Hexa-X: WP3 – Deliverable D3.3

Final models and measurements for localisation and sensing

CHA, EAB, OUL, QRT, SAG

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Mission and scope

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- Hexa-X WP3 (*6D High-Resolution Localisation and Sensing*) focuses on:
  1. Exploring the potential of technological advances in communication systems (including from within the project) for the purpose of localisation and sensing, leveraging the geometric nature of the propagation channel at millimetre wave (mmW) frequencies (including 100-300 GHz), while accounting for severe hardware limitations;
  2. Harnessing high-resolution location and map information for existing (communication, security) and novel applications.

- This report is the third and final deliverable of project Hexa-X WP3, focuses on the final models and measurements, performance evaluation of new signal designs (including results from measurements from the over-the-air (OTA) demonstration) and algorithms, and evaluation of location-based services.

HORIZON 2020 Hexa-X 5G PPP The 5G Infrastructure Public Private Partnership

Call: H2020-ICT-2020-2

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Project Name:

A flagship for B5G/6G vision and intelligent fabric of technology enablers connecting human, physical, and digital worlds

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Deliverable D3.3

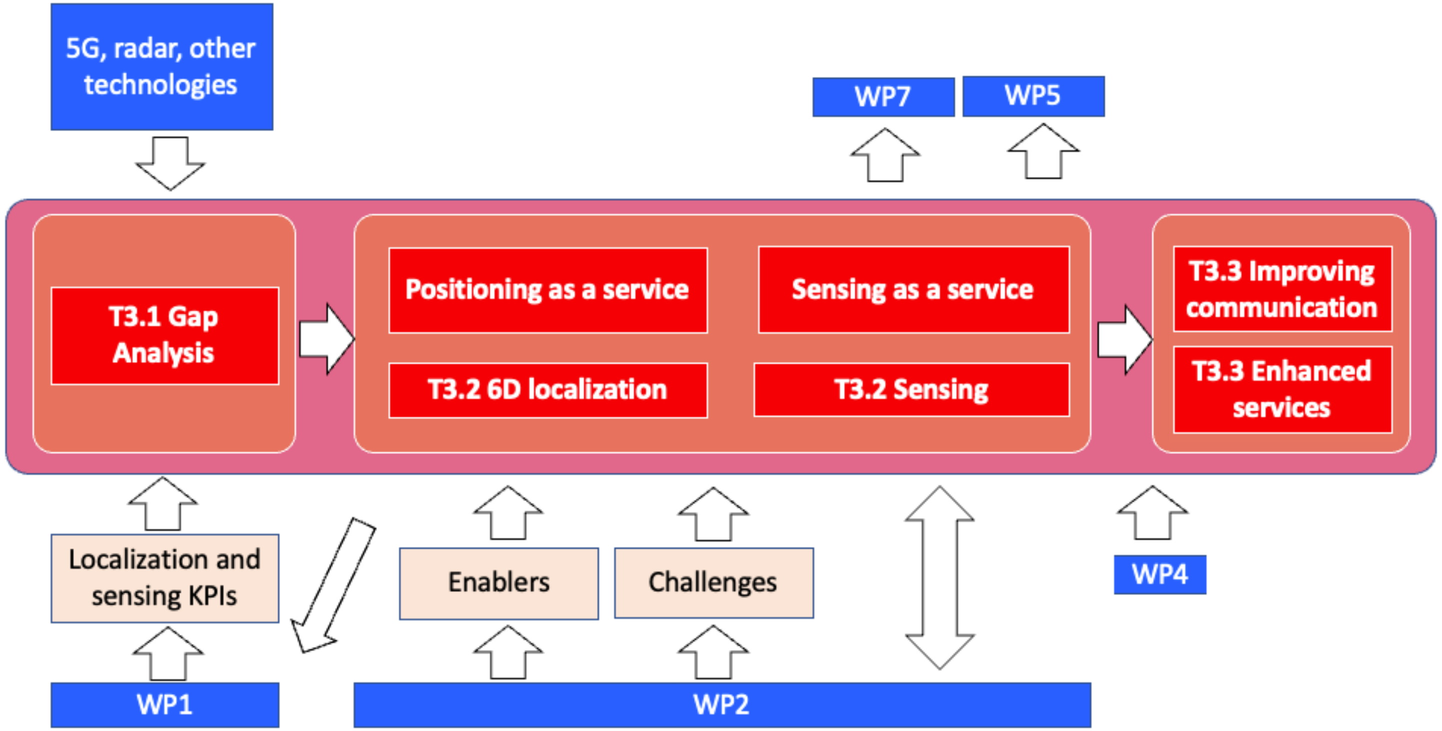
Final models and measurements for localisation and sensing

Date of delivery:	01/05/2023	Version:	1.1
Start date of project:	01/01/2021	Duration:	30 months

WP3 within Hexa-X

From/to other WPs

- Several WP1 use cases families are extremely challenging from a localisation and sensing perspective and have been studied in WP3.
- WP2 radio technologies, WP4 AI-based methods, WP5 architectures enable improved localisation and sensing.
- WP2 channel models and hardware limitations require different treatment for localisation and sensing than for communication.
- WP2 communication needs location and environment information to operate with low overhead.
- WP3 provides requirements to WP1 and WP2 (spectrum, rate, latency).
- WP3 enables WP7 special-purpose functionality.



Three main tasks:

- T3.1 Definition of use cases and requirements, complemented with a gap analysis.
- T3.2 Development of methods, signals, and protocols for localisation and mapping.
- T3.3 Establishment of location and mapping-enhanced service operation.

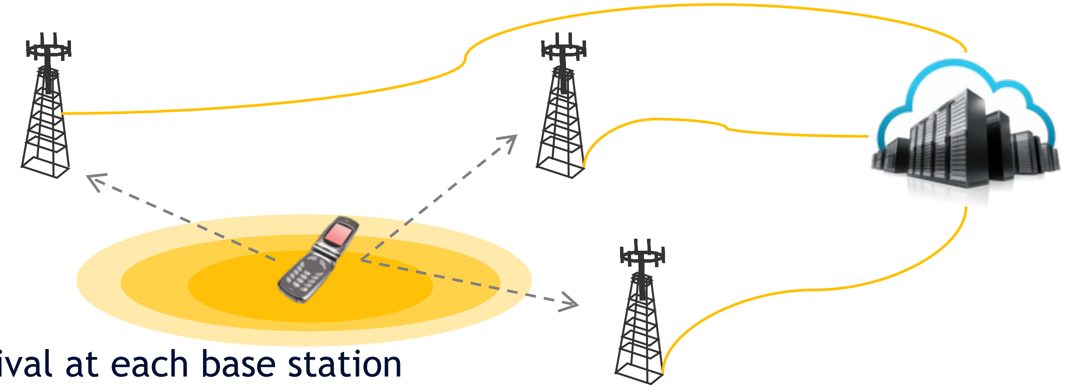
Outline

- Fundamentals on localisation and sensing
- Localisation and sensing in the 6G ecosystem
  - Emerging services layer
  - KPI perspective
  - KVI perspective
- Final models
- Final methods
- Impact of hardware impairments
- Over-the-air demonstrations
- Conclusions

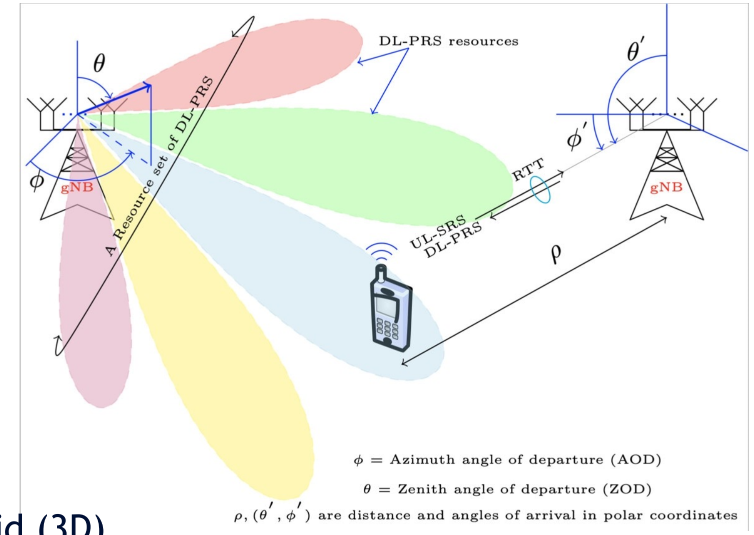
Fundamentals on localisation and sensing

Positioning / localisation - fundamentals

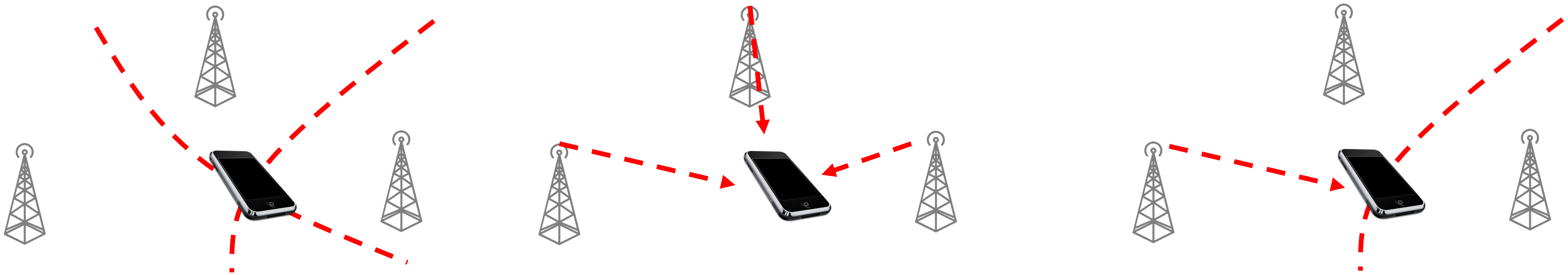
Operation



- Estimate time-of-arrival at each base station
- Differential measurement no longer depends on the user equipment (UE) clock bias
- Each time-difference-of-arrival (TDOA) measurement defines a hyperbola (2D) or hyperboloid (3D)
- Can be complemented with angle-of-departure measurements in downlink



https://www.ericsson.com/en/blog/2020/12/5g-positioning--what-you-need-to-know

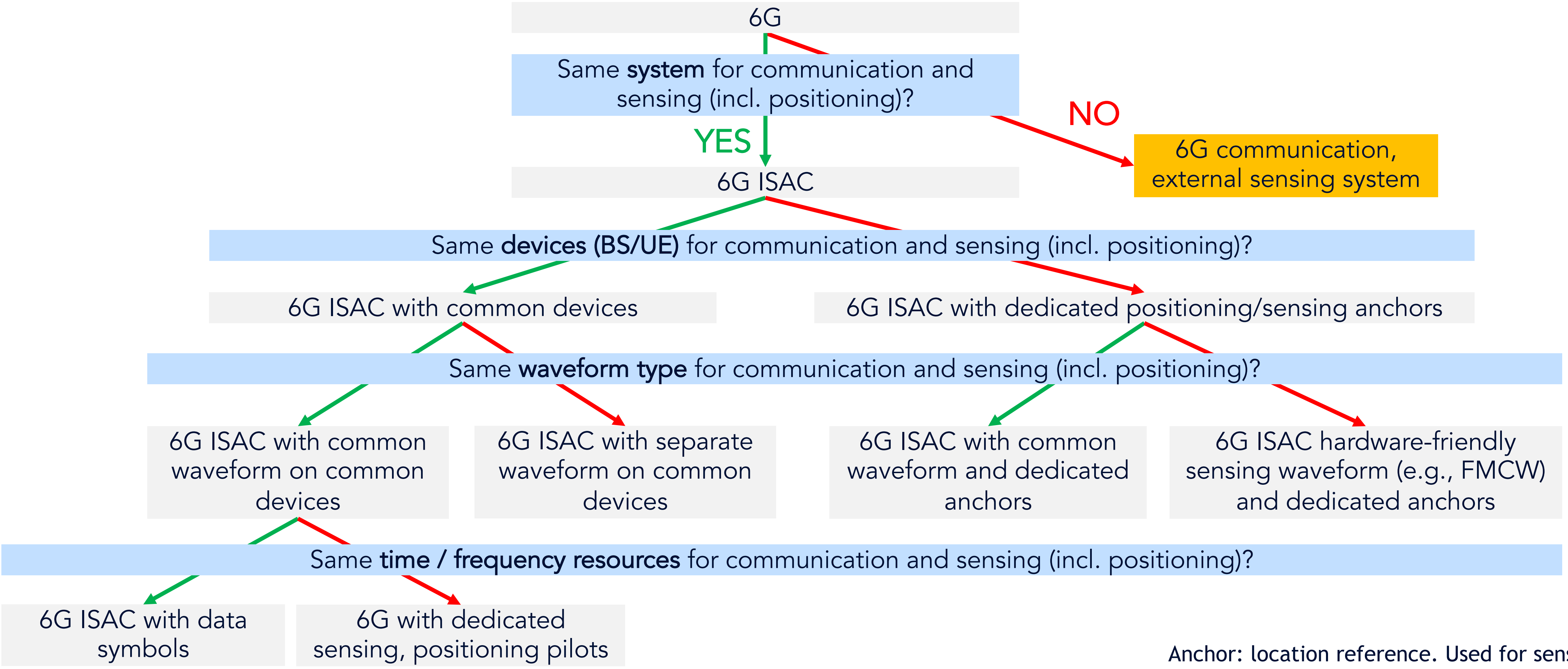


Sensing fundamentals

- *Sensing:* the detection of events or changes in an environment, based on radio signals. Pre-processing for positioning
- *Radar-like sensing:* channel parameter estimation/detection, target detection, estimation and tracking
- *Non-radar-like sensing:* extract features from signals for regression and classification
- Further divisions include monostatic, bistatic, multistatic, synthetic aperture, and passive sensing

Integrated and joint communication and sensing

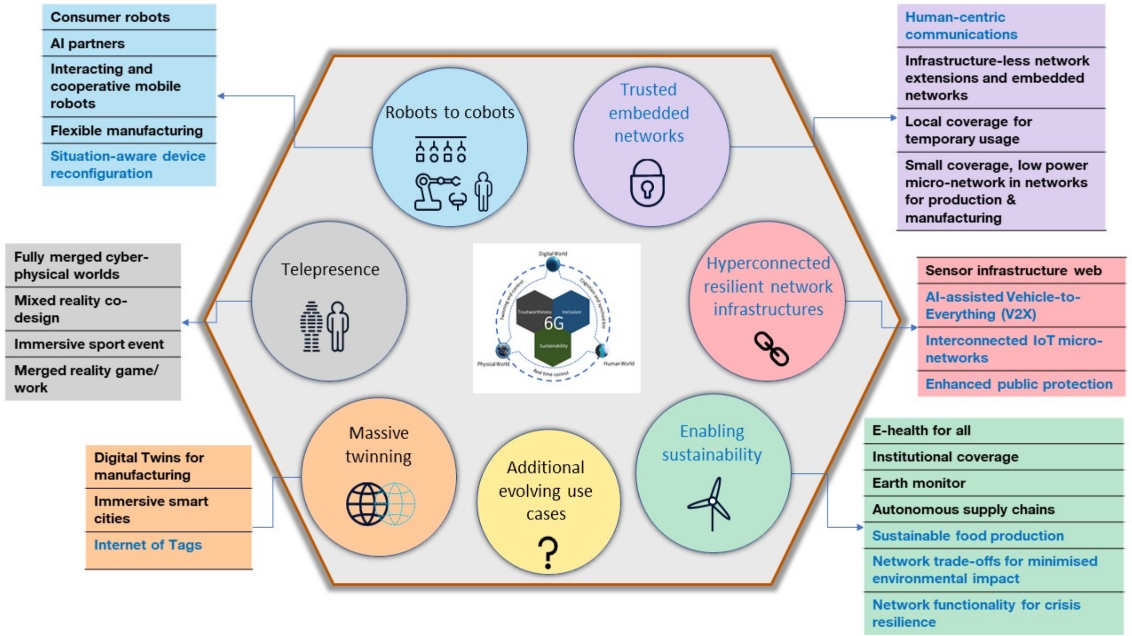
- Many combinations to combine communication and sensing (including positioning) in 6G



Anchor: location reference. Used for sensing or localisation

Main performance metrics / KPIs

- Accuracy in position and orientation
- Resolution to separate objects / paths
- Latency to support high mobility applications
- Range to provide coverage
- KPIs defined based on use cases
- KPIs put requirements on bandwidth, array sizes, deployments, etc



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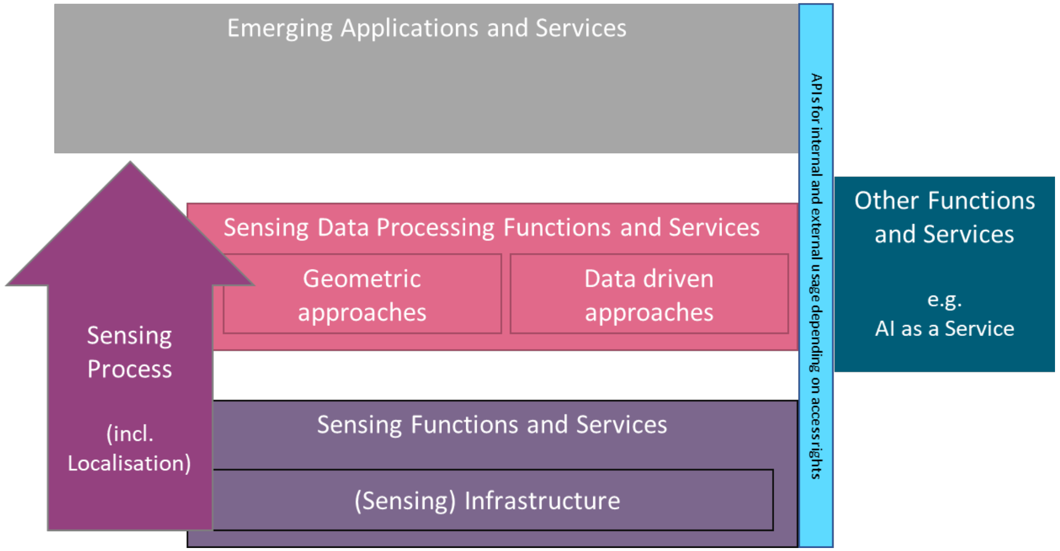
Localisation and sensing in the 6G ecosystem

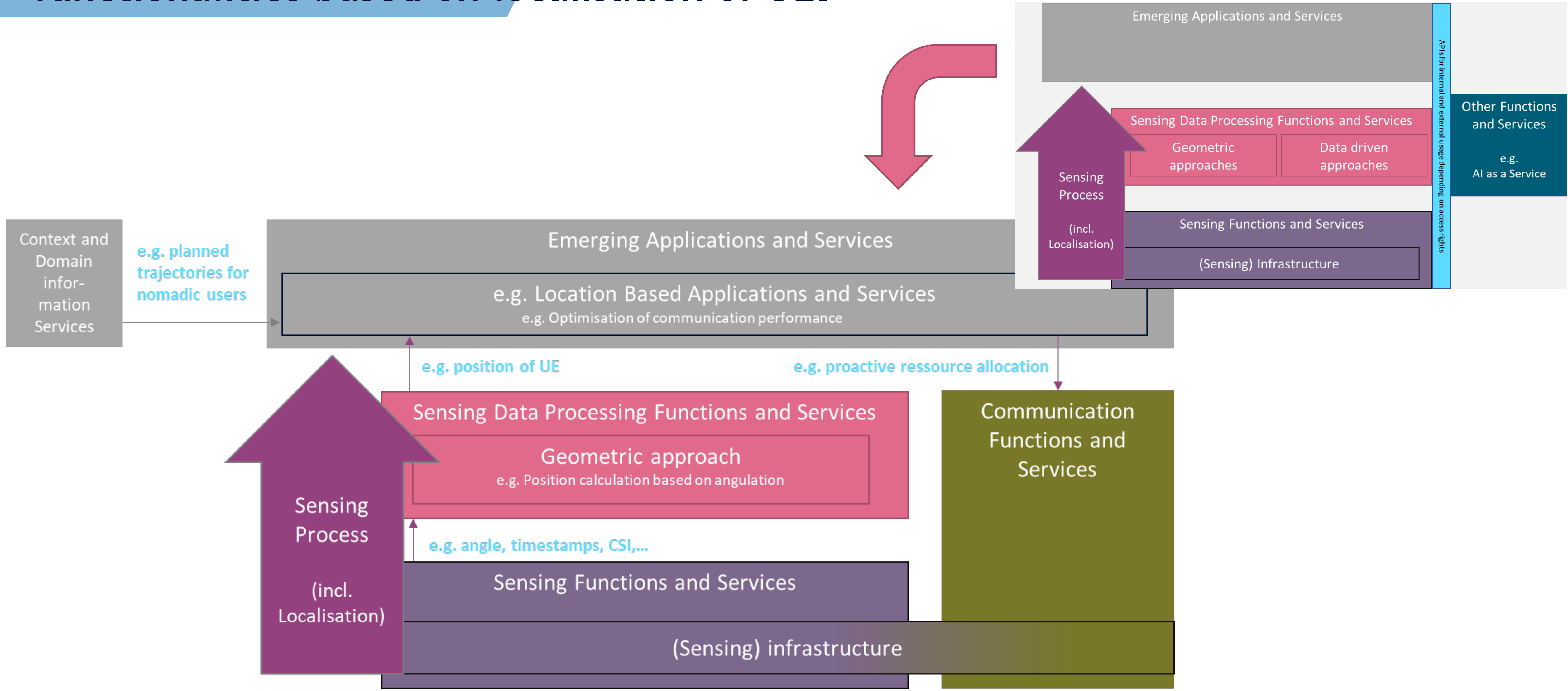
Emerging services layer

- **Sensing Functions and Services**
  - Infrastructure and means to configure
  - Estimation of delay/angle parameters
  - Extraction of features
  - Fusion of information
- **Sensing Data Processing Functions and Services**
  - Model-based / geometry-based
  - Data-driven / AI-based
  - Fusion of information

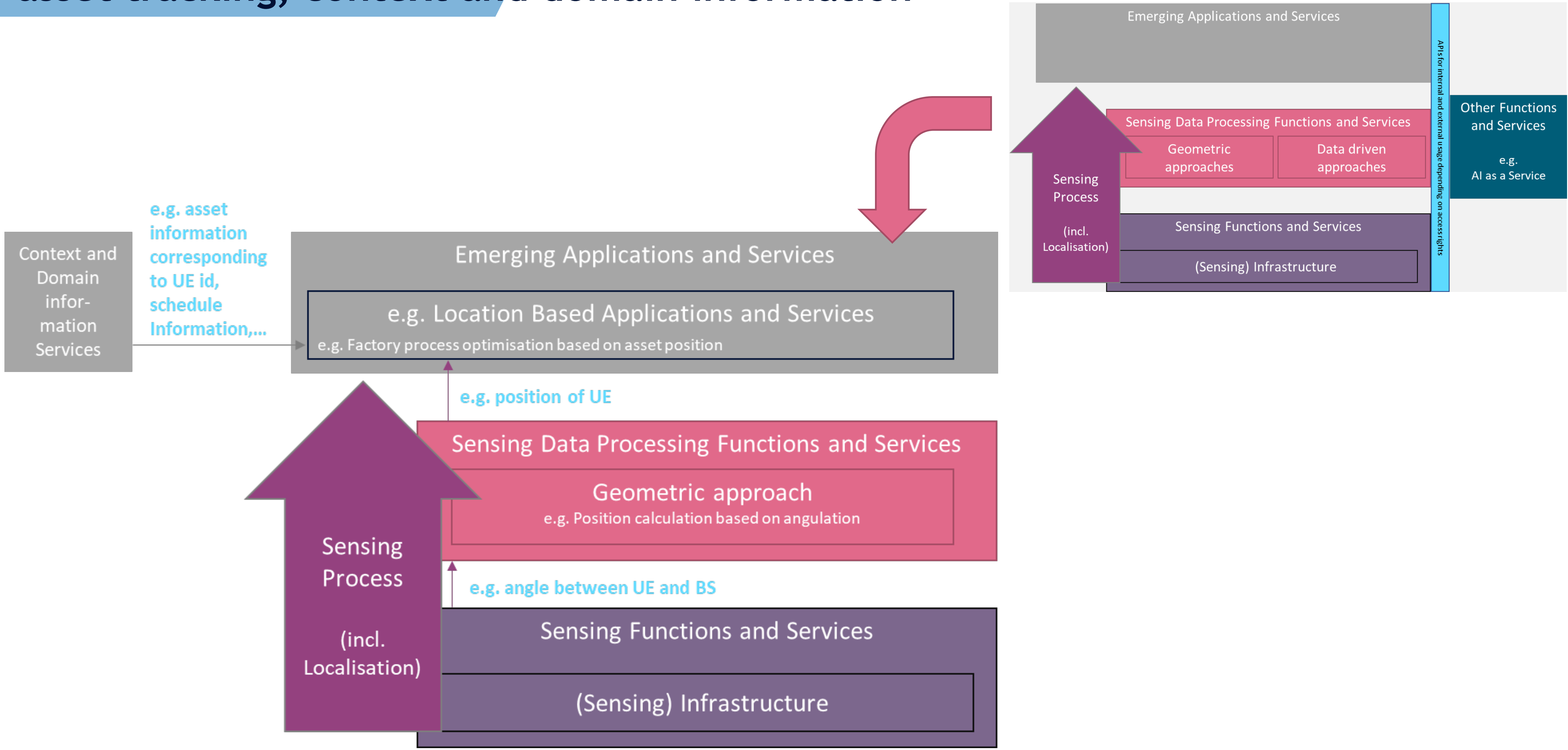


- **Emerging Applications and Service**
  - *E.g.: Location-based services*: use of absolute / relative location of UEs/ targets to generate network internal and external value added services
  - *Context/domain information services*: deliver additional (non-sensing-based) information of the surroundings, such as process or domain information, to optimise certain scenarios or processes.

Example 1: optimisation of communication and network functionalities based on localisation of UEs



Example 2: optimisation of factory processes based on combination of asset tracking, context and domain information



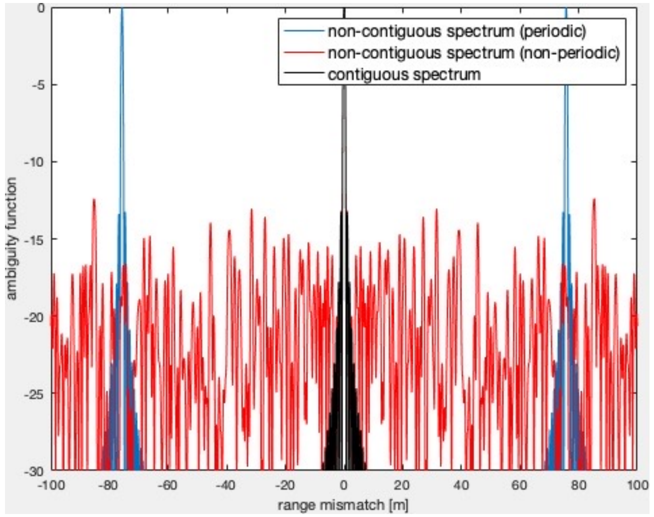
Localisation and sensing in the 6G ecosystem

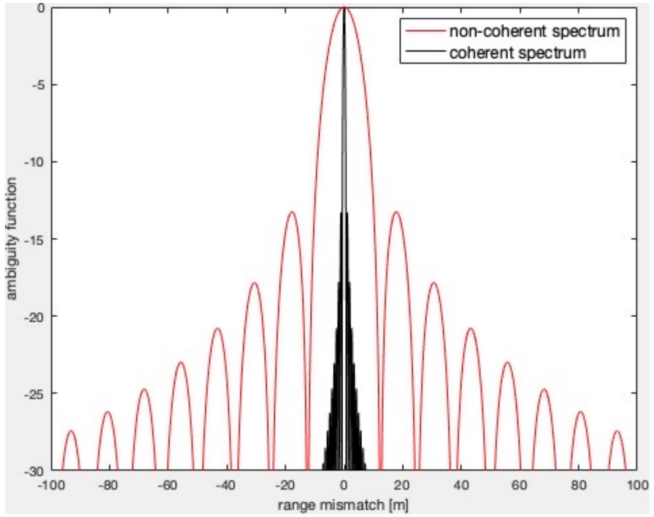
KPIs and implications

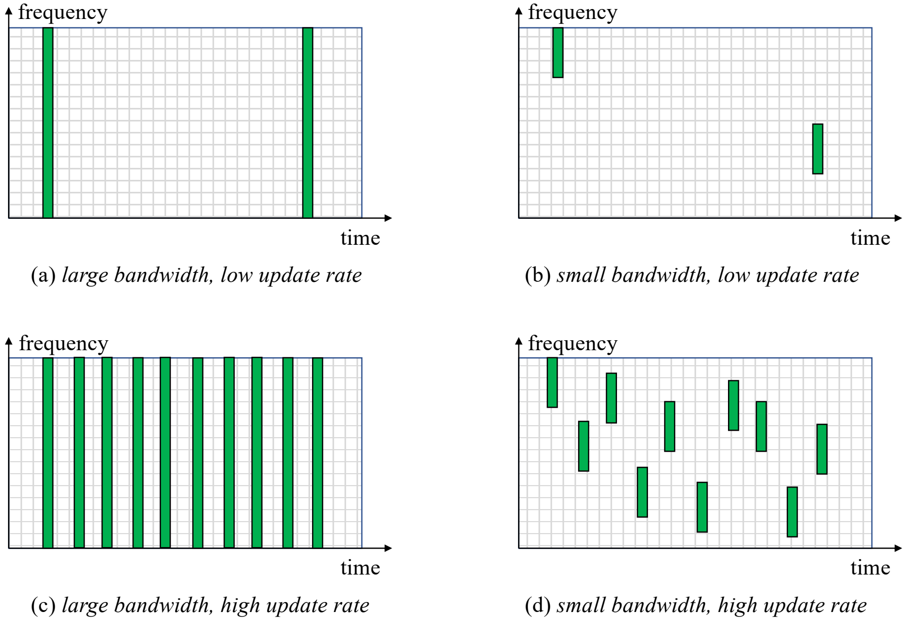
- Meeting KPIs
  - Sufficient bandwidth and time
  - Sufficiently large arrays
- Bandwidth requires spectrum
  - Contiguous
  - Phase coherent
  - Available
  - Contained
- Resource allocation
  - Space, time, and frequency resources
  - Infractructure optimization

Parameter / Use case	Extended reality positioning	Bistatic digital twin use	Monostatic sensor infrastructure web
Bandwidth	3 GHz	3 GHz	300 MHz
Synchronization requirements	3 ps	30 ps	70 ps
Maximum end-to-end-latency	1 ms	10 ms	2 ms
UE array size	2 cm x 2 cm	N/A	N/A
UE beam resolution	1 degree	N/A	N/A
Sensor array size	20 cm x 20 cm	214x214	10 cm x 10 cm

Spectrum aspects







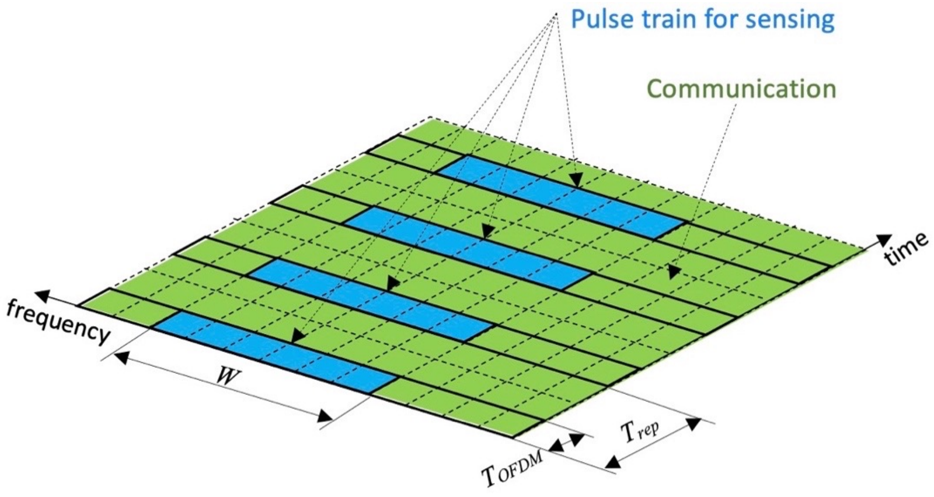
Non-contiguous spectrum leads to "grating lobes"

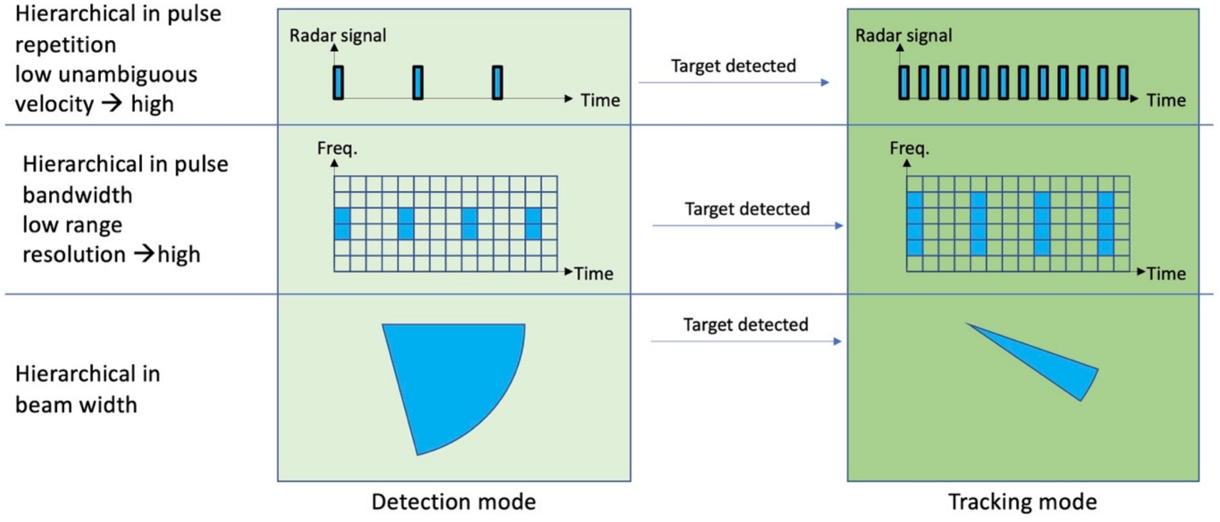
Non-phase coherent spectrum leads to reduced resolution

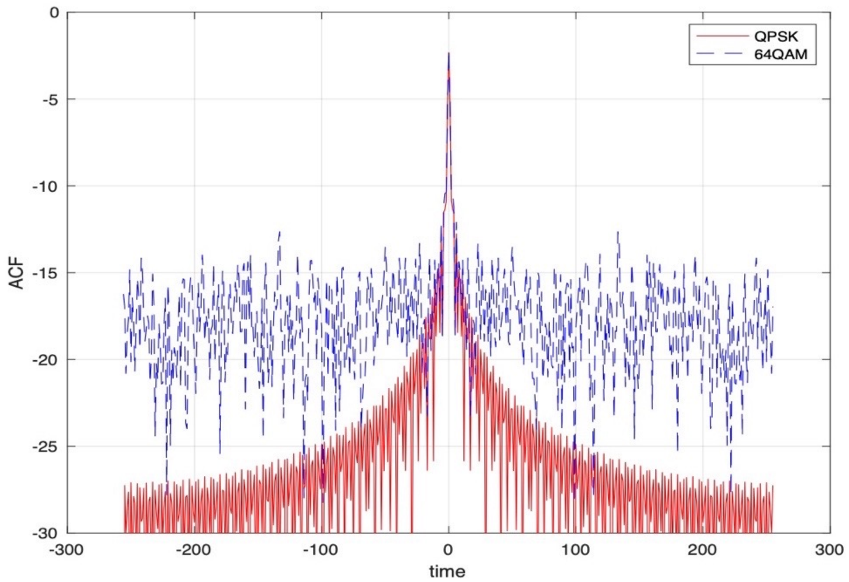
Spectrum should be available in time and frequency

Allocation of space, time, frequency resources

- Time-frequency perspective
  - Focus on OFDM-like waveforms
  - Dedicated pilots vs use of modulated data
  - Constant-modulus constellations preferred
- Space perspective







Ambiguity function for different modulation formats

Infrastructure optimization

- Fixed, moving, nomadic components
- General formulation

Minimize with respect to resources	*Objective (resources)*
	Constraint (resources)

- Examples:
  - Anchor layout optimization
  - UAV trajectory optimization
  - Adaptive network configuration (compute/storage)

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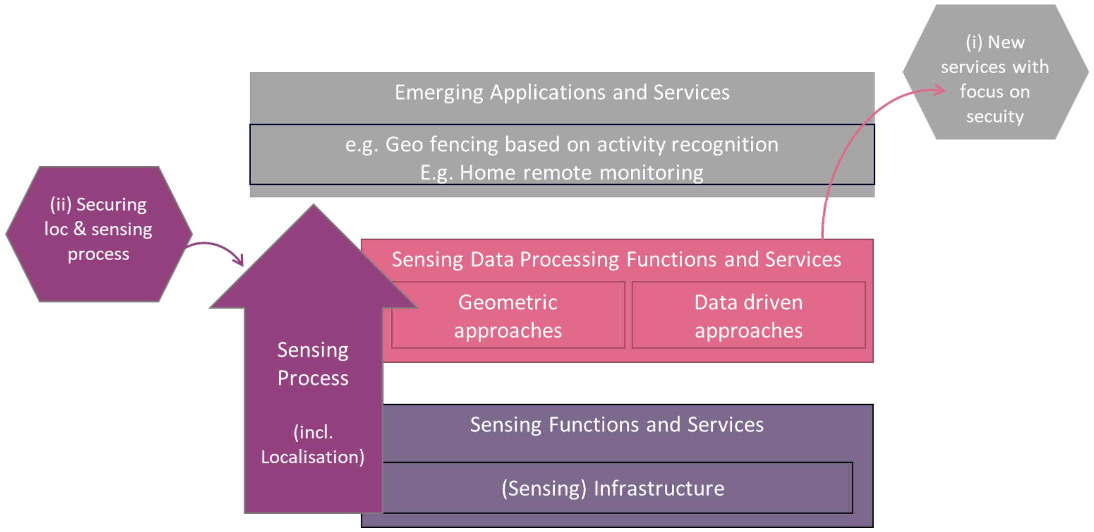
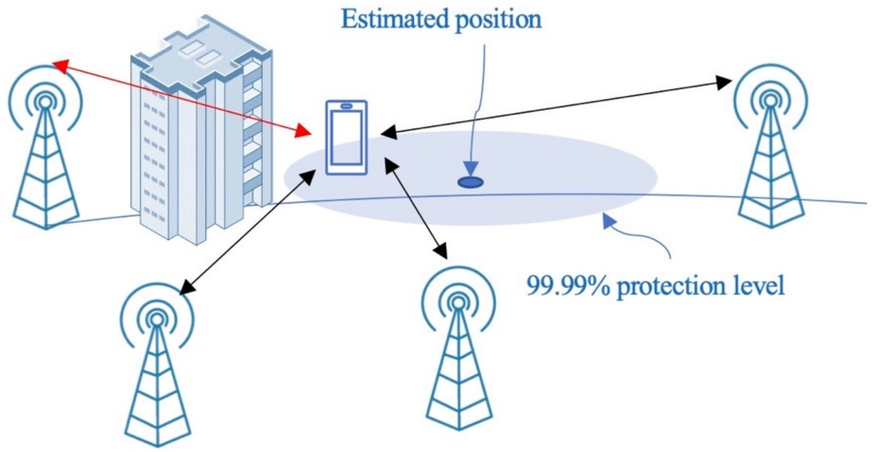
Localisation and sensing in the 6G ecosystem

KVIs and implications

- *Trustworthiness*
  - Security:
    - Localisation and sensing information used for security applications
    - Securing the localisation and sensing process itself
  - Safety/dependability:
    - Localisation and sensing information can be used to support "safety use cases"
    - Failsafe localisation and sensing system
  - Privacy
    - User privacy
    - Asset privacy
- *Inclusiveness*
  - Human-machine interaction
  - Support people who are not able to interact with systems
- *Sustainability*
  - Sustainability supported by localisation and sensing
  - Sustainable localisation and sensing

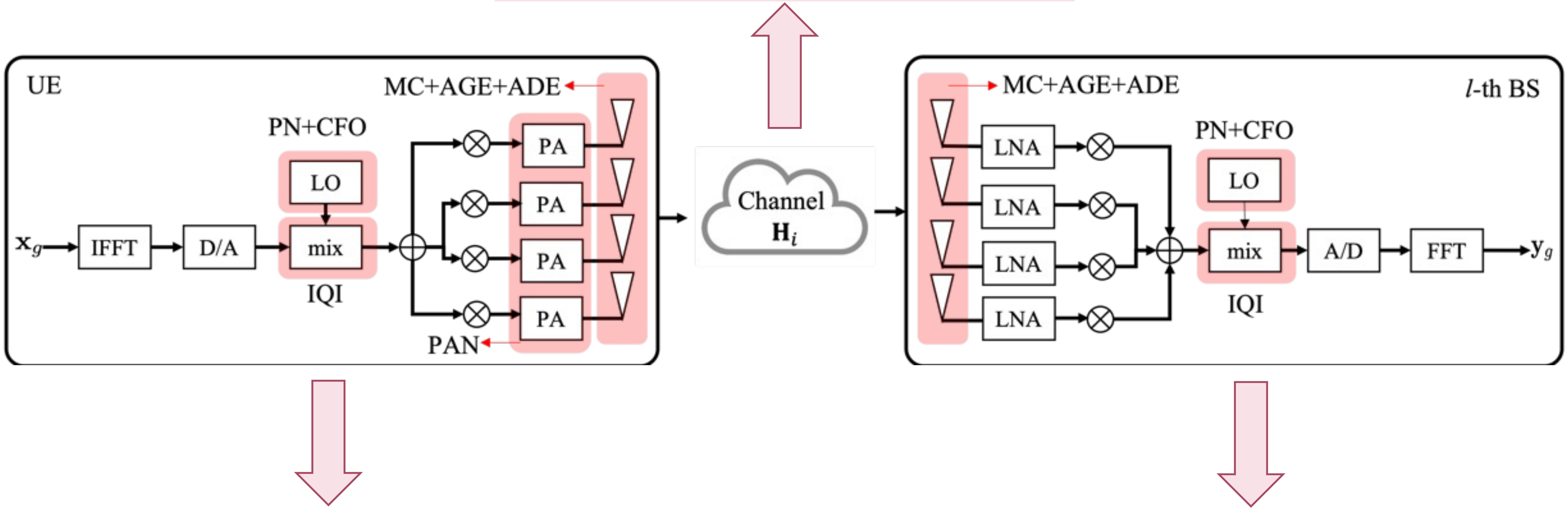




Final models

Final models

Channel models



Hardware impairment models

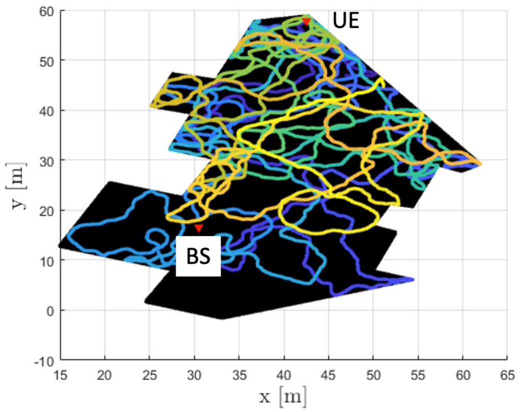
Hardware impairment models

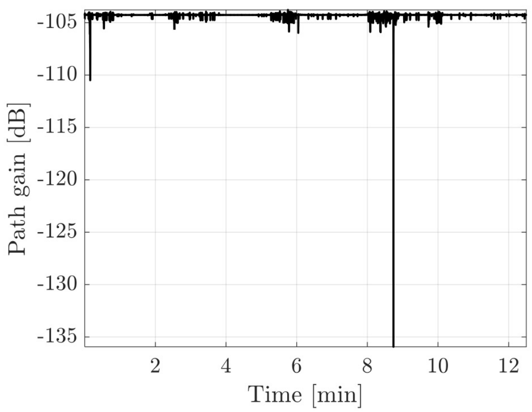
Channel models

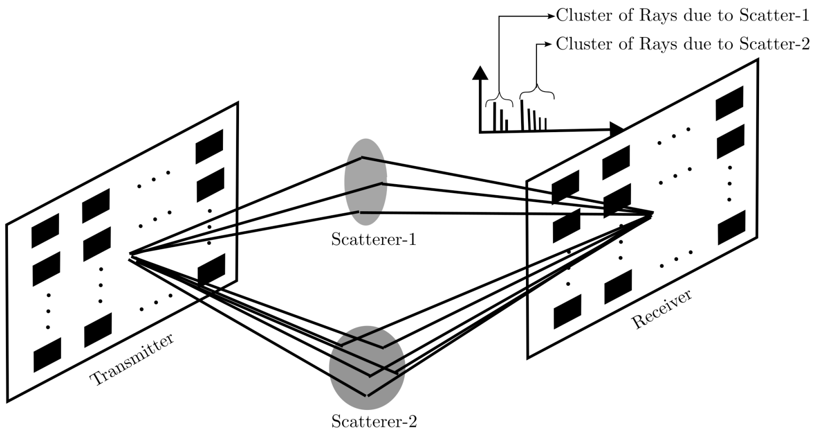
- Account for
  - Different frequency bands
  - Material properties
  - Dynamics (including blockage)
- Relies mainly on WP2 work
- Generic model for frequency response

$$\boldsymbol{H}_{n,k} = \sum_{l=1}^{L} \alpha_l \boldsymbol{a}_{rx}(\theta_l)\boldsymbol{a}_{tx}^{T}(\phi_l) e^{-j2\pi n \Delta_f \tau_l} e^{-j2\pi k T_s \nu_l}$$

- Extensions
  - Near-field propagation
  - Beam squint
  - Inter-carrier interference
  - …

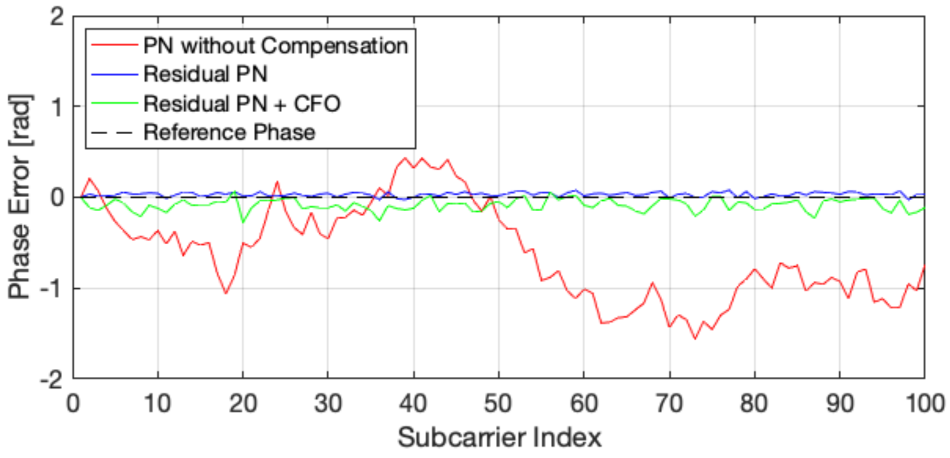


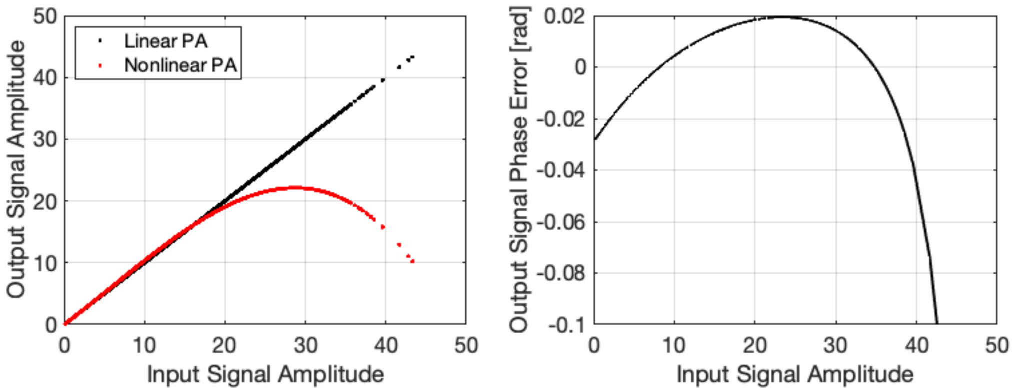




Hardware impairment models

- Account for
  1. Phase noise and carrier frequency offsets
  2. Mutual coupling
  3. Power amplifier nonlinearity
  4. Array calibration error
  5. In-phase and quadrature imbalance
- Models same as for communication (see D2.3), but different impact





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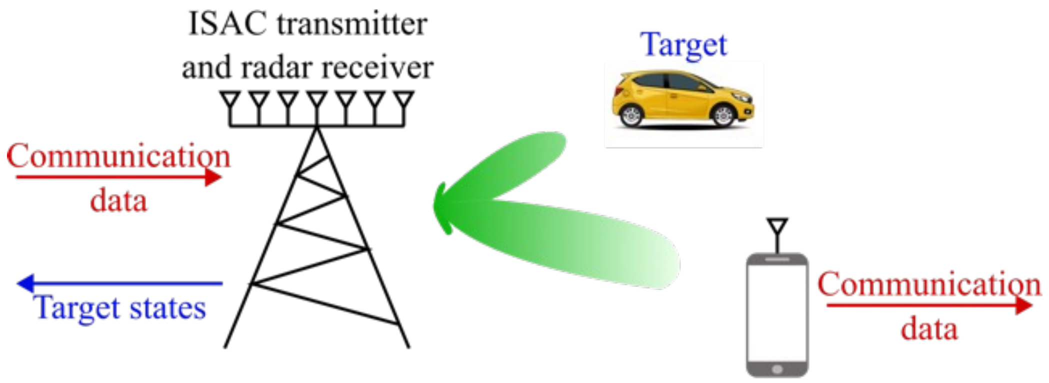
Final methods

Overview

	monostatic sensing	bistatic sensing	multistatic sensing	Location-aided communication
Model-based	sensing	Localisation, sensing, ISAC	localisation	Using RIS
AI-based	ISAC	sensing		See [HEX22-D32]

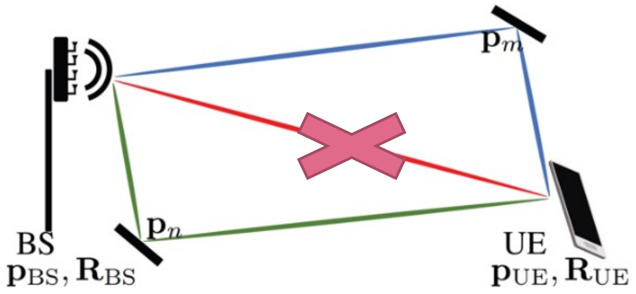
Final methods

- WP3 considered a wide variety of methods, model-based and AI-based
- Methods include
  - 6D localisation and bistatic sensing under LOS and blocked LOS
  - Signal design for localization and sensing
  - Monostatic integrated sensing and communication
  - Bi-static integrated sensing and communication
  - Multistatic integrated sensing and communication
  - Coverage analysis
  - Location-aided communication

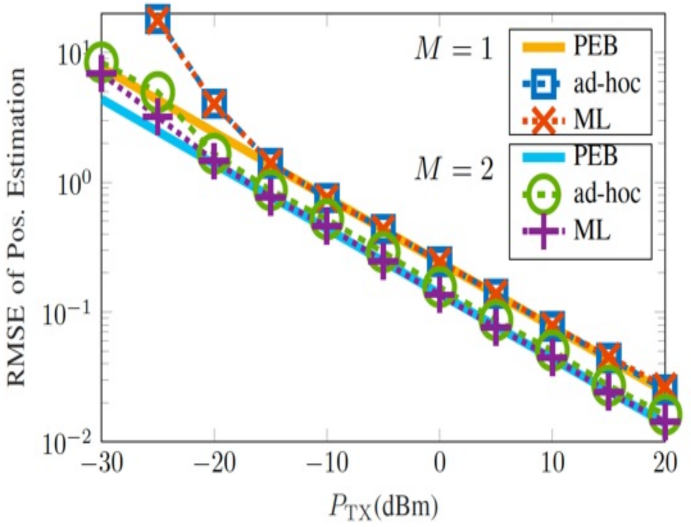


6D localisation and sensing

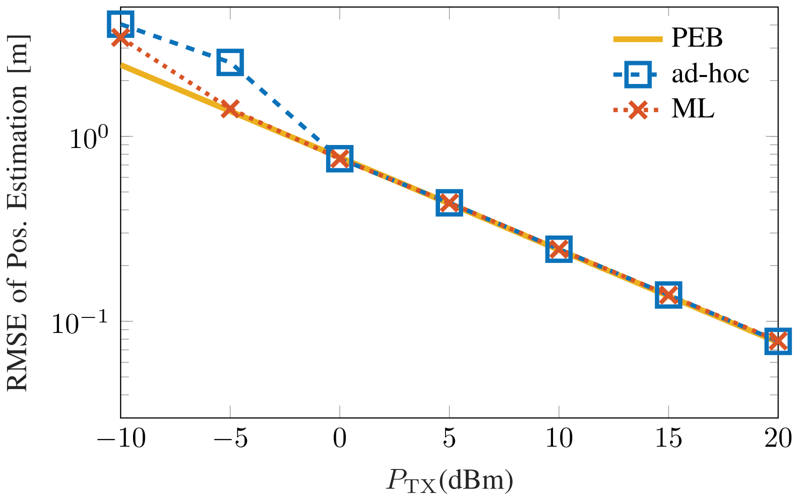
- **Problem**
  - Estimation of 3D position, 3D orientation, and clock offset of an unsynchronised multi-antenna user from downlink MIMO-OFDM signals
  - LOS path from BS may be blocked
- **Solution**
  - Two-stage localisation process:
    - Determination of the marginal posterior densities of AoAs, AoDs, and ToAs
    - Maximum likelihood estimation over manifolds



Schematic of the system model for 6D localisation with a single BS.



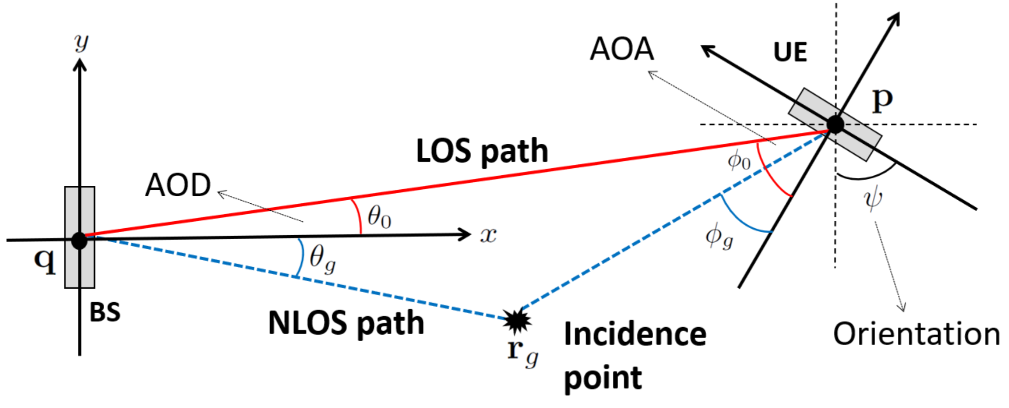
With LOS path



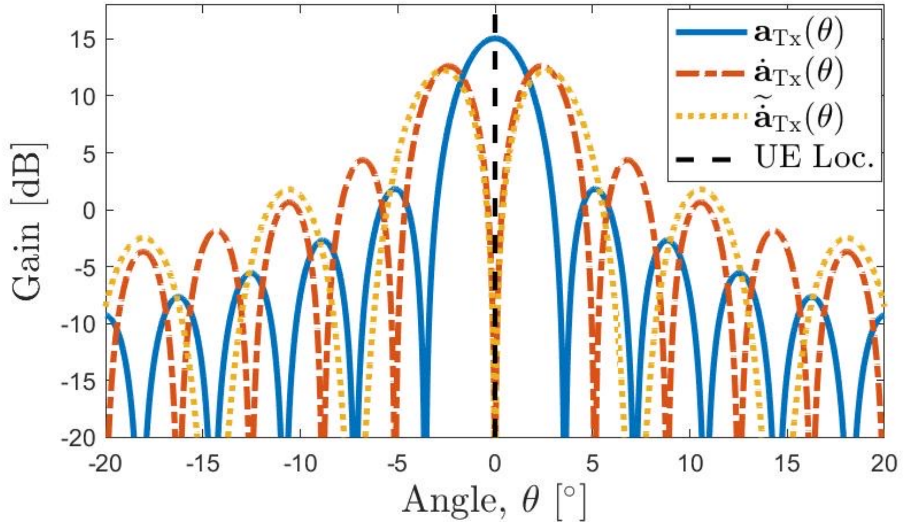
Without LOS path

Signal design for localization and sensing

- **Problem**
  - Different from communications, localisation and sensing performance rely on directional and derivative beams
- **Solution**
  - Signal design in the spatial domain to boost the accuracy of angle-based measurements:
    - Precoding vectors employed by a BS to steer downlink signals towards the desired direction
  - Downlink precoders are optimised to maximise the localisation accuracy of UE under a-priori information on the locations of UE and incidence points
  - Codebook construction based on directional and derivative beams
  - Proposed codebook with power allocation outperforms conventional codebook consisting only of directional beams



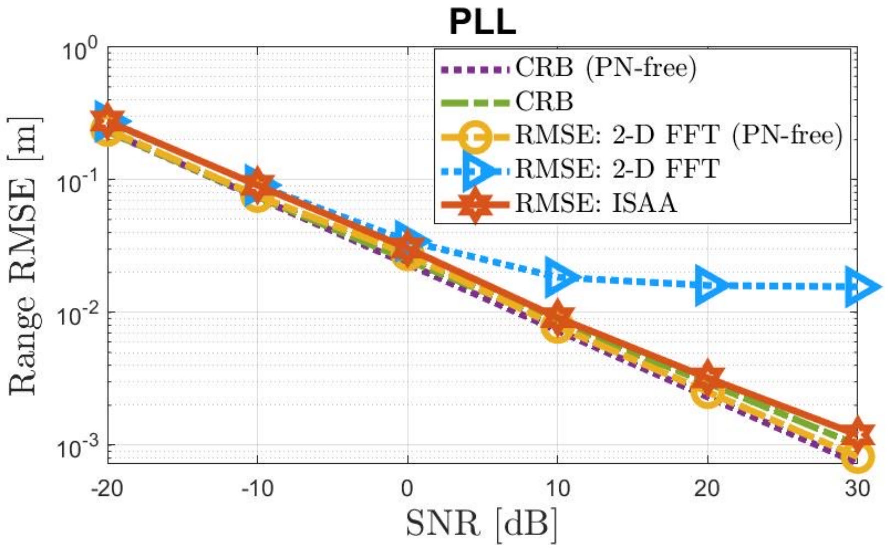
Localisation geometry with unknown incidence point location.



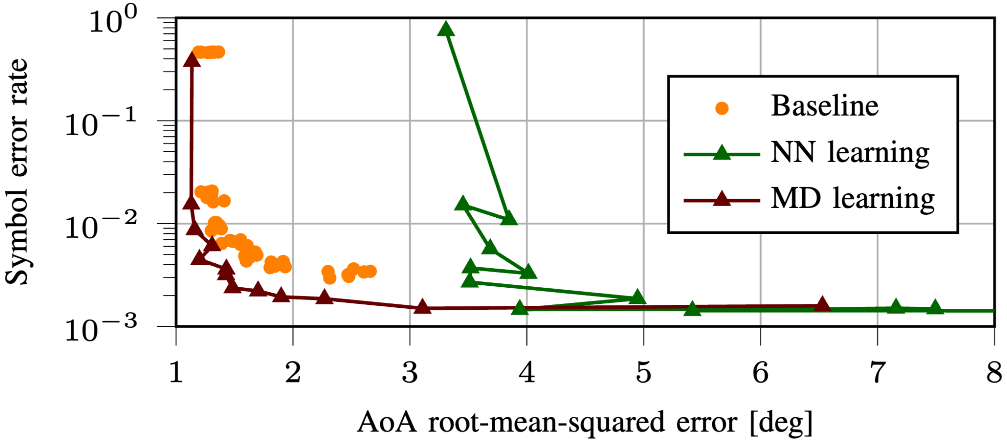
ULA beampatterns at the BS transmitter

Monostatic integrated sensing and communication

- **Problems**
  1. Phase noise (PN) limits sensing accuracy at high SNRs
  2. AI-based methods for ISAC have high complexity and they tend to overfit to training data
- **Solutions**
  1. PN effect can be modeled and mitigated
     a. Statistical modeling of self-referenced/differential PN in monostatic sensing
     b. Developing PN mitigation algorithms via iterated small angle approximation (ISAA) of PN
  2. Structured learning approaches
     a. Replace some components of standard approaches by learnable networks



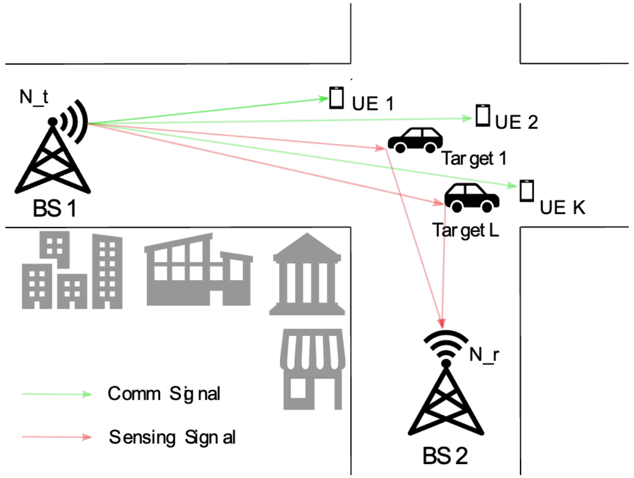
Proposed method (ISAA) reduces impact of phase noise



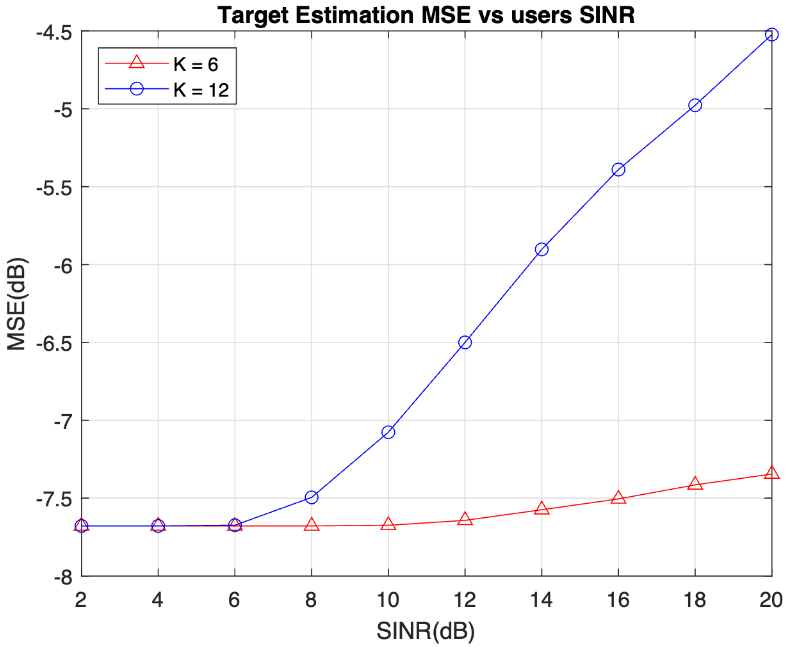
Proposed model-driven (MD) learning outperforms neural network (NN) learning under complexity constraint

Bi-static integrated sensing and communication

- **Problem**
  - How to serve several users and detect several targets?
  - Communication quality of service should be met
- **Solution**
  - Optimize beamforming to minimize target localisation error, subject to communication constraints
  - Solve with convex optimization



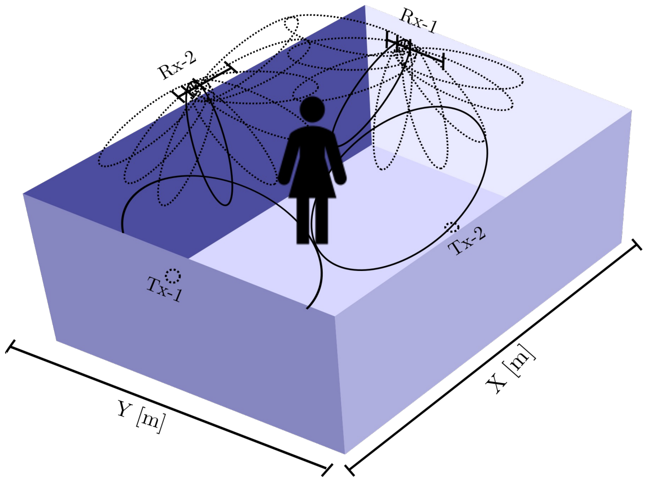
Bi-static ISAC system of two MIMO BSs, K single antenna UEs and L sensing targets.



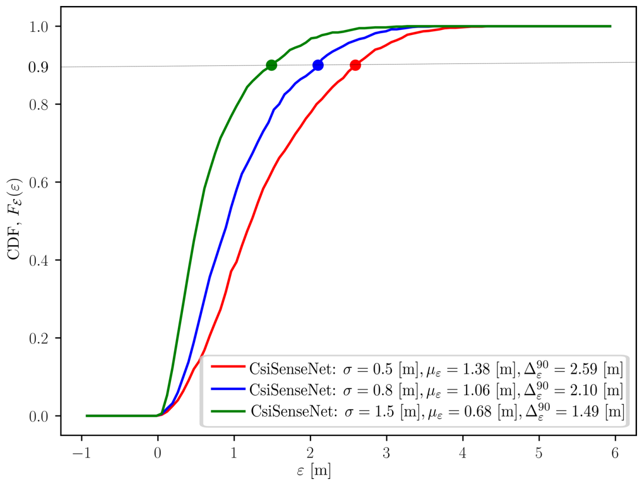
Trade-off between target estimation MSE and per user SINR threshold for single target scenario, when the number of communication users are K=6 and K=12.

Multistatic integrated sensing and communication

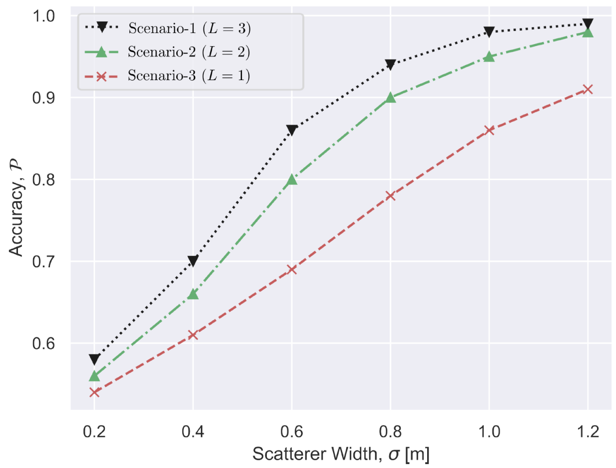
- **Problem**
  - Detect passive targets from MIMO waveforms
  - Identify the state of the target such as position
  - Reuse communication signals
- **Solution**
  - Extract CSI from multiple receivers
  - Stack into a feature vector
  - Supervised machine learning



Passive indoor sensing using communication infrastructure.



Position error distribution with the size of the target for a deployment with 3 distributed MIMO links.



Accuracy of detection variation with the size of the target for different deployment.

Coverage analysis

- **Problem**
  - Providing simultaneous communication coverage and localisation coverage for XR applications
- **Solution**
  - Optimise number of BS, placement, and array structures

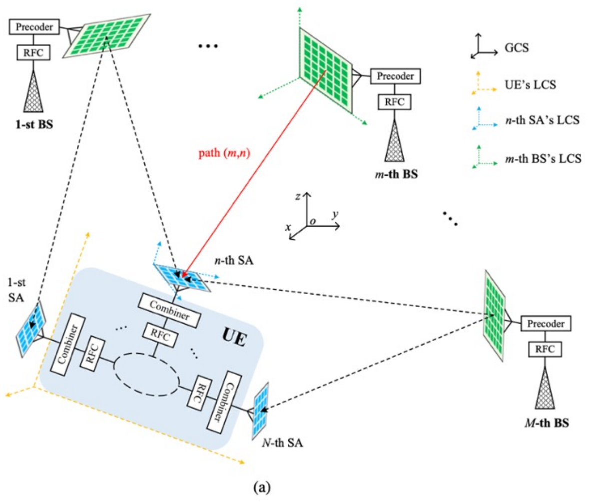
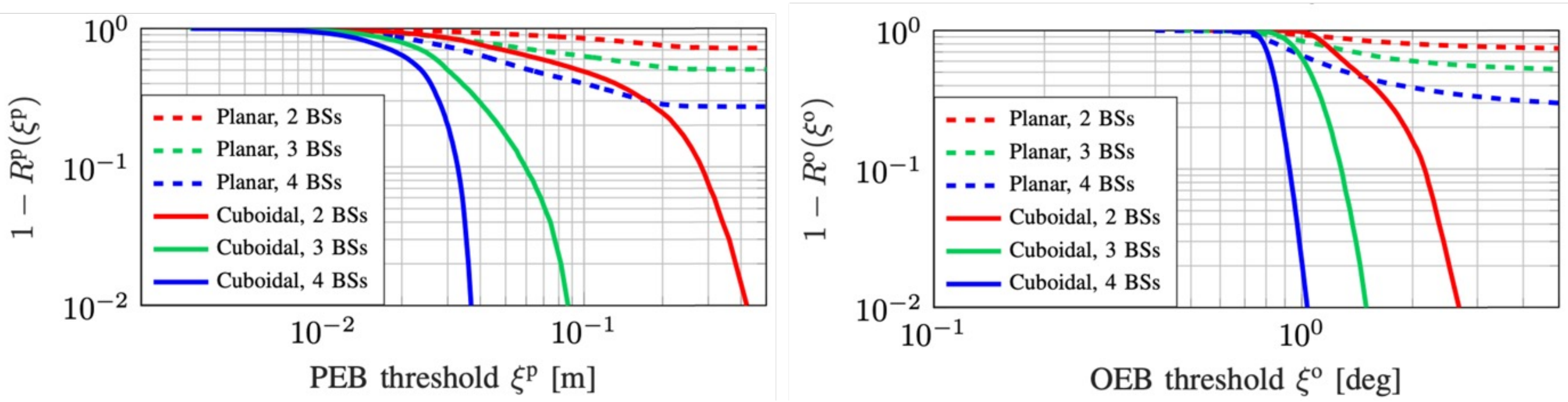


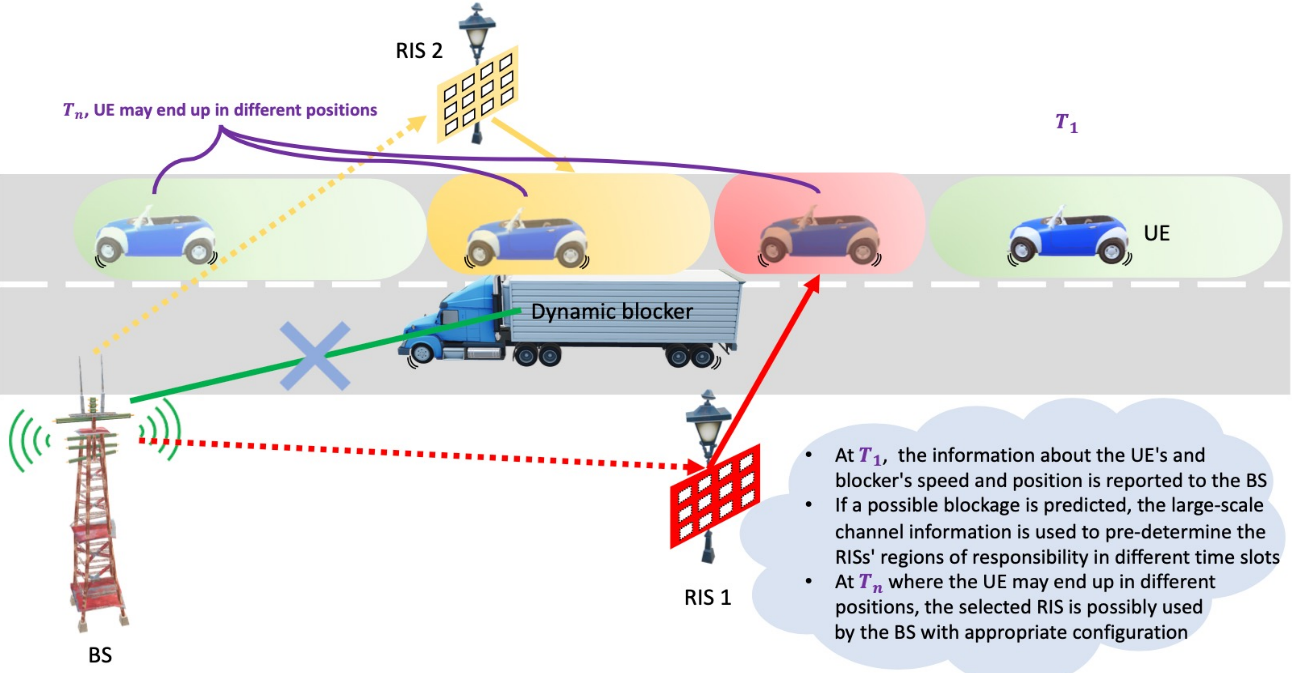
Illustration of the considered geometric model. A downlink MIMO wireless system with multiple BSs and one UE equipped with a 3D array



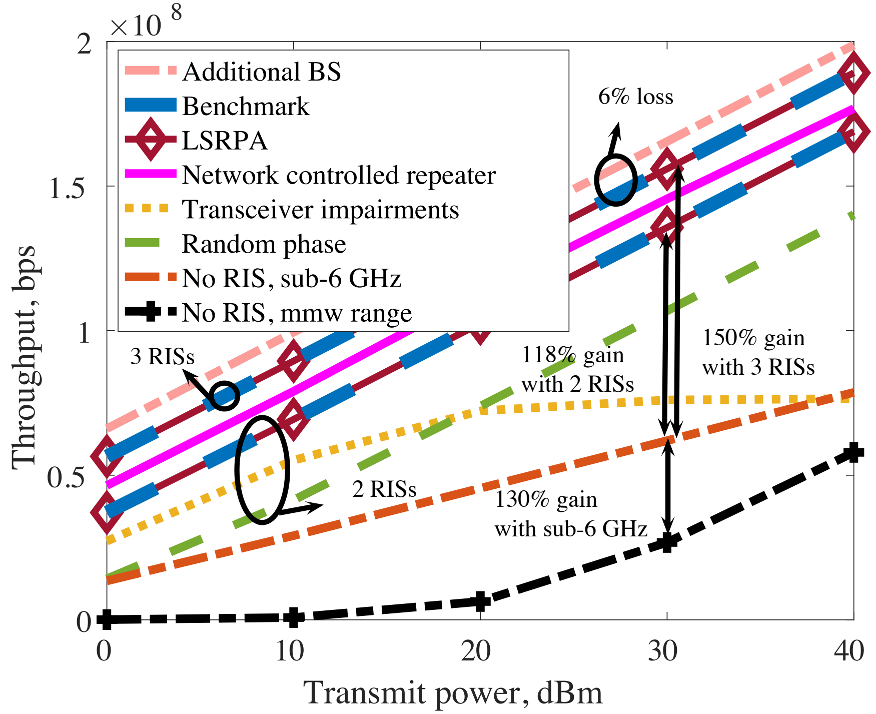
Position quality (PEB) and orientation estimation quality (OEB) coverage of the two types of arrays under {2,3,4} BSs.

Location-aided communication

- **Problem**
  - LOS blockage leads to communication performance drop
  - Large overhead with channel estimation for all links
- **Solution**
  - Use location information to pre-allocate additional infractructure (e.g., RIS) when needed



The proposed blockage pre-avoidance scheme in RIS-aided vehicular networks.



Conclusions:

1. The proposed large-scale based RIS pre-assignment (LSRPA) scheme can reach the same performance compared to the benchmark, with much less overhead.
2. Additional BS deployment and network-controlled repeater could overperform RIS-based scheme with more cost.
3. Transceiver impairment affects the system performance drastically.

Location-aided communication performance evaluation

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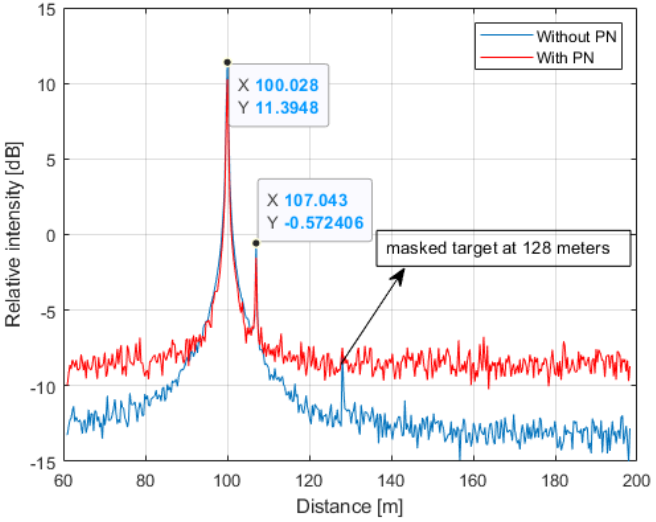
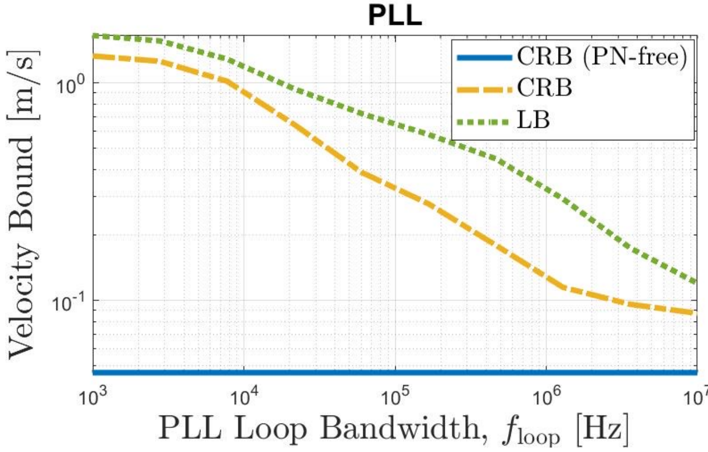
Impact of hardware impairments

Hardware impairments

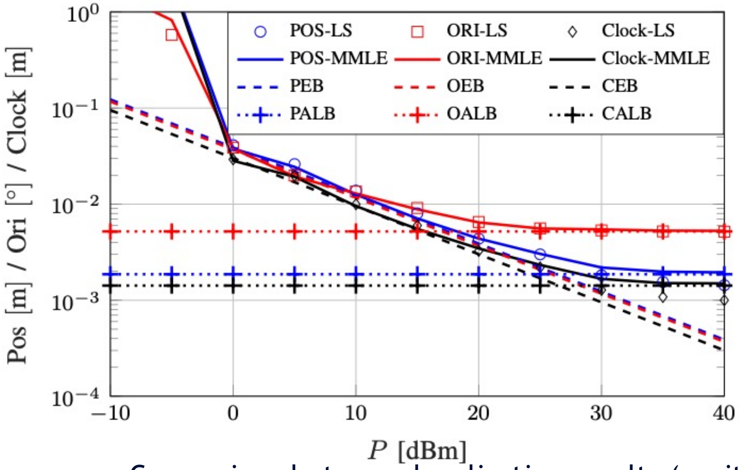
- Several hardware impairments were considered in different studies
    - Bistatic sensing
    - Monostatic sensing
    - Localisation
- Impact on localisation and sensing different than for communication
- At high SNR, hardware impairments will dominate



Bistatic sensing: Range spectrum map considering the effect of phase noise

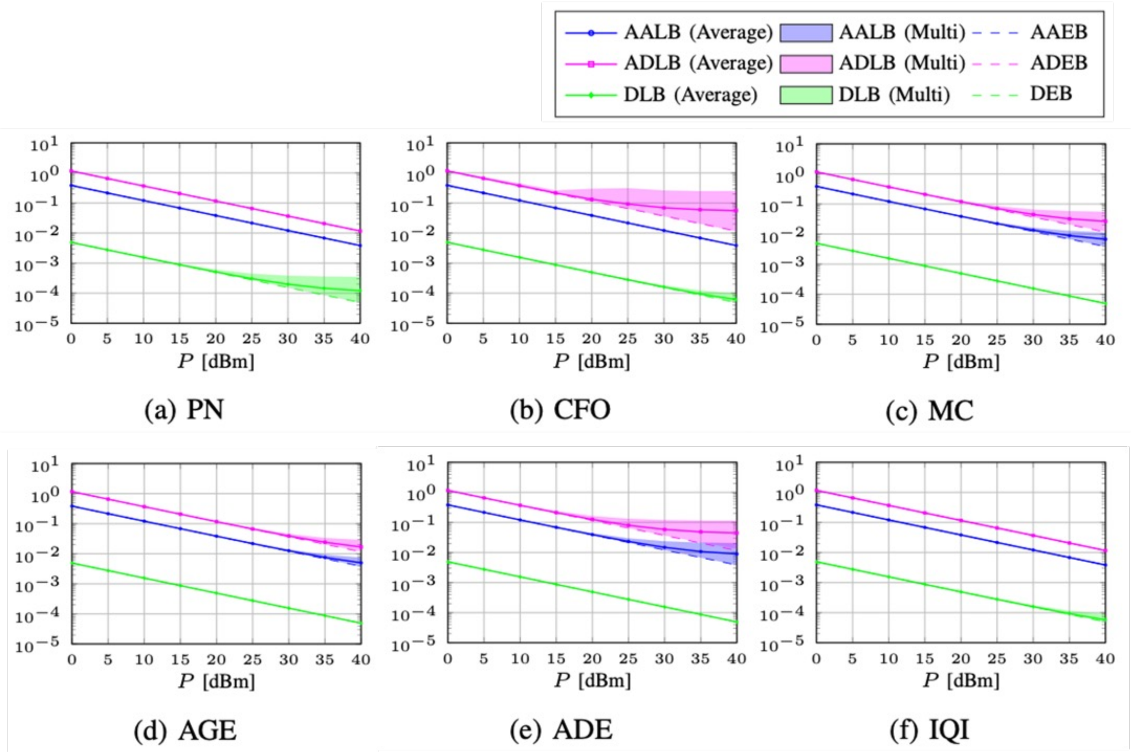


Monostatic sensing: Theoretical bounds on velocity estimation under the impact of PN, as a function of PLL loop bandwidth.

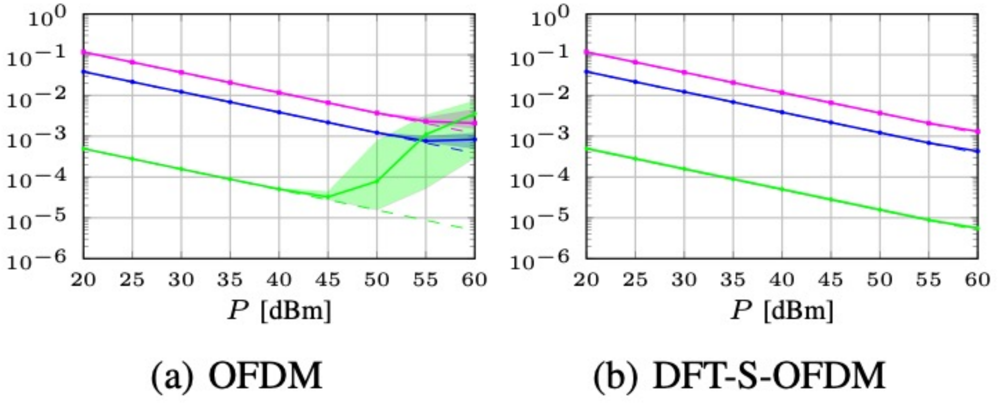


Comparison between localisation results (position, orientation, and clock offset estimation) and different lower bounds (CRB of the MM and the LB of the mismatched estimator).

Detailed analysis on channel parameter estimation



LBs of channel parameter estimation under different types of impairment with multiple realizations: (a) Phase noise, (b) Carrier frequency offset, (c) Mutual coupling, (d) Array gain error, (e) Antenna displacement error, (f) IQ-imbalance.

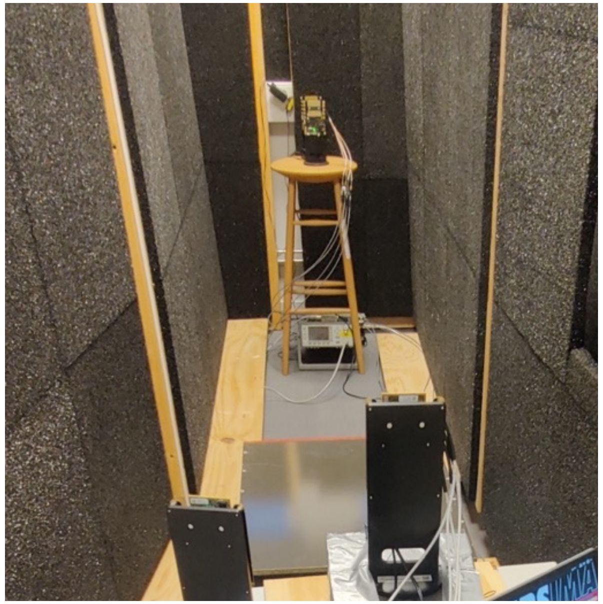


The effect of power amplifier on channel parameters estimation using (a) OFDM, and (b) DFT-S-OFDM.

Over-the-air demonstrations

Localisation experiments

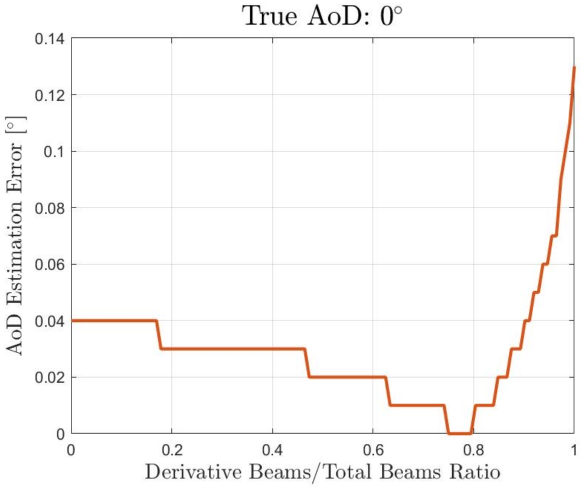
Setup

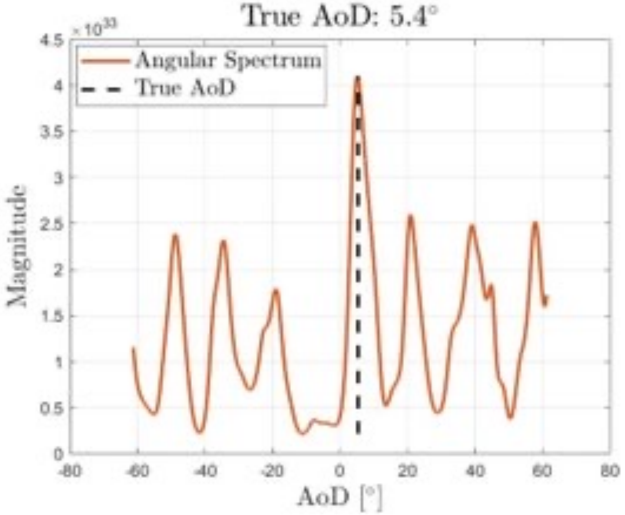


Xilinx Zync Ultrascale+ RFSoC ZCU111 evaluation kit, 2 SiversIMA semiconductors EVK06002 57-71 GHz radio evaluation kits and a PC for data processing.

Study impact of beam design on AoD estimation

Results





- AoD estimation error with respect to the ratio of the number of derivative beams to the total number of beams employed (directional + derivative beams)
- Angular spectrum corresponding to AoD estimation objective function
- Very accurate AoD estimation results can be achieved in the presence of a-priori information on the receiver location (11.6 degrees in our case) in a LOS-only propagation environment.

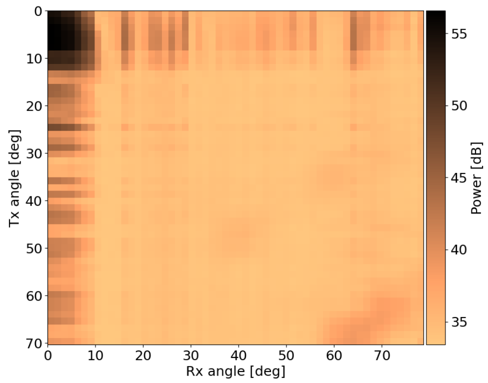
Sensing experiments

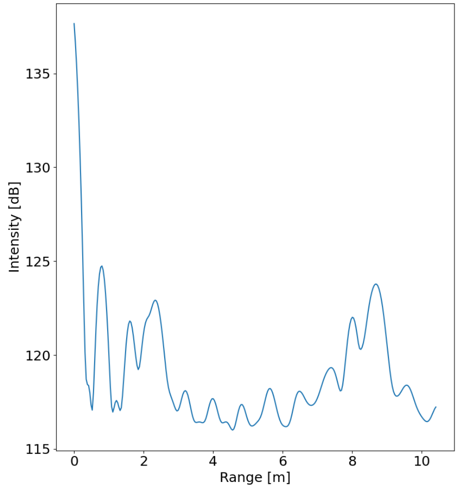
Setup

Xilinx Zync Ultrascale+ RFSoC ZCU111 evaluation kit, 2 SiversIMA semiconductors EVK06002 57-71 GHz radio evaluation kits and a PC for data processing.

Evaluate performance of passive object positioning

Background measurement



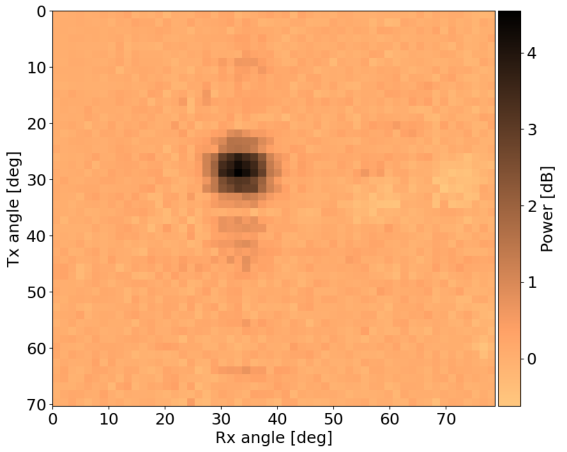


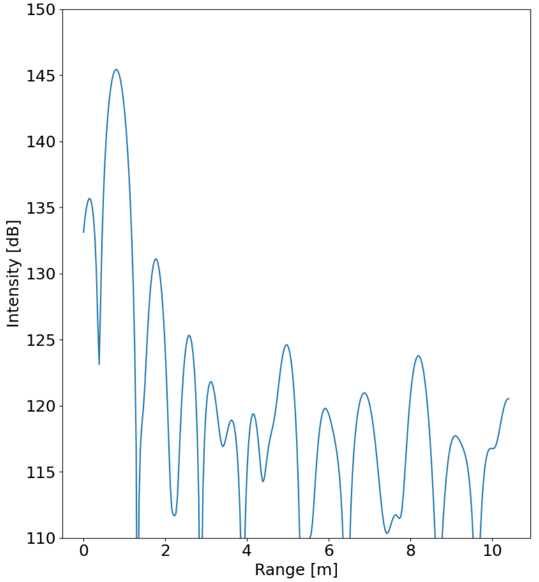
The left figure shows the received power as a function of the different Tx and Rx beams. The LoS path is clear in the top left corner and a few reflections can be seen in the bottom right corner.

The right figure shows the corresponding range plot (averaged over all beam combinations), calculated from the channel estimation of the received signal. The LoS peak is calibrated to be at 0 m, the other peaks originates from reflections in the environment

Sensing results

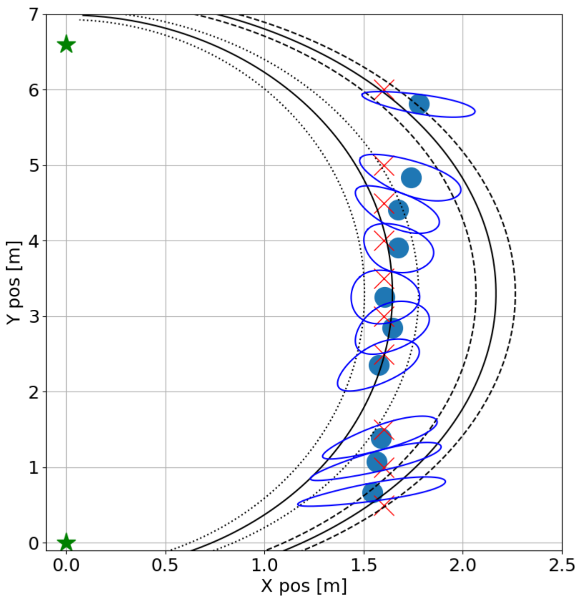
With background subtraction

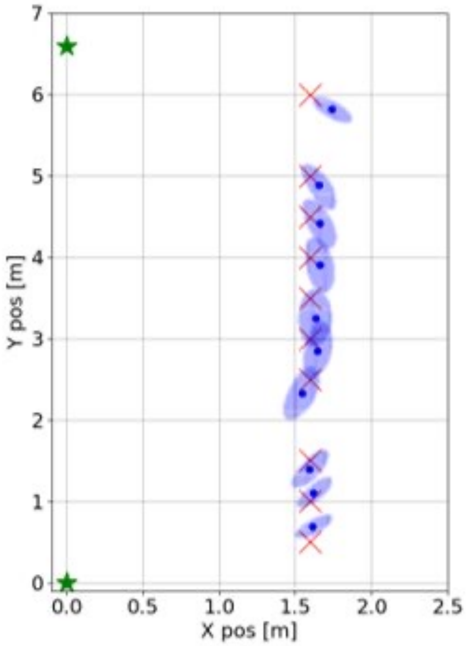




- By subtracting the background, a person standing in the corridor can be clearly detected as the black region in the right figure and the peak in the right figure
- The position can be calculated from both the angle and range information

Calculating position





- Green stars = Tx/Rx positions, red crosses = true position, black lines = position from range, blue dots and lines = position from angles
- The left figure shows the estimated position together with the 1 sigma error bounds
- Only two range positions are shown for visibility
- By combining the angle and range information, the combined position estimate in the right figure is obtained. The 1 sigma error bound is indicated as the shaded blue regions

Conclusions

Conclusion

- Localisation and sensing: tightly integrated with communication in 6G
- Localisation and sensing must be an inherent part of the 6G architecture
- Management and orchestration should ensure that all services and application (both from within the network as well as external to it) can be fulfilled by the network
- KPI: Supporting the KPIs of the Hexa-X use case families places demands on the infrastructure, the hardware, as well as the bandwidth and time resources
- KVI: Localisation and sensing play a dual role (enables and introduces new challenges)
- Models: channel and hardware models were proposed and applied
- Methods: model-based and AI-based methods for localisation and sensing each have benefits and drawbacks
- Demonstrations:
  - Localisation: optimised beams will significantly improve localisation
  - Sensing: accurate tracking of a passive object in a cluttered indoor environment

Thank you!

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Hexa-X

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