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

Part II: Distributed Communication-Aided Sensing

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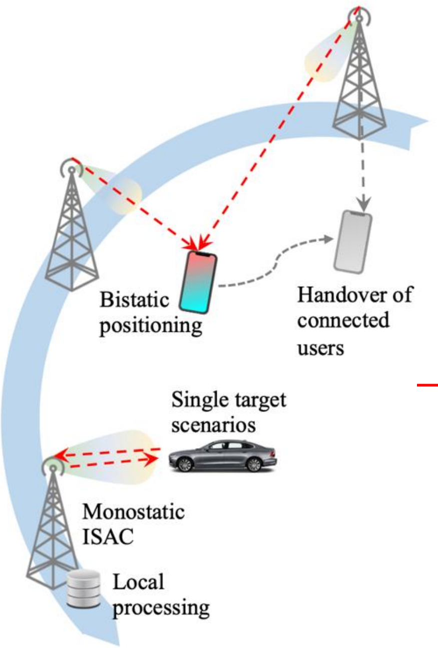
Outline

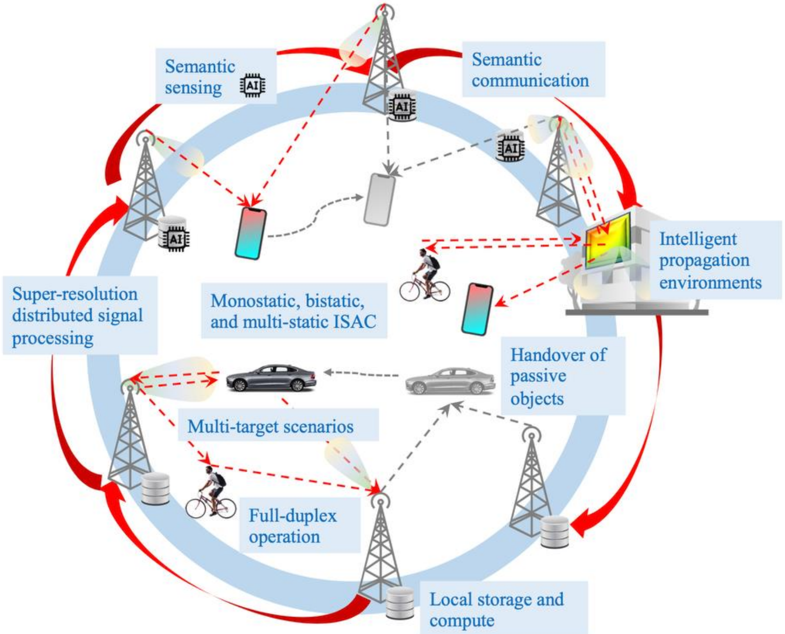
- Part I: Fundamentals of DISAC operations and systems (Presenter: Henk Wymeersch, 60 mins)
- Part II: Distributed Communication-Aided Sensing (Presenter: Hui Chen, 60 mins)
- Part III: Distributed Sensing-Aided Communications (Presenter: George C. Alexandropoulos, 60 mins)

Part II: Distributed Communication-Aided Sensing

- Distributed Sensing System
- Sensing Scenarios and Algorithms
- Coordination and Optimization in Sensing
- Sensing Anchor Calibration
- Security Aspects



From ISAC to DISAC



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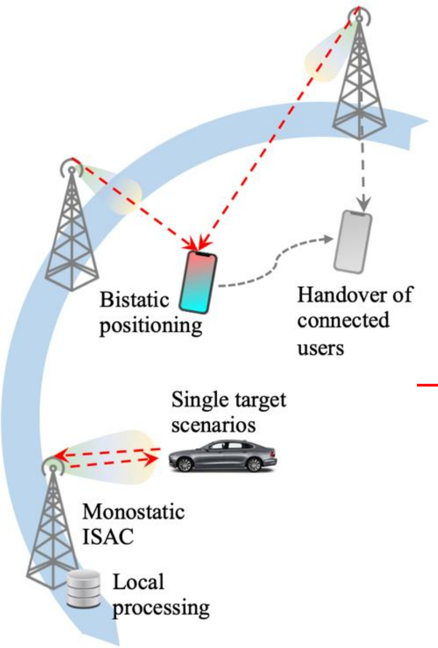
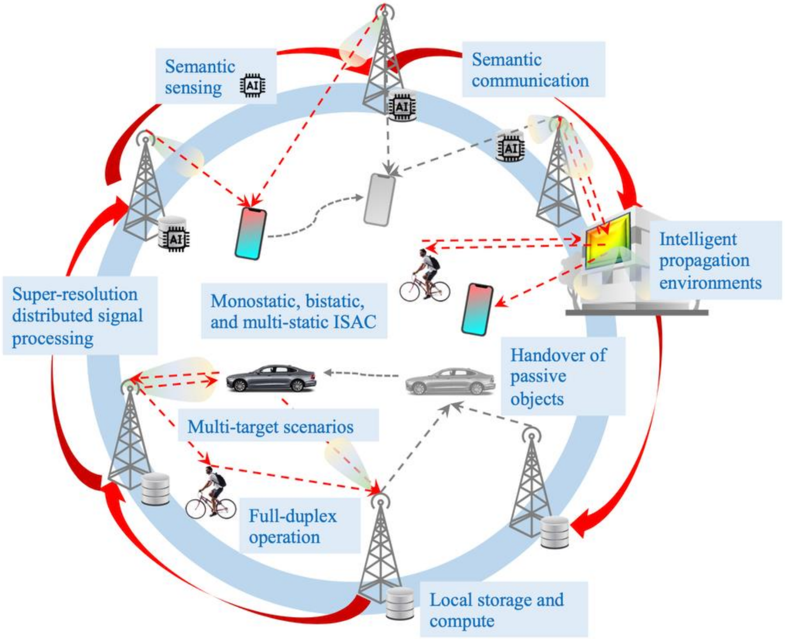
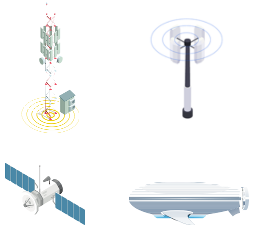


From ISAC to DISAC

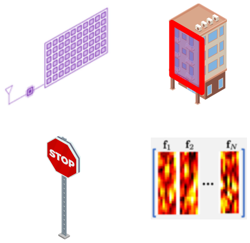


Components in DISAC Systems

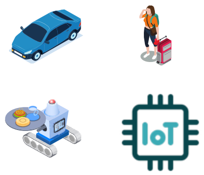
Access Points (Active Anchors):
- BS (with/without radar function)
- Roadside unit (light-weight)
- NTN APs (e.g., LEO, HAPEs)



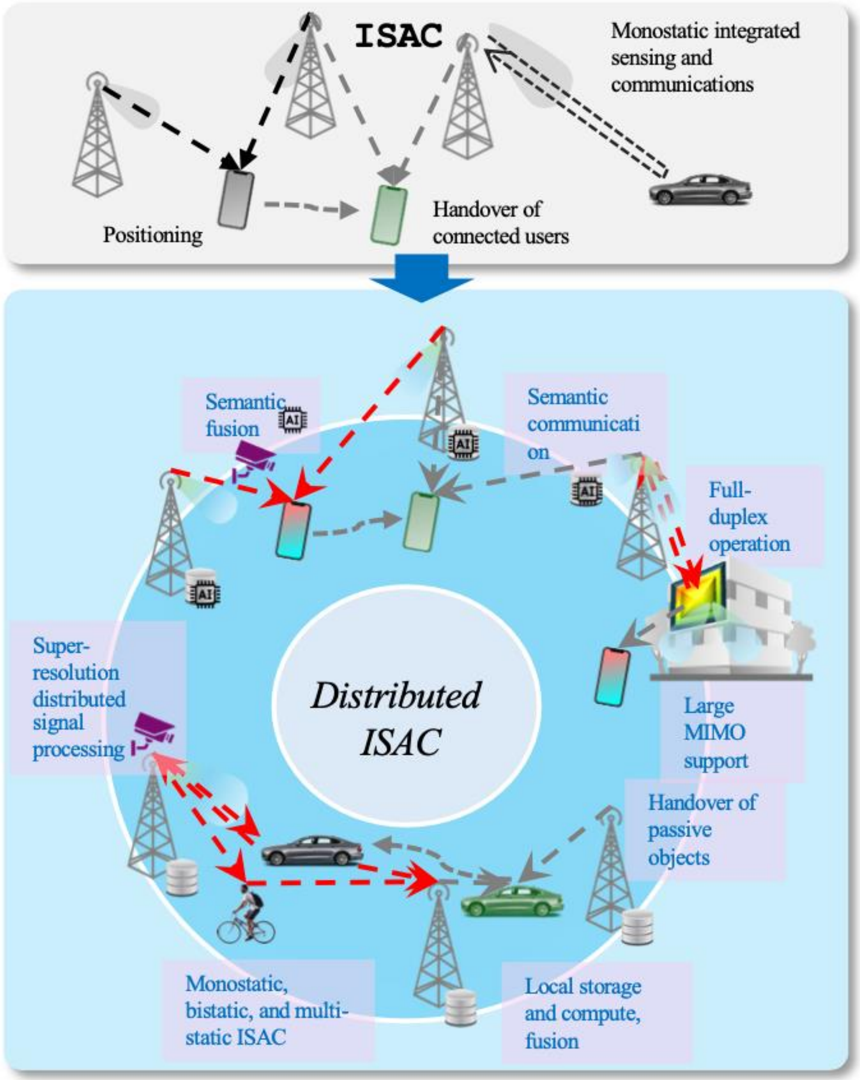
Landmarks (Passive Anchors):
- RIS (passive or low-cost)
- Reflective surfaces
- Scattering points
- Fingerprints



Connected Users (Target/Assisting anchor):
- Vehicular users (mobile)
- Vulnerable users (limited capability)
- Factory robots (cooperation and control)
- IoT devices (low-cost)



DISAC systems will deal with heterogeneous devices!



Strinati, Emilio Calvanese, George C. Alexandropoulos, Navid Amani, Maurizio Crozzoli, Giyyarpuram Madhusudan, Sami Mekki, Francois Rivet et al. "Toward Distributed and Intelligent Integrated Sensing and Communications for 6G Networks." *IEEE Wireless Communications* 32, no. 1 (2025): 60-67.

System: High-frequency vs. Low-frequency

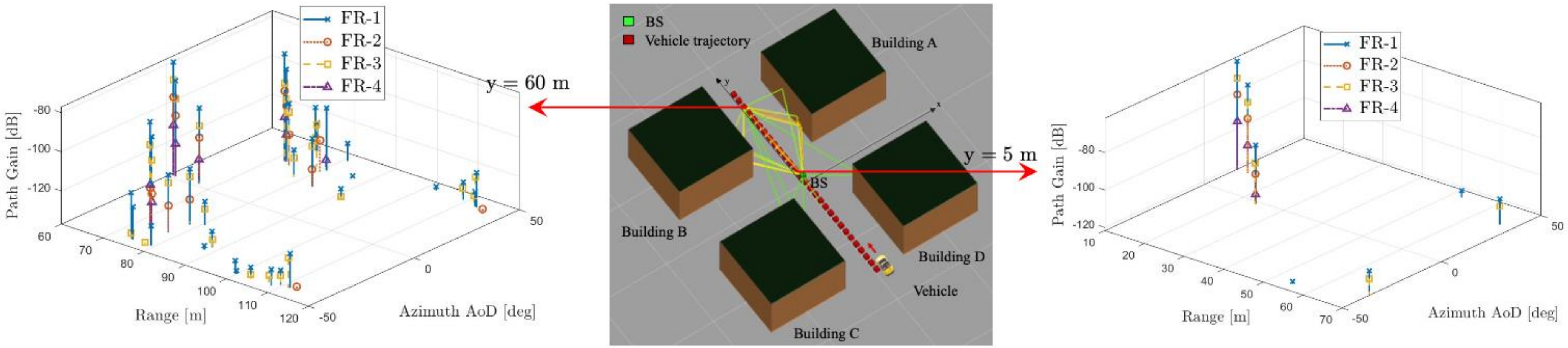
No good or bad signals, just suitable band

5G/6G Frequency Band [1]:

- FR1 (410 MHz – 7.125 GHz) → Low
- FR2 (24 – 75 GHz) → High
- FR3 (7-15 GHz) → Medium
- FR4 (100– 300 GHz) → High

↑ Phase synchronization
Better coverage
Digital arrays

↓ Angular resolution (aperture)
Delay resolution (bandwidth)
Deterministic channel



Visualization of signal paths for different frequency band (FR1-FR4)

[1] 3GPP, "Feasibility study on integrated sensing and communication (Release 19)," Tech. Rep. 22.837, V19.4.0, June 2024.

Uncontrollable Channels: ‘High frequency’

- 3D, analog, MIMO system
- 28 GHz
- K subcarriers, G transmissions

Received symbol: $y_{g,k} = \mathbf{w}_g^\top \mathbf{H}_k \mathbf{v}_g x_{g,k} + n_{g,k}$

$$\mathbf{H}_k = \underbrace{\alpha d_k(\tau)\mathbf{a}_\mathrm{R}(\boldsymbol{\varphi}_\mathrm{R})\mathbf{a}_\mathrm{T}^\top(\boldsymbol{\varphi}_\mathrm{T})}_{\text{LOS path}} + \underbrace{\sum_{p=1}^{P} \alpha_p d_{p,k}(\tau_p)\mathbf{a}_\mathrm{R}(\boldsymbol{\varphi}_{\mathrm{R},p})\mathbf{a}_\mathrm{T}^\top(\boldsymbol{\varphi}_{\mathrm{T},p})}_{\text{NLOS paths}},$$

LOS Channel: $\mathbf{H}_k = \alpha d_k(\tau)\mathbf{a}_\mathrm{R}(\boldsymbol{\varphi}_\mathrm{R})\mathbf{a}_\mathrm{T}^\top(\boldsymbol{\varphi}_\mathrm{T})$

Steering vector at Tx (Angle of Departure)

Steering vector at Rx (Angle of Arrival)

Phase change across subcarriers (Delay)

Complex channel gain (nuisance unknown)

3xN Antenna Position Matrix

$$\mathbf{a}(\boldsymbol{\varphi}) = e^{j\frac{2\pi f_c}{c}\mathbf{Z}^\top \mathbf{t}(\boldsymbol{\varphi})}$$

$$d_k(\tau) = e^{-j2\pi k \Delta_f \tau}$$

$$\alpha = \rho e^{-j\xi}$$

Direction Vector

Subcarrier Spacing

* In low-frequency communication systems, H_k is modeled as i.i.d. Gaussian for analysis

Uncontrollable Channels: ‘Low frequency’

- 3D, digital, SIMO system
- 3.5 GHz
- K subcarriers, N antennas

Received symbol:

$$\boldsymbol{y}_{n,k} = \boldsymbol{h}_{n,k} s_k \sqrt{P_\mathrm{t}} + \boldsymbol{w}^{\mathrm{DMC}}_{n,k} s_k + \boldsymbol{z}_{n,k} \quad \in \mathbb{C}^{M\times 1}$$

$$\boldsymbol{h}_{n,k} = \sum_{\kappa=0}^{N_\mathrm{c}-1} \rho_{n,\kappa} e^{j\phi_{n,\kappa}} \boldsymbol{a}(\theta_{n,\kappa}) e^{-j2\pi k \Delta_f \tilde{\tau}_{n,\kappa}}$$

1. No AOD (single antenna UE)

~~Steering vector at Tx (Angle of Departure)~~

Phase change across subcarriers (Delay)

Steering vector at Rx (Angle of Arrival)

Complex channel gain (time and phase sync)

$$\phi_{n,\kappa} = -2\pi f_\mathrm{c} \tau_{n,\kappa} + \varphi_{n,\kappa} + \delta_{\phi,n}$$

Reflection-induced phase-shift

Radio strip phase-offset

2. Phase-coherent ($\delta_{\phi,n} = \delta_\phi$)

$$\boldsymbol{w}^{\mathrm{DMC}}_{n} \sim \mathcal{CN}_{MK}(\boldsymbol{0}, \boldsymbol{R}^{\mathrm{DMC}}(\boldsymbol{\eta}_{\mathrm{DMC}}))$$

Stochastic component

Fascista, Alessio, Benjamin JB Deutschmann, Musa Furkan Keskin, Thomas Wilding, Angelo Coluccia, Klaus Witrisal, Erik Leitinger, Gonzalo Seco-Granados, and Henk Wymeersch. "Joint Localization, Synchronization and Mapping via Phase-Coherent Distributed Arrays." IEEE Journal of Selected Topics in Signal Processing (2025).

Controllable Channels: RIS Channel Model

$$\mathbf{y}^{\text{Passive}}_{\text{B},g,k} = \mathbf{W}_{\text{B}}^{\top}(\underbrace{\mathbf{h}_{\text{L},k}x_k}_{\text{LoS path}} + \underbrace{\mathbf{H}_{\text{R2},k}\boldsymbol{\Omega}_{\text{P},g}\mathbf{h}_{\text{R1},k}x_k}_{\text{RIS path}} + \mathbf{n}_{g,k}).$$

Far-field Channel model (familiar, right? :)

$$\mathbf{H}_k = \underbrace{\alpha d_k(\tau)\mathbf{a}_{\text{R}}(\boldsymbol{\varphi}_{\text{R}})\mathbf{a}_{\text{T}}^{\top}(\boldsymbol{\varphi}_{\text{T}})}_{\text{LOS path}} + \underbrace{\sum_{p=1}^{P} \alpha_p d_{p,k}(\tau_p)\mathbf{a}_{\text{R}}(\boldsymbol{\varphi}_{\text{R},p})\mathbf{a}_{\text{T}}^{\top}(\boldsymbol{\varphi}_{\text{T},p})}_{\text{NLOS paths}},$$

$$\mathbf{H}_k = \alpha d_k(\tau)\mathbf{a}_{\text{R}}(\boldsymbol{\varphi}_{\text{R}})\mathbf{a}_{\text{T}}^{\top}(\boldsymbol{\varphi}_{\text{T}})$$

Steering vector at Tx (Angle of Departure)

Steering vector at Rx (Angle of Arrival)

Phase change across subcarriers (Delay)

Complex channel gain (nuisance unknown)

$$\mathbf{a}(\boldsymbol{\varphi}) = e^{j\frac{2\pi f_c}{c}\mathbf{Z}^{\top}\mathbf{t}(\boldsymbol{\varphi})}$$

3xN Antenna Position Matrix ($\mathbf{Z}$)

Direction Vector ($\mathbf{t}(\boldsymbol{\varphi})$)

$$d_k(\tau) = e^{-j2\pi k\Delta_f\tau}$$

Subcarrier Spacing (Δ_f)

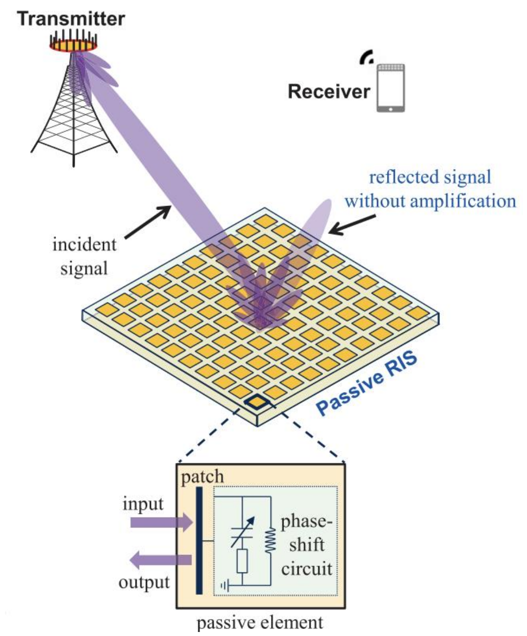
$$\alpha = \rho e^{-j\xi}$$

Equivalent array gain with RIS profile $\boldsymbol{\Omega}$:

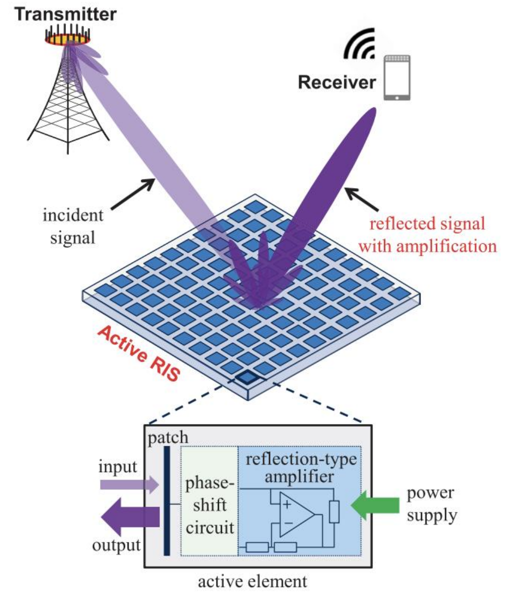
- For a fixed RIS profile, we can characterize that path with a complex number.
- Only for diagonal RIS profile

$$\mathcal{A}_g(\boldsymbol{\theta}_{\text{RB}}, \boldsymbol{\theta}_{\text{RU}}) = \mathbf{a}_{\text{R}}(\boldsymbol{\theta}_{\text{RB}})^{\top}\boldsymbol{\Omega}_g\mathbf{a}_{\text{R}}(\boldsymbol{\theta}_{\text{RU}}) = \boldsymbol{\omega}_g^{\top}(\mathbf{a}_{\text{R}}(\boldsymbol{\theta}_{\text{RB}}) \odot \mathbf{a}_{\text{R}}(\boldsymbol{\theta}_{\text{RU}})).$$

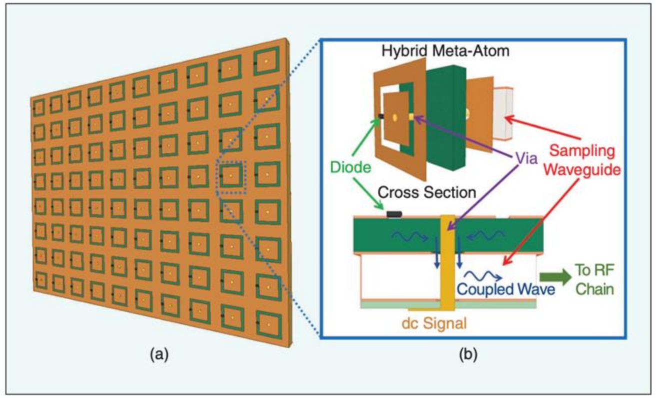
Different RIS Structures



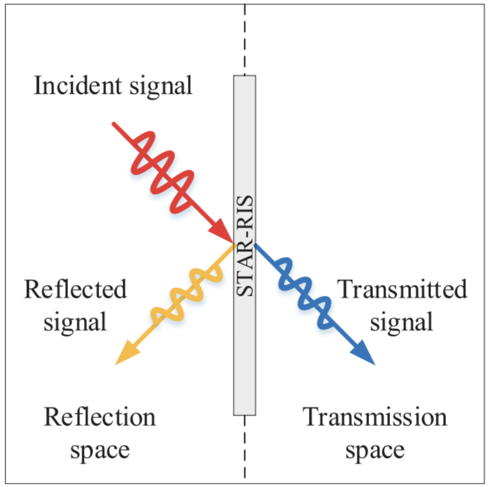
Passive RIS
(only reflecting)



Active RIS
(amplified reflection
with added noise)



Hybrid RIS
(extra processing unit)



STAR RIS
(simultaneously
transmitting and
reflecting)

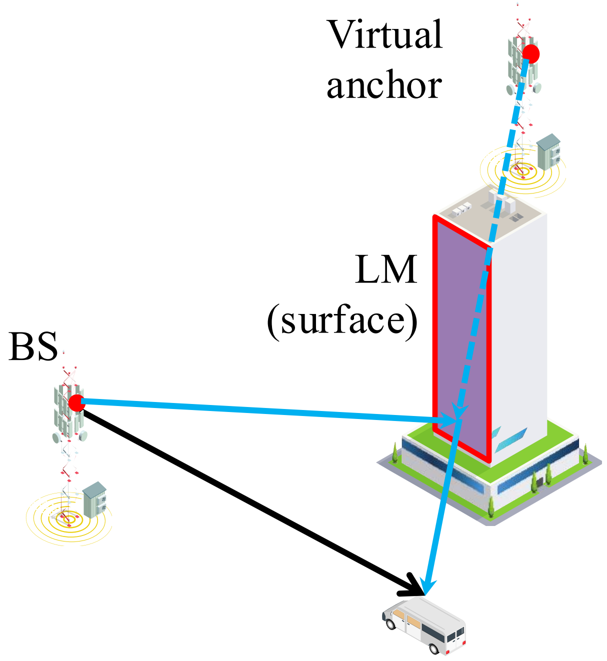
More recent beyond diagonal RIS, stacked intelligent meta-surfaces (SIM)

Zhang, Zijian,et al. "Active RIS vs. passive RIS: Which will prevail in 6G?." *IEEE TCOM* 2022.

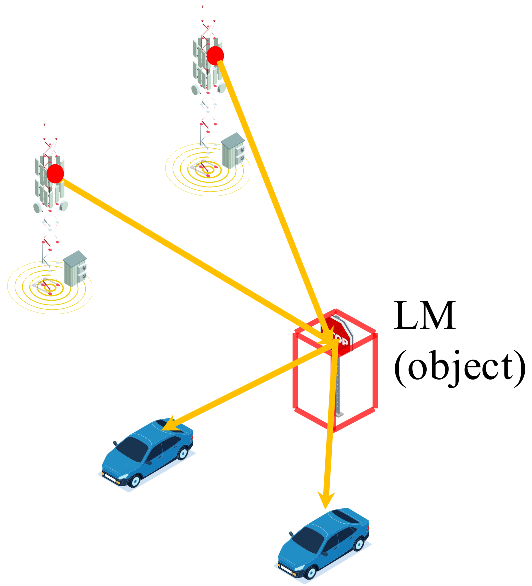
Alexandropoulos, George C., et al. "Hybrid reconfigurable intelligent metasurfaces: Enabling simultaneous tunable reflections and sensing for 6G wireless communications." *IEEE VTM* 2023.

Mu, Xidong, et al. "Simultaneously transmitting and reflecting (STAR) RIS aided wireless communications." *IEEE TWC* (2021).

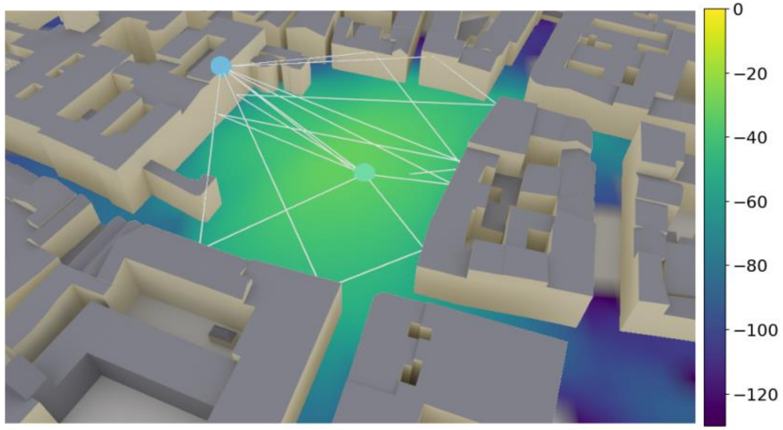
Geometric Information in the Channel



Reflectors
(can be modeled as
virtual anchors)



Scattering points
(AOA & AOD are
from this object)

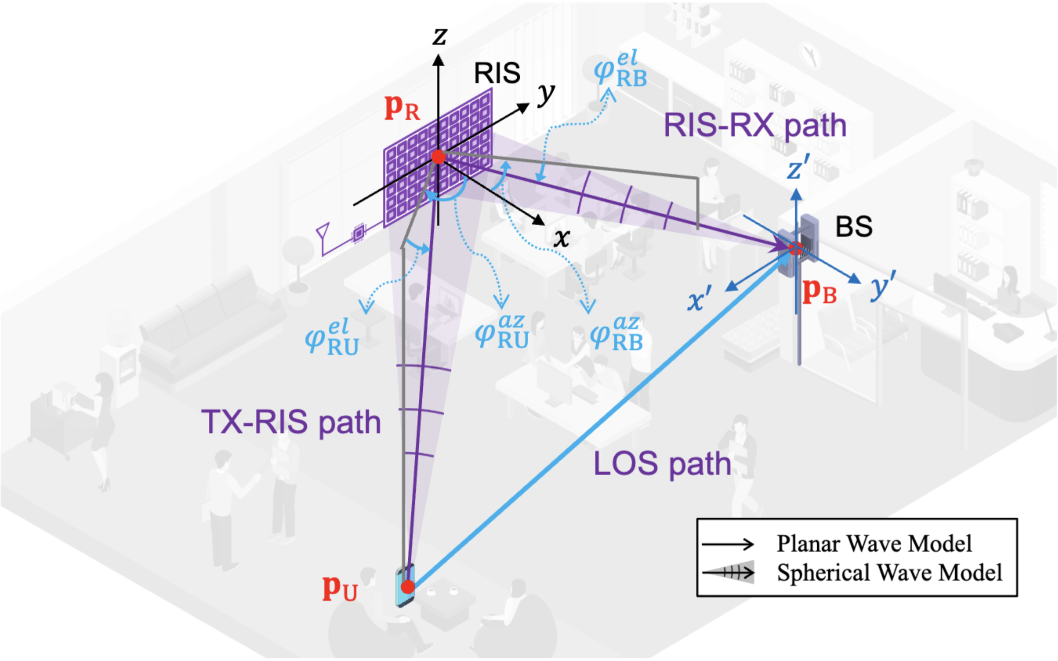


Fingerprints
(too complicated to
represent geometrically)

More deterministic at high frequencies, more stochastic at low frequencies.

State Parameters vs. Channel Parameters

Geometry Relationship (3D)



Start with a simple MISO/SIMO, stationary case

Delay

$$\tau_\mathrm{L} = \|\mathbf{p}_\mathrm{U} - \mathbf{p}_\mathrm{B}\|/c + \Delta,$$

$$\tau_\mathrm{R} = \|\mathbf{p}_\mathrm{U} - \mathbf{p}_\mathrm{R}\|/c + \|\mathbf{p}_\mathrm{R} - \mathbf{p}_\mathrm{B}\|/c + \Delta,$$

Angle

$$\theta^\mathrm{az}_\mathrm{BU} = \arctan2([\mathbf{R}_\mathrm{B}^\top(\mathbf{p}_\mathrm{U} - \mathbf{p}_\mathrm{B})]_2, [\mathbf{R}_\mathrm{B}^\top(\mathbf{p}_\mathrm{U} - \mathbf{p}_\mathrm{B})]_1),$$
$$\theta^\mathrm{el}_\mathrm{BU} = \arcsin([\mathbf{R}_\mathrm{B}^\top(\mathbf{p}_\mathrm{U} - \mathbf{p}_\mathrm{B})]_3/\|\mathbf{p}_\mathrm{U} - \mathbf{p}_\mathrm{B}\|).$$

Direction Vector

$$\mathbf{t}_\mathrm{BU} = \mathbf{t}(\boldsymbol{\theta}_\mathrm{BU}) = \begin{bmatrix} \cos(\theta^\mathrm{az}_\mathrm{BU})\cos(\theta^\mathrm{el}_\mathrm{BU}) \\ \sin(\theta^\mathrm{az}_\mathrm{BU})\cos(\theta^\mathrm{el}_\mathrm{BU}) \\ \sin(\theta^\mathrm{el}_\mathrm{BU}) \end{bmatrix}.$$

$$\boxed{\mathbf{y}^\mathrm{Passive}_{\mathrm{B},g,k} = \mathbf{W}_\mathrm{B}^\top(\underbrace{\mathbf{h}_{\mathrm{L},k}x_k}_{\text{LoS path}} + \underbrace{\mathbf{H}_{\mathrm{R2},k}\boldsymbol{\Omega}_{\mathrm{P},g}\mathbf{h}_{\mathrm{R1},k}x_k}_{\text{RIS path}} + \mathbf{n}_{g,k}).}$$

RIS profile

$$\boldsymbol{\Omega}_{\mathrm{P},g} = \mathrm{diag}(\boldsymbol{\omega}_{\mathrm{P},g} \odot \mathbf{m}),$$

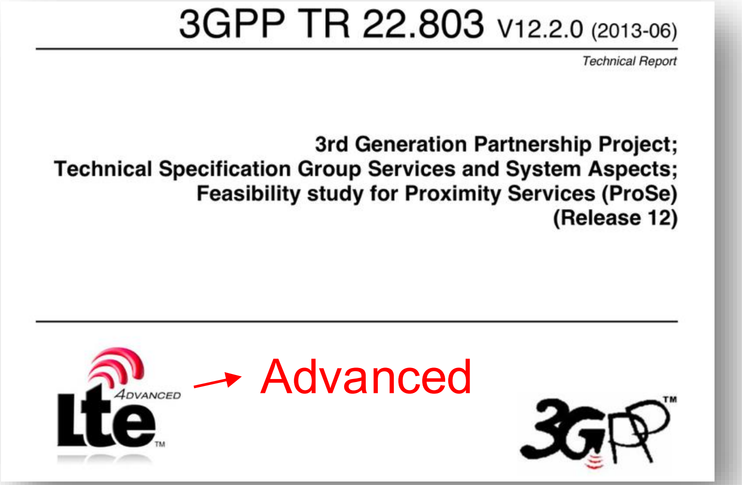
Mask vector

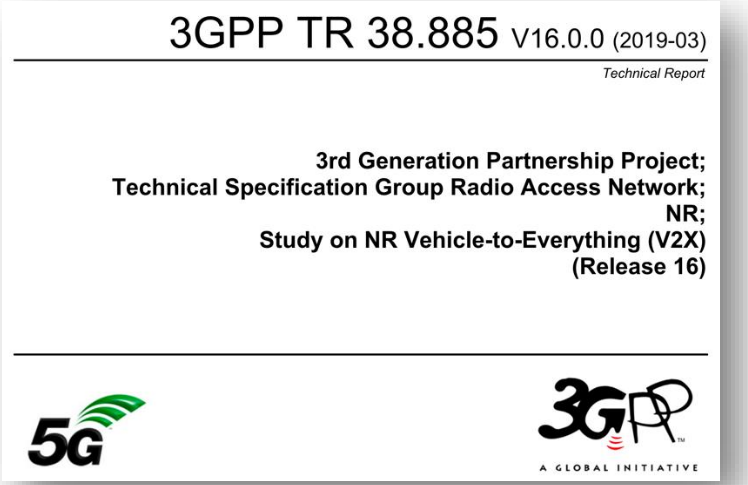
$$m_n = \begin{cases} \kappa_n e^{j\psi_n}, & \text{faulty element} \\ 1, & \text{normal element} \end{cases},$$

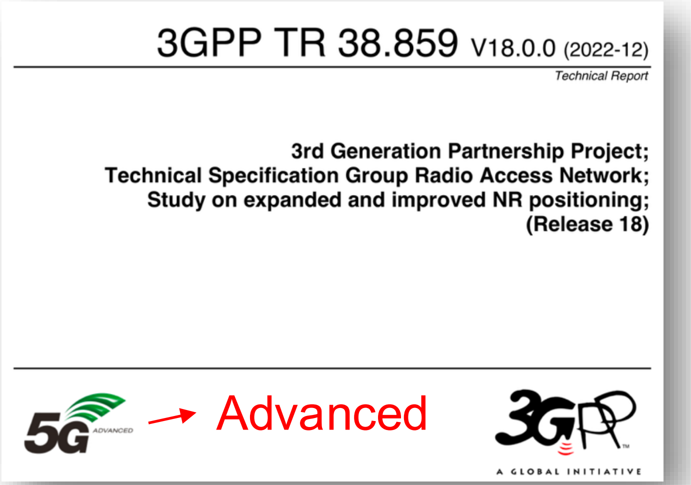
Hui Chen, Hyowon Kim, Reza Ghazalian, Cuneyd Ozturk, Mustafa Ammous, Yu Ge, Musa Furkan Keskin, Sinan Gezici, Shahrokh Valaee, Henk Wymeersch. “Calibration in RIS-aided Localization System” (Ongoing Book chapter)

User: Cooperative vs Non-Cooperative

- 3GPP: The 3rd Generation Partnership Project (3GPP) is an umbrella term for a number of standards organizations which develop protocols for mobile telecommunications.


3GPP TR 22.803 V12.2.0 (2013-06)
Technical Report
3rd Generation Partnership Project;
Technical Specification Group Services and System Aspects;
Feasibility study for Proximity Services (ProSe)
(Release 12)


3GPP TR 38.885 V16.0.0 (2019-03)
Technical Report
3rd Generation Partnership Project;
Technical Specification Group Radio Access Network;
NR;
Study on NR Vehicle-to-Everything (V2X)
(Release 16)


3GPP TR 38.859 V18.0.0 (2022-12)
Technical Report
3rd Generation Partnership Project;
Technical Specification Group Radio Access Network;
Study on expanded and improved NR positioning;
(Release 18)

4G LTE-Advanced Rel-12 (2013)
D2D + Proximity Services

5G NR Rel-16 (2019)
Support FR1 and FR2 (mmWave)

5G NR-Advanced Rel-18 (2022)
Enhance NR positioning

UE-UE communication is not forgotten with time :)

Sidelink Communication

- Sidelink communication: direct communication between terminal nodes or UEs without data going through the APs [5, 6].

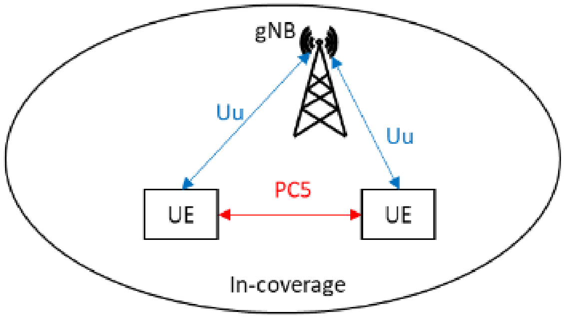


Figure 5.1-1: In-coverage scenario

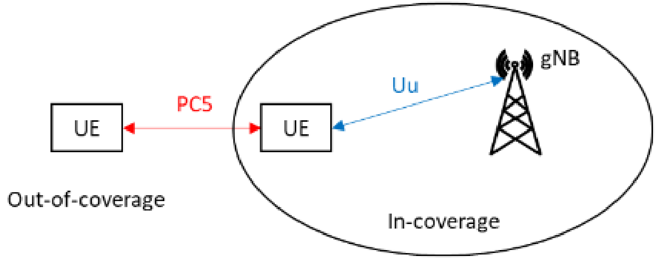


Figure 5.1-2: Partial coverage scenario

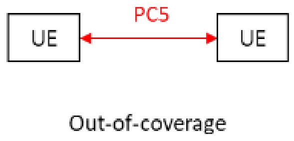


Figure 5.1-3: Out-of-coverage scenario

More L&S opportunities with sidelink going to the mmWave FR2 band

5.5 Spectrum

For V2X use case, the ITS-dedicated spectrum can be considered for PC5 interface, and the spectrum licensed to mobile network operators (including FR2) and the unlicensed spectrum can be considered for both Uu and PC5 interfaces. Note that there is no mechanism corresponding to regulatory requirements to use unlicensed spectrum in Rel-17 NR sidelink.

For public safety use case, the spectrum licensed to mobile network operators (including FR2) can be considered for both Uu and PC5 interfaces.

Frequency Range 2 [edit]

Band ⇕	*f* (GHz) ⇕	Common name	Subset of band	Uplink / Downlink[C 1] (GHz) ⇕	Channel bandwidths[C 2] (MHz)	Notes
n257	28	LMDS		26.50 – 29.50	50, 100, 200, 400	
n258	26	K-band		24.25 – 27.50	50, 100, 200, 400	
n259	41	V-band		39.50 – 43.50	50, 100, 200, 400	
n260	39	Ka-band		37.00 – 40.00	50, 100, 200, 400	
n261	28	Ka-band	n257	27.50 – 28.35	50, 100, 200, 400	
n262	47	V-band		47.20 – 48.20	50, 100, 200, 400	
n263	60	V-band		57.00 – 71.00	100, 400, 800, 1600, 2000	[D 1]
Band	*f* (GHz)	Common name	Subset of band	Uplink / Downlink (GHz)	Channel bandwidths (MHz)	Notes

[4] 3GPP TR 38.845 V17.0.0: Study on scenarios and requirements of in-coverage, partial coverage, and out-of-coverage NR positioning use cases
[5] 3GPP TS 23.287: Architecture enhancements for 5G System (5GS) to support Vehicle-to-Everything (V2X) services
[6] https://en.wikipedia.org/wiki/5G_NR_frequency_bands

Key Takeaways (Sensing Systems)

- **Heterogeneous nodes:** BSs, RISs, vehicles, IoT, and robots act as anchors or targets.
- **Frequency matters:** FR1–FR4 offer different sensing/comm trade-offs (e.g., resolution vs. coverage).
- **Channel regimes:** High-frequency enables geometric inference; low-frequency offers better synchronization.
- **Programmable environments:** RIS variants (passive/active/STAR) act as virtual anchors.
- **Cooperative gain:** Sidelink and multi-node cooperation enhance coverage and positioning.

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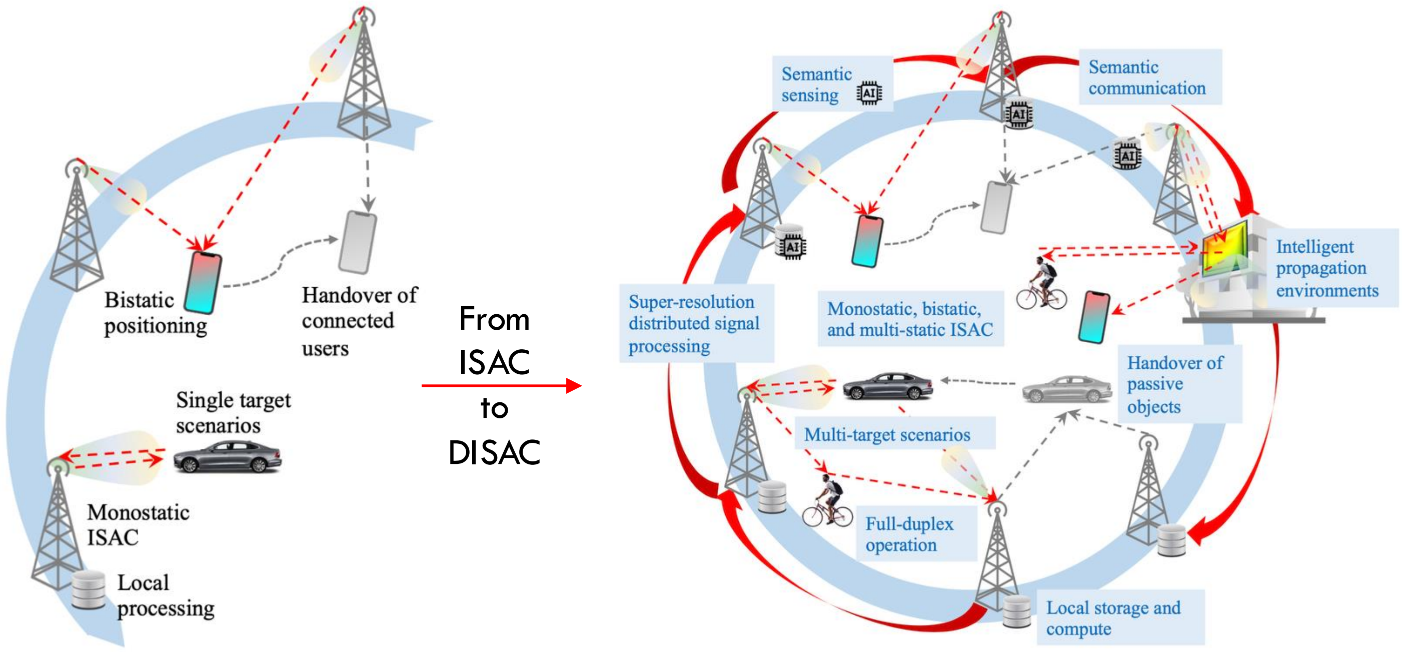


Use Case 1: Smart Factory

Use Case Overview

- **Scenario:** AGVs operate autonomously or with human interaction on a factory floor.
- **Frequencies:** FR1 (Sub-6 GHz) for reliable control communication, FR2 (mmWave) for high-resolution sensing and localization.
- **Technologies:** Distributed Radio SLAM, mmWave sensing, DISAC coordination via sensing management function (SeMF).

Key Components

- **AGVs:** Equipped with mmWave radios and sensors (LIDAR, etc.).
- **BS (Base Station):** Maintains robust communication with AGVs.
- **SeMF (Sensing Mgmt. Function):** Coordinates sensing & communication resources.
- **DISAC Edge Intelligence:** Enables distributed fusion and task-driven optimization.

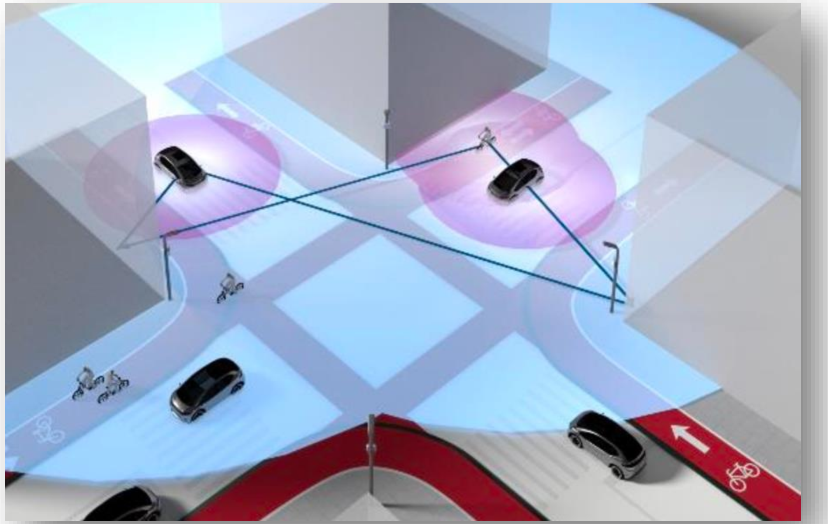
Metric	ISAC	DISAC Improvement
Mapping Time	Long (single AGV)	Reduced via parallel sensing
Mapping Accuracy	Baseline	Improved via sensor fusion
Outage Probability	Higher (single point of failure)	Lower (redundancy)
Decision Latency	High (centralized)	Low (edge/local processing)

6G-DISAC deliverable D2.1: Preliminary version of scenarios, use cases and KPIs

Use Case 2: VRU protection at a smart intersection

Use Case Overview

- **Scenario**: Pedestrians and vehicles share urban intersections.
- **Goal**: Real-time detection & protection of **Vulnerable Road Users (VRUs)**.
- **Approach**: Distributed, cooperative sensing + low-latency AI decision-making.



Key Components

- **IoT Sensors**: Radar, LIDAR, cameras at traffic points.
- **6G Infrastructure**: Ensures ultra-low latency and massive device connectivity.
- **Traffic Control Center**: Central AI-powered decision node.
- **Connected Devices**: Vehicles & smartphones act as sensing and alerting nodes.

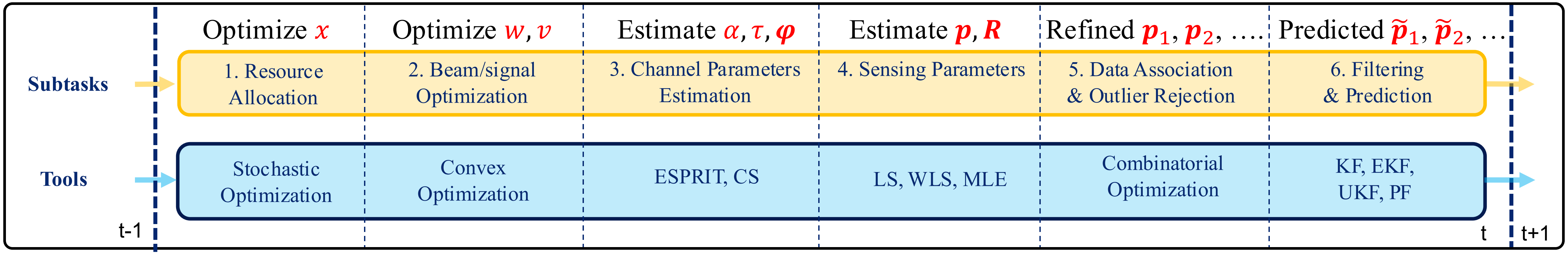
Metric	ISAC	DISAC Improvement
Response Time	Delayed (centralized)	Faster (distributed sensing)
Detection Error Rate	Higher (limited view)	Lower (multi-view fusion)
Robustness	Low (fragile to failures)	High (redundancy & edge AI)

6G-DISAC deliverable D2.1: Preliminary version of scenarios, use cases and KPIs

Sensing Pipeline

Synergy between communication and sensing

Sensing pipeline



Recall:

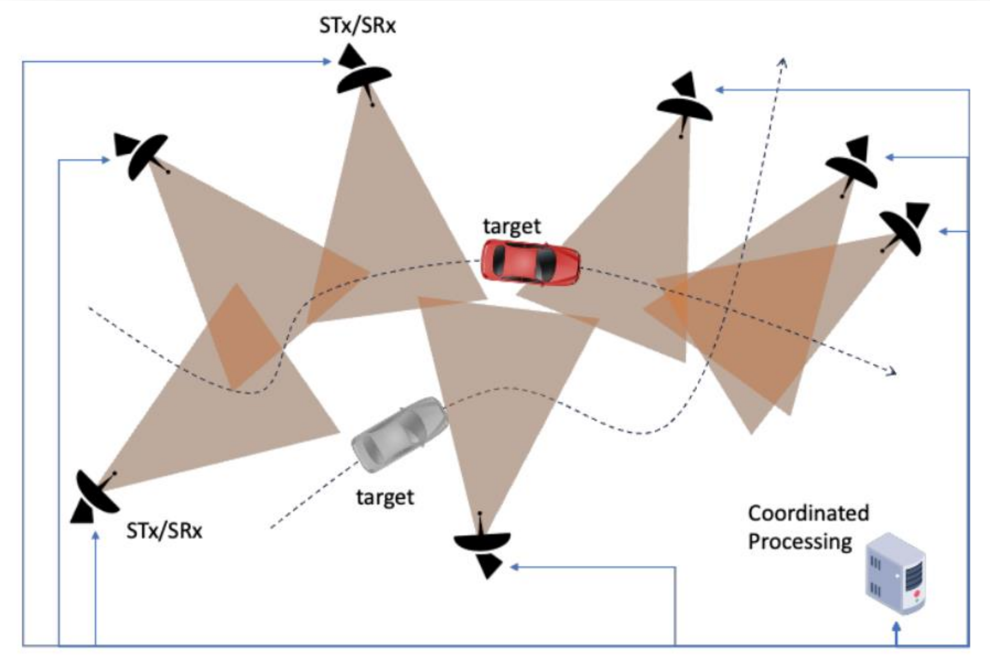
$$y_{g,k} = \mathbf{w}_g^\top \mathbf{H}_k \mathbf{v}_g x_{g,k} + n_{g,k}$$

$$\mathbf{H}_k = \underbrace{\alpha d_k(\tau)\mathbf{a}_\mathrm{R}(\varphi_\mathrm{R})\mathbf{a}_\mathrm{T}^\top(\varphi_\mathrm{T})}_{\text{LOS path}} + \underbrace{\sum_{p=1}^{P} \alpha_p d_{p,k}(\tau_p)\mathbf{a}_\mathrm{R}(\varphi_{\mathrm{R},p})\mathbf{a}_\mathrm{T}^\top(\varphi_{\mathrm{T},p})}_{\text{NLOS paths}},$$

Sensing Algorithms (from ISAC to DISAC)

- Sensing in ISAC
  - Single BS Positioning
  - Single BS Sensing

- Sensing in DISAC
  - BS (synchronization, backhaul aspects, power allocation)
  - UE (coordination, processing, doppler)



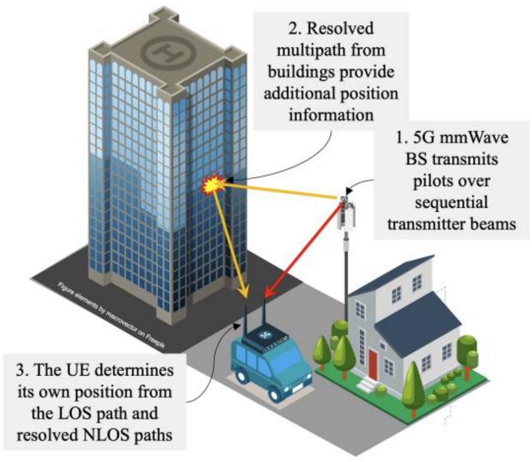
Goal: Accurate detection, sensing, and localization

Features: Distributed (coverage) + Semantic (efficiency)

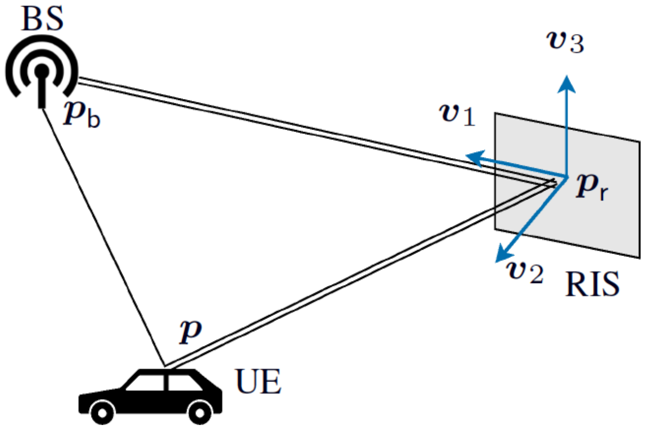
6G-DISAC deliverable D2.2: Preliminary version of the distributed ISAC architecture

Single-BS Positioning

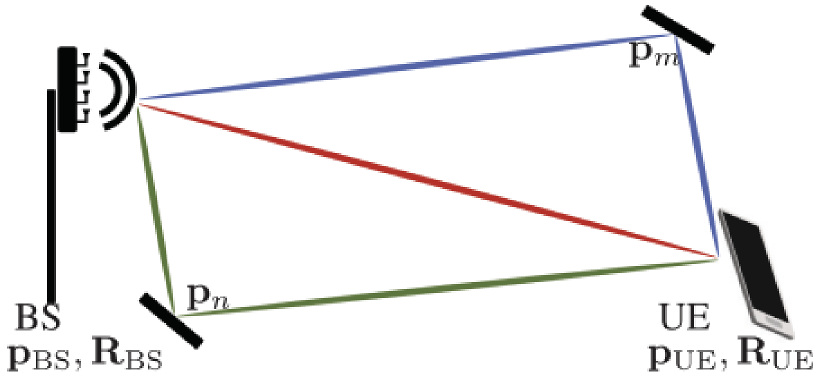
Map-enabled Localization



RIS-enabled Localization

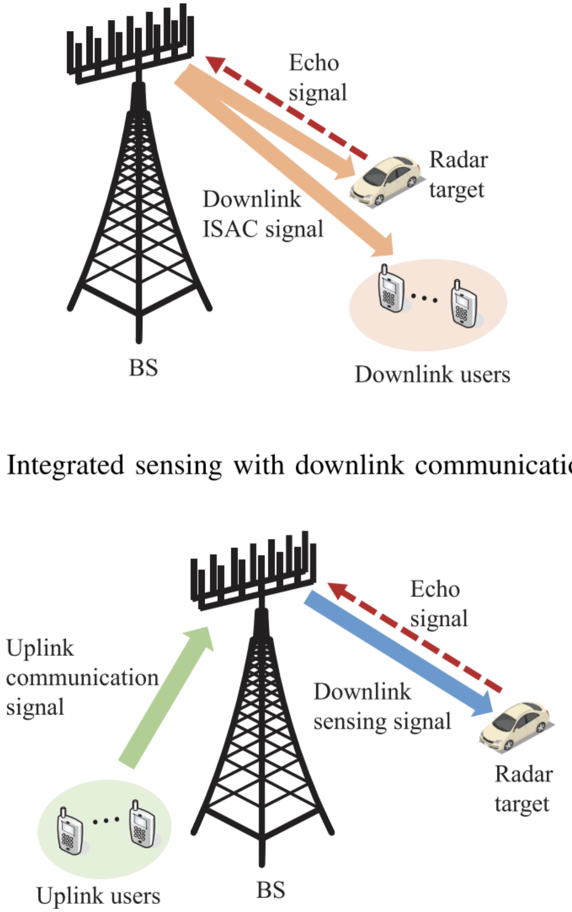


NLOS path-enabled 6D Localization



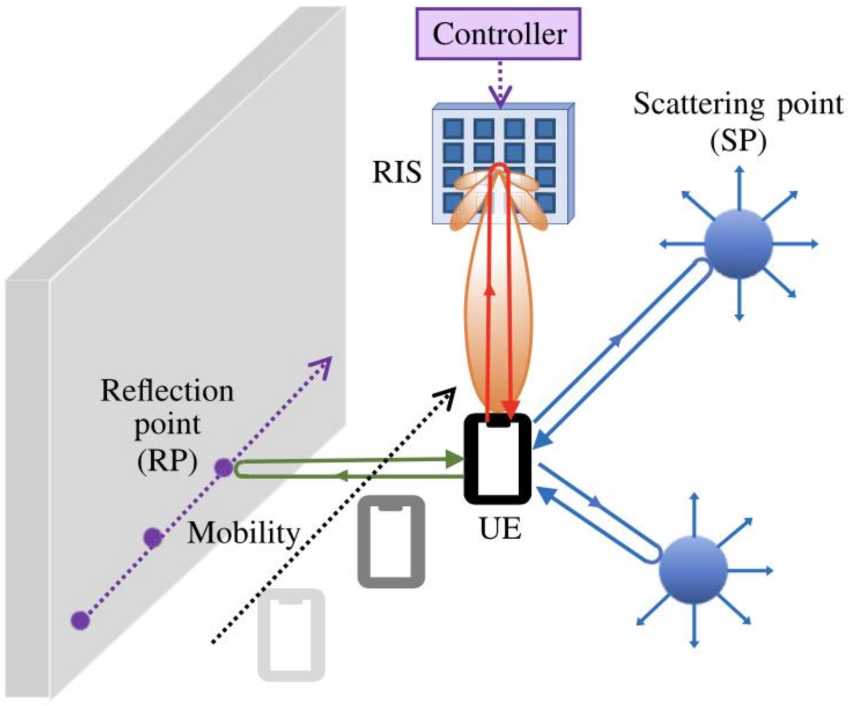
[1] Ge, Yu, Hedieh Khosravi, Fan Jiang, Hui Chen, Simon Lindberg, Peter Hammarberg, Hyowon Kim et al. "Experimental validation of single BS 5G mmWave positioning and mapping for intelligent transport." *arXiv preprint arXiv:2303.11995* (2023).
[2] Keykhosravi, Kamran, Musa Furkan Keskin, Gonzalo Seco-Granados, and Henk Wymeersch. "SISO RIS-enabled joint 3D downlink localization and synchronization." In *ICC 2021-IEEE International Conference on Communications*, pp. 1-6. IEEE, 2021.
[3] Nazari, Mohammad A., Gonzalo Seco-Granados, Pontus Johannisson, and Henk Wymeersch. "MmWave 6D radio localization with a snapshot observation from a single BS." IEEE Transactions on Vehicular Technology (2023).
Mendrzik, Rico, Henk Wymeersch, Gerhard Bauch, and Zohair Abu-Shaban. "Harnessing NLOS components for position and orientation estimation in 5G millimeter wave MIMO." IEEE Transactions on Wireless Communications 18, no. 1 (2018): 93-107.

Single-BS Sensing



(a) Integrated sensing with downlink communication.

(b) Integrated sensing with uplink communication.



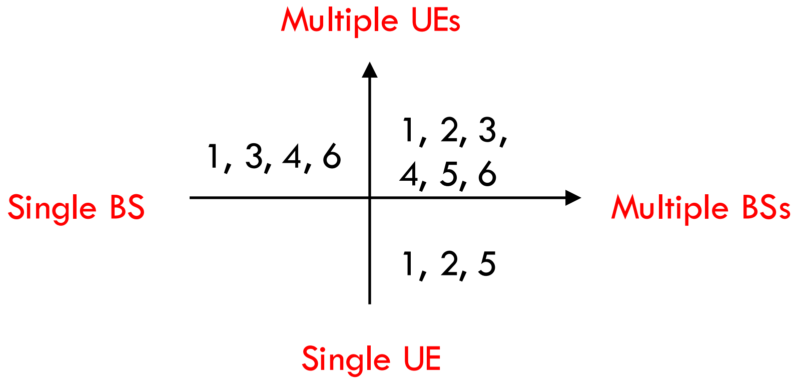
[1] He, Zhenyao, Wei Xu, Hong Shen, Derrick Wing Kwan Ng, Yonina C. Eldar, and Xiaohu You. "Full-duplex communication for ISAC: Joint beamforming and power optimization." *IEEE Journal on Selected Areas in Communications* 41, no. 9 (2023): 2920-2936.

[2] Kim, Hyowon, Hui Chen, Musa Furkan Keskin, Yu Ge, Kamran Keykhosravi, George C. Alexandropoulos, Sunwoo Kim, and Henk Wymeersch. "RIS-enabled and access-point-free simultaneous radio localization and mapping." IEEE Transactions on Wireless Communications 23, no. 4 (2023): 3344-3360.

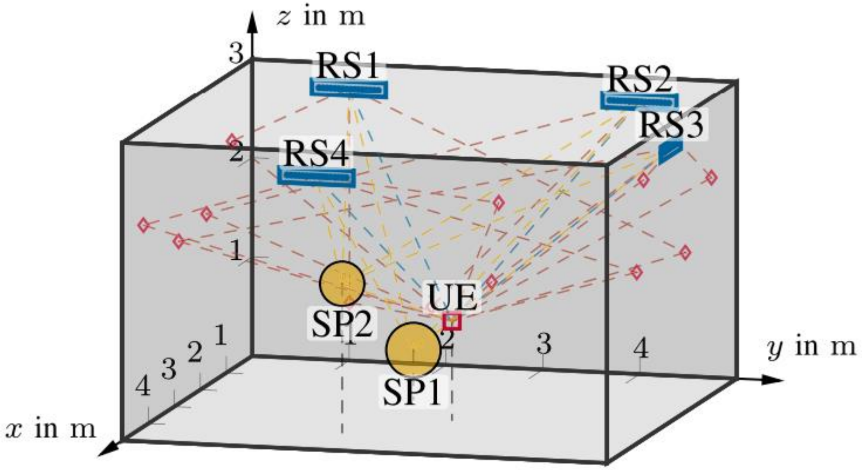
Selected DISAC Tasks

	Task	Goals	Features	Selected Algorithms
1	Joint estimation	Estimate position, velocity, and channel parameters jointly based on the signals received from N users and M anchors	Scalability	Expectation maximization, graph-based inference, belief propagation
2	Global synchronization	Align global time and phase offsets across distributed nodes	Multi-anchor	Maximum likelihood, alternating optimization
3	Distributed processing	Minimize global loss across local estimates with consensus	Edge computing	Distributed stochastic gradient descent (SGD), federated learning
4	Interference handling	Recover signals from superimposed measurements	Concurrent transmission	Blind source separation, spatial filtering
5	Target handover	Maintain continuity of target state estimate across nodes during handover	Tracking	Distributed Kalman figure, particle filter
6	Data/target association	Assign observations to targets (especially under ambiguity or occlusion)	Multi-target	Hungarian method, Multiple hypothesis tracking (MHT), global nearest neighbor (GNN)

More challenging when dealing with multi-anchor and multi-target scenarios



Joint Localization, Synchronization and Mapping



Scenario

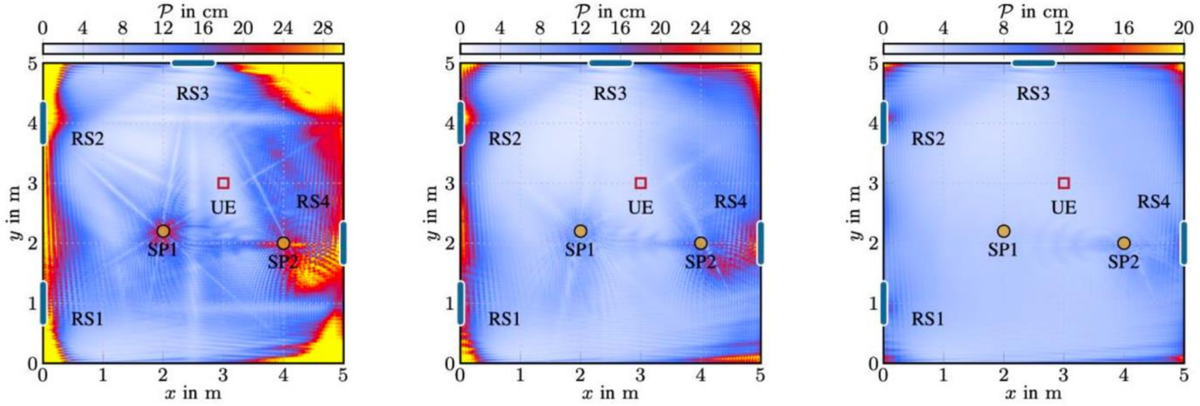
- **Single-antenna UE**, a network of **phase- and time-synchronized** APs, indoors.
- UE is unsynchronized with APs → requires estimation of clock and phase offsets.
- Mixed propagation with LoS and NLoS (reflections, scatterers).
- Objective: Joint estimation of UE location, offsets, and scattering point (SP) positions for full situ awareness.

Methods:

- Phase offset estimation using carrier phase of LoS paths.
- Joint UE location and clock offset estimation via LoS and reflected paths.
- Null-space transformation to enhance multipath resolution.

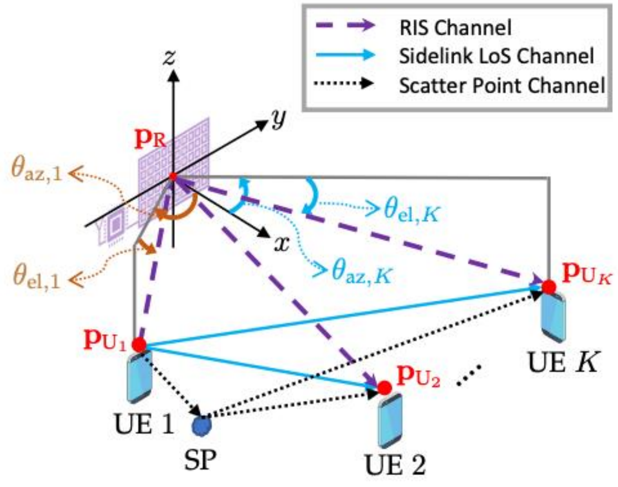
Selected Results

- **Low BW**: Overlapping paths cause degraded accuracy, especially in corners.
- **Mid BW**: Delay resolution improves for LoS and RPs, SP overlaps persist.
- **High BW**: Full path separation achieved, delay dominates, resulting in smooth and accurate localization across the environment.



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.

3D Cooperative Positioning Via RIS and Sidelink Communications



Scenario

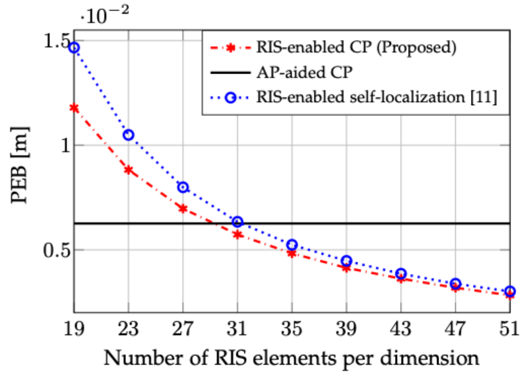
- Multiple single-antenna UE, one RIS, no access point (AP)
- RIS changes its profile for spatial frequency estimation
- Objective: Estimate the locations of all the UEs

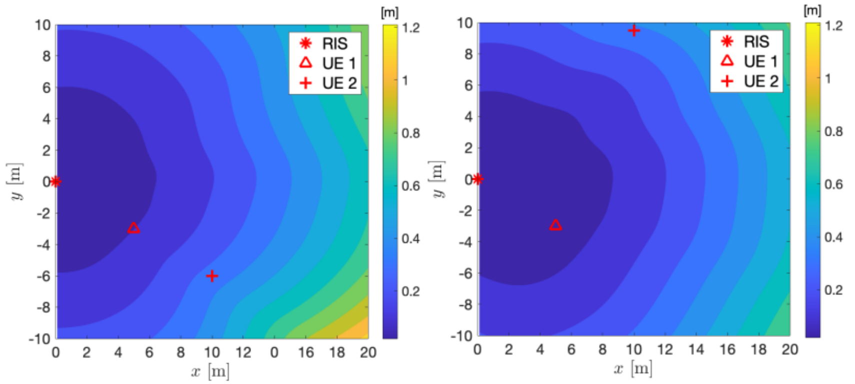
Methods:

- Design the RIS phase profile with directional and derivative beams
- Propose a power allocation strategy among UEs
- Develop low-complexity estimators for channel parameters and UE positions

Selected Results

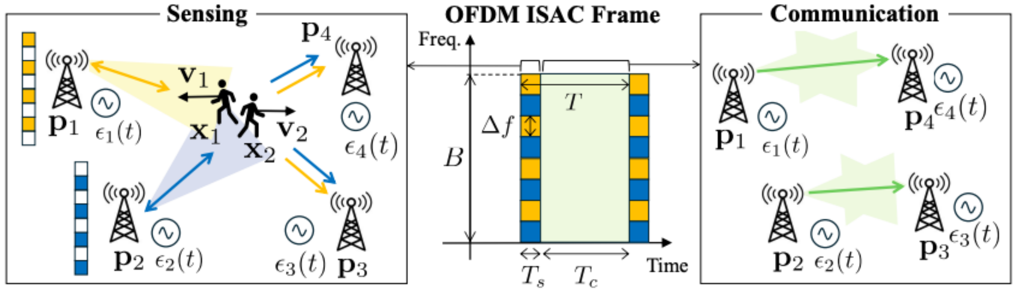
- AP-free CP performance is comparable to AP-based benchmark with sufficient elements.
- Localization performance largely relies on anchor and UE layouts





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.

Coherent Imaging of Moving Targets with Distributed ISAC

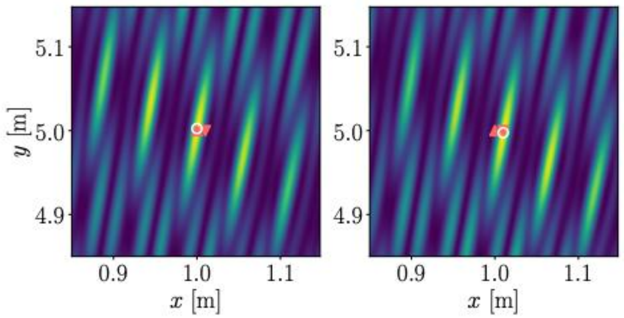


Scenario

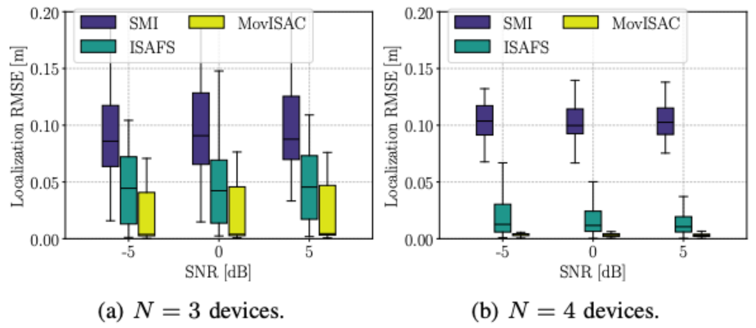
- Distributed ISAC networks with asynchronous OFDM-based devices.
- Targets are moving with unknown positions and velocities.
- Goal: Joint imaging, localization, and velocity estimation
- **Methods:**
- Over-the-Air Synchronization: Compensates time, frequency, and phase offsets among ISAC devices.
- Doppler-Space Association: Matches Doppler shifts with spatial peaks using a novel association algorithm.
- Target-Specific Imaging: Applies Doppler pre-compensation to focus on one moving target per image.
- Iterative Refinement: Enhances position and velocity estimation with minimal complexity.

Selected Results

- Effective even with closely spaced targets (as small as 1 cm apart) and clutter-rich environments.
- Robust to synchronization errors and scalable to real-time implementation.



MovISAC images with N = 4 ISAC devices



Localization RMSE comparison

Pegoraro, Jacopo, Dario Tagliaferri, and Joerg Widmer. "MovISAC: Coherent Imaging of Moving Targets with Distributed Asynchronous ISAC Devices." arXiv preprint arXiv:2502.08236 (2025).

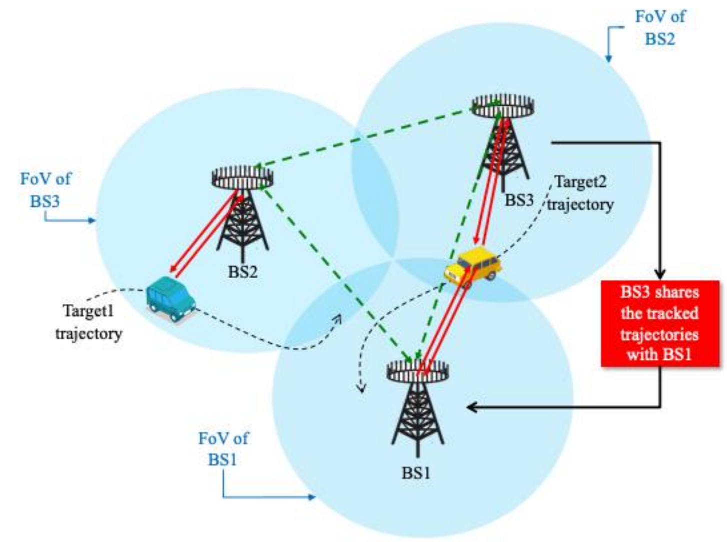
Target Handover in Distributed Integrated Sensing and Communication

Scenario

- Large-scale decentralized sensing, multiple BSs
- Each BS performs monostatic sensing in its own field-of-view (FoV)
- Cooperative tracking is enabled via trajectory sharing between BSs

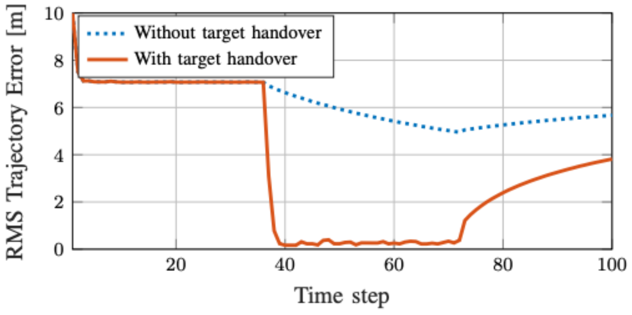
Methods:

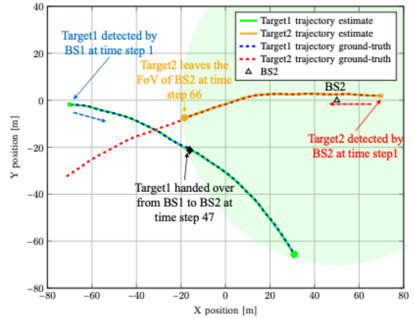
- Channel Parameter Estimation: Each BS estimates target delays and angles from received signals.
- TPMBM Filtering: A Trajectory Poisson Multi-Bernoulli Mixture filter is applied for local target tracking.
- Seamless Handover: When a target is about to exit one BS's FoV, trajectory info is shared with the next BS to continue tracking.



Selected Results

- The TPMBM filter accurately tracks targets despite clutter, showing robustness.
- The scheme enables stable and continuous multi-BS target tracking across the sensing area.





Ge, Yu, Ossi Kaltiokallio, Hui Chen, Jukka Talvitie, Yuxuan Xia, Giyyarpuram Madhusudan, Guillaume Larue, Lennart Svensson, Mikko Valkama, and Henk Wymeersch. "Target Handover in Distributed Integrated Sensing and Communication." IEEE *ICC 2025*

Summary of Existing DISAC Works

Distributed setting (separated sensing and communication) :

- Distributed MIMO
  - Wang, Dongming, Jiangzhou Wang, Xiaohu You, Yan Wang, Ming Chen, and Xiaoyun Hou. "Spectral efficiency of distributed MIMO systems." IEEE Journal on Selected Areas in Communications 31, no. 10 (2013): 2112-2127.
  - Del Coso, Aitor, Umberto Spagnolini, and Christian Ibars. "Cooperative distributed MIMO channels in wireless sensor networks." IEEE Journal on Selected Areas in Communications 25, no. 2 (2007): 402-414.
- Cooperative localization (anchors are by default distributed… for TDOA/TOA)
  - Patwari, Neal, Joshua N. Ash, Spyros Kyperountas, Alfred O. Hero, Randolph L. Moses, and Neiyer S. Correal. "Locating the nodes: cooperative localization in wireless sensor networks." IEEE Signal processing magazine 22, no. 4 (2005): 54-69.
  - Wymeersch, Henk, Jaime Lien, and Moe Z. Win. "Cooperative localization in wireless networks." Proceedings of the IEEE 97, no. 2 (2009): 427-450.
- Multistatic Radar system:
  - Chernyak, Victor S. Fundamentals of multisite radar systems: multistatic radars and multistatic radar systems. Routledge, 2018.
  - Godrich, Hana, Athina P. Petropulu, and H. Vincent Poor. "Power allocation strategies for target localization in distributed multiple-radar architectures." IEEE Transactions on Signal Processing 59, no. 7 (2011): 3226-3240.

Around 2022, most of the focuses are on ISAC

- Tan, Danny Kai Pin, Jia He, Yanchun Li, Alireza Bayesteh, Yan Chen, Peiying Zhu, and Wen Tong. "Integrated sensing and communication in 6G: Motivations, use cases, requirements, challenges and future directions." In 2021 1st IEEE International Online Symposium on Joint Communications & Sensing (JC&S), pp. 1-6. IEEE, 2021.
- Cui, Yuanhao, Fan Liu, Xiaojun Jing, and Junsheng Mu. "Integrating sensing and communications for ubiquitous IoT: Applications, trends, and challenges." IEEE network 35, no. 5 (2021): 158-167.
- Liu, Fan, Yuanhao Cui, Christos Masouros, Jie Xu, Tony Xiao Han, Yonina C. Eldar, and Stefano Buzzi. "Integrated sensing and communications: Toward dual-functional wireless networks for 6G and beyond." IEEE journal on selected areas in communications 40, no. 6 (2022): 1728-1767.
- Liu, An, Zhe Huang, Min Li, Yubo Wan, Wenrui Li, Tony Xiao Han, Chenchen Liu et al. "A survey on fundamental limits of integrated sensing and communication." IEEE Communications Surveys & Tutorials 24, no. 2 (2022): 994-1034.

DISAC summary from 2023 (next page)

Selected Existing DISAC Works

1. Gao, Peng, Lixiang Lian, and Jinpei Yu. "Cooperative ISAC with direct localization and rate-splitting multiple access communication: A Pareto optimization framework." IEEE journal on selected areas in communications 41, no. 5 (2023): 14
2. Wei, Zhiqing, Hanyang Qu, Yuan Wang, Xin Yuan, Huici Wu, Ying Du, Kaifeng Han, Ning Zhang, and Zhiyong Feng. "Integrated sensing and communication signals toward 5G-A and 6G: A survey." IEEE Internet of Things Journal 10, no. 13 (2023): 11068-11092.
3. Li, R., Xiao, Z. and Zeng, Y., 2023. Towards seamless sensing coverage for cellular multi-Static integrated sensing and communication. IEEE Transactions on Wireless Communications.
4. Thomä, Reiner, and Thomas Dallmann. "Distributed ISAC systems–multisensor radio access and coordination." In 2023 20th European Radar Conference (EuRAD), pp. 351-354. IEEE, 2023.
5. Xu, Dongfang, Ata Khalili, Xianghao Yu, Derrick Wing Kwan Ng, and Robert Schober. "Integrated sensing and communication in distributed antenna networks." In 2023 IEEE International Conference on Communications Workshops (ICC Workshops), pp. 1457-1462.
6. Behdad, Z., Demir, Ö.T., Sung, K.W., Björnson, E. and Cavdar, C., 2024. Multi-static target detection and power allocation for integrated sensing and communication in cell-free massive MIMO. IEEE Transactions on Wireless Communications.
7. Zou, Q., Behdad, Z., Demir, Ö.T. and Cavdar, C., 2024. Distributed Versus Centralized Sensing in Cell-Free Massive MIMO. IEEE Wireless Communications Letters.
8. Yan, Weixian, Ozan Alp Topal, Zinat Behdad, Özlem Tuğfe Demir, and Cicek Cavdar. "Communicate or Sense? AP Mode Selection in mmWave Cell-Free Massive MIMO-ISAC." In 2024 58th Asilomar Conference on Signals, Systems, and Computers, pp. 889-893. IEEE, 2024.
9. Rivetti, S., Demir, O.T., Bjornson, E. and Skoglund, M., 2024. Clutter-Aware Target Detection for ISAC in a Millimeter-Wave Cell-Free Massive MIMO System. arXiv preprint arXiv:2411.08759.
10. Meng, K., Han, K., Masouros, C. and Hanzo, L., 2024. Network-level ISAC: Performance Analysis and Optimal Antenna-to-BS Allocation. arXiv preprint arXiv:2410.06365.
11. Salem, A., Meng, K., Masouros, C., Liu, F. and Lopez-Perez, D., 2024. Rethinking dense cells for integrated sensing and communications: A stochastic geometric view. IEEE Open Journal of the Communications Society.
12. Meng, K., Masouros, C., Petropulu, A.P. and Hanzo, L., 2024. Cooperative ISAC Networks: Performance Analysis, Scaling Laws and Optimization. arXiv preprint arXiv:2404.14514.
13. Meng, K., Masouros, C., Chen, G. and Liu, F., 2024. Network-level integrated sensing and communication: Interference management and BS coordination using stochastic geometry. IEEE Transactions on Wireless Communications.
14. Babu, N., Masouros, C., Papadias, C.B. and Eldar, Y.C., 2024. Precoding for multi-cell ISAC: from coordinated beamforming to coordinated multipoint and bi-static sensing. arXiv preprint arXiv:2402.18387.
15. 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.
16. Sakhnini, A., Guenach, M., Bourdoux, A., Sahli, H. and Pollin, S., 2022, May. A target detection analysis in cell-free massive MIMO joint communication and radar systems. In ICC 2022-IEEE International Conference on Communications (pp. 2567-2572). IEEE.
17. Lou, X., Xia, W., Jin, S. and Zhu, H., 2024. Beamforming Optimization in Distributed ISAC System with Integrated Active and Passive Sensing. IEEE Transactions on Communications.
18. Demirhan, U. and Alkhateeb, A., 2024. Cell-free ISAC MIMO systems: Joint sensing and communication beamforming. IEEE Transactions on Communications.
19. Yang, X., Wei, Z., Xu, J., Fang, Y., Wu, H. and Feng, Z., 2024. Coordinated transmit beamforming for networked ISAC with imperfect CSI and time synchronization. IEEE Transactions on Wireless Communications.
20. Elfiatoure, M., Mohammadi, M., Ngo, H.Q. and Matthaiou, M., 2024. Multiple-Target Detection in Cell-Free Massive MIMO-Assisted ISAC. arXiv preprint arXiv:2404.17263.
21. Han, K., Meng, K. and Masouros, C., 2025. Signaling Design for Noncoherent Distributed Integrated Sensing and Communication Systems. arXiv preprint arXiv:2501.18264.
22. 96-1515.E, 2023.

Summary of the SOTA

- Almost no papers on **Rx-side algorithms.** Many many papers on beamforming design.
- Almost no papers on **Doppler** / target mobility
- No papers consider **data association** aspects: most have single target.
- Almost no papers consider **backhaul** aspects
- Almost no papers consider **sync** aspects
- Few papers consider **fusion** of monostatic (with non-idealities) + bi/multi-static
- Few papers consider **localization** of UEs.
- Few papers consider **security, imaging, semantic…**
- …

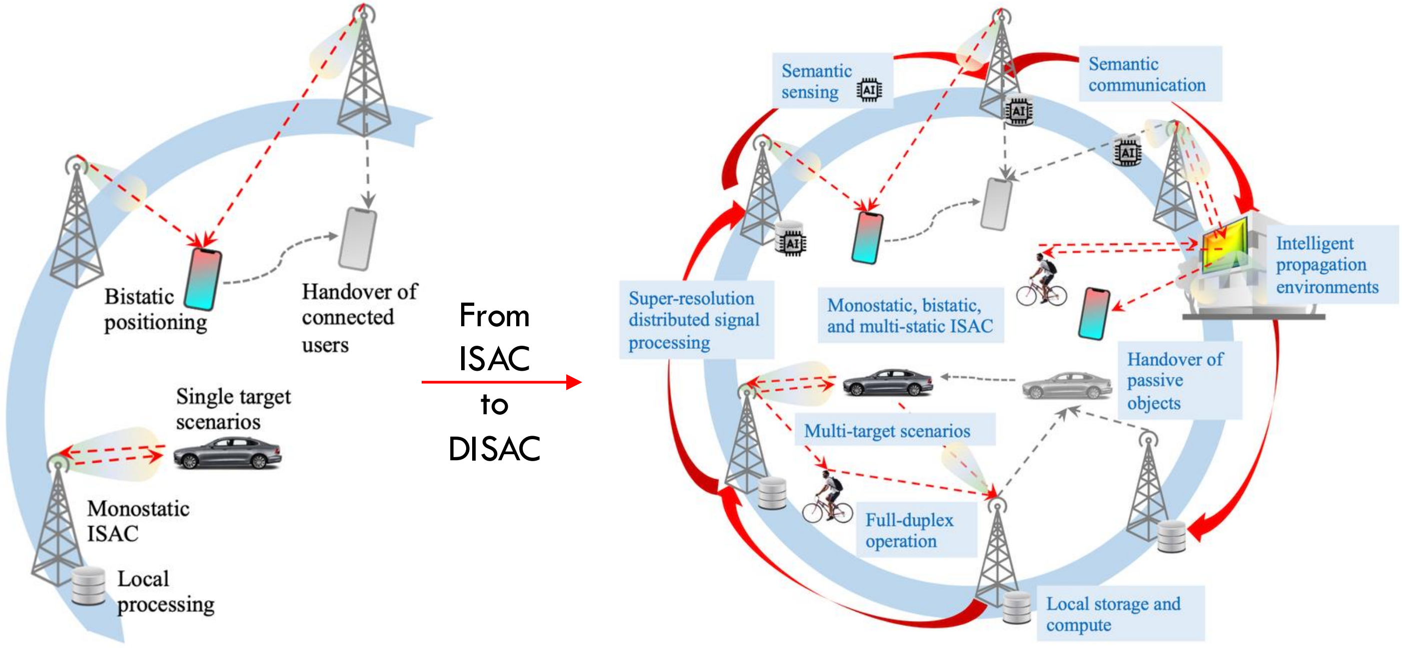
Lots of opportunities in this field! :)

Key Takeaways (Sensing Algorithms)

- **Distributed & cooperative**: Multi-node sensing improves coverage and robustness.
- **Modular tasks**: Supports joint estimation, synchronization, tracking, and handover.
- **Edge intelligence**: Uses distributed learning (e.g., federated SGD, graph inference).
- **Semantic & geometric fusion**: Combines raw signals with task-aware information.
- **Robustness**: Handles mobility, multipath, and sync errors with tailored techniques.

Part II: Distributed Communication-Aided Sensing

- Distributed Sensing System
- Sensing Scenarios and Algorithms
- Coordination and Optimization in Sensing
- Sensing Anchor Calibration
- Security Aspects



ISAC vs DISAC Comparison

What makes DISAC optimization different from ISAC?

Aspect	ISAC	DISAC
Optimization Objective	Local utility maximization (e.g., localization error)	Joint global optimization for sensing, comm, energy, and semantic task relevance
Decision Variables	Node-local beamforming, waveform, and resource split	Distributed control over beams, power, RIS, task assignment, and mobility-aware scheduling
Constraint Handling	Local constraints (power, latency)	Heterogeneous and global constraints (EMF, compute limits, dynamic interference, RIS config)
Computation & Coordination	Centralized or semi-static resource allocation	Fully distributed optimization via ADMM, consensus, or ML-driven orchestration
Learning & Adaptation	Limited local learning; often offline	Federated and graph-based learning for real-time adaptation under uncertainty

Five Selected DISAC optimization problems:

1. **Layout Optimization**: Determine optimal placement of BSs, RISs, sensors, and anchors to maximize certain objectives.
2. **Scheduling & Node Selection**: Select which nodes (sensing/comm units) should be active in each frame or task based on utility and constraints.
3. **Resource Allocation**: Dynamically allocate power, bandwidth, and time across tasks and nodes to optimize system performance.
4. **Beam Optimization**: Jointly design transmit and receive beams for both sensing accuracy and communication quality.
5. **Data Representation**: Efficiently encode and transmit task-relevant and semantic information under bandwidth and latency constraints.

DISAC Optimization Problem Formulation

Optimize variables $\boldsymbol{v}$ to maximize a utility function L, subject to system constraints $\boldsymbol{g}_c(\boldsymbol{v})$.

$$\boldsymbol{v} = \arg\max_{\boldsymbol{v}} L(\boldsymbol{v})$$
$$\text{s.t. } \boldsymbol{g}_c(x) \leq 0$$

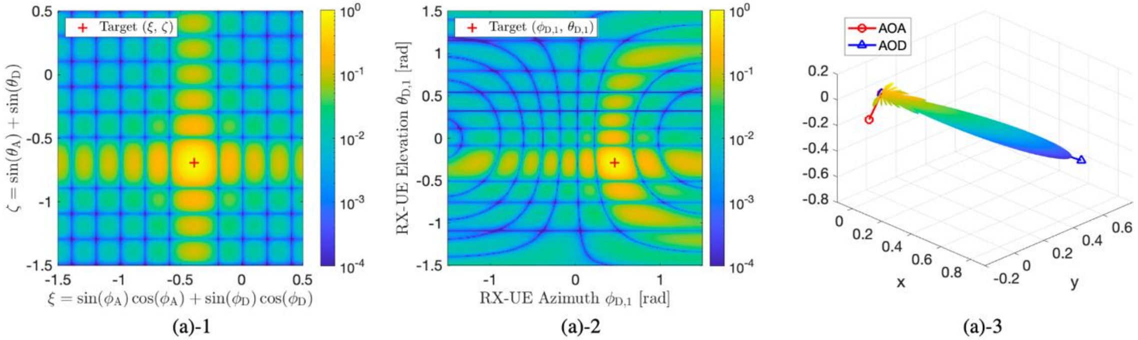
Task	Variables
Layout Optimization	Anchor locations: $\{\boldsymbol{p}_m\}_{m\in\mathcal{M}}$
Scheduling & Node Selection	Node i is active at time t: $\{s_{m,t} \in \{0,1\}\}$
Resource Allocation	Power, bandwidth, time slot: $\{P_m, B_m, T_m\}$
Beam Optimization	Beamformer, combiner: $\{\boldsymbol{w}_m, \boldsymbol{f}_m\}$
Data Representation	Compression codes, semantic features: $\{\boldsymbol{q}_m, \boldsymbol{\phi}_m\}$

Objective	Utility Function
Sensing Accuracy	$L_{sen} = -\sum_n \text{MSE}(\widehat{\boldsymbol{p}}_n, \boldsymbol{p}_n)$
Communication Sum Capacity	$L_{com} = \sum_n \log_2(1+\text{SNR}_n)$
Coverage	$L_{cov} = Vol(\bigcup_i \text{FoV}_n)$
Energy Efficiency	$L_{ee} = \frac{\alpha_s L_{sen} + L_{com}}{\sum_m P_m}$
Semantic Utility	$L = \sum_i I(\boldsymbol{\phi}_i;\ \boldsymbol{y}_i)$

Constraints	Formulation
Layout constrains	Node position within a specific area $p_m \in \mathcal{A}$
Power Constraints	$\sum_m P_m \leq P_{tot}, 0 \leq P_m \leq P_{max}$
Scheduling Constraints	$\sum_m s_{m,t} \leq M_{max}, \forall t$
Beamforming Constraints	Power-constrained beamformer $\lVert w_i \rVert^2 < 1$ or a fixed codebook $w_i \in \mathcal{W}$
Data Semantics Constraints	Limited number of bits $\lVert q_m \rVert_0 < k$

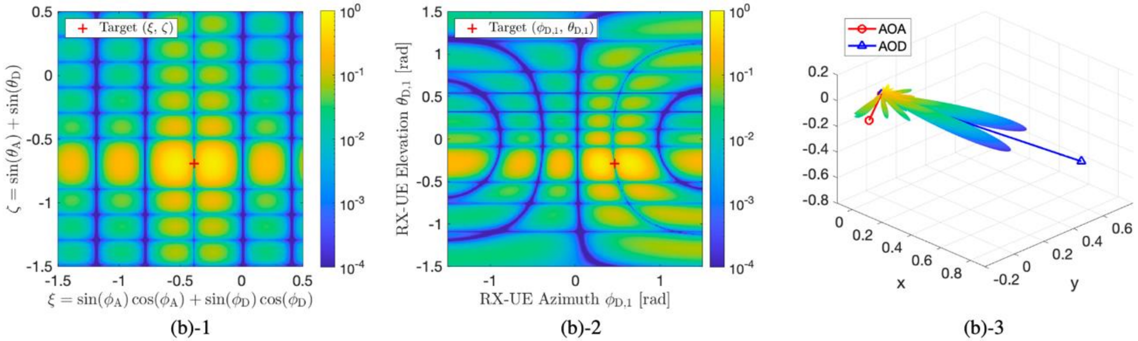
Model-based Beam Design

Directional beam



(a) DIR beam $\boldsymbol{\omega}_1$

Derivative beam

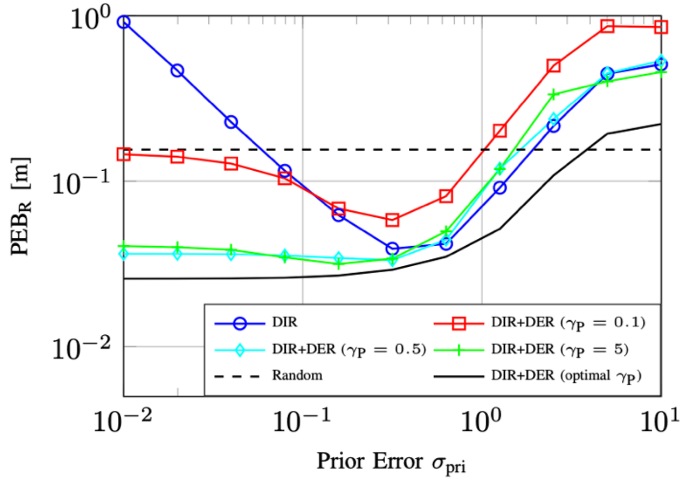


(b) DER beam $\boldsymbol{\omega}_2$

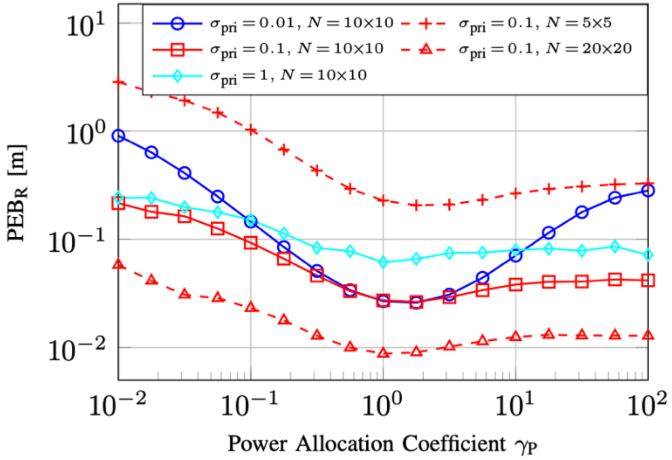
$$\boldsymbol{\omega}^{(1)} = \mathbf{a}_R^*(\xi,\zeta) = e^{-j\frac{2\pi f_c}{c}\mathbf{Z}^\top[0,\xi,\zeta]^\top},$$

$$\boldsymbol{\omega}^{(2)} = \frac{\partial \mathbf{a}_R^*(\xi,\zeta)}{\partial \xi} = \boldsymbol{\omega}^{(1)} \odot (-j\frac{2\pi f_c}{c}\mathbf{Z}^\top[0,1,0]^\top),$$

$$\boldsymbol{\omega}^{(3)} = \frac{\partial \mathbf{a}_R^*(\xi,\zeta)}{\partial \zeta} = \boldsymbol{\omega}^{(1)} \odot (-j\frac{2\pi f_c}{c}\mathbf{Z}^\top[0,0,1]^\top),$$



DIR codebook: bounds decrease and increase, which can be mitigated by power control.

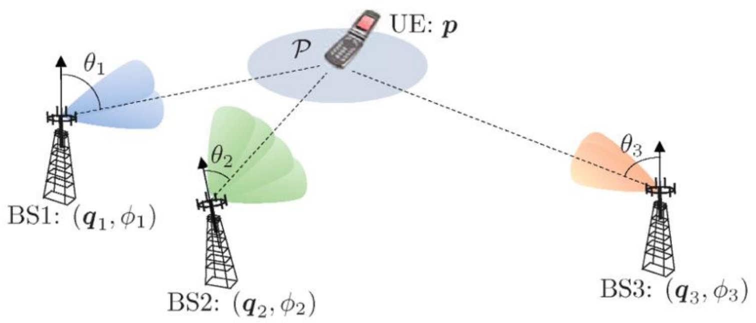


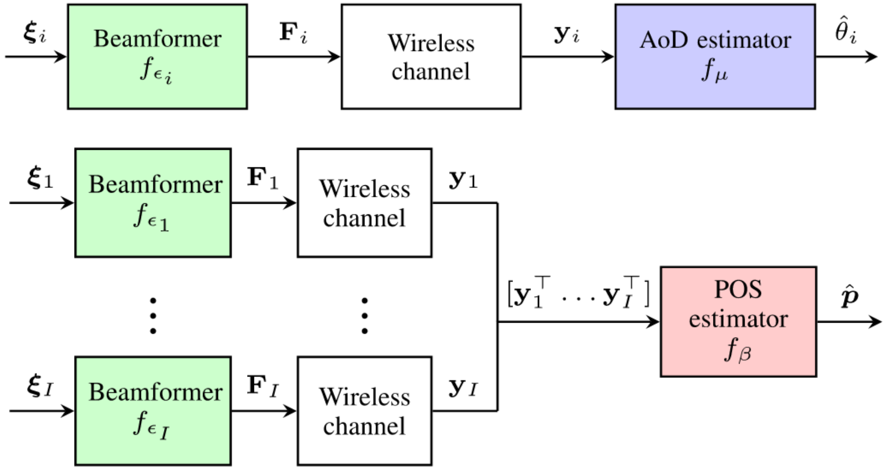
Power control is important when the prior error level is small, and the selection depends on the RIS size.

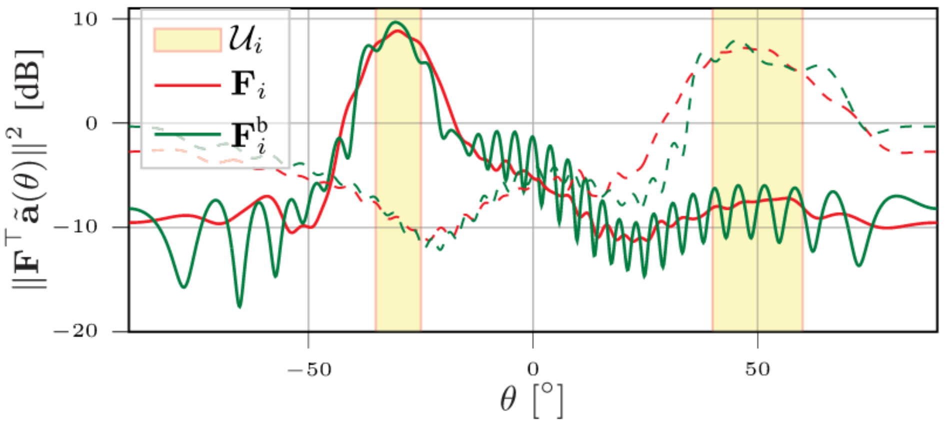
Chen, Hui, Pinjun Zheng, Musa Furkan Keskin, Tareq Al-Naffouri, and Henk Wymeersch. "Multi-RIS-enabled 3D sidelink positioning." *IEEE Transactions on Wireless Communications* 23, no. 8 (2024): 8700-8716.

Learning-based Beam Design

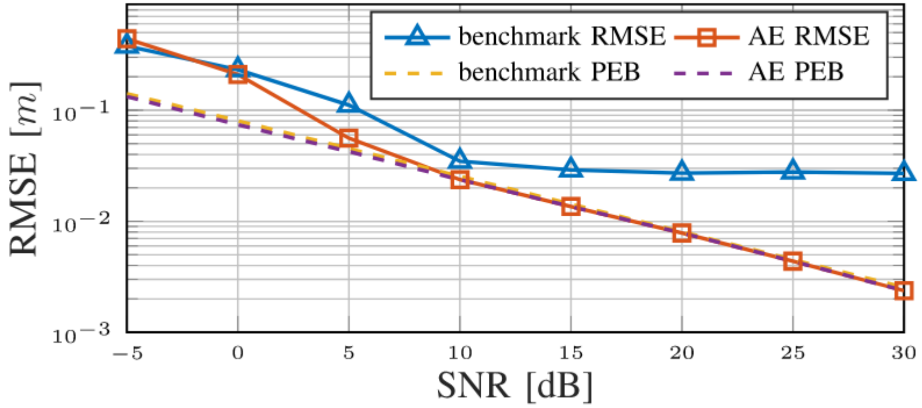
Multi-BS positioning (antenna displacement error)







Learned beam pattern differs from the benchmark and provides better performance



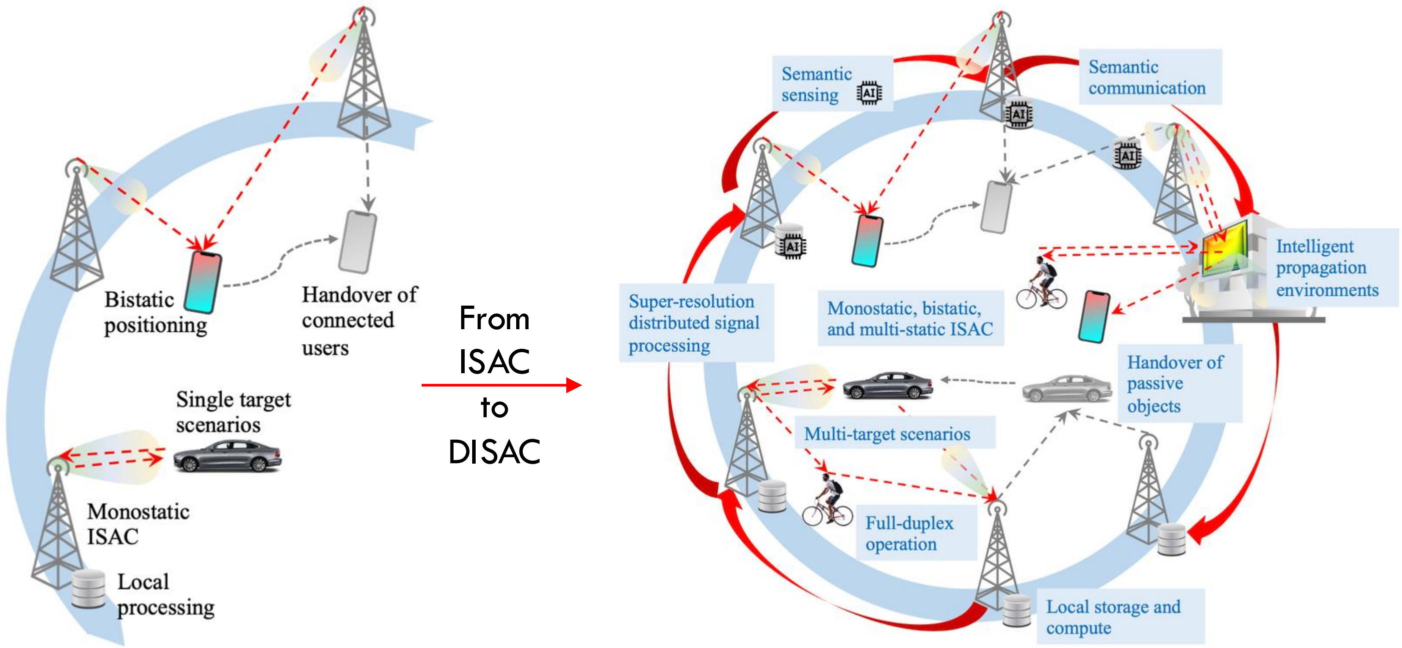
Rivetti, Steven, José Miguel Mateos-Ramos, Yibo Wu, Jinxiang Song, Musa Furkan Keskin, Vijaya Yajnanarayana, Christian Häger, and Henk Wymeersch. "Spatial signal design for positioning via end-to-end learning." *IEEE Wireless Communications Letters* 12, no. 3 (2023): 525-529.

Key Takeaways (Optimization in Sensing Systems)

- **Joint Optimization**: Integrates layout, scheduling, resources, beams, and data representation.
- **Cross-Layer Trade-offs**: Balances physical, informational, and semantic performance.
- **Dynamic Adaptability**: Supports scalable, heterogeneous, and time-varying systems.
- **Learning + Optimization**: Combines distributed learning with sensing-aware optimization.
- **Open Challenges**: Online re-optimization, scalability under uncertainty, multi-task adaptation.

Part II: Distributed Communication-Aided Sensing

- Distributed Sensing System
- Sensing Scenarios and Algorithms
- Coordination and Optimization in Sensing
- Sensing Anchor Calibration
- Security Aspects



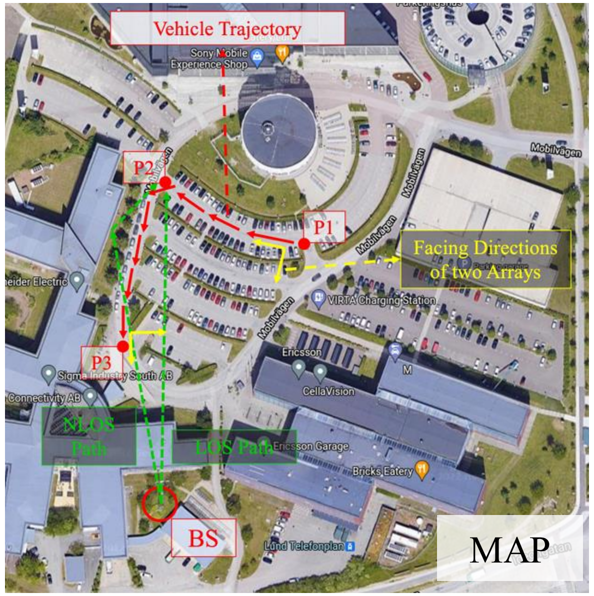
Why Calibration?

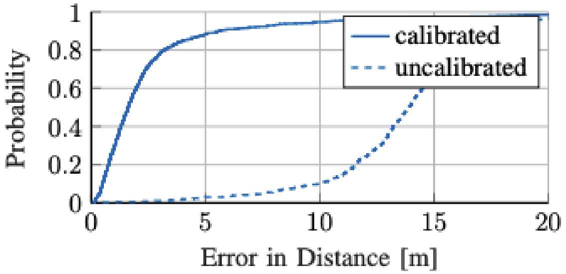
Theoretical (simulations):

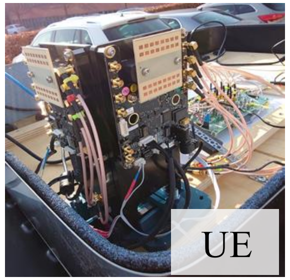
- Sub-cm accuracy can be achieved using 400MHz BW, 28 GHz system

Reality (experiments):

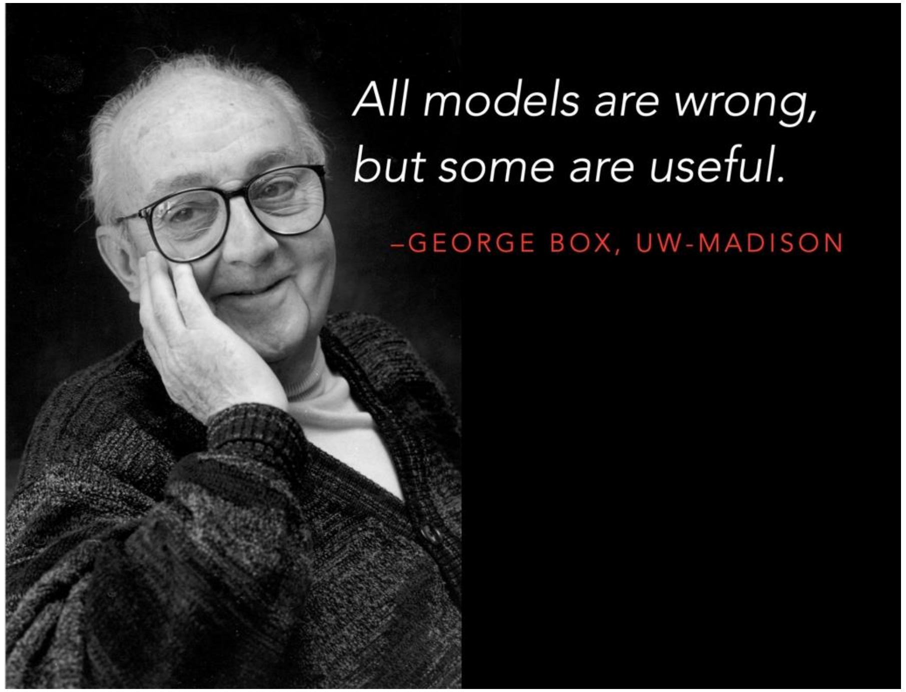
- 90% of the estimations are below 5 m







Ge, Yu, et al. "Experimental validation of single BS 5G mmWave positioning and mapping for intelligent transport." *arXiv preprint arXiv:2303.11995* (2023).

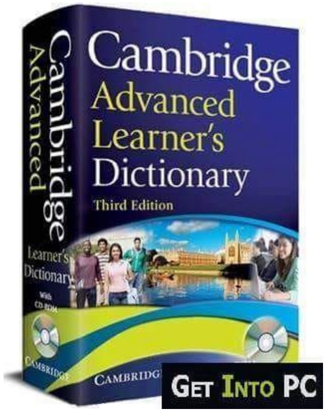


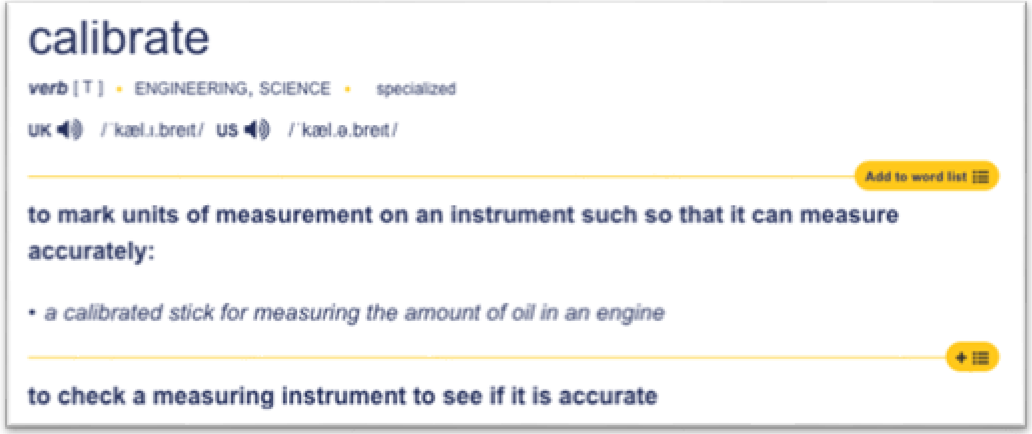
😱: All my works are wrong ??!!

😮👈: At least some are useful !!??

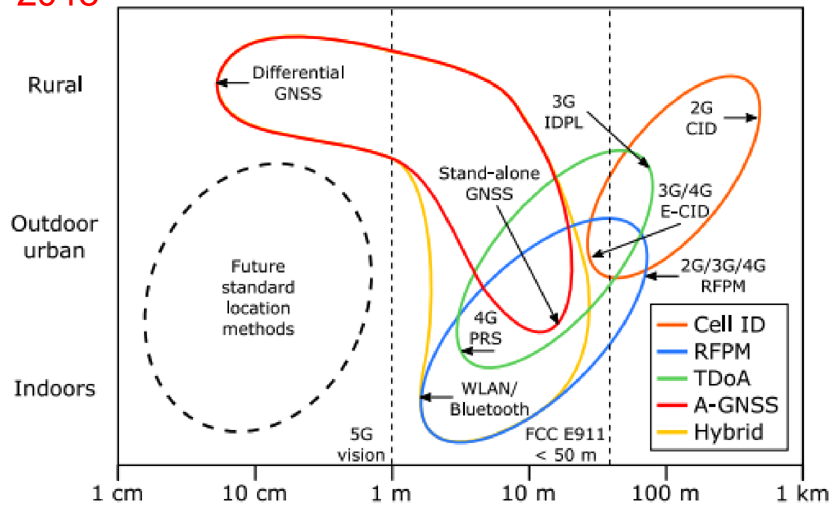
Calibration

Definition of ’calibrate‘
(Cambridge Dictionary)



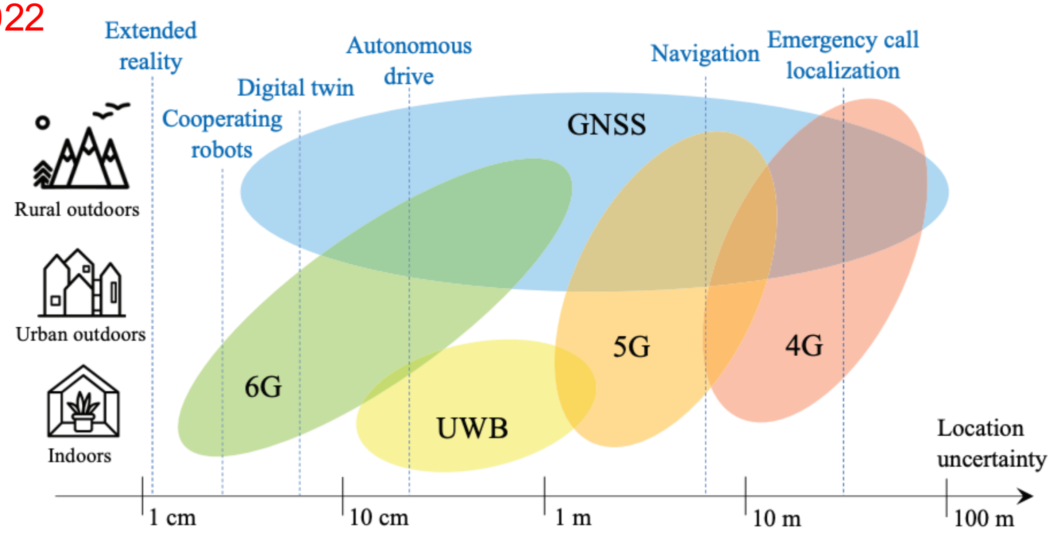

calibrate
verb [T] • ENGINEERING, SCIENCE • specialized
UK /ˈkæl.ɪ.breɪt/ US /ˈkæl.ə.breɪt/
Add to word list
to mark units of measurement on an instrument such so that it can measure accurately:
• a calibrated stick for measuring the amount of oil in an engine
to check a measuring instrument to see if it is accurate

2018



5G Vision
(sub-meter)
Too ambitious?

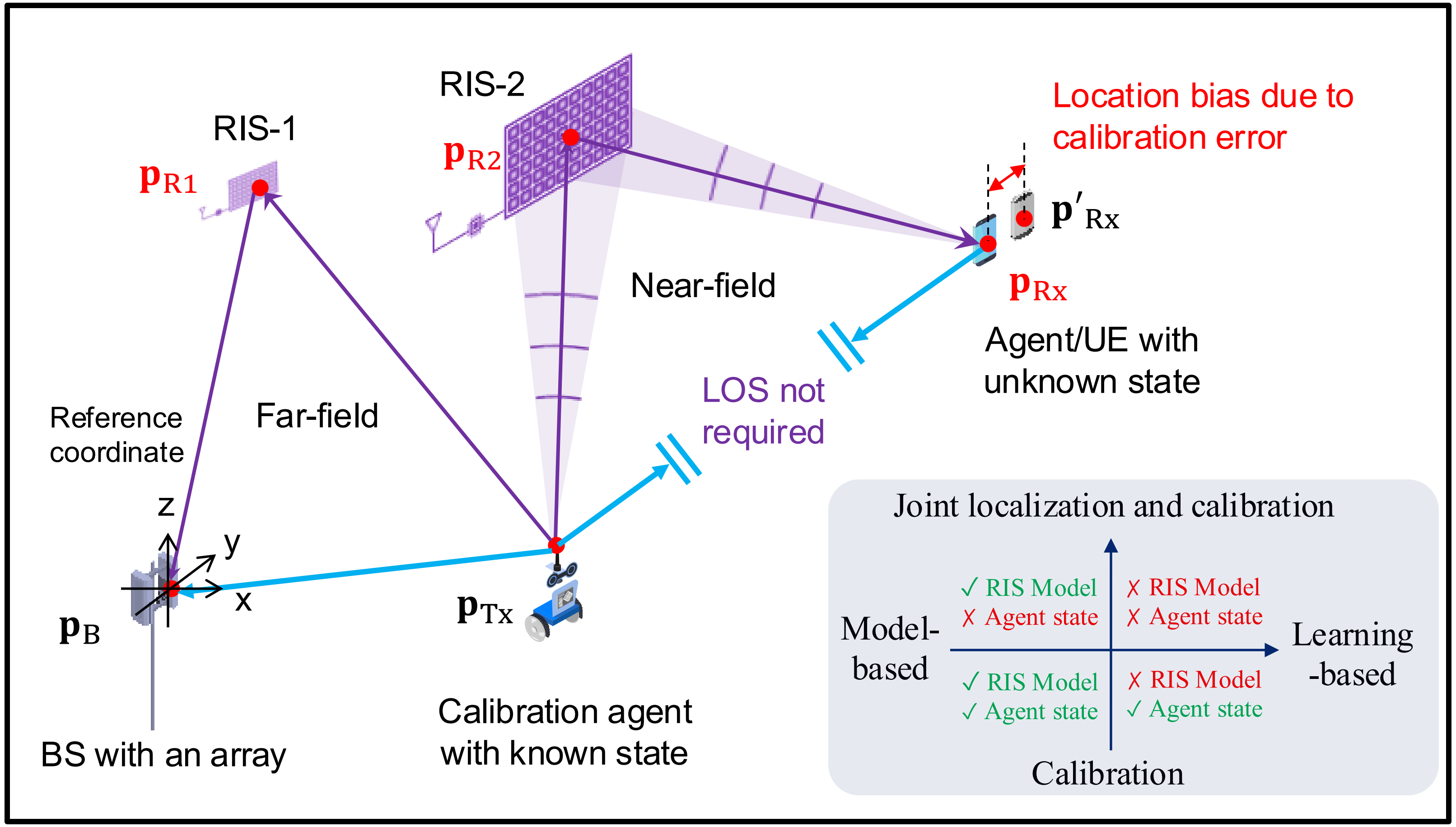
2022



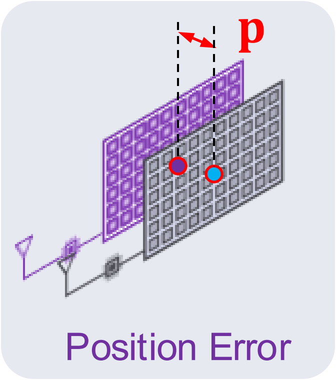
[1] Wymeersch, Henk, and Gonzalo Seco-Granados. "Radio localization and sensing—Part II: State-of-the-art and challenges." *IEEE Communications Letters* 26, no. 12 (2022): 2821-2825.
[2] del Peral-Rosado, José A. et al. "Survey of cellular mobile radio localization methods: From 1G to 5G." IEEE Communications Surveys & Tutorials 20, no. 2 (2017): 1124-1148.

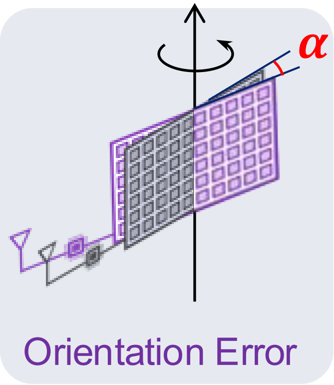
Calibration Parameters

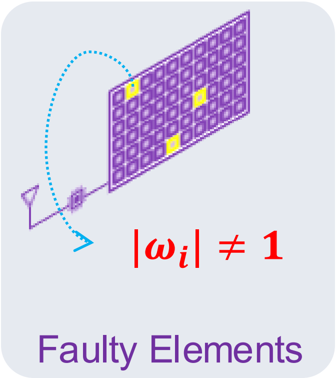
Geometry and Hardware

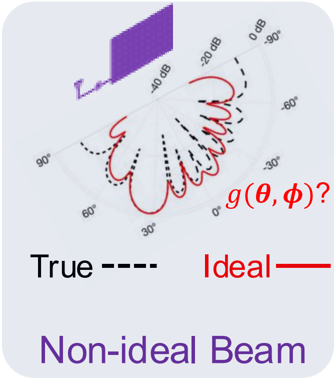


Exemplar calibration scenarios:



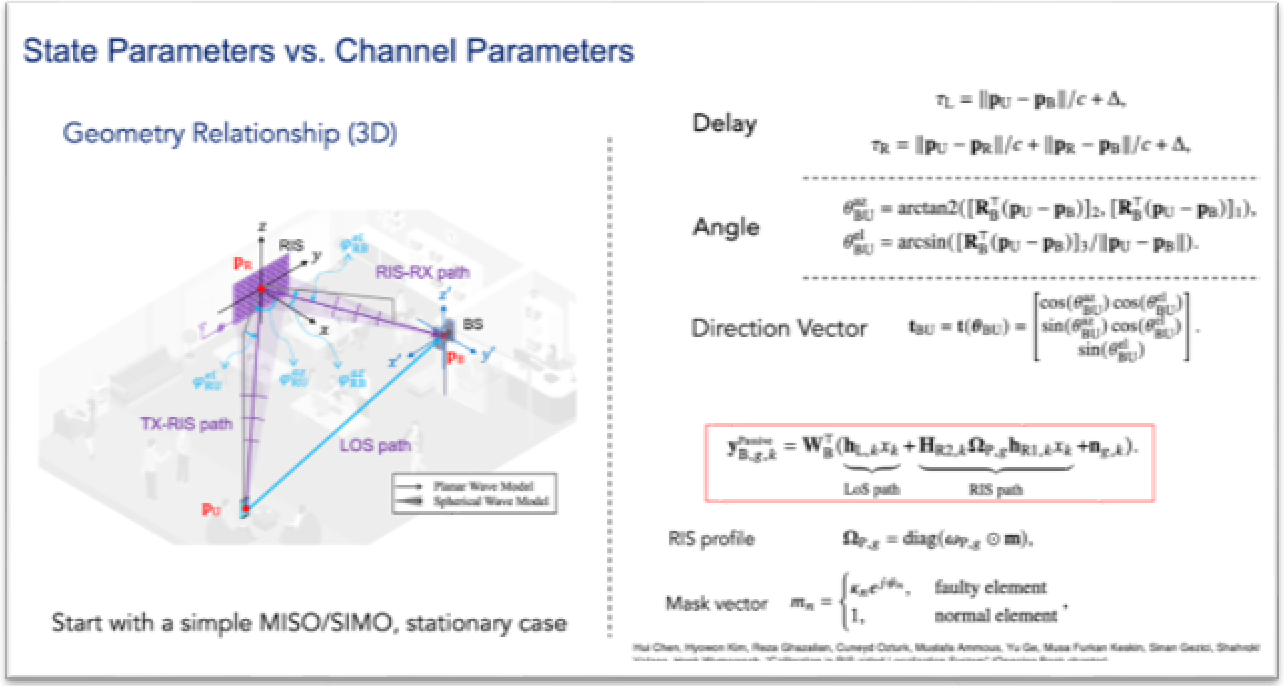






Geometry

Recall state vs channel parameters



Calibration types

- **Calibration:** Estimate RIS state with known BS and UE state
- **Joint calibration and localization:** Estimate RIS and UE state with known BS state (or self-calibration)

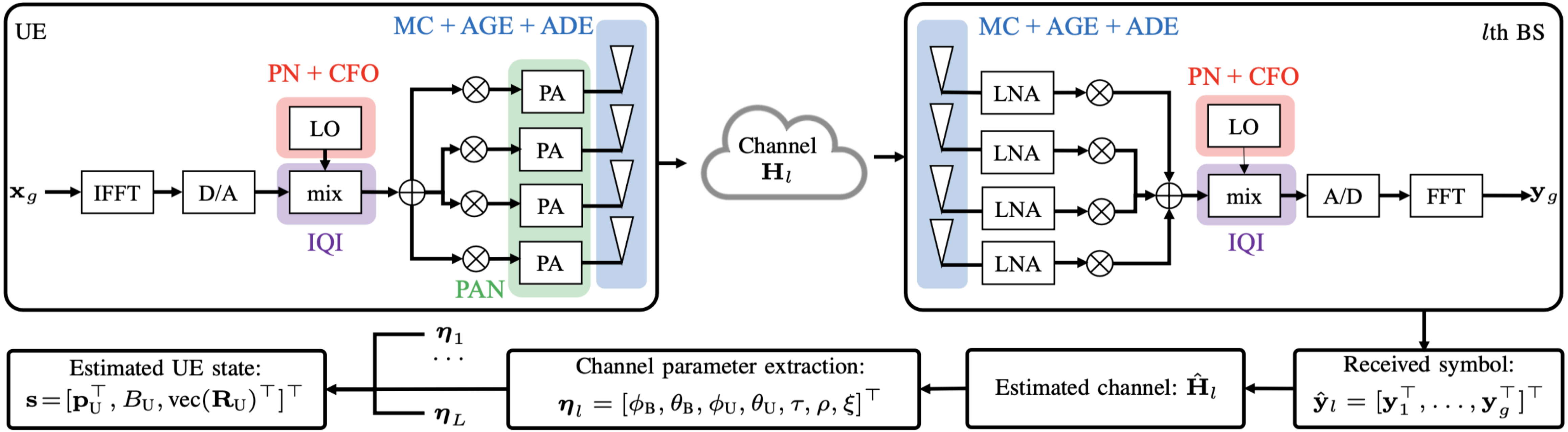
$$\boxed{\mathbf{y}^{\text{Passive}}_{\text{B},g,k} = \mathbf{W}_{\text{B}}^{\top}(\underbrace{\mathbf{h}_{\text{L},k}x_k}_{\text{LoS path}} + \underbrace{\mathbf{H}_{\text{R2},k}\boldsymbol{\Omega}_{\text{P},g}\mathbf{h}_{\text{R1},k}x_k}_{\text{RIS path}} + \mathbf{n}_{g,k}).}$$

$$\mathcal{A}_g(\boldsymbol{\theta}_{\text{RB}}, \boldsymbol{\theta}_{\text{RU}}) = \mathbf{a}_{\text{R}}(\boldsymbol{\theta}_{\text{RB}})^{\top}\boldsymbol{\Omega}_g\mathbf{a}_{\text{R}}(\boldsymbol{\theta}_{\text{RU}}) = \boldsymbol{\omega}_g^{\top}(\mathbf{a}_{\text{R}}(\boldsymbol{\theta}_{\text{RB}}) \odot \mathbf{a}_{\text{R}}(\boldsymbol{\theta}_{\text{RU}})).$$

HWI Model for OFDM Systems (Without RIS)

PN: Phase Noise
CFO: Carrier Frequency Offset
PA: Power Amplifier Nonlinearity
MC: Mutual Coupling
AGE: Array Gain Error
ADE: Antenna Displacement Error
IQI: In-phase and Quadrature Imbalance

3D, uplink, analog, MIMO: L BSs + 1 UE with clock offset



Chen, Hui, Musa Furkan Keskin, Sina Rezaei Aghdam, Hyowon Kim, Simon Lindberg, Andreas Wolfgang, Traian E. Abrudan, Thomas Eriksson, and Henk Wymeersch. "Modeling and Analysis of OFDM-based 5G/6G Localization under Hardware Impairments." *IEEE Transactions on Wireless Communications* (2023).

System Model - HWI-free Model

- 3D uplink, analog, MIMO system
- Multiple BSs, 1 UE
- K subcarriers, G transmissions

HWI-free channel model (for a specific BS-UE link)

Received symbol: $y_{g,k} = \mathbf{w}_g^\top \mathbf{H}_k \mathbf{v}_g x_{g,k} + n_{g,k}$

Channel matrix: $\mathbf{H}_k = \alpha D_k(\tau) \mathbf{a}_{\mathrm{B}}(\phi_{\mathrm{B}}, \theta_{\mathrm{B}}) \mathbf{a}_{\mathrm{U}}^\top(\phi_{\mathrm{U}}, \theta_{\mathrm{U}})$

Steering vector at UE(Angle of Departure) $\mathbf{a}_{\mathrm{U}}(\theta_{\mathrm{U}}, \phi_{\mathrm{U}}) = e^{j\frac{2\pi f_c}{c}\tilde{\mathbf{D}}_{\mathrm{U}}^\top \tilde{\mathbf{t}}_{\mathrm{U}}}$

Steering vector at BS (Angle of Arrival) $\mathbf{a}_{\mathrm{B}}(\theta_{\mathrm{B}}, \phi_{\mathrm{B}}) = e^{j\frac{2\pi f_c}{c}\tilde{\mathbf{D}}_{\mathrm{B}}^\top \tilde{\mathbf{t}}_{\mathrm{B}}}$

Phase change across subcarriers (Delay) $D_k(\tau) = e^{-j2\pi k \Delta_f \tau}$

Complex channel gain (nuisance unknown) $\alpha = \rho e^{-j\xi}$

Very well structured in the HWI-free model ! ☺

System Model - Impaired Model

Signal model with the considered HWIs

$$\underbrace{\mathbf{y}_g}_{(\in\mathcal{C}^{K\times 1})} = \mathbf{F}\big(\underbrace{\alpha_{\mathrm{B}}}_{\text{IQI, Rx}}\big(\underbrace{\mathbf{E}_{\mathrm{B},g}\boldsymbol{\Xi}_{\mathrm{B},g}}_{\text{PN+CFO, Rx}}\mathbf{F}^{\mathsf{H}}(\underbrace{\check{\mathbf{X}}_g\check{\mathbf{H}}^{\top}\mathbf{w}_g \odot \mathbf{d}(\tau)}_{\check{\mathbf{y}}_g=(\mathbf{w}_g^{\top}\check{\mathbf{H}}\tilde{\mathbf{X}}_g^{\top})^{\top}\odot\mathbf{d}(\tau)})\big)\big) + \underbrace{\beta_{\mathrm{B}}}_{\text{IQI, Rx}}\big(\underbrace{\mathbf{E}_{\mathrm{B},g}\boldsymbol{\Xi}_{\mathrm{B},g}}_{\text{PN+CFO, Rx}}\mathbf{F}^{\mathsf{H}}(\check{\mathbf{X}}_g\check{\mathbf{H}}^{\top}\mathbf{w}_g \odot \mathbf{d}(\tau))\big)^{*}\big) + \mathbf{n}_g$$

$$\underbrace{\check{\mathbf{H}}}_{(\in\mathcal{C}^{N_{\mathrm{B}}\times N_{\mathrm{U}}})} = \alpha \underbrace{\mathbf{C}_{\mathrm{B}}}_{\text{MC, Rx}}\big(\underbrace{\overbrace{\boldsymbol{b}_{\mathrm{B}}(\boldsymbol{\varphi}_{\mathrm{B}})}^{\text{AGE, Rx}} \odot e^{j\frac{2\pi}{\lambda}\overbrace{\tilde{\mathbf{D}}_{\mathrm{B}}^{\top}}^{\text{ADE, Rx}}\tilde{\mathbf{t}}_{\mathrm{B}}(\boldsymbol{\varphi}_{\mathrm{B}})}}_{\text{steering vector at Rx, } \tilde{\mathbf{a}}_{\mathrm{B}}(\boldsymbol{\varphi}_{\mathrm{B}})}\big)\big(\underbrace{\overbrace{\boldsymbol{b}_{\mathrm{U}}(\boldsymbol{\varphi}_{\mathrm{U}})}^{\text{AGE, Tx}} \odot e^{j\frac{2\pi}{\lambda}\overbrace{\tilde{\mathbf{D}}_{\mathrm{U}}^{\top}}^{\text{ADE, Tx}}\tilde{\mathbf{t}}_{\mathrm{U}}(\boldsymbol{\varphi}_{\mathrm{U}})}}_{\text{steering vector at U, } \tilde{\mathbf{a}}_{\mathrm{U}}(\boldsymbol{\varphi}_{\mathrm{U}})}\big)\underbrace{\mathbf{C}_{\mathrm{U}}^{\top}}_{\text{MC, Tx}}$$

$$\underbrace{\check{\mathbf{X}}_g}_{(\in\mathcal{C}^{K\times N_{\mathrm{U}}})} = \mathbf{F}^{H}\underbrace{\mathbf{h}_{\mathrm{PA}}}_{\text{PA, only Tx}}\big(\underbrace{\overbrace{\mathbf{E}_{\mathrm{U}}\boldsymbol{\Xi}_{\mathrm{U}}}^{\text{PN+CFO, Tx}}(\overbrace{\alpha_{\mathrm{U}}}^{\text{IQI, Tx}}\mathbf{F}^{\mathsf{H}}\mathbf{x}_g + \overbrace{\beta_{\mathrm{U}}}^{\text{IQI, Tx}}\mathbf{F}^{\mathsf{H}}\mathbf{x}_g^{*})\mathbf{v}_g}_{\text{time domain signal before PA}}\big)$$

PN: Phase Noise

CFO: Carrier Frequency Offset

MC: Mutual Coupling

PA: Power Amplifier Nonlinearity

AGE: Array Gain Error

ADE: Antenna Displacement Error

IQI: In-phase and Quadrature Imbalance

The impairment level (except PA) is controlled by a coefficient.

E.g., Residual PN $\omega_{g,k} \sim \mathcal{N}(0, \sigma^2_{\mathrm{PN}})$, Residual CFO $\epsilon \sim \mathcal{N}(0, \sigma^2_{\mathrm{CFO}})$

$$\mathbf{H}_k = \alpha D_k(\tau)\mathbf{a}_{\mathrm{B}}(\phi_{\mathrm{B}}, \theta_{\mathrm{B}})\mathbf{a}_{\mathrm{U}}^{\top}(\phi_{\mathrm{U}}, \theta_{\mathrm{U}})$$

More complicated than the previous one ! ☹

Even more complicated for RIS channels ! ☹ ☹

System Model: Mismatched vs. ‘True’ Model

Why are we using MM?

- Simple modeling (valid for low frequency systems)
- Convenient for signal processing algorithm design

Who is our enemy?!
What to calibrate?!
Model mismatch

When should we use TM?

- Always if complexity allows. Or we can use the MM with tolerable performance loss.
- The complexity is introduced with model itself and additional unknowns

We like something simple

$$\underbrace{\mathbf{y}_g}_{(\in\mathcal{C}^{K\times 1})} = \mathbf{F}(\underbrace{\alpha_{\mathrm{B}}}_{\text{IQI, Rx}}(\underbrace{\mathbf{E}_{\mathrm{B},g}\boldsymbol{\Xi}_{\mathrm{B},g}}_{\text{PN+CFO, Rx}}\mathbf{F}^{\mathsf{H}}\underbrace{(\check{\mathbf{X}}_g\check{\mathbf{H}}^{\top}\mathbf{w}_g\odot\mathbf{d}(\tau))}_{\check{\mathbf{y}}_g=(\mathbf{w}_g^{\top}\check{\mathbf{H}}\check{\mathbf{X}}_g^{\top})^{\top}\odot\mathbf{d}(\tau)})) + \underbrace{\beta_{\mathrm{B}}}_{\text{IQI, Rx}}(\underbrace{\mathbf{E}_{\mathrm{B},g}\boldsymbol{\Xi}_{\mathrm{B},g}}_{\text{PN+CFO, Rx}}\mathbf{F}^{\mathsf{H}}(\check{\mathbf{X}}_g\check{\mathbf{H}}^{\top}\mathbf{w}_g\odot\mathbf{d}(\tau)))^*) + \mathbf{n}_g$$

$$\underbrace{\check{\mathbf{H}}}_{(\in\mathcal{C}^{N_{\mathrm{B}}\times N_{\mathrm{U}}})} = \alpha\underbrace{\mathbf{C}_{\mathrm{B}}}_{\text{MC, Rx}}\underbrace{(\overbrace{\boldsymbol{b}_{\mathrm{B}}(\boldsymbol{\varphi}_{\mathrm{B}})}^{\text{AGE, Rx}}\odot e^{j\frac{2\pi}{\lambda}\overbrace{\tilde{\mathbf{D}}_{\mathrm{B}}^{\top}}^{\text{ADE, Rx}}\tilde{\mathbf{t}}_{\mathrm{B}}(\boldsymbol{\varphi}_{\mathrm{B}})})}_{\text{steering vector at Rx, }\tilde{\mathbf{a}}_{\mathrm{B}}(\boldsymbol{\varphi}_{\mathrm{B}})}\underbrace{(\overbrace{\boldsymbol{b}_{\mathrm{U}}(\boldsymbol{\varphi}_{\mathrm{U}})}^{\text{AGE, Tx}}\odot e^{j\frac{2\pi}{\lambda}\overbrace{\tilde{\mathbf{D}}_{\mathrm{U}}^{\top}}^{\text{ADE, Tx}}\tilde{\mathbf{t}}_{\mathrm{U}}(\boldsymbol{\varphi}_{\mathrm{U}})})}_{\text{steering vector at U, }\tilde{\mathbf{a}}_{\mathrm{U}}(\boldsymbol{\varphi}_{\mathrm{U}})}\underbrace{\mathbf{C}_{\mathrm{U}}^{\top}}_{\text{MC, Tx}}$$

$$\underbrace{\check{\mathbf{X}}_g}_{(\in\mathcal{C}^{K\times N_{\mathrm{U}}})} = \mathbf{F}^H\underbrace{\mathbf{h}_{\mathrm{PA}}}_{\text{PA, only Tx}}\underbrace{(\overbrace{\mathbf{E}_{\mathrm{U}}\boldsymbol{\Xi}_{\mathrm{U}}}^{\text{PN+CFO, Tx}}(\overbrace{\alpha_{\mathrm{U}}}^{\text{IQI, Tx}}\mathbf{F}^{\mathsf{H}}\mathbf{x}_g + \overbrace{\beta_{\mathrm{U}}}^{\text{IQI, Tx}}\mathbf{F}^{\mathsf{H}}\mathbf{x}_g^*)\mathbf{v}_g)}_{\text{time domain signal before PA}}$$

PN: Phase Noise
CFO: Carrier Frequency Offset
MC: Mutual Coupling
PA: Power Amplifier Nonlinearity
AGE: Array Gain Error
ADE: Antenna Displacement Error
IQI: In-phase and Quadrature Imbalance

MLE and Mismatched MLE

- Maximum likelihood estimator (MLE)

$$[\hat{\mathbf{p}}_{\mathrm{MLE}}, \hat{\alpha}_{\mathrm{MLE}}] = \arg\max_{\mathbf{p},\alpha} \ln f_{\mathrm{TM}}(\mathbf{y}|\alpha, \mathbf{p})$$

$$\mathbf{y} \sim f_{\mathrm{TM}}(\mathbf{y}|\alpha, \mathbf{p}), \ \ \mathbf{y} \in \mathbb{C}^{\mathcal{G}K \times 1}$$

- TM data + TM model: Maximum likelihood estimator (MLE)

$$\hat{\mathbf{p}}_{\mathrm{MLE}} = \arg\min_{\mathbf{p}} \left\| \mathbf{y} - \frac{\bar{\boldsymbol{\eta}}(\mathbf{p})^{\mathsf{H}}\mathbf{y}}{\|\bar{\boldsymbol{\eta}}(\mathbf{p})\|^2} \bar{\boldsymbol{\eta}}(\mathbf{p}) \right\|^2$$

Noise-free TM observation

$$\bar{\boldsymbol{\eta}}(\mathbf{p}) = \bar{\boldsymbol{\mu}}(\alpha, \mathbf{p})/\alpha$$
$$\bar{\boldsymbol{\mu}}(\alpha, \mathbf{p}) = [\bar{\boldsymbol{\mu}}_{1,1}^{\top}, \dots, \bar{\boldsymbol{\mu}}_{G,K}^{\top}]^{\top}$$
$$\bar{\boldsymbol{\mu}}_{g,k} = \mathbf{W}_g^{\top}\mathbf{h}_k^{\mathrm{TM}} x_{g,k}$$

- TM data + MM model: Mismatched maximum likelihood estimator (MMLE)

$$\hat{\mathbf{p}}_{\mathrm{MMLE}} = \arg\min_{\mathbf{p}} \left\| \mathbf{y} - \frac{\tilde{\boldsymbol{\eta}}(\mathbf{p})^{\mathsf{H}}\mathbf{y}}{\|\tilde{\boldsymbol{\eta}}(\mathbf{p})\|^2} \tilde{\boldsymbol{\eta}}(\mathbf{p}) \right\|^2$$

Noise-free MM observation

$$\tilde{\boldsymbol{\eta}}(\mathbf{p}) = \tilde{\boldsymbol{\mu}}(\alpha, \mathbf{p})/\alpha$$
$$\tilde{\boldsymbol{\mu}}(\alpha, \mathbf{p}) = [\tilde{\boldsymbol{\mu}}_{1,1}^{\top}, \dots, \tilde{\boldsymbol{\mu}}_{G,K}^{\top}]^{\top}$$
$$\tilde{\boldsymbol{\mu}}_{g,k} = \mathbf{W}_g^{\top}\mathbf{h}_k^{\mathrm{MM}} x_{g,k}$$

Chen, Hui, Ahmed Elzanaty, Reza Ghazalian, Musa Furkan Keskin, Riku Jäntti, and Henk Wymeersch. "Channel model mismatch analysis for XL-MIMO systems from a localization perspective." In *GLOBECOM 2022-2022 IEEE Global Communications Conference*, pp. 1588-1593. IEEE, 2022.

Estimators and Lower Bounds - MCRB

- LB of the state parameters

$$\mathrm{LB} = \mathrm{LB}(\bar{\boldsymbol{\theta}}, \boldsymbol{\theta}_0) = \underbrace{\mathbf{A}_{\boldsymbol{\theta}_0}^{-1}\mathbf{B}_{\boldsymbol{\theta}_0}\mathbf{A}_{\boldsymbol{\theta}_0}^{-1}}_{\mathrm{MCRB}(\boldsymbol{\theta}_0)} + \underbrace{(\bar{\boldsymbol{\theta}} - \boldsymbol{\theta}_0)(\bar{\boldsymbol{\theta}} - \boldsymbol{\theta}_0)^\top}_{\mathrm{Bias}(\boldsymbol{\theta}_0)}$$

Pseudo-true parameter

Parameter vector for the TM

Minimize Kullback–Leibler divergence between $f_{\mathrm{MM}}(\mathbf{y}|\boldsymbol{\theta})$ and $f_{\mathrm{TM}}(\mathbf{y}|\bar{\boldsymbol{\theta}})$

- Other parameters

$$\boldsymbol{\theta}_0 = \arg\min_{\boldsymbol{\theta}} \|\bar{\boldsymbol{\mu}}(\bar{\boldsymbol{\theta}}) - \tilde{\boldsymbol{\mu}}(\boldsymbol{\theta})\|^2,$$

$$[\mathbf{A}_{\boldsymbol{\theta}_0}]_{i,j} = \frac{2}{\sigma_n^2}\mathrm{Re}\left[\frac{\partial^2\tilde{\boldsymbol{\mu}}(\boldsymbol{\theta})}{\partial\theta_i\partial\theta_j}\boldsymbol{\epsilon}(\boldsymbol{\theta}) - \frac{\partial\tilde{\boldsymbol{\mu}}(\boldsymbol{\theta})}{\partial\theta_j}\left(\frac{\partial\tilde{\boldsymbol{\mu}}(\boldsymbol{\theta})}{\partial\theta_i}\right)^{\mathsf{H}}\right]\Bigg|_{\boldsymbol{\theta}=\boldsymbol{\theta}_0}$$

$$[\mathbf{B}_{\boldsymbol{\theta}_0}]_{i,j} = \frac{4}{\sigma_n^4}\mathrm{Re}\left[\frac{\partial^2\tilde{\boldsymbol{\mu}}(\boldsymbol{\theta})}{\partial\theta_i}\boldsymbol{\epsilon}(\boldsymbol{\theta})\right]\mathrm{Re}\left[\frac{\partial^2\tilde{\boldsymbol{\mu}}(\boldsymbol{\theta})}{\partial\theta_j}\boldsymbol{\epsilon}(\boldsymbol{\theta})\right] + \frac{2}{\sigma_n^2}\mathrm{Re}\left[\frac{\partial\tilde{\boldsymbol{\mu}}(\boldsymbol{\theta})}{\partial\theta_j}\left(\frac{\partial\tilde{\boldsymbol{\mu}}(\boldsymbol{\theta})}{\partial\theta_i}\right)^{\mathsf{H}}\right]\Bigg|_{\boldsymbol{\theta}=\boldsymbol{\theta}_0}$$

- The derived LB satisfies

$$\mathbb{E}_{\mathrm{TM}}\{(\hat{\boldsymbol{\theta}}_{\mathrm{MMLE}} - \bar{\boldsymbol{\theta}})(\hat{\boldsymbol{\theta}}_{\mathrm{MMLE}} - \bar{\boldsymbol{\theta}})^\top\} \geq \mathrm{LB}(\bar{\boldsymbol{\theta}}, \boldsymbol{\theta}_0)$$

- MCRB is SNR dependent (like CRB), dominates in low SNR
- Bias is a fixed term, dominates in high SNR

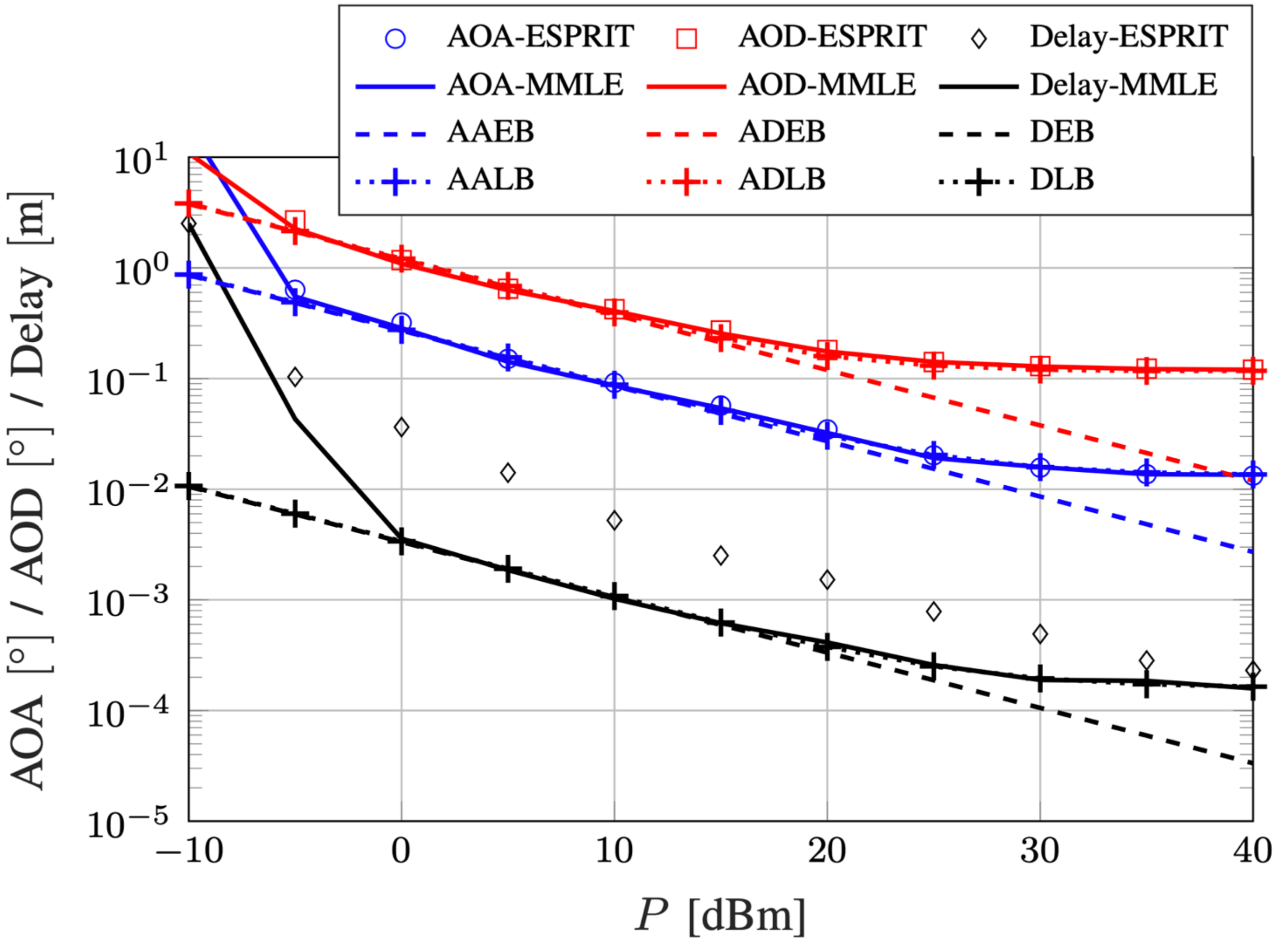
Initial Results: Channel Parameter Estimation

Bounds vs. estimators for channel estimation

- Two estimators: ESPRIT, MMLE (markers vs. solid)
- Two bounds: CRB, LB (dashed vs. dotted cross)

Main findings

- CRBs (AAEB, ADEB, DEB)of the ideal model decrease with transmit power
- LBs will saturate (equals to a constant) in high transmit power
- Refined results using MMLE (initialized with ESPRIT estimation) can attach the derived LB



AOA, AOD, Delay estimation

Localization under Hardware Impairment

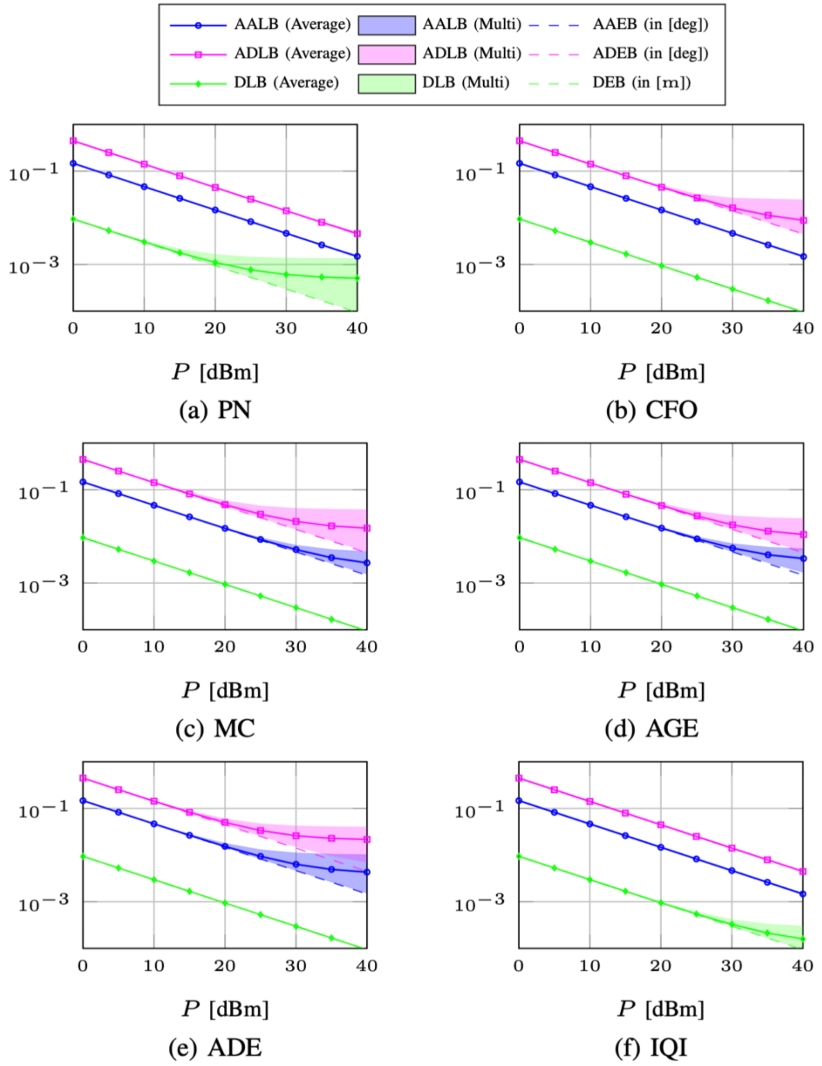


TABLE III

THE EFFECTS OF HWIS ON LOCALIZATION AND COMMUNICATIONS

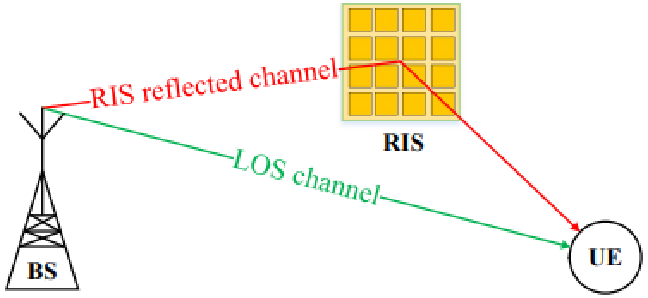
Type of HWI	AOD	AOA	TOA	SER
Phase Noise	L	L	H	H
Carrier Frequency Offset	H*	H*	L	L
Mutual Coupling	H	H	L	L
Power Amplifier Nonlinearity	H*	H*	H*	H*
Array Gain Error	H	H	L	L
Antenna Displacement Error	H	H	L	L
IQ Imbalance	L	L	H	H

*The effect of CFO on angle estimations depends on the sweeping order and number of transmissions. The effect of PAN depends on the transmit power and the nonlinear region of the amplifier.

Chen, Hui, Musa Furkan Keskin, Adham Sakhnini, Nicoló Decarli, Sofie Pollin, Davide Dardari, and Henk Wymeersch. "6G localization and sensing in the near field: Fundamentals, opportunities, and challenges." IEEE Wireless Communications (2023).

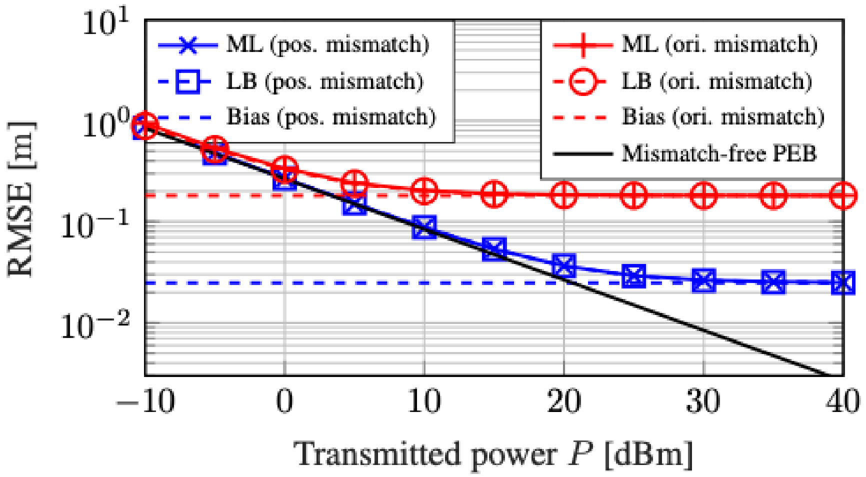
RIS Localization under Geometry Mismatch

SISO localization

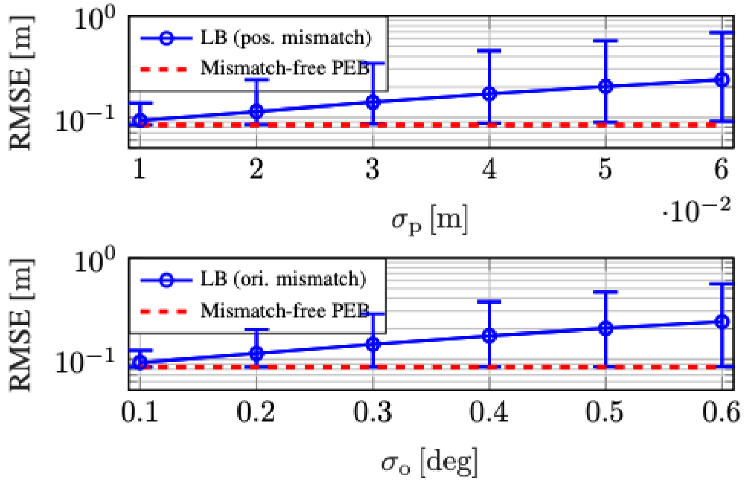


Main findings

- MLB saturates at high SNR
- MCRB analysis suggests how accurate calibration need to be performed to reach the performance requirement



ML-RMSE, LB, and bias term versus transmitted power (SNR) for RIS position mismatch (υ = 0.01 × 1 m) and orientation mismatch (ν = 0.5 × 1 deg).



LB and PEB versus different levels of RIS position mismatch ($\sigma_p = \{1, 2, 3, 4, 5, 6\} \times 0.01$ m) and orientation mismatch ($\sigma_o = \{1, 2, 3, 4, 5, 6\} \times 0.1$ deg).

Zheng, Pinjun, Hui Chen, Tarig Ballal, Henk Wymeersch, and Tareq Y. Al-Naffouri. "Misspecified Cramér-Rao bound of RIS-aided localization under geometry mismatch." In *ICASSP 2023-2023 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, pp. 1-5. IEEE, 2023.

Multi-static Sensing of RIS (Geometry)

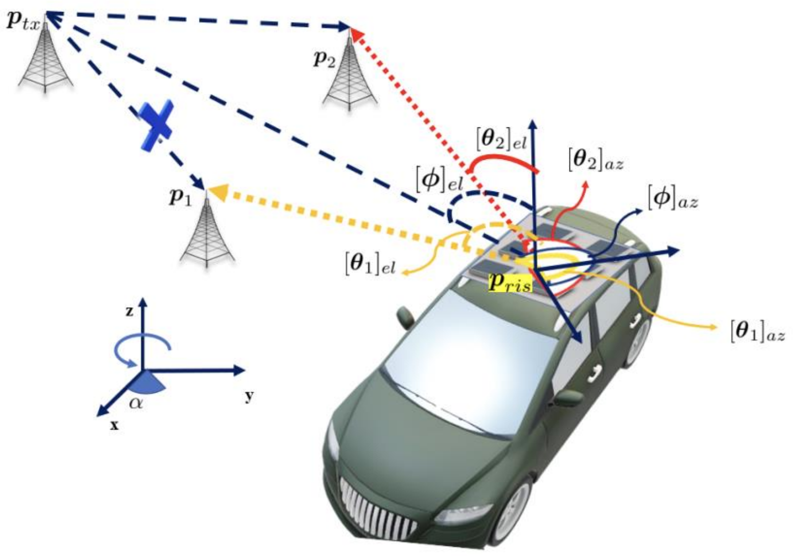
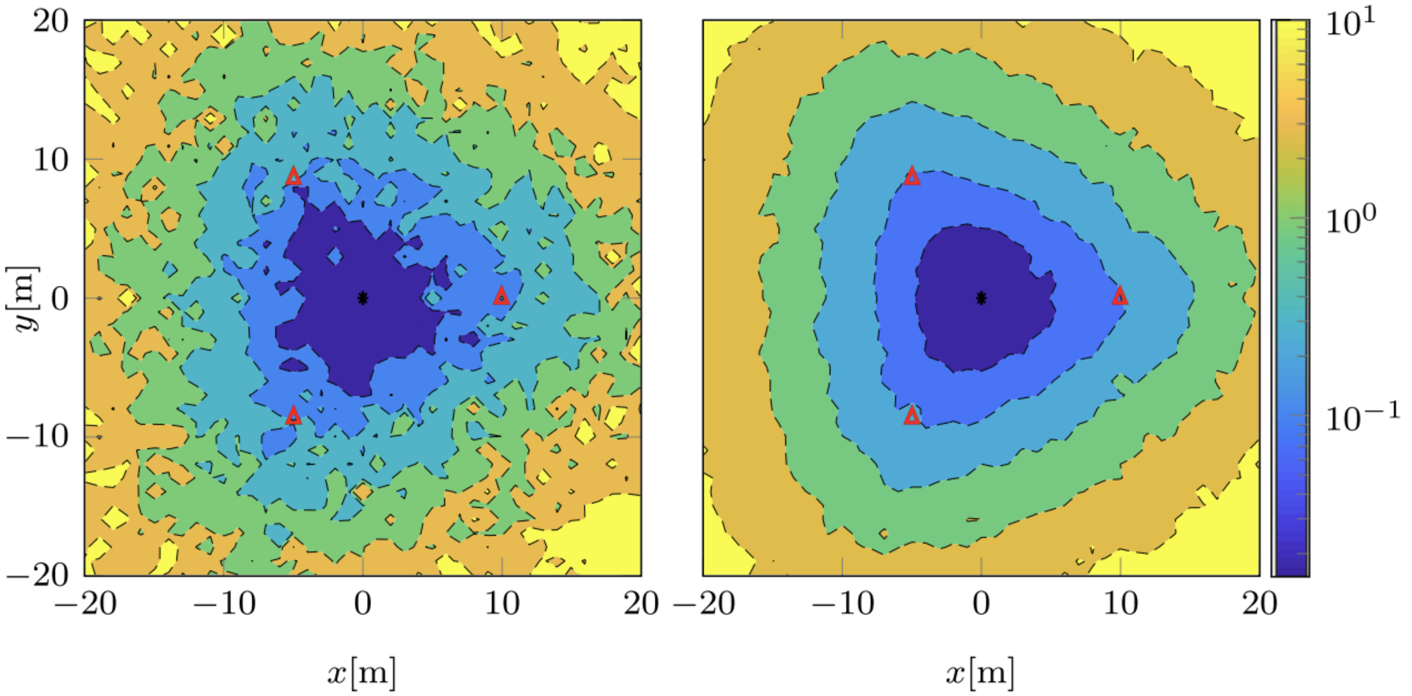


Fig. 1: The considered system model comprising a single-antenna TX, M single-antenna RXs (here, $M = 2$ for illustrational simplicity), and an RIS with unknown 3D position and 1D orientation α (w.r.t. the z axis).



Multiple known transmitters & receivers

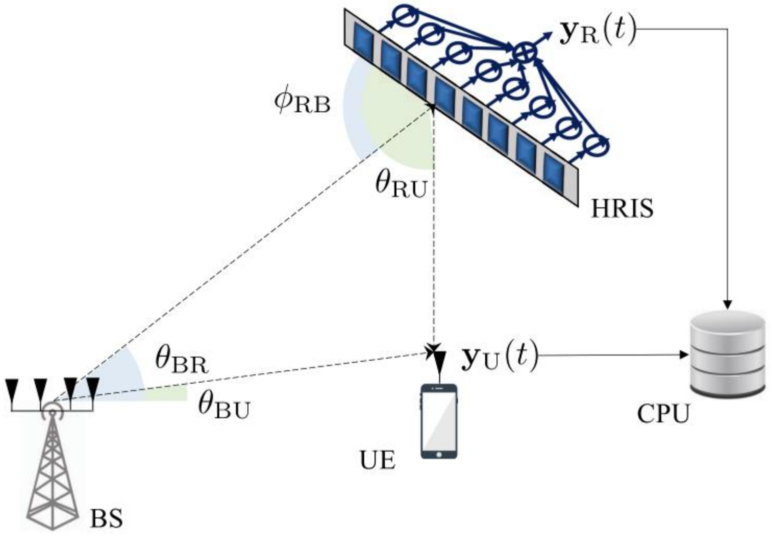
⇩

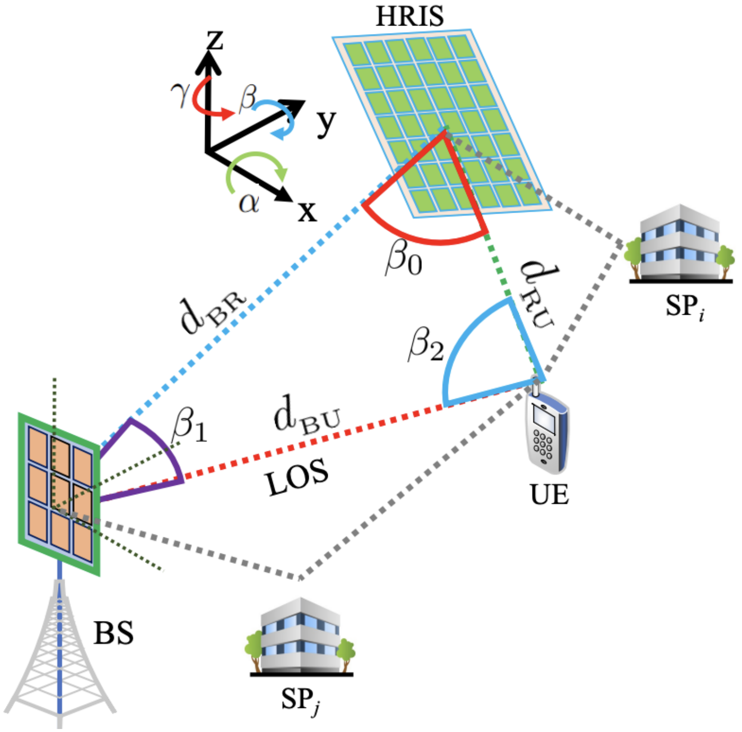
The state of a RIS (a target equipped with a RIS)

Ghazalian, Reza, Hui Chen, George C. Alexandropoulos, Gonzalo Seco-Granados, Henk Wymeersch, and Riku Jäntti. "RIS Position and Orientation Estimation via Multi-Carrier Transmissions and Multiple Receivers." In *ICC 2023-IEEE International Conference on Communications*, pp. 2915-2920. IEEE, 2023.

Keykhosravi, Kamran, Musa Furkan Keskin, Satyam Dwivedi, Gonzalo Seco-Granados, and Henk Wymeersch. "Semi-passive 3D positioning of multiple RIS-enabled users." *IEEE Transactions on Vehicular Technology* 70, no. 10 (2021): 11073-11077.

Joint Calibration and Localization (Geometry)





Step summary:
1 Estimate angles at the BS and RIS
2 Estimate the delay of both path
3 Perform localization and calibration

$$\hat{d} \triangleq d_{\mathrm{BR}} + d_{\mathrm{RU}} - d_{\mathrm{BU}} = c(\hat{\tau}_{\mathrm{BRU}} - \hat{\tau}_{\mathrm{BU}})$$

$$\sin(\beta_0)/d_{\mathrm{RU}} = \sin(\beta_1)/d_{\mathrm{BU}} = \sin(\beta_2)/d_{\mathrm{BR}}$$

Law of sines

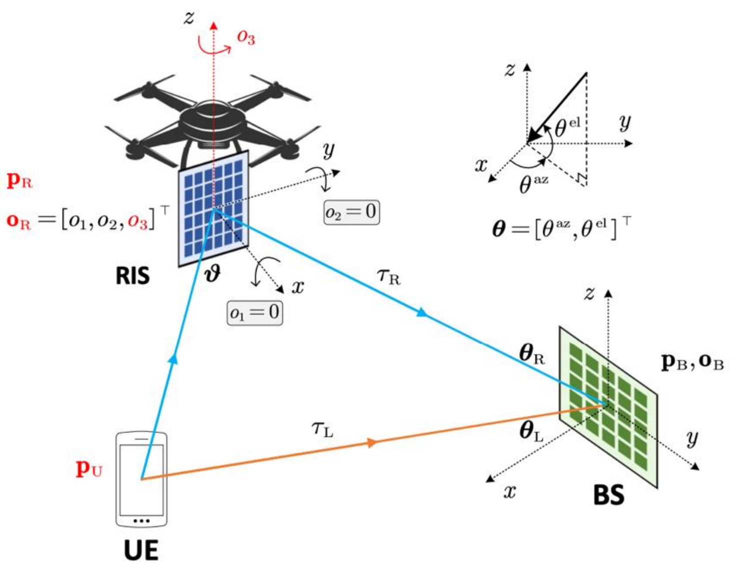
$$\hat{d}_{\mathrm{BU}} = \frac{\hat{d}\sin\beta_1}{\sin\beta_0 + \sin\beta_2 - \sin\beta_1}$$

$$\hat{d}_{\mathrm{BR}} = \frac{\hat{d}\sin\beta_2}{\sin\beta_0 + \sin\beta_2 - \sin\beta_1}$$

Ghazalian, Reza, Hui Chen, George C. Alexandropoulos, Gonzalo Seco-Granados, Henk Wymeersch, and Riku Jäntti. "Joint user localization and location calibration of a hybrid reconfigurable intelligent surface." IEEE Transactions on Vehicular Technology (2023).

Ghazalian, Reza, George C. Alexandropoulos, Gonzalo Seco-Granados, Henk Wymeersch, and Riku Jäntti. "Joint 3D User and 6D Hybrid Reconfigurable Intelligent Surface Localization." arXiv preprint arXiv:2401.03852 (2024).

Joint RIS Calibration and UE Positioning (Geometry)



$$\mathbf{y}_{g,k} = \mathbf{W}^\mathsf{H} \left(\mathbf{h}_\mathrm{L}^k x_{g,k} + \mathbf{H}_{\mathrm{R},2}^k \boldsymbol{\Gamma}_g \mathbf{h}_{\mathrm{R},1}^k x_{g,k} + \boxed{\mathbf{H}_{\mathrm{R},2}^k \boldsymbol{\Gamma}_g \mathbf{n}_r} + \boxed{\mathbf{n}_0}\right)$$

Active RIS introduced noise

Noise at the receiver

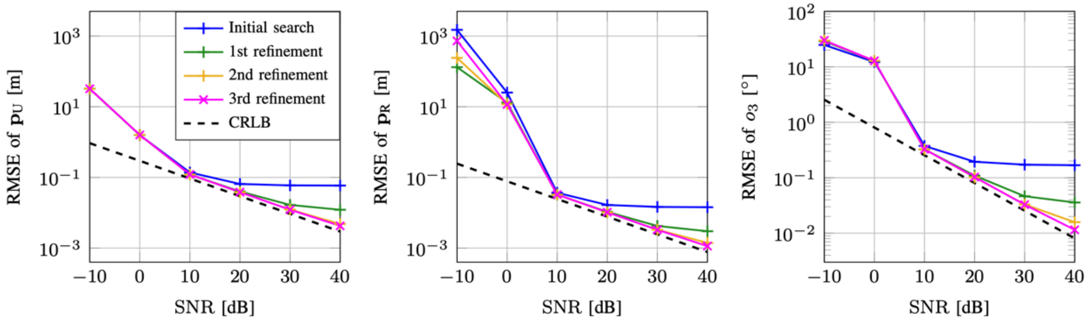
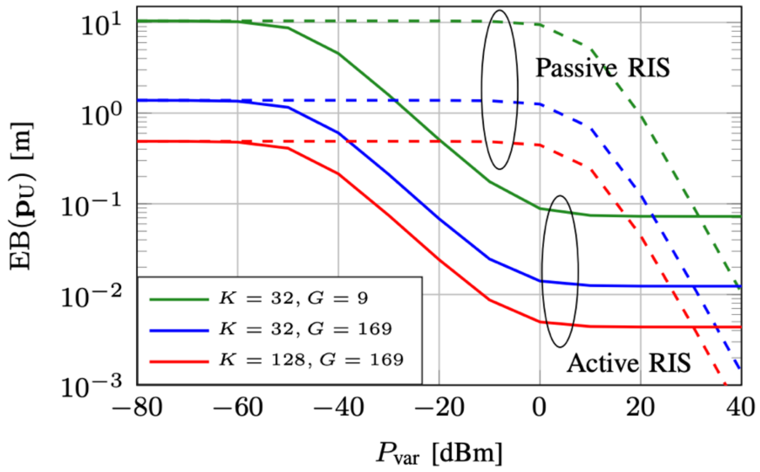


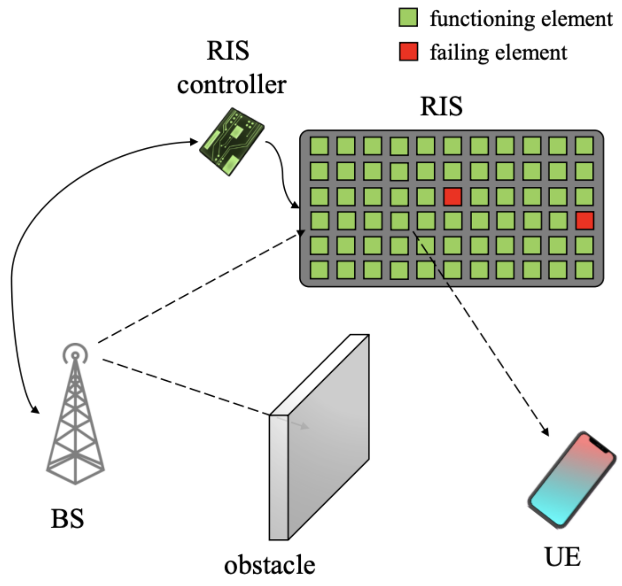
Fig. 5: The evaluation of RMSE of $\mathbf{p}_\mathrm{U}$, $\mathbf{p}_\mathrm{R}$ and o_3 versus received SNR for different numbers $(0, 1, 2, 3)$ of grid refinements.

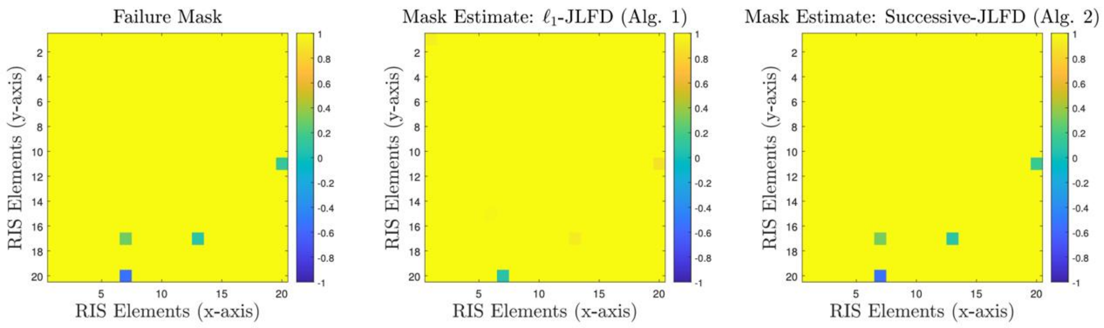


Active RIS performance saturates (so did the mismatched model)

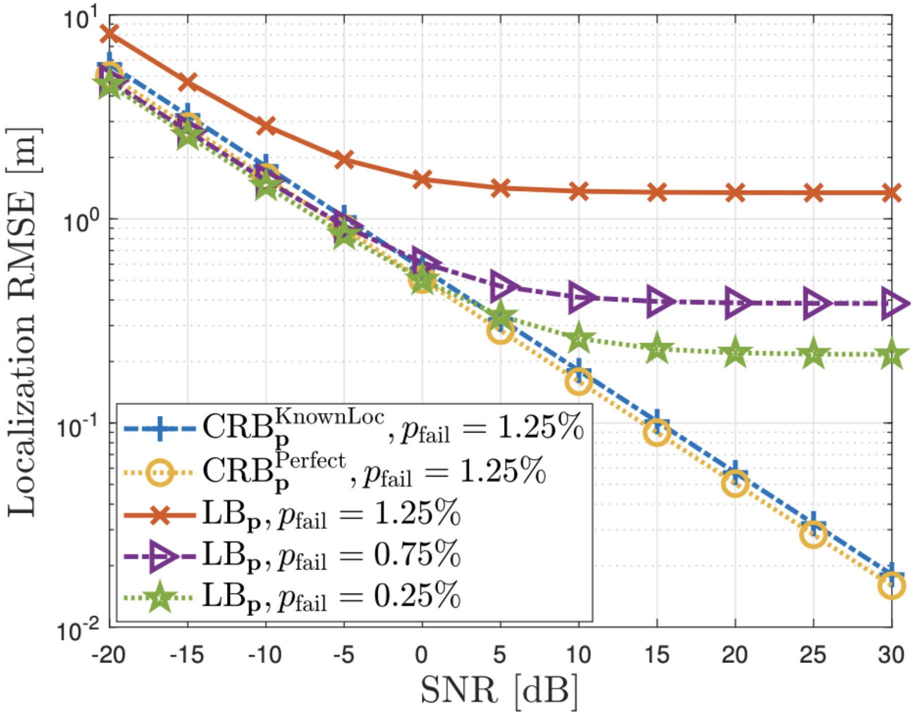
Zheng, Pinjun, Hui Chen, Tarig Ballal, Mikko Valkama, Henk Wymeersch, and Tareq Y. Al-Naffouri. "JrCUP: Joint RIS calibration and user positioning for 6G wireless systems." *IEEE Transactions on Wireless Communications* (2023).

Localization under Pixel Failures (hardware)



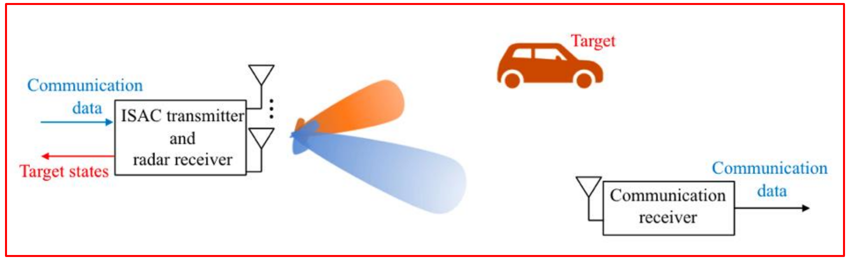


Faulty pixels can be well-calibrated



Ozturk, Cuneyd, Musa Furkan Keskin, Vincenzo Sciancalepore, Henk Wymeersch, and Sinan Gezici. "Ris-aided localization under pixel failures." *IEEE Transactions on Wireless Communications* (2024).

Learning-based ISAC



End-to-end learning (displacement error)

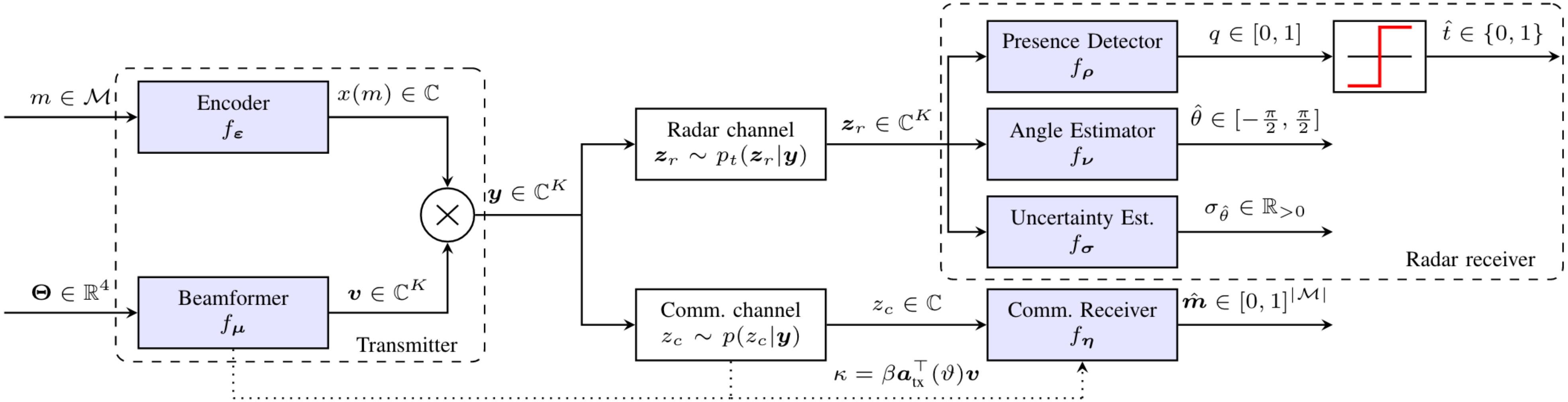


Fig. 1: Block diagram of the ISAC system model. The blocks highlighted in blue are implemented as trainable NNs as part of the proposed AE. The radar receiver is assumed to be co-located with the transmitter, while the communication receiver is remote.

Radar: $\mathcal{J}_{\text{NLL}}(\varepsilon, \mu, \rho, \nu, \sigma) = \mathcal{J}_{\text{TD}} + p(t = 1)\mathcal{J}_{\text{TR}}.$

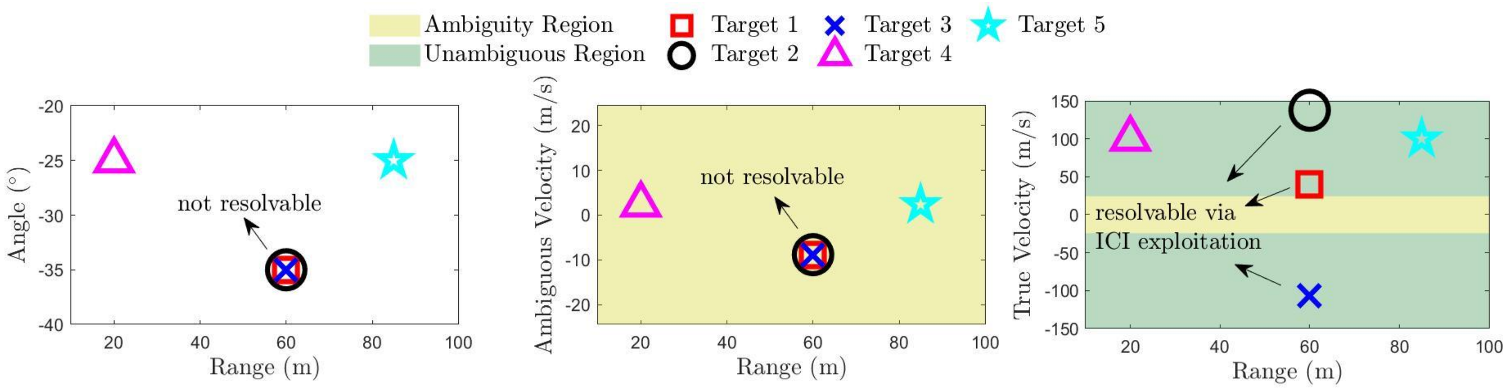
Communication: $$\mathcal{J}_{\text{CE}}(\varepsilon, \mu, \eta) = -\mathbb{E}\left[\sum_{j=1}^{C} m_j^{\text{enc}} \log(\hat{m}_j)\right].$$

ISAC: $\mathcal{J}_{\text{ISAC}}(\varepsilon, \mu, \rho, \sigma, \nu, \eta) = \omega_r \mathcal{J}_{\text{NLL}} + (1 - \omega_r)\mathcal{J}_{\text{CE}}$

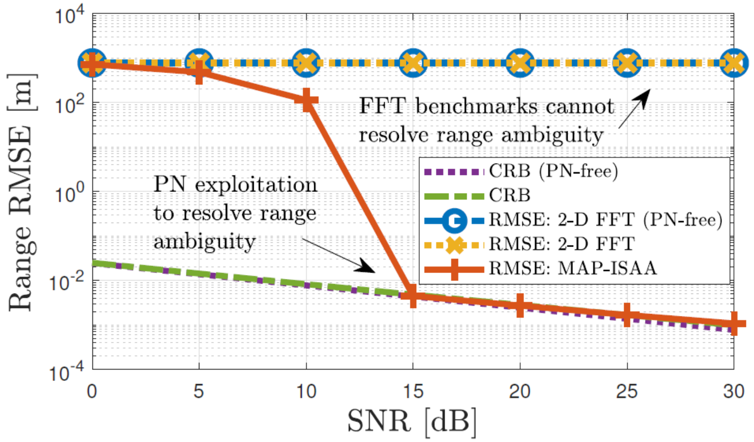
Mateos-Ramos, José Miguel, Jinxiang Song, Yibo Wu, Christian Häger, Musa Furkan Keskin, Vijaya Yajnanarayana, and Henk Wymeersch. "End-to-end learning for integrated sensing and communication." In ICC 2022-IEEE International Conference on Communications, pp. 1942-1947. IEEE, 2022.

Next Steps for Hardware Impairments: from Calibration to Exploitation

ICI exploitation:
- Significant increase of maximum unambiguous Doppler
- Improved delay-Doppler-angle resolvability



PN exploitation
- Statistics of unknown random perturbations (i.e., PN) become target signatures
- Delay-dependent PN statistics to resolve range ambiguity



RIS-aided sensing is less explored!

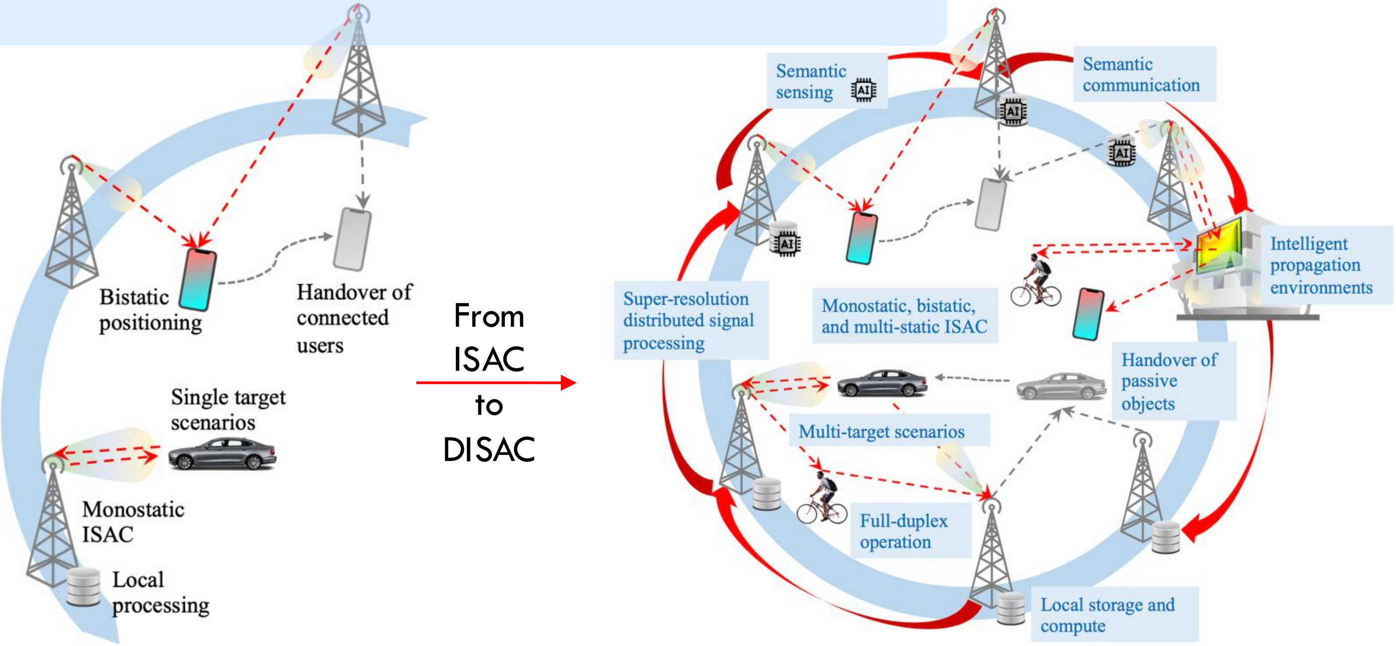
M. F. Keskin, H. Wymeersch, and V. Koivunen, "**MIMO-OFDM Joint Radar-Communications: Is ICI Friend or Foe?**," *IEEE Journal of Selected Topics in Signal Processing*, vol. 15, no. 6, pp. 1393–1408, Nov. 2021.
M. F. Keskin, H. Wymeersch, and V. Koivunen, "**Monostatic Sensing With OFDM Under Phase Noise: From Mitigation to Exploitation**," *IEEE Transactions on Signal Processing*, vol. 71, pp. 1363-1378, 2023.

Key Takeaways (Calibration)

- **Calibration is critical**: Bridges gap between theoretical and real-world performance.
- **Model mismatch**: Geometry and HWIs (e.g., PN, CFO, ADE) degrade performance.
- **Bound analysis**: MCRB is a useful to for mismatch analysis, suggesting calibration strategies.
- **Joint estimation**: Calibration and localization simultaneously is a practical solution.
- **New trends**: Turn impairments (e.g., PN, ICI) into useful sensing features.

Part II: Distributed Communication-Aided Sensing

- Distributed Sensing System
- Sensing Scenarios and Algorithms
- Coordination and Optimization in Sensing
- Sensing Anchor Calibration
- Security Aspects



Security in Sensing: Types and Definitions

“Security is the condition of a system that prevents unauthorized access to, or manipulation of, system and data resources, ensuring confidentiality, integrity, and availability.”

— *NIST SP (*National Institute of Standards and Technology Special Publication*) 800-160 Vol. 1 (2018)*

Aspect	**Communication**	**Sensing (DISAC)**
Confidentiality (Privacy)	Protect transmitted messages or user identity	Target/user identity from being inferred
Integrity (Reliability)	No message tampering	Ensure physical-world data is truthful
Availability (Robustness)	Maintain connectivity	Maintain sensing performance under attack
Authentication*	Validate source/destination identity	Validate source of sensing input (e.g.,from which UE/RIS)

Prospective Solutions to Enhance 6G Physical Layer Security

6G PHY technologies	Reference	Security & privacy issues	Key solutions	Key points	Open problems
mmWave MIMO beamforming	[103], [108], [146]	Eavesdropping Jamming Pilot contamination Location exposure	● Frequency hopping ● Injecting artificial noise or friendly jamming ● Utilize beam alignment ● Physical key generation ● Physical coding	Secrecy rate maximization	● Optimal beam alignment ● AI-based low-complexity anti-jamming ● High-performance coding ● Energy efficient solutions
Large Intelligent Surface	[119], [118]	Eavesdropping Location exposure	● Frequency hopping ● Injecting artificial noise or friendly jamming, ● Physical key generation ● Physical coding	Secrecy rate maximization	● Optimal LIS deployment ● AI-enabled LIS ● Specific LIS applications ● Energy efficient solutions
NOMA	[121], [122], [115]	Eavesdropping Power allocation contamination Location exposure Signal space expose	● Frequency hopping ● Physical key generation ● Physical coding	Secrecy rate maximization	● Security for NOMA-VLC, NOMA-THz, NOMA-LIS networks
Holographic radio	[94], [123]	Eavesdropping Location exposure	● Utilize beam alignment ● Randomly power limits ● Access point placement ● Physical key generation ● Physical coding	Secrecy rate maximization	● Optimal radio management ● Joint RF and non-RF hardware ● Holographic radio-LIS integration ● Energy efficient solutions
Terahertz communications	[125], [126], [127]	Eavesdropping Jamming Location exposure	● Frequency hopping ● Randomly power limits ● Access point placement ● Utilize beam alignment ● Injecting artificial noise or friendly jamming ● Physical key generation ● Physical coding	Secrecy rate maximization	● Optimal THz base stations ● Optimal THz-LIS integration ● Optimal beam alignment ● ● AI-based low-complexity anti-jamming solutions ● High-performance coding ● Optimal mmWave-THz links ● Energy efficient solutions
VLC communications	[128], [129], [132]	Eavesdropping Obscured attacks	● Frequency hopping ● Injecting artificial noise or friendly jamming ● Physical key generation ● Physical coding	Secrecy rate maximization	● NOMA-VLC performance ● VLC/LiFi deployment ● Optimal VLC access points
Molecular communications	[86], [93], [135]	Device configuration manipulation, kills the molecules, attacking bio-machines from Internet environment Data leakage	● Biochemical cryptography ● Firewall, IDS to detect attacks from the Internet	Confidentiality & Integrity	● Energy efficient solutions ● Secure Internet access
Physical-aided security	[137], [136], [138]	Sybil attack Physical data tampering Trajectory tracking	● Physical layer authentication	Exploit physical signal attributes to detect special attacks	● AI-based low-complexity solution ● Multi-attribute multi-observation technique

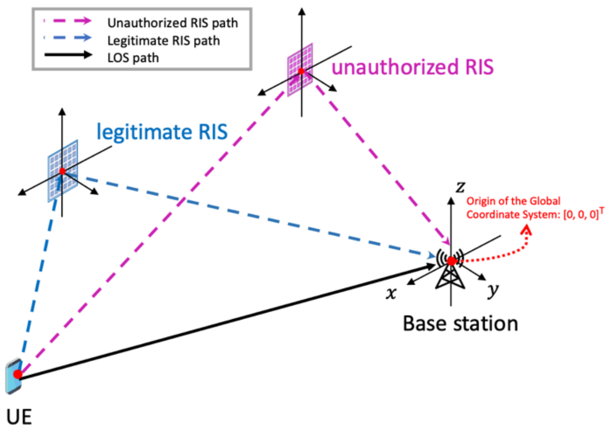
Nguyen, Van-Linh, Po-Ching Lin, Bo-Chao Cheng, Ren-Hung Hwang, and Ying-Dar Lin. "Security and privacy for 6G: A survey on prospective technologies and challenges." *IEEE Communications Surveys & Tutorials* 23, no. 4 (2021): 2384-2428.

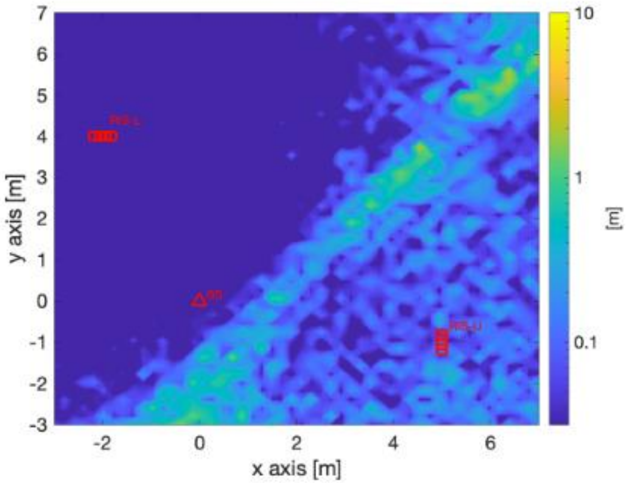
New Threats and Opportunities introduced by DISAC

Threat	Description	Why It Emerges in DISAC	Impacted Aspects	New Research Opportunities
Multi-node Spoofing	Adversary injects false reflections across distributed nodes	Multiple sensing agents increase the attack surface	Integrity, Authenticity	Secure waveform design; spatial consistency checks; coordinated anomaly detection
Data Poisoning	Malicious node injects false or biased sensing reports	Distributed fusion relies on partially trusted sources	Integrity, Authenticity	Trust-aware fusion algorithms; robust outlier detection in sensing networks
Consensus Attacks	Disrupting agreement during distributed decision-making	DISAC systems use consensus protocols for coordination	Availability	Secure consensus protocols; Byzantine-resilient fusion strategies
Coordination Exploits	Desynchronizing nodes to degrade performance or inject errors	Multiple nodes may be asynchronously operated or loosely coordinated	Availability, Integrity	Secure time/frequency synchronization; resilient multi-node scheduling
RIS Hijacking	Unauthorized control or manipulation of RIS configurations	RIS lacks physical security in heterogeneous systems	Integrity, Confidentiality	Authentication mechanisms for RIS; secure RIS control channel design
Topology Spoofing	Faking node position or identity to mislead system	Node location/identity critical for sensing models	Authenticity, Integrity	Secure node identification and localization; location-aware trust systems

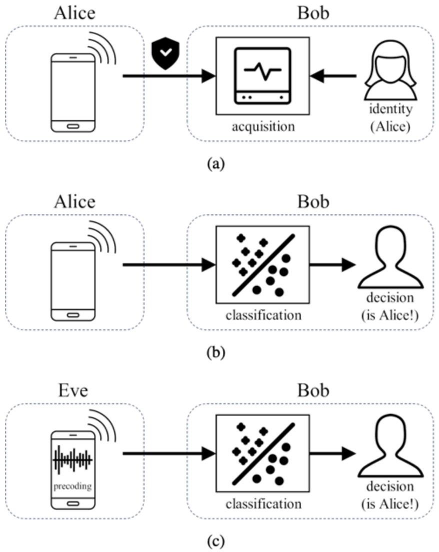
Case Study

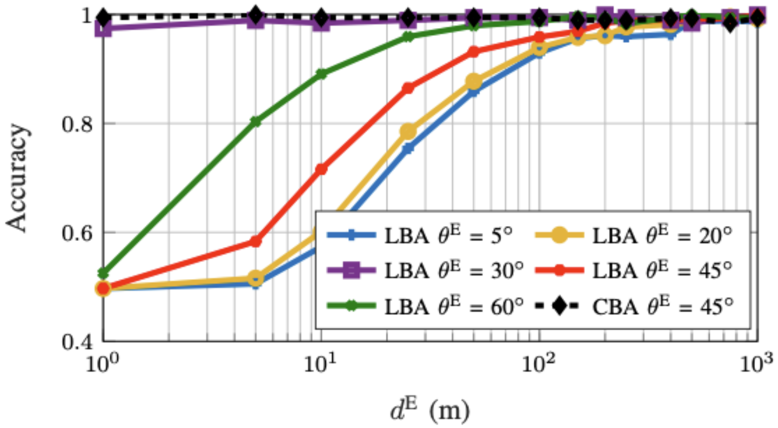
Localization under RIS attack





Physical layer authentication

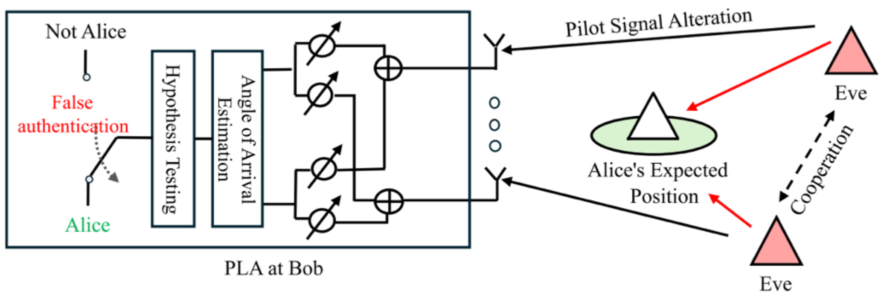


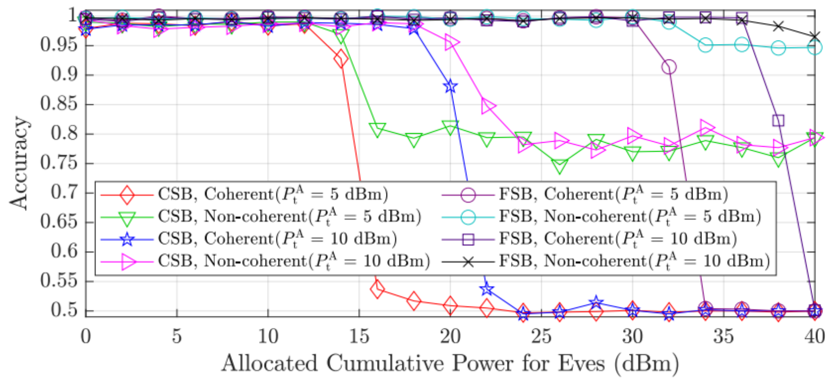


[1] Li, Mengting, Hui Chen, Alireza Pourafzal, and Henk Wymeersch. "RIS-Aided Positioning Under Adverse Conditions: Interference from Unauthorized RIS." *arXiv preprint arXiv:2502.19928* (2025).
[2] Srinivasan, Muralikrishnan, Linda Senigagliesi, Hui Chen, Arsenia Chorti, Marco Baldi, and Henk Wymeersch. "Aoa-based physical layer authentication in analog arrays under impersonation attacks." In *2024 IEEE 25th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, pp. 496-500. IEEE, 2024.

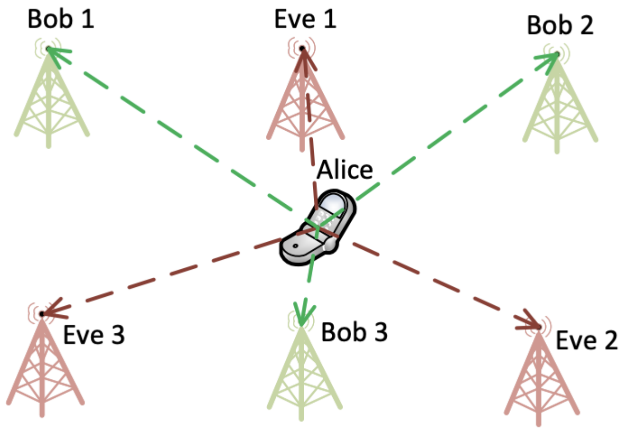
Case Study

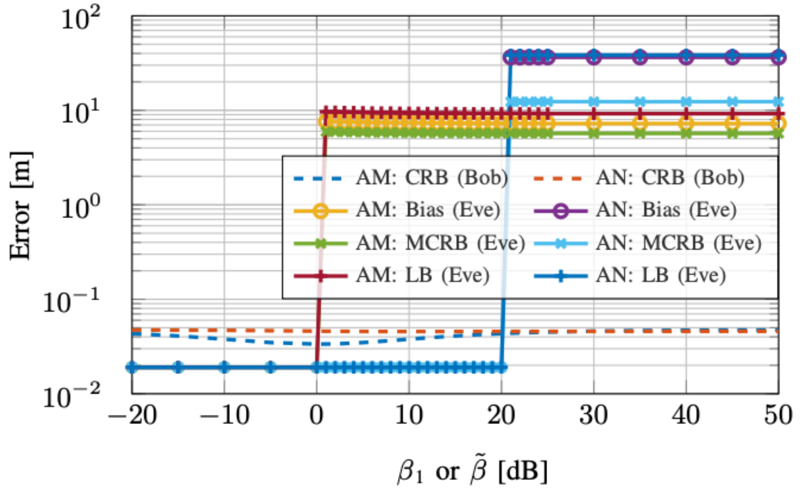
Cooperative attack on angle-based authentication





Artificial multipath/noise for location privacy protection





[1] Li, Mengting, Hui Chen, Alireza Pourafzal, and Henk Wymeersch. "RIS-Aided Positioning Under Adverse Conditions: Interference from Unauthorized RIS." *arXiv preprint arXiv:2502.19928* (2025).
[2] Srinivasan, Muralikrishnan, Linda Senigagliesi, Hui Chen, Arsenia Chorti, Marco Baldi, and Henk Wymeersch. "Aoa-based physical layer authentication in analog arrays under impersonation attacks." In *2024 IEEE 25th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, pp. 496-500. IEEE, 2024.

Key Takeaways (Calibration)

- **Cross-layer concern:** Security spans both comm and sensing layers.
- **New threats:** Distributed design enables spoofing, poisoning, and sync attacks.
- **Extended goals:** Add authenticity, privacy, and resilience to classic CIA.
- **Trust-aware fusion:** Handle uncertainty from partially trusted nodes.
- **Co-design needed:** Security must be built into waveforms design, coordination, and fusion.

Emerging Technologies

World Economic Forum
Top 10 Emerging Technologies of 2024

Contents

World Economic Forum Virtu... Home Artificial Intelligence Emerging Technologies

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Top 10 Emerging Technologies 2025

Wednesday 3 September, 15:00-15:45 (Europe/Paris time zone)

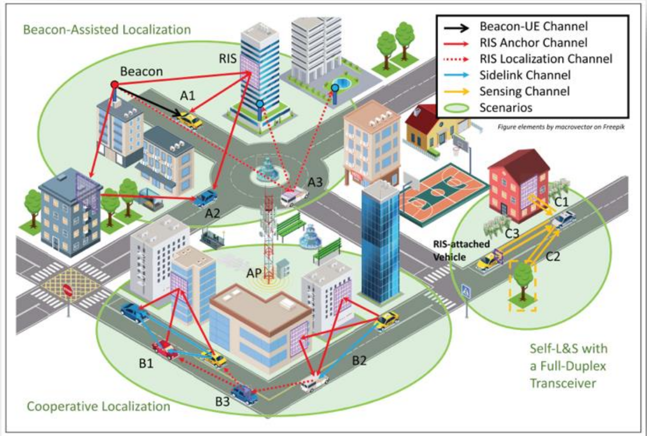
Virtual Session

Somehow related to DISAC

We are on the good track!??

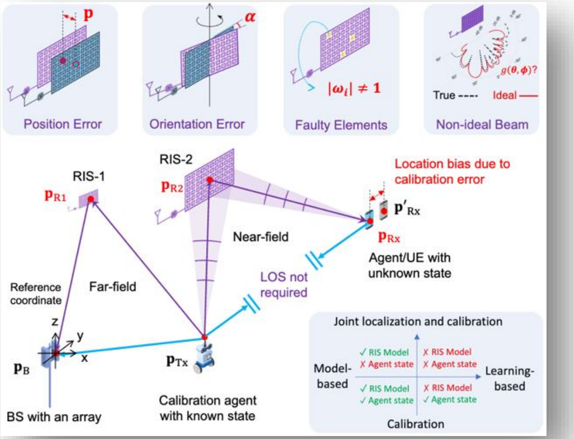
https://www3.weforum.org/docs/WEF_Top_10_Emerging_Technologies_of_2024.pdf

One Step Further



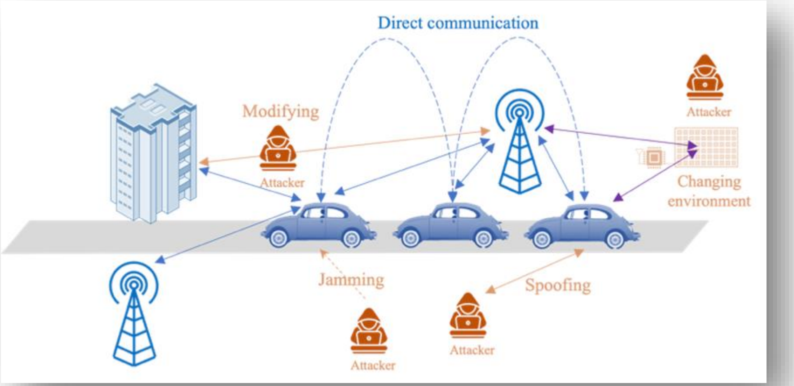
Inclusiveness

- Distributed algorithm
- Coordination protocol
- Anchor layout design



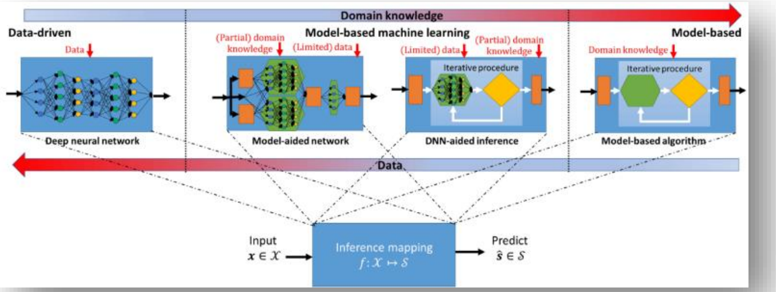
Sustainability

- Accurate channel model
- Complexity-accuracy tradeoff
- Resource allocation



Trustworthiness

- Privacy protection
- Localization attack
- Sensing attack



Algorithms

Tools: From model to learning, to hybrid

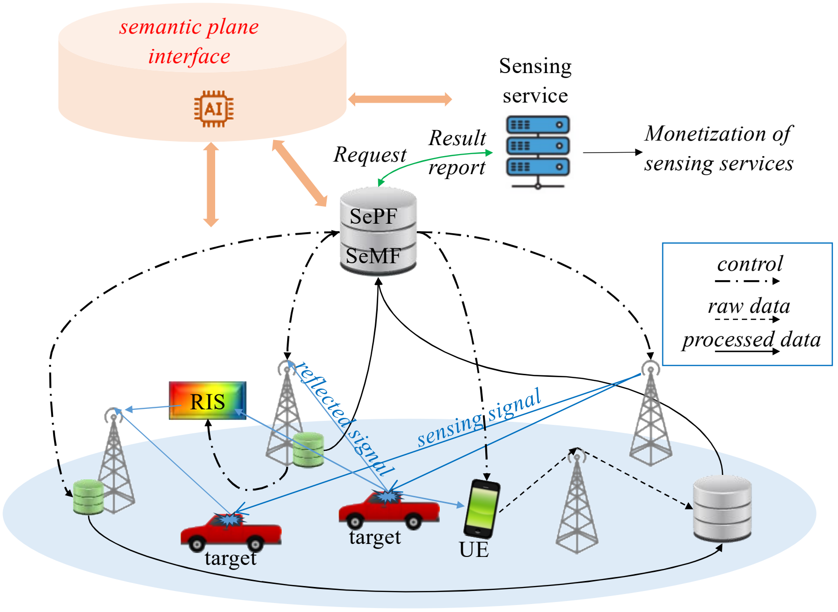
- Optimization algorithm
- Localization & sensing algorithm
- semantic information sharing

What is the next:
Try our best to meet 6G requirements
If not, well, we still have 7G/8G/9G …😂

Distributed Intelligent Sensing And Communications for 6G

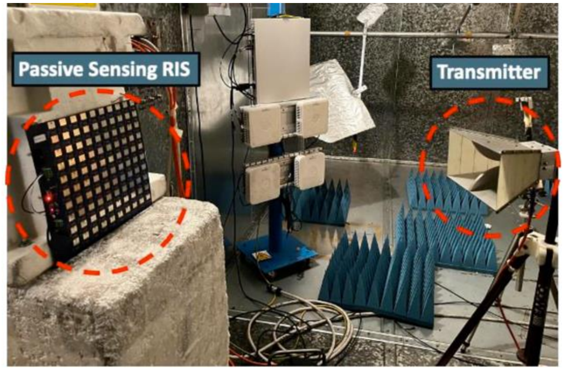
Project Objectives

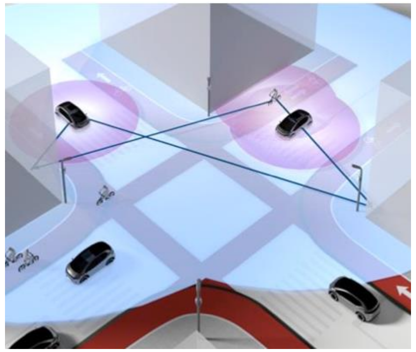
- **O1: Optimization of the physical layer for intelligent ISAC**
  - Waveforms, semantic-aware coding, multi-frequency bands, reflective and sensing RIS
- **O2: Super-resolution distributed sensing**
  - Extract 3D information and semantics, compress, share, and send minimal information
- **O3: Sensing-aided 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





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European Commission | 6GSNS

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

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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

- Part I: Fundamentals of DISAC operations and systems (Presenter: Henk Wymeersch, 50 mins)
- Part II: Distributed Communication-Aided Sensing (Presenter: Hui Chen, 60 mins)
- Part III: Distributed Sensing-Aided Communications (Presenter: George C. Alexandropoulos, 60 mins)