Multi-Sensor Fusion for Extended Object Tracking Exploiting Active and Passive Radio Signals

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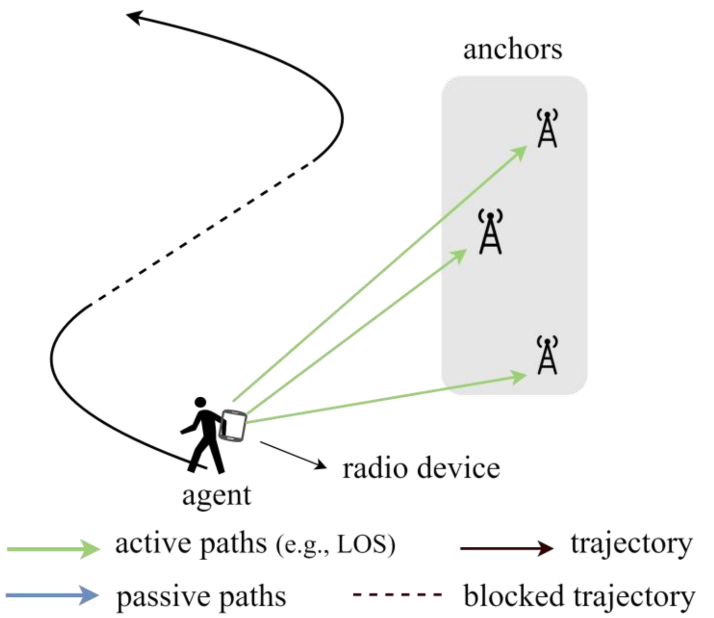
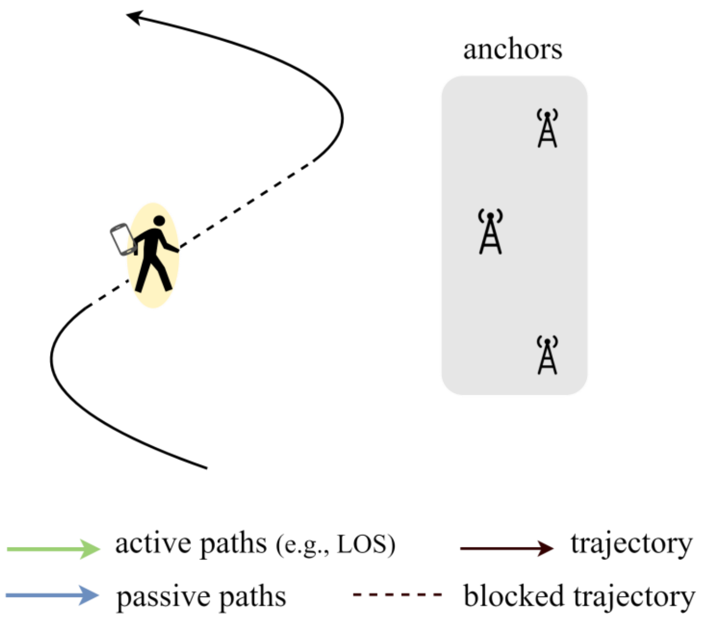
Background

- An agent carries a **radio device** while walking along a path;
- The device communicates with fixed **anchors** (radio transceivers) in the environment;
- The anchors use the signals to **estimate the device's position.**

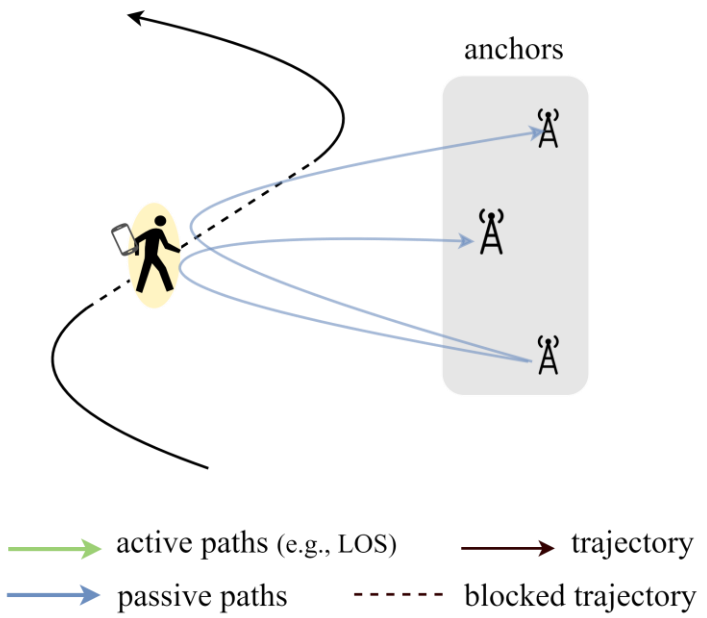
When LOS signals are available, positioning can be guaranteed from distance measurements.



When LOS signals are blocked, estimates can drift or fail.



Research Hypothesis: Reflected signals contain hidden position information.

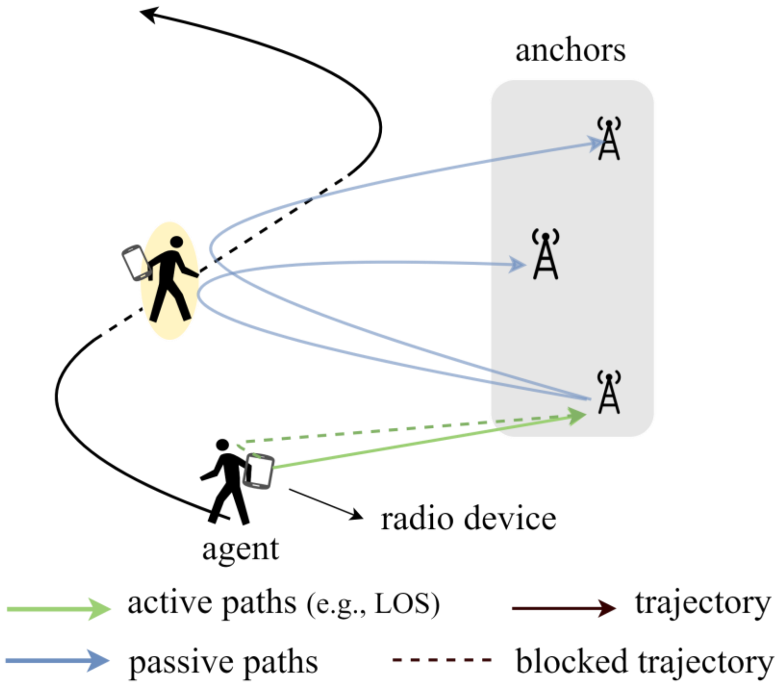


❑ Research Problem

- Robust localization of a radio device when the agent blocks direct LOS (line-of-sight) links.

❑ Assumptions

- Agent blocks LOS paths partially → incomplete active measurement (e.g., LOS) data;
- No obstruction of passive paths→ passive radar measurements (reflected paths) are always available.



❑ Solutions

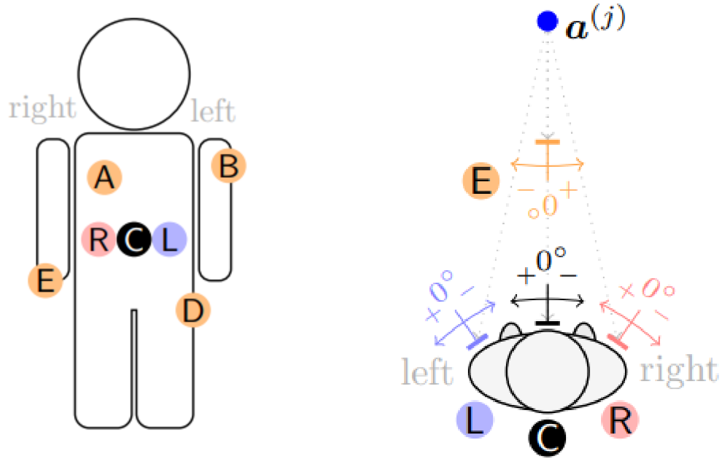
- Treat the agent as an **extended object (EO)**, not a point object;
- Fuse active and passive measurements from multiple anchors.

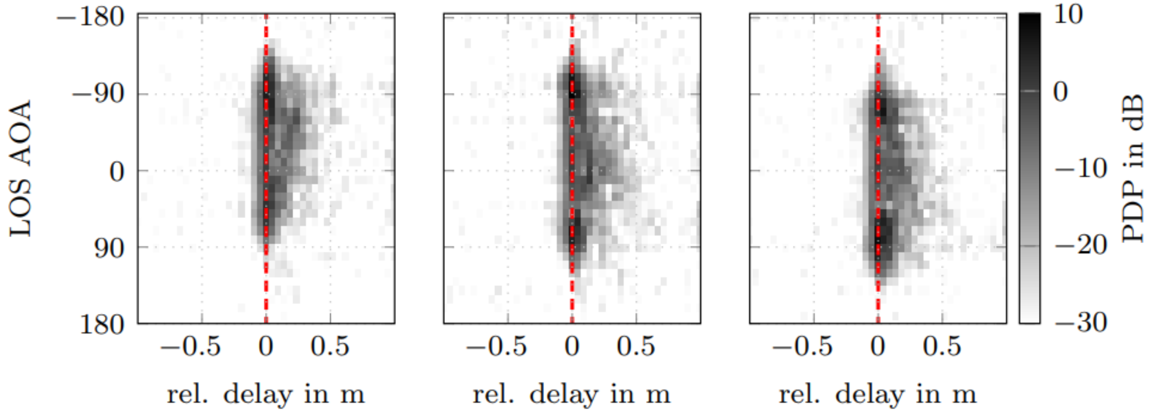
Modelling

Extended Object Modelling

Measured off-body UWB channel shows[1]

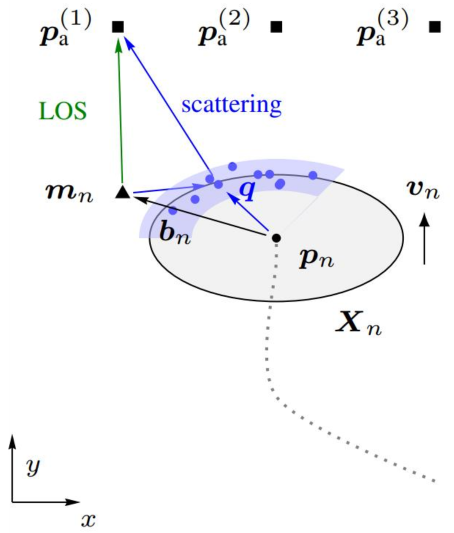
- Strong scattering at the body surface;
- Direction-dependent shadowing.



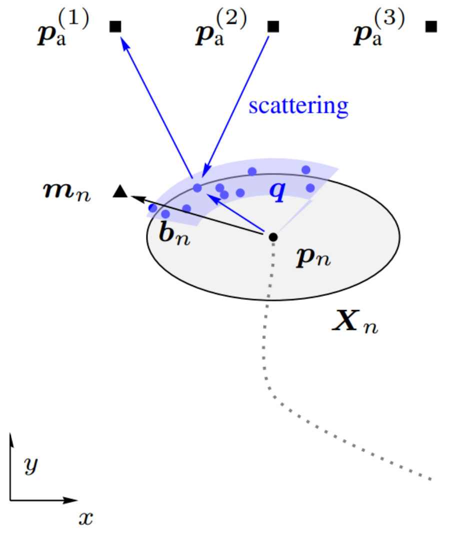


(d) left torso (L) (e) center torso (C) (f) right torso (R)

- The agent is modelled by an ellipse $\boldsymbol{X}_n = [l_n \; w_n]$
- Scatter points q originate from a annulus sector on the surface of the ellipse;
- The annulus sector's opening angle is set by the anchors' truncated field-of-view.
- Augmented EO states $\boldsymbol{y}_n = [\boldsymbol{p}_n \; \boldsymbol{v}_n \; \boldsymbol{X}_n]$



Active case

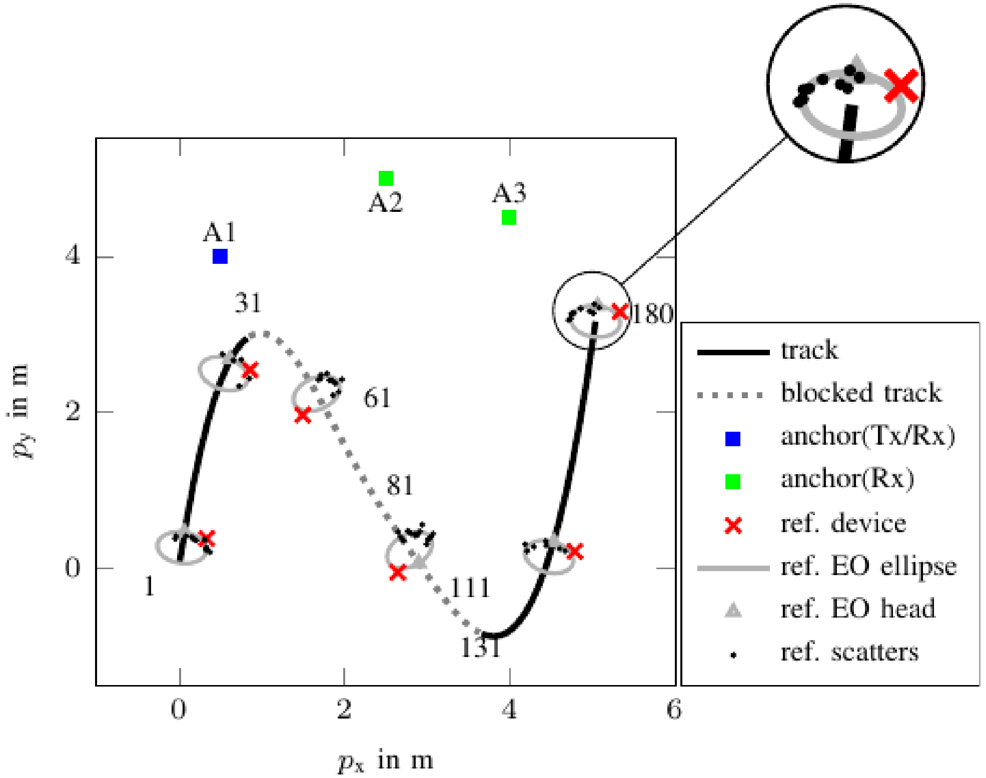


Passive case

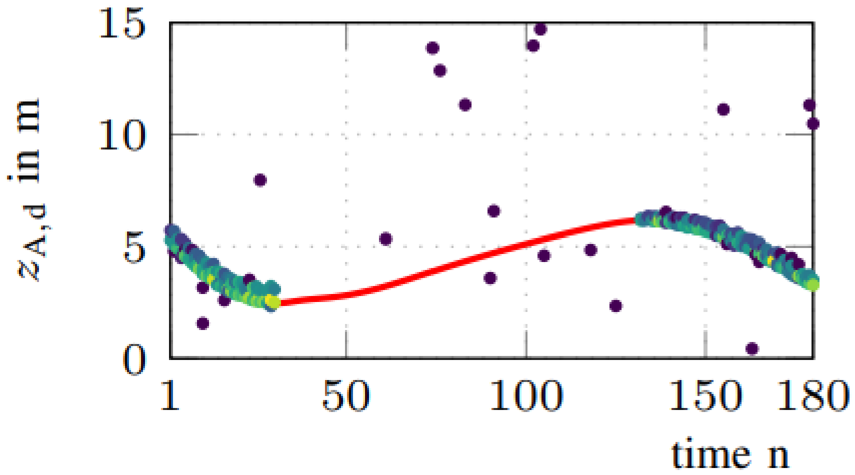
Active and Passive Distance Measurements

Geometric representation

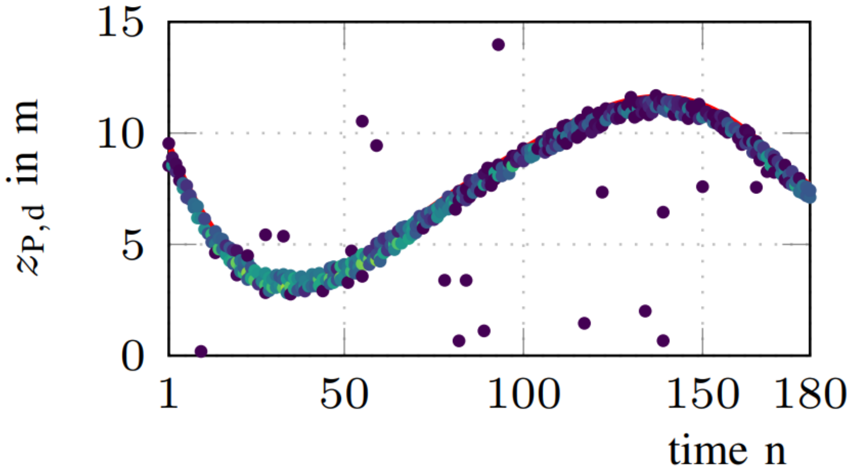
- Obstructed steps by the agent: [31,130]
- The device is rigidly attached to the agent with a fixed orientation and distance.
- Active measurements: device-to-Rx
- Passive measurements: Tx-EO-Rx



Active measurements transmitted from device and received by A2



Passive measurements transmitted from A1 and received by A2



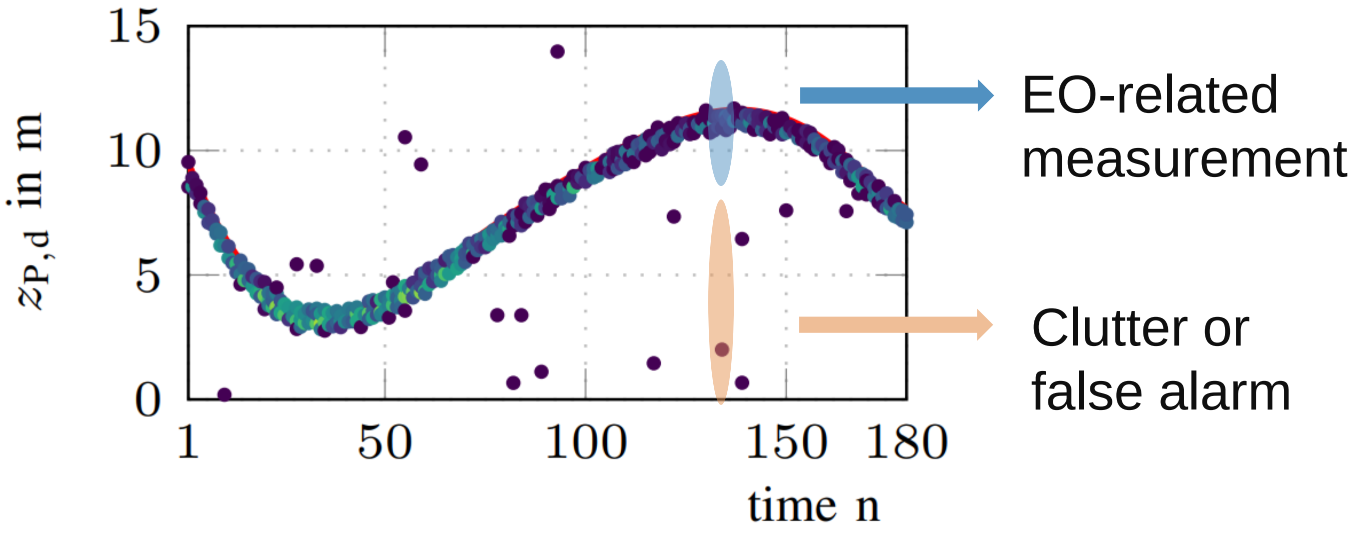
Challenge: Data Association Uncertainty

- An extended object generates **multiple scattering measurements** in each anchor pair.

  → Classical probabilistic data association (PDA) [2] assuming one measurement per object **fails.**
- Measurement origin is unknown: LOS, scattering, or clutter.

Solution: Multi-Measurement PDA

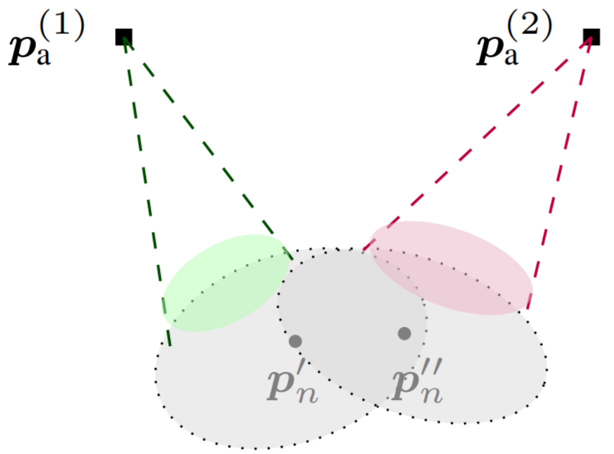
- For **each measurement,** weight all hypotheses and soft associate. $\zeta(\boldsymbol{z}_{n,l}|\boldsymbol{y}_n) = \sum_{a=0}^{1} g(\boldsymbol{z}_{n,l}|\boldsymbol{y}_n, a_{n,l})$
- For each step n, make use of **multiple** EO-related measurements. $p(\boldsymbol{y}_n) = \prod_l \zeta(\boldsymbol{z}_{n,l}|\boldsymbol{y}_n)$



Weight	Association Variables
0.7	$a_{n,l} = 1$, EO-related
0.3	$a_{n,l} = 0$, clutter
0.2	$a_{n,l} = 1$, EO-related
0.8	$a_{n,l} = 0$, clutter

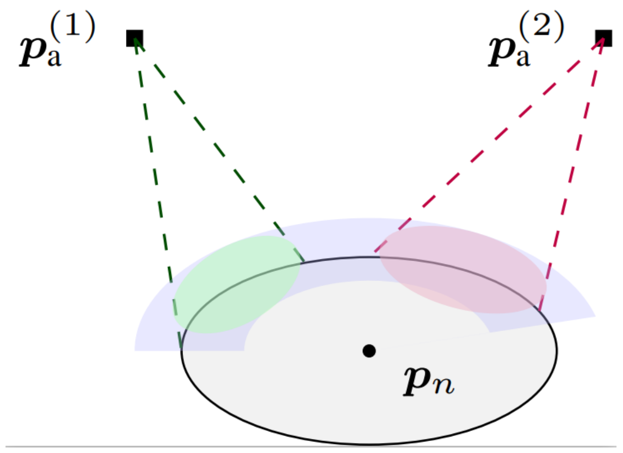
Multi-Sensor Fusion

- Each anchor provides only partial, view-dependent information (e.g., delay, scattering).
- Fusion resolves ambiguity by combining complementary views.
- **Goal**: Jointly estimate positions and EO shape $\boldsymbol{y}_n = [\boldsymbol{p}_n \, \boldsymbol{v}_n \, \boldsymbol{X}_n]$



Combine likelihoods from all anchors

$$p(\boldsymbol{y}_n) = \prod_j g(\boldsymbol{z}_n^{(j)} | \boldsymbol{y}_n)$$



Before fusion

- Partial observation
- Multiple possible positions / shapes

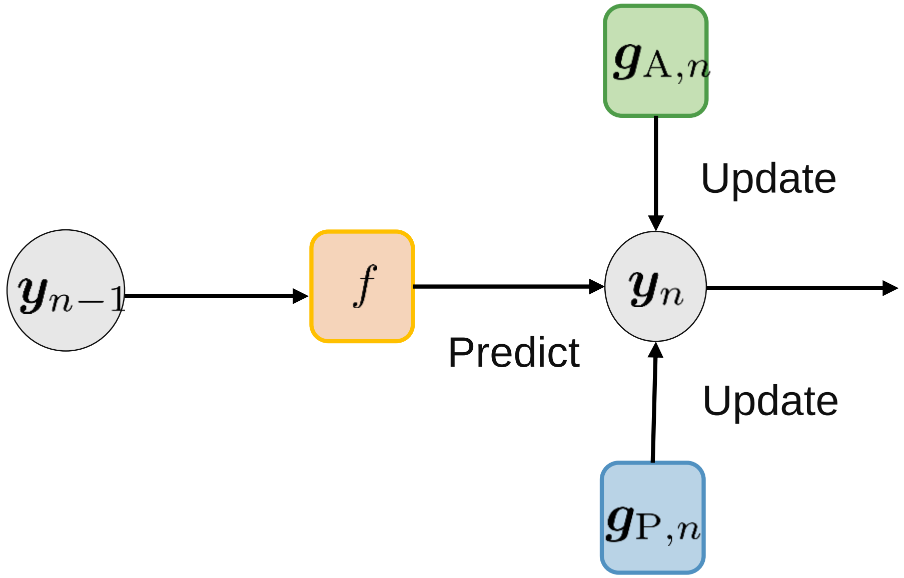
After fusion

- Complementary views
- Consistent estimate of position / shape

Bayesian Framework for Extended Object Tracking

Fuse Data from Active and Passive Measurements

- to deal with the absence of LOS



Joint posterior PDF

$$p(\boldsymbol{y}_n|\boldsymbol{z}_{\mathrm{A},n},\boldsymbol{z}_{\mathrm{P},n}) \propto g_{\mathrm{A}}(\boldsymbol{z}_{\mathrm{A},n}|\boldsymbol{y}_n)\, g_{\mathrm{P}}(\boldsymbol{z}_{\mathrm{P},n}|\boldsymbol{y}_n)\, f(\boldsymbol{y}_n|\boldsymbol{y}_{n-1})$$

Posterior ∝ Active LHF x Passive LHF x Prior

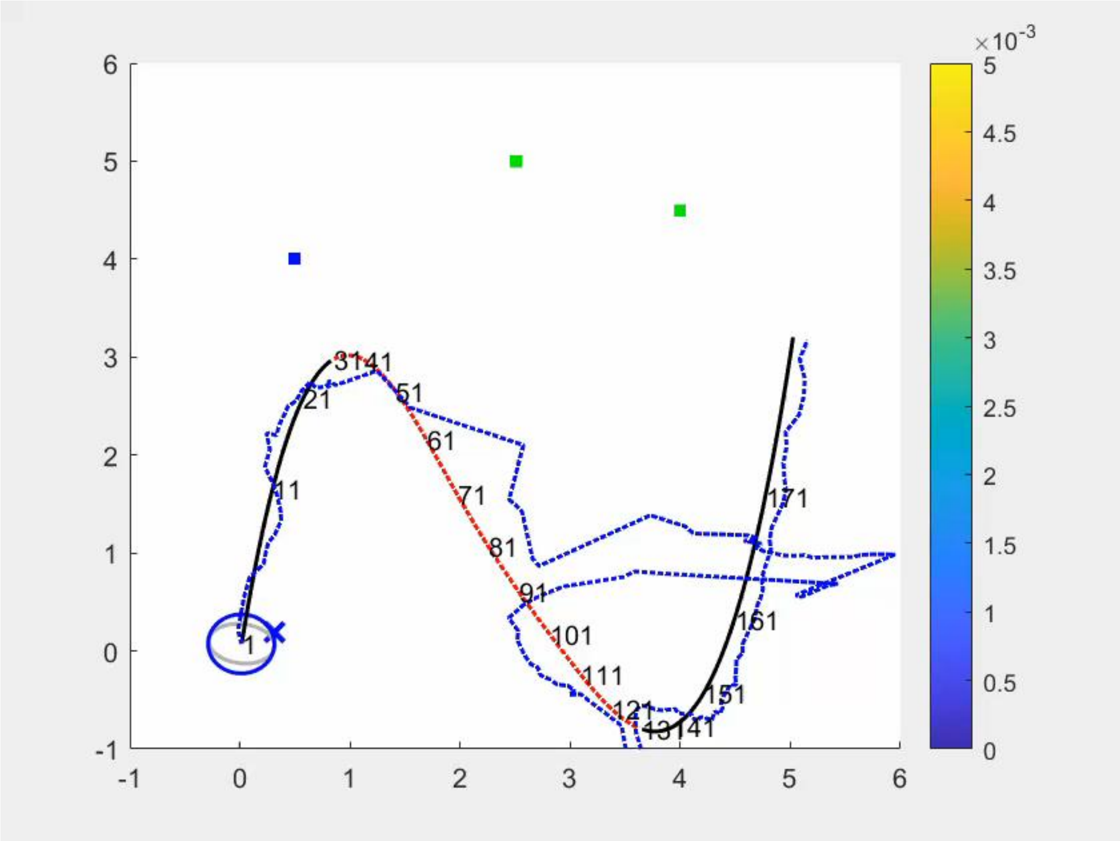
To solve the problem

- Compute the marginal posterior PDF of the device and EO states.
- Pass messages on a factor graph follows the sum-product algorithms (SPA).

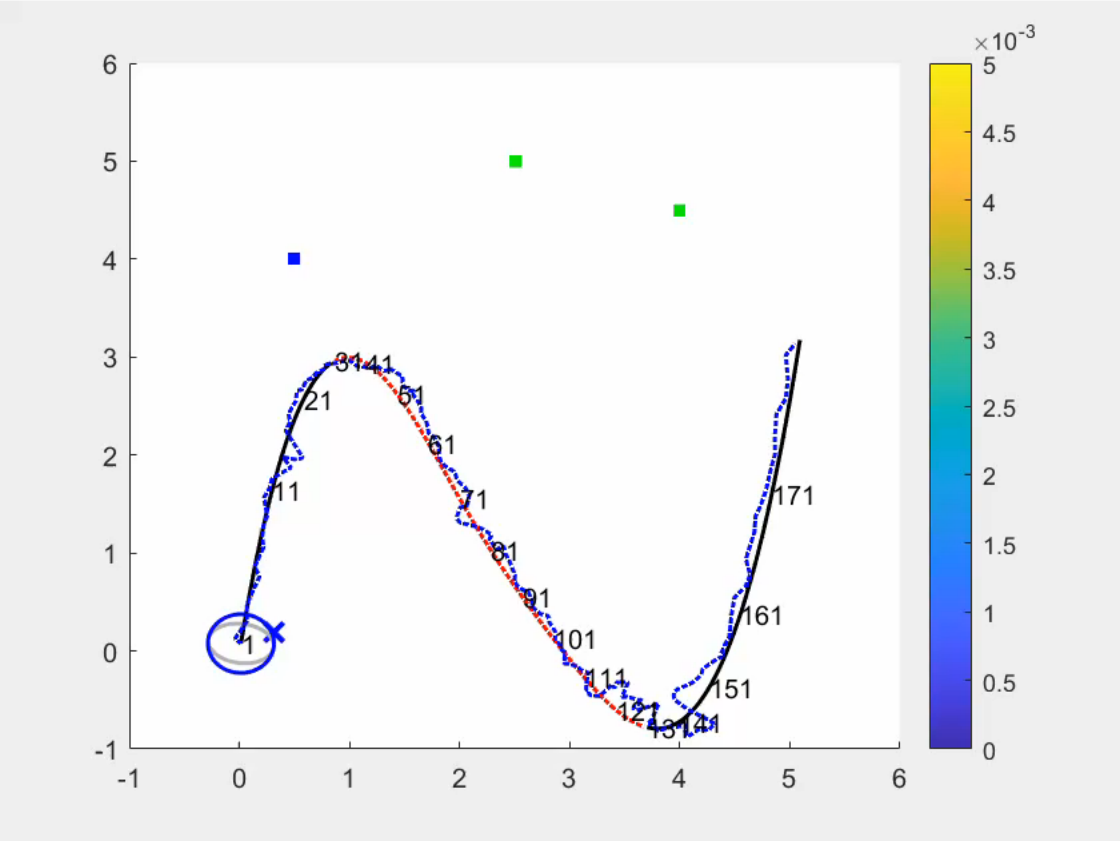
Particle Implementation

- The posterior distribution is approximated by 5,000 particles and its weights.
- Each particle's **weight** represents its relative ***belief*** given the measurements.
- The **spatial spread** of the particles reflects the ***uncertainty*** of estimated states.

Gray: reference EO
Red: reference device
Blue: estimated EO and device



Realization of the method with **only active** measurements



Realization of the method with **active & passive** measurements

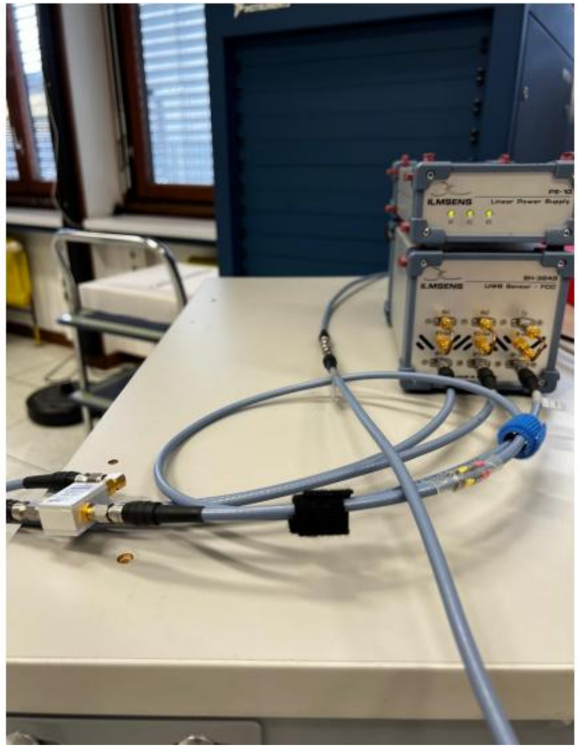
Validation

Measurement Campaign

- 2 RX antennas and 1 Tx antenna are placed in the environment.
- Qualisys tracking system is used to measure the *reference* positions of the agent and radio device.

Agent with a device

Environment



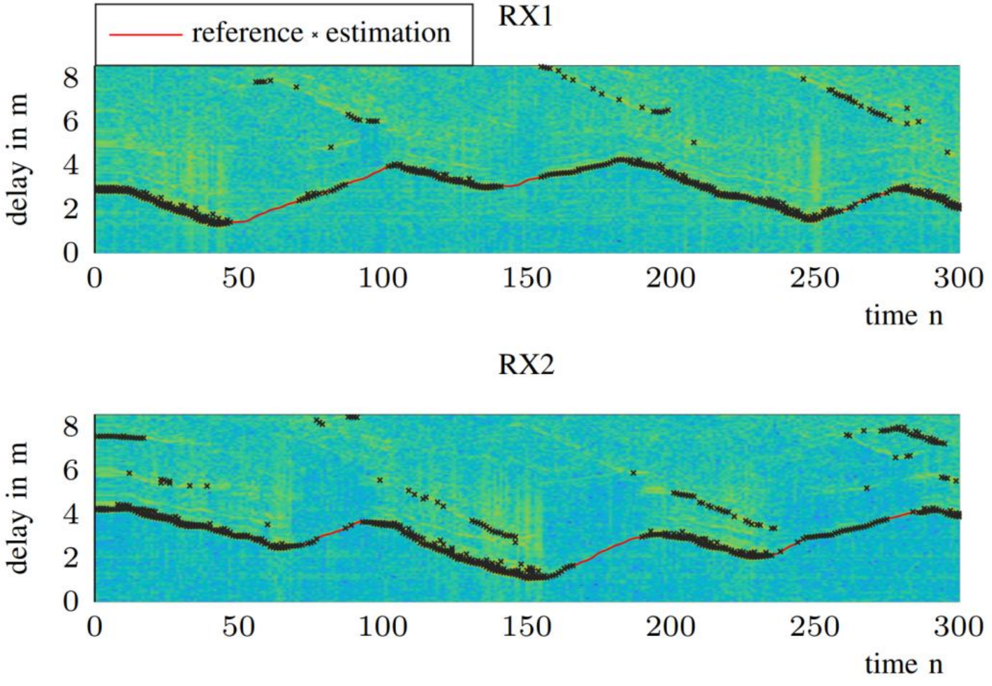
Channel sounder

Measurement Campaign

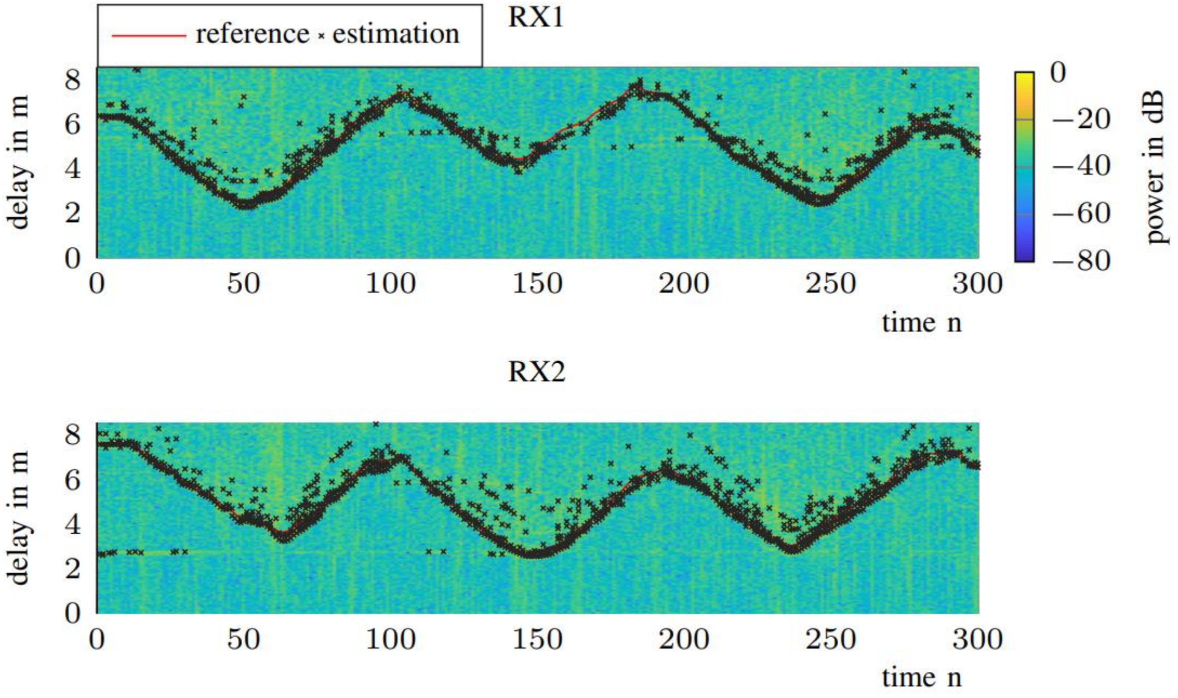
- Measurement frequency for both active and passive measurements is 5Hz.
- The measurement period is 60s in total.

Measured channel impulse response (CIR) from multiple anchors

- Extract delays from received signals by a channel estimation algorithm CEDA[3].
- When the bandwidth is 3GHz, abundant scatter paths can be observed.



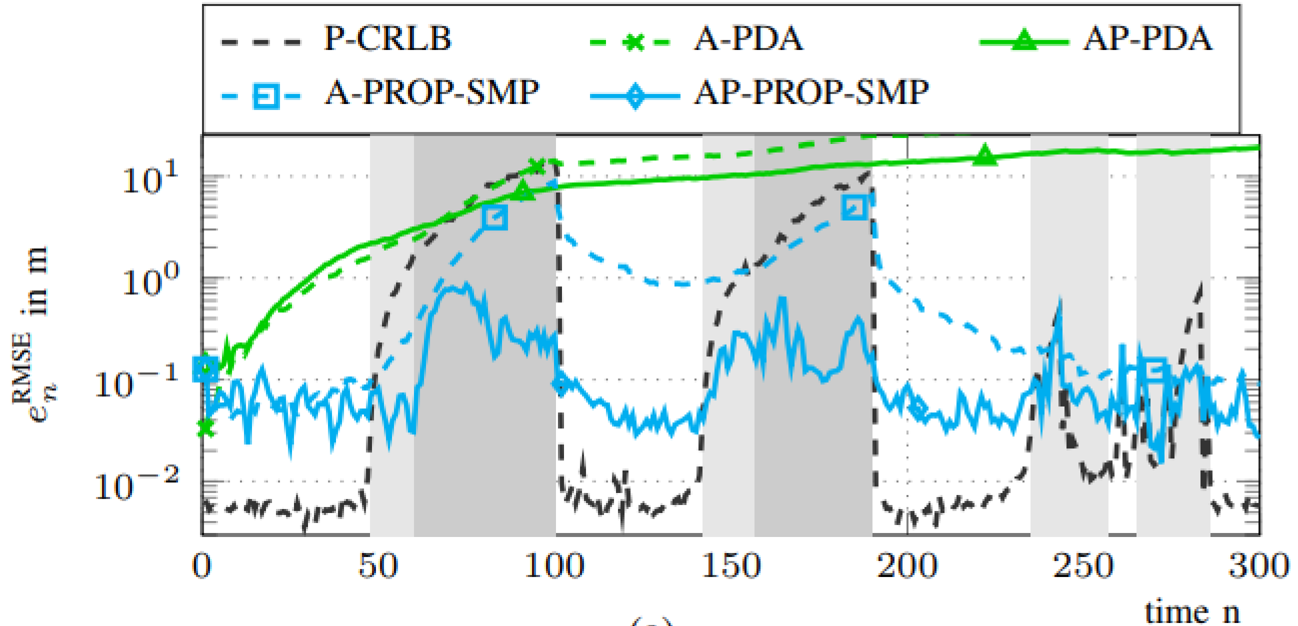
Active measurements



Passive measurements

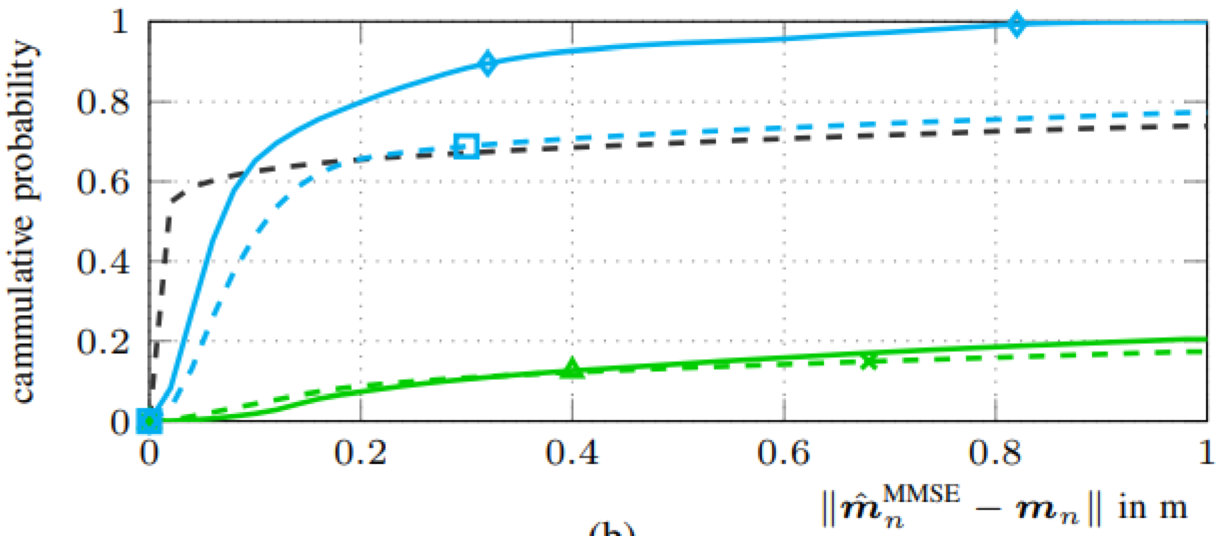
Performance Evaluation with Real Radio Measurements

- Numerical results of different methods in real radio measurements.
- The bandwidth is 3GHz.



(a)

RMSE of the estimated device position



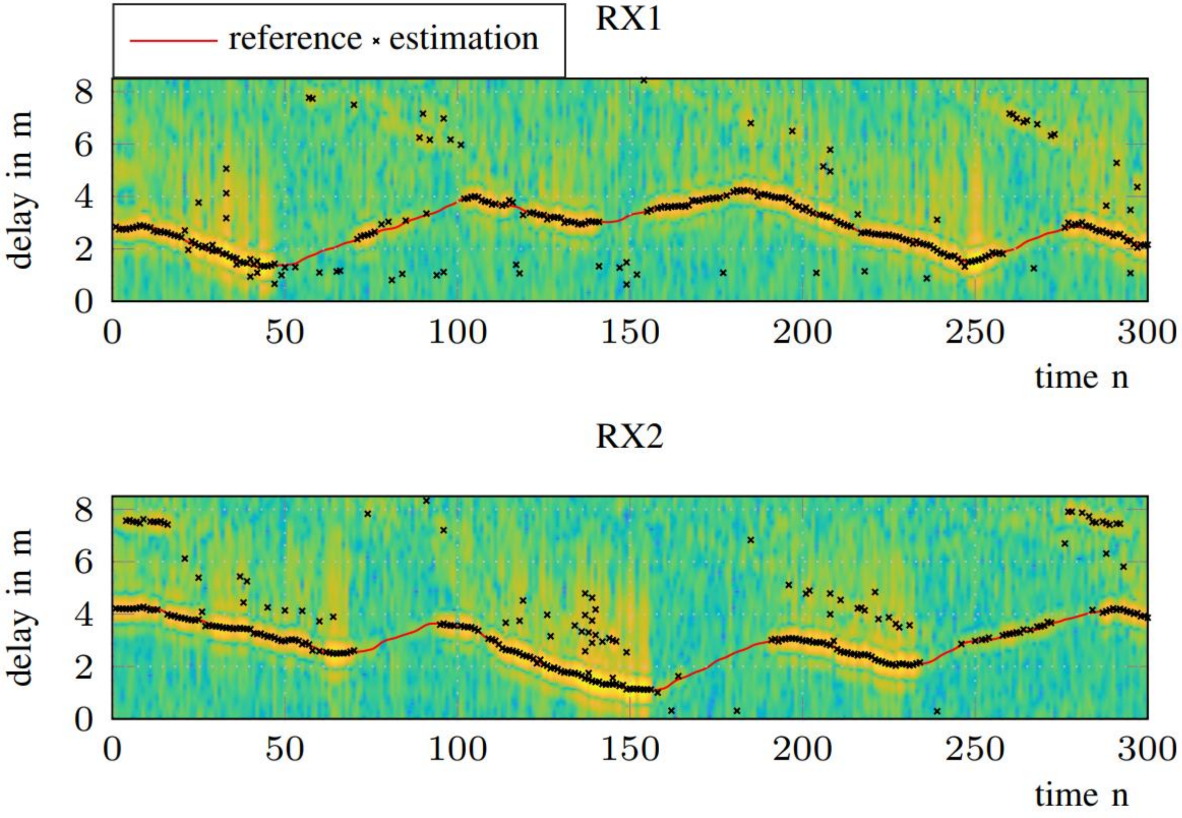
(b)

CDF of the RMSE based on numerical simulations

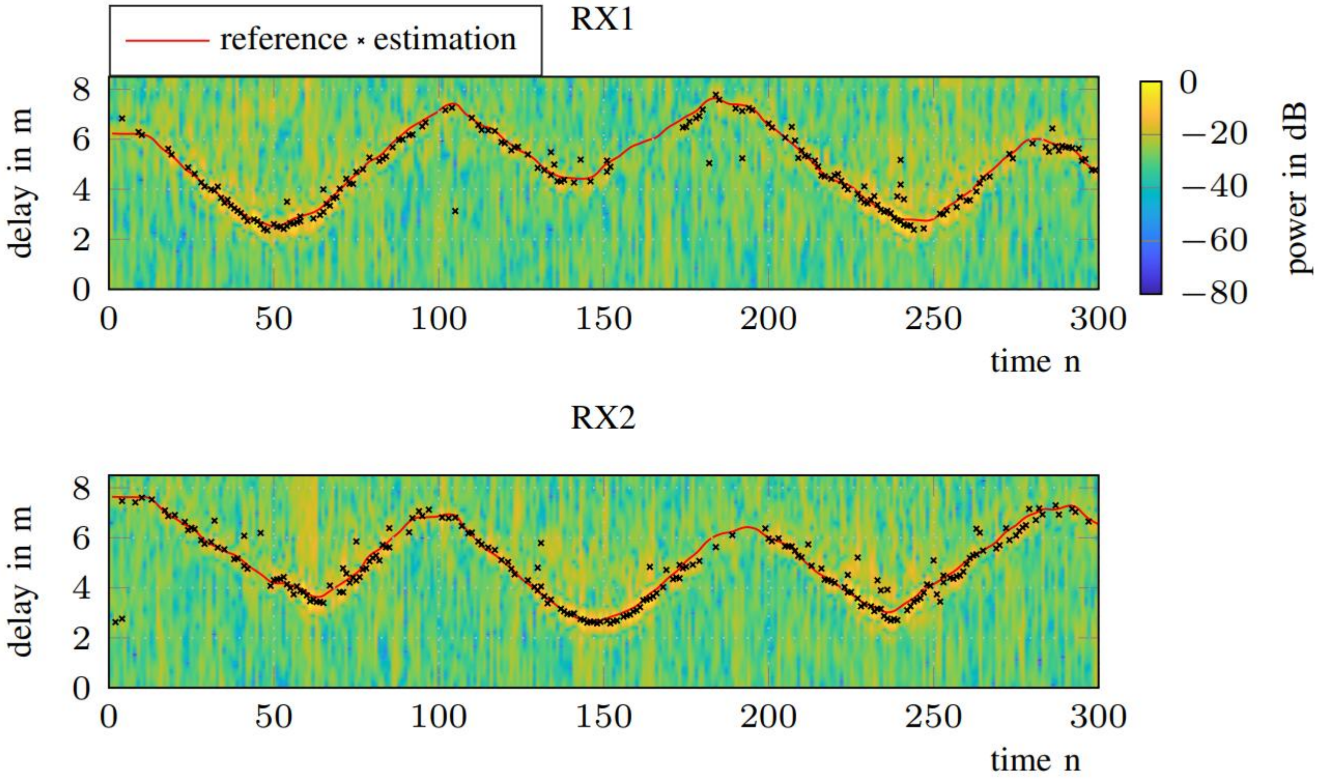
- Grey shades indicate missing active measurements;
- P-CRLB: posterior Cramer-Rao lower bound;
- A-PDA and AP-PDA: classic PDA [2] w/o and w/ passive measurements;
- A-PROP-SMP and AP-PROP-SMP: **proposed methods** w/o and w/ passive measurements.

Measurement Campaign

- When bandwidth is 500MHz, the CIR exhibits less scattered component, more clutter.



Active measurements



Passive measurements

Performance Evaluation with Real Radio Measurements

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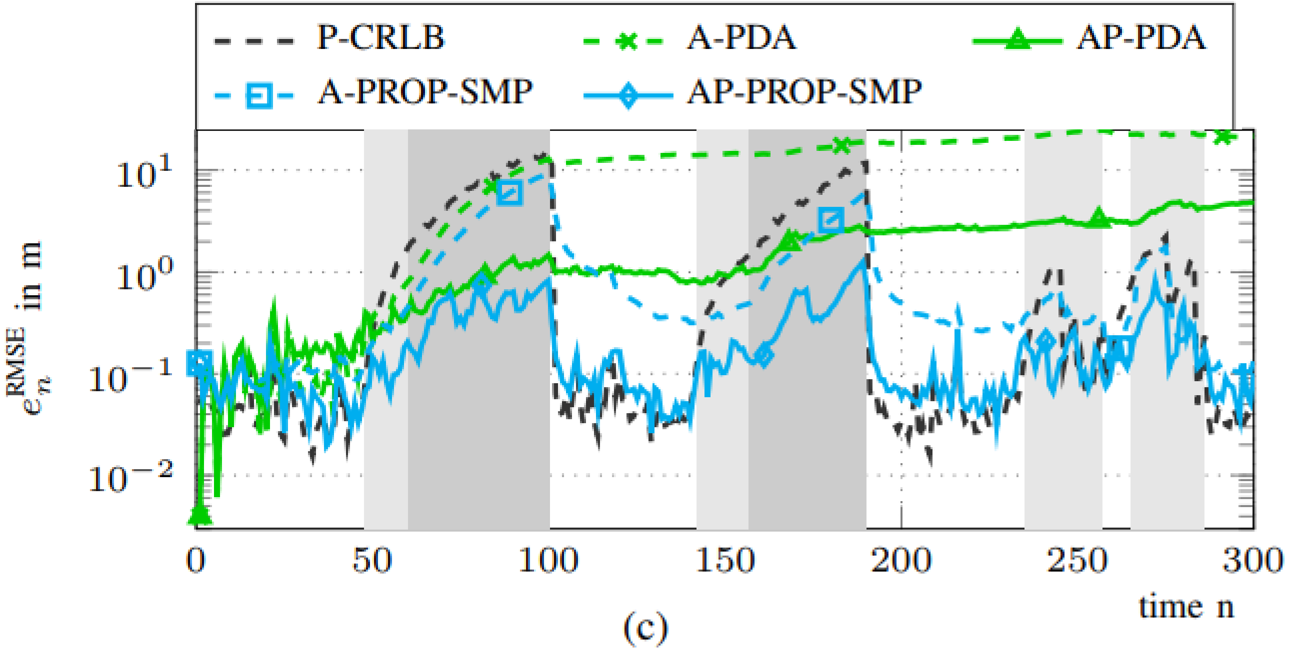
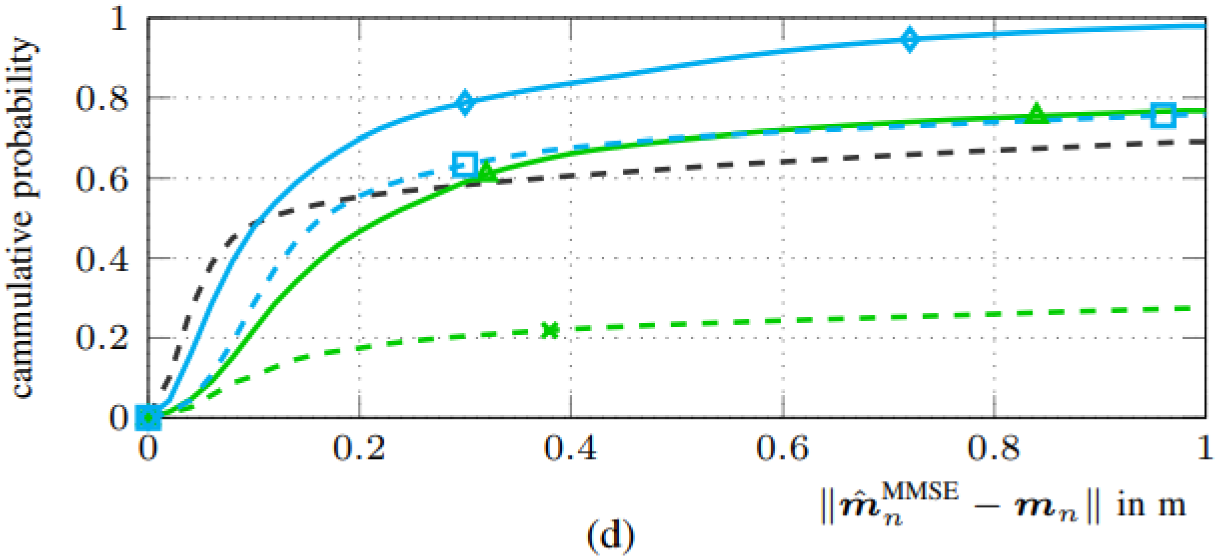


RMSE of the estimated device position



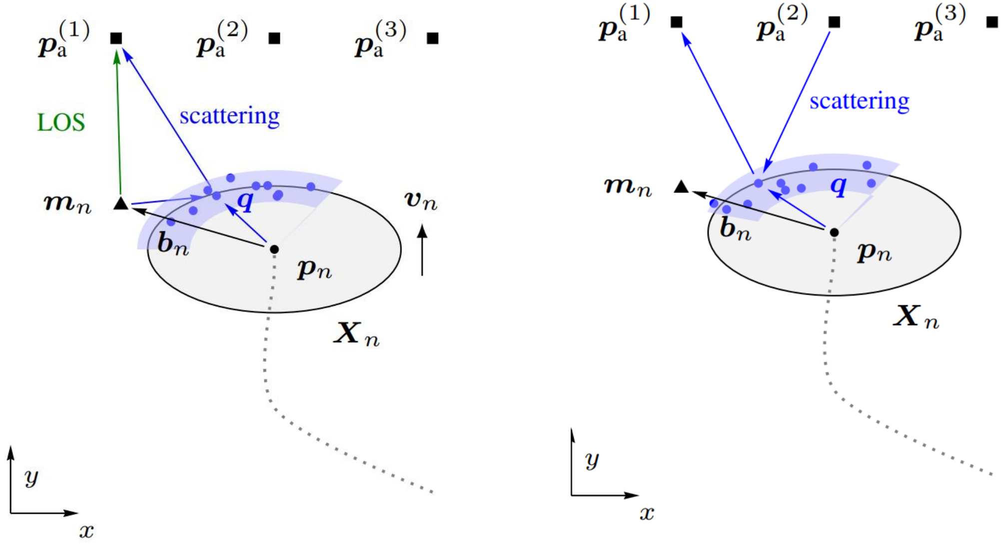
CDF of the RMSE based on numerical simulations

Our **proposed** AP-PROP-SMP significantly reduces the RMSE, compared to methods using only active measurements or the classical PDA under point-object assumption.

Conclusions

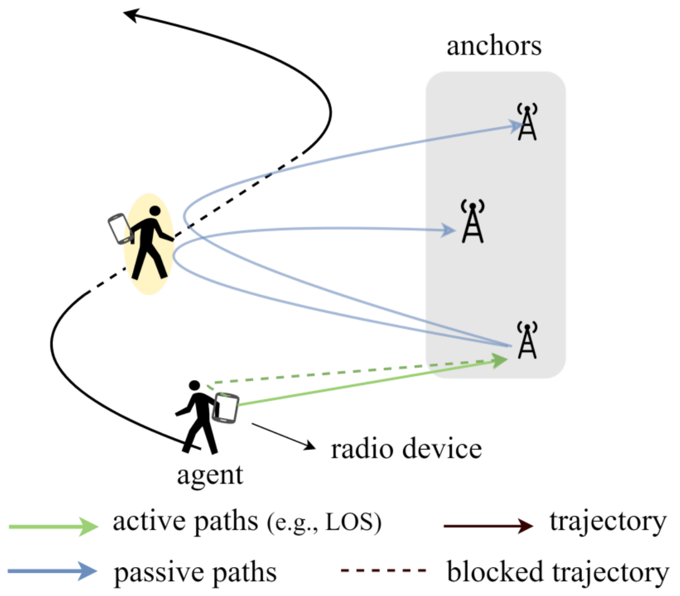
❑ Contributions

- Direction-dependent surface-scattering EO models for radio sensing.
- Fusion of active and passive measurements.
- Multi-sensor, multi-measurement PDA algorithm.



❑ Take-away

- Passive (reflected) signals improve robustness in OLOS (caused by agent) [1].



[1] Zhu, H., Venus, A., Leitinger, E., and Witrisal, K. Multi-Sensor Fusion for Extended Object Tracking Exploiting Active and Passive Radio Signals. *ArXiv*. https://arxiv.org/abs/2509.03686

Reference

[1] T. Wilding, E. Leitinger, U. Muehlmann, and K. Witrisal, “Modeling human body influence in UWB channels,” in Proc. IEEE 31st Annu. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC), London, UK, Aug. 2020, pp. 1–6.
[2] Y. Bar-Shalom, F. Daum, and J. Huang, “The probabilistic data association filter,” IEEE Control Syst. Mag., vol. 29, no. 6, pp. 82–100, Dec 2009.
[3] S. Grebien, E. Leitinger, K. Witrisal, and B. H. Fleury, “Super-resolution estimation of UWB channels including the dense component – An SBL inspired approach,” IEEE Trans. Wireless Commun., vol. 23, no. 8, pp. 10 301–10 318, Feb. 2024.

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