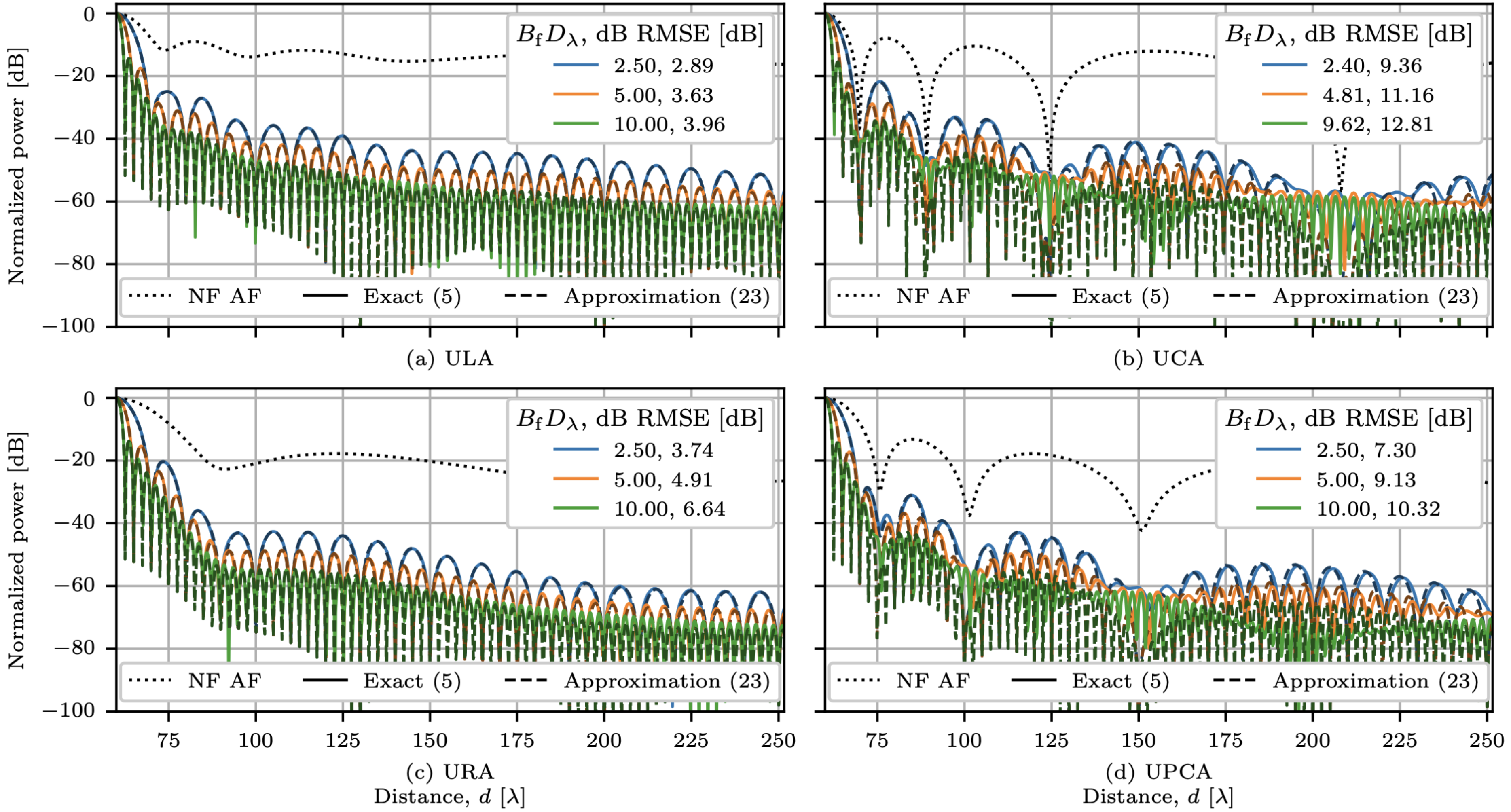
Adding bandwidth to the near field

f_c	B	M	D_λ	$B_f D_\lambda$
3.5 GHz	100 MHz	128	63.5	1.81
7.8 GHz	200 MHz	256	127.5	3.27
15 GHz	400 MHz	512	255.5	6.81
28 GHz	1 GHz	256	127.5	4.55
79 GHz	4 GHz	256	127.5	6.46



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

Comparison of the ambiguity function



$D=50\lambda$

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

Outline

1. Basics (cell-free) sensing ✓
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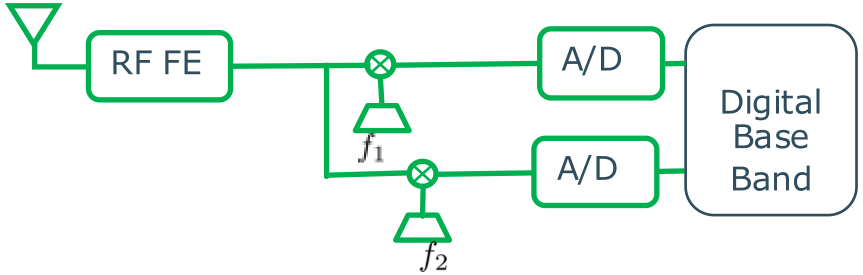
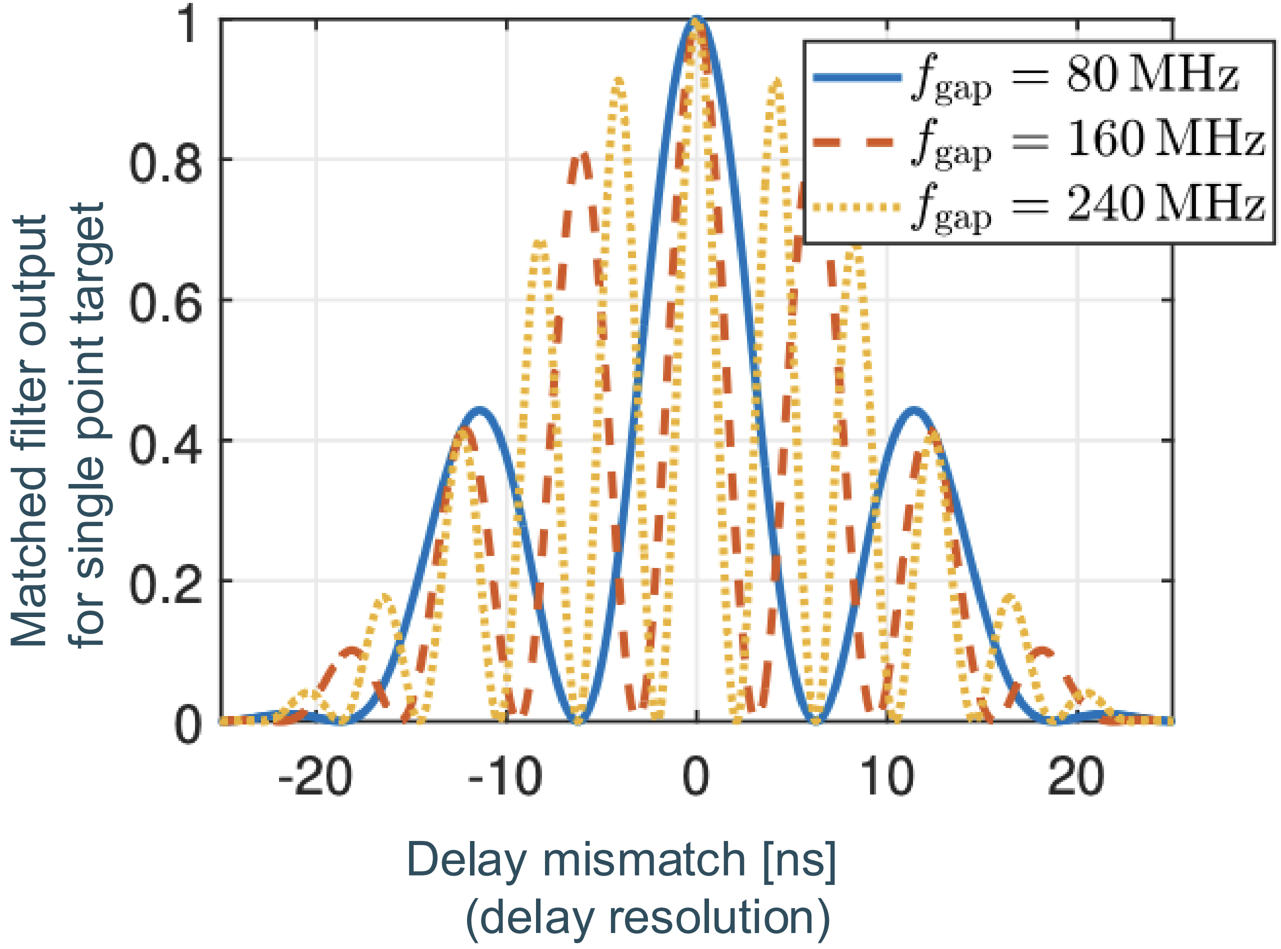
Multi-band Frequency-Adaptive Sensing



$$f_{gap} = f_2 - f_1$$
$$B = 40\ \text{MHz}$$

Goal: resolve multiple targets



Finding a precise range/delay

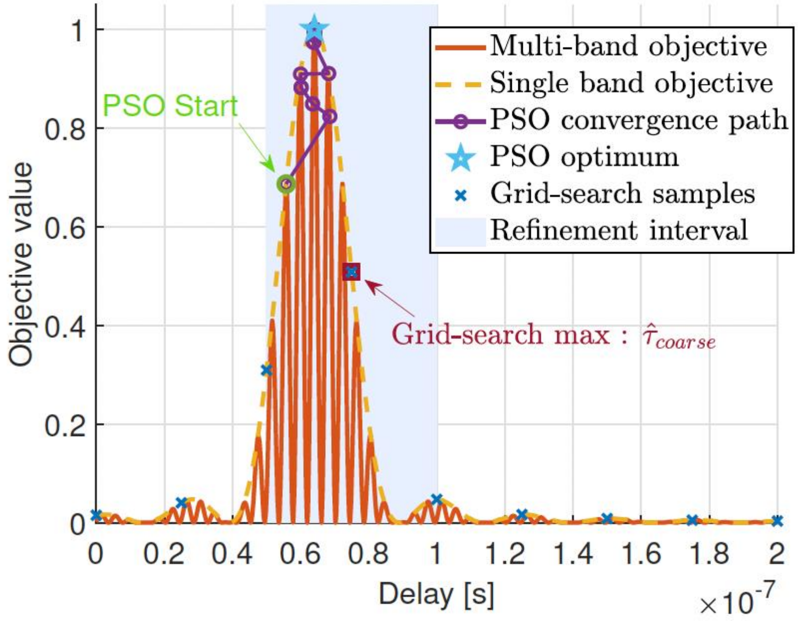


Fig. 3. TSPSO delay estimation for a single target at delay 62 ns, $f_{gap} = 240\,\text{MHz}$, $T = 2$ and $M_b \Delta f = 40\,\text{MHz}$.

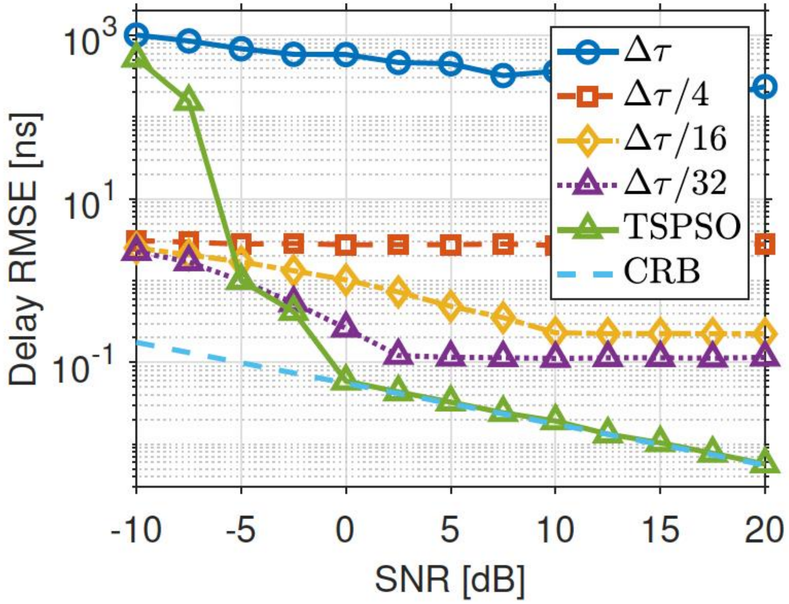
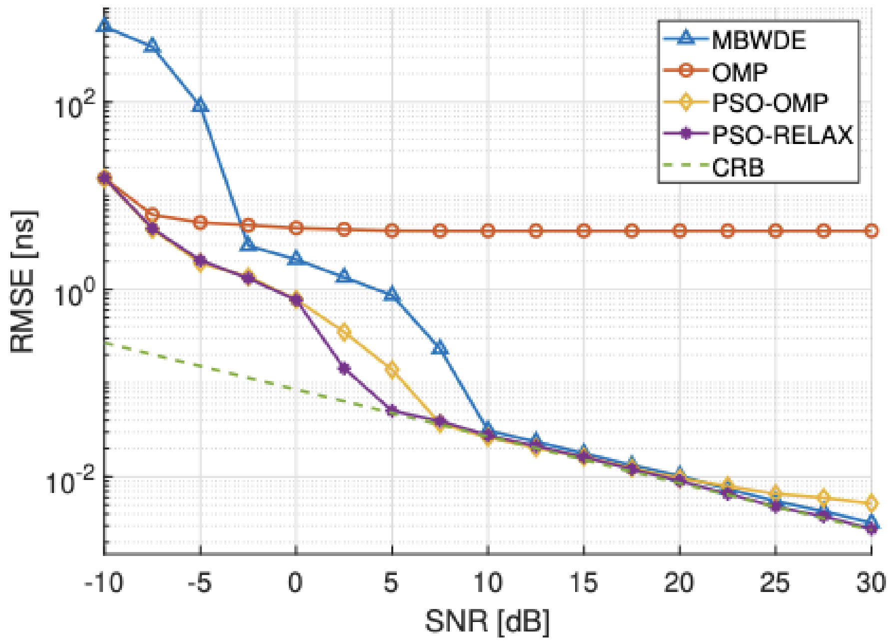


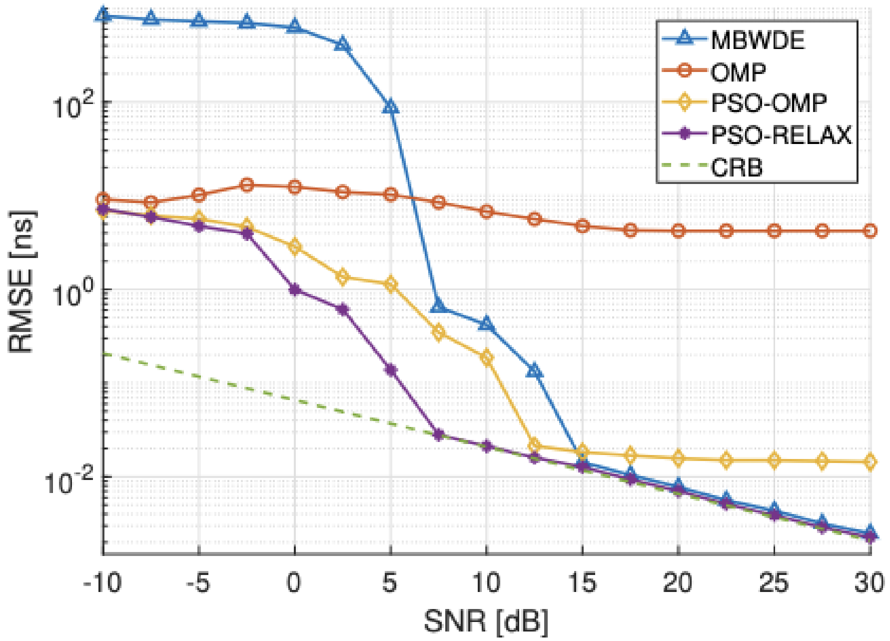
Fig. 4. RMSE performance of the PSO-based delay estimator compared with the grid search ($T = 2$, $f_{\text{gap}} = 240$ MHz, and $M_b \Delta f = 40$ MHz.)

Finding multiple targets

- L= 2 targets or 3 targets; Bound achieved



(b) $L = 2, \ \boldsymbol{\tau} = [66, 100]$ ns



(c) $L = 3, \ \boldsymbol{\tau} = [66, 100, 133]$ ns

Outline

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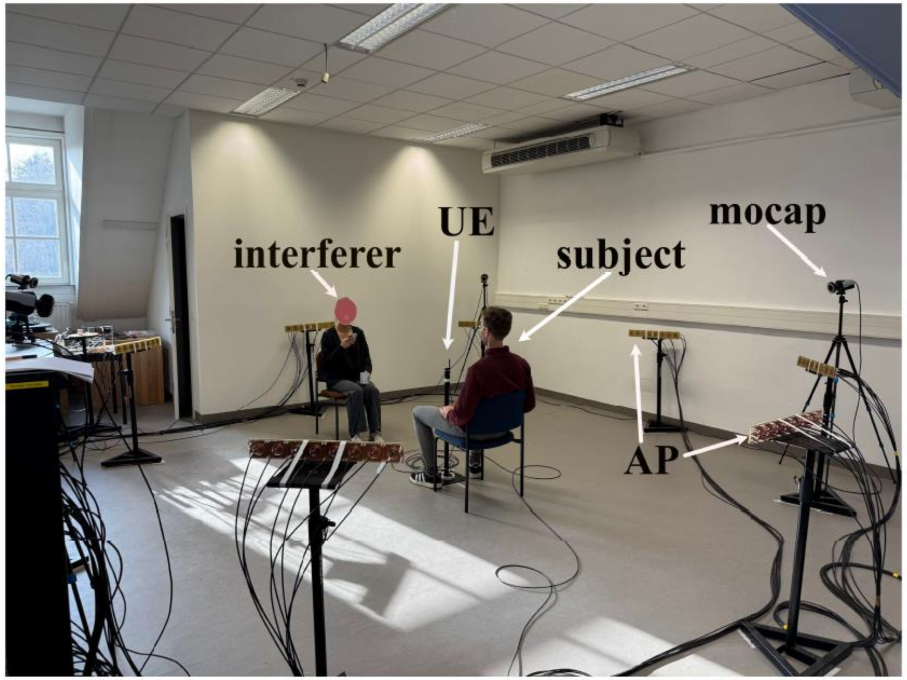
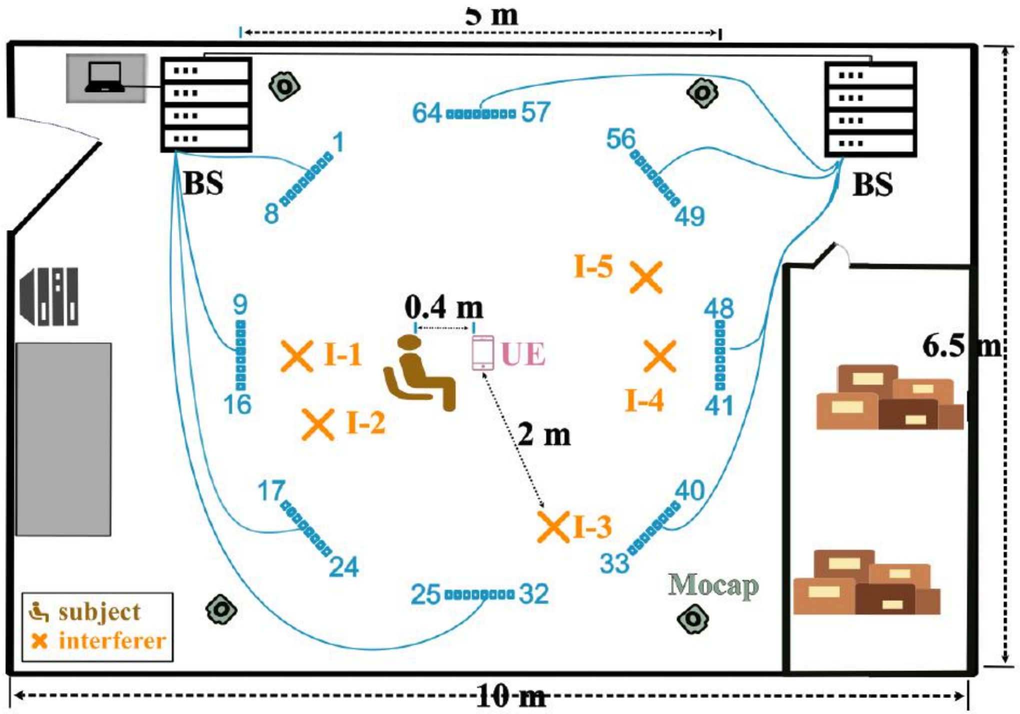
Using UE signals indoor for vital sign sensing



(a) Measurement environment.

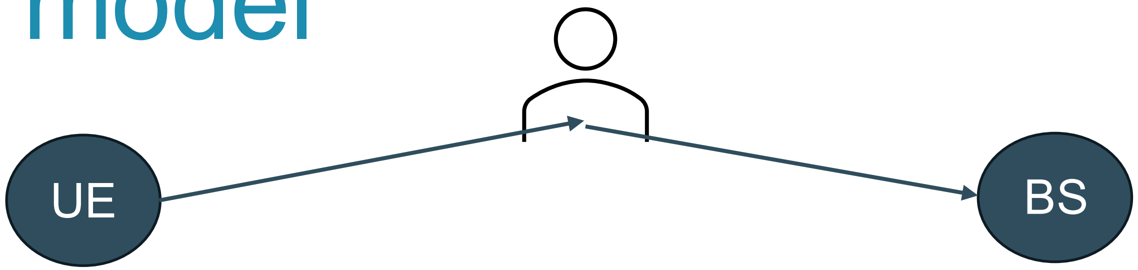


(b) Measurement floorplan.

Fig. 9. Measurement setup in the KU Leuven Massive MIMO Lab. (a) Experimental scene with subject, UE, APs, interferer, and MoCap cameras. (b) Corresponding floorplan of the lab indicating the locations of the subject, five interferer positions (I-1 to I-5), the APs (64 antennas distributed across 8 subarrays), and MoCap cameras.

H. Xiong, R. Beerten, Q. Zhang, Y. Miao, Z. Cui and S. Pollin, "Fundamentals and Experiments of Robust Respiration Sensing via Cell-Free Massive MIMO," in IEEE Journal on Selected Areas in Communications, vol. 44, pp. 959-974, 2026

System model



$$\hat{b}_m(t) = \angle\big(h_m(\hat{d}, t)\big).$$

Dynamic channel length

$$r_{ml}^{(\mathrm{tx})}(t) = \underbrace{\breve{r}_{ml}^{(\mathrm{tx})}}_{\text{initial path length}} + \underbrace{b(t)\cos\left(\frac{\beta_{ml}}{2}\right)}_{\text{projected fluctuation}},$$

$$r_{ml}^{(\mathrm{rx})}(t) = \underbrace{\breve{r}_{ml}^{(\mathrm{rx})}}_{\text{initial path length}} + \underbrace{b(t)\cos\left(\frac{\beta_{ml}}{2}\right)}_{\text{projected fluctuation}},$$

$\cos\left(\frac{\beta_{ml}}{2}\right)$ is the bistatic projection term

Single dynamic path (channel)

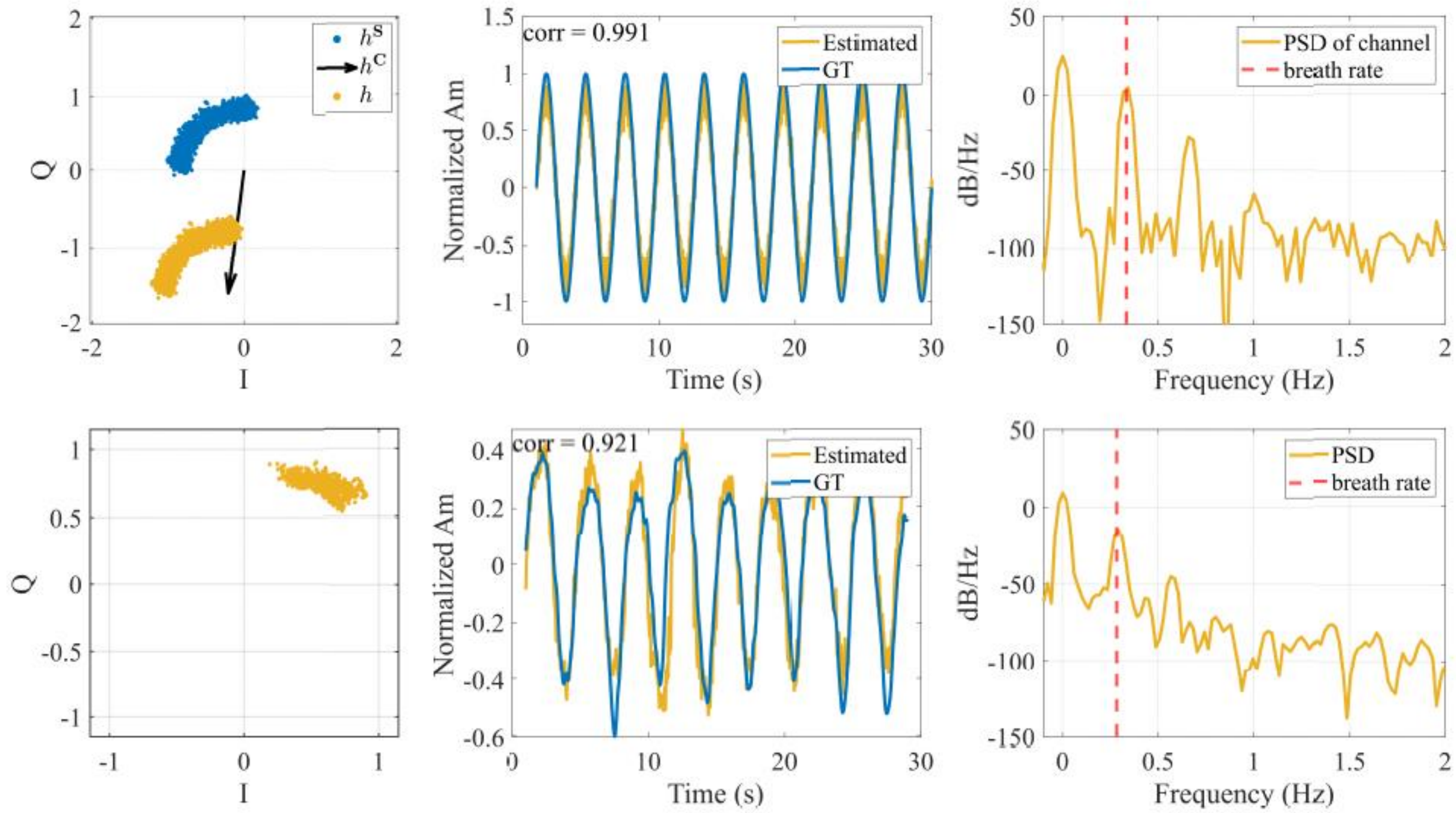
$$x_{ml}(k,t) = \frac{\kappa}{r_{ml}^{(tx)}(t)\, r_{ml}^{(rx)}(t)} e^{-j2\pi f_k \frac{r_{ml}^{(tx)}(t) + r_{ml}^{(rx)}(t)}{c}}.$$

Measured channel

$$\begin{aligned} h_m(k,t) &= h_m^{\boldsymbol{S}}(k,t) + h_m^{\boldsymbol{C}}(k) + \eta_m(k,t) \\ &= \sum_{l\in \boldsymbol{S}}^{\boldsymbol{S}} x_{ml}(k,t) + \sum_{l\in \boldsymbol{C}}^{\boldsymbol{C}} x_{ml}(k) + \eta_m(k,t), \end{aligned}$$

H. Xiong, R. Beerten, Q. Zhang, Y. Miao, Z. Cui and S. Pollin, "Fundamentals and Experiments of Robust Respiration Sensing via Cell-Free Massive MIMO," in IEEE Journal on Selected Areas in Communications, vol. 44, pp. 959-974, 2026

Single target channel (complex, time, PSD)

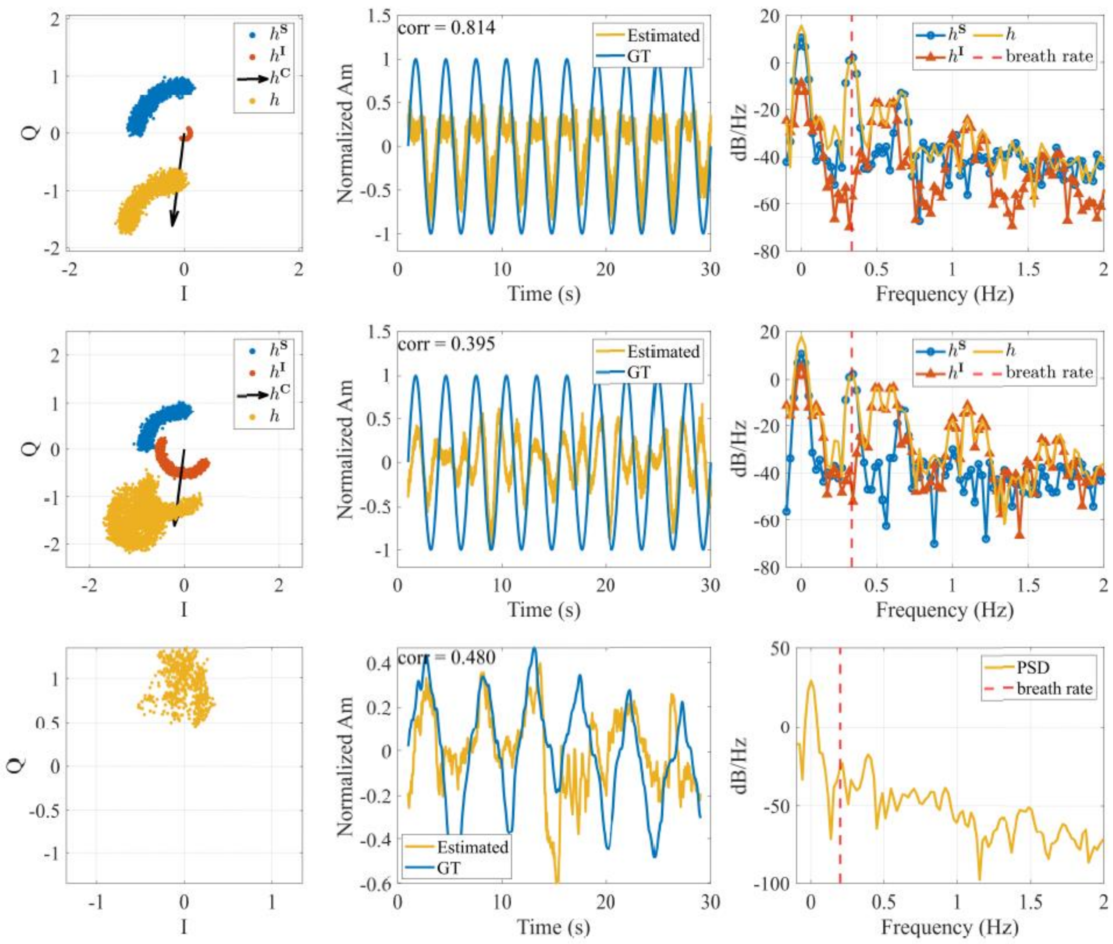


Simulation

Measurement

H. Xiong, R. Beerten, Q. Zhang, Y. Miao, Z. Cui and S. Pollin, "Fundamentals and Experiments of Robust Respiration Sensing via Cell-Free Massive MIMO," in IEEE Journal on Selected Areas in Communications, vol. 44, pp. 959-974, 2026

Multi target channel (complex, time, PSD)



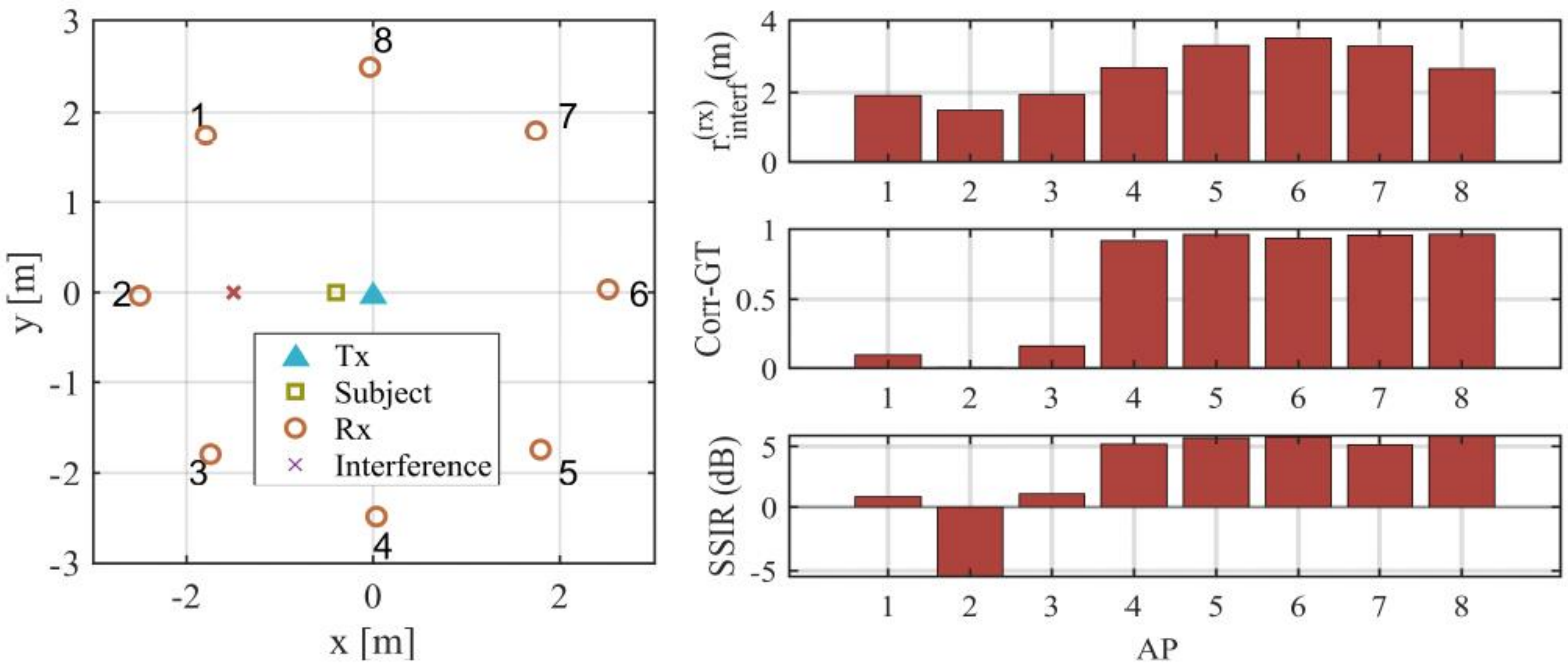
Simulation (Tx close to target)

Simulation (Tx close to target and interferer)

Measurement

H. Xiong, R. Beerten, Q. Zhang, Y. Miao, Z. Cui and S. Pollin, "Fundamentals and Experiments of Robust Respiration Sensing via Cell-Free Massive MIMO," in IEEE Journal on Selected Areas in Communications, vol. 44, pp. 959-974, 2026

Measured breathing pattern as function of antenna location (simulation)



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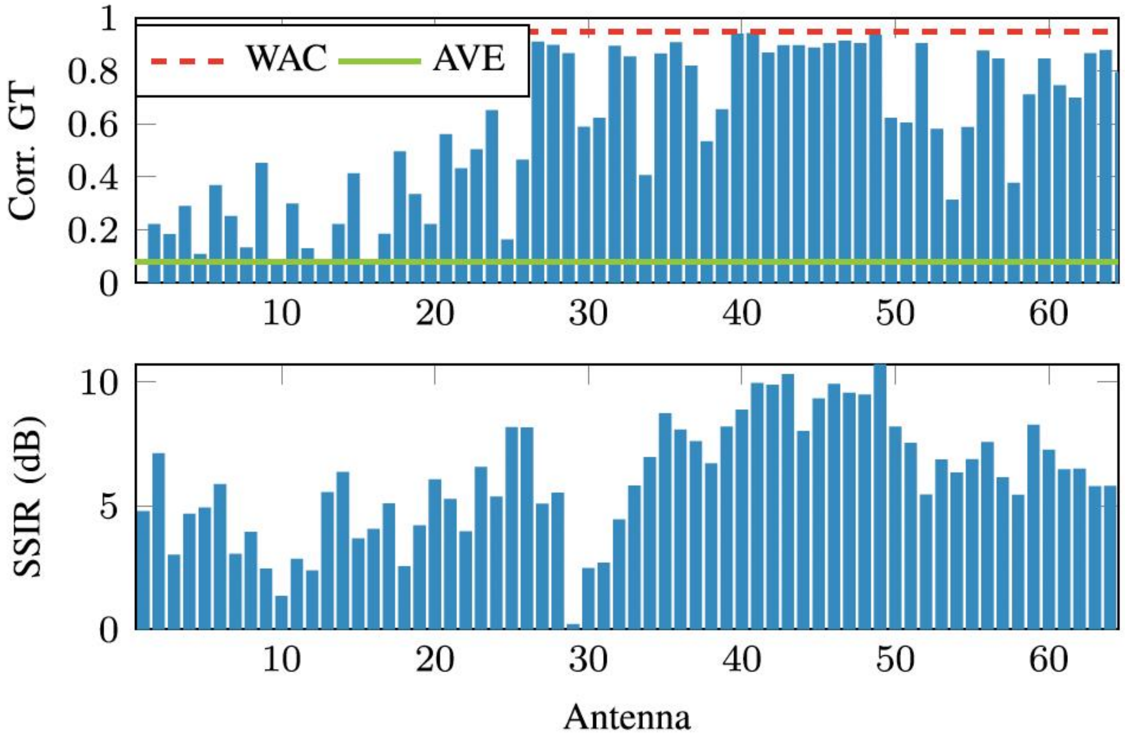
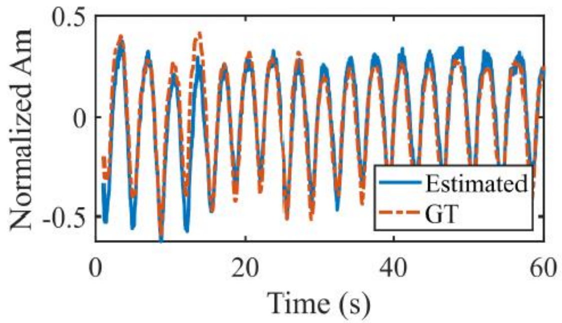
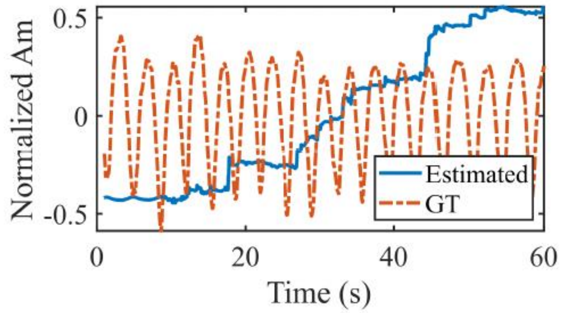
Measurement results under interference

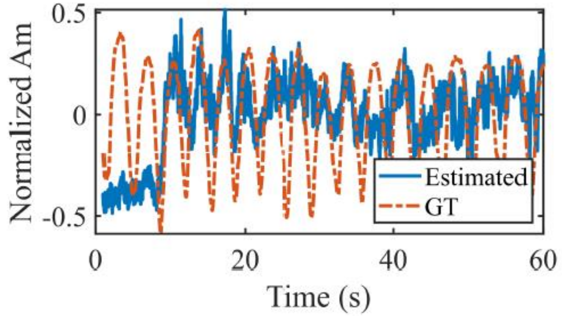




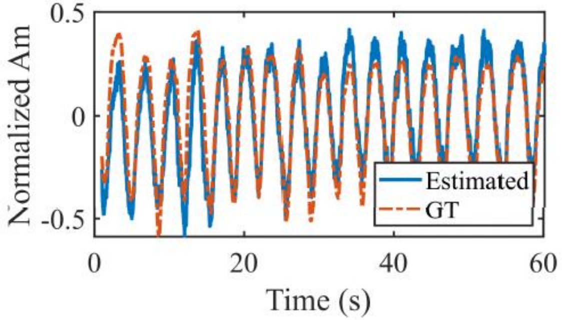
(b) WAC combining, corr = 0.948.



(c) AVE combining, corr = 0.079.



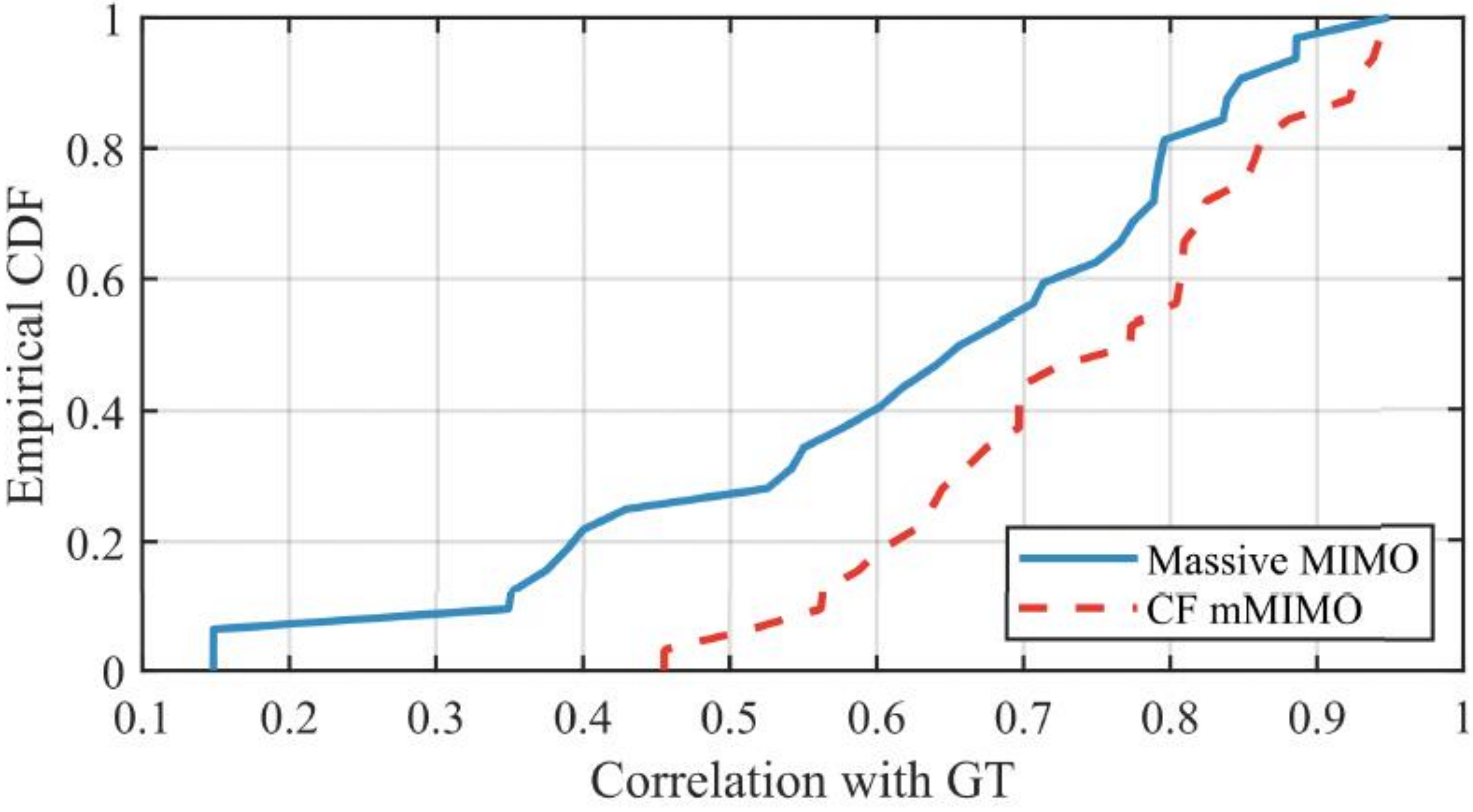
(d) The 1st antenna: corr = 0.223.



(e) The 26th antenna, corr = 0.910.

H. Xiong, R. Beerten, Q. Zhang, Y. Miao, Z. Cui and S. Pollin, "Fundamentals and Experiments of Robust Respiration Sensing via Cell-Free Massive MIMO," in IEEE Journal on Selected Areas in Communications, vol. 44, pp. 959-974, 2026

A case for indoor cell-free MIMO (measured results)



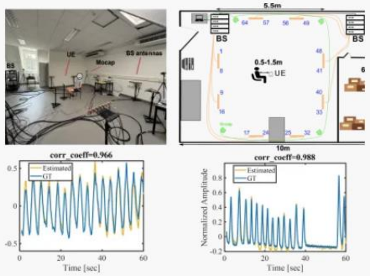
H. Xiong, R. Beerten, Q. Zhang, Y. Miao, Z. Cui and S. Pollin, "Fundamentals and Experiments of Robust Respiration Sensing via Cell-Free Massive MIMO," in IEEE Journal on Selected Areas in Communications, vol. 44, pp. 959-974, 2026

Datasets, code, challenges, focus periods…

Datasets

Standard Dataset

Respiration Sensing with Cell-free Massive MIMO



★★★★★
Average: 5 (43 votes)

Citation Author(s): Haoqiu Xiong (KU Leuven)
Robbert Beerten (KU Leuven)
Sofie Pollin (KU Leuven & IMEC)

Submitted by: Haoqiu Xiong

Last updated: Thu, 02/26/2026 - 12:38

DOI: 10.21227/0dey-xx67

Research Article Link: BS-Breath: Respiration Sensing with Cell-free Massive MIMO

Categories: Signal Processing
Communications
Health

Keywords: Integrated Sensing and Communication, cell-free massive MIMO, respiration sensing.

CITE SHARE/EMBED

[Xiong, Haoqiu, et al. "BS-Breath: Respiration Sensing with Cell-free Massive MIMO." *IEEE ICASSP 2025*]

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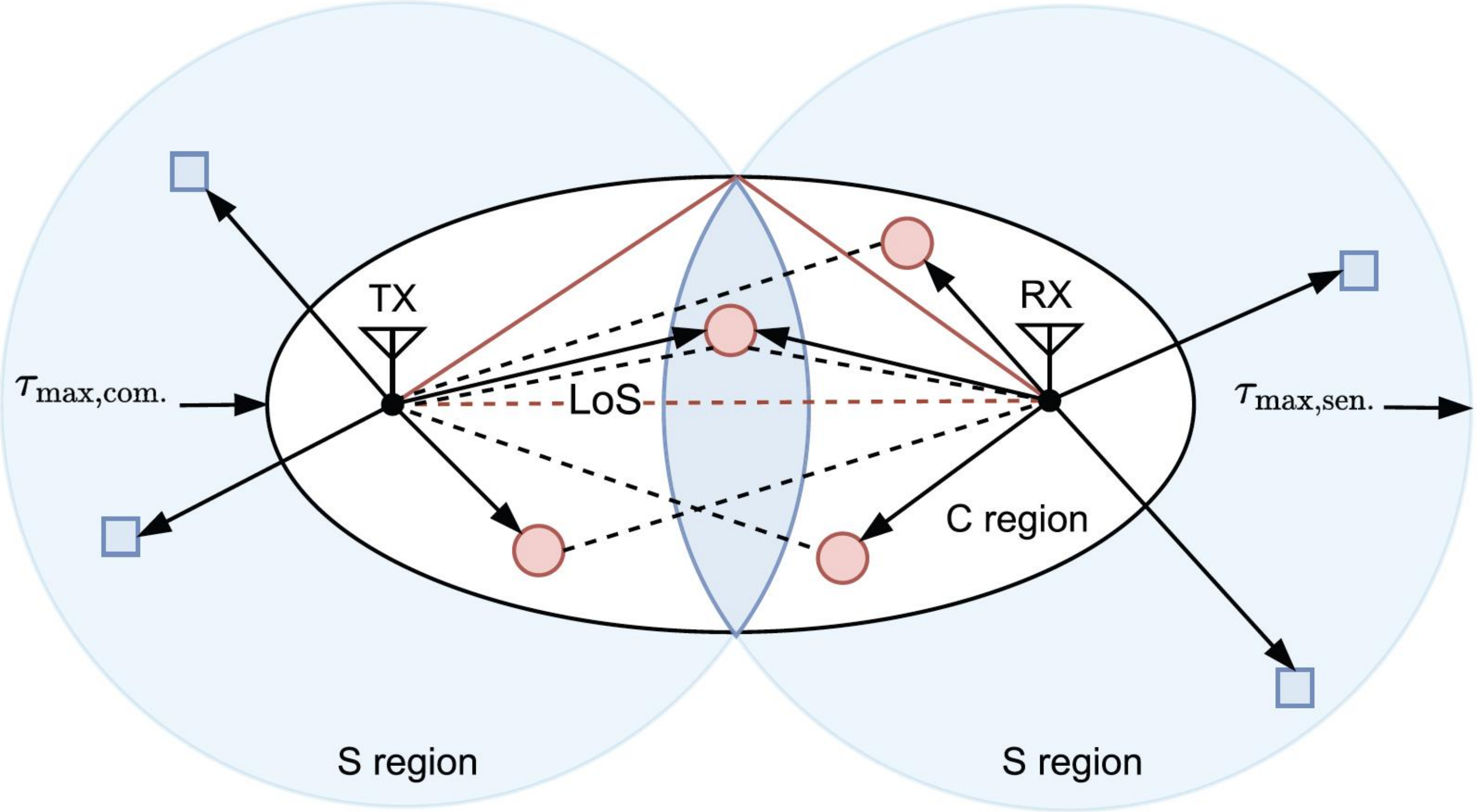
Outline

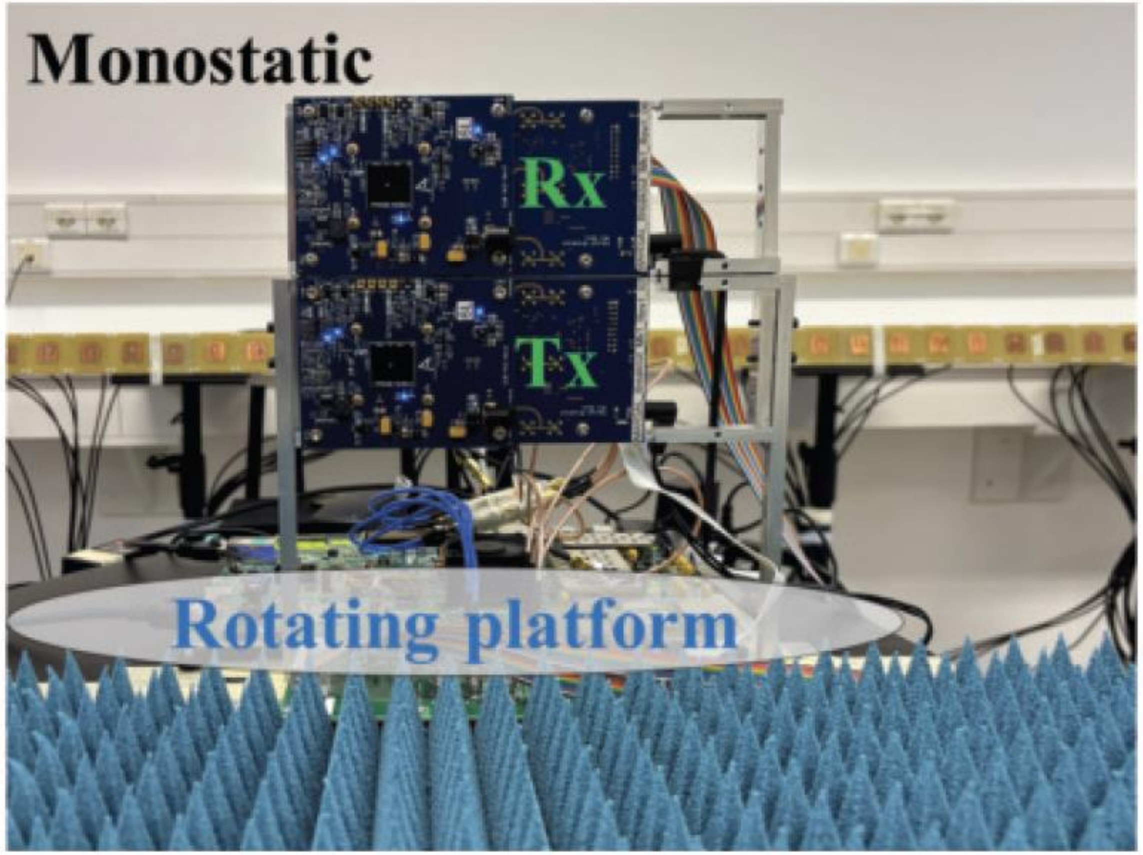
1. Basics (cell-free) sensing ✓
2. Near-field range resolution ✓
3. Non-contiguous bandwidth ✓
4. Cell-free vital sign sensing ✓
5. Sensing for communication — Skip it time needed
6. Call for more data and frictionless reproducability

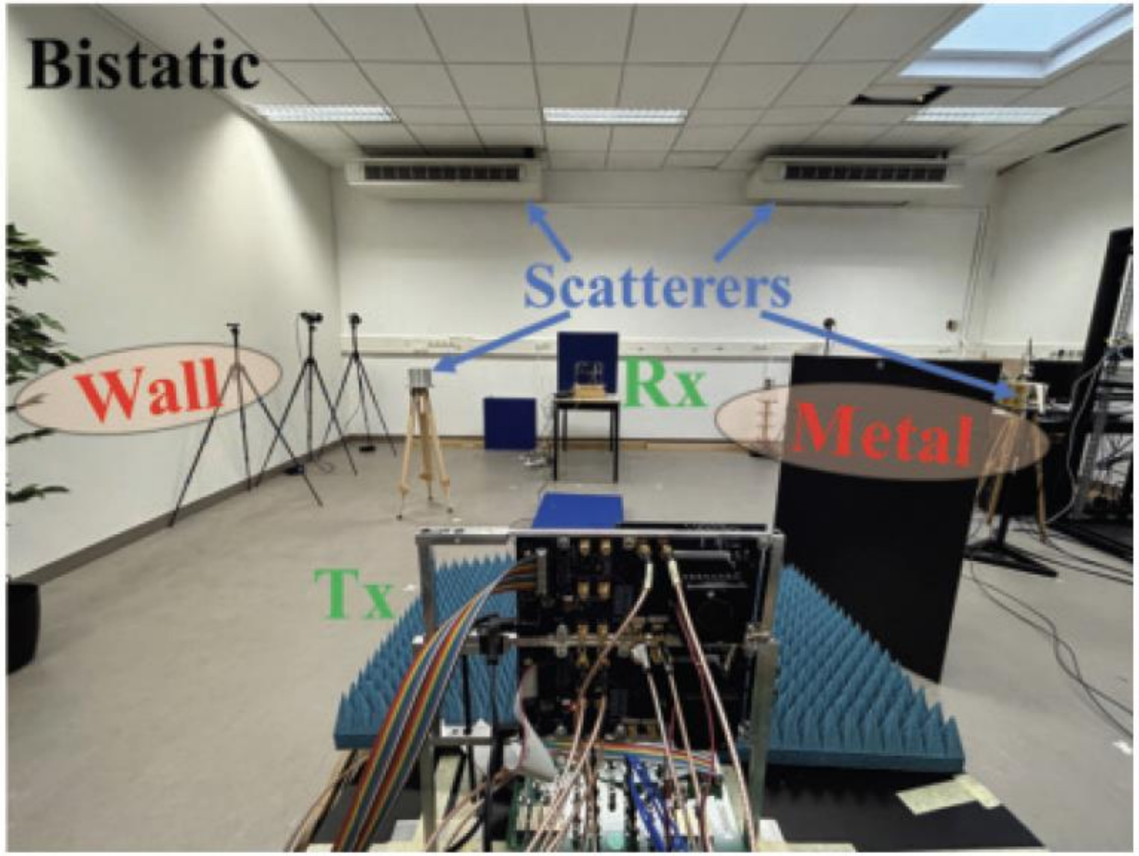
Sensing and communication in the same environment



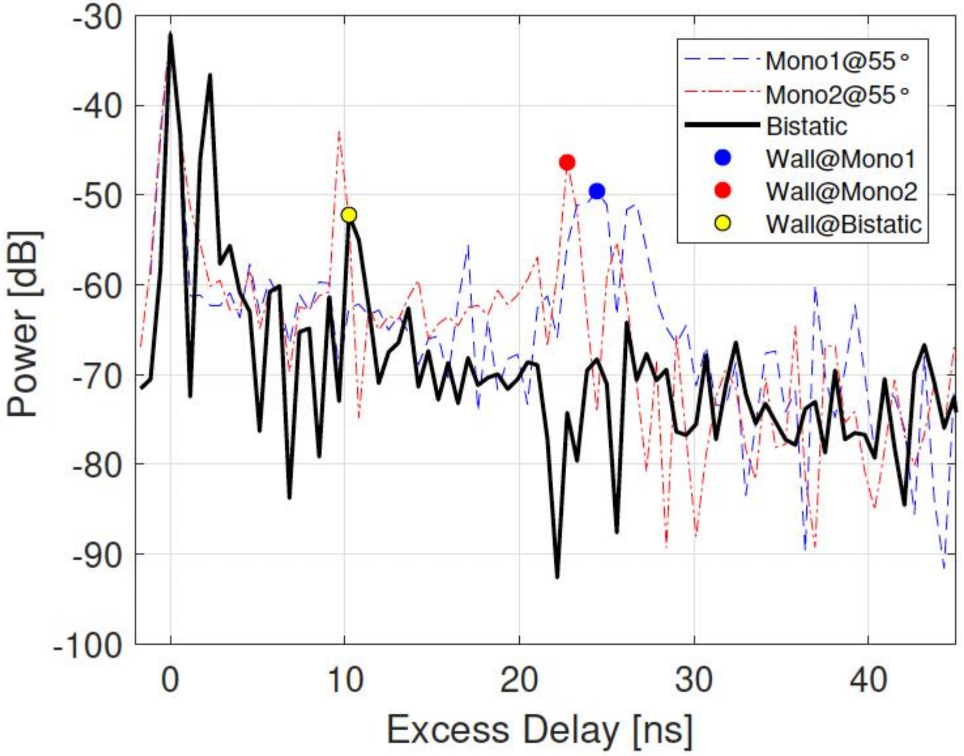
Z. Cui and S. Pollin, "Extracting the Communication Channel From Monostatic Sensing Channels: From Propagation to Impact Analysis," in IEEE Transactions on Antennas and Propagation, vol. 73, no. 8, pp. 6193-6198, Aug. 2025

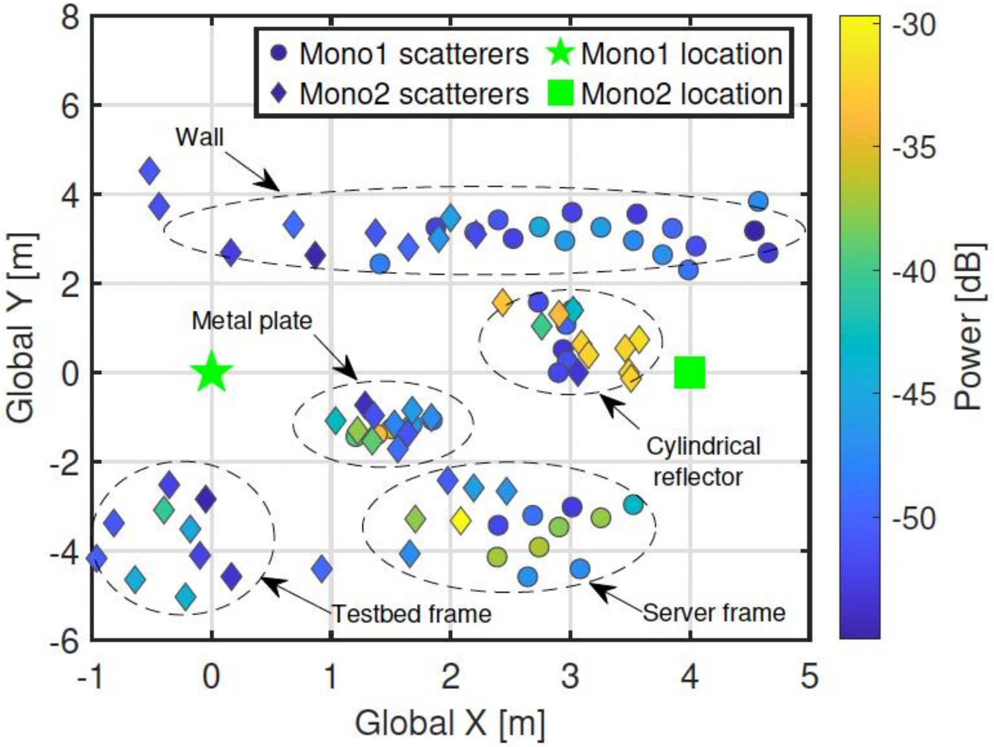
Measurement setup with B = 1,76 GHz and   fc = 13,75 MHz.





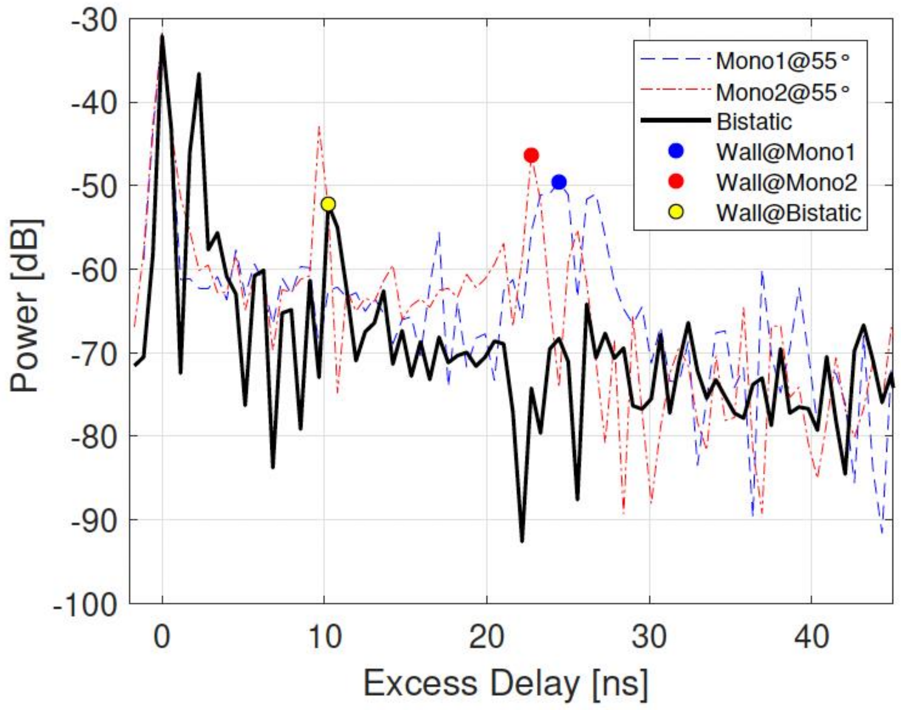
Extracted reflections from two monostatic locations

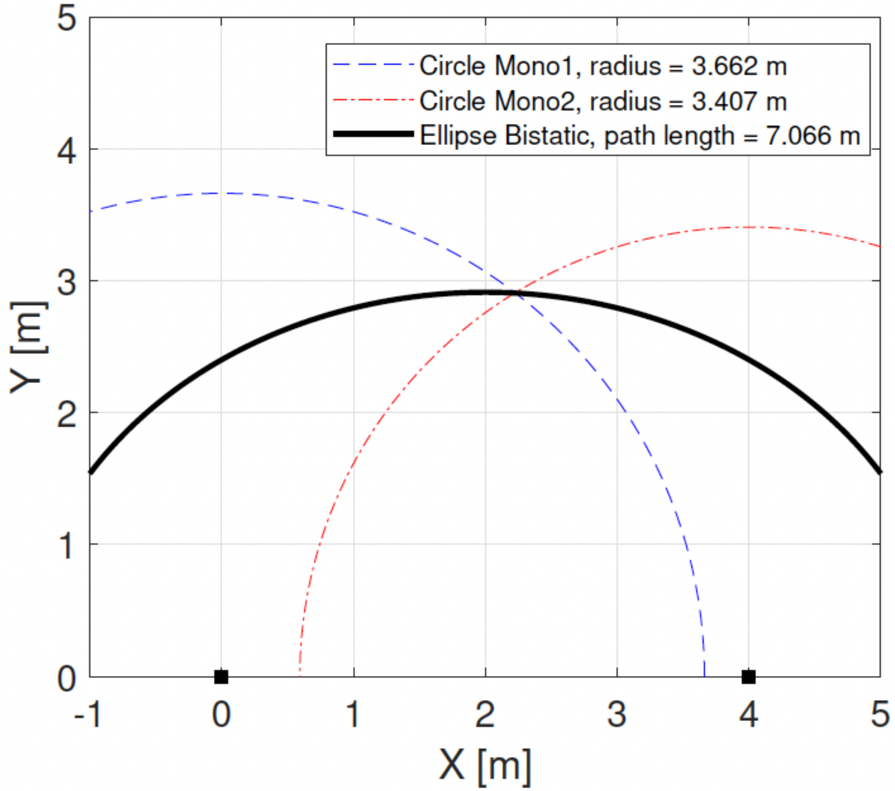




$$\mathbf{m}_1(\theta_a, R) = \begin{bmatrix} x_1 + R\cos\theta_a \\ y_1 - R\sin\theta_a \end{bmatrix}, \mathbf{m}_2(\theta_a, R) = \begin{bmatrix} x_2 - R\cos\theta_a \\ y_2 - R\sin\theta_a \end{bmatrix},$$

Monostatic reflections and link with bistatic multipath





Outline

1. Basics (cell-free) sensing ✓
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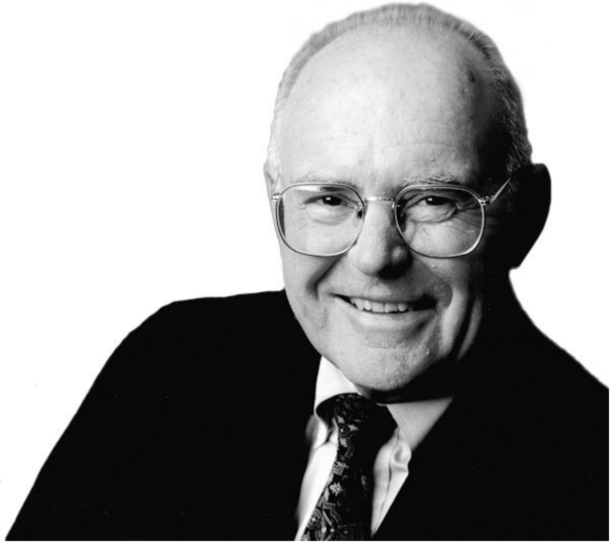
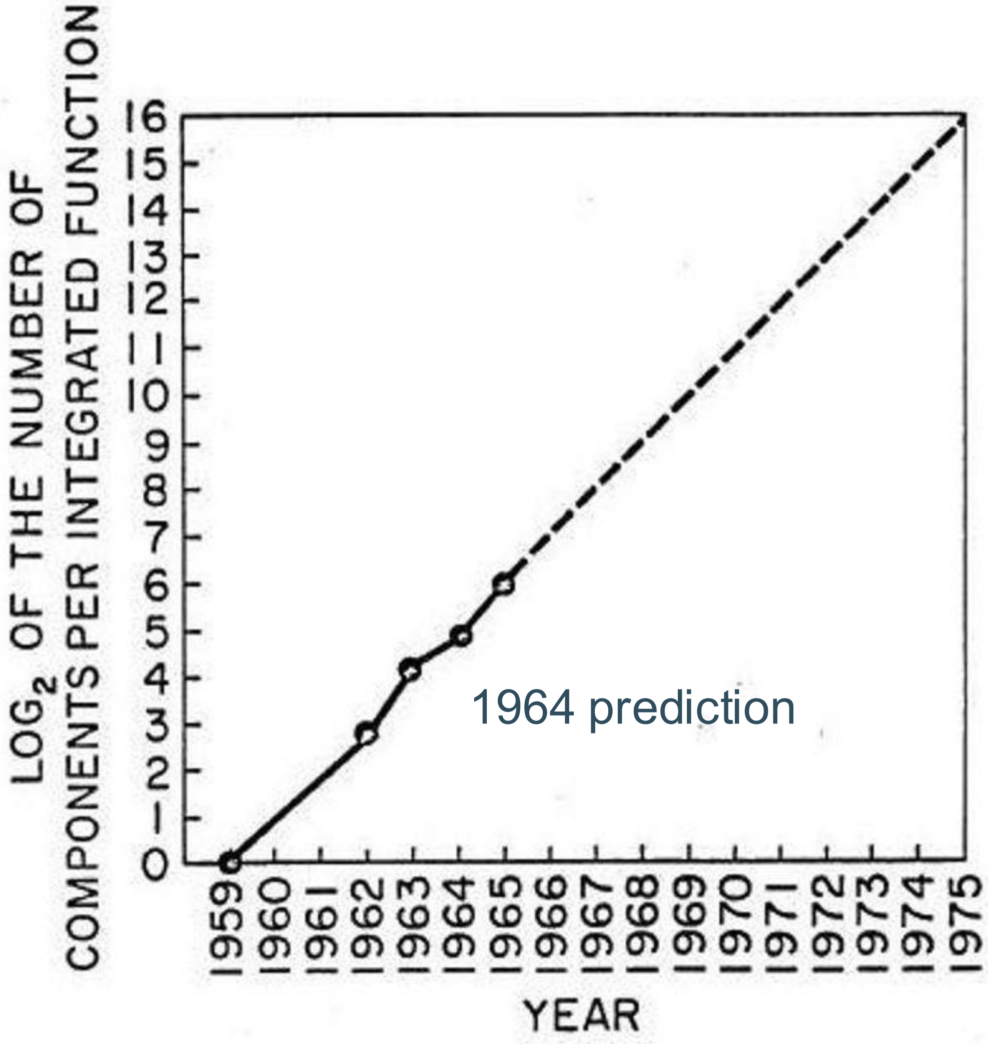
Compute: doubling every 24 months

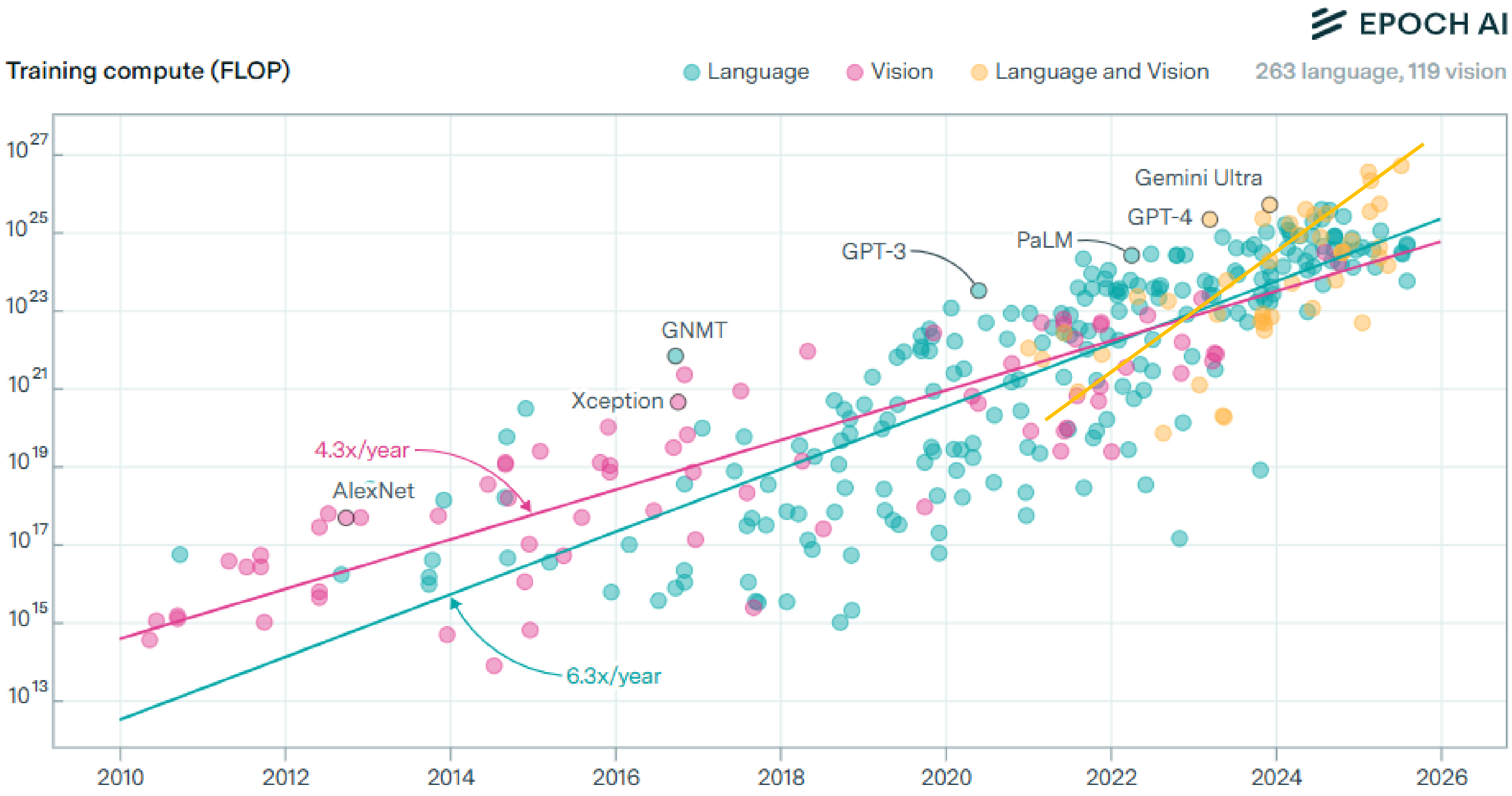
- Factor 30.000.000 in 5 years!





[Moore, Gordon E. "Cramming More Components onto Integrated Circuits." *Electronics*, vol. 38, no. 8, 1965, pp. 114–117.]

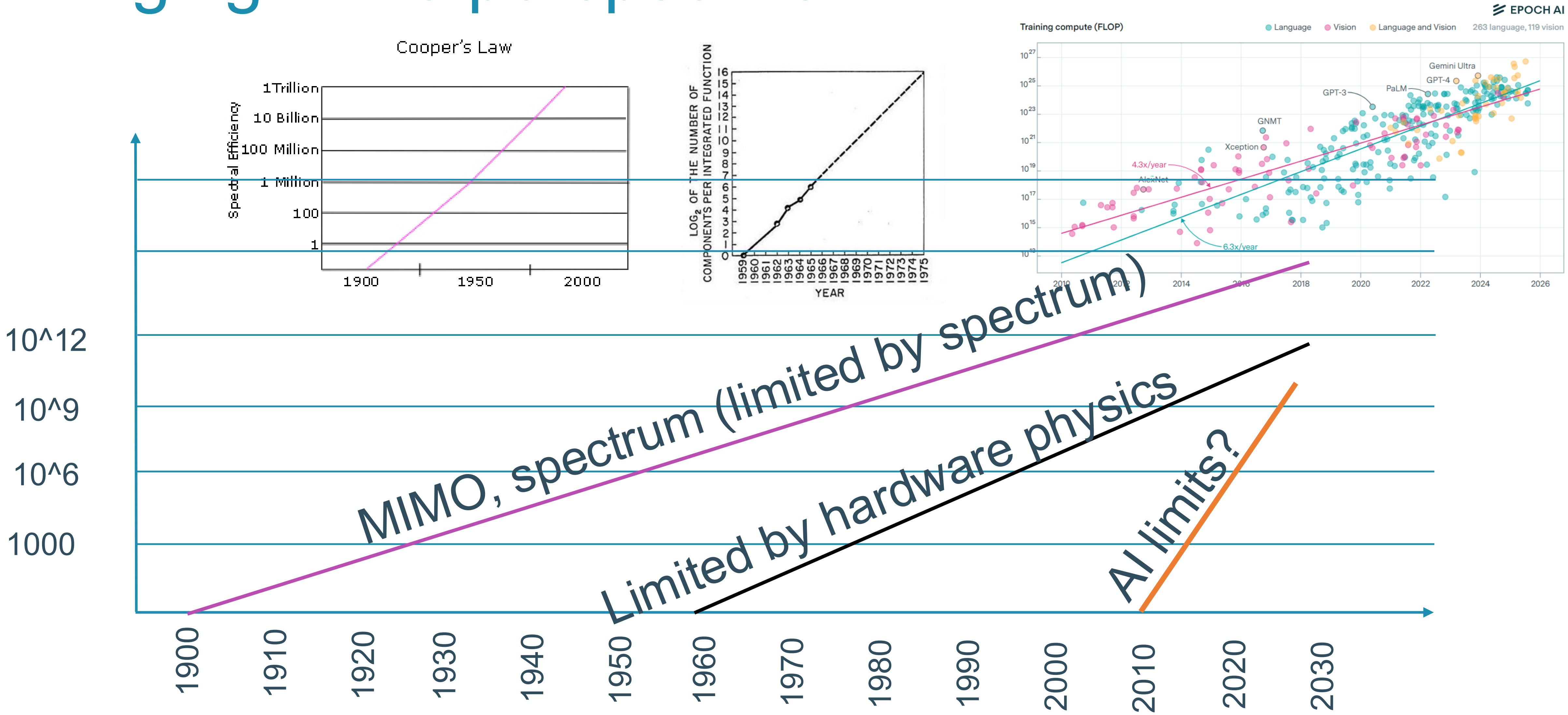
AI models: 5x every year
That is 10^35 times in 50 year… 10 million in 10 years



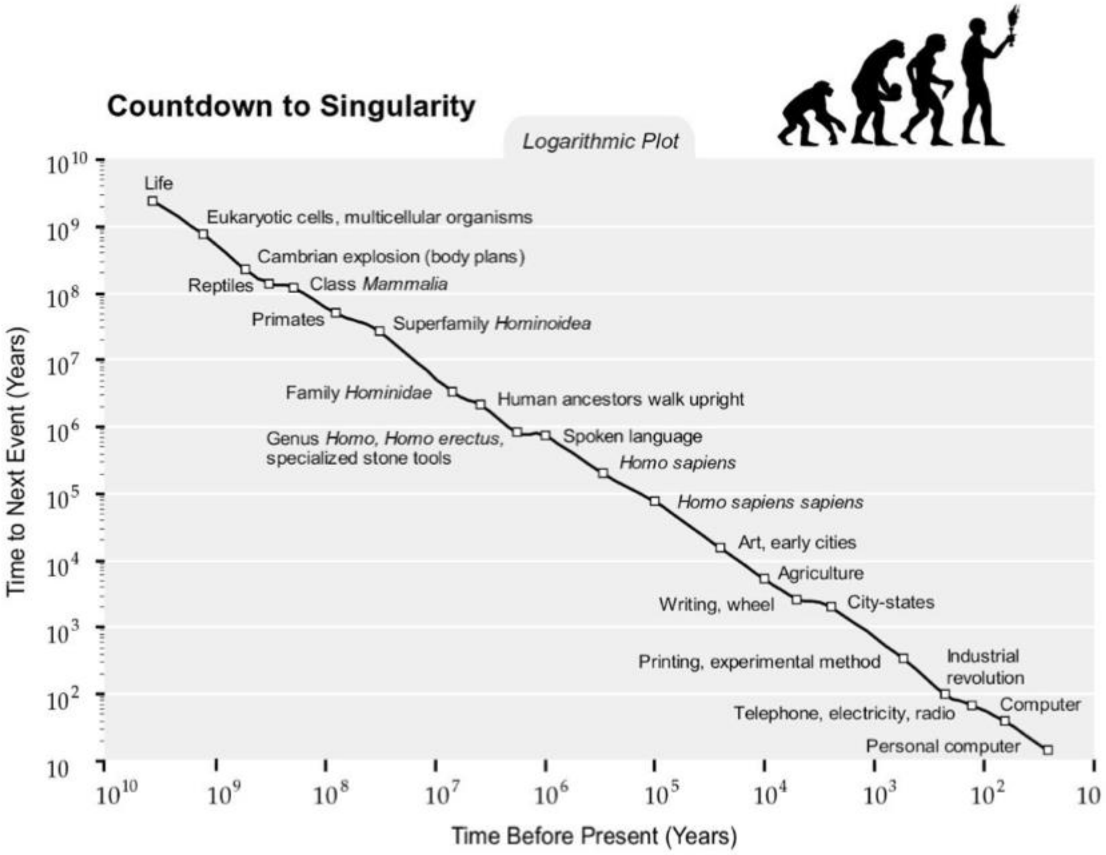
10^12	tera	T
10^15	peta	P
10^18	exa	E
10^21	zetta	Z
10^24	yotta	Y
10^27	ronna	R
10^30	quetta	Q

Epoch AI. “Training Compute of Frontier AI Models Grows by 4-5× per Year.” *Epoch AI Blog*, 28 May 2024, https://epoch.ai/blog/training-compute-of-frontier-ai-models-grows-by-4-5x-per-year

Bringing it into perspective



The reproducibility singularity



Core principle:

- The law of accelerating returns
- All technological progress is exponential
- Each technology enables acceleration of innovation

Kurzweil predicts that by **2045**, AI will:

- Be **billions of times more powerful** than human intelligence.
- Lead to **unprecedented technological progress**, eliminating disease, aging, and resource scarcity.

At this point, technological progress will become **uncontrollable and unpredictable**, marking the **singularity**.

[Donoho, D. (2024). Data Science at the Singularity . *Harvard Data Science Review, 6*(1).]

Understanding the **rapid progress in/with AI**
Frictionless Reproducibility

The three initiatives are related but separate; and all three have to come together, and in a particularly strong way, to provide the conditions for the new era. Here they are:

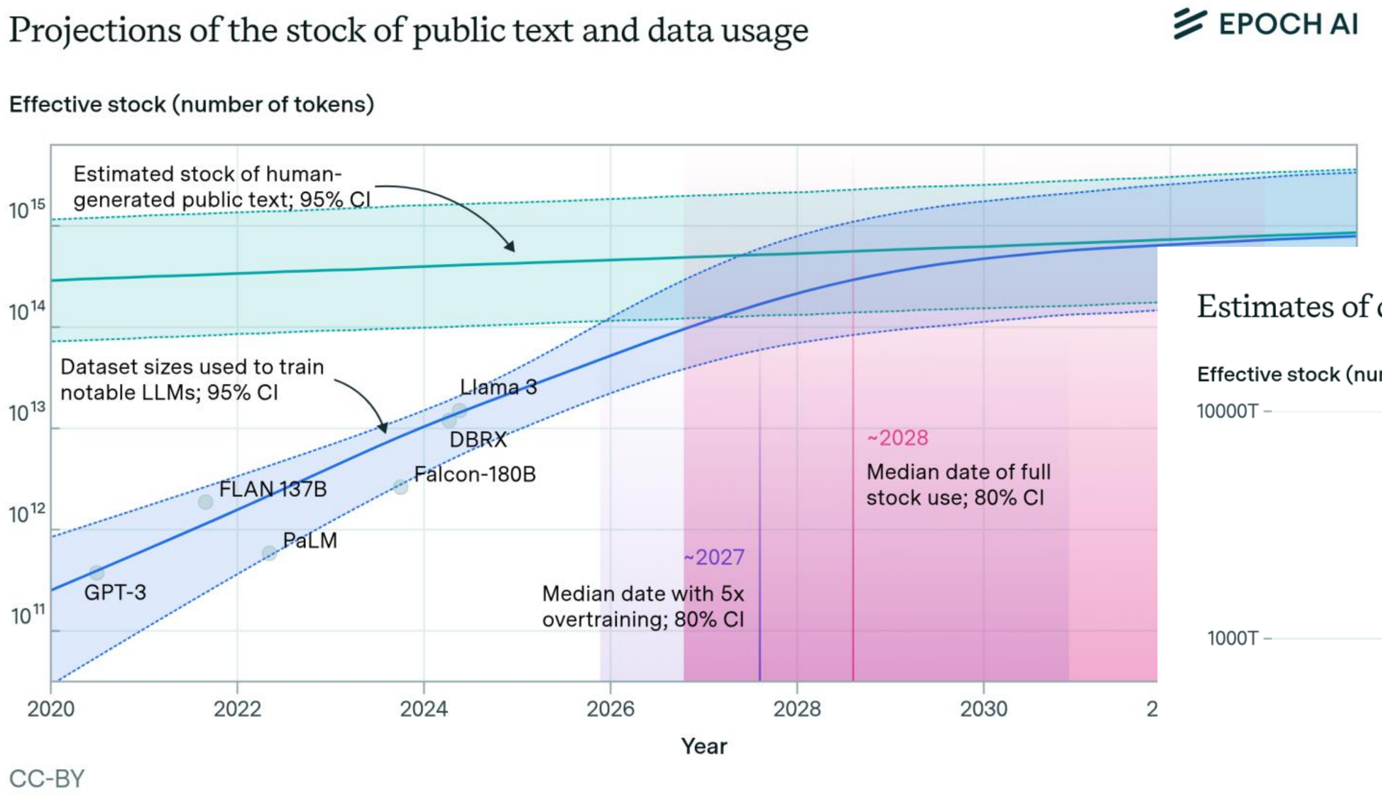
[**FR-1: Data**] datafication of everything, with a culture of research data sharing. One can now find datasets publicly available online on a bewildering variety of topics, from chest x-rays to cosmic microwave background measurements to uber routes to geospatial crop identifications.

[**FR-2: Re-execution**] research code sharing including the ability to exactly re-execute the same complete workflow by different researchers.

[**FR-3: Challenges**] adopting challenge problems as a new paradigm powering scientific research. The paradigm includes: a shared public dataset, a prescribed and quantified task performance metric, a set of enrolled competitors seeking to outperform each other on the task, and a public leaderboard. Thousands of such challenges with millions of entries have now taken place, across many fields.

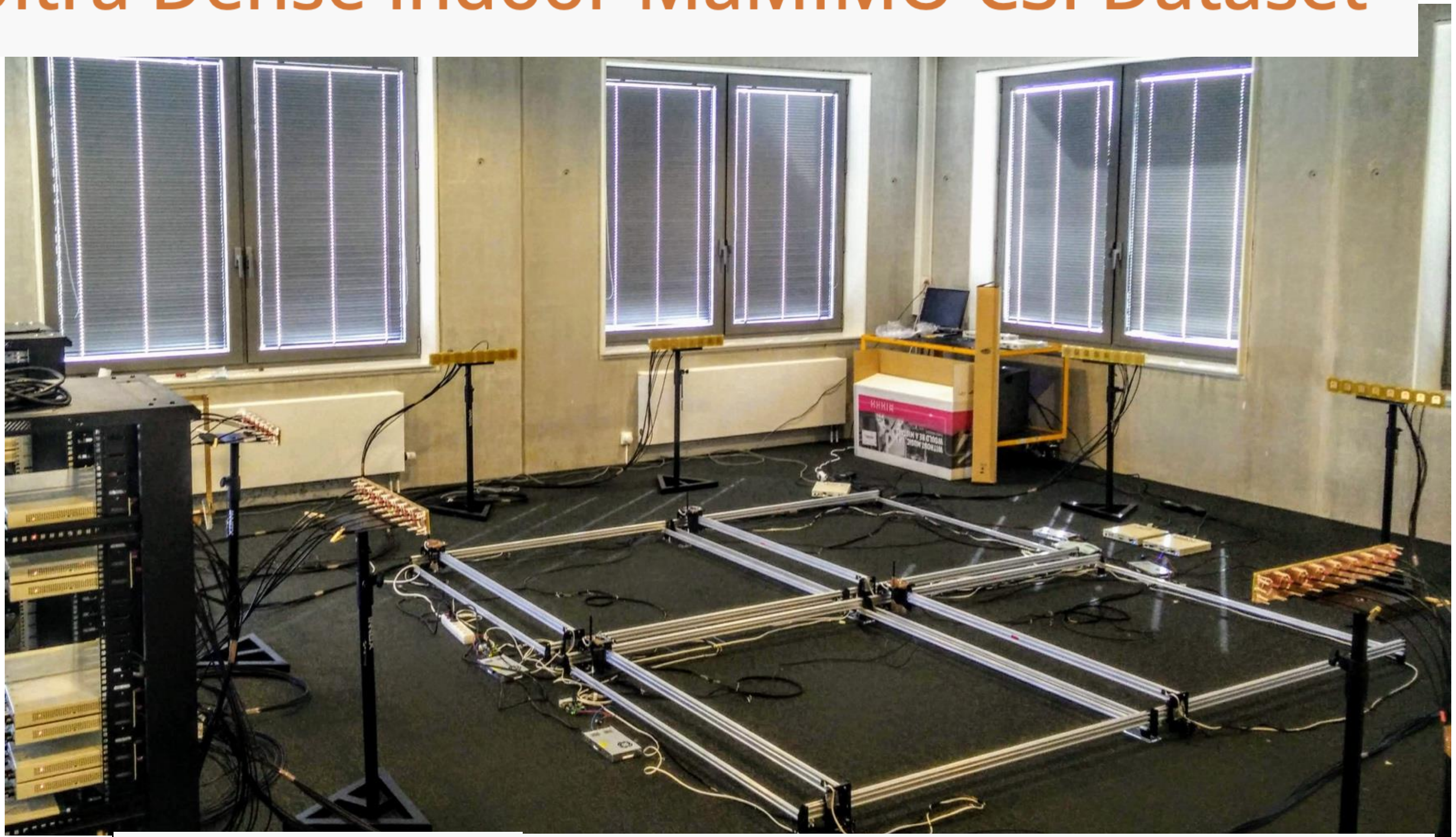
[Donoho, D. (2024). Data Science at the Singularity. *Harvard Data Science Review*, *6*(1).]

AI limit: high quality data!

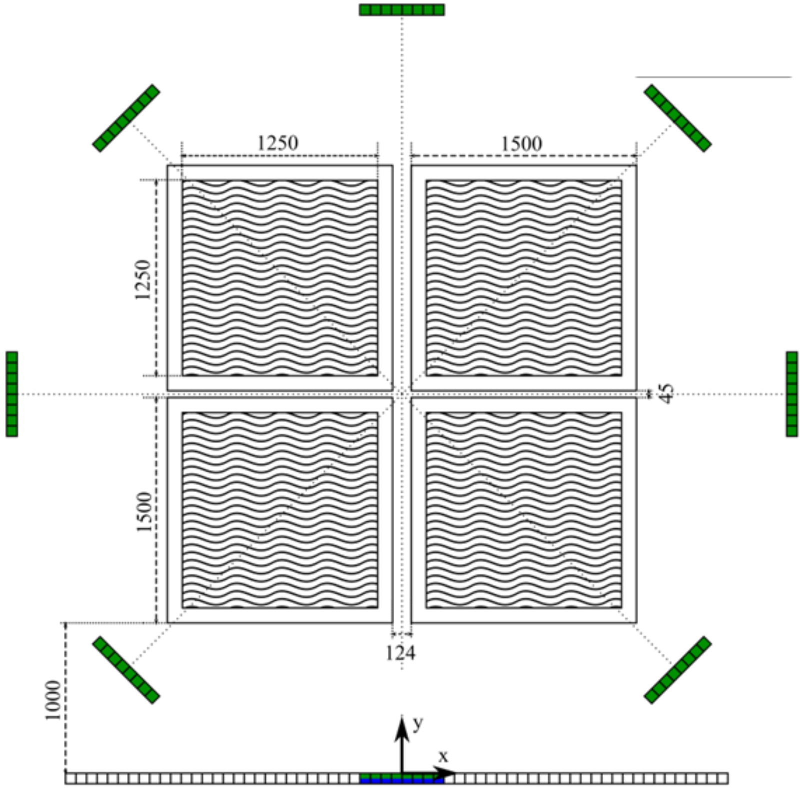


Automated measurement and labeling setup

Ultra Dense Indoor MaMIMO CSI Dataset



Antenna Array



IEEEDataPort
Datasets

Average: 5 (238 votes)   10207 views   1095854 downloads

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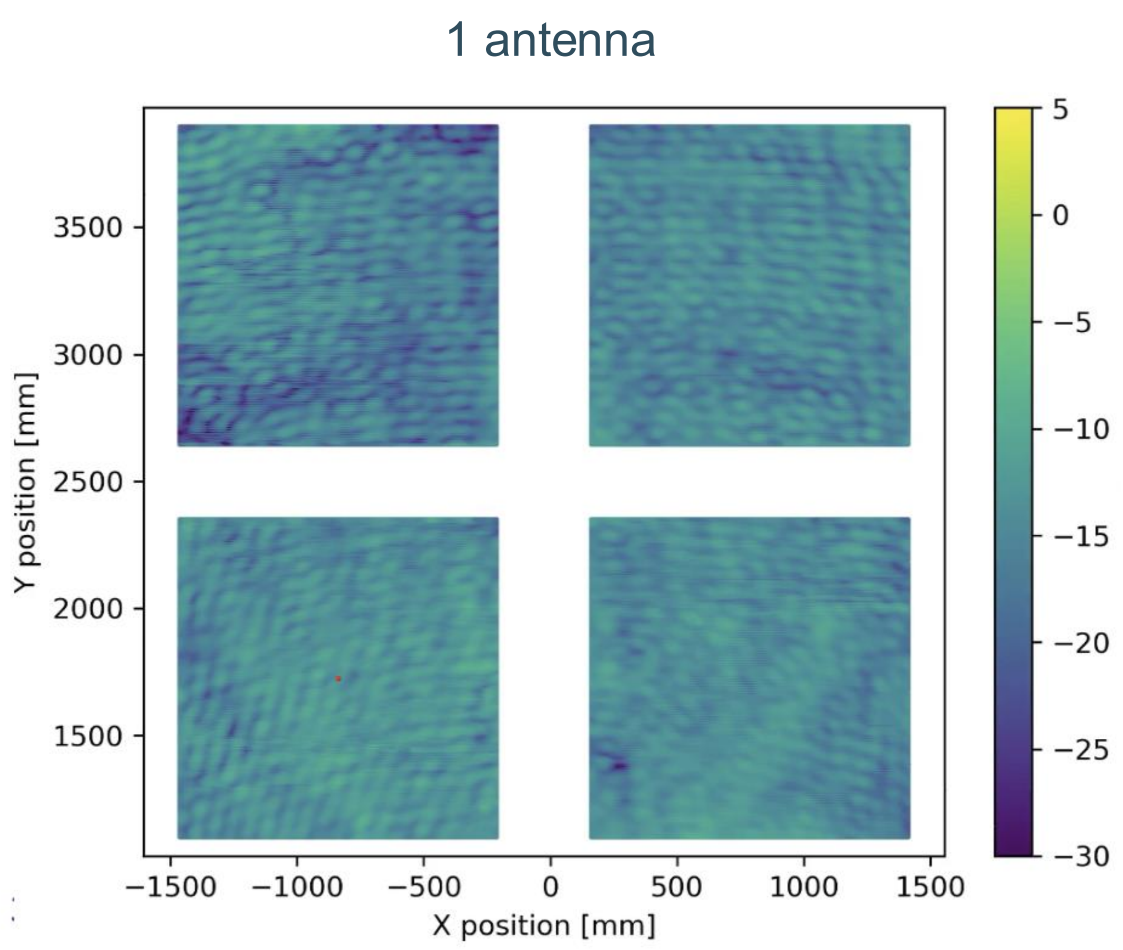
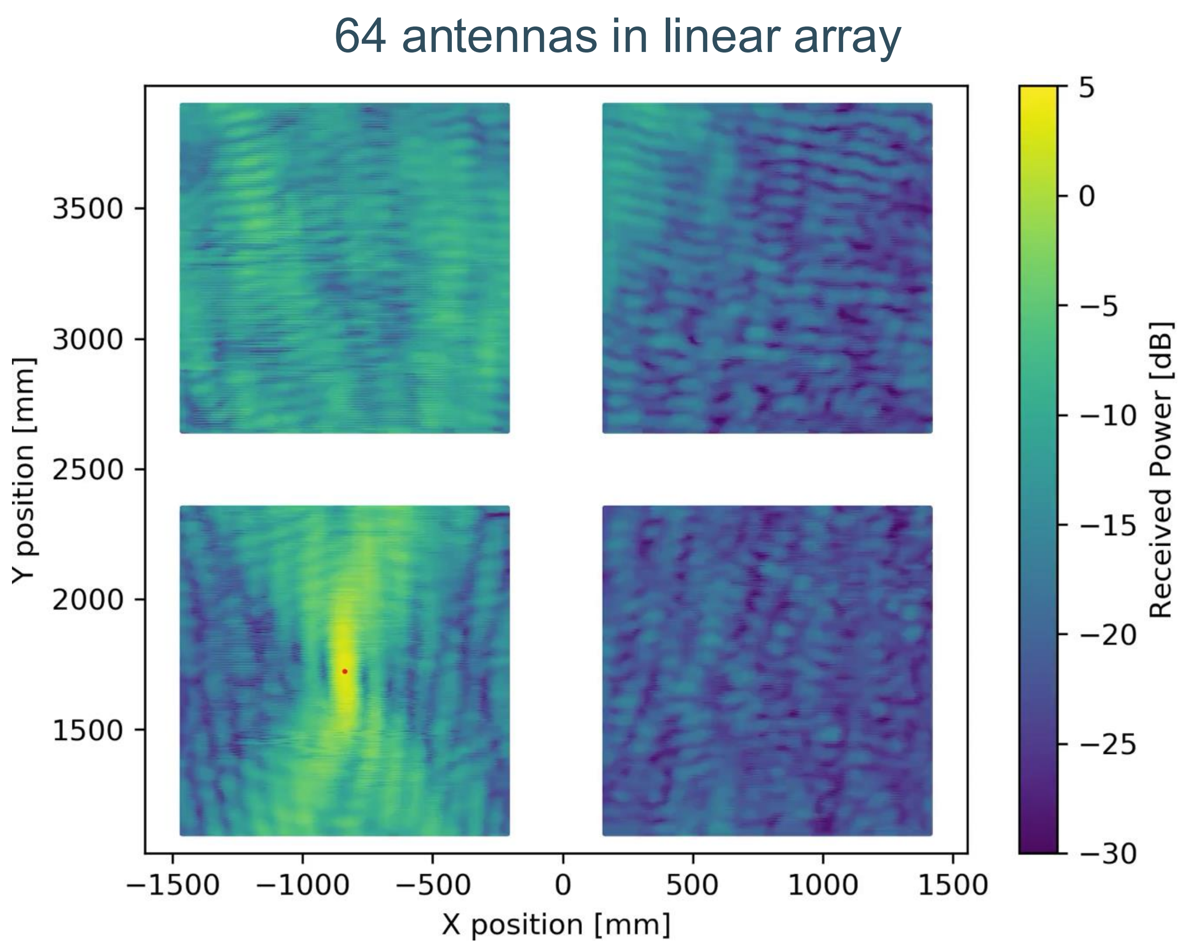
With (implicit) location information, we can accurately focus the signal on a certain target





Tx

Array

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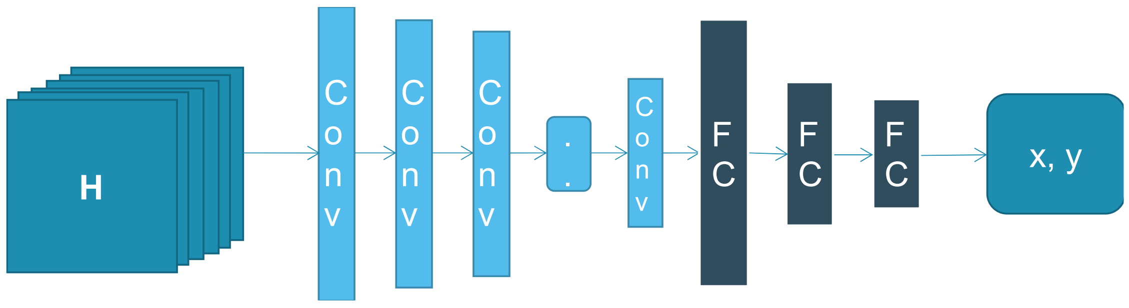
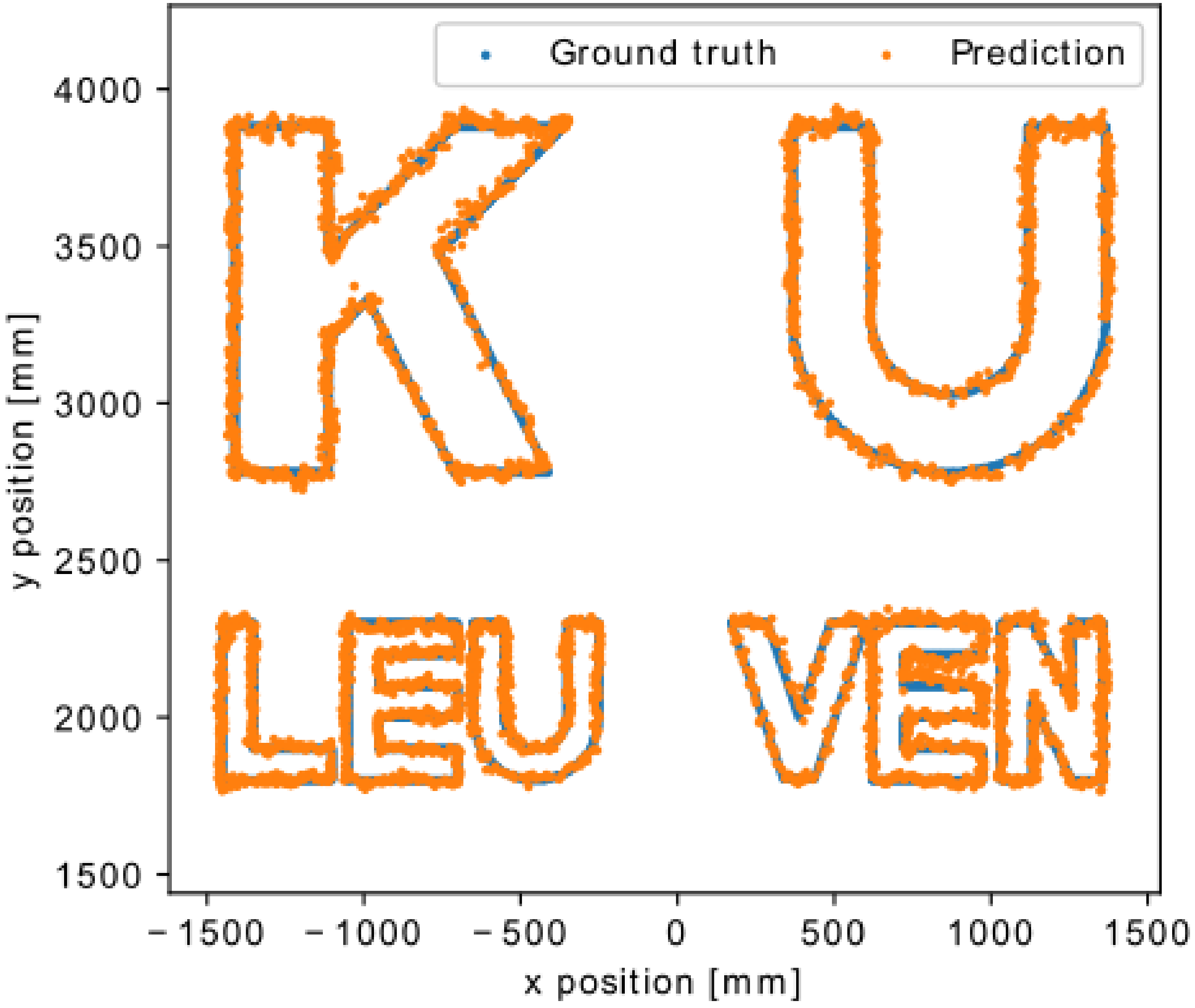
With machine learning: from implicit to explicit location sensing



Implicit

Excplicit



Fragmentation of our field

- Synthetic datasets
  - DeepMIMO/Sionna
  - Fully controllable/scalable but not sure how realistic
- Measurement datasets
  - E.g., dense Massive MIMO dataset
  - Realistic but limited scope
- Wi-Fi sensing datasets
  - E.g., Human sensing

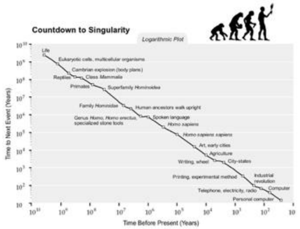
- Challenge:
  - Models trained on one dataset fail on others
  - No equivalent of “Imagenet” for communication

Conclusions

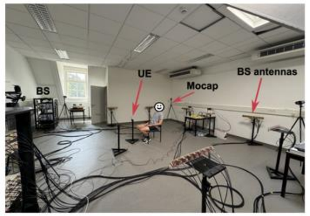
- **Massive**
  - Densification and disaggregation
  - AI-driven control Apps: rApp, xApp, dApp
- **Data-driven**
  - Data Sharing
  - Re-execution
  - Challenges
- **Integrated Communication and Sensing**
  - Presented some examples on sensing with communication signals
  - Resolution matters
  - Coherent combining for extended targets open challenge… RF imagenet …?

(multi-band] Cell-free O-RAN for ISAC

Frictionless
Reproducability
& Challenges!



Multi-static human and Environment sensing



Thanks!

sofie.pollin@kuleuven.be