RF Positioning, Mapping and SLAM
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Towards 6G Situational Awareness

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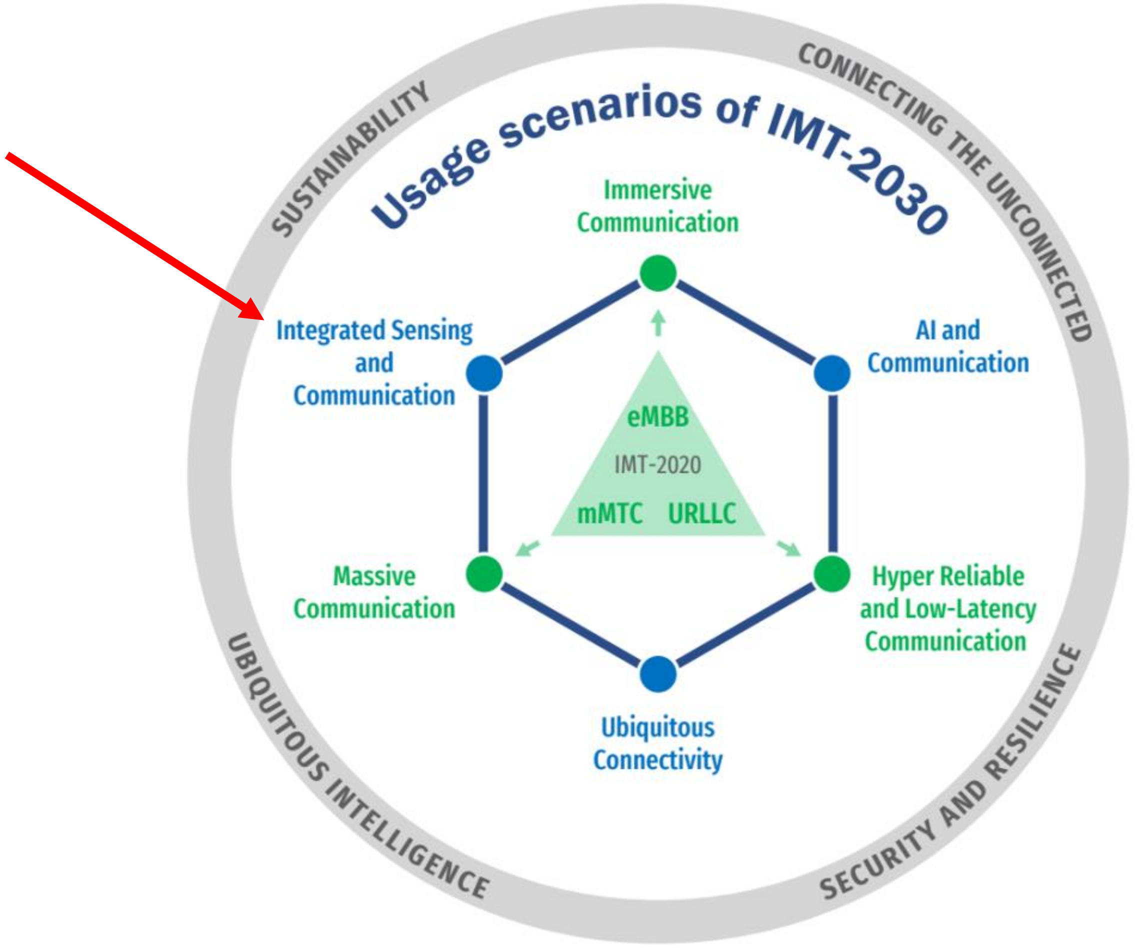
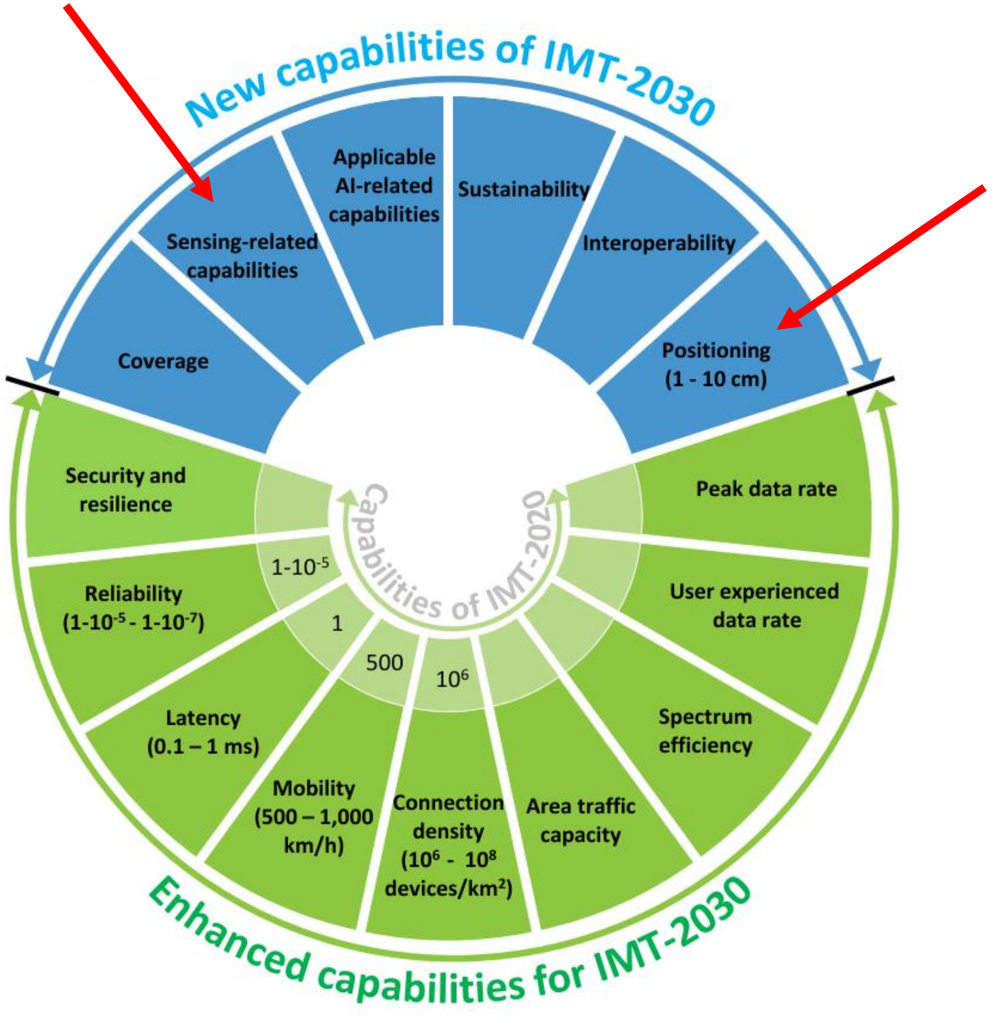
ITU 6G / IMT-2030 Perspective





Source: Recommendation ITU-R M.2160-0 (11/2023), Framework and overall objectives of the future development of IMT for 2030 and beyond

Positioning and SLAM – basics

- **UE positioning**
  - ✓ 3D location
  - ✓ 3D orientation, speed, heading
  - ✓ Possibly also e.g. UE clock offset/drift
- **Simultaneous localization and mapping, SLAM**
  - ✓ In addition to UE positioning, estimate also the locations and possibly other features of the scattering points
- **Sensing and mapping**
  - ✓ UE-based monostatic sensing and mapping
  - ✓ gNB-based monostatic or multistatic sensing and mapping
- **Technical basis** comes from the ability to measure path-wise propagation delays and angles while understanding the problem geometry
- Further extensions can cover e.g. refining also gNB coordinates or estimating gNB array orientation (both assumed classically known)

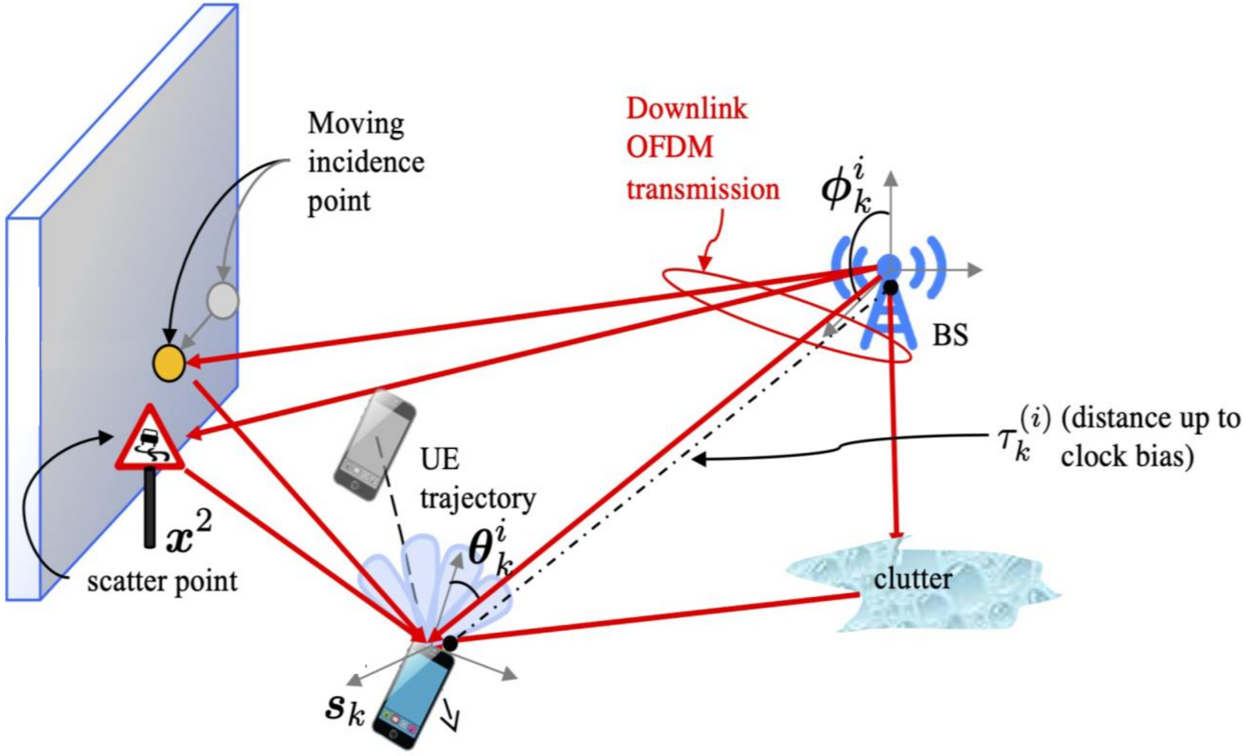


Figure source: Y. Ge et al., "A Computationally Efficient EK-PMBM Filter for Bistatic mmWave Radio SLAM," *IEEE Journal on Selected Areas in Communications*, vol. 40, no. 7, pp. 2179-2192, July 2022.

SLAM turns multipath from foe to fried !

Positioning and SLAM – basics, cont’d

New types of measurements, e.g., carrier phase

- ✓ On top of more ordinary time-of-flight and angle-related measurements; allows super-accurate ranging
- ✓ Subject to solving the so-called integer ambiguity challenge

Operation in near-field region (opposed to classical far-field)

- ✓ Can easily take place, e.g., in distributed phase-coherent beamforming systems (cell-free systems, D-MIMO)
- ✓ Can be beneficial for positioning & sensing (e.g. beam-focusing allows to extract also distance information, not only direction information)

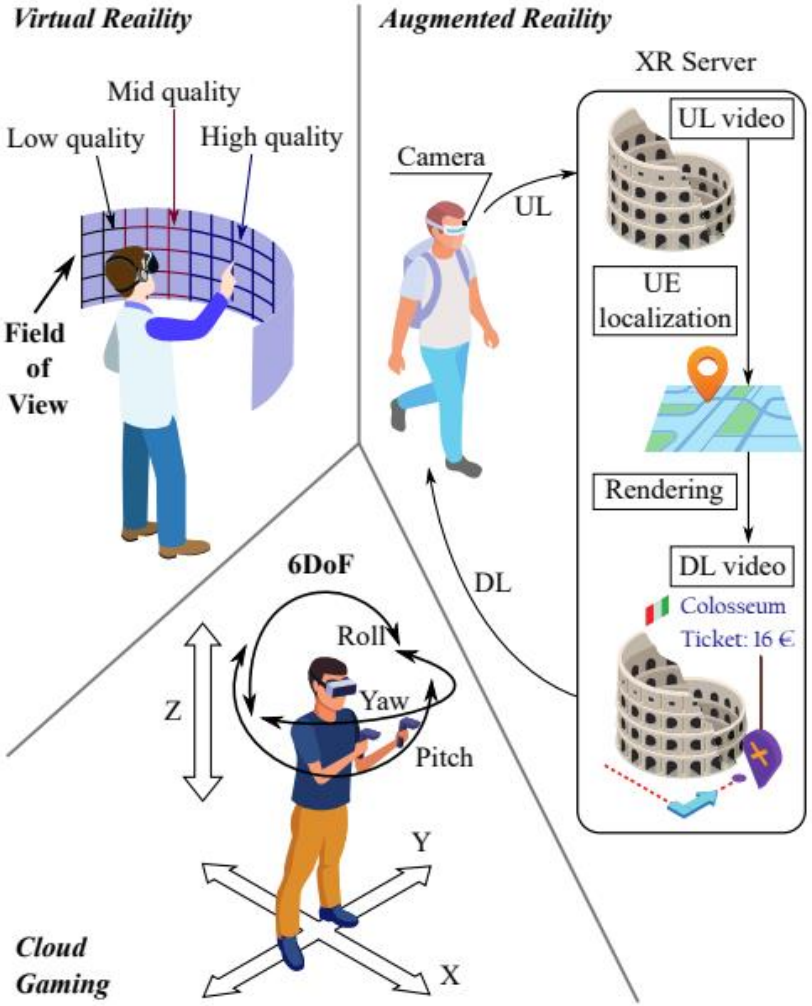
New applications, e.g., XR positioning and the 6DoF challenge

- ✓ Fast photo-realistic content rendering => network needs XR headset 3D location and 3D orientation information, with super-good accuracy and low latency

Going beyond point targets in mapping and SLAM

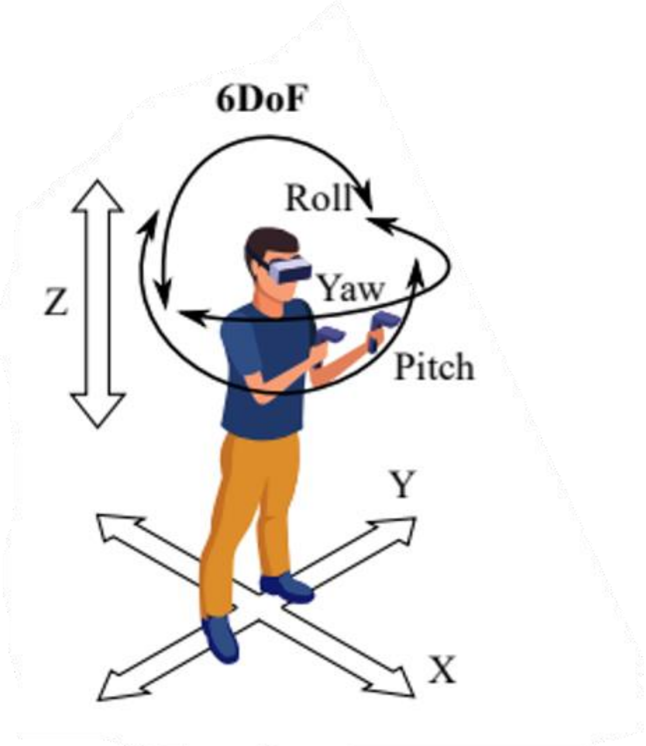
- ✓ Extracting semantic information, e.g., target/object material and/or shape
- ✓ Extended object estimation and tracking (EOE, EOT)

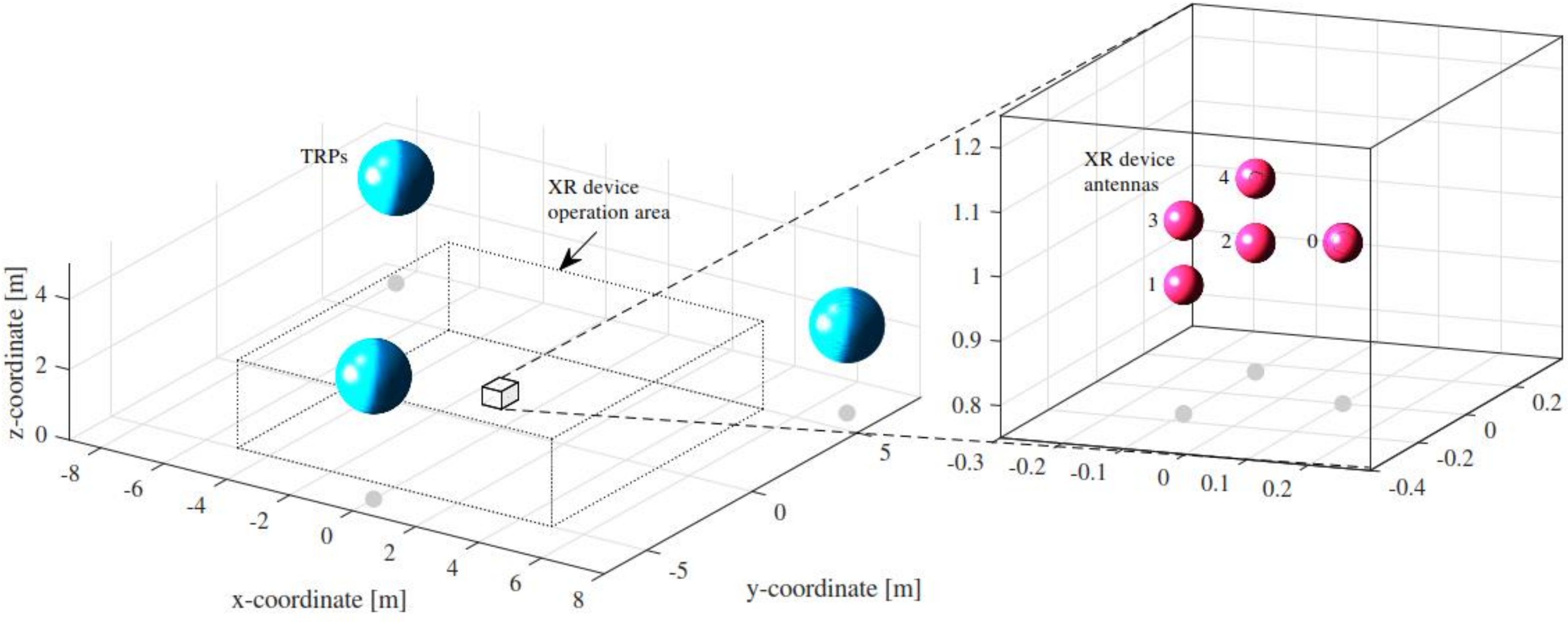
Figure source: V. Petrov et al., "Standardization of Extended Reality (XR) over 5G and 5G-Advanced 3GPP New Radio,“ arXiv:2203.02242 .



Source: J. Talvitie, M. Säily, and M. Valkama, "Orientation and Location Tracking of XR Devices: 5G Carrier Phase-Based Methods,“ *IEEE Journal of Selected Topics in Signal Processing (JSTSP)*, vol. 17, no. 5, pp. 919-934, Sept. 2023.

Example: 6DoF XR Tracking





Approach: Use uplink-based XR headset antenna-level carrier phase measurements

- Essentially ranging for the individual antenna points of the headset
- Can be done at mm- or cm-level accuracy – given that the notorious problem of integer ambiguities can be solved
- 3D orientation and 3D location can be then solved through geometry
- Allows for the adoption of EKF-based tracking, can also be generalized to unknown headset antenna geometry
- All math and actual algorithm descriptions: available in the paper ☺

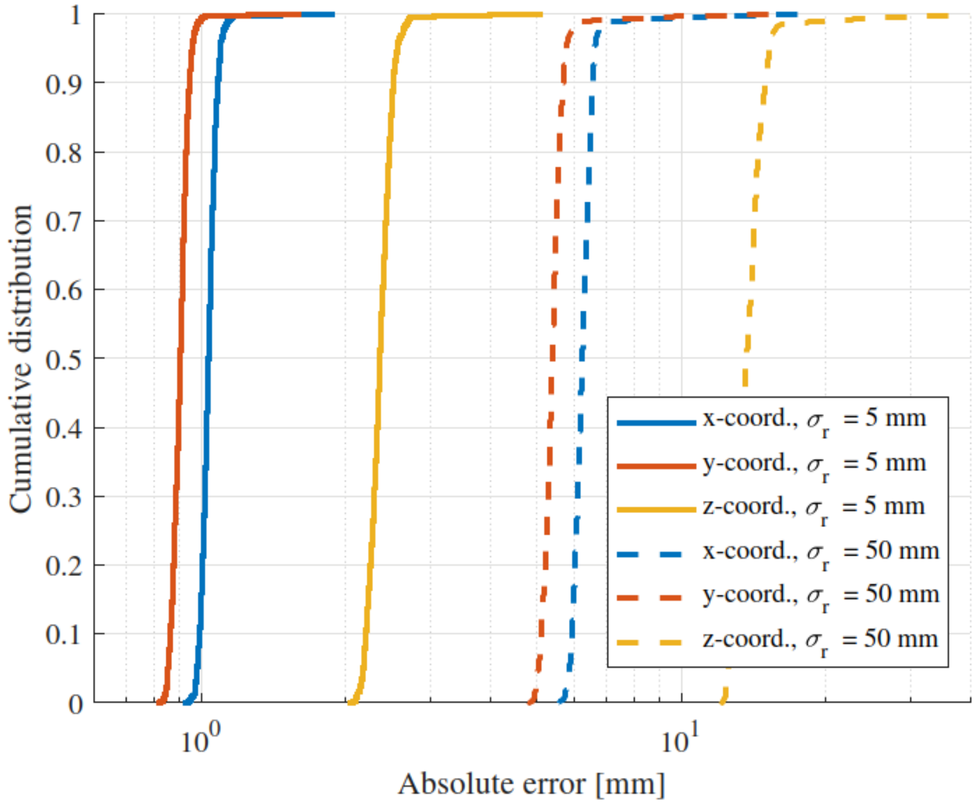
Source: J. Talvitie, M. Säily, and M. Valkama, "Orientation and Location Tracking of XR Devices: 5G Carrier Phase-Based Methods,“ *IEEE Journal of Selected Topics in Signal Processing (JSTSP)*, vol. 17, no. 5, pp. 919-934, Sept. 2023.

6DoF XR Tracking, cont’d

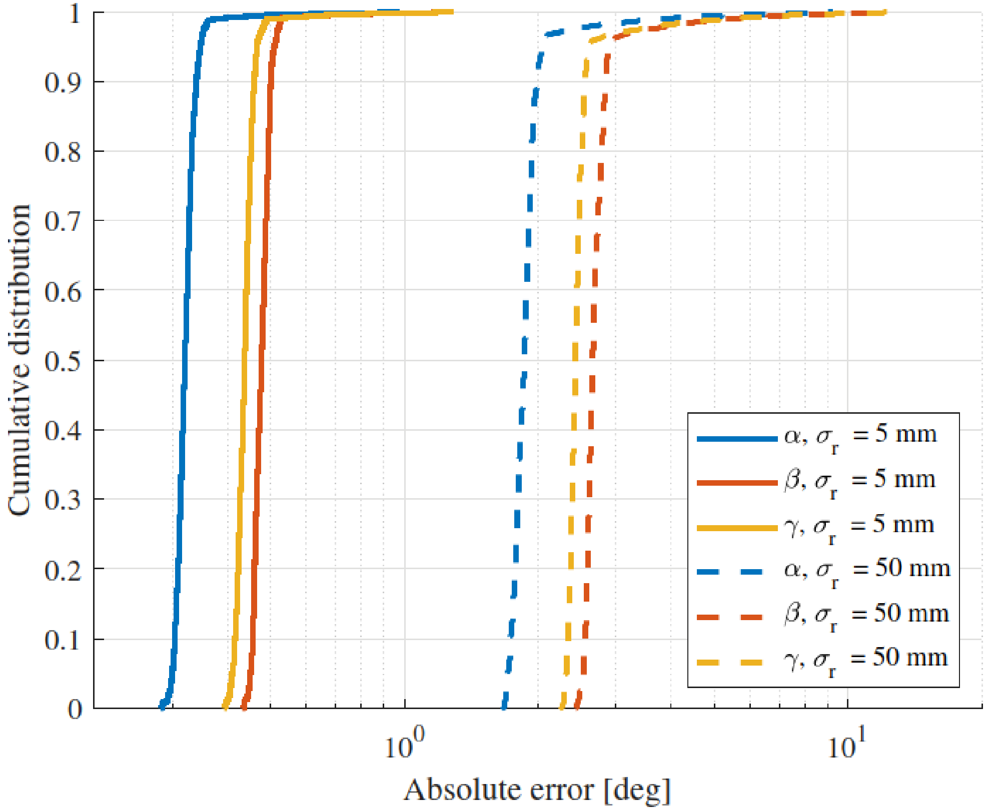
Example results

- FR1 / 3.5 GHz and FR2 / 28GHz both assessed, with different antenna level ranging error stds
- 5 antennas in XR headset, 3 TRPs observing and measuring with orthogonal uplink SRS type physical reference signals (all math and algo details in the article)

3D position accuracy



3D orientation accuracy

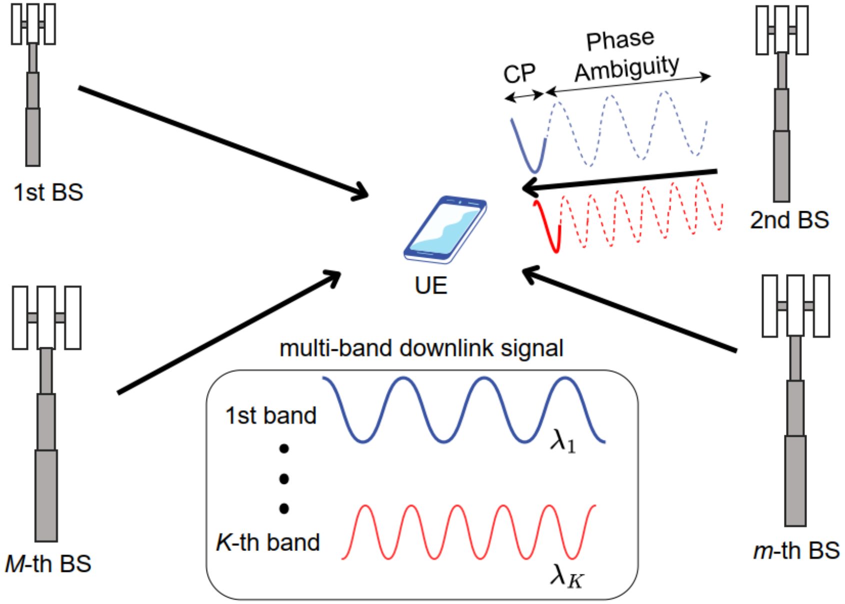


Source: E. Shourezari *et al.*, "Multi-band Carrier Phase Positioning toward 6G: Performance Bounds and Efficient Estimators,“ *IEEE Transactions on Wireless Communications*, submitted, 2025/2026. Available: https://arxiv.org/abs/2601.05178

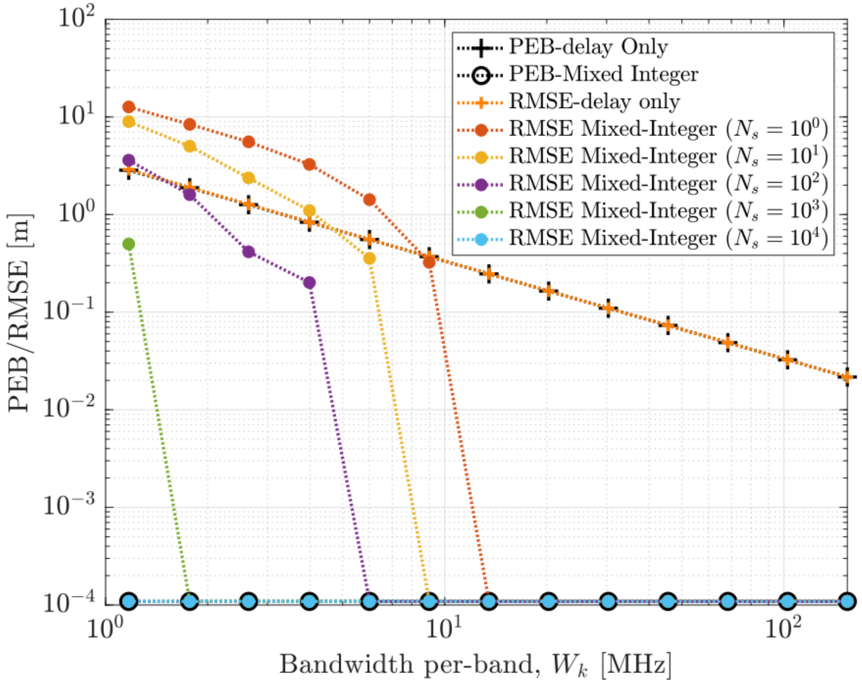
Example: CPP and multi-frequency measurements

Harnessing multi-frequency measurements via carrier aggregation (CA) can help a great deal to resolve the integer ambiguity challenge

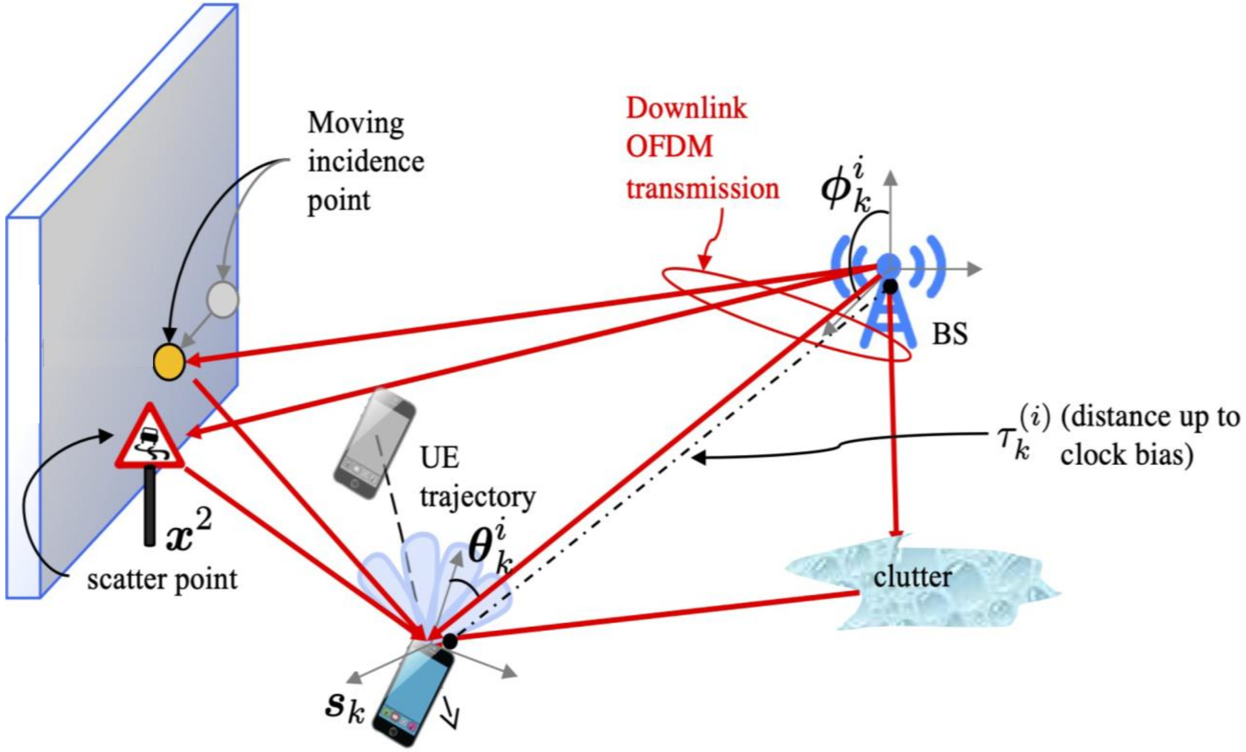
- Formal performance bounds in terms of mixed-integer CRBs as well as practical estimators reaching the bounds available in the above article
- One performance example below – so much more in the above paper



FR1+FR3 dual-band CA example



Radio SLAM, recent examples



- Scenario: ordinary UE-BS/gNB topology
  - ✓Unknown UE location and map/environment
  - ✓Estimate jointly using TOA, AOA and AOD measurements, building on reference signals (e.g. downlink PRS)
- **Technical approach: Formulate the problem using random finite sets (RFSs), to allow for unknown and time-varying NLOS incidence points, misdetections, clutter and measurement ambiguities**
- All the gory details available for example in the below papers, with EK-PHD, EK-PMBM and RB-PHD Bayesian filtering approaches

O. Kaltiokallio, Y. Ge, J. Talvitie, H. Wymeersch, and M. Valkama, ”mmWave Simultaneous Localization and Mapping Using a Computationally Efficient EK-PHD Filter”, *24th International Conference on Information Fusion*, Nov. 2021.

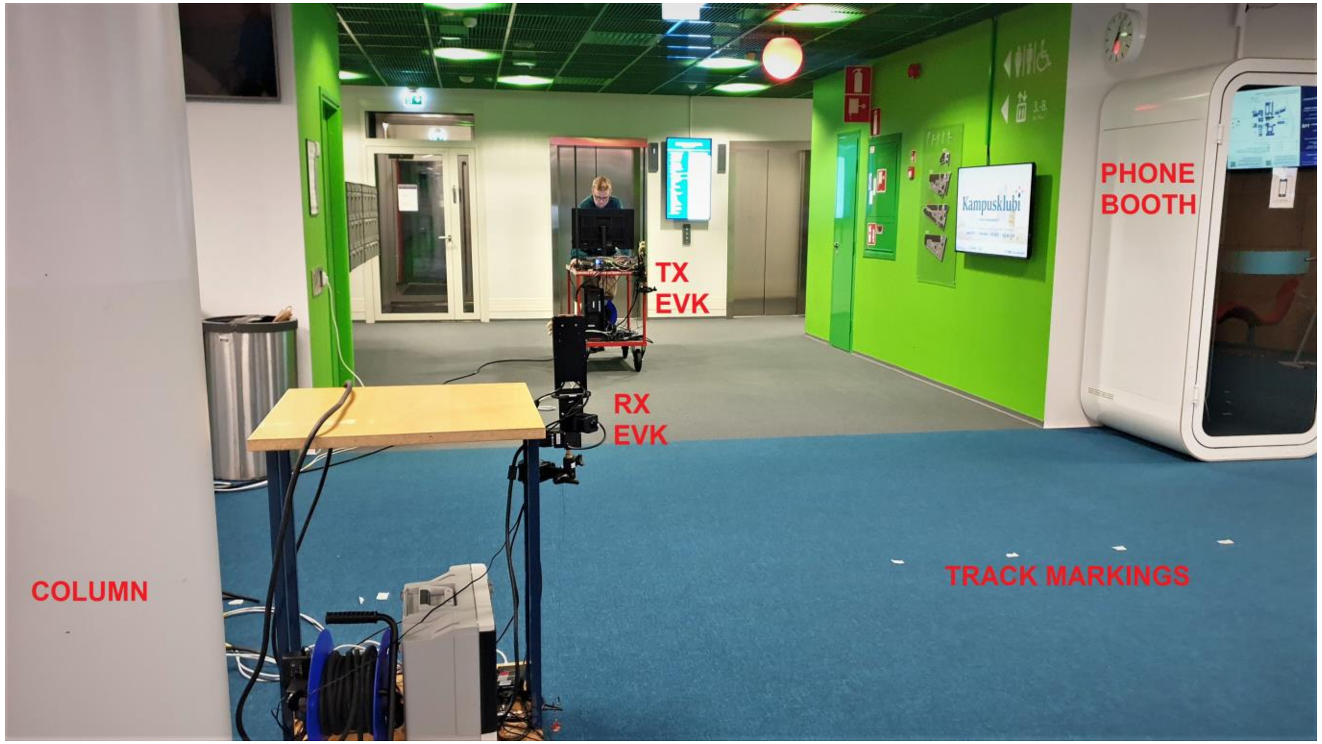
Y. Ge, O. Kaltiokallio, H. Kim, F. Jiang, J. Talvitie, M. Valkama, L. Svensson, S. Kim, and H. Wymeersch, “A computationally efficient EK-PMBM filter for bistatic mmWave radio SLAM,” *IEEE Journal on Selected Areas in Communications*, vol. 40, no. 7, pp. 2179-2192, July 2022.

O. Kaltiokallio *et al.*, "Towards Real-time Radio-SLAM via Optimal Importance Sampling," *IEEE SPAWC 2022*.

E. Rastorgueva-Foi, O. Kaltiokallio et al., “Millimeter-wave Radio SLAM: End-to-End Processing Methods and Experimental Validation,” *IEEE Journal on Selected Areas in Communications*, vol. 42, no. 9, pp. 2550-2567, Sept. 2024.

Source: E. Rastorgueva-Foi, O. Kaltiokallio et al., “Millimeter-wave Radio SLAM: End-to-End Processing Methods and Experimental Validation,” *IEEE Journal on Selected Areas in Communications*, vol. 42, no. 9, pp. 2550-2567, Sept. 2024.

Radio SLAM, RB-PHD – mmWave measurements

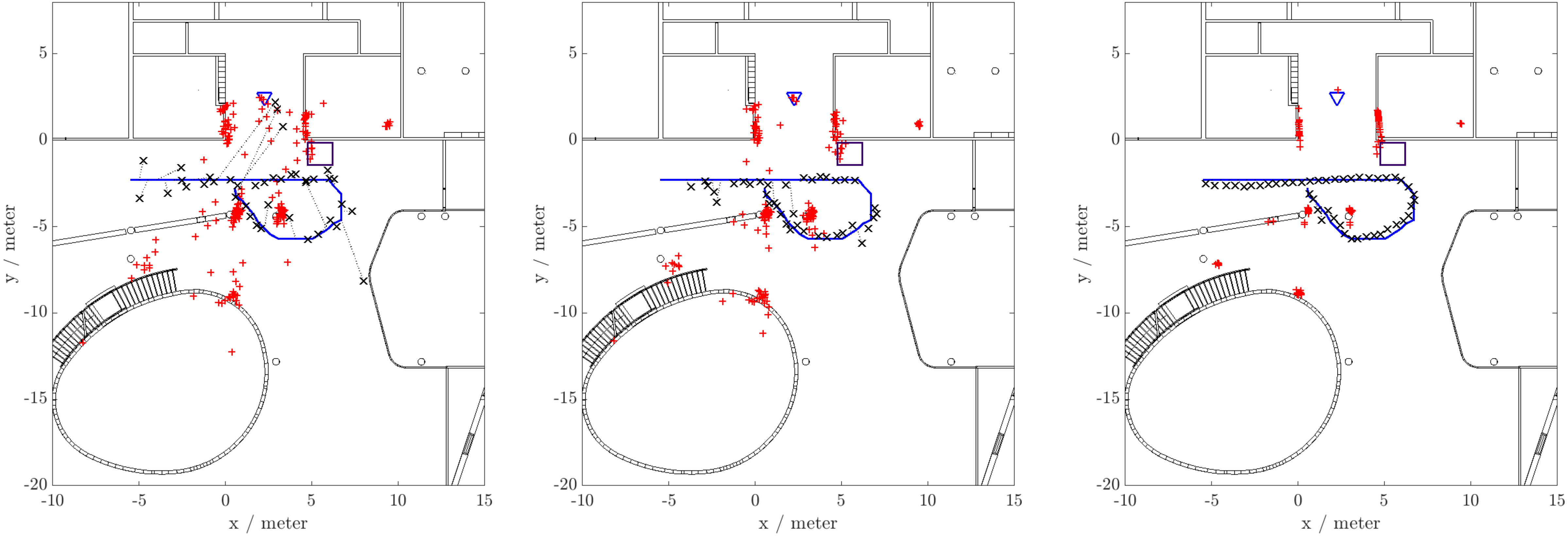


MEASUREMENT PARAMETERS	
Center frequency	60 GHz
Bandwidth	400 MHz
SCS	120 kHz
Antenna array size	16 x 4
3dB beamwidth	~10 deg
Signal type	PRS (DL)
PRS comb factor	2
PRS symbols per slot	1

- Stationary Tx/gNB and moving Rx/UE
- Both equipped with Sivers Semiconductors 60 GHz beamforming evaluation kits (EVKs), allowing for electrical beamforming and beamsweaping

Case 2: Unsynchronized Clocks

▽ gNB location
— True UE trace
x Estimated UE location(s)
\+ Landmark locations



NLOS SLAM [2]

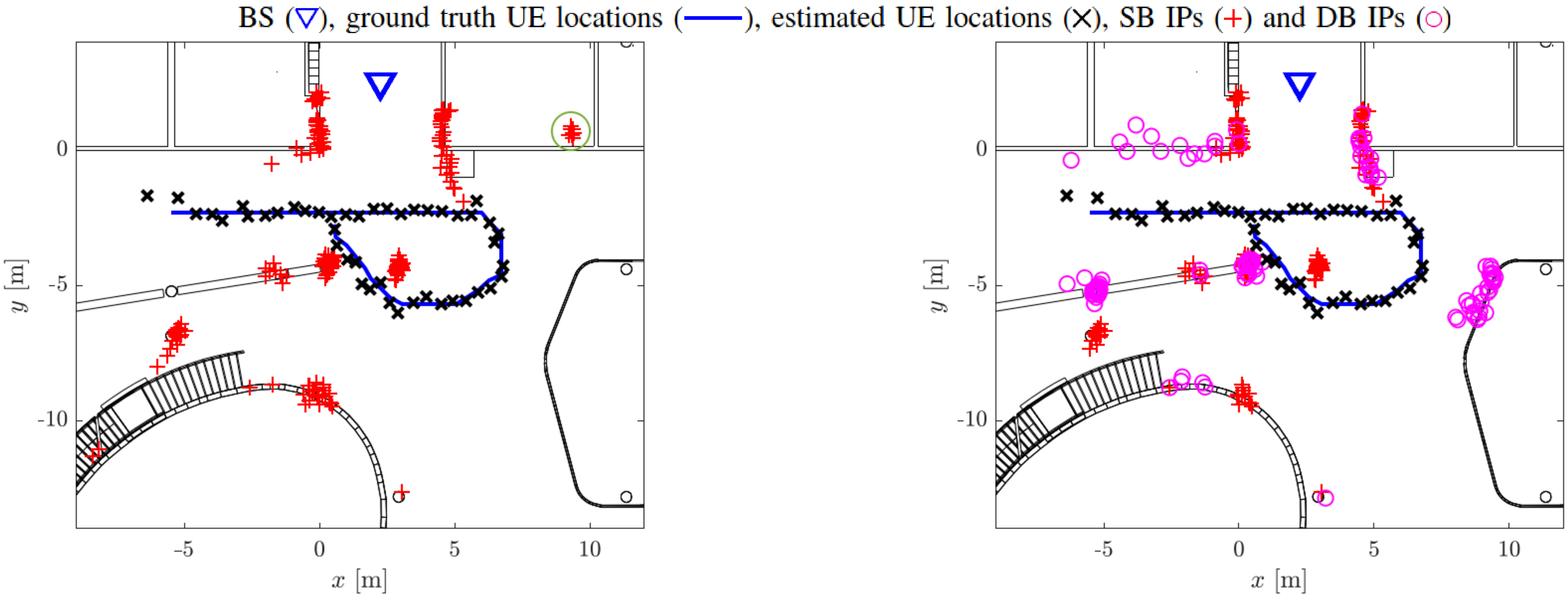
LOS+NLOS SLAM [3]

RB-PHD SLAM 2.0 [1,4]

[1] O. Kaltiokallio *et al.*, "Towards Real-time Radio-SLAM via Optimal Importance Sampling," IEEE SPAWC 2022.
[2] F. Wen and H. Wymeersch, “5G Synchronization, Positioning, and Mapping From Diffuse Multipath”, IEEE Wireless Commun. Lett., vol. 10, no. 1, Jan. 2021.
[3] A. Shahmansoori et al. “Position and Orientation Estimation Through Millimeter-Wave MIMO in 5G Systems” IEEE Trans. Wireless Commun., vol. 17, no. 3, Mar. 2018.
[4] E. Rastorgueva-Foi, O. Kaltiokallio et al., “Millimeter-wave Radio SLAM: End-to-End Processing Methods and Experimental Validation,” *IEEE Journal on Selected Areas in Communications*, vol. 42, no. 9, pp. 2550-2567, Sept. 2024.

Extension to multi-bounce SLAM

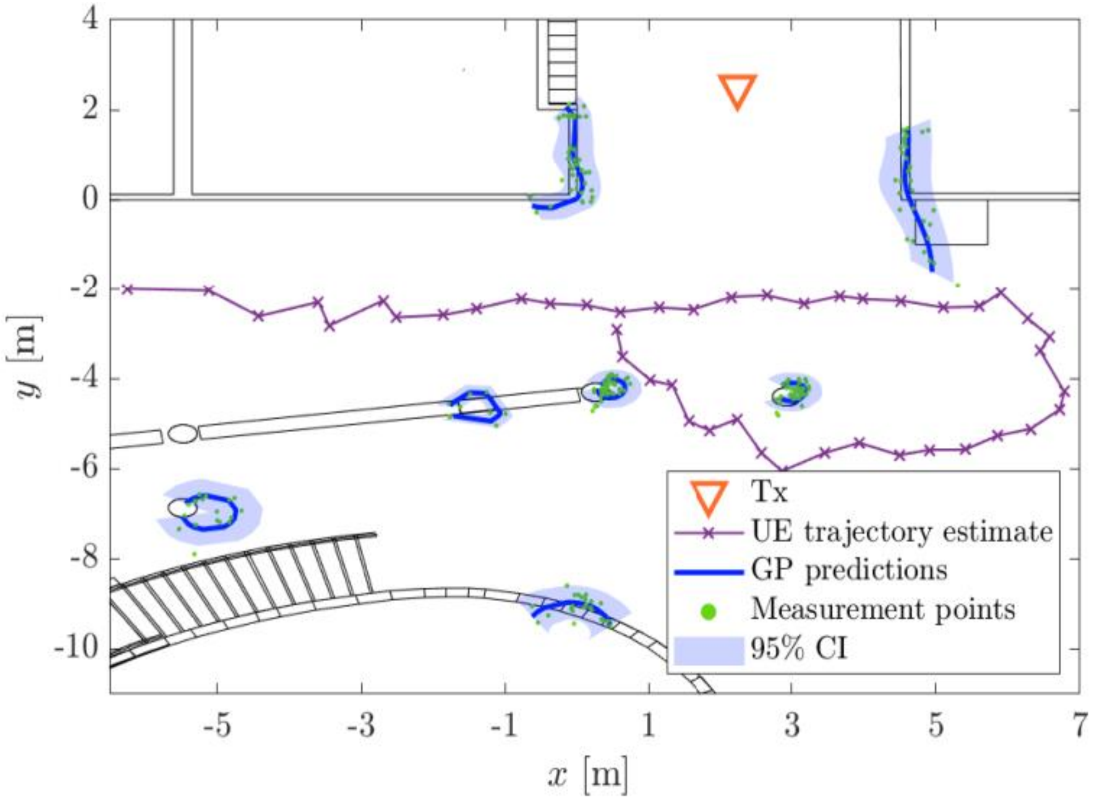
Real-world complex propagation environments have also lots of EM wave material interaction points (IPs) beyond single-bounce paths => more complex geometry but can also be harnessed for improved situational awareness and accuracy

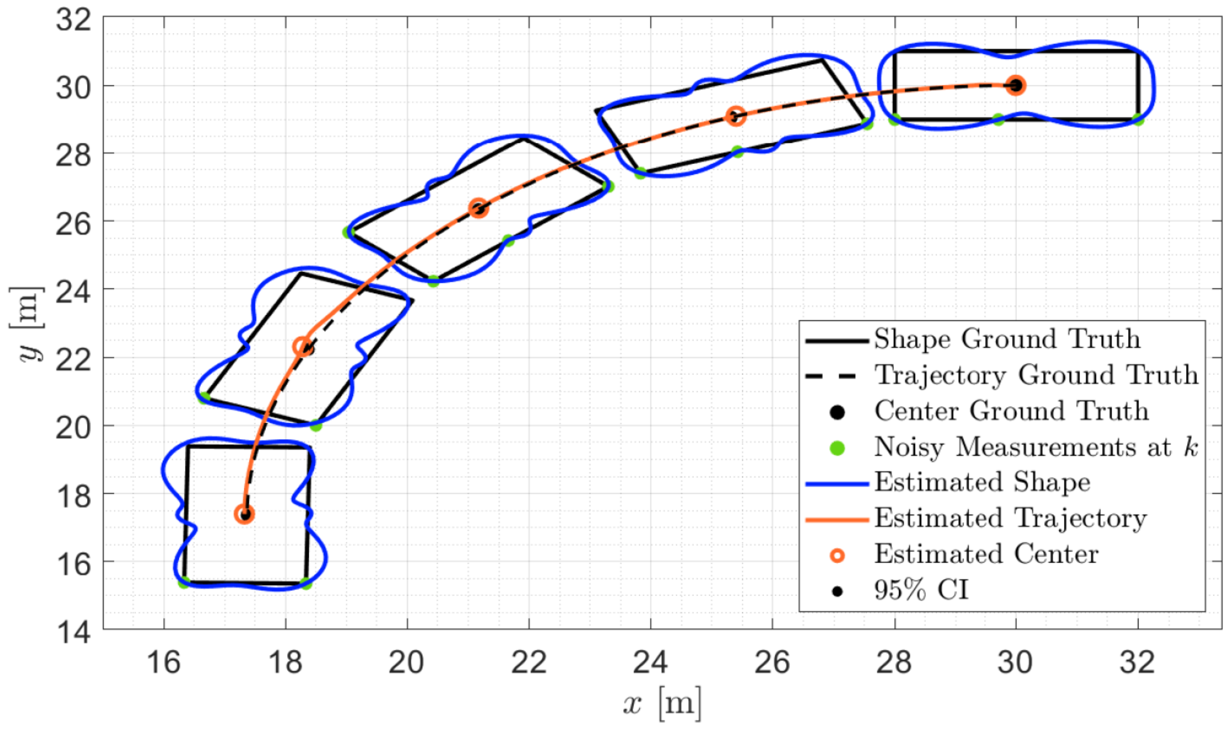


O. Kaltiokallio, Y. Ge, J. Talvitie, E. Rastorgueva-Foi, H. Wymeersch, and M. Valkama, “Bistatic mmWave Mapping in Obstructed Environments Using Double-bounce Signals,” in Proc. IEEE SPAWC 2024, Sept. 2024.

Extension to extended object estimation

Trying to understand, model and estimate the environment as true surfaces and objects with actual shares other than just point scatterers; also tracking of moving extended objects





M.E. Pihtil, O. Kaltiokallio, J. Equi, J. Talvitie, E.S. Lohan, E. Basar, and M. Valkama, "Gaussian Process-Based Extended Object Estimation for 6G ISAC at Millimeter-Wave Frequencies," EuCAP 2026, accepted, to appear. Partially UNPUBLISHED WORK © Tampere University.

Short conclusions

- Well defined 5G positioning procedures exist, also tons of ready processing algorithms for C-band and mmW implementations
- Timely issues include e.g. carrier phase – based approaches, and super-low positioning latency and super-good accuracy e.g. for XR applications – ongoing timely work
- Capabilities for environment sensing, mapping and SLAM building up, possible already in 5G-Advanced – further opportunities in 6G
- Lots of good academic basic research done, however **good room for innovation potential and practical impact** still e.g. in making things work in practical complex scattering environments – also lots on ongoing work here
- New elements: for example phase-coherent distributed systems and/or RIS, also **6 > 5** ☺

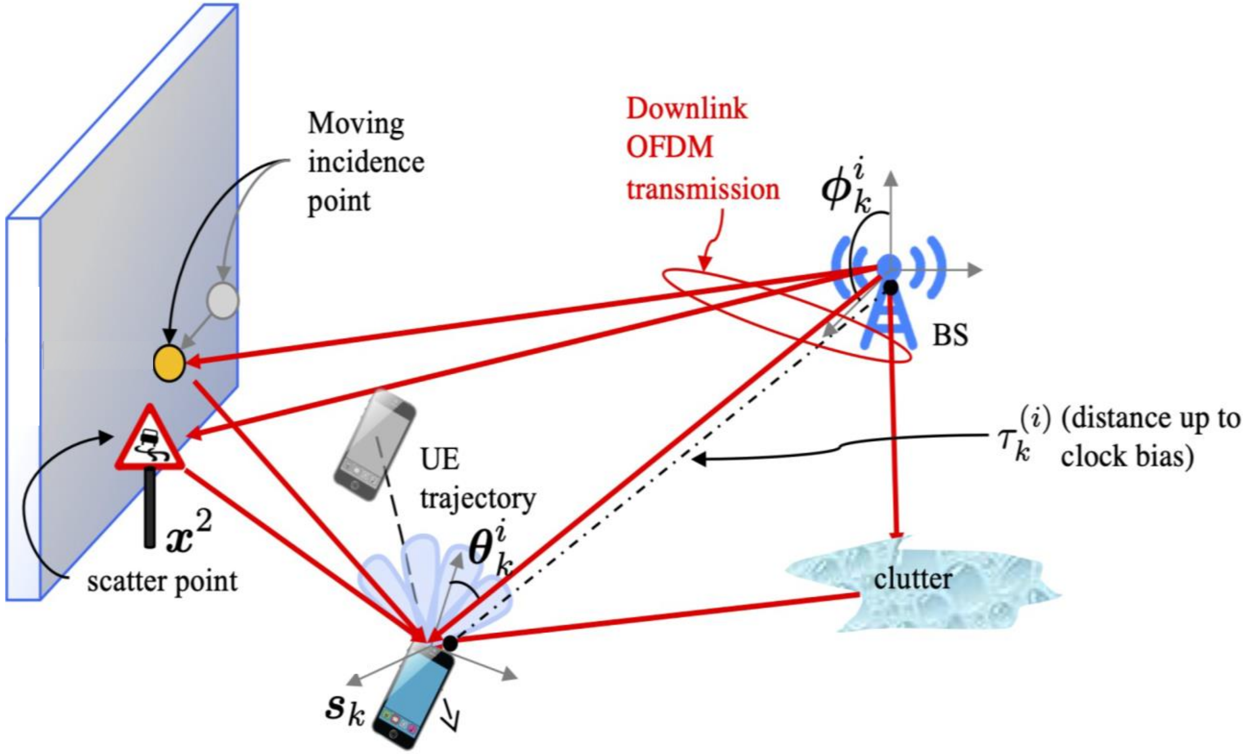


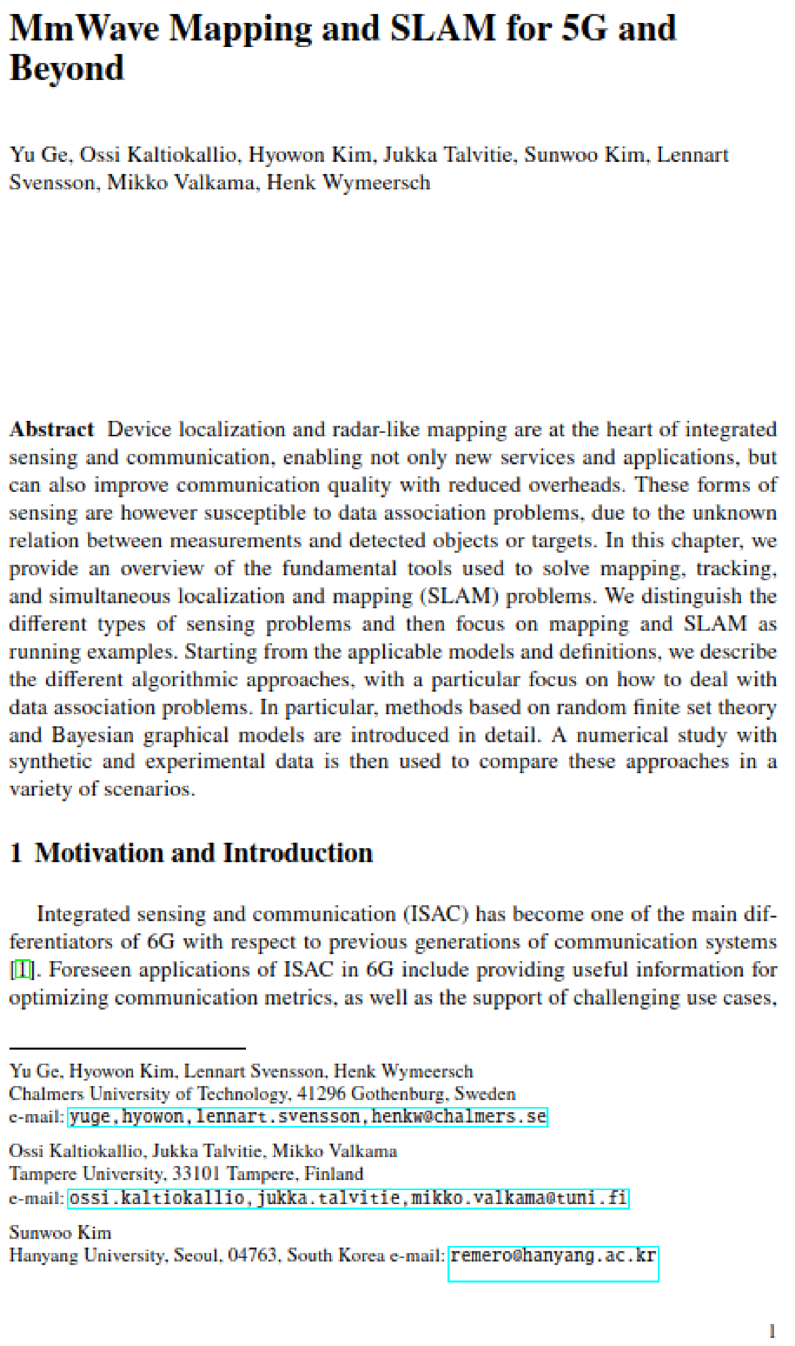
Figure source: Y. Ge et al., "A Computationally Efficient EK-PMBM Filter for Bistatic mmWave Radio SLAM," *IEEE Journal on Selected Areas in Communications*, vol. 40, no. 7, pp. 2179-2192, July 2022.

Small ad … ☺

- Book chapter overviewing mmWave mapping and SLAM in 5G/6G cellular available
- Part of the 6G ISAC book edited by Fan Liu, Yonina C. Eldar, Christos Masouros (published by Springer) – book is available
- Also available in Arxiv, at

  https://arxiv.org/abs/2211.16024

- Joint effort with Prof. Henk Wymeersch and his group at Chalmers
- Contains common sense descriptions, examples and good set of references



MmWave Mapping and SLAM for 5G and Beyond

Yu Ge, Ossi Kaltiokallio, Hyowon Kim, Jukka Talvitie, Sunwoo Kim, Lennart Svensson, Mikko Valkama, Henk Wymeersch

Abstract Device localization and radar-like mapping are at the heart of integrated sensing and communication, enabling not only new services and applications, but can also improve communication quality with reduced overheads. These forms of sensing are however susceptible to data association problems, due to the unknown relation between measurements and detected objects or targets. In this chapter, we provide an overview of the fundamental tools used to solve mapping, tracking, and simultaneous localization and mapping (SLAM) problems. We distinguish the different types of sensing problems and then focus on mapping and SLAM as running examples. Starting from the applicable models and definitions, we describe the different algorithmic approaches, with a particular focus on how to deal with data association problems. In particular, methods based on random finite set theory and Bayesian graphical models are introduced in detail. A numerical study with synthetic and experimental data is then used to compare these approaches in a variety of scenarios.

1 Motivation and Introduction

Integrated sensing and communication (ISAC) has become one of the main differentiators of 6G with respect to previous generations of communication systems [1]. Foreseen applications of ISAC in 6G include providing useful information for optimizing communication metrics, as well as the support of challenging use cases,

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Some example recent works

- C. B. Barneto, T. Riihonen, S. D. Liyanaarachchi, M. Heino, N. González-Prelcic and M. Valkama, "Beamformer Design and Optimization for Joint Communication and Full-Duplex Sensing at mm-Waves," ***IEEE Transactions on Communications***, vol. 70, no. 12, pp. 8298-8312, Dec. 2022.
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- C. Baquero Barneto, S. D. Liyanaarachchi, M. Heino, T. Riihonen, and M. Valkama, “Joint Multi-User Communication and MIMO Radar Through Full-Duplex Hybrid Beamforming,” in ***Proc. IEEE Symposium on Joint Communications and Sensing***, 2021.
- S.D. Liyanaarachchi, C. Baquero Barneto, T. Riihonen, and M. Valkama, “Experimenting Joint Vehicular Communications and Sensing with Optimized 5G NR Waveform,” ***IEEE Vehicular Technology Conference***, Apr. 2021.
- J. Talvitie, O. Kaltiokallio, E. Rastorgueva-Foi, C. B. Barneto, M. F. Keskin, H. Wymeersch, and M. Valkama, ”Indoor Mapping with a Mobile Radar Using an EK-PHD Filter,” in ***Proc. IEEE PIMRC 2021***, Sept. 2021.

Some example recent works, cont’d

- O. Kaltiokallio, Y. Ge, J. Talvitie, H. Wymeersch, and M. Valkama, ”mmWave Simultaneous Localization and Mapping Using a Computationally Efficient EK-PHD Filter,” in ***Proc. 24th International Conference on Information Fusion***, Nov. 2021.
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Some example recent works, cont’d

- O. Kaltiokallio, R. Hostettler, Y. Ge, H. Kim, J. Talvitie, H. Wymeersch and M. Valkama, "A Multihypotheses Importance Density for SLAM in Cluttered Scenarios," ***IEEE Transactions on Robotics***, vol. 40, pp. 1019-1035, 2024.
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