Distributed Integrated Sensing and Communications:
Foundations, Opportunities, and Challenges

Part I: Fundamentals of DISAC operations and systems

CHALMERS

Henk Wymeersch, Hui Chen, George C. Alexandropoulos

National and Kapodistrian University of Athens

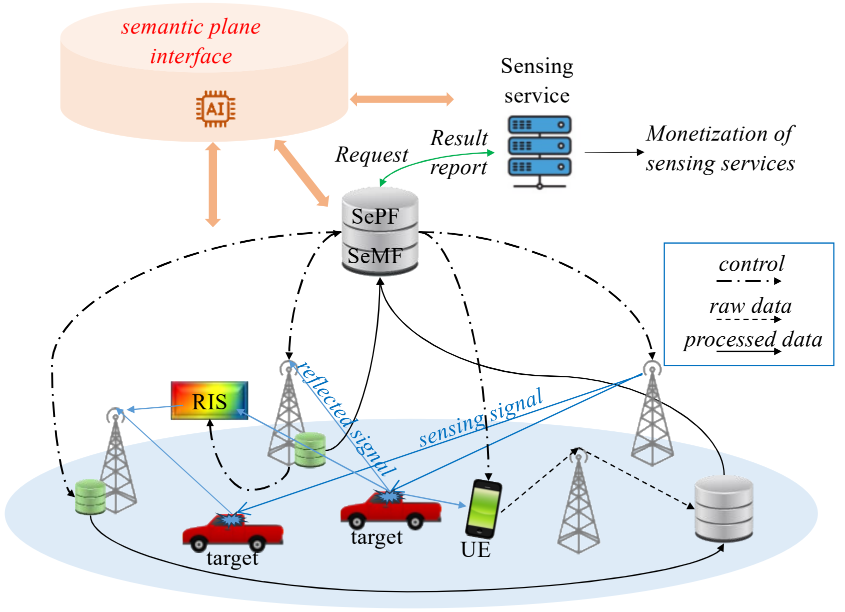
Outline

- Part I: Fundamentals of DISAC operations and systems (Presenter: Henk Wymeersch, 60 mins)
- Part II: Distributed Communication-Aided Sensing (Presenter: Hui Chen, 60 mins)
- Part III: Distributed Sensing-Aided Communications (Presenter: George C. Alexandropoulos, 60 mins)

Distributed Intelligent Sensing And Communications for 6G

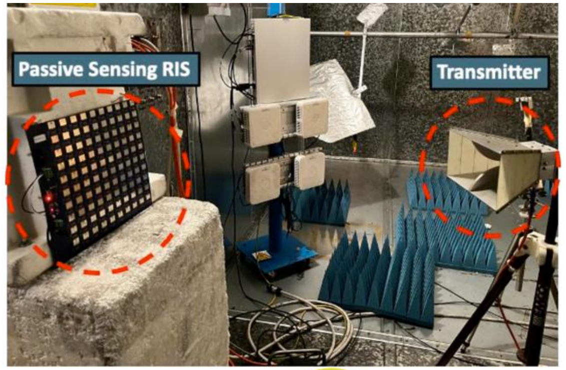
Project Objectives

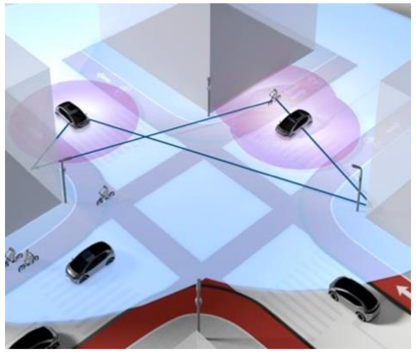
- **O1: Optimization of the physical layer for intelligent ISAC**
  - Waveforms, semantic-aware coding, multi-frequency bands, reflective and sensing RIS
- **O2: Super-resolution distributed sensing**
  - Extract 3D information and semantics, compress, share, and send minimal information
- **O3: Sensing-aided communication techniques**
  - Substantially reduced requirements, active beamforming, and full-duplex systems
- **O4: Resource allocation schemes and protocols**
  - Dynamically evolving scenarios, heterogeneous nodes, goal-oriented and contextual information
- **O5: Develop and validate the DISAC architecture**
  - Emphasis on collaborative and distributed sensing



Project Targets

- cm-level **localisation** accuracy
- **Multi-band** operation with ISAC techniques
- Cell-free networking, massive **MIMO** or **RISs**
- Control energy and **EMF** exposure levels
- Innovative **AI/ML** architecture and **semantic** waveforms
- New and diverse **application** domains





3-year project
- 1 Jan. 2024 – 31 Dec. 2026

10 partners including
- 3 from Academia
- 1 research centre
- 6 from Industry

1st year outputs:
- 5 deliverables
- 18 publications
- 32 communication actions
- 11 SDO contributions

5 Proof of Concepts including:
- Sounder-based setup
- Waveform testing platform
- Semantic DISAC setup
- Sensing RIS
- Radio-SLAM field trial

Project Coordinator
Dr. Emilio CALVANESE STRINATI
emilio.calvanese-strinati@cea.fr

Technical Manager
Henk Wymeersch
henkw@chalmers.se

www.6gdisac-project.eu/
@6G_DISAC_SNS
/6G-DISAC

The SNS JU project 6G-DISAC has received funding under the EU's Horizon Europe research and innovation program under Grant Agreement No 101139130.

Outline

- Foundations of ISAC
- Visions and principles of DISAC
- Examples of DISAC

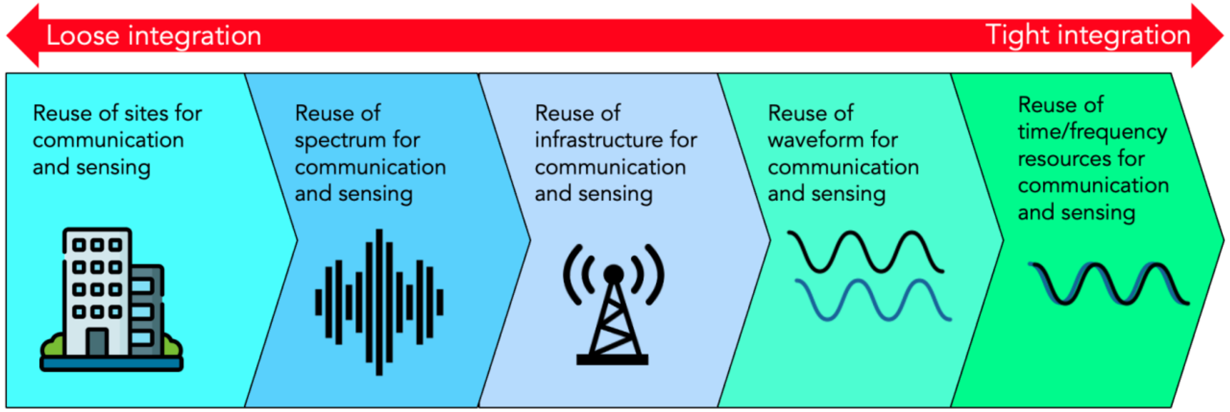
Outline

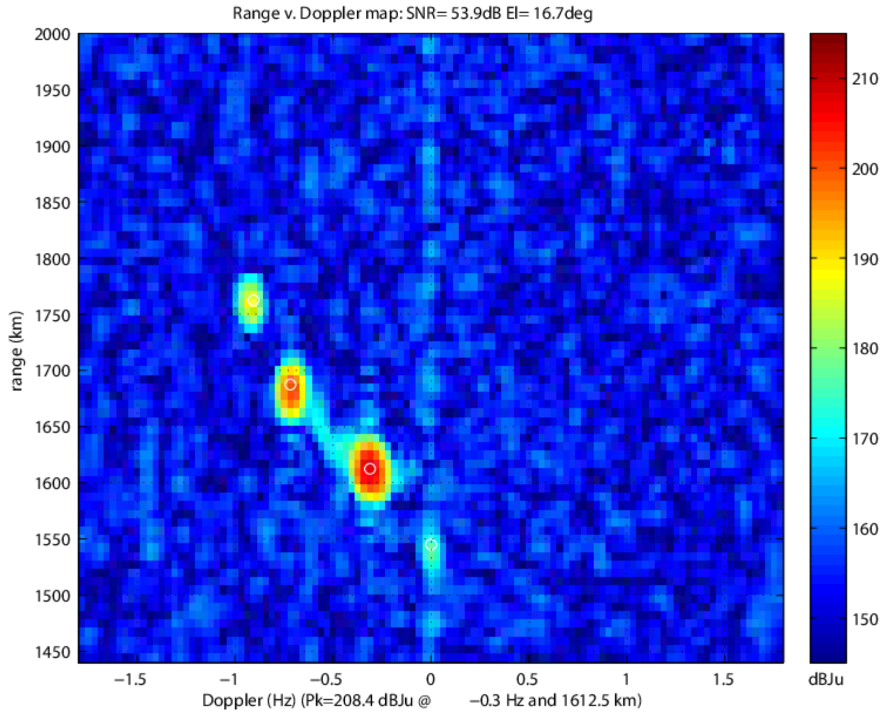
- Foundations of ISAC
- Visions and principles of DISAC
- Examples of DISAC

Wymeersch, H., Tervo, N., Wänstedt, S., Saleh, S., Ahlendorf, J., Akgul, O., ... & Ujjwal, S. (2025). Cross-layer Integrated Sensing and Communication: A Joint Industrial and Academic Perspective. *arXiv preprint arXiv:2505.10933*.

What is ISAC?

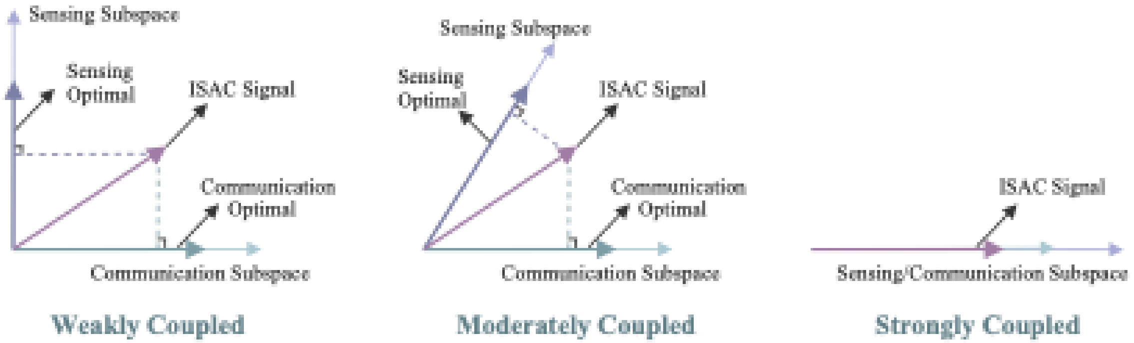
- *Definition:* ISAC integrates communication and sensing into a single system.
- *Benefits:*
  - Re-use of hardware.
  - Conservation of resources.
  - Cross-functional advantages.
- *Functionalities:*
  - **Sensing:** Receives and processes radio signals for specific services. Typically radar-like sensing.
  - **Positioning:** Determines coordinates of a connected device. Sometimes also localization is used.
  - **Localization:** Includes estimation of the location of passive objects.
- *Integration Levels:* From Site (Level 0) to Radio Resources (Level 4)





ISAC trade-offs and synergies

- Level 0 - Integration of Sites: N/A
- Level 1 - Integration of Spectrum:
  - Interference coordination
  - Resource allocation
  - Synchronization
- Level 2 - Integration of Hardware
  - Lower cost
  - Calibration
  - Synchronization
- Level 3 Integration (Dedicated Pilots):
  - Trade-offs in pilot duration, frequency, and bandwidth.
  - Multiple-antenna (MIMO) systems optimize for either scanning or tracking.
  - Mutual interference management for multiple transmitters.
- Level 4 Integration (Shared Radio Resources):
  - Optimizes the same radio resources for both communication and sensing.
  - Trade-offs in frequency and spatial resource allocation.
- Key Insight: While there are trade-offs, the knowledge gained from sensing (e.g., user location) can improve communication performance, turning trade-offs into synergies.



Liu, F., Zheng, L., Cui, Y., Masouros, C., Petropulu, A.P., Griffiths, H. and Eldar, Y.C., 2023. Seventy years of radar and communications: The road from separation to integration. *IEEE Signal Processing Magazine*, *40*(5), pp.106-121.

ISAC performance metrics

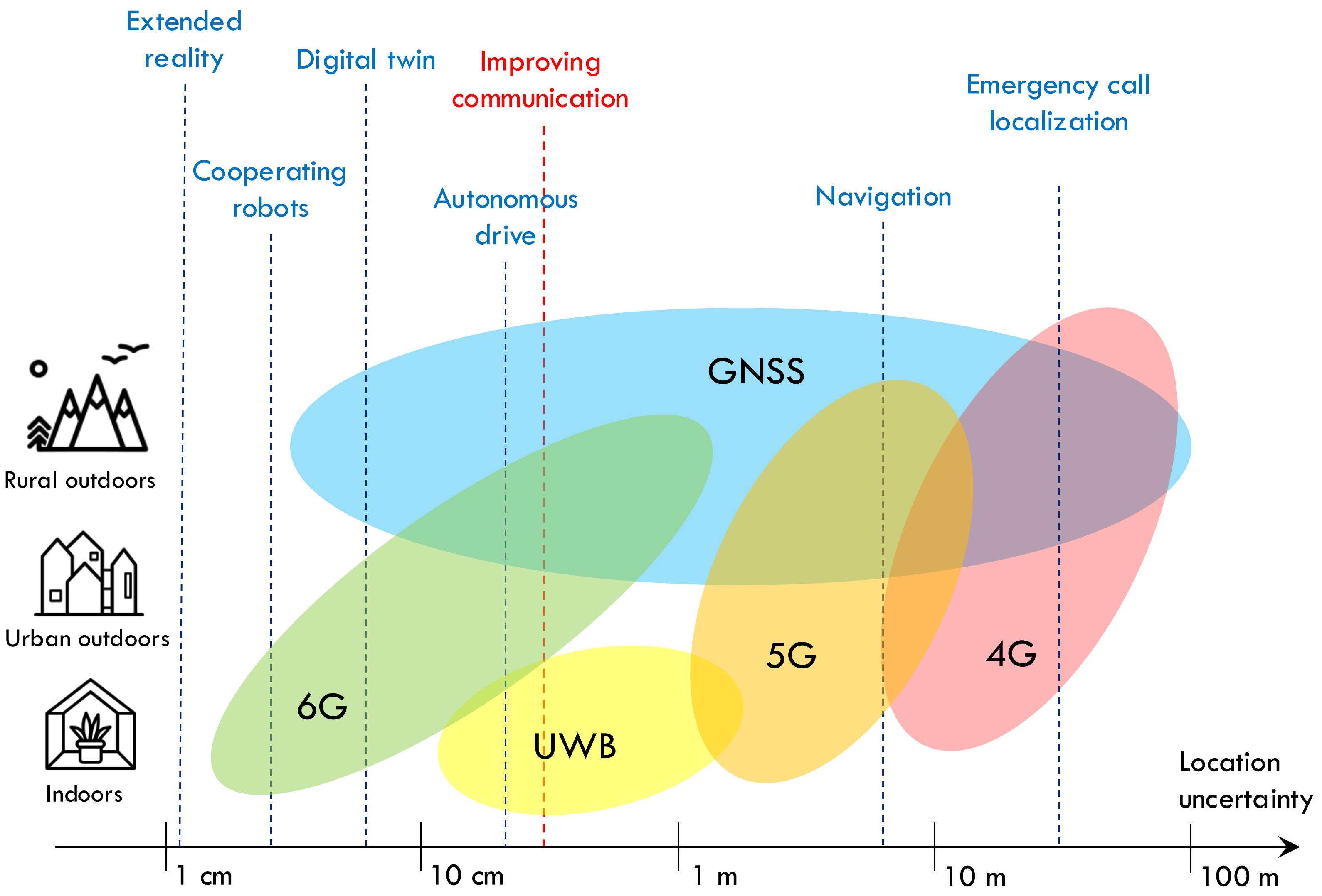
- **Communication**
  - Communication rate, spectral efficiency, SNR, EVM
  - Power consumption, energy efficiency
  - Latency
  - Reliability
  - Important bound: capacity: $C = W \log_2(1 + \mathrm{SINR})$

- **Sensing**
  - Accuracy (RMSE, percentile, GOSPA)
  - Positioning latency (between request and result)
  - Positioning availability / coverage
  - Detection probability (or SNR)
  - Resolution (multipath resolvability)
  - Power consumption, energy efficiency
  - Important bound: Cramér-Rao bound: $\mathrm{var}(\hat{\theta}) \geq 1/I(\theta)$


ISAC applications

- *Telecommunications*: Optimizes mobile network performance, especially with mmWave communications.
- *UAV Management and Safety*: Detects and tracks drones in restricted airspace.
- *Automotive & Smart Transportation*: Non-line-of-sight detection to enhance road safety.
- *Industry & Logistics*: Supports navigation for Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs).
- *Digital Twinning*: Creates dynamic digital replicas for real-time monitoring and decision-making.

6G: new use cases, new requirements



Wymeersch, H. and Seco-Granados, G., 2022. Radio localization and sensing—Part I: Fundamentals. *IEEE Communications Letters*, *26*(12), pp.2816-2820.

Wymeersch, H. and Seco-Granados, G., 2022. Radio Localization and Sensing—Part II: State-of-the-Art and Challenges. *IEEE Communications Letters*, *26*(12), pp.2821-2825.

The (ISAC?) wireless channel

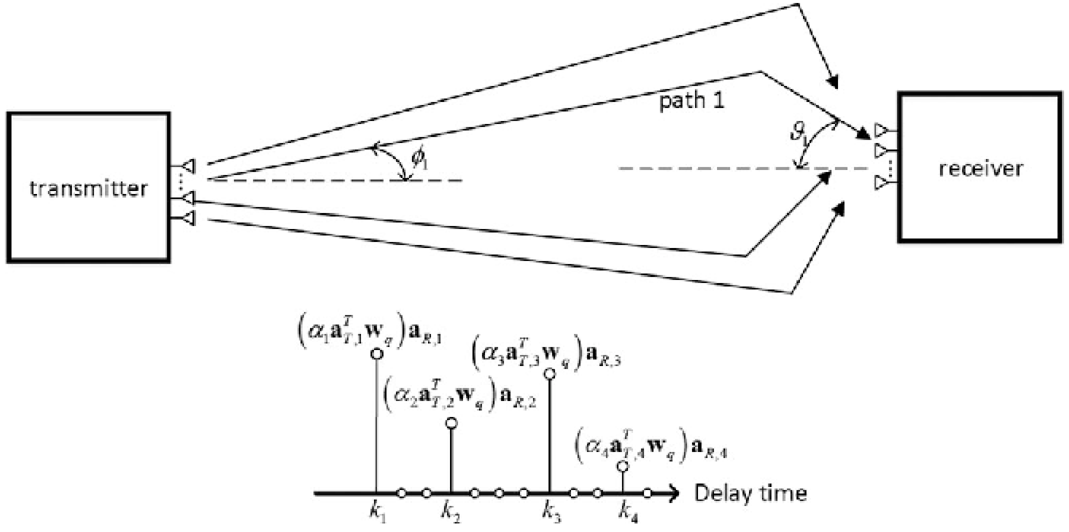
- Communication channel models $\mathrm{vec}(\mathbf{H}) \sim \mathcal{CN}(\mathbf{0}, \sigma^2 \boldsymbol{I})$
- Rayleigh origin: many paths + central limit theorem
- At higher frequencies:
  - Severe shadowing: paths cannot penetrate objects
  - Objects appear more rough: less reflection
  - Overall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



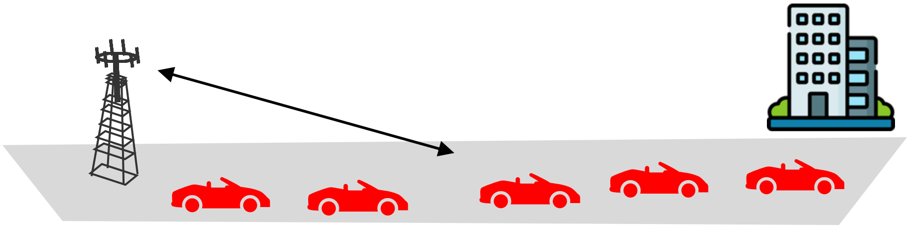
Source: Chen, Chih-Yu, and Wen-Rong Wu. "Joint AoD, AoA, and channel estimation for MIMO-OFDM systems." IEEE Transactions on Vehicular Technology 67, no. 7 (2018): 5806-5820.

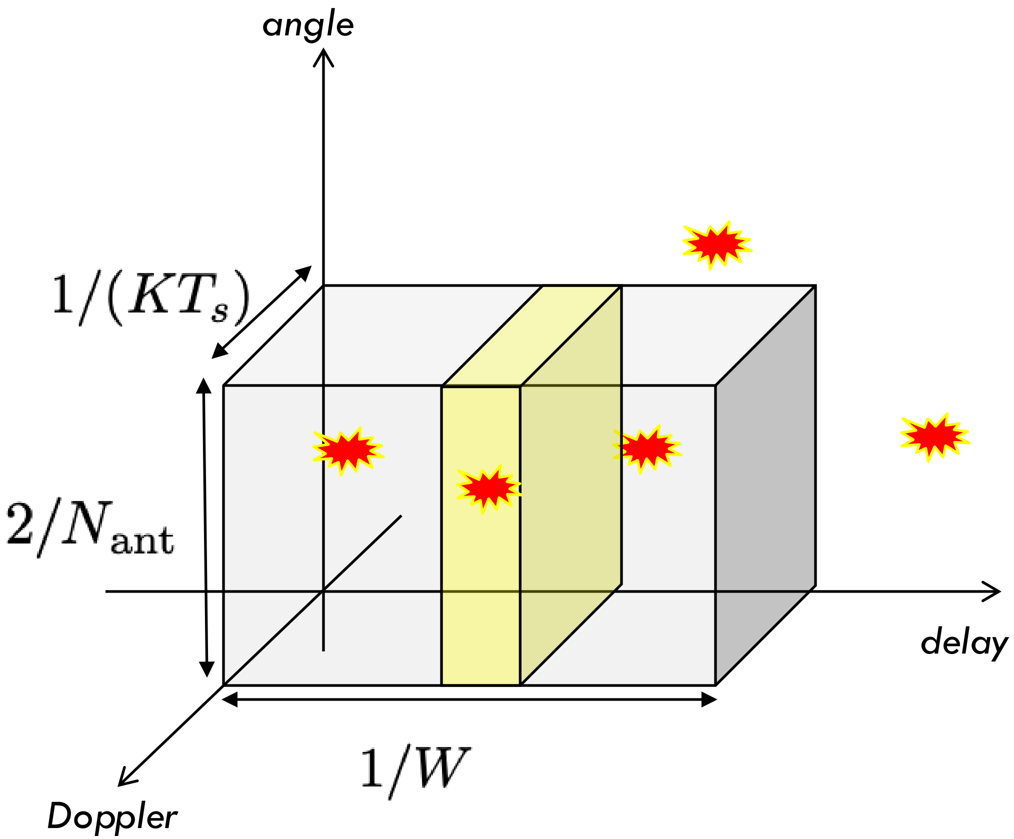
The vanilla ISAC observation model

- Example:
  - Wideband: objects are separated
  - Narrowband: objects looks as merged into one
- Resolution: ability to resolve paths / objects
  - Delay / range resolution: $|\tau_l - \tau_{l'}| > 1/W$
  - Angle resolution: $|\theta_l - \theta_{l'}| > 2/N_{\text{ant}}$
  - Doppler resolution: $|\nu_l - \nu_{l'}| > 1/(KT_s)$
- Resolution in at least one domain is needed
- All domains have similar form:

$$y_n = \sum_{l=0}^{L} \alpha_l e^{jn\omega_l} + n_n$$

- Frequency interpretation
  - Observation over subcarriers: $2\pi\tau_l\Delta_f$
  - Observation over antennas: $\pi \sin\theta_l$
  - Observation over time: $2\pi\nu_l T_s$
- Exceptions
  - Beamspace observations, Doppler & AOD coupling



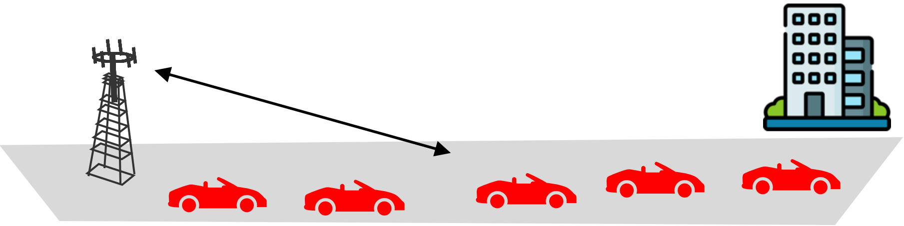


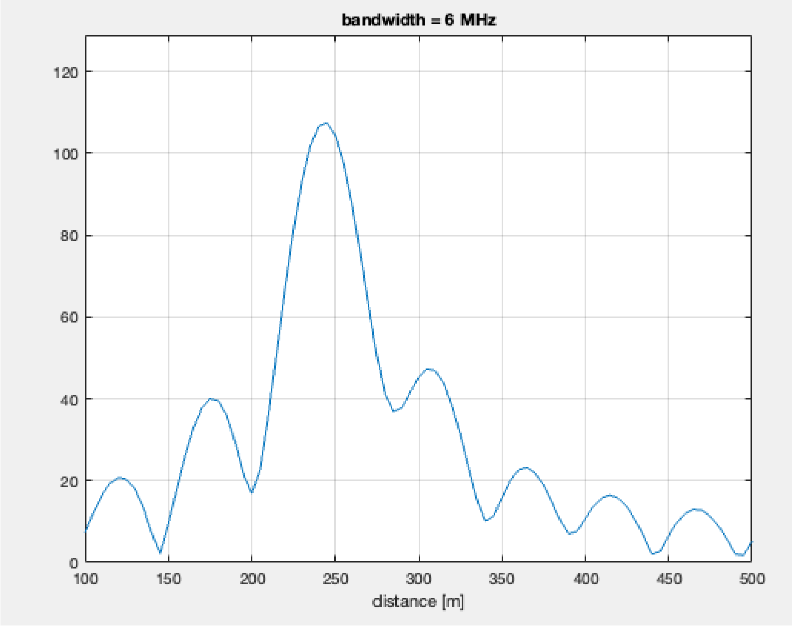
One-dimensional harmonic retrieval (HR)

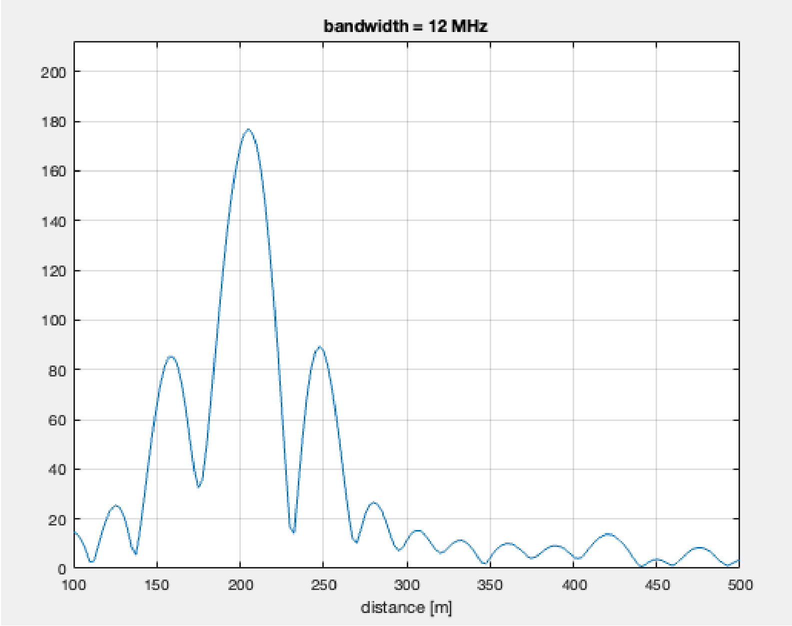
- Observation $y_n = \sum_{l=0}^{L} \alpha_l e^{jn\omega_l} + n_n \quad n = 0, 1, \ldots, N-1 \quad \omega_l \in [0, 2\pi]$
- Suppose each $\omega_l \approx 2\pi m_l / N, m_l \in \{0, 1, 2, \ldots, N-1\}$
- Then $y_n = \sum_{l=0}^{L} \alpha_l e^{j2\pi n m_l / N} + n_n$
- Vectorizing, we can express the observation as a combination of DFT columns
- Last step: correlate with IDFT matrix $\mathbf{z} = \mathbf{F}^H \mathbf{y}$ and look for peaks
- More sophisticated methods exist than correlation-based processing

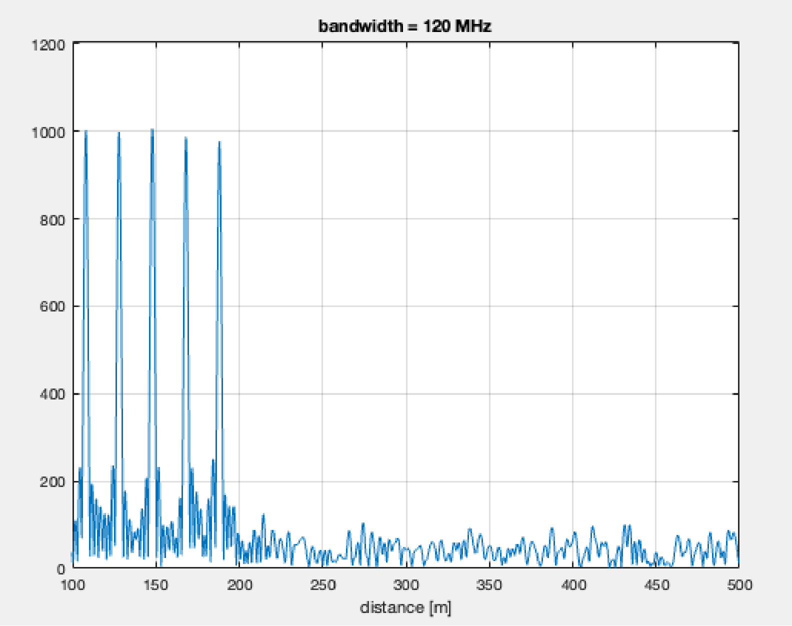
Recovering the locations: harmonic retrieval

- Model $y_n = \sum_{l=0}^{L} \alpha_l e^{j2\pi n \Delta_f d_l / c} + n_n$
- Vary the bandwidth: $W = N\Delta_f$
- FFT output









Accuracy is only meaningful when objects can be resolved

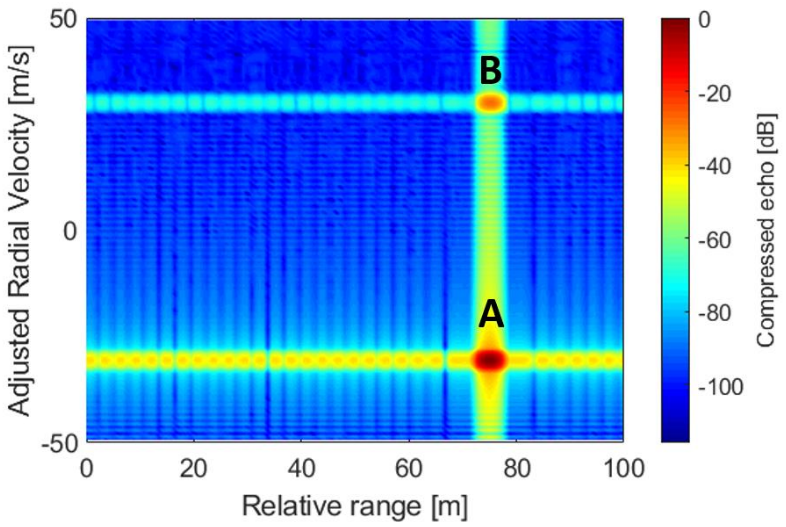
Target detection and estimation: a 2D example of the same principle

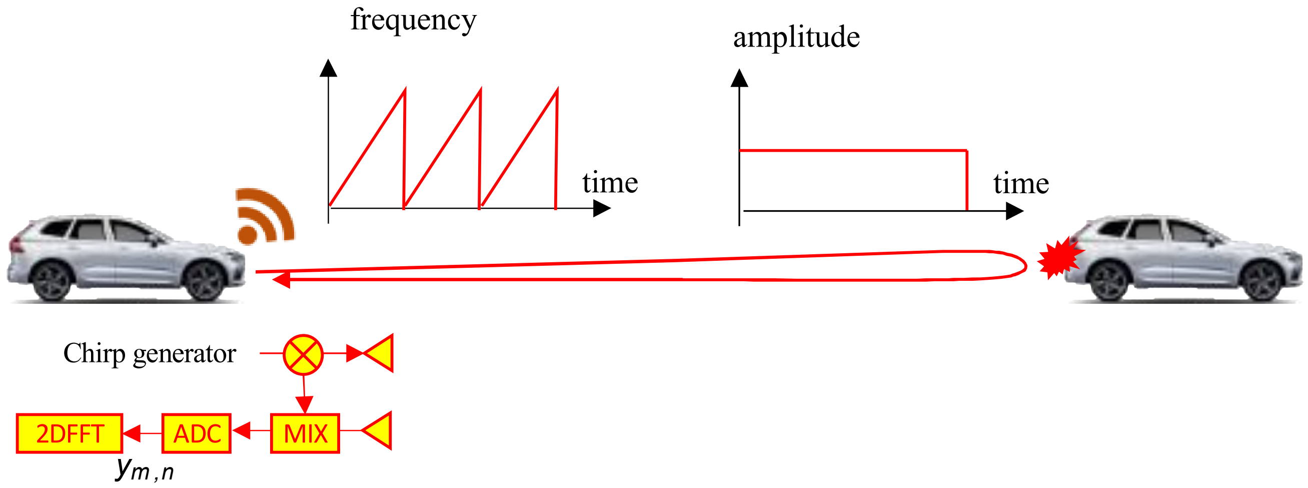
- Sample signal across time and frequency (approximately true for both FMCW and OFDM)

$$r_k[nT_s] = \sum_{l=0}^{L-1} \alpha_l e^{-\jmath 2\pi n T_s \tau_l B/T} e^{+\jmath 2\pi f_c \nu_l m T} + \text{noise}$$

$$\mathbf{R} = \sum_{l=0}^{L-1} \alpha_l \mathbf{d}(\tau_l) \mathbf{b}^\top(\nu_l) + \text{noise}$$

- Peaks in 2D FFT provide range/Doppler of targets





- Detection of multiple targets (e.g., CFAR)

Sturm, C. and Wiesbeck, W., 2011. Waveform design and signal processing aspects for fusion of wireless communications and radar sensing. Proceedings of the IEEE, 99(7), pp.1236-1259.

Tool: Fisher information and CRB

Problem: estimate deterministic unknown $\mathbf{x}$ from observation $\mathbf{z}$ given statistical model $p(\mathbf{z}|\mathbf{x})$

- **The Fisher information matrix (FIM):** measures "the amount of information the observation carries about the unknown"

$$\mathbf{J}(\mathbf{x}) = \mathbb{E}_{\mathbf{z}}\{\nabla_{\mathbf{x}} \log p(\mathbf{z}|\mathbf{x})\, \nabla_{\mathbf{x}}^{\mathrm{T}} \log p(\mathbf{z}|\mathbf{x})\}$$

- FIM relates to estimation error covariance of any unbiased estimator $\hat{\mathbf{x}}(\mathbf{z})$

$$\mathbb{E}\{(\mathbf{x}-\hat{\mathbf{x}})(\mathbf{x}-\hat{\mathbf{x}})^{\mathrm{T}}\} \succeq \mathbf{J}^{-1}(\mathbf{x})$$

- **Cramér-Rao bound:** lower bound on estimation error variance

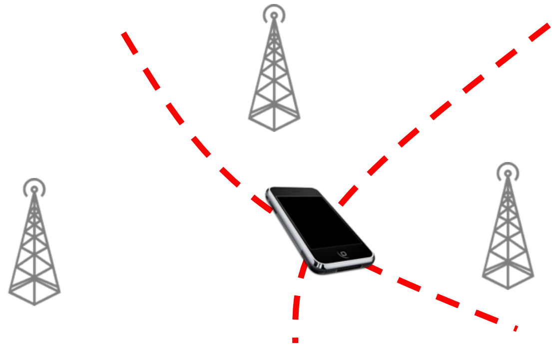
$$\mathbb{E}\{||\mathbf{x}-\hat{\mathbf{x}}||^2\} \geq \mathrm{tr}(\mathbf{J}^{-1}(\mathbf{x}))$$

- Gaussian noise case is easier:

$$\mathbf{z} = \mathbf{m}(\mathbf{x}) + \mathbf{n}, \mathbf{n} \sim \mathcal{CN}(0, \mathbf{\Sigma})$$

$$\mathbf{J}(\mathbf{x}) = \Re\left\{\nabla_{\mathbf{x}} \mathbf{m}^{\mathrm{H}}(\mathbf{x}) \mathbf{\Sigma}^{-1} \nabla_{\mathbf{x}} \mathbf{m}(\mathbf{x})\right\}$$

From measurements to positions



- Delay-based positioning:

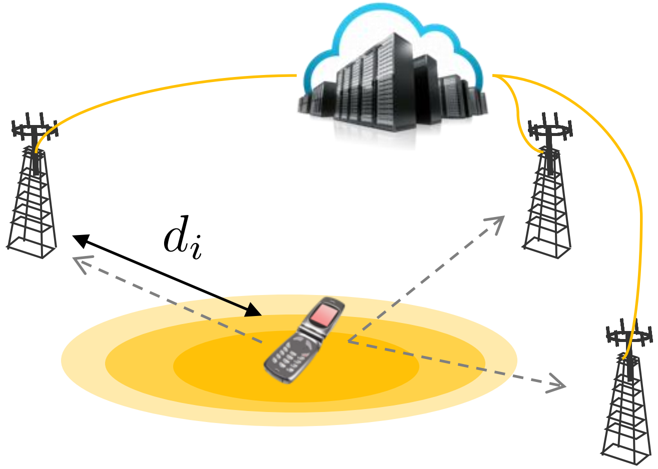
$$\mathbf{y} = \mathbf{f}(\mathbf{x}) + \mathbf{n}$$

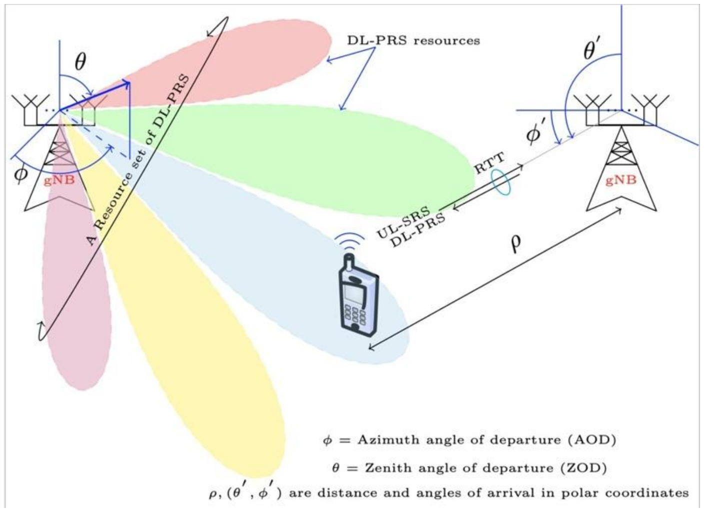
- Practical challenges
  - Data may not be known $$y_n = \sum_{l=0}^{L} \alpha_l e^{jn\omega_l} x_n + n_n$$
  - Even known data leads to noise enhancement $$\tilde{y}_n = \sum_{l=0}^{L} \alpha_l e^{jn\omega_l} + n_n / x_n$$
  - Measurement are affected by sync errors: clock bias, CFO: $$\hat{\tau}_l = d_l / c + B$$ $$\hat{\nu}_l = \frac{1}{\lambda} \boldsymbol{u}_l^\top \boldsymbol{v} + \eta$$
  - UE position and orientation must be known for UE-involved sensing

5G approach: time-difference-of-arrival (TDOA)

Operation

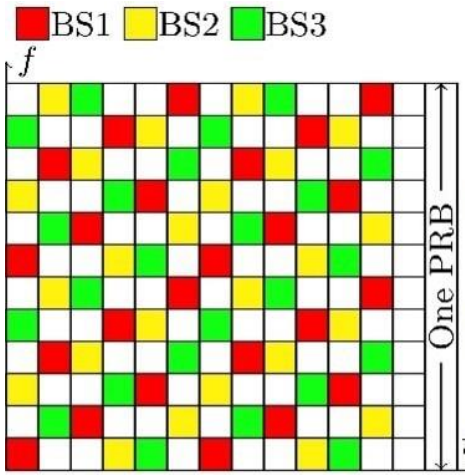
- Estimate $\hat{\tau}_i = d_i/c + B + n_i$
- Differential measurement: remove bias
- Find intersection of several hyperbola $y_i = \hat{\tau}_i - \hat{\tau}_0, i > 0$
- 400 MHz bandwidth at FR2: meter-level positioning
- Relies on LOS connection to many BS
- BSs should be time-synchronized





Many enhancements in 3GPP R16, 17, 18

- UL and DL-TDOA, Multi-RTT
- DL-AOD, UL-AOA
- Multipath reporting, carrier phase positioning, AI

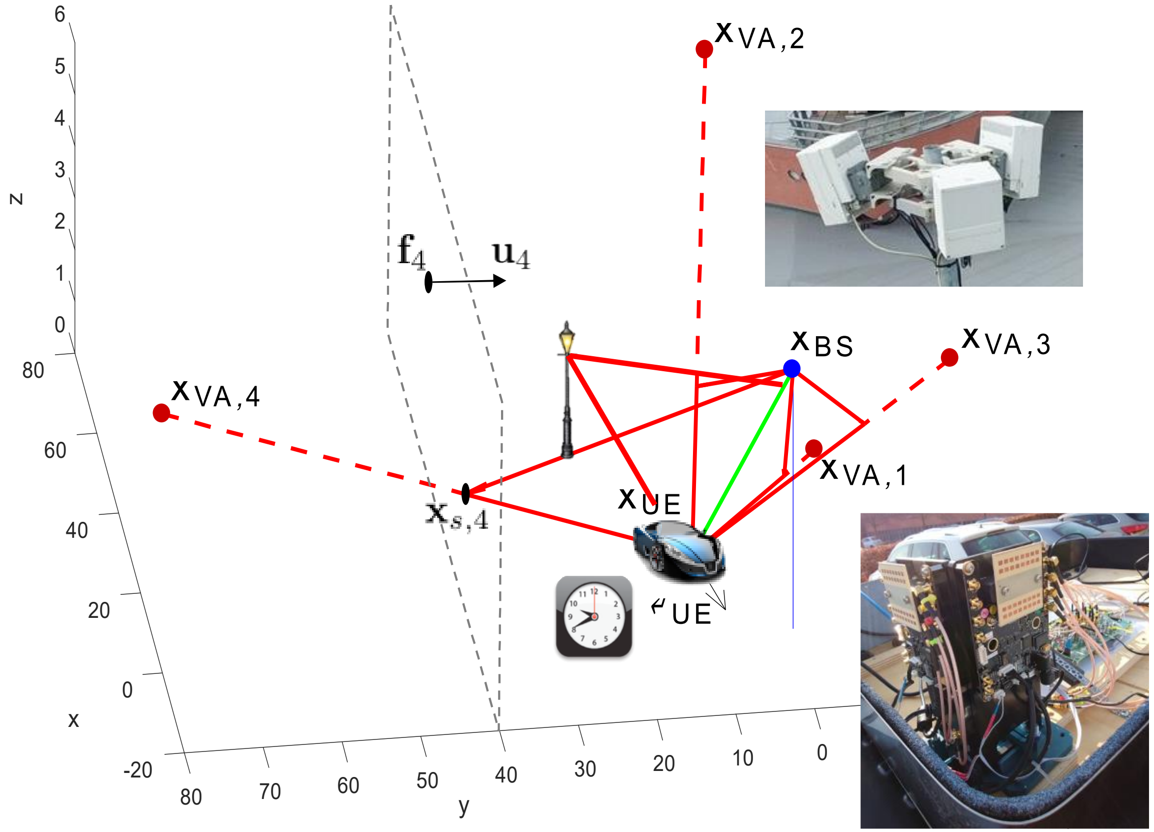


(a) A PRS pattern

Dwivedi S, Shreevastav R, Munier F, Nygren J, Siomina I, Lyazidi Y, Shrestha D, Lindmark G, Ernström P, Stare E, Razavi SM. "Positioning in 5G networks", IEEE Communications Magazine. 2021 Dec 30;59(11):38-44.

ISAC with UEs: radio SLAM

- **Conventional thinking:** multipath is foe
- **Insight:** With angle measurements at UE and BS:
  - Each multipath component has 3 geometric unknowns, up to 5 observables
  - So multipath can be our friend!
- **Outcomes:**
  - Multipath can be exploited to perform single-BS UE positioning, synchronization, and environment mapping → *Radio-SLAM*
  - Even possible without LOS path.
  - Synchronization problem solved "by nature".
- **Validation:**
  - https://www.youtube.com/watch?v=wAV0_uMpSDo
  - Collaboration with Lund Univ. QAMCOM, Ericsson, Magna, CEVT



Ge, Y., Kaltiokallio, O., Kim, H., Jiang, F., Talvitie, J., Valkama, M., Svensson, L., Kim, S. and Wymeersch, H., 2022. A computationally efficient EK-PMBM filter for bistatic mmWave radio SLAM. IEEE Journal on Selected Areas in Communications, 40(7), pp.2179-2192.

Ge, Y., Khosravi, H., Jiang, F., Chen, H., Lindberg, S., Hammarberg, P., Kim, H., Brunnegård, O., Eriksson, O., Olsson, B.E. and Tufvesson, F., 2023. Experimental Validation of Single BS 5G mmWave Positioning and Mapping for Intelligent Transport. IEEE TVT, 2024.

Outline

- Foundations of ISAC
- Visions and principles of DISAC
- Examples of DISAC

DISAC vision papers

INTEGRATING SENSING INTO COMMUNICATIONS IN MULTI-FUNCTIONAL NETWORKS

Multi-View Sensing for Wireless Communications: Architectures, Designs, and Opportunities

Xin Tong, Zhaoyang Zhang, and Zhaohui Yang

6G WIRELESS TECHNOLOGIES AND SYSTEMS

COOPERATIVE INTEGRATED SENSING AND COMMUNICATION IN 6G: FROM OPERATORS PERSPECTIVE

Xiaoyun Wang, Zixiang Han, Rongyan Xi, Guangyi Liu, Lincong Han, Jing Jin, Yahui Xue, Liang Ma, Yajuan Wang, Tao Jiang, Mengting Lou, Qixing Wang, and Jiangzhou Wang

INTEGRATED SENSING AND COMMUNICATIONS FOR 6G

COLLABORATIVE SENSING IN PERCEPTIVE MOBILE NETWORKS: OPPORTUNITIES AND CHALLENGES

Lei Xie, Shenghui Song, Yonina C. Eldar, and Khaled B. Letaief

6G WIRELESS TECHNOLOGIES AND SYSTEMS

TOWARD DISTRIBUTED AND INTELLIGENT INTEGRATED SENSING AND COMMUNICATIONS FOR 6G NETWORKS

Emilio Calvanese Strinati, George C. Alexandropoulos, Navid Amani, Maurizio Crozzoli, Giyyarpuram Madhusudan, Sami Mekki, Francois Rivet, Vincenzo Sciancalepore, Philippe Sehier, Maximilian Stark, and Henk Wymeersch

This article has been accepted for inclusion in a future issue of this magazine. Content is final as presented, with the exception of pagination.

ACCEPTED FROM OPEN CALL

COOPERATIVE ISAC NETWORKS: OPPORTUNITIES AND CHALLENGES

Kaitao Meng, Christos Masouros, Athina P. Petropulu, and Lajos Hanzo

ABSTRACT

sensing side, the ISAC network can cover larger

Relatively new area with lots of research potential!

We will analyze these papers to identify key research directions

DISAC Bingo!

DISAC vision papers

INTEGRATING SENSING INTO COMMUNICATIONS IN MULTI-FUNCTIONAL NETWORKS

Multi-View Sensing for Wireless Communications: Architectures, Designs, and Opportunities

Xin Tong, Zhaoyang Zhang, and Zhaohui Yang

6G WIRELESS TECHNOLOGIES AND SYSTEMS

Cooperative Integrated Sensing and Communication in 6G: From Operators Perspective

Xiaoyun Wang, Zixiang Han, Rongyan Xi, Guangyi Liu, Lincong Han, Jing Jin, Yahui Xue, Liang Ma, Yajuan Wang, Tao Jiang, Mengting Lou, Qixing Wang, and Jiangzhou Wang

INTEGRATED SENSING AND COMMUNICATIONS FOR 6G

Collaborative Sensing in Perceptive Mobile Networks: Opportunities and Challenges

Lei Xie, Shenghui Song, Yonina C. Eldar, and Khaled B. Letaief

6G WIRELESS TECHNOLOGIES AND SYSTEMS

Toward Distributed and Intelligent Integrated Sensing and Communications for 6G Networks

Emilio Calvanese Strinati, George C. Alexandropoulos, Navid Amani, Maurizio Crozzoli, Giyyarpuram Madhusudan, Sami Mekki, Francois Rivet, Vincenzo Sciancalepore, Philippe Sehier, Maximilian Stark, and Henk Wymeersch

This article has been accepted for inclusion in a future issue of this magazine. Content is final as presented, with the exception of pagination.

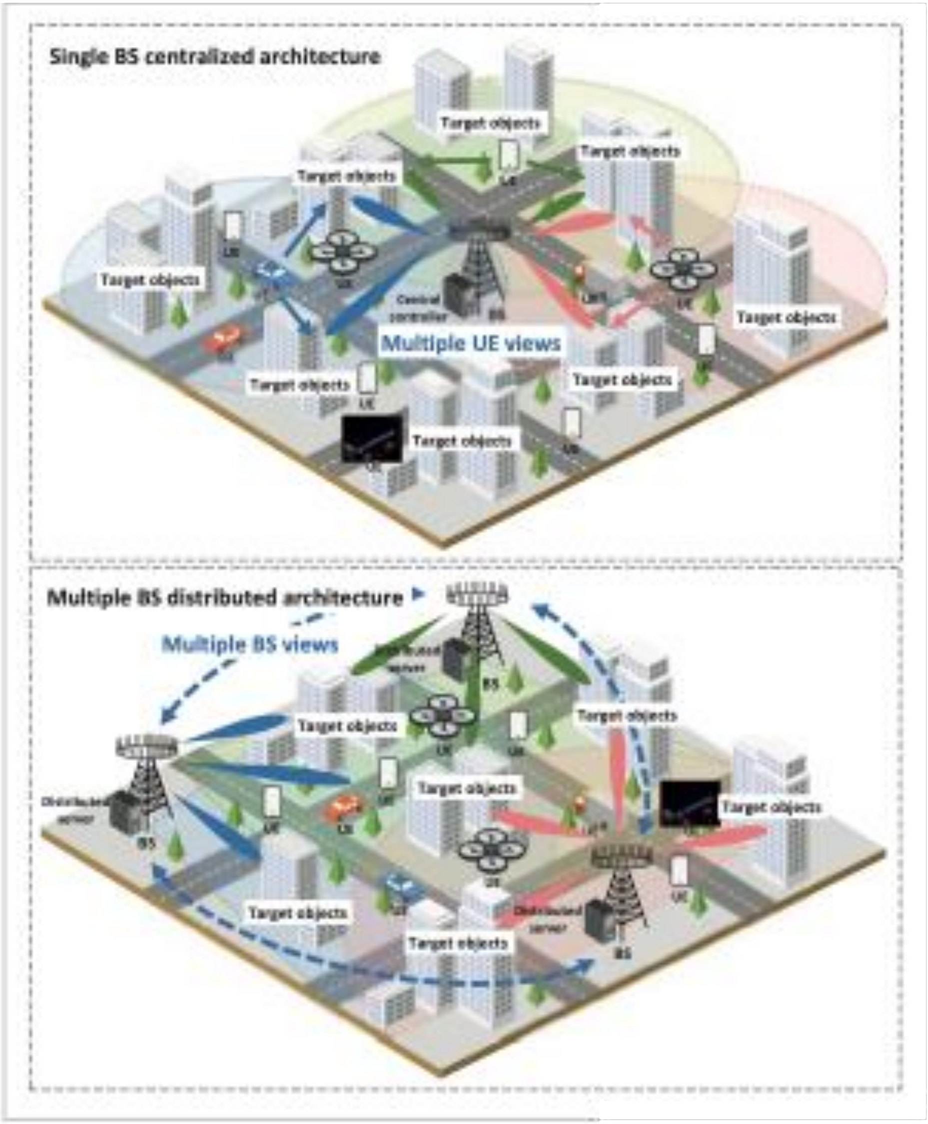
ACCEPTED FROM OPEN CALL

Cooperative ISAC Networks: Opportunities and Challenges

Kaitao Meng, Christos Masouros, Athina P. Petropulu, and Lajos Hanzo

Multi-View Sensing for Wireless Communications: Architectures, Designs, and Opportunities

- **Data:** Tong, X., Zhang, Z. and Yang, Z., 2023. Multi-view sensing for wireless communications: Architectures, designs, and opportunities. IEEE Communications Magazine, 61(5), pp.40-46.
- **Main idea:** One TX-RX pair provides only a partial view. Multiple UEs and/or multiple BSs provide multi-view
- **Challenge:** Signals are scattered, reflected, blocked in different ways for each TX-RX pair
- **DISAC metrics**
  - Accuracy
  - Resolution
  - Compute cost
  - Communication overhead
- **Waveform design:** radar waveform or communication waveform
- **Beamforming design:** Directional or scanning
- **Information processing:** Distributed or centralized



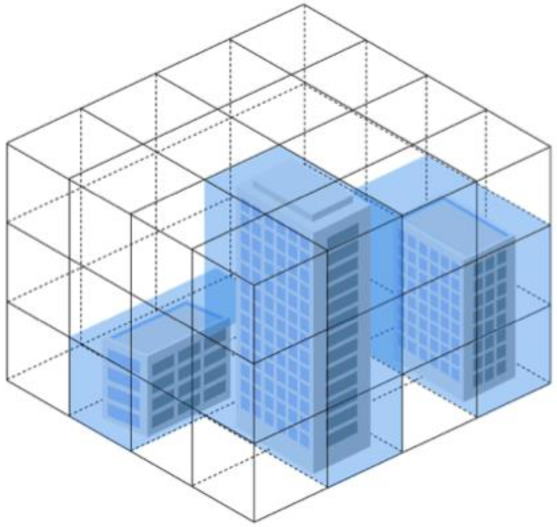
Model-based Methods

- **Multi-radar sensing**
  - Multiple radar units (multi-RX, multi-TX)
  - Non-coherent, time coherent: local estimation and fusion
  - Phase coherence: similar to imaging
- **Imaging-based sensing**
  - Divide region into small boxes
  - Stack all observations $\mathbf{Y}(n_{\mathrm{R}}) = \mathbf{S}\left(\mathbf{H}^{\mathrm{S}}(n_{\mathrm{R}}) + \mathbf{H}^{\mathrm{LOS}}(n_{\mathrm{R}})\right) + \mathbf{W},$
  - Channel response is known, but occlusion and reflection per pixel is not

$$\mathbf{H}^{\mathrm{S}}(n_{\mathrm{R}}) = \tilde{\mathbf{H}}(n_{\mathrm{R}})\,\boldsymbol{x}$$
$$= \left[\mathbf{H}(n_{\mathrm{R}}) \odot \mathbf{V}(n_{\mathrm{R}})\right]\boldsymbol{x}$$

  - Relies on phase coherent TX and RX
  - Solution based on GAMP
  - Distributed implementation for multi-BS

Gogineni, S. and Nehorai, A., 2011. Target estimation using sparse modeling for distributed MIMO radar. IEEE Transactions on Signal Processing, 59(11), pp.5315-5325.
Hassanien, A., Vorobyov, S.A. and Gershman, A.B., 2012. Moving target parameters estimation in noncoherent MIMO radar systems. IEEE Transactions on Signal Processing, 60(5), pp.2354-2361.
Zhang, G., Yi, W., Varshney, P.K. and Kong, L., 2023. Direct target localization with quantized measurements in noncoherent distributed MIMO radar systems. IEEE Transactions on Geoscience and Remote Sensing, 61, pp.1-18.



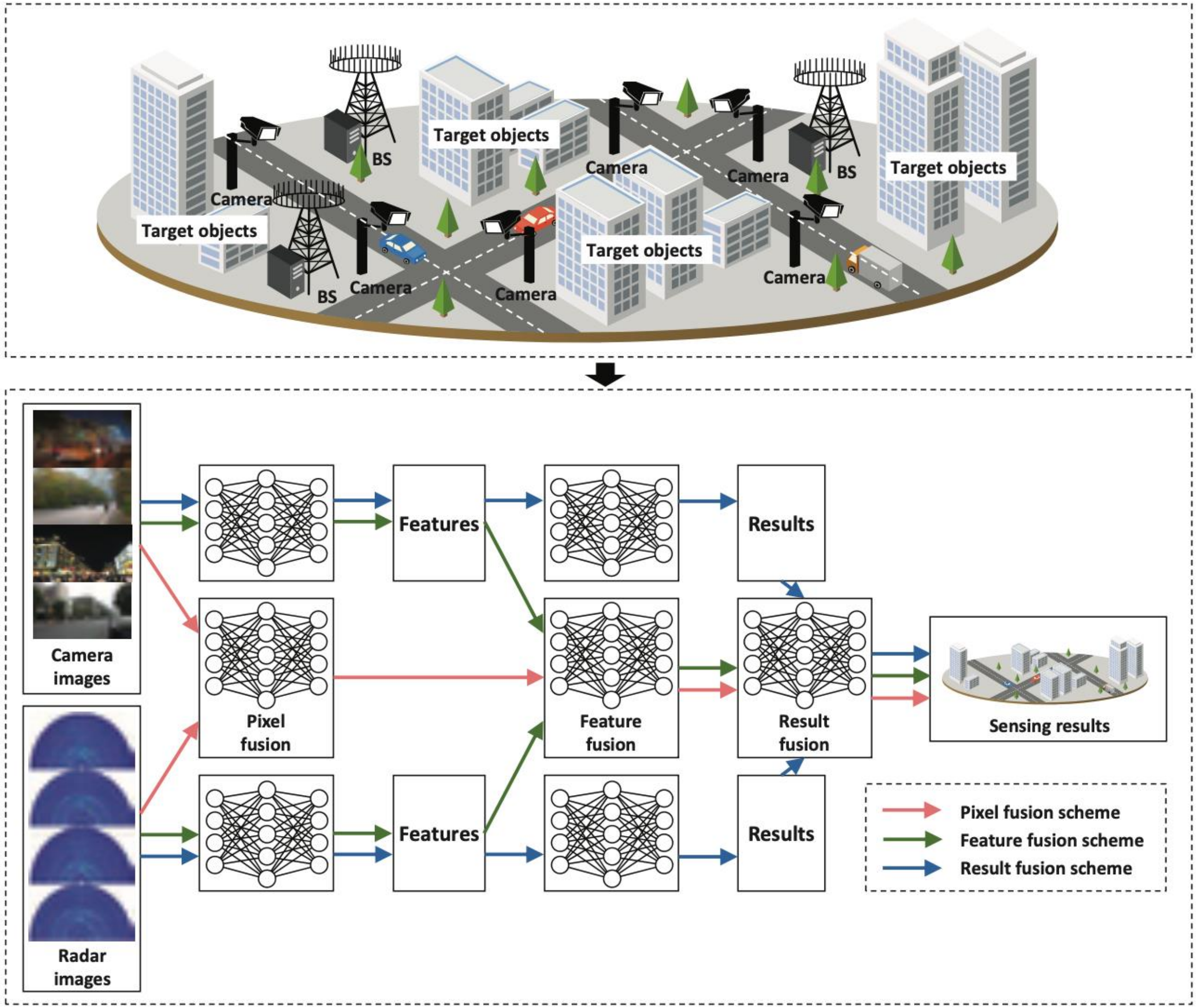
Tong, X., Zhang, Z. and Yang, Z., 2023. Multi-view sensing for wireless communications: Architectures, designs, and opportunities. *IEEE Communications Magazine*, *61*(5), pp.40-46.

Model-based Methods

Methods		Key features	Advantages	Disadvantages
Multi-radar-based method		• Communication and radar signal processing are separate but share the same devices and resources. • Sensing signals are designed as radar waveforms. • Repeatedly scanning on multi-channel multi-carrier resources.	• Large environment sensing range. • Simple system structure and signal processing method. • Good at detecting and tracking moving targets.	• Sensing signals are difficult to integrate with communication signals. • Require additional radar hardware design. • Require Communication and collaboration design.
CS-based method	Single BS centralized scheme	• The same hardware and architecture as the single BS communication network. • Designed ISAC signals for UEs and the BS based on communication symbols. • The BS executes centralized algorithms to jointly process multi-UE signals.	• Easy to deploy and compatible with communication systems. • Small interference to the communication process is, and small communication overhead. • The multi-UEs based 3D point cloud reconstruction results can accurately describe the shape of the object.	• The sensing range of a single BS is small. • Point cloud processing requires high computing power and storage of device hardware. • Environment sensing accuracy decreases as the environment becomes denser.
	Multiple BS distributed scheme	• The same hardware and architecture as multiple BSs distributed communication network. • Jointly designed ISAC signals for multiple BSs and UEs. • Multiple BSs execute distributed algorithms to jointly process multi-UE signals.	• Compatible with existing multiple BS distributed network systems. • Small interference to the communication process, and large environment sensing range. • The multi-UEs and multi-BSs reconstruction results can accurately describe the shape of the object.	• The distributed processing algorithm among multiple BSs increases communication overhead. • Point cloud processing requires high computing power and storage of device hardware. • Environment sensing accuracy decreases as the environment becomes denser.

AI-based Methods

- **Distributed inference:** local NN per BS, local decision
- **Multi-agent reinforcement learning:** different levels of cooperation (e.g., signal optimization)
- **Federated learning:** learn local NN per BS and share across BSs. Privacy preservation.
- **Distributed deep unfolding:** local processing approach
- Also suitable for multi-modal data



Lessons: DISAC Bingo!

Multiple views of targets						
Distributed processing						
Phase synchronization						
Distributed AI						

DISAC vision papers

INTEGRATING SENSING INTO COMMUNICATIONS IN MULTI-FUNCTIONAL NETWORKS

Multi-View Sensing for Wireless Communications: Architectures, Designs, and Opportunities

Xin Tong, Zhaoyang Zhang, and Zhaohui Yang

6G WIRELESS TECHNOLOGIES AND SYSTEMS

COOPERATIVE INTEGRATED SENSING AND COMMUNICATION IN 6G: FROM OPERATORS PERSPECTIVE

Xiaoyun Wang, Zixiang Han, Rongyan Xi, Guangyi Liu, Lincong Han, Jing Jin, Yahui Xue, Liang Ma, Yajuan Wang, Tao Jiang, Mengting Lou, Qixing Wang, and Jiangzhou Wang

INTEGRATED SENSING AND COMMUNICATIONS FOR 6G

COLLABORATIVE SENSING IN PERCEPTIVE MOBILE NETWORKS: OPPORTUNITIES AND CHALLENGES

Lei Xie, Shenghui Song, Yonina C. Eldar, and Khaled B. Letaief

6G WIRELESS TECHNOLOGIES AND SYSTEMS

TOWARD DISTRIBUTED AND INTELLIGENT INTEGRATED SENSING AND COMMUNICATIONS FOR 6G NETWORKS

Emilio Calvanese Strinati, George C. Alexandropoulos, Navid Amani, Maurizio Crozzoli, Giyyarpuram Madhusudan, Sami Mekki, Francois Rivet, Vincenzo Sciancalepore, Philippe Sehier, Maximilian Stark, and Henk Wymeersch

ABSTRACT

This article has been accepted for inclusion in a future issue of this magazine. Content is final as presented, with the exception of pagination.

ACCEPTED FROM OPEN CALL

COOPERATIVE ISAC NETWORKS: OPPORTUNITIES AND CHALLENGES

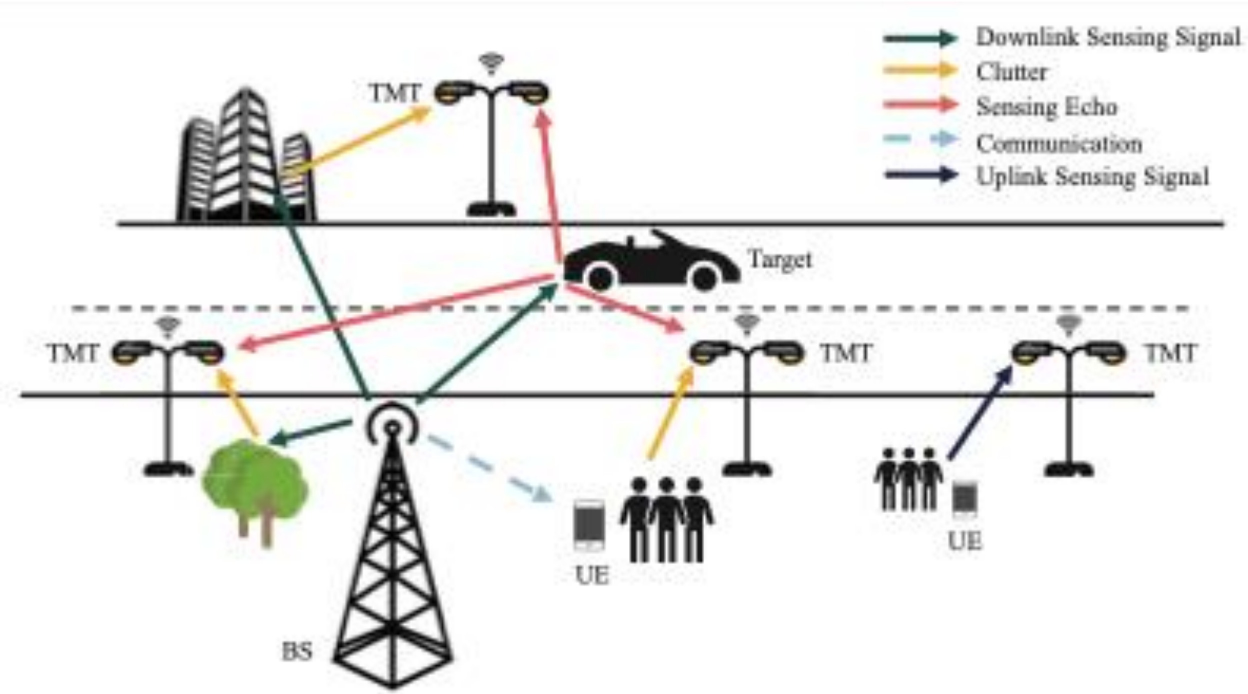
Kaitao Meng, Christos Masouros, Athina P. Petropulu, and Lajos Hanzo

ABSTRACT

sensing side, the ISAC network can cover larger

Collaborative sensing in perceptive mobile networks: Opportunities and challenges

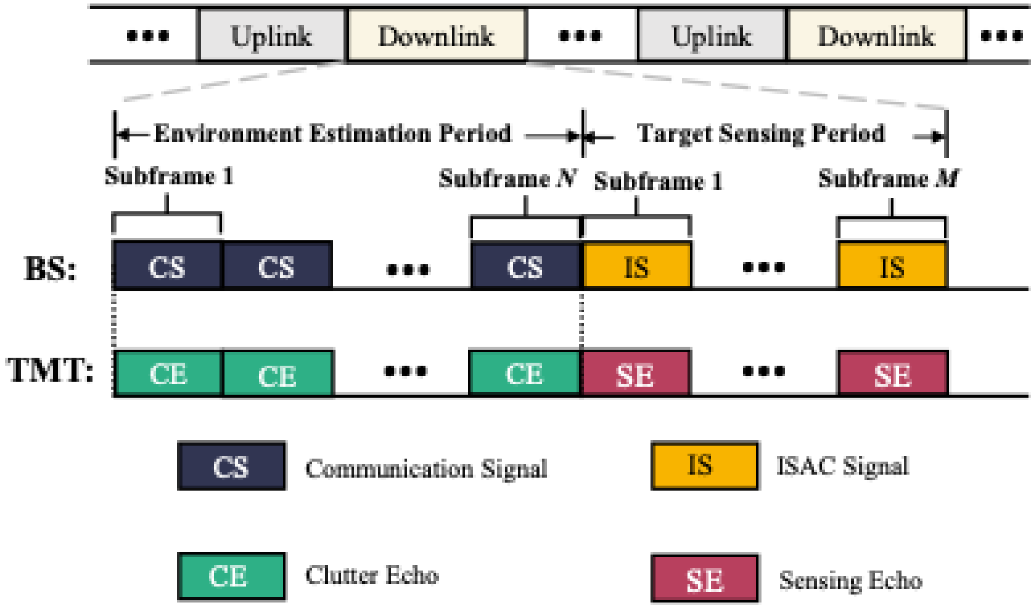
- **Data:** Xie, L., Song, S., Eldar, Y.C. and Letaief, K.B., 2023. Collaborative sensing in perceptive mobile networks: Opportunities and challenges. IEEE wireless communications, 30(1), pp.16-23.
- **Main idea:** networked multi-view sensing, “PMN” concept, high density of BSs, distributed and connected sensing nodes. Enhance communication. Dedicated target monitoring terminals (TMT).
- **Challenges:** interference between sensing and communication, computation and communication overheads, high-speed targets and latency constraints



Architecture and protocols

- Network architectures
  1. Monostatic sensing with full-duplex nodes
  2. Separate TX and RX with network sync
  3. New passive target monitoring terminals with network sync
- Protocols
  – Multi-stage scanning and processing
  – Separate clutter estimation and target sensing
  – Interference management

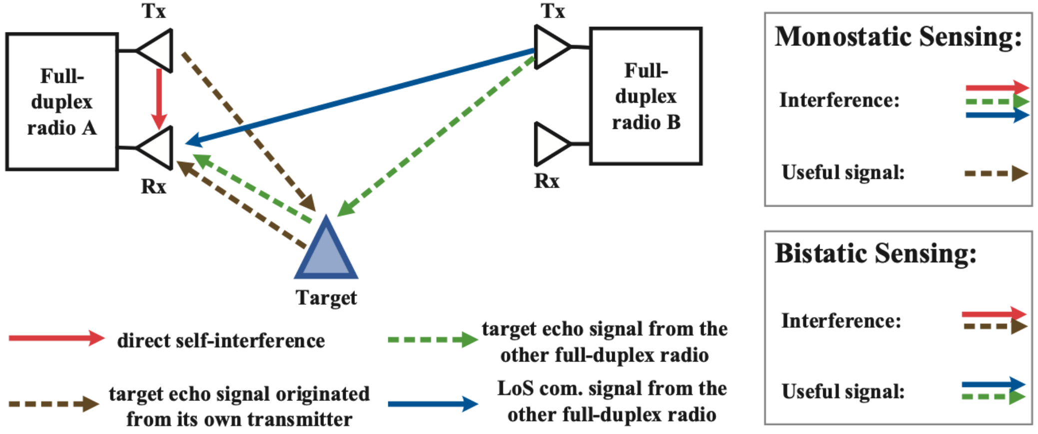
	Sensing Transmitter	Sensing Receiver	Full-Duplex	Synchronization
Mono-static DFRC	BS	BS	Required	Not Required
PMN-RRU	RRU	RRU	Not Required	Required
PMN-TMT	BS	TMT	Not Required	Required

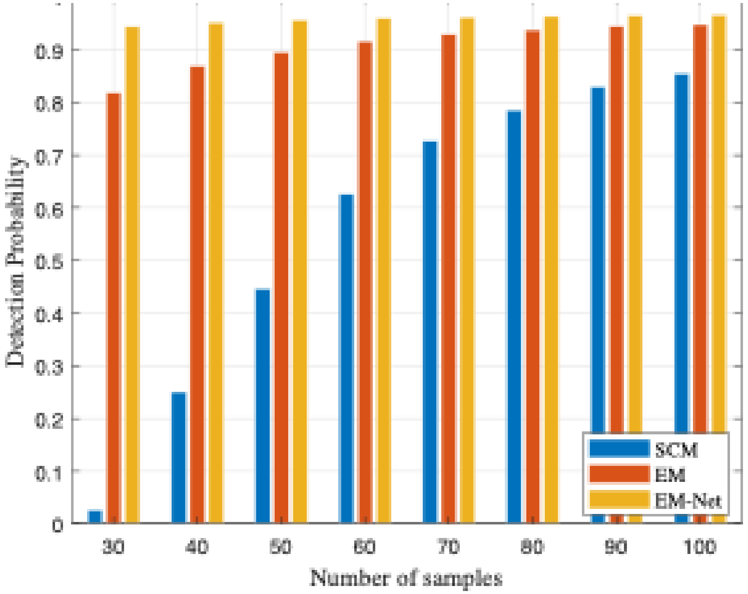


Challenges

- **Interference management**
  - Monostatic self-interference: full-duplex SI cancellation (analog and digital)
  - Interference between sensing and communication: sensing signals are interference for communication and vice versa. Mitigate by signal design (weighted signals) and signal processing
  - Interference due to varying statistics: TX signal affects perceived clutter statistics (e.g., fine beams)
- **Networked sensing**
  - Single link perspective: Single view, performance depends on SNR, number of antennas. No diversity.
  - Multi-link perspective: multi-view, macro diversity. Sensor selection is important
  - Fusion: signal-level vs information-level
- **Environment sensing**
  - Clutter estimation among several nodes
  - Communication-efficient information sharing

Tang, A., Wang, X. and Zhang, J.A., 2024. Interference management for full-duplex ISAC in B5G/6G networks: Architectures, challenges, and solutions. *IEEE Communications Magazine*, *62*(9), pp.20-26.

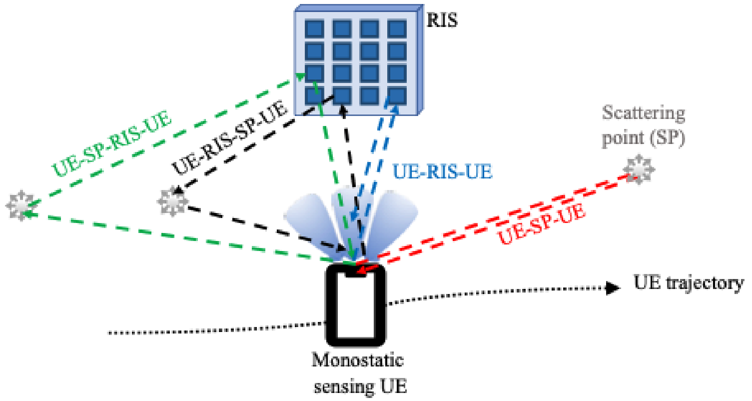


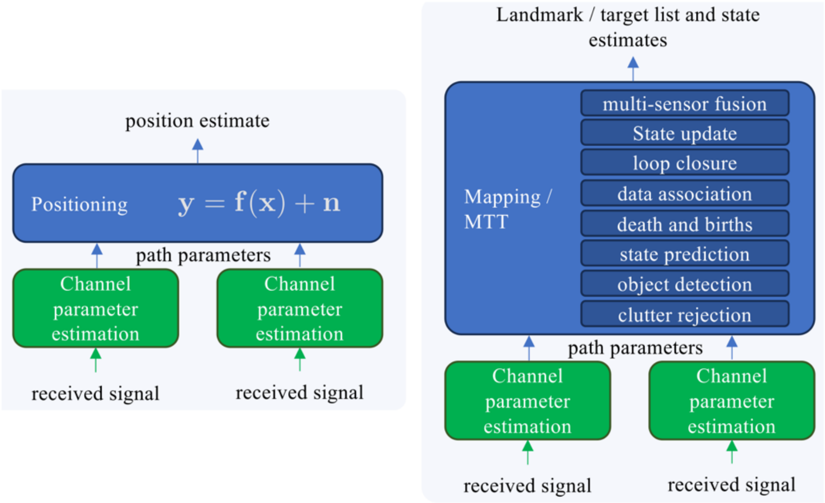


Future directions

- **Target tracking:** Target handover using Kalman filter, SLAM, AI-methods
- **Joint networked and local sensing:** on vehicle vs networked sensors. Different roles due to latency differences.
- **RIS-aided sensing:** create new sensing paths at mmWave, additional location and velocity information
- **Joint active and passive sensing:** use data signals for sensing
- **Sensing-aided communication:** sensing-aided channel estimation and beam-tracking
- **Synchronization:** heterogeneous node types

Kim, H., Fascista, A., Chen, H., Ge, Y., Alexandropoulos, G.C., Seco-Granados, G. and Wymeersch, H., 2023, May. RIS-aided monostatic sensing and object detection with single and double bounce multipath. In *2023 IEEE International Conference on Communications Workshops (ICC Workshops)* (pp. 1883-1889). IEEE.





González-Prelcic, N., Keskin, M.F., Kaltiokallio, O., Valkama, M., Dardari, D., Shen, X., Shen, Y., Bayraktar, M. and Wymeersch, H., 2024. The integrated sensing and communication revolution for 6G: Vision, techniques, and applications. *Proceedings of the IEEE*.

Lessons: DISAC Bingo!

Multiple views of targets	Monostatic sensing and full-duplex	RIS-aided ISAC				
Distributed processing	Interference management	Sensing-aided comm				
Phase synchronization	Fusion	Time, freq. sync.				
Distributed AI	Clutter estimation	Architecture and protocols				
Dedicated sensing devices	Tracking and target handover					

DISAC vision papers

INTEGRATING SENSING INTO COMMUNICATIONS IN MULTI-FUNCTIONAL NETWORKS

Multi-View Sensing for Wireless Communications: Architectures, Designs, and Opportunities

Xin Tong, Zhaoyang Zhang, and Zhaohui Yang

6G WIRELESS TECHNOLOGIES AND SYSTEMS

COOPERATIVE INTEGRATED SENSING AND COMMUNICATION IN 6G: FROM OPERATORS PERSPECTIVE

Xiaoyun Wang, Zixiang Han, Rongyan Xi, Guangyi Liu, Lincong Han, Jing Jin, Yahui Xue, Liang Ma, Yajuan Wang, Tao Jiang, Mengting Lou, Qixing Wang, and Jiangzhou Wang

INTEGRATED SENSING AND COMMUNICATIONS FOR 6G

COLLABORATIVE SENSING IN PERCEPTIVE MOBILE NETWORKS: OPPORTUNITIES AND CHALLENGES

Lei Xie, Shenghui Song, Yonina C. Eldar, and Khaled B. Letaief

6G WIRELESS TECHNOLOGIES AND SYSTEMS

TOWARD DISTRIBUTED AND INTELLIGENT INTEGRATED SENSING AND COMMUNICATIONS FOR 6G NETWORKS

Emilio Calvanese Strinati, George C. Alexandropoulos, Navid Amani, Maurizio Crozzoli, Giyyarpuram Madhusudan, Sami Mekki, Francois Rivet, Vincenzo Sciancalepore, Philippe Sehier, Maximilian Stark, and Henk Wymeersch

This article has been accepted for inclusion in a future issue of this magazine. Content is final as presented, with the exception of pagination.

ACCEPTED FROM OPEN CALL

COOPERATIVE ISAC NETWORKS: OPPORTUNITIES AND CHALLENGES

Kaitao Meng, Christos Masouros, Athina P. Petropulu, and Lajos Hanzo

ABSTRACT

sensing side, the ISAC network can cover larger

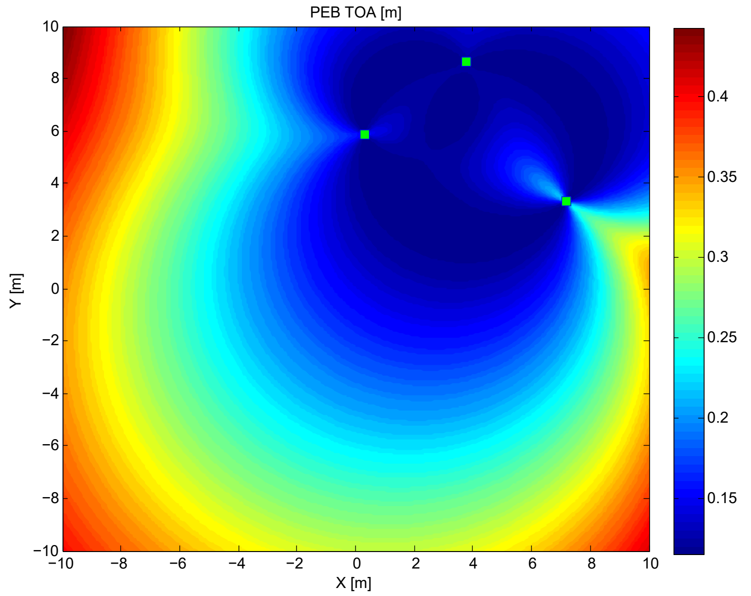
Cooperative ISAC networks: Opportunities and challenges

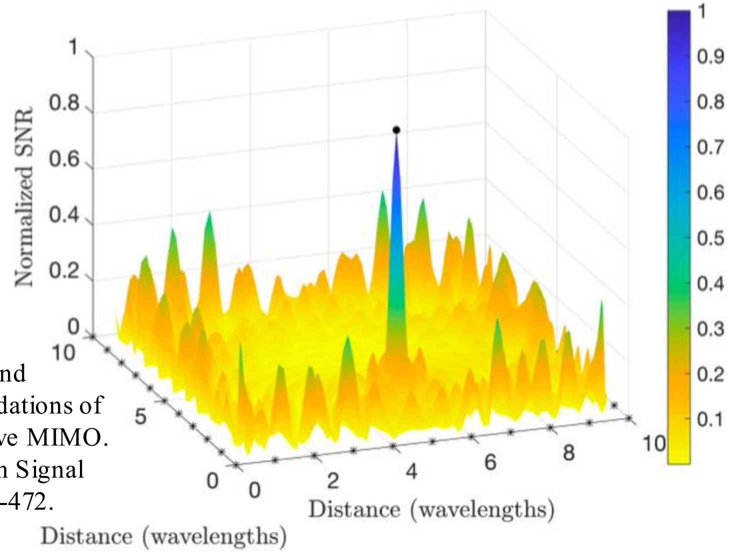
- **Data:** Meng, K., Masouros, C., Petropulu, A.P. and Hanzo, L., 2024. Cooperative ISAC networks: Opportunities and challenges. IEEE Wireless Communications.
- **Main idea:** ISAC networks (multi-cell collaboration) lead to new metrics, optimization of new degrees of freedom, cooperation regimes and trade-offs.
- **Benefits:** larger sensing coverage, enhanced assistance between sensing and comm.
- **Challenges:** synchronization (time, CFO, phase noise), backhaul constraints, security and privacy (secure comms *and* secure sensing)

ISAC Levels	Performance metrics	Optimization DoF	Resource constraints	Cooperation frameworks	Trade-offs
System-level ISAC	SINR, achievable rate, outage probability, CRLB, sensing rate, MMSE	Resource allocation, antenna selection, beamforming	Power, time, energy constraints	synergy between S&C functionalities, user/target/BS collaboration	Deterministic and random signals, channel correlation
Network-level ISAC	CRLB coverage probability, joint S&C ASE, networked energy efficiency	BS density, cooperative cluster size, cell association	Joint S&C backhaul capacity, BS load, interference nulling DoF	BS topology design, distributed dynamic cluster	Correlation between signals transmitted by different BSs, deployment geometry

What’s new with cooperative ISAC?

- **New metrics:** spatial distribution of link-level metrics
- **New optimization:** allocation across several TX and RX nodes. Clustering of BSs for cooperation.
- **New constraints:** backhaul capacity
- **New architecture:** high sensing data volumes, time sync, radio resource management
- **New trade-offs:** BS deployments, correlation among TX signals
- **New applications:**
  - Space-air-ground ISAC
  - Multi-modal sensing (e.g., radar)
  - Vehicular ISAC networks: extend field of view





Demir, Ö.T., Björnson, E. and Sanguinetti, L., 2021. Foundations of user-centric cell-free massive MIMO. Foundations and Trends® in Signal Processing, 14(3-4), pp.162-472.

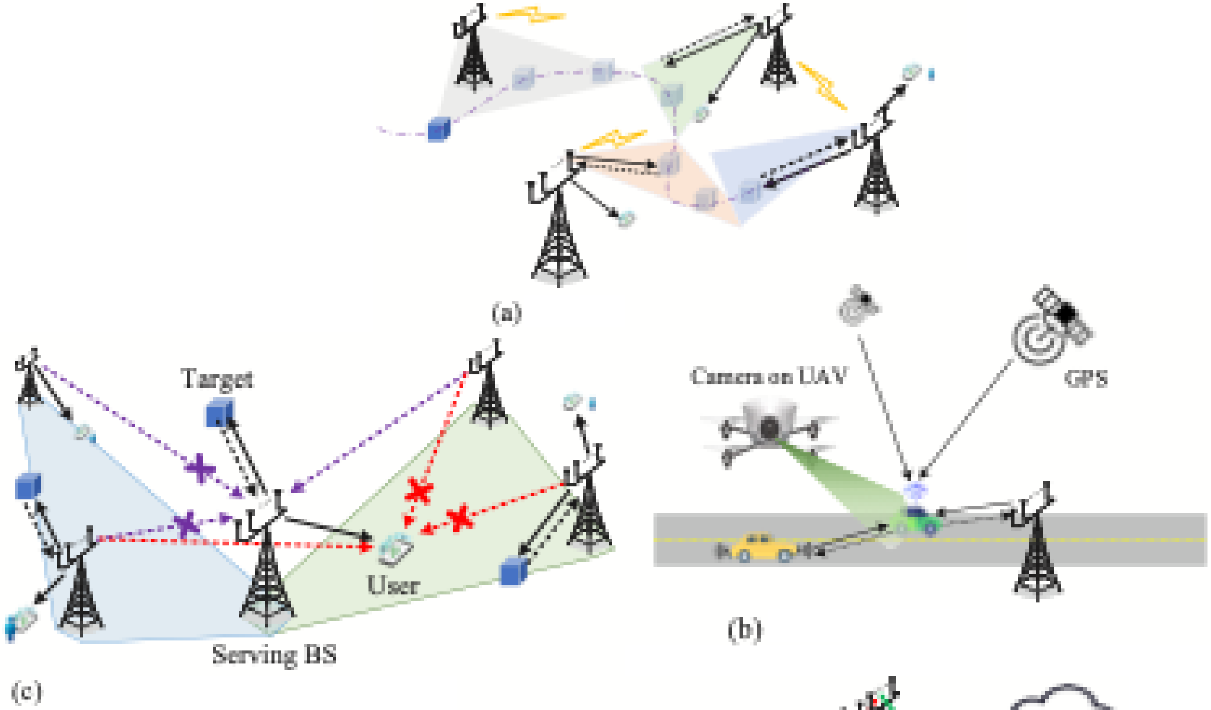
Levels of cooperation

a. Coordinated Cell Association: target handover

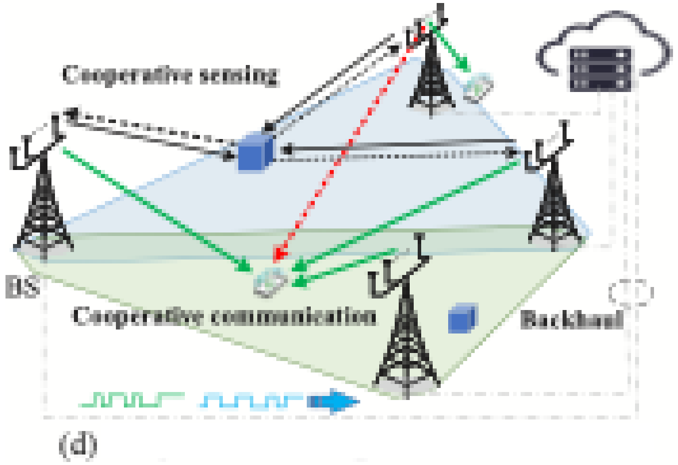
b. Collaborative Data Fusion: diversity and SNR gain improves sensing detection and accuracy

c. Coordinated Beamforming for Interference Management: sensing beam in null space of communication channels. Also BS-BS interference.

d. Cooperative Sensing and Communication: coherent vs non-coherent approaches

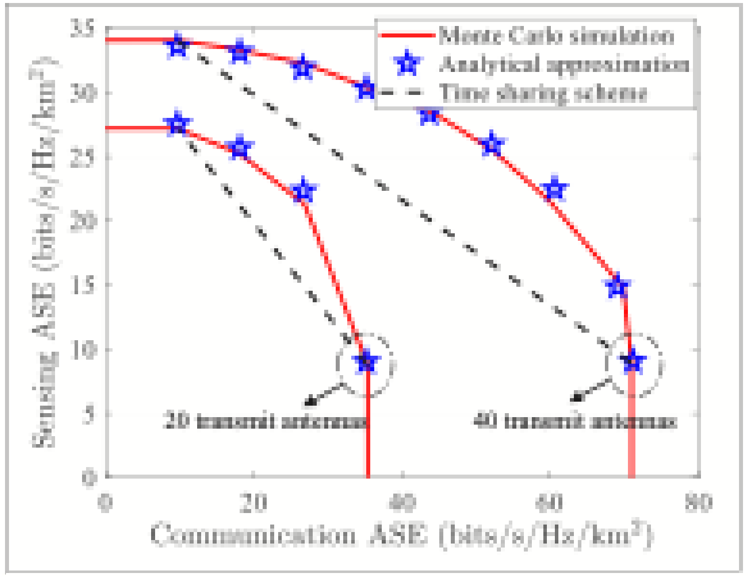


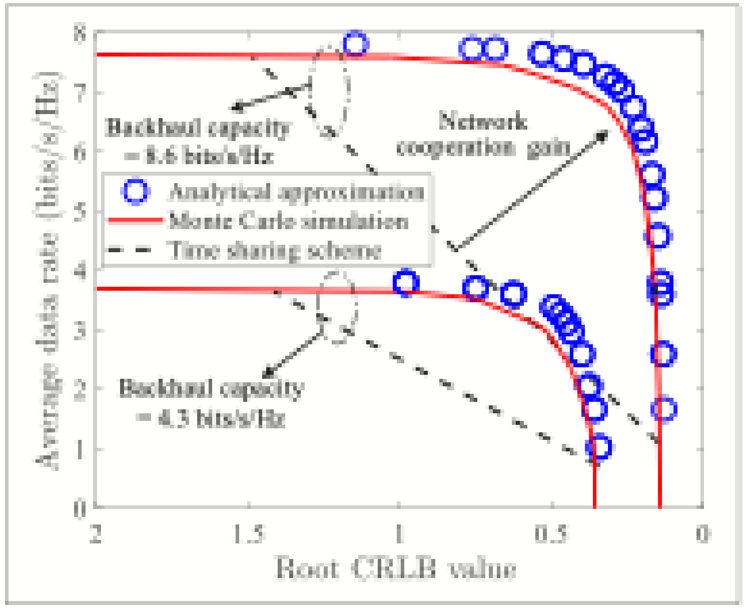
Cooperation Level		Requirement				
		Information Sharing	Transmission Latency	Time Synchronization	Signaling overhead	Performance gain
Coordinated Cell Association		Target/user/BS state	Task level	No	Low	Low
Collaborative data fusion		Estimated parameters	Frame level	No	Medium	Medium
Interference management		User/target CSI	No	No	Medium	High
Cooperative S&C	Non-coherent	Data/echo signal	Frame level	Symbol level	Very high	High
	Coherent	CSI and data/echo signal		Phase level	Very high	Very high



Trade-offs and synergies

- Sensing-assisted communication: reduce beamforming overhead, avoid blockages
- Communication-assisted sensing: compute offloading, over-the-air computation for fusion
- Trade-offs and synergies: careful consideration





Lessons: DISAC Bingo!

Multiple views of targets	Monostatic sensing and full-duplex	RIS-aided ISAC	Backhaul capacity			
Distributed processing	Interference management	Sensing-aided comm	Semantic comm.			
Phase synchronization	Fusion	Time, freq. sync.	Privacy and security			
Distributed AI	Clutter estimation	Architecture and protocols				
Dedicated sensing devices	Tracking and target handover	DISAC metrics				

DISAC vision papers

INTEGRATING SENSING INTO COMMUNICATIONS IN MULTI-FUNCTIONAL NETWORKS

Multi-View Sensing for Wireless Communications: Architectures, Designs, and Opportunities

Xin Tong, Zhaoyang Zhang, and Zhaohui Yang

6G WIRELESS TECHNOLOGIES AND SYSTEMS

COOPERATIVE INTEGRATED SENSING AND COMMUNICATION IN 6G: FROM OPERATORS PERSPECTIVE

Xiaoyun Wang, Zixiang Han, Rongyan Xi, Guangyi Liu, Lincong Han, Jing Jin, Yahui Xue, Liang Ma, Yajuan Wang, Tao Jiang, Mengting Lou, Qixing Wang, and Jiangzhou Wang

INTEGRATED SENSING AND COMMUNICATIONS FOR 6G

COLLABORATIVE SENSING IN PERCEPTIVE MOBILE NETWORKS: OPPORTUNITIES AND CHALLENGES

Lei Xie, Shenghui Song, Yonina C. Eldar, and Khaled B. Letaief

6G WIRELESS TECHNOLOGIES AND SYSTEMS

TOWARD DISTRIBUTED AND INTELLIGENT INTEGRATED SENSING AND COMMUNICATIONS FOR 6G NETWORKS

Emilio Calvanese Strinati, George C. Alexandropoulos, Navid Amani, Maurizio Crozzoli, Giyyarpuram Madhusudan, Sami Mekki, Francois Rivet, Vincenzo Sciancalepore, Philippe Sehier, Maximilian Stark, and Henk Wymeersch

This article has been accepted for inclusion in a future issue of this magazine. Content is final as presented, with the exception of pagination.

ACCEPTED FROM OPEN CALL

COOPERATIVE ISAC NETWORKS: OPPORTUNITIES AND CHALLENGES

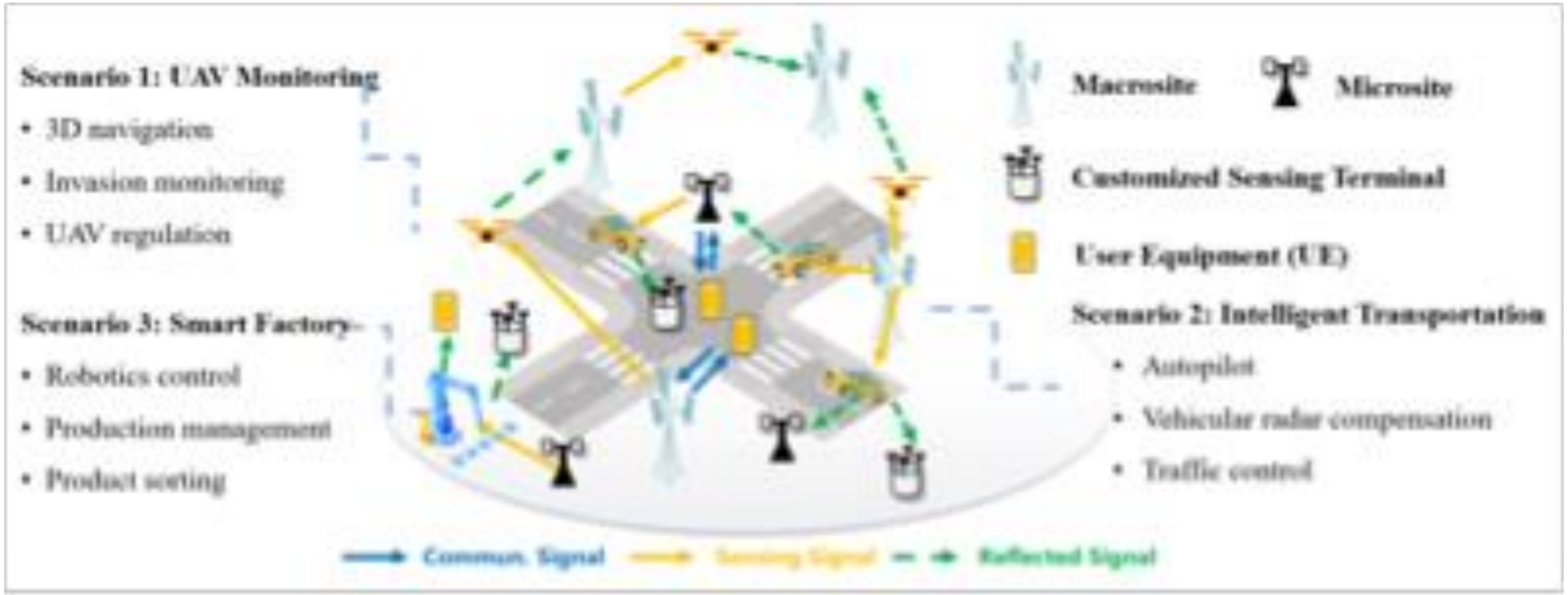
Kaitao Meng, Christos Masouros, Athina P. Petropulu, and Lajos Hanzo

ABSTRACT

sensing side, the ISAC network can cover larger

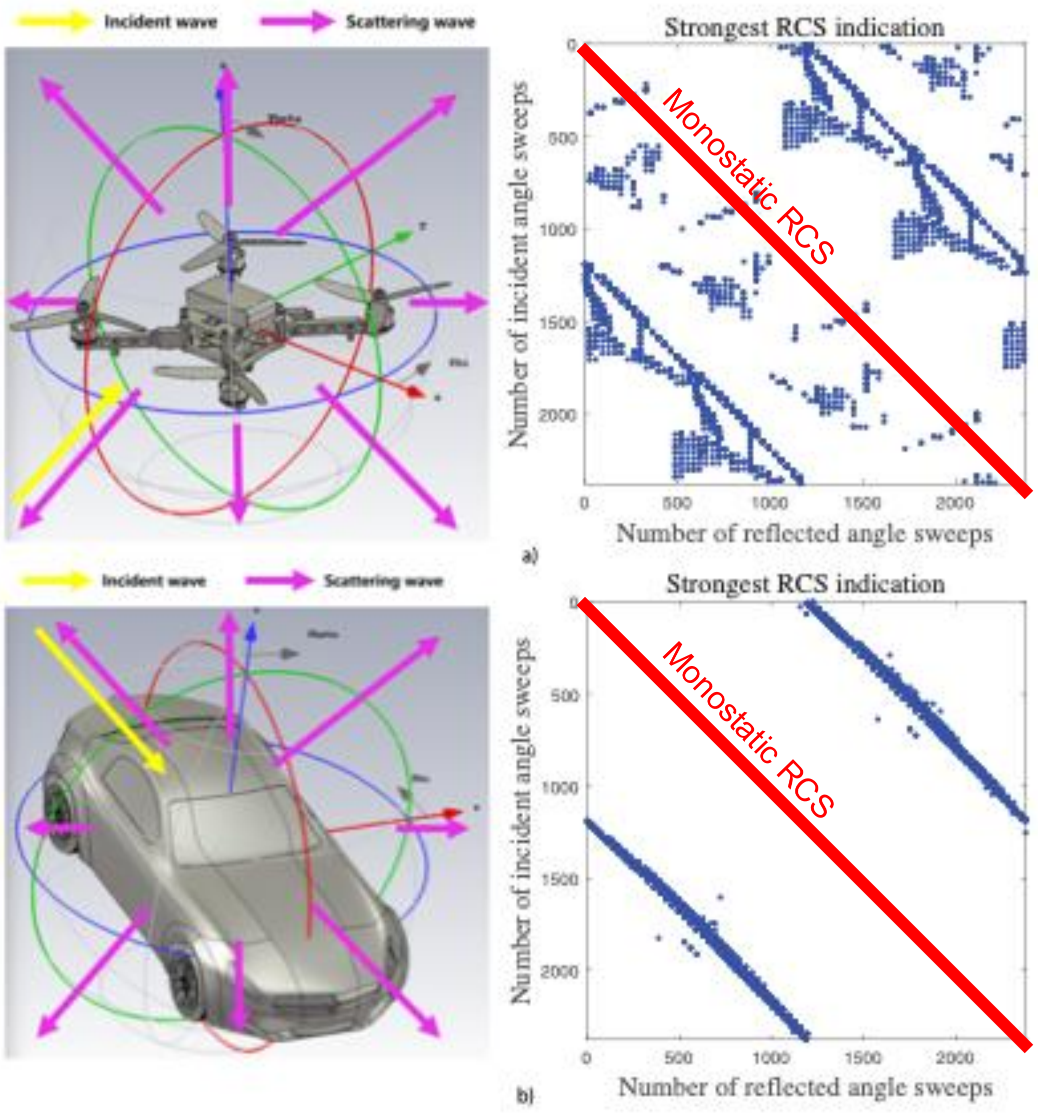
Cooperative Integrated Sensing and Communication in 6G: From Operators Perspective.

- **Data:** Wang, X., Han, Z., Xi, R., Liu, G., Han, L., Jin, J., Xue, Y., Ma, L., Wang, Y., Jiang, T. and Lou, M., 2025. Cooperative Integrated Sensing and Communication in 6G: From Operators Perspective. IEEE Wireless Communications, 32(1), pp.52-59.
- **Main idea:** sensing in wide areas, cooperation among nodes. Include customized sensing terminals.
- **Challenges:** interference, monostatic sensing is too expensive, tight synchronization, LOS blockage, sensing protocols and functions



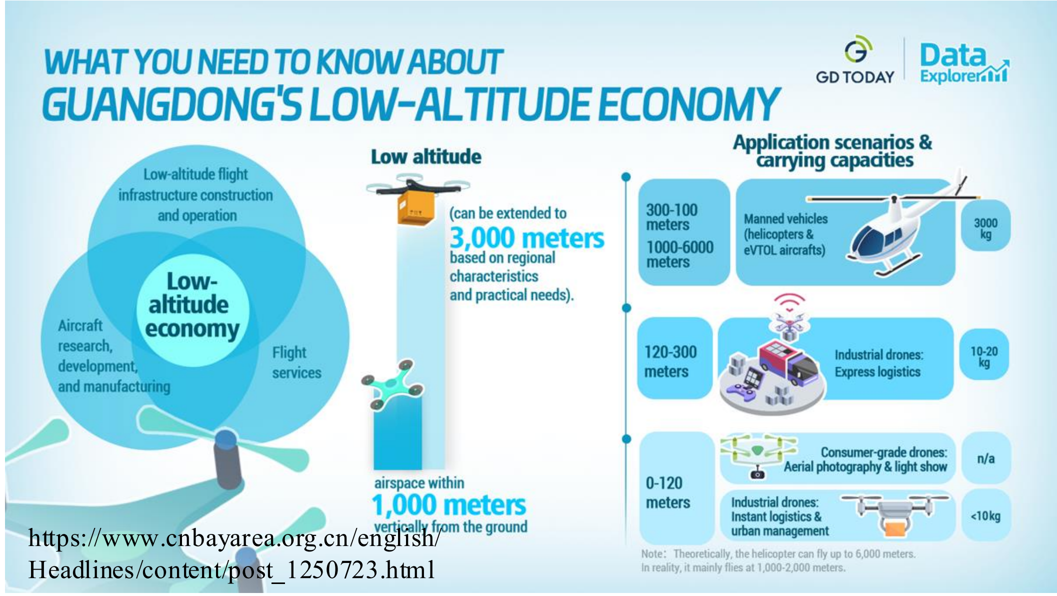
Advantages, KPIs

- **Radar cross section gains:** Bistatic RCS provides multiple views, wider coverage, better object identification, while monostatic RCS is only one direction
- **LOS path gains:** more sensing links means higher probability of LOS
- **Cooperation gains:** fusion from different sensors, averaging of biases. Deployment optimization freedom.
- **Boost KPIs:** Sensing probability, Sensing accuracy Sensing capacity (scaling)



Business models

For-profit



https://www.cnbayarea.org.cn/english/Headlines/content/post_1250723.html

Non-for-profit

https://www.theengineer.co.uk/content/news/ai-and-6g-technologies-developed-for-safe-interconnected-mobility/

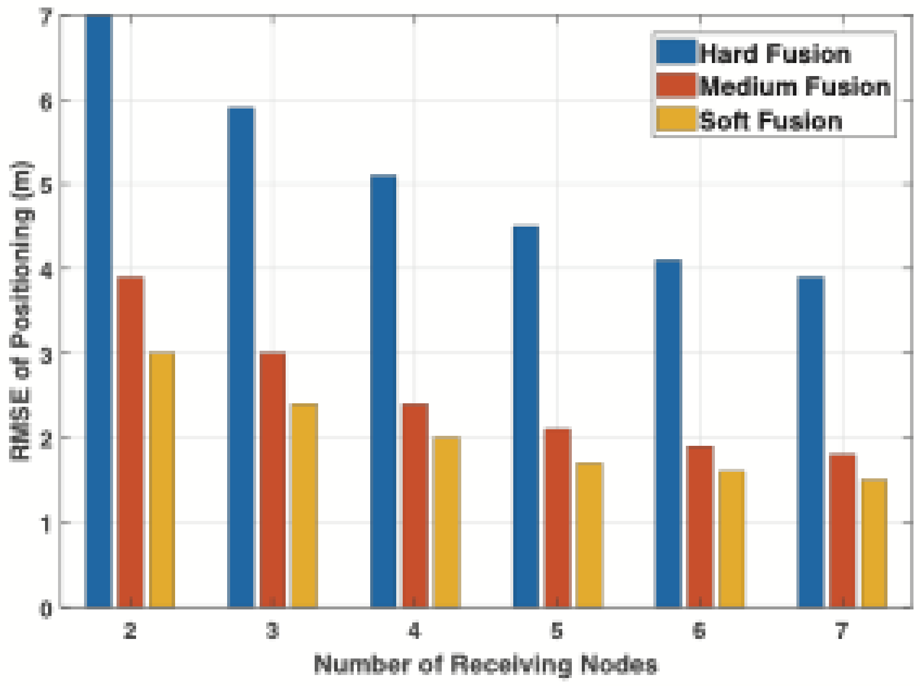
subsidies

tax incentives

user credit

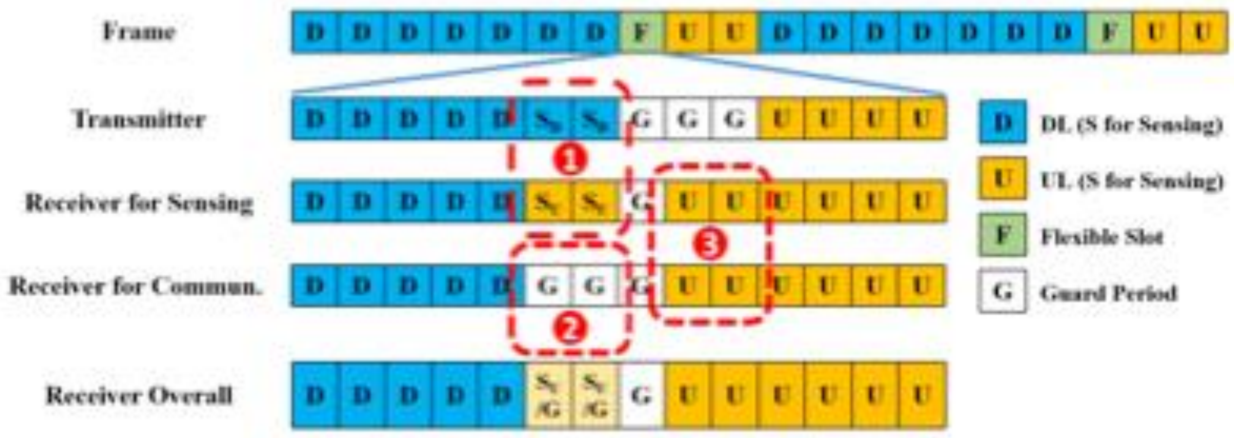
Challenges

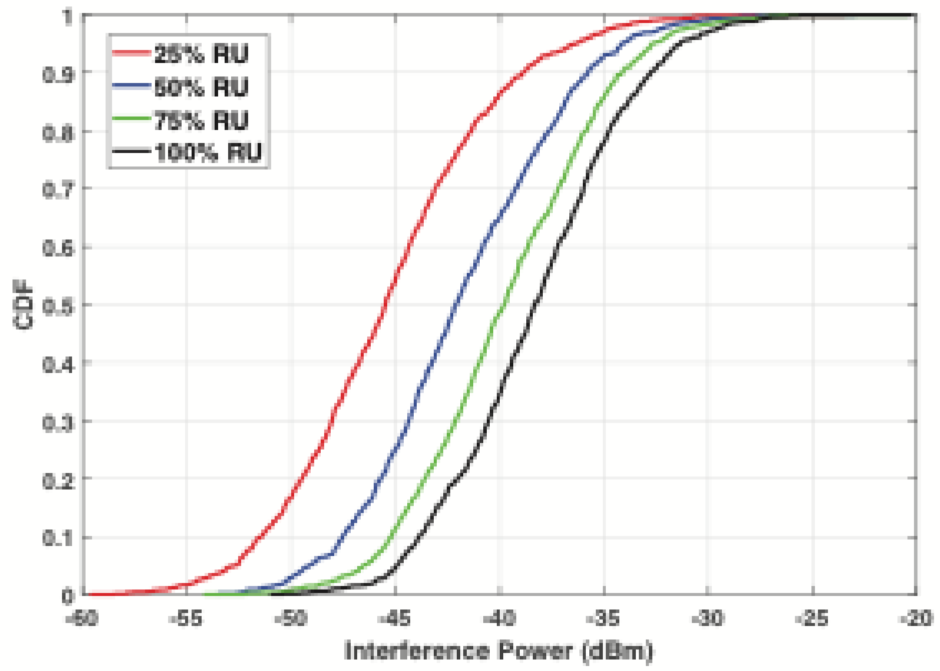
- **Synchronization**
  - time and frequency sync needed to turn delays and Dopplers into distances and velocities
  - LOS path can be used as a reference, when available
  - Known reflectors could be used as a reference, when LOS is not available.
- **NLOS sensing**
  - NLOS identification
  - NLOS incidence point localization
  - Use Doppler to separate from clutter
- **Multi-node fusion**
  - Hard fusion: position level
  - Medium fusion: channel parameter level
  - Soft fusion: IQ level
- **Privacy and security**
  - Identify targets and track them over time.
  - Fake objects
  - Eavesdroppers, intruder detection
  - Trust in operators and authenticated UEs



Protocol design

- **Frame structure** in UL and DL should accommodate sensing, accommodate long sensing paths by adding guard period
- **Resource allocation:** TX and RX sensing resources should be synchronized, sensing and communication resources should be synchronized
- **Information sharing:** Node locations, waveform, signals, resources, beams
- **Interference management:** space, time, frequency coordination, power control.





Lessons: DISAC Bingo!

Multiple views of targets	Monostatic sensing and full-duplex	RIS-aided ISAC	Backhaul capacity			
Distributed processing	Interference management	Sensing-aided comm	Semantic comm.			
Phase synchronization	Fusion	Time, freq. sync.	New business models			
Distributed AI	Clutter estimation	Architecture and protocols	Privacy and security			
Dedicated sensing devices	Tracking and target handover	DISAC metrics	Testbeds			

DISAC vision papers

INTEGRATING SENSING INTO COMMUNICATIONS IN MULTI-FUNCTIONAL NETWORKS

Multi-View Sensing for Wireless Communications: Architectures, Designs, and Opportunities

Xin Tong, Zhaoyang Zhang, and Zhaohui Yang

6G WIRELESS TECHNOLOGIES AND SYSTEMS

COOPERATIVE INTEGRATED SENSING AND COMMUNICATION IN 6G: FROM OPERATORS PERSPECTIVE

Xiaoyun Wang, Zixiang Han, Rongyan Xi, Guangyi Liu, Lincong Han, Jing Jin, Yahui Xue, Liang Ma, Yajuan Wang, Tao Jiang, Mengting Lou, Qixing Wang, and Jiangzhou Wang

INTEGRATED SENSING AND COMMUNICATIONS FOR 6G

COLLABORATIVE SENSING IN PERCEPTIVE MOBILE NETWORKS: OPPORTUNITIES AND CHALLENGES

Lei Xie, Shenghui Song, Yonina C. Eldar, and Khaled B. Letaief

6G WIRELESS TECHNOLOGIES AND SYSTEMS

TOWARD DISTRIBUTED AND INTELLIGENT INTEGRATED SENSING AND COMMUNICATIONS FOR 6G NETWORKS

Emilio Calvanese Strinati, George C. Alexandropoulos, Navid Amani, Maurizio Crozzoli, Giyyarpuram Madhusudan, Sami Mekki, Francois Rivet, Vincenzo Sciancalepore, Philippe Sehier, Maximilian Stark, and Henk Wymeersch

ABSTRACT

This article has been accepted for inclusion in a future issue of this magazine. Content is final as presented, with the exception of pagination.

ACCEPTED FROM OPEN CALL

COOPERATIVE ISAC NETWORKS: OPPORTUNITIES AND CHALLENGES

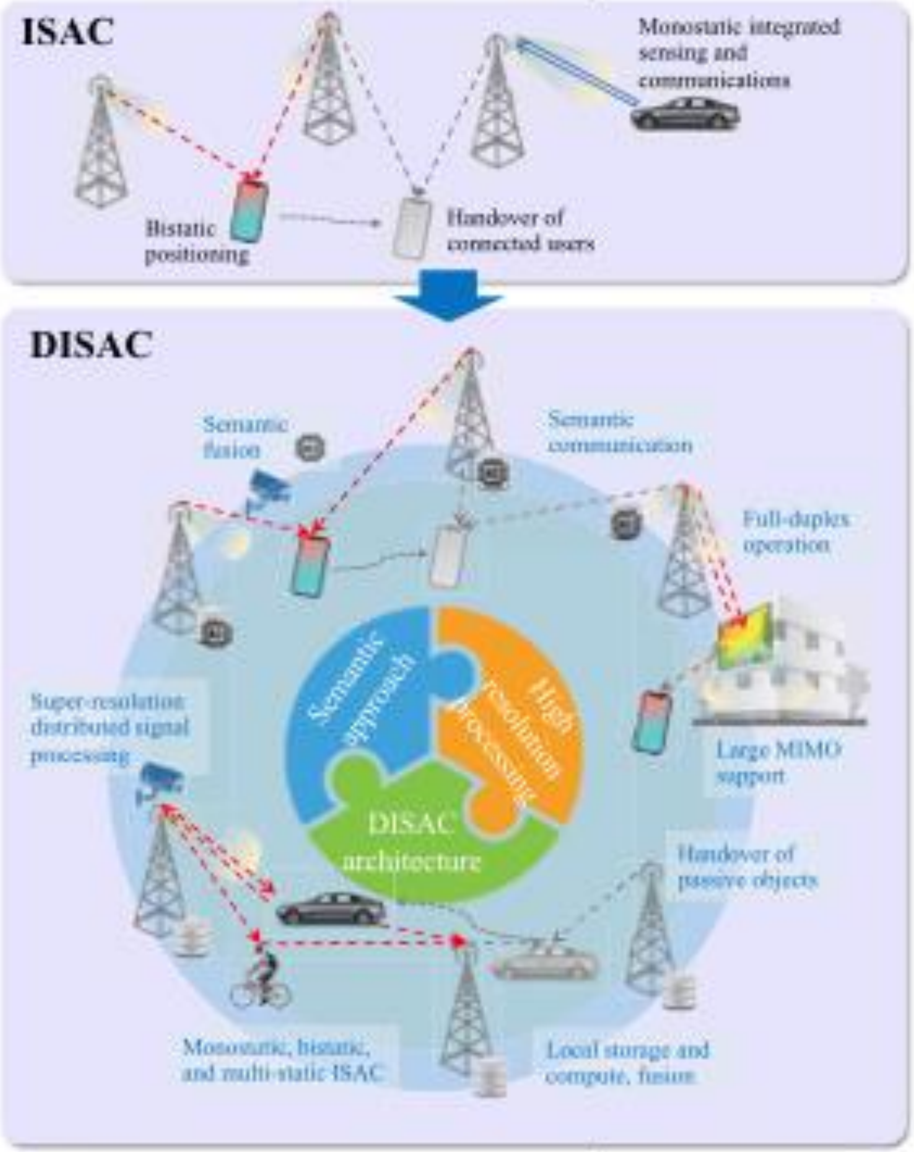
Kaitao Meng, Christos Masouros, Athina P. Petropulu, and Lajos Hanzo

ABSTRACT

sensing side, the ISAC network can cover larger

Toward Distributed and Intelligent Integrated Sensing and Communications for 6G Networks

- **Data:** Strinati, E.C., Alexandropoulos, G.C., Amani, N., Crozzoli, M., Madhusudan, G., Mekki, S., Rivet, F., Sciancalepore, V., Sehier, P., Stark, M. and Wymeersch, H., 2025. Toward Distributed and Intelligent Integrated Sensing and Communications for 6G Networks. IEEE Wireless Communications, 32(1), pp.60-67.
- **Main idea:** going from single link ISAC to distributed ISAC. Tracking users and objects over extended space and time. Augment classical KPIs with KVIs. Semantic awareness and fusion with external sensors.
- **Key components:**
  - **Architecture:** distributed operations, functions, AI, central vs local processing, exposure to non-3GPP sensors
  - **Semantic and goal-oriented framework:** selection, resource allocation, transmission, processing , information sharing and fusion
  - **High-resolution distributed processing**



DISAC use cases

- Analysis based on 3GPP use cases
- Several cover extended view over space and time
- Almost all use cases can benefit from the DISAC key components
- Important unifying use case is digital twinning

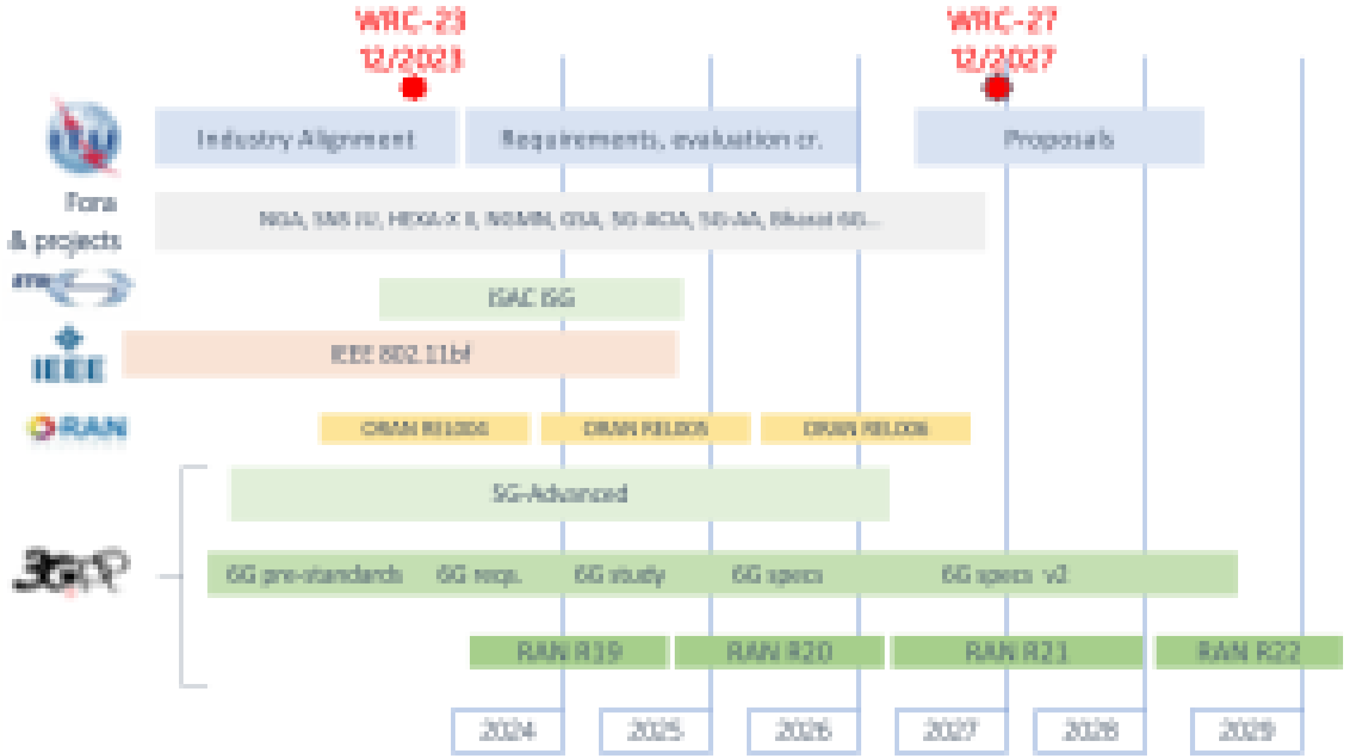
- Challenges to realize DISAC
  - **Algorithmic:** how to realize the semantic and goal-oriented approach?
  - **PoC:** demonstration of DISAC is much more involved than ISAC
  - **Standards:** waveforms, metric, models, control signaling, data formats

Use Case from [2] (sections)	MMTCCxDI	GeMBB	URLLCCC	Semantic	DISAC Architecture (D) distributed processing; (W) wide perspective over space and time; and (S) support for non-3GPP sensors	DISAC Semantic Approach (R) resourceefficient operation (including compression of data); (A) AI-based and semantic reasoning; and (M) multi-modal sensing	DISAC High-Resolution Processing (D) distributed sensing and (E) extreme requirements
Intrusion detection in/around smart homes (5.1, 5.6, 5.16)	✓		✓	✓	✓(S)	✓(R, A, M)	
Highway, railway intrusion detection (5.2, 5.7)		✓			✓(D, W)	✓(A)	✓(E)
Rainfall monitoring (5.3)	✓	✓			✓(D), ✓(W)	✓(A)	✓(D)
Transparent sensing (5.4)	✓		✓		✓(S)	✓(R, A, M)	
Sensing for flooding (5.5)	✓	✓		✓	✓(D, W)	✓(A)	✓(D)
Automotive maneuvering and navigation (5.8, 5.26, 5.30)	✓		✓	✓	✓(D, W, S)	✓(R, A, M)	✓(D, E)
AGV detection and tracking in factories (5.9)	✓	✓	✓		✓(D, W)		✓(D)
UAV trajectory tracing and intrusion detection (5.10, 5.13, 5.22)		✓	✓	✓	✓(D, W, S)	✓(R, A, M)	✓(D, E)
Crossroads with/without obstacle (5.11)			✓	✓	✓(S)	✓(A, M)	✓(E)
UAV and robot collision avoidance (5.12, 5.23)	✓	✓	✓		✓(D, W)	✓(R)	✓(D, E)
Tourist spot traffic management (5.14)	✓		✓	✓	✓(D, W)	✓(A)	
Sleep and health monitoring (5.15, 5.17, 5.18)	✓	✓			✓(D, W)	✓(A)	✓(D)
Sensor groups (5.19)			✓	✓	✓(D, S)	✓(R, A, M)	✓(D, E)
Parking space determination (5.20)	✓	✓			✓(W)	✓(R, A)	✓(E)
Seamless XR streaming (5.21)			✓	✓	✓(S)	✓(R, A, M)	
Immersive experience (5.25)			✓	✓		✓(A)	✓(E)
Public safety (5.27)	✓	✓	✓		✓(D, W, S)	✓(M)	✓(D, E)
Vehicles sensing for ADAS (5.28)	✓		✓	✓	✓(D, S)		✓(E)
Gesture recognition (5.29, 5.24)	✓		✓	✓		✓(A)	✓(E)
Blind spot detection (5.31)	✓		✓	✓	✓(A)		
Sensing and positioning in factory hall (5.32)	✓	✓	✓	✓	✓(W, S)	✓(R, A, M)	✓(D, E)

TABLE 1. An overview of the ISAC use cases from [2, section 5], the four 6G services from [3, section 2.2] (i.e., massive machine-type communications supporting distributed intelligence (MMTCCXDI); globally-enhanced mobile broadband (GEMBB); ultra-reliable, low-latency computation, communication, and control (URLLCCC); semantic services and whether and how they would benefit from the disac cornerstones summarized in Fig. 1 (if not, the cell is empty). ADAS: advanced driver assistance system; AGV: automated guided vehicle; UAV: unmanned aerial vehicle; XR: extended reality.

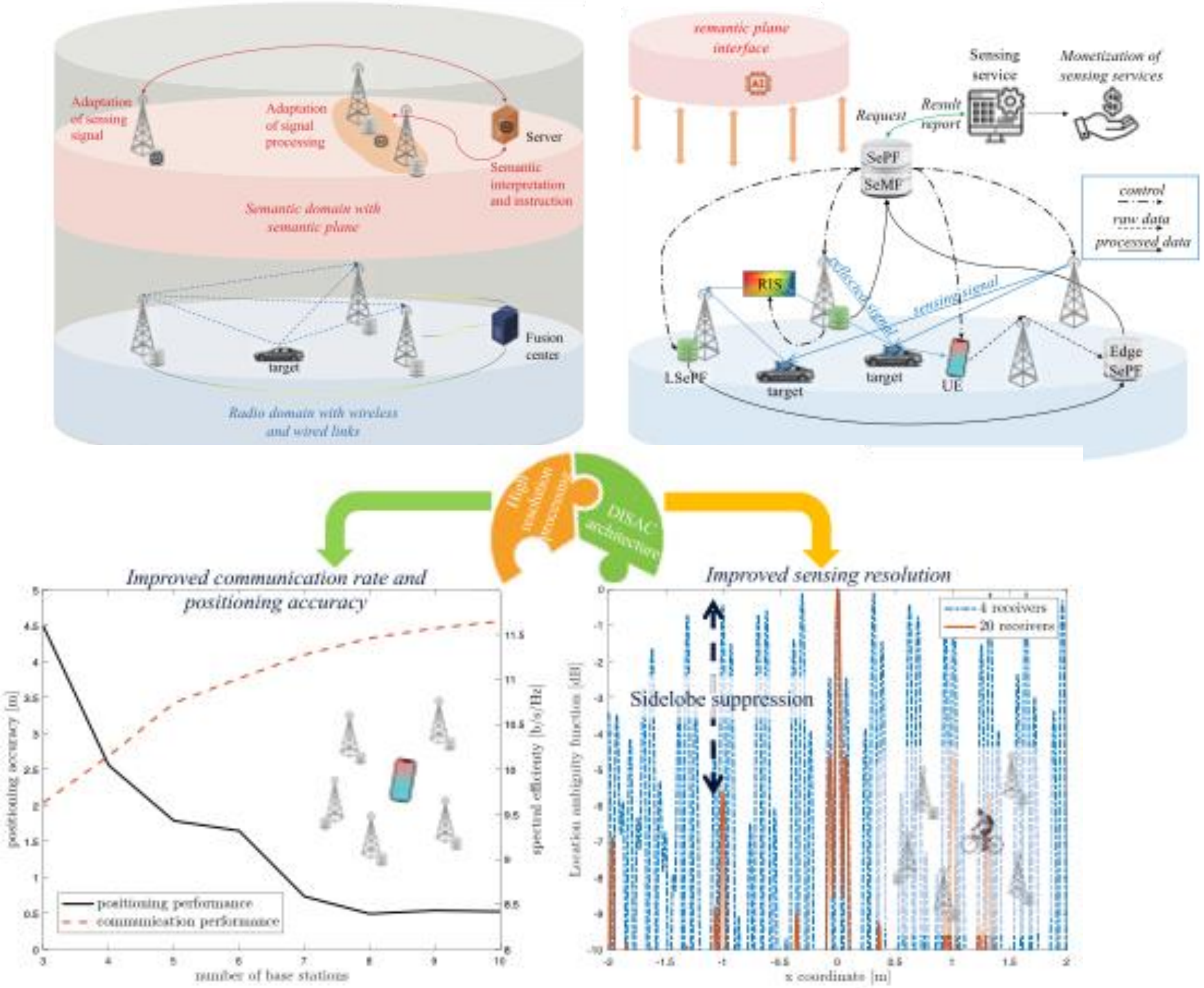
Standardization

- **ISAC**
  - ETSI: use cases, models, architecture, security and privacy
  - 3GPP: use cases, models.
  - ITU: network as a sensor
  - IEEE: modified PHY and MAC, applications such presence detection, gesture classification, vital sign monitoring
- **AI/ML**
  - 3GPP: higher layer functions for energy savings, load balancing. Further work on lower layer planned.
  - IEEE. Standing committee on AI/ML applications in 802.11
- **AI+ISAC:** N/A



Four DISAC enablers

- **Native semantic / goal-oriented framework:** optimization of transmitter, receiver, sharing, compression over time
- **Optimized PHY:** distributed signal processing, Bayesian inference, phase coherent processing, sensing-aided communication
- **Intelligent resource allocation:** semantic/goal oriented to cope with large data volumes, heterogenous capacities. Support for large MIMO and RIS.
- **Evolved architecture:** distributed processing with heterogenous devices, semantic layer support, business potential.



Lessons: DISAC Bingo!

Multiple views of targets	Monostatic sensing and full-duplex	RIS-aided ISAC	Backhaul capacity	KVIs		
Distributed processing	Interference management	Sensing-aided comm	Semantic comm.	Standards		
Phase synchronization	Fusion	Time, freq. sync.	New business models			
Distributed AI	Clutter estimation	Architecture and protocols	Privacy and security			
Dedicated sensing devices	Tracking and target handover	DISAC metrics	Testbeds			

Lessons: DISAC Bingo! What is missing?

Multiple views of targets	Monostatic ensing and ull-duplex	RIS-aided ISAC	Backhaul capacity	KVIs	?	?
Distributed processing	Interference management	Sensing-aided comm	Semantic comm.	Standards	?	?
Phase synchronizat ion	Fusion	Time, freq. sync.	New business dels	?	?	?
Distributed AI	Clutter estimation	Architecture and ocols	Privacy and security	?	?	?
Dedicated sensing devices	Tracking nd target handover	DISAC metrics	Testbeds	?	?	?

Keyword	Expectations	Infrastructure	Protocols	Standards	Commercialization
Multiple views of targets	✅				
Monostatic sensing and full-duplex	✅	✅			
RIS-aided ISAC	✅		✅		
Backhaul capacity		✅			✅
KVIs	✅			✅	✅
Distributed processing		✅	✅		
Interference management			✅		
Sensing-aided comm	✅		✅		✅
Semantic comm.	✅		✅		✅
Standards				✅	✅
Phase synchronization	✅		✅	✅	
Fusion	✅		✅		
Time, freq. sync.	✅		✅	✅	
New business models					✅
Architecture and protocols			✅	✅	
Privacy and security	✅		✅		✅
Distributed AI	✅	✅			
Clutter estimation	✅				
Dedicated sensing devices		✅			
Tracking and target handover	✅		✅		
DISAC metrics	✅			✅	
Testbeds		✅			✅

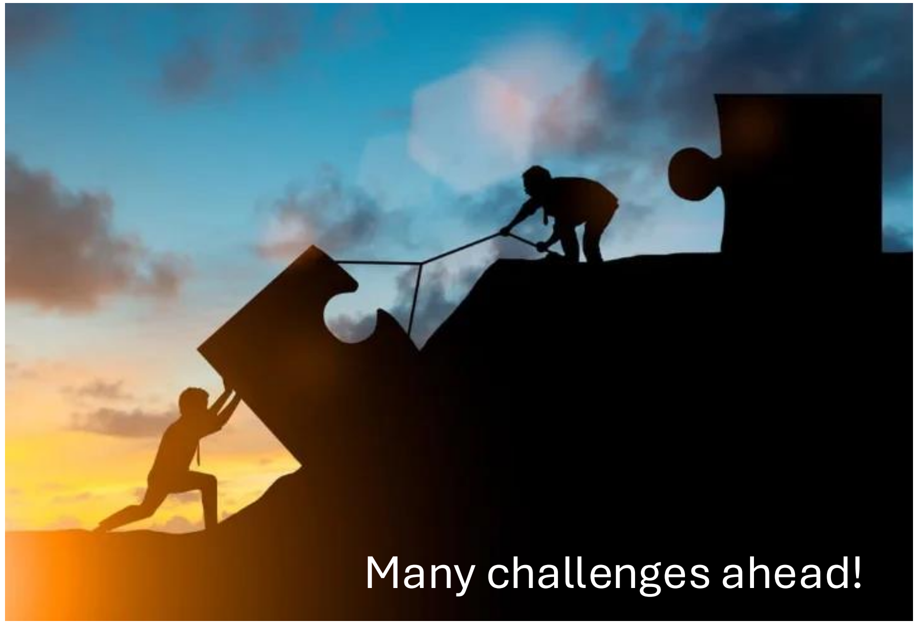
Outline

- Foundations of ISAC
- Visions and principles of DISAC
- Examples of DISAC

Examples of DISAC

Example Setups

- Multi-BS imaging
- Multi-BS monostatic ISAC
- Multi-BS bistatic ISAC
- Phase-coherent DISAC
- Multi-UE ISAC



Example Problems

- Synchronization in time, frequency, phase
- TX selection
- Resource allocation
- Waveform design
- Interference coordination
- Handover
- Local vs central processing
- AI vs model-based processing
- Fusion with external sensors
- Interaction with use cases, e.g., improving communication
- …

Phase-coherent DISAC

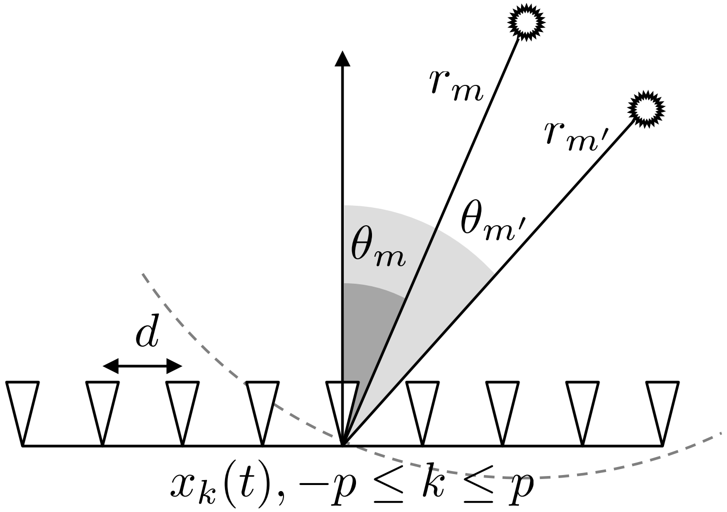
- The near-field ISAC scenarios
- Example of uplink positioning
- Example of downlink positioning

Phase-coherent DISAC

- The near-field ISAC scenarios
- Example of uplink positioning
- Example of downlink positioning

Near-field phase-coherent ISAC

- **Near-field localization:** long history, dating back to source localization with microphones [1]
- **Principle [2]:** phase across array with respect to phase reference



Far-field model (plane wave)

$$\boldsymbol{x}(t) = \sum_{m=1}^{M} s_m(t)\boldsymbol{a}(\theta_m) + \boldsymbol{w}(t)$$

Near-field model (wavefront curvature)

$$\boldsymbol{x}(t) = \sum_{m=1}^{M} \alpha_{m,k} s_m(t)\boldsymbol{a}(\theta_m, r_m) + \boldsymbol{w}(t)$$

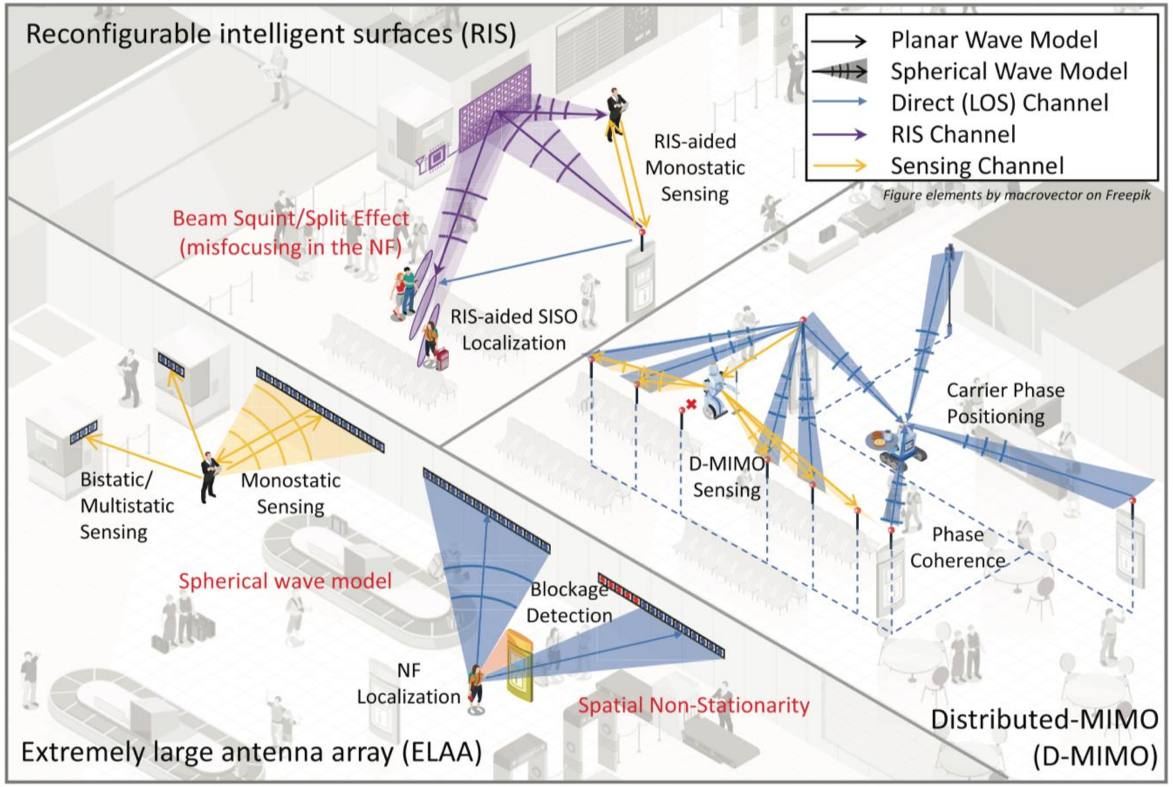
- Audio: narrowband signals, unknown with given statistics
- 5G/6G: Wideband signals, known (pilots) or partially known (data), subject to fading and multipath
- Far-field model is special case of near-field model.

[1] Chen, J.C., Hudson, R.E. and Yao, K., 2002. Maximum-likelihood source localization and unknown sensor location estimation for wideband signals in the near-field. *IEEE transactions on Signal Processing*, *50*(8), pp.1843-1854

[2] Grosicki, E., Abed-Meraim, K. and Hua, Y., 2005. A weighted linear prediction method for near-field source localization. IEEE Transactions on Signal Processing, 53(10), pp.3651-3660.

Near-field phase-coherent ISAC

- Embodiment #1: Extra-large (XL) MIMO
- Embodiment #2: Reconfigurable intelligent surfaces (RIS)
- Embodiment #3: Cell-free MIMO
- Embodiment #4: Carrier phase positioning
- Embodiment #5: Distributed MIMO radar
- Embodiments with large SIM, RA, FA, MA, …



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*.

Embodiment #1: extra-large (XL) MIMO

- BS arrays with 100s - 1000s of elements, $\lambda/2$ spacing
- UEs with small arrays
- Hybrid architecture, array-of-subarray, or low-rate ADCs needed
- Signal model:

$$\boldsymbol{y}_n(t) = \boldsymbol{W}^H(t)\sum_m \boldsymbol{\gamma}_m \odot \boldsymbol{a}_n(\boldsymbol{p}_m) \odot \boldsymbol{d}_n(\tau_m) s_{m,n}(t) + \boldsymbol{W}^H(t)\boldsymbol{h}_{\mathrm{NLOS}} + \boldsymbol{W}^H\boldsymbol{w}_n(t)$$

Beam-space observation, subcarrier n, symbol t

Non-stationary channel

Frequency-dependent near-field response

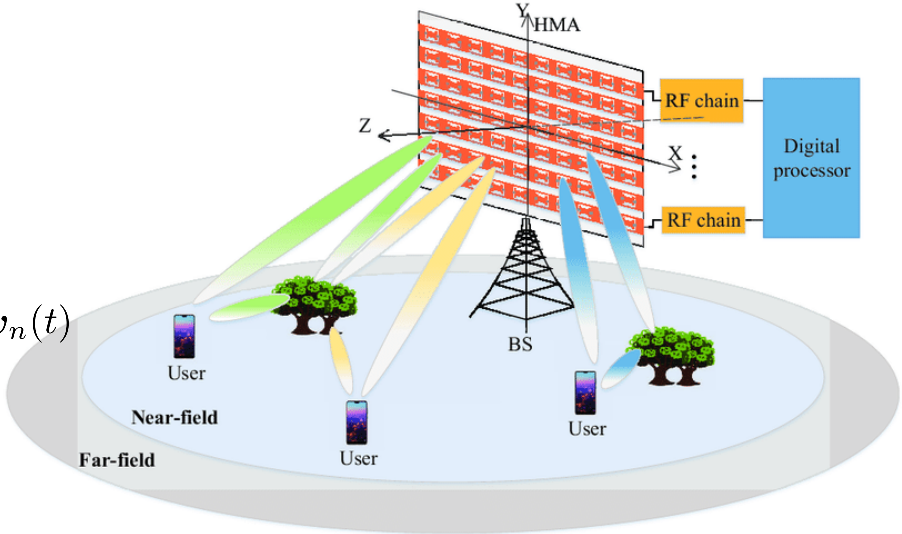
Delay depends on source and RX antenna

Pilots or data

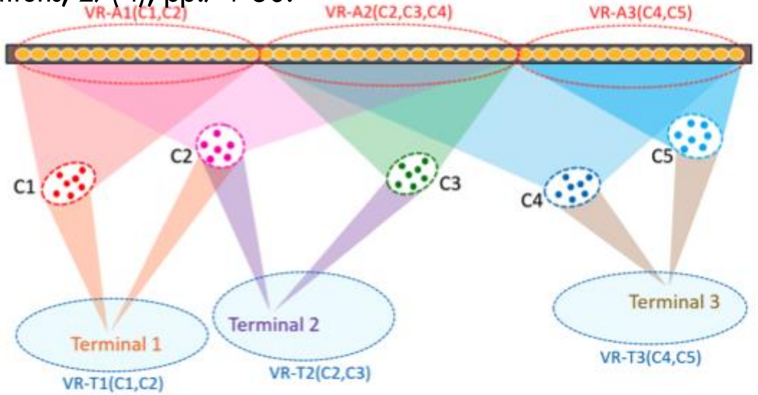
NLOS part of the channel (reflections, scattering)

- More complicated than standard models: no easy tensor decomposition, more complex processing
- NLOS part can be harnessed for sensing

Source: Xu, J., You, L., Alexandropoulos, G.C., Yi, X., Wang, W. and Gao, X., 2022. Near-field wideband extremely large-scale MIMO transmission with holographic metasurface antennas. arXiv preprint arXiv:2205.02533.



De Carvalho, E., Ali, A., Amiri, A., Angjelichinoski, M. and Heath, R.W., 2020. Non-stationarities in extra-large-scale massive MIMO. IEEE Wireless Communications, 27(4), pp.74-80.



Embodiment #2: RIS

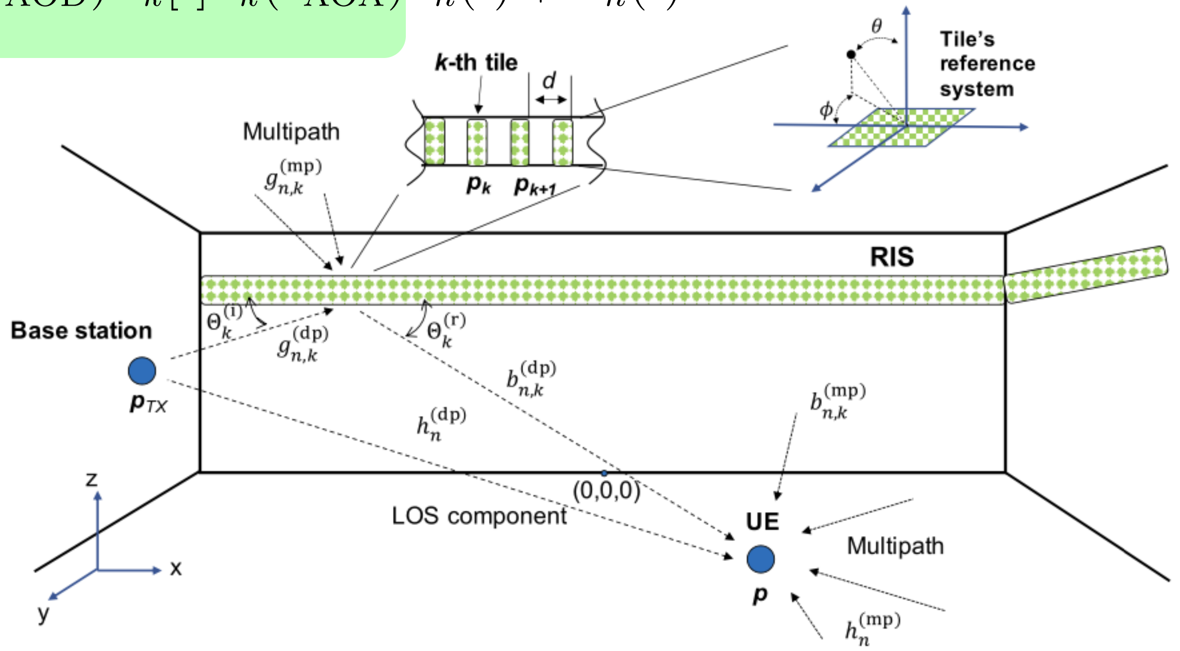
- BS and UE may have 1 antenna, beamspace models
- Large RIS with analog control, may be split into tiles

Far-field response of tile k

$$y_n(t) = h_{\mathrm{LOS}} x_{n,t} + \sum_k \alpha_k(\boldsymbol{p}_{\mathrm{UE}}) e^{-\jmath 2\pi n \Delta_f \tau_k} \boldsymbol{a}_k^T(\theta_{\mathrm{AOD}}) \Omega_k[t] \boldsymbol{a}_k(\theta_{\mathrm{AOA}}) x_n(t) + w_n(t)$$

Sum over tiles

Phase correction for phase coherence with RIS phase center



Dardari, D., Decarli, N., Guerra, A. and Guidi, F., 2021. LOS/NLOS near-field localization with a large reconfigurable intelligent surface. IEEE Transactions on Wireless Communications, 21(6), pp.4282-4294.

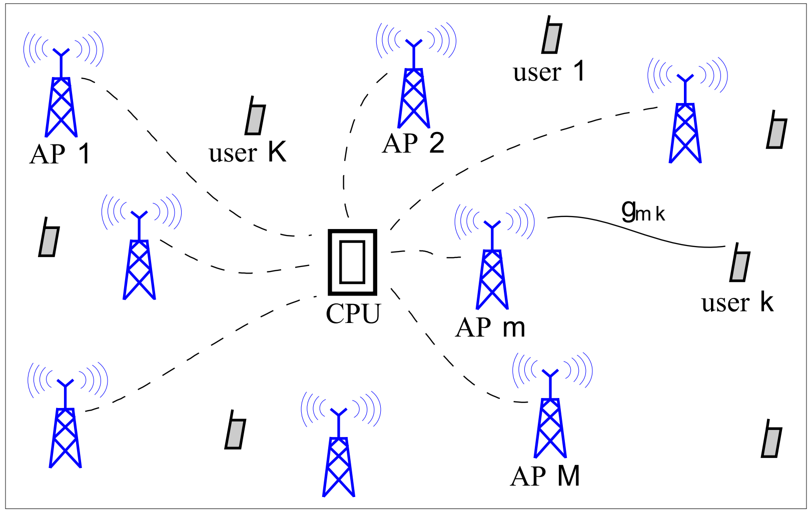
- Challenging to separate signals from each tile, requires orthogonal coding among the RIS
- Simplified model without tiles

Near-field response of entire RIS

$$y_n(t) = h_{\mathrm{LOS}} x_{n,t} + \alpha e^{-\jmath 2\pi \Delta_f \tau_k} \boldsymbol{a}^T(\boldsymbol{p}_{\mathrm{UE}}) \Omega[t] \boldsymbol{a}(\boldsymbol{p}_{\mathrm{UE}}) x_n(t) + w_n(t)$$

Embodiment #3: cell-free MIMO

Ngo, H.Q., Ashikhmin, A., Yang, H., Larsson, E.G. and Marzetta, T.L., 2017. Cell-free massive MIMO versus small cells. *IEEE Transactions on Wireless Communications*, *16*(3), pp.1834-1850.



Source: https://ma-mimo.ellintech.se/2019/01/25/beamforming-from-distributed-arrays/ and https://jemengineering.com/blog-what-is-beamforming/

- Many distributed access points
- Localization during uplink pilot transmission

Subcarrier n, symbol t, AP m

Per AP amplitude

Delay to AP m

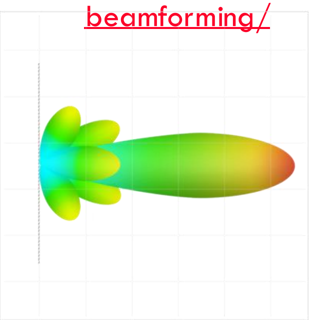
Phase with respect to phase reference

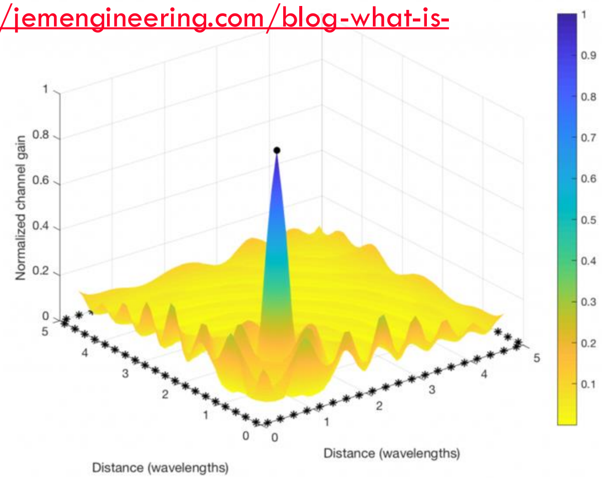
$$y_{n,m}(t) = \alpha_m e^{-\jmath 2\pi n \Delta_f \tau_m} e^{\jmath \frac{2\pi}{\lambda} r_{m,\text{ref}}} x_n(t) + h_{\text{NLOS},m,n} x_n(t) + w_{n,m}(t)$$

$$r_{m,\text{ref}} = \|\boldsymbol{p}_{\text{ue}} - \boldsymbol{p}_m\| - \|\boldsymbol{p}_{\text{ue}} - \boldsymbol{p}_{\text{ref}}\|$$

$$\tau_m = \|\boldsymbol{p}_{\text{ue}} - \boldsymbol{p}_m\|/c + B_{\text{ue}}$$

- Scalability a major issue
- Phase coherence more likely in FR1
- Multipath severe in FR1, more emphasis on AI-based localization
- Challenging in downlink





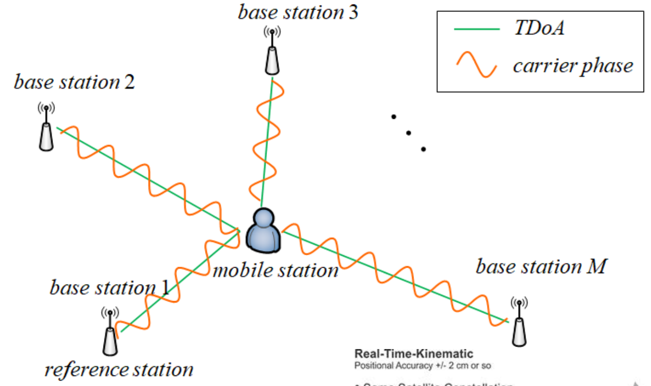
Embodiment #4: carrier phase positioning

- Principles from GNSS
- Phase-synchronized transmitters (satellites)
- Terrestrial receiver and terrestrial reference station
- Receiver computes time differences and phase differences
- Simplified uplink model

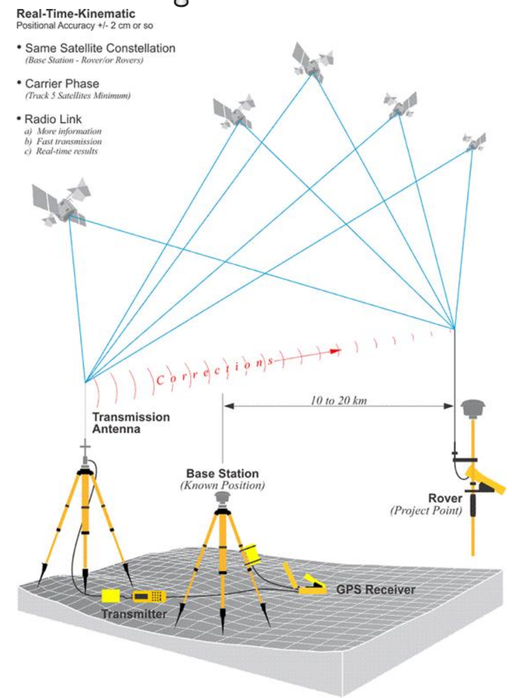
$$y_{n,m}(t) = \alpha_m e^{-\jmath 2\pi n \Delta_f \tau_m} e^{\jmath \theta_m} x_n(t) + h_{\text{NLOS},m,n} x_n(t) + w_{n,m}(t)$$
$$\tau_m = \|\boldsymbol{p}_m - \boldsymbol{p}_{\text{UE}}\|/c + B_{\text{ue}}$$
$$\theta_m = \frac{2\pi}{\lambda}\|\boldsymbol{p}_m - \boldsymbol{p}_{\text{UE}}\| + \phi_{\text{ue}}$$

- Identical to cell-free MIMO positioning!

Fan, S., Ni, W., Tian, H., Huang, Z. and Zeng, R., 2021. Carrier phase-based synchronization and high-accuracy positioning in 5G new radio cellular networks. IEEE Transactions on Communications, 70(1), pp.564-577.



https://www.e-education.psu.edu/geog862/node/1725



Embodiment #5: Distributed MIMO radar

Haimovich, A.M., Blum, R.S. and Cimini, L.J., 2007. MIMO radar with widely separated antennas. *IEEE signal processing magazine*, *25*(1), pp.116-129.

- Several Tx, several Rx
- Orthogonal Tx waveforms $s_k(t)$

$$\int_T s_k(t)s_m^*(t-\tau)dt = 0 \text{ for all } k \neq m,$$

- Q targets
- Observation at Rx *l*:

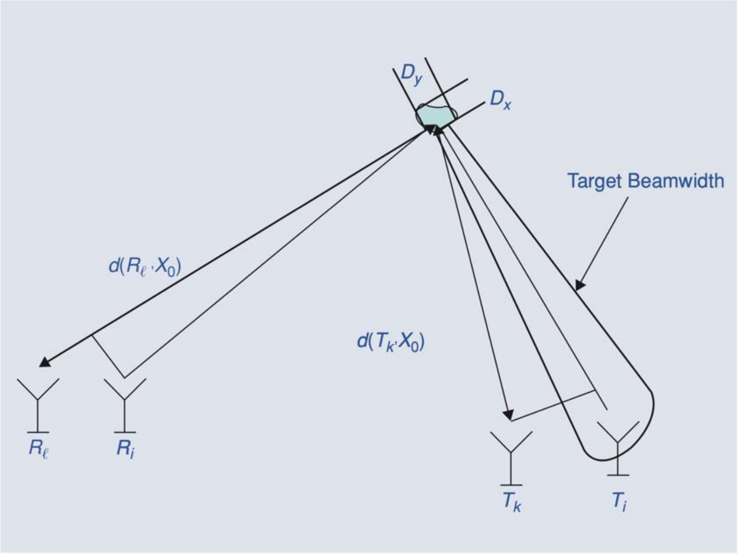
Unresolved delay

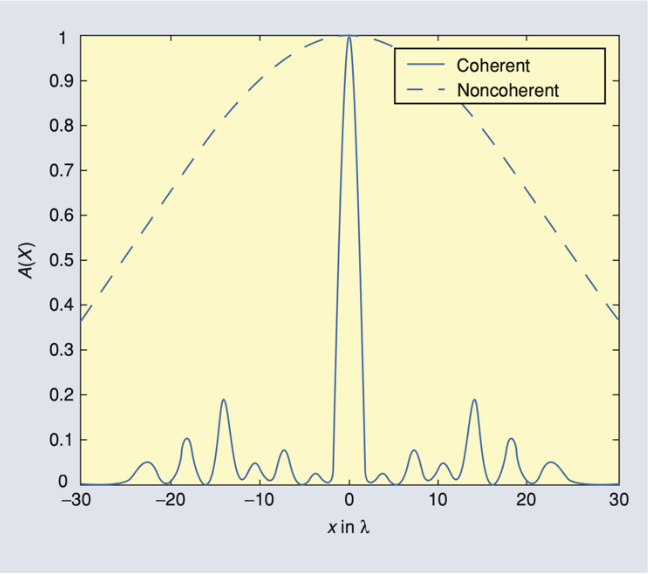
$$r_\ell(t) = \sqrt{\frac{E}{M}} \sum_{k=1}^{M} h_{\ell k} s_k(t - \tau_{tk}(X_0) - \tau_{r\ell}(X_0)) + w_\ell(t),$$

$$h_{\ell k} = \sum_{q=1}^{Q} h_{\ell k}^{(q)}.$$

$$h_{\ell k}^{(q)} = \zeta_q \exp\left(-j\, 2\pi f_c[\tau_{tk}(X_q) + \tau_{r\ell}(X_q)]\right)$$

Phase (near-field effect)

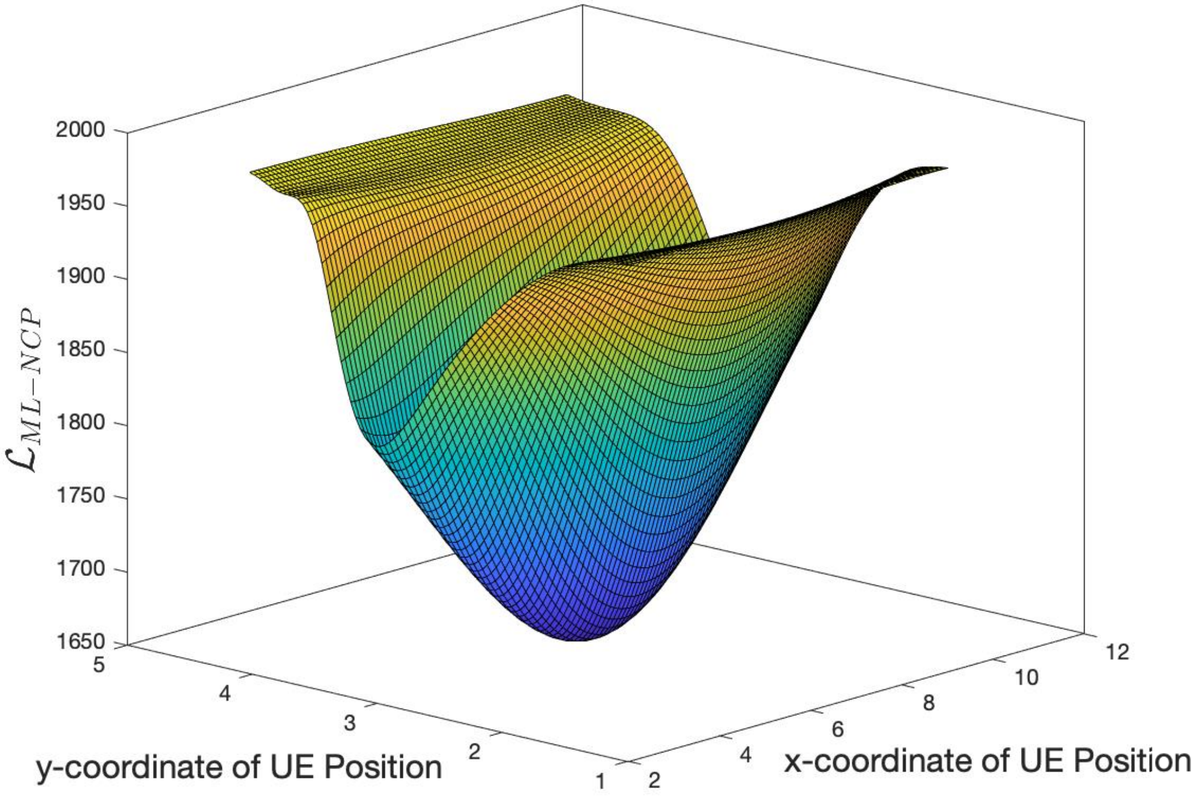




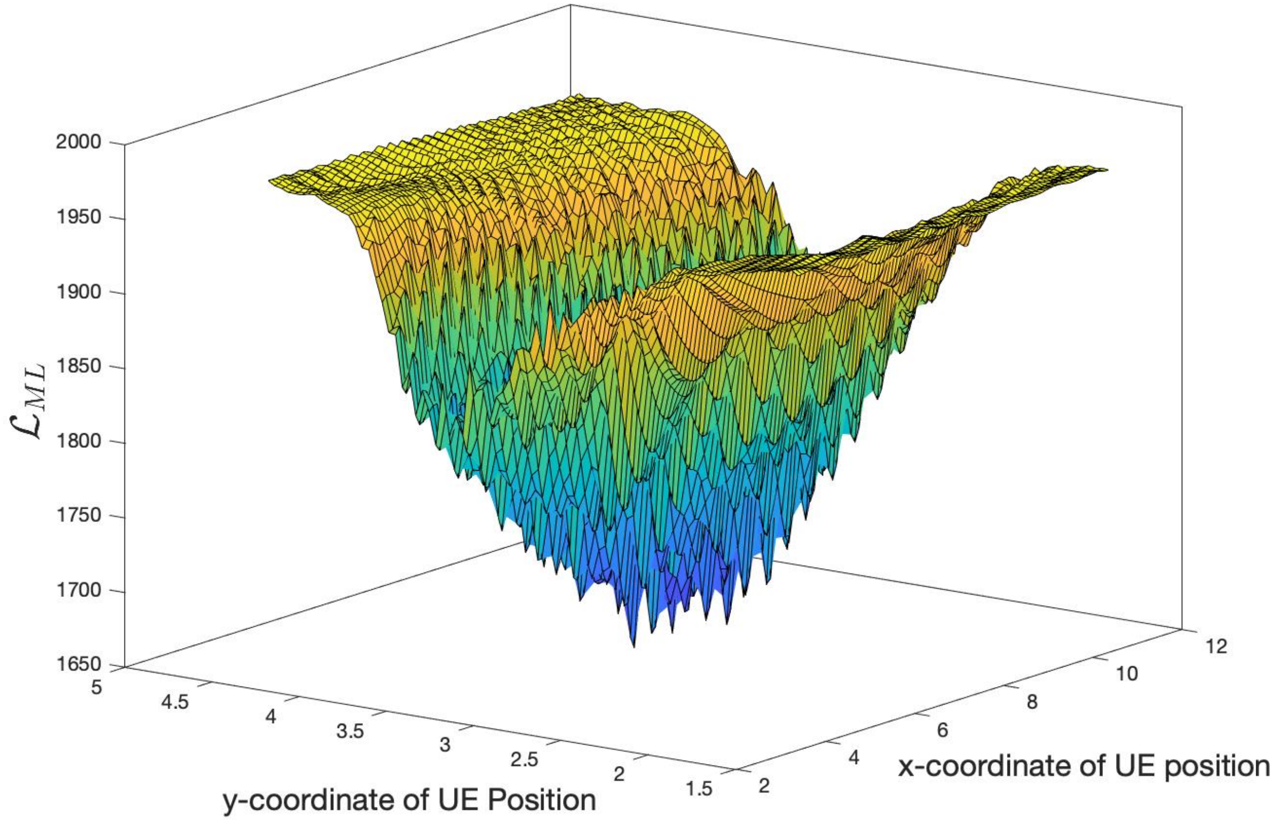
Coherent and noncoherent ambiguity functions for a 9 × 9 MIMO radar system.

A common challenge with phase-coherent DISAC

- Likelihood function



Delay and angle information per AP

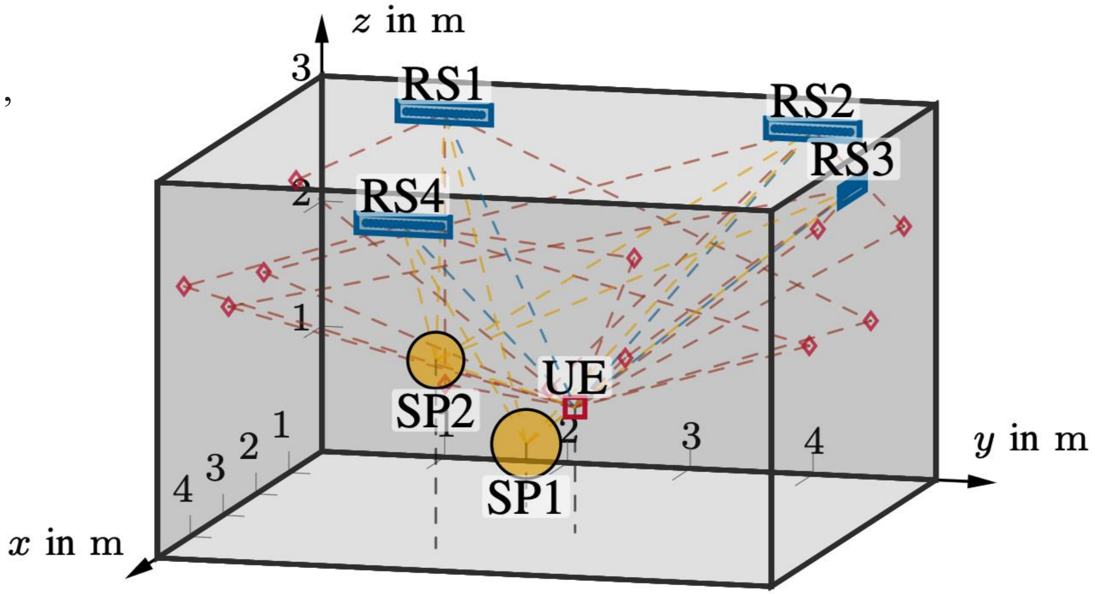


+ phase coherence among APs

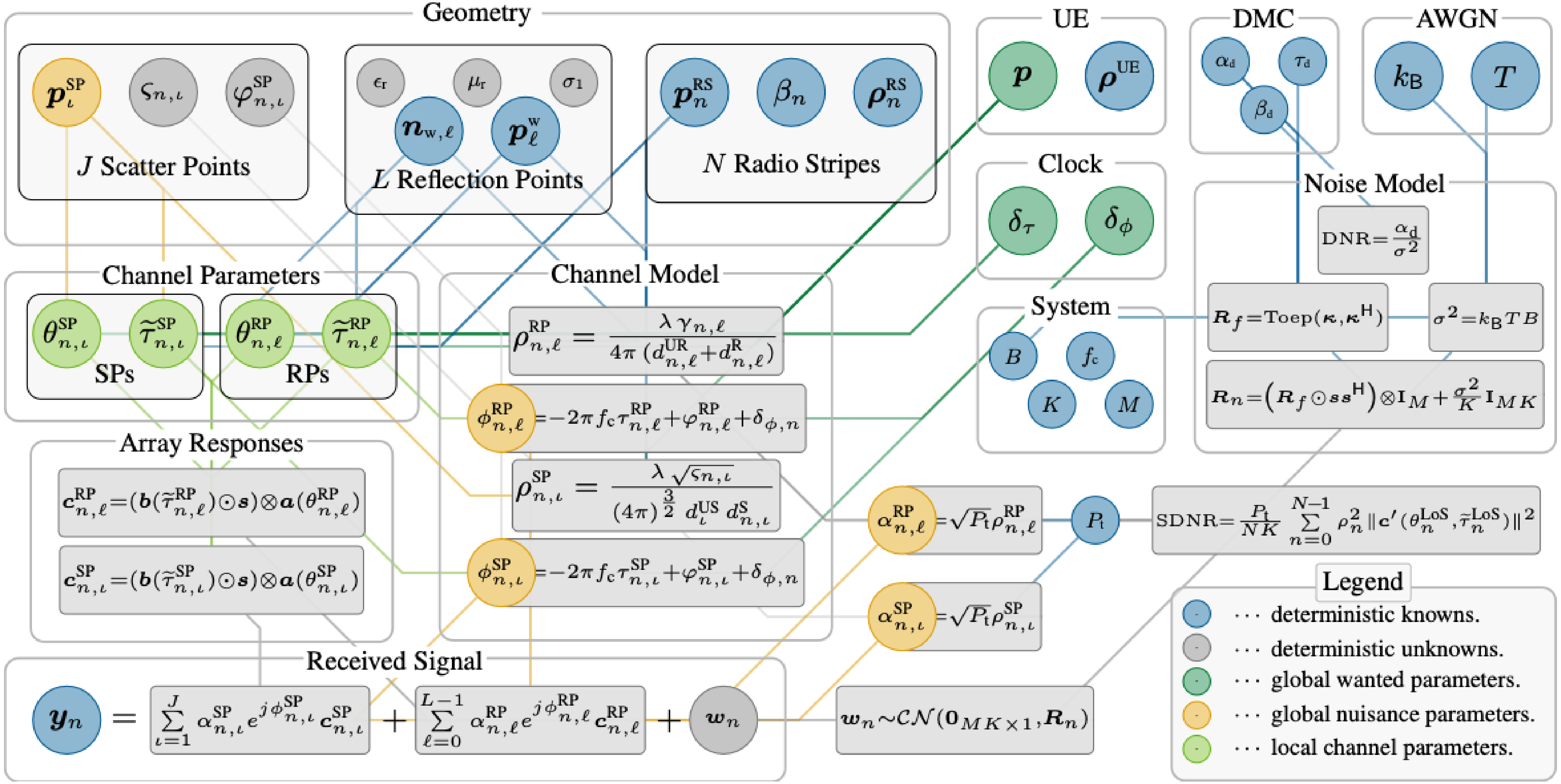
Phase-coherent DISAC

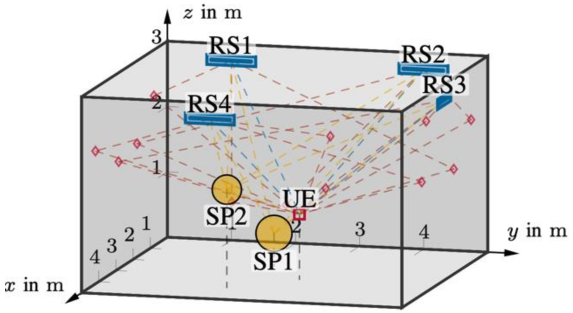
- The near-field ISAC scenarios
- Example of uplink positioning
- Example of downlink positioning

Fascista, A., Deutschmann, B.J., Keskin, M.F., Wilding, T., Coluccia, A., Witrisal, K., Leitinger, E., Seco-Granados, G. and Wymeersch, H., 2025. Joint Localization, Synchronization and Mapping via Phase-Coherent Distributed Arrays. *IEEE Journal of Selected Topics in Signal Processing*.



Model – graphical representation





Method

- Starting principle: maximum likelihood

$$\hat{\boldsymbol{\eta}}^{\mathrm{ML}} = \arg\max_{\boldsymbol{\eta}} \; p(\{\boldsymbol{Y}_n\}_{n=1}^{N} \mid \boldsymbol{\eta}),$$

$$\boldsymbol{\eta} = [\underbrace{\boldsymbol{p}^{\mathsf{T}} \; \boldsymbol{\delta}^{\mathsf{T}} \; \boldsymbol{p}^{\mathrm{SP}^{\mathsf{T}}}}_{\boldsymbol{\eta}_w} \; \underbrace{\boldsymbol{\phi}^{\mathsf{T}} \; \boldsymbol{\alpha}^{\mathsf{T}}}_{\boldsymbol{\eta}_n}]^{\mathsf{T}}$$

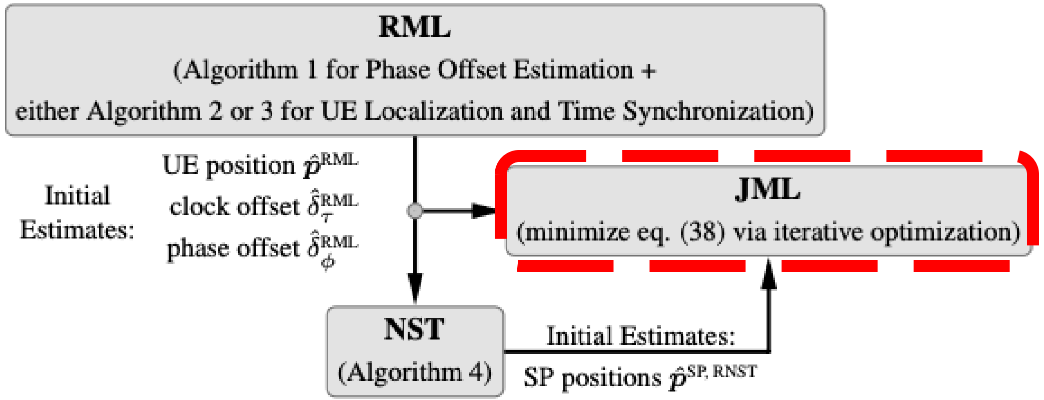
where

$$\log p(\boldsymbol{Y}_n \mid \boldsymbol{\eta}) = -\Big\| \boldsymbol{R}_n^{-1/2} \Big[\boldsymbol{y}_n - \sum_{\ell=0}^{L-1} \gamma_{n,\ell}^{\mathrm{RP}} \boldsymbol{c}(\theta_{n,\ell}^{\mathrm{RP}}, \tilde{\tau}_{n,\ell}^{\mathrm{RP}}) - \sum_{\iota=1}^{J} \gamma_{n,\iota}^{\mathrm{SP}} \boldsymbol{c}(\theta_{n,\iota}^{\mathrm{SP}}, \tilde{\tau}_{n,\iota}^{\mathrm{SP}}) \Big] \Big\|^2 - MK \log \pi - \log\det \boldsymbol{R}_n \;,$$

- Solve as many parameters a possible in closed form

$$\mathcal{L}^{\mathrm{ML}}(\boldsymbol{\eta}_w) = \sum_{n=1}^{N} \left\| \boldsymbol{y}_n' - \boldsymbol{B}_n(\boldsymbol{\eta}_w) \mathring{\boldsymbol{B}}_n^{\dagger}(\boldsymbol{\eta}_w) \mathring{\boldsymbol{y}}_n' \right\|^2$$

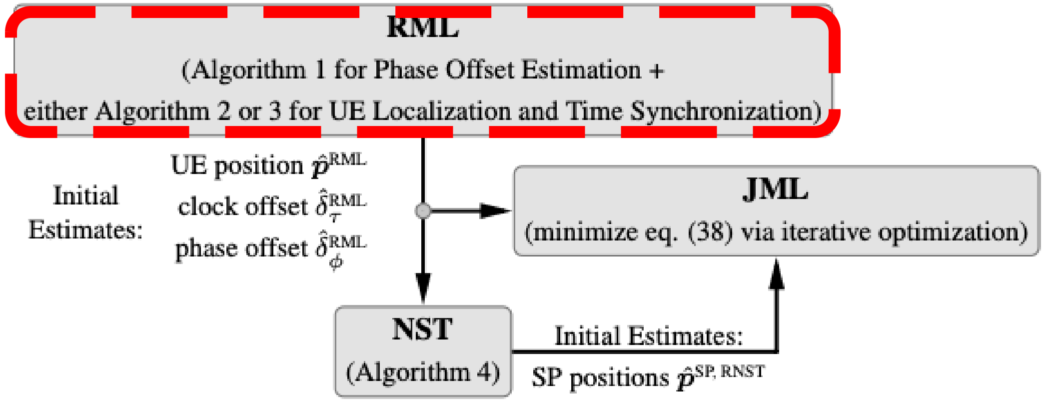
$$\boldsymbol{\eta}_w \doteq [\boldsymbol{p}^{\mathsf{T}} \; \delta_\tau \; \delta_\phi \; \boldsymbol{p}^{\mathrm{SP}^{\mathsf{T}}}]^{\mathsf{T}}$$



Method

- Principle: simplify the model: (i) ignore SPs

$$\mathcal{L}^{\text{RML}}(\bar{\eta}) = \sum_{n=1}^{N} \Big\| \boldsymbol{y}'_n - \alpha_n^{\text{LoS}} e^{j\phi_n^{\text{LoS}}} \boldsymbol{c}'(\theta_n^{\text{LoS}}, \bar{\tau}_n^{\text{LoS}}) - \sum_{\ell=1}^{L-1} \gamma_{n,\ell}^{\text{SP}} \boldsymbol{c}'(\theta_{n,\ell}^{\text{SP}}, \bar{\tau}_{n,\ell}^{\text{SP}}) \Big\|^2, \quad \bar{\eta} = [\underbrace{\boldsymbol{p}^\top \ \delta_\tau \ \delta_\phi}_{\bar{\eta}_{\text{m}}} \ \underbrace{\boldsymbol{\alpha}^{\text{SP}} \ \boldsymbol{\phi}^{\text{SP}}}_{\bar{\eta}_{\text{n}}}]^\top$$



- (ii) ignore coherence, then channel gains can be estimated in closed form, conditional on position and clock offset

$$\mathcal{L}^{\text{RML-NCP}}(\bar{\eta}_{\text{m}}) = \sum_{n=1}^{N} \left\| \boldsymbol{y}'_n - \boldsymbol{C}'_n(\boldsymbol{p}, \delta_\tau)\boldsymbol{\gamma}_n \right\|^2,$$

$$\hat{\boldsymbol{\gamma}}_n(\boldsymbol{p}, \delta_\tau) = \left(\boldsymbol{C}'_n(\boldsymbol{p}, \delta_\tau)\right)^\dagger \boldsymbol{y}'_n$$

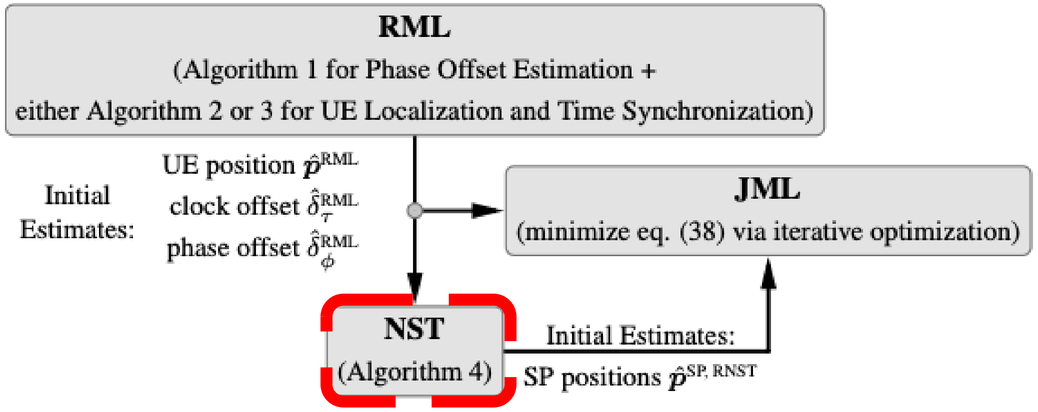
- (iii) estimate ToA at each RS, and compute clock bias conditional on UE position

$$\hat{\delta}_{\tau,n}(\boldsymbol{p}) = \hat{\bar{\tau}}_n - \frac{1}{c}\|\boldsymbol{p} - \boldsymbol{p}_n^{\text{RS}}\|$$

- Search over UE position

$$\hat{\boldsymbol{p}}^{\text{RML}} = \arg\min_{\boldsymbol{p}} \ \mathcal{L}^{\text{RML}}(\boldsymbol{p}, \hat{\delta}_\tau(\boldsymbol{p})),$$

Method



- Mapping of SP locations, given UE location
- Null-space transformation

Received Signal

$$\boldsymbol{y}_n = \sum_{\iota=1}^{J} \alpha_{n,\iota}^{\mathrm{SP}} e^{j\phi_{n,\iota}^{\mathrm{SP}}} \boldsymbol{c}_{n,\iota}^{\mathrm{SP}} + \sum_{\ell=0}^{L-1} \alpha_{n,\ell}^{\mathrm{RP}} e^{j\phi_{n,\ell}^{\mathrm{RP}}} \boldsymbol{c}_{n,\ell}^{\mathrm{RP}} + \boldsymbol{w}_n$$

- LOS and RPs paths are now known, so we can reconstruct the steering vectors **c.**
- Determine the null space

$$\boldsymbol{K}_n = \mathrm{null}(\boldsymbol{C}_n^{\prime\mathsf{H}}(\hat{\boldsymbol{p}}^{\mathrm{RML}}, \hat{\delta}_{\tau}^{\mathrm{RML}})) \in \mathbb{C}^{MK \times MK-L},$$

- Remove LOS and RP paths

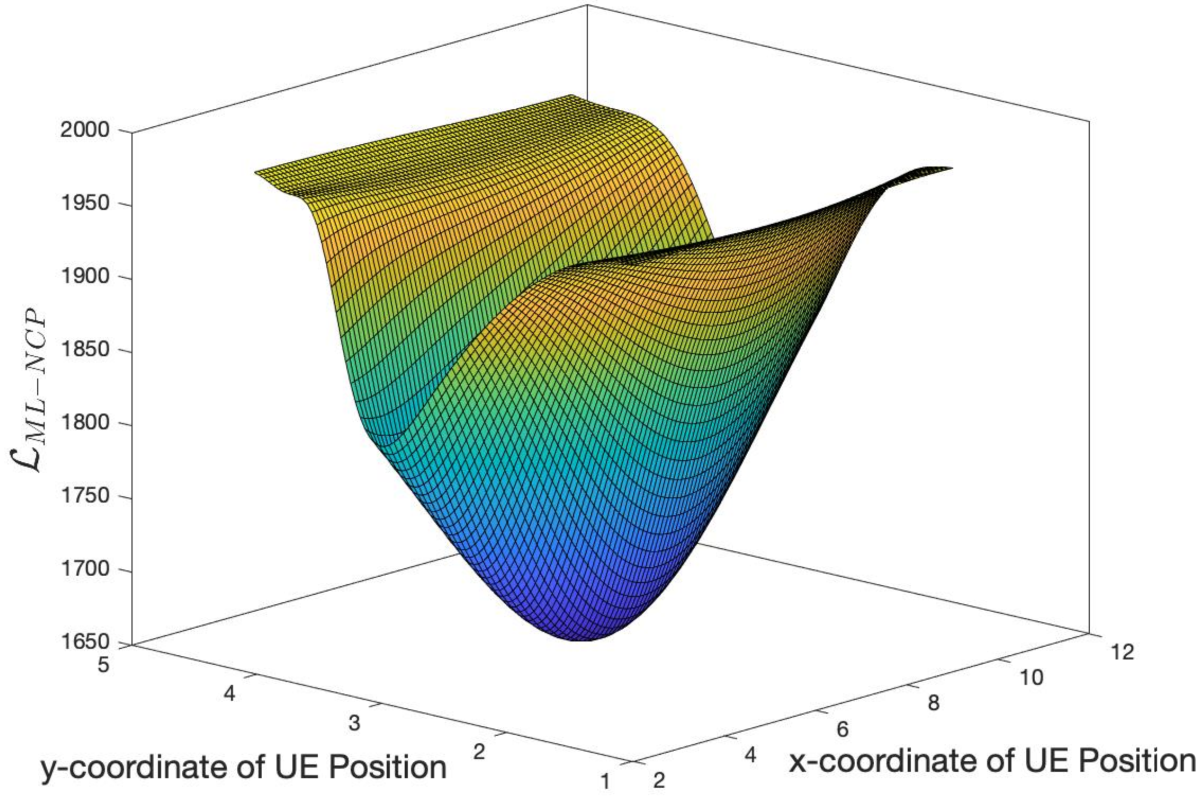
$$\boldsymbol{\zeta}_n = \boldsymbol{K}_n^{\mathsf{H}} \boldsymbol{y}_n^{\prime},$$

$$\boldsymbol{\zeta}_n = \sum_{\ell=0}^{L-1} \gamma_{n,\ell}^{\mathrm{RP}} \underbrace{\boldsymbol{K}_n^{\mathsf{H}} \boldsymbol{c}^{\prime}(\boldsymbol{\theta}_{n,\ell}^{\mathrm{RP}}, \bar{\tau}_{n,\ell}^{\mathrm{RP}})}_{\approx 0} + \sum_{\iota=1}^{J} \gamma_{n,\iota}^{\mathrm{SP}} \boldsymbol{K}_n^{\mathsf{H}} \boldsymbol{c}^{\prime}(\boldsymbol{\theta}_{n,\iota}^{\mathrm{SP}}, \bar{\tau}_{n,\iota}^{\mathrm{SP}}) + \boldsymbol{v}_n,$$

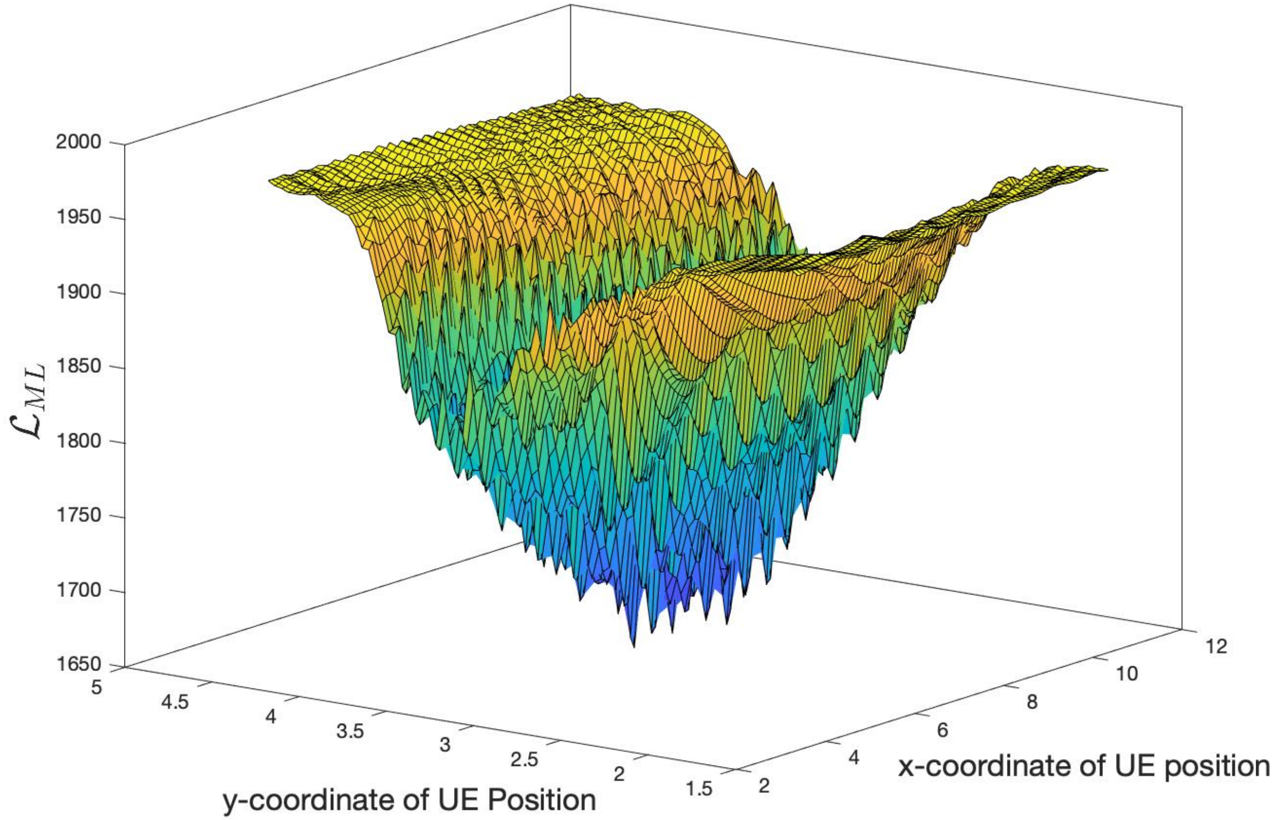
- Construct 1 SP cost function and look for peaks (3D search)

Uplink positioning with cell-free MIMO / radio stripes

- Likelihood function



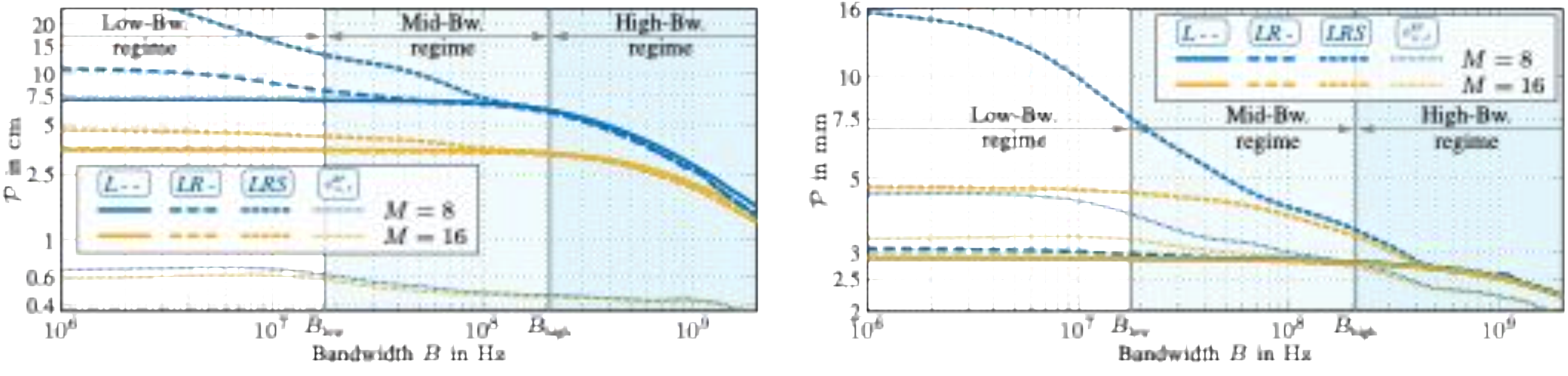
Delay and angle information per AP



+ phase coherence among APs

Performance examples: bounds, 3.5 GHz

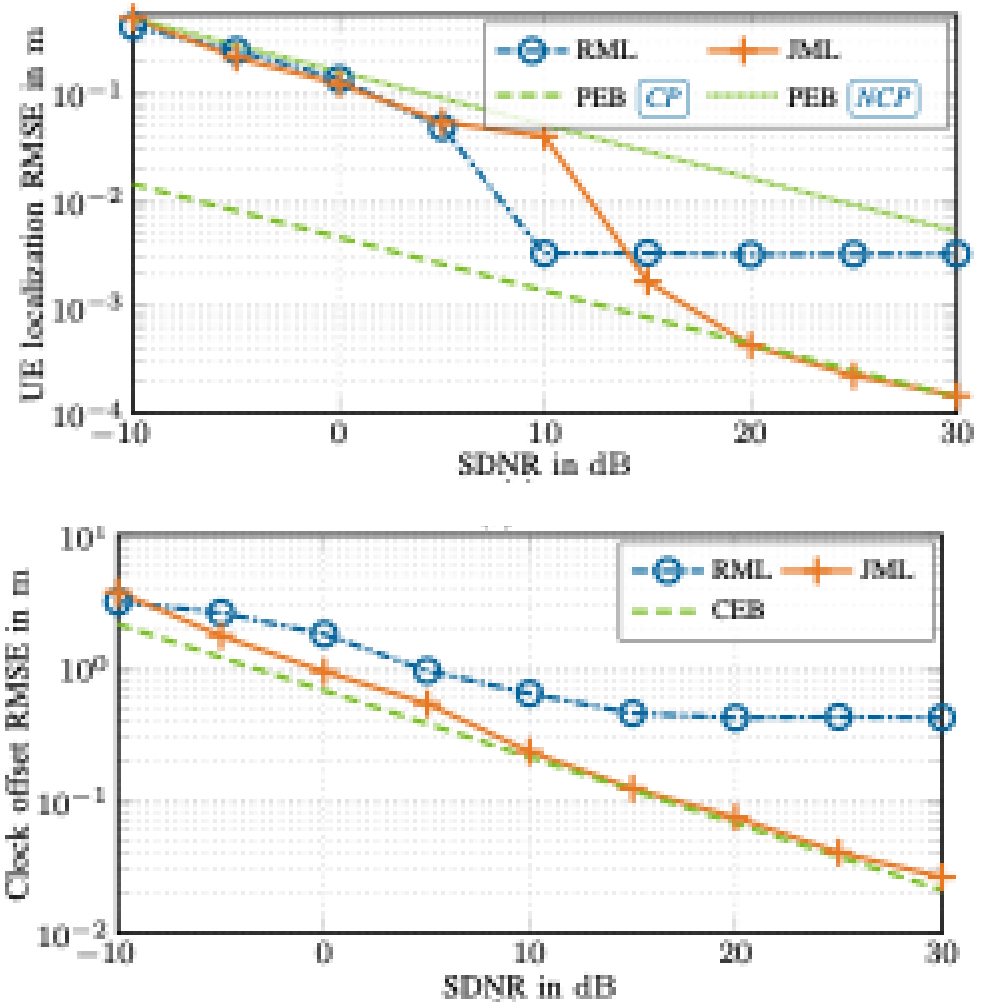
- Vary bandwidth and number of antennas
- L: LOS, R: reflections: S: scatter point

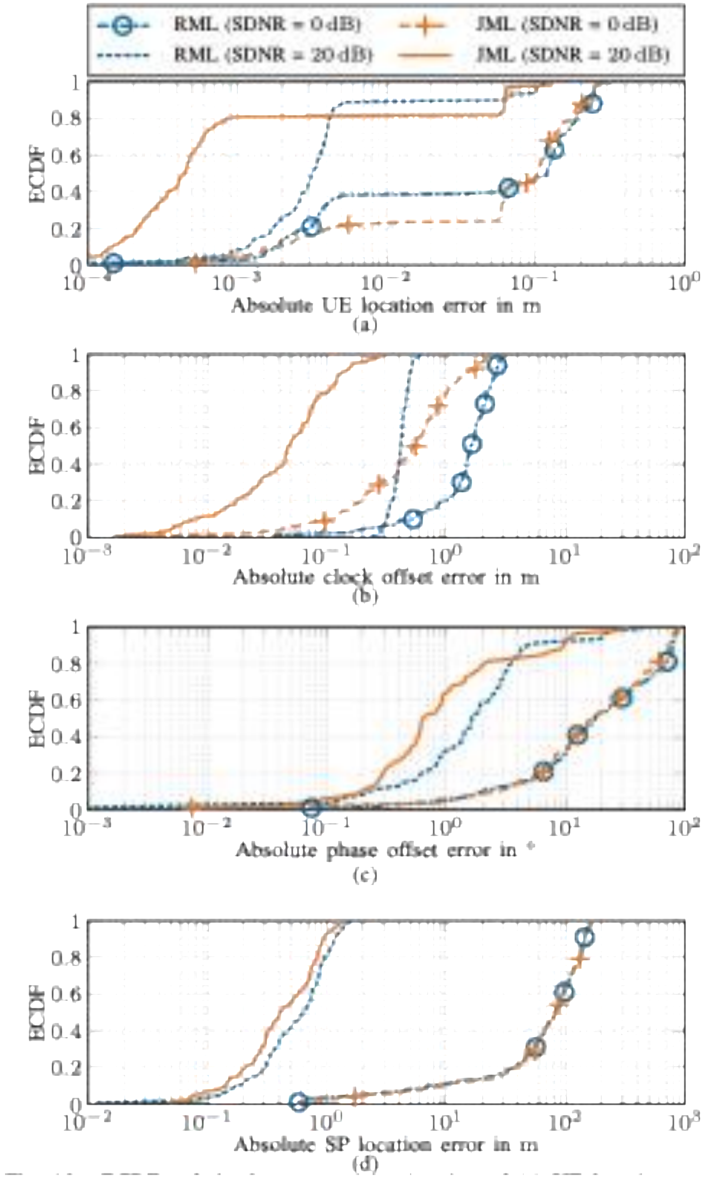


(a) NCP

(b) CP

Performance example estimators





Phase-coherent DISAC

- The near-field ISAC scenarios
- Example of uplink positioning
- Example of downlink positioning

Sauradeep Dey, Musa Furkan Keskin, Dario Tagliaferri, Gonzalo Seco-Granados, Henk Wymeersch, “Joint Localization and Synchronization in Downlink Distributed MIMO”, EUSIPCO 2025.

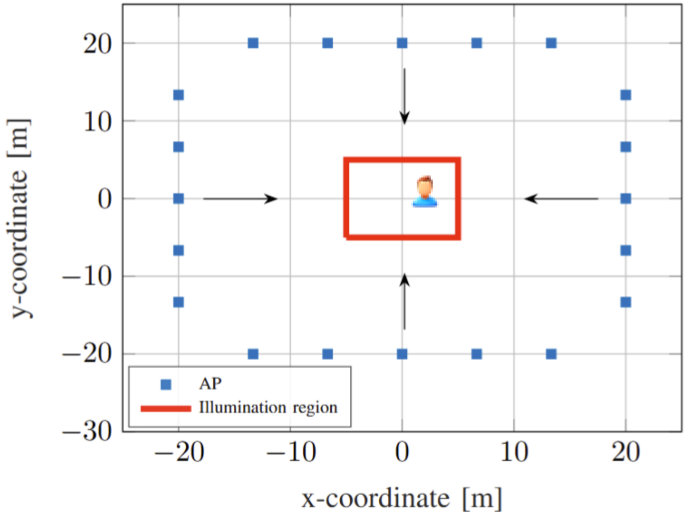
Model

- **Downlink Distributed MIMO System**
- **System Setup:**
  - M APs, each with N antennas
  - Single-antenna UE, at an unknown position in the uncertainty region
  - APs are synchronized, but UE has a phase offset with the network
  - Channel between the AP and UE

$$\mathbf{h}_m = \alpha_m e^{j\delta_s} e^{-j2\pi f_0 \tau_m} \mathbf{a}(\theta_m) \triangleq \alpha_m e^{j\phi_m} \mathbf{a}(\theta_m).$$

- **Signal Transmission:**
  - APs focus signals on K illumination points over time T
  - Single carrier transmission
- **Problem Statement**
  - To estimate the UE position and phase offset under 2 protocols

$$y_m[k] = \sqrt{P_m}\,\mathbf{h}_m^{\top}\mathbf{f}_m[k]s_m[k] + n_m[k], \quad y[k] = \sum_{m=1}^{M} \sqrt{P_m}\,\mathbf{h}_m^{\top}\mathbf{f}_m[k]s_m[k] + n[k],$$



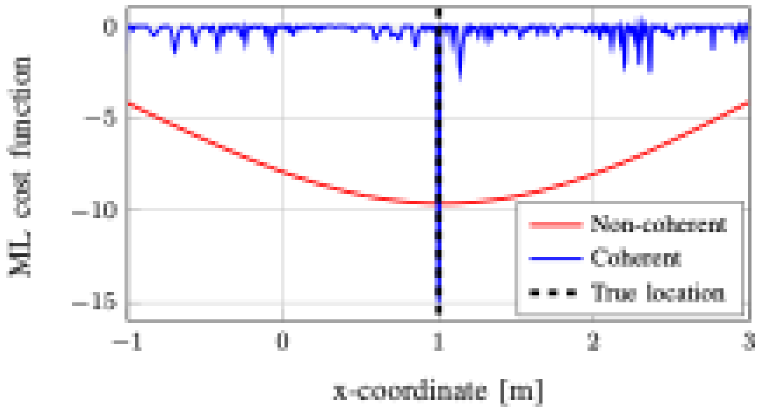
Method: maximum likelihood with grid search

- For each protocol
  - Coherent estimator – P1

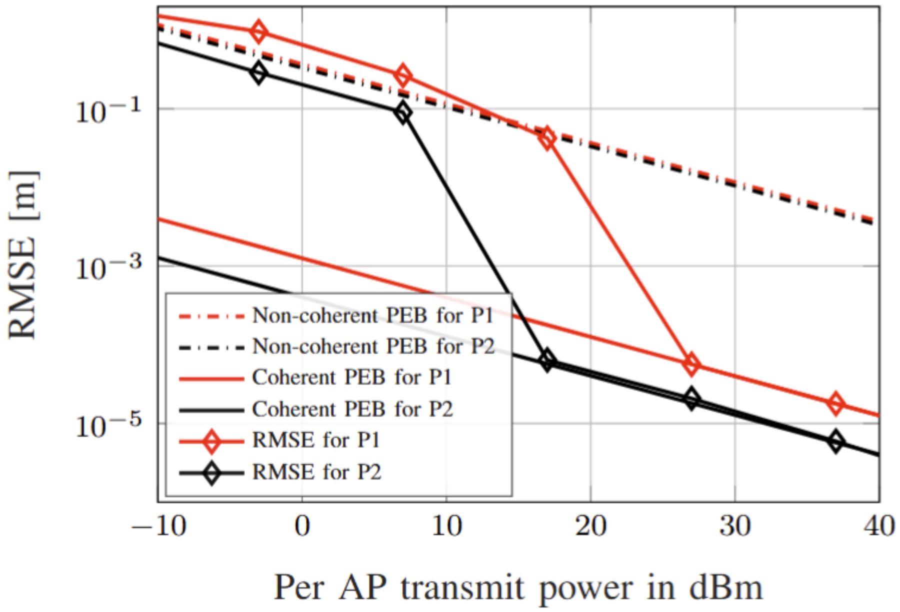
$$\hat{\eta} = \arg\min_{\eta} \sum_{m=1}^{M} \sum_{k \in \mathcal{T}_m} |y[k] - e^{j\delta_\phi} \alpha_m x_m[k]|^2.$$

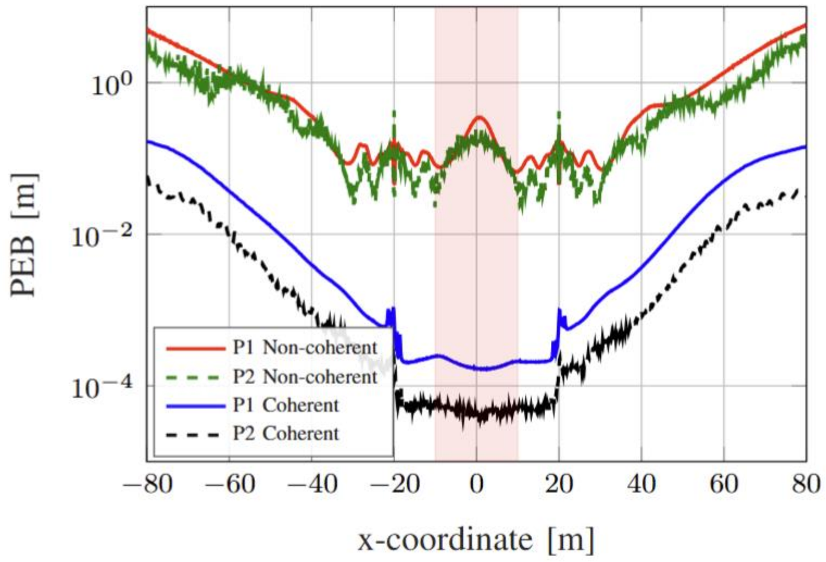
  - Non-coherent estimator – P1

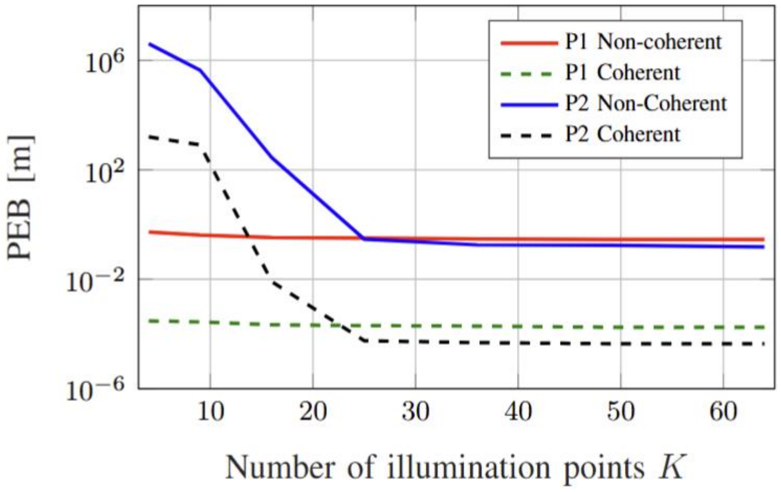
$$[\hat{\mathbf{u}}, \hat{\boldsymbol{\beta}}] = \arg\min_{\{\mathbf{u},\boldsymbol{\beta}\}} \sum_{m=1}^{M} \sum_{k \in \mathcal{T}_m} |y[k] - \beta_m z_m[k]|^2.$$



Performance examples at 3.5 GHz

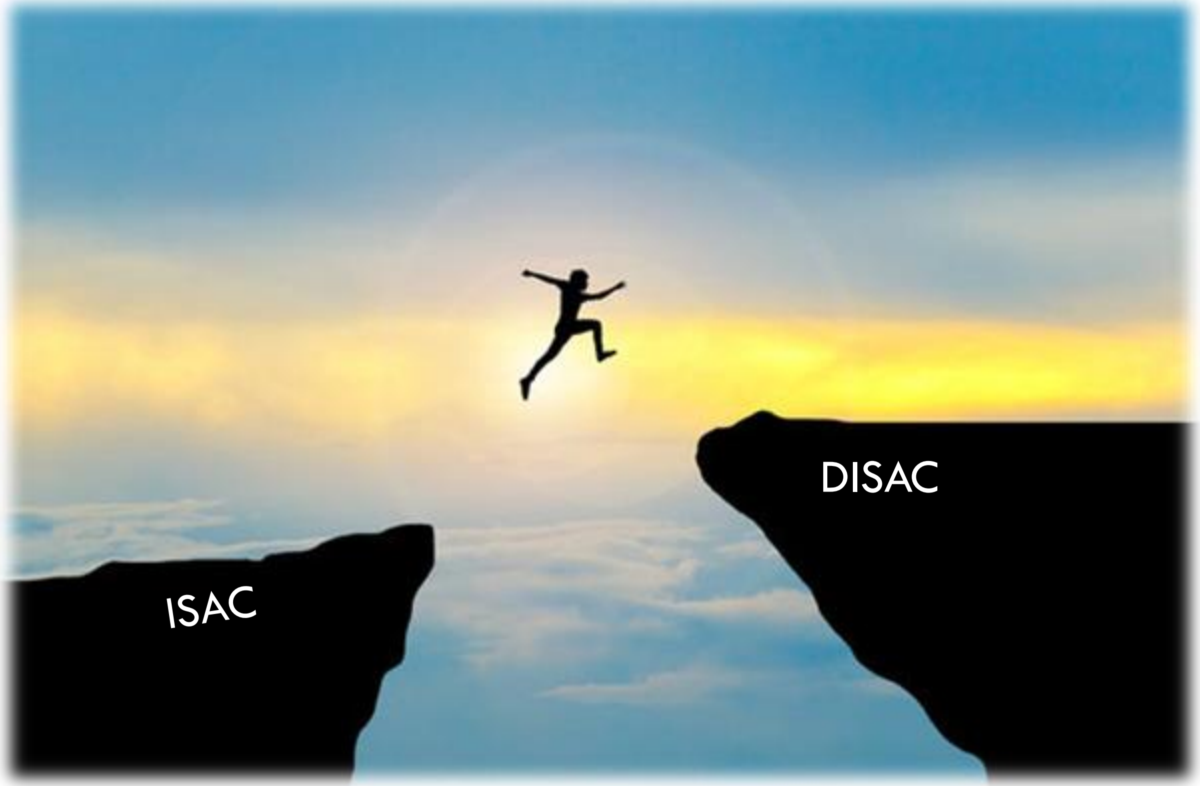






Conclusions

- Localization always considered distributed deployments. Some sensing systems as well.
- ISAC in distributed systems is new territory that must be explored to make ISAC a reality.
- Synchronization, interference, and overheads are major challenges.



Outline

- Part I: Fundamentals of DISAC operations and systems (Presenter: Henk Wymeersch, 60 mins)
- Part II: Distributed Communication-Aided Sensing (Presenter: Hui Chen, 60 mins)
- Part III: Distributed Sensing-Aided Communications (Presenter: George C. Alexandropoulos, 60 mins)