Hexa-X: WP3 – Deliverable D3.2

Initial models and measurements for localisation and sensing

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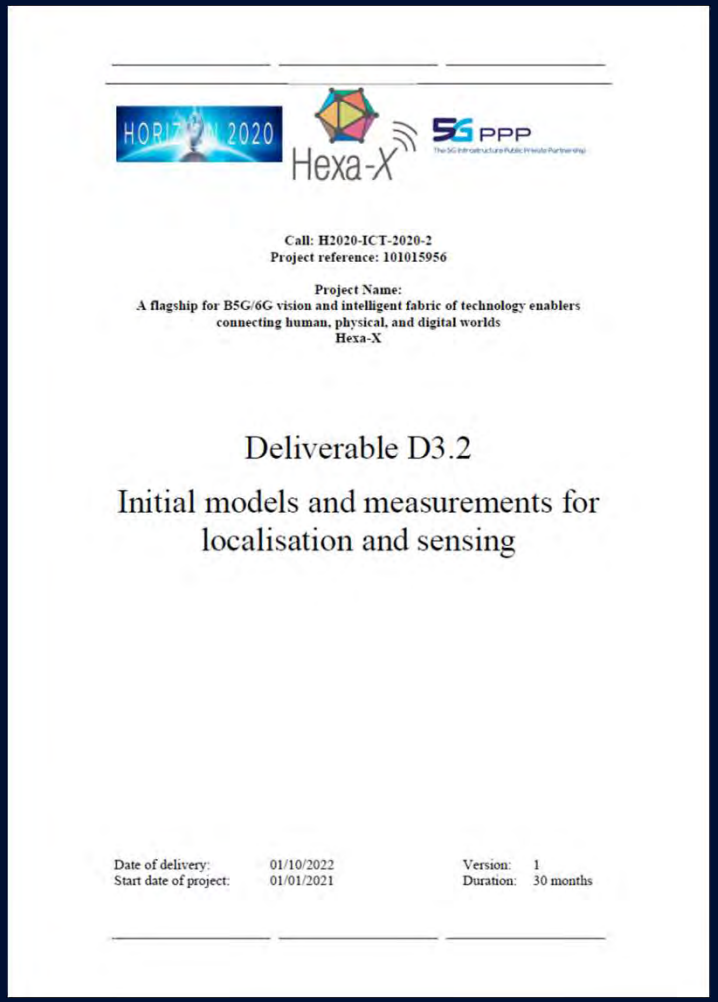
hexa-x.eu

Mission and scope

- Hexa-X WP3 (***6G High-Resolution Localisation and Sensing***) focuses on:
  i. 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;
  ii. harnessing high-resolution location and map information for existing (communication, security) and novel applications.

- This report is the second deliverable of project Hexa-X WP3, focuses on the initial findings towards models, methods, signals, measurements, and the protocols for localisation and mapping, as well as providing the vision of how accurate location and sensing information can enable and enrich applications.



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Project Name:
A flagship for B5G/6G vision and intelligent fabric of technology enablers connecting human, physical, and digital worlds
Hexa-X

Deliverable D3.2

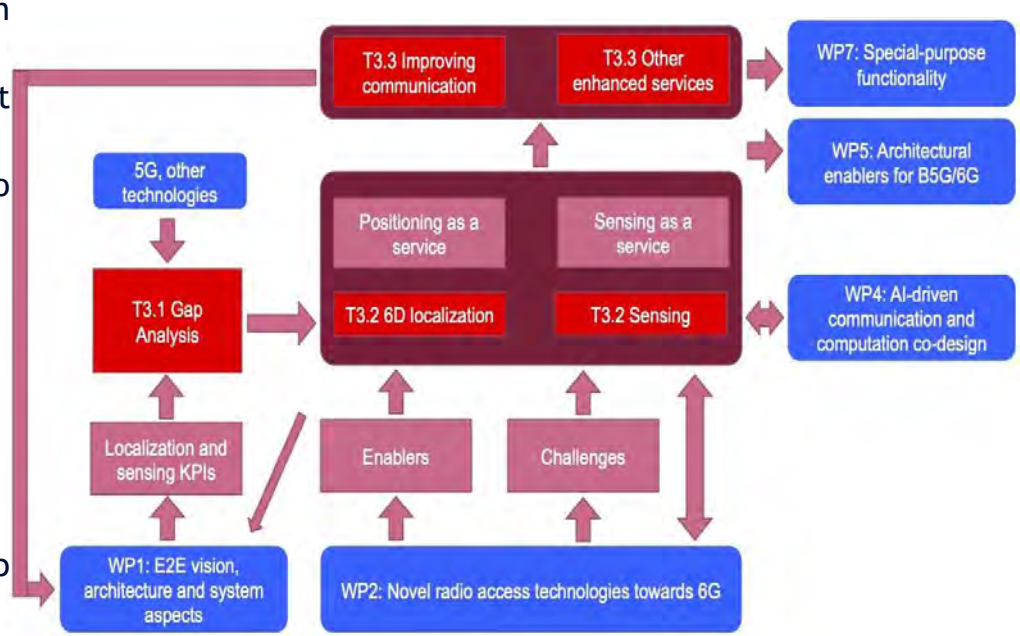
Initial models and measurements for localisation and sensing

Date of delivery: 01/10/2022 Version: 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 will be studied in WP3.
- WP2 radio technologies, WP4 AI-based methods, WP5 architectures can enable improved localisation and sensing.
- WP2 channel models and hardware limitations require different treatment for localisation and sensing than for communication.
- WP2 communication will need 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.

Methods, signals, and protocols for localisation and mapping

Methods, signals, and protocols for localisation and mapping

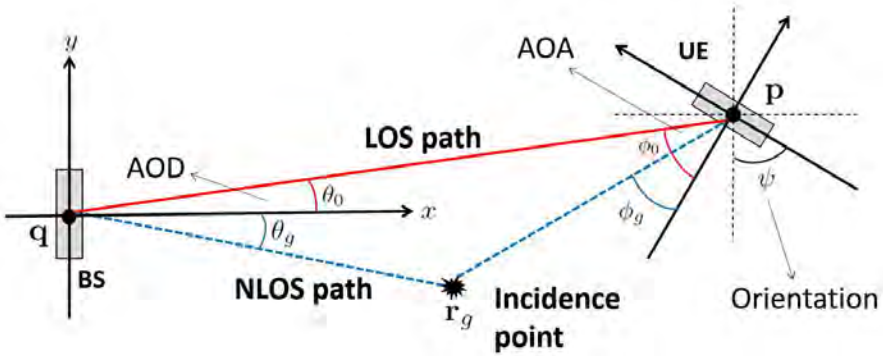
- **Main emphasis:** methods, signals, and protocols for localisation and mapping in communication systems are presented.

- **Sequential of several processes in localization and sensing:**
  - Signal design
  - Signal transmission and reception
  - Channel parameter estimation
  - Localisation and sensing

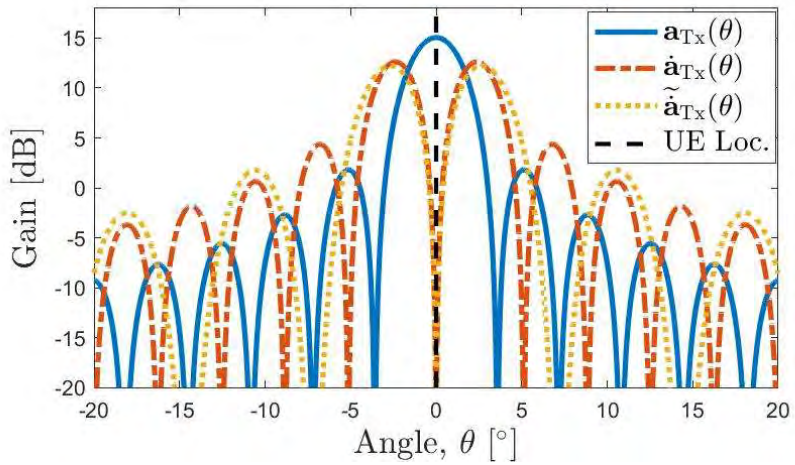
- **Experimental activities on different aspects of the 6G technology:**
  - Interference mitigation and coordination
  - Performance Evaluation

Spatial signal optimization for localization and sensing

- **Problem/ challenge to be addressed**
  - Different from communications, localisation and sensing performance rely on directional and derivative beams
- **Initial proposed solution framework**
  - 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



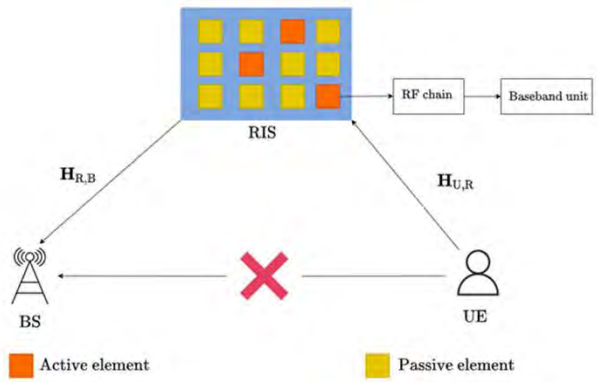
Localisation geometry with unknown incidence point location.



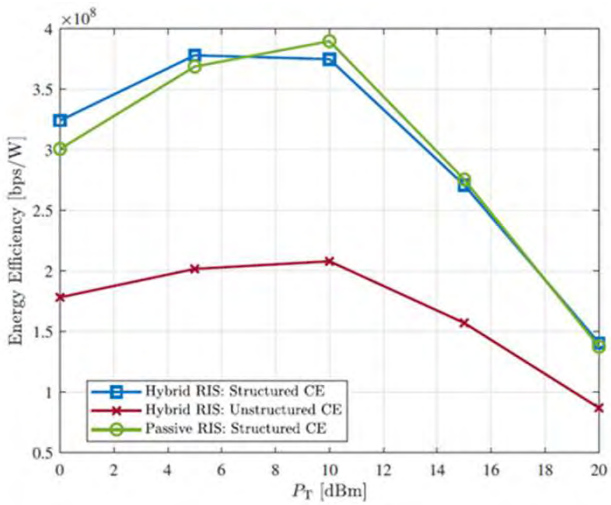
ULA beampatterns at the BS transmitter

Structured and unstructured channel estimation

- **Problem/ challenge to be addressed**
  - Accurate CSI acquisition to utilise RIS gain:
    - Challenging task due to the large number of passive elements
- **Initial proposed solution framework**
  - Hybrid RIS can simplify the CSI acquisition
  - Recover the channel matrices based on the received signals at the RIS and BS
  - Unstructured methods for recovering the UE-RIS channel matrix without prior information on the propagation environment
  - Structured methods for reducing the training overhead, especially in mmW band with sparse channels



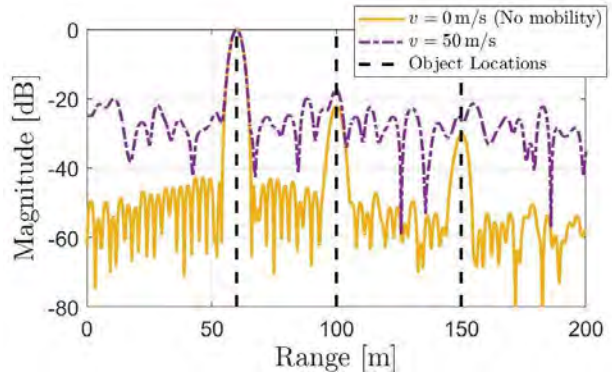
Hybrid RIS-assisted MIMO system.



Energy efficiency of the RIS-assisted MIMO system versus transmit power

Radar sensing under inter-carrier-interference (ICI)

- **Problem/ challenge to be addressed**
  - ICI challenge for OFDM integrated radar-communications systems in high-mobility scenarios:
    - Loss of orthogonality
    - Doppler shifts of mobile objects
  - ICI mitigation in OFDM radar sensing
- **Initial proposed solution framework**
  - Targets detection and delay-Doppler-angle parameters estimation by cancelling the effect of ICI
  - Doppler information embedded in ICI to resolve Doppler ambiguity

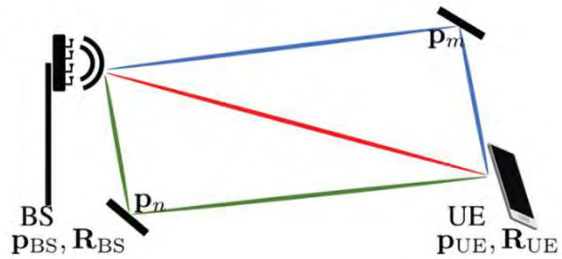


Range profiles of OFDM radar with and without relative mobility.

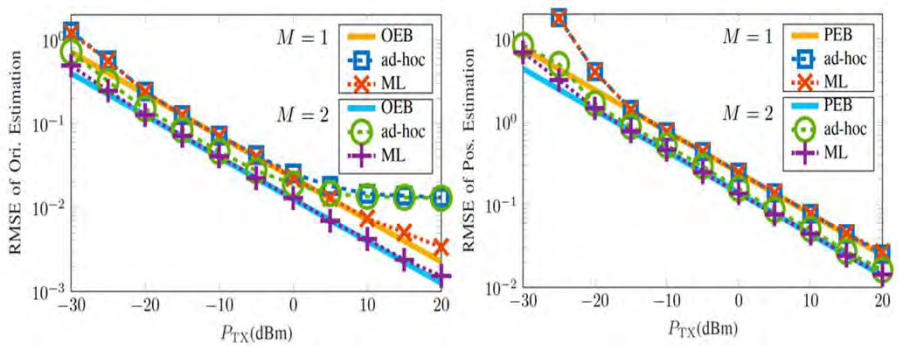
Three-step ICI-aware multi-target detector and delay-Doppler-angle estimator.

Single snapshot-based 6D localisation and sensing

- **Problem/ challenge to be addressed**
  - Estimation of 3D position, 3D orientation, and clock offset of an unsynchronised multi-antenna user
  - Estimate unknowns using snapshot observation obtained from downlink MIMO-OFDM signals
- **Initial proposed solution framework**
  - Two-stage localisation process:
    - Determination of the marginal posterior densities of AoAs, AoDs, and ToAs
    - Maximum likelihood estimation to determine the localisation unknowns



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

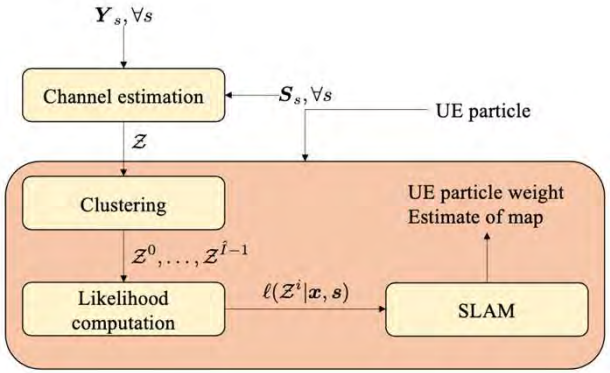


RMSE of orientation and position estimation

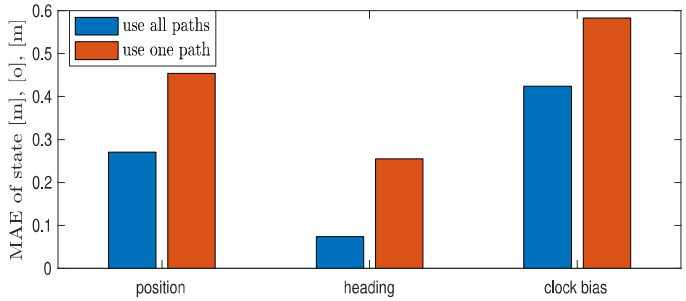
Simultaneous localisation and mapping (SLAM)

- **Problem/ challenge to be addressed**
  - Estimate the UE location and orientation
  - Synchronise with the BS
  - Provide a radar-like map of the environment

- **Initial proposed solution framework**
  - Layered approach after downlink transmission:
    - Channel parameter estimation
    - Unordered elements grouping
    - SLAM filters



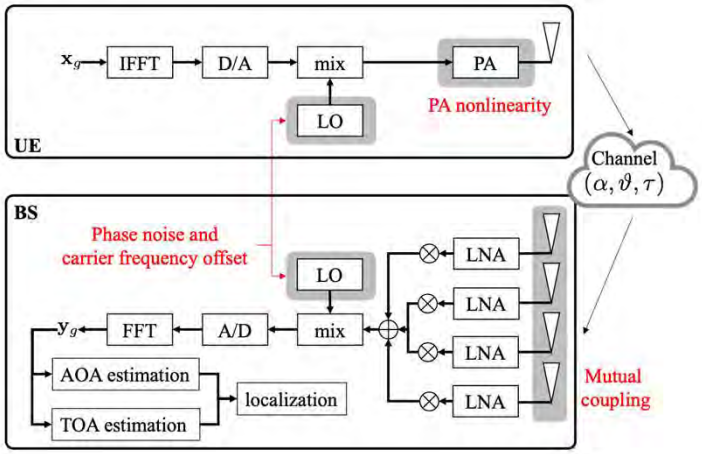
The SLAM framework from the observation Y_S.



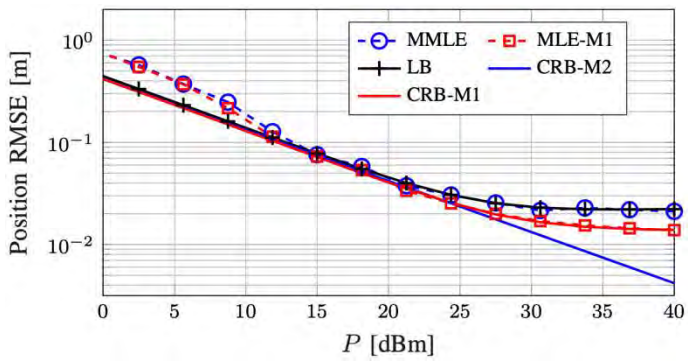
The comparison of vehicle state estimation results between two cases.

Impact of hardware impairments (HWIs)

- **Problem/ challenge to be addressed**
  - Signal distortion due to HWIs affects the localisation
  - Evaluate the localisation degradation due to HWIs
- **Initial proposed solution framework**
  - Two types of signal models, M1 and M2:
    - M1: with the knowledge of the various HWIs
    - M2: the mismatched model
  - MLE: the observed signal vector is generated from the same model used by the algorithm
  - MMLE: the observed signal vector is generated from a different model than what is used by the algorithm



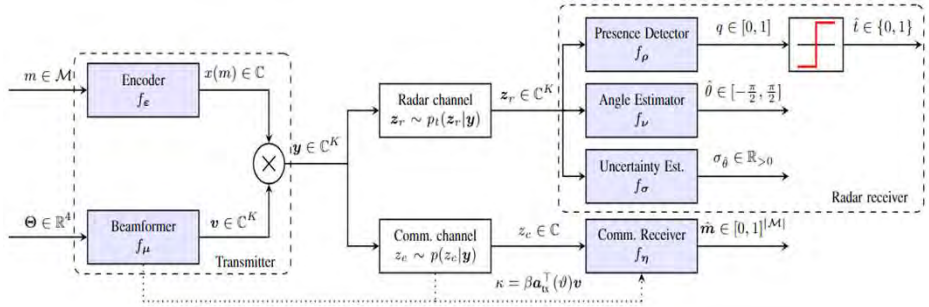
Block diagram of considered hardware impairments at transceiver.



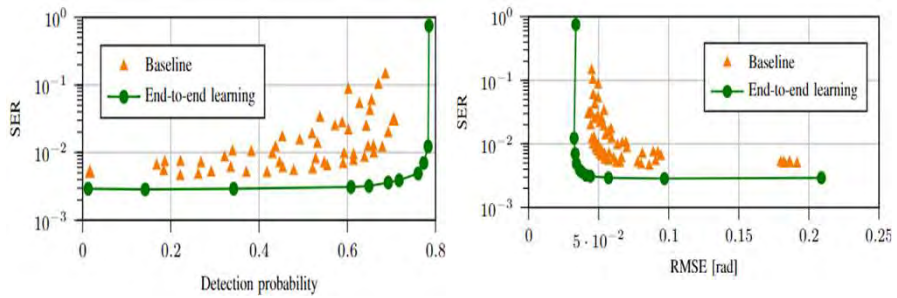
The comparison between estimator results and different lower bounds.

Integrated sensing and communication under HWIs

- **Problem/ challenge to be addressed**
  - ISAC signal optimisation in the spatial domain
    - Sensitive to model mismatch
- **Initial proposed solution framework**
  - End-to-end learning for transceiver training
  - Optimise a radar component together with the communication receiver



Block diagram of ISAC system model.

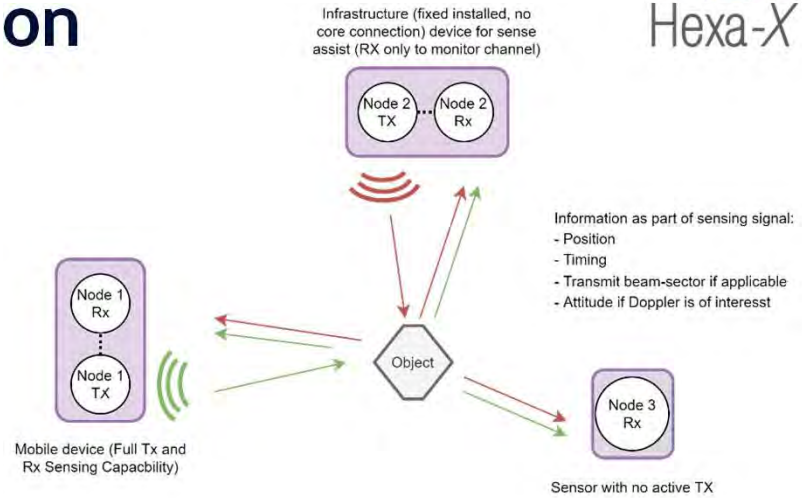


ISAC trade-off results with hardware impairments.

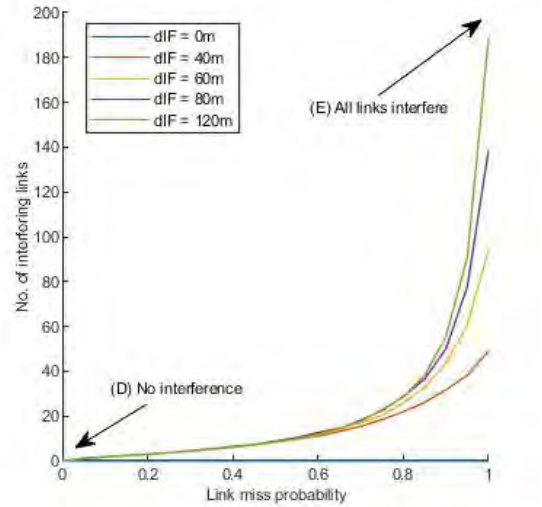
Interference mitigation and coordination

- **Problem/ challenge to be addressed**
  - Interference between sensing nodes with uncoordinated time/frequency resources
    - Robust waveforms
    - Reduced likelihood of interference
    - Central resource allocation

- **Initial proposed solution framework**
  - Random Access and communication-aided channel access
    - Low channel usage
    - High channel usage
  - Limits in the communication-aided sensing/channel access performance



Interference node definition

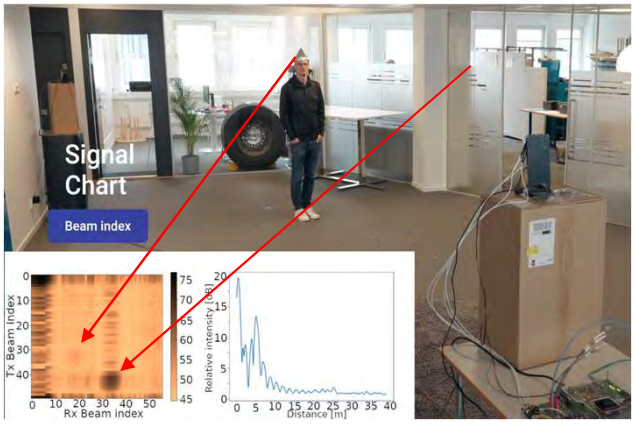


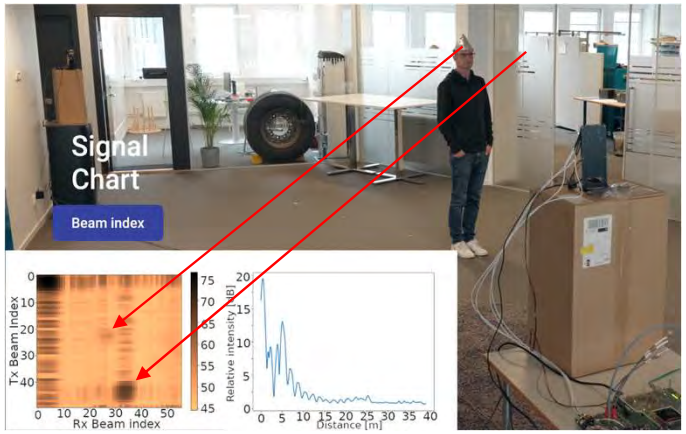
Maximum number of simulated interfering links.

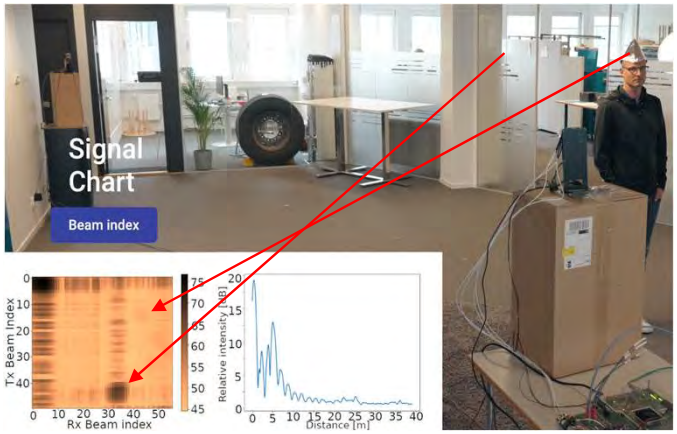
Performance evaluation

- **Problem/ challenge to be addressed**
  - A platform for integrated communication, localisation, and sensing
  - To make proof of concepts, verify simulation results and demonstrate different use cases

- **Initial proposed solution framework**
  - Using a bi-static setup with a carrier frequency of 69 GHz







https://www.youtube.com/watch?v=8uNwjm5FvL4

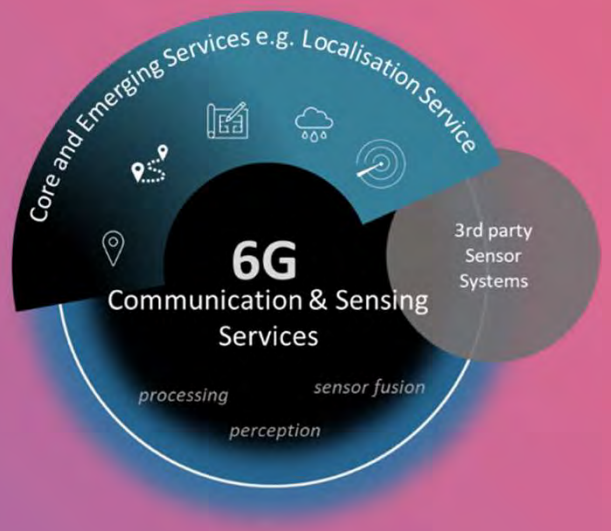
Enhanced Location and Sensing Services

Enhanced location and sensing services

- Localisation will not be a by-product of the communication development anymore but integrated from the system outset and thus must become one of the design targets.

- Develop a vision on interrelations between, sensing, sensor fusion, localisation and emerging services which also serves as input for the architectural design of next generation networks.

  - **Enabling and enriching applications**
  - **Supporting communication with localisation and sensing services**
  - **Implications of localisation and sensing for the next-generation mobile networks**

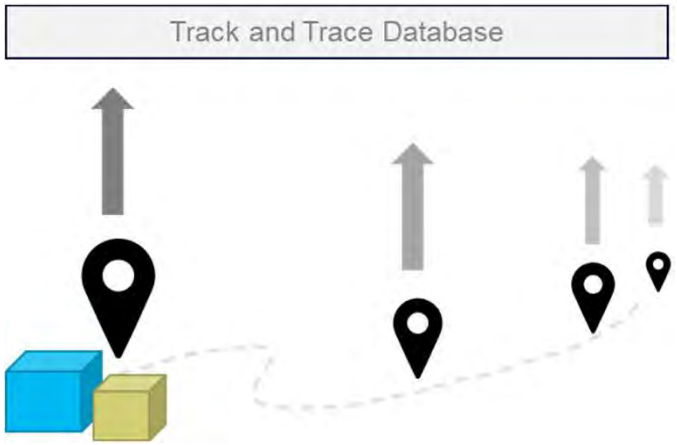


Location information to enhance security use cases

- **Problem/ challenge to be addressed**

  - Many use cases exist that deal with security and are based on the availability of correct, uncompromised location information.

    - Secure track and trace
    - Location-based access control
    - Geo-fencing for mobile machines
    - Security gates



Non-radar type sensing: landscape sensing

- **Problem/ challenge to be addressed**
  - Sensing of UEs macro environment
- **Initial proposed solution framework**
  - Prediction of UEs macro environments such as forests, streets, buildings, waterbody, etc.
  - Benefits RAN functionalities such as handover management, beamforming, etc.
  - Large scale channel statistics such as path-gains from multiple cooperating BS

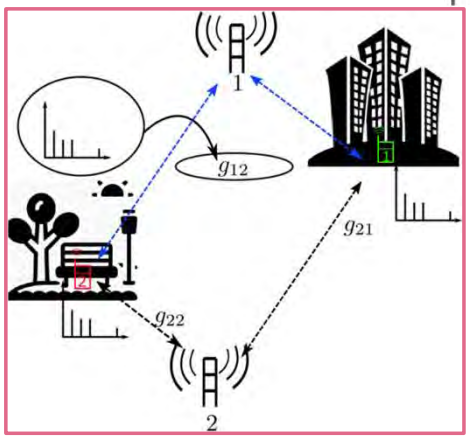
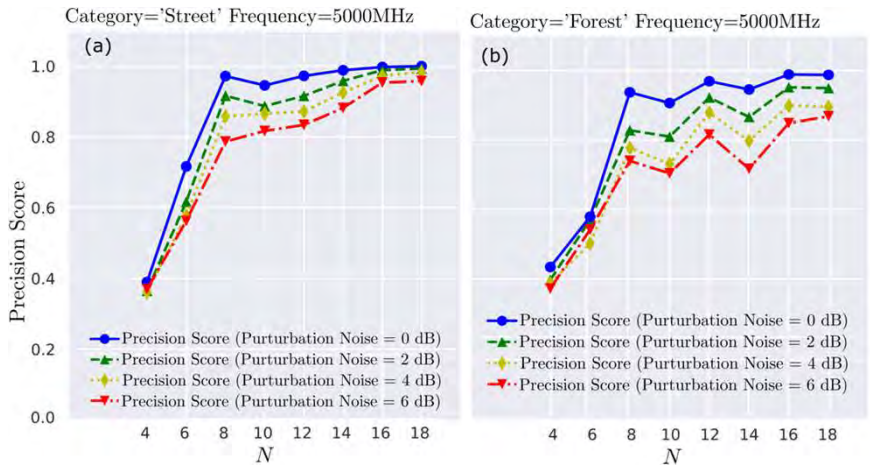


Illustration of the UEs in forest and urban landscape.



Performance of random-forest based AI method for “Forest” and “Street”.

Non-radar type sensing: contextual sensing

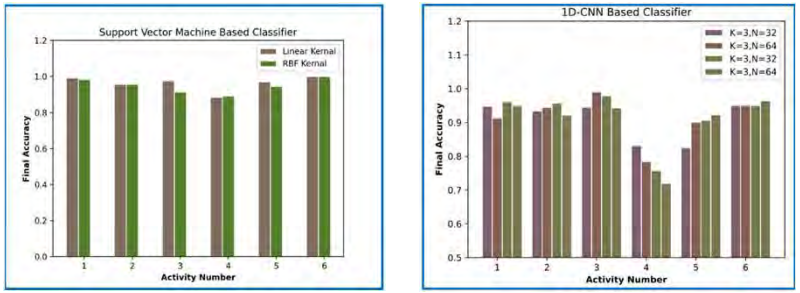
- **Problem/ challenge to be addressed**
  - Identifying the target context, which can aid in the higher-level tasks
    - Human Activity Detection (HAD)

- **Initial proposed solution framework**
  - Identify common activities such as sitting, standing, walking, etc.
    - Industrial control to prevent accidents
    - Elderly care
    - Detecting coma patients
    - Neurological disorders

  - AI Methods for HAD
    - Feature engineering-based methods requiring domain expertise
    - Feature agnostic method

Activity description.

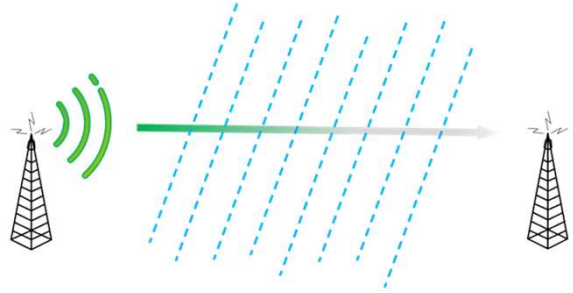
Activity-ID	Activity-Name	Type
1	Walking	Dynamic
2	Walking Upstairs	Dynamic
3	Walking Downstairs	Dynamic
4	Sitting	Static
5	Standing	Static
6	Laying	Static



Accuracy of the detection of various human activities.

Sensing information to enable weather monitoring

- **Problem/ challenge to be addressed**
  - Channel knowledge for a general understanding of the environment
    - Weather monitoring:
      - Particle or pollution detection
      - Rain and snow detection



Rain measurement by sensing.

- **Initial proposed solution framework**
  - Vulnerability of the electromagnetic waves (10-100 GHz) to rain
  - Better resolution with higher accuracy

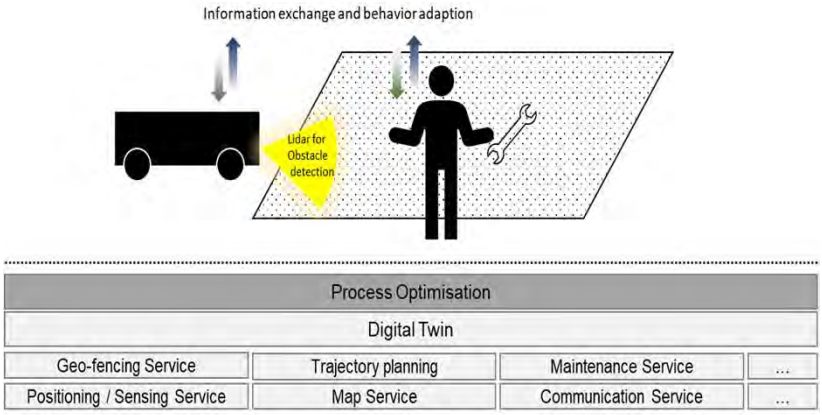
Comparison of different rainfall measurement methods.

	Rain gauge	Weather radar	Microwave link
Time resolution	15 min	5-15 min	10 s
Spatial resolution	~2 dm^2	~1 km^2	~ 100 m
Coverage area	~2 dm^2	~200 km radius	~ 100 m
Accuracy on the ground level	Very good	Not good	good

Map information to optimise factory environments

- **Problem/ challenge to be addressed**
  - Digitalisation of enterprises by generating, combining, and analysing data, processes, and decisions within factories and enterprises
    - Combining the digital world with the physical world based on a comprehensive digital twin

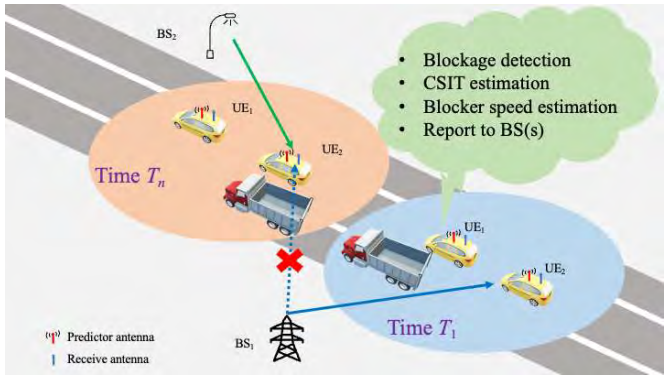
- **Initial proposed solution framework**
  - Automated guided vehicles (AGV).



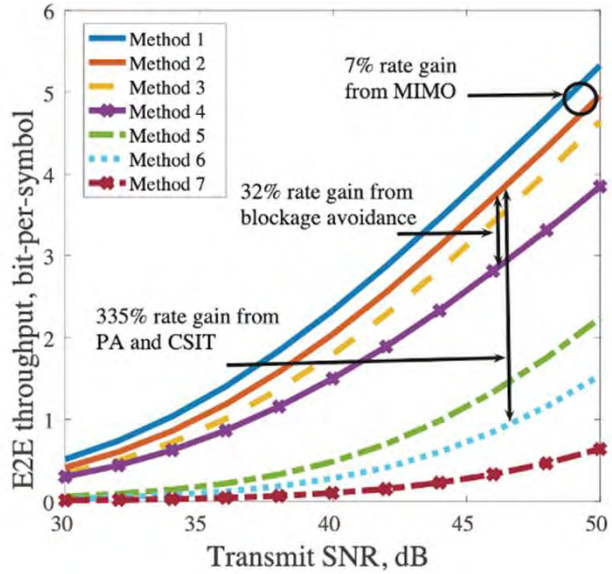
Sketch of AGV maintenance area and some required services.

Context-aided communications for dynamic blockage avoidance

- **Problem/ challenge to be addressed**
  - Similar communication performance inside moving vehicles as at home/office
  - Connected vehicles realise advanced traffic features
    - Reliable communication links
    - Stable control loop
- **Initial proposed solution framework**
  - Context information-assisted communications to avoid dynamic blockage:
    - BS could potentially predict the position of UE and blockers
    - Predictor antenna for channel variance mitigation



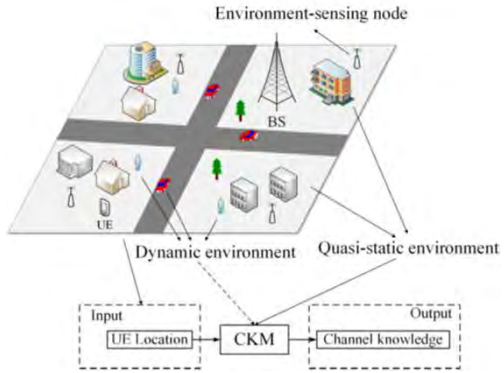
Proposed setup to avoid temporal blockages and the CSIT outdating.



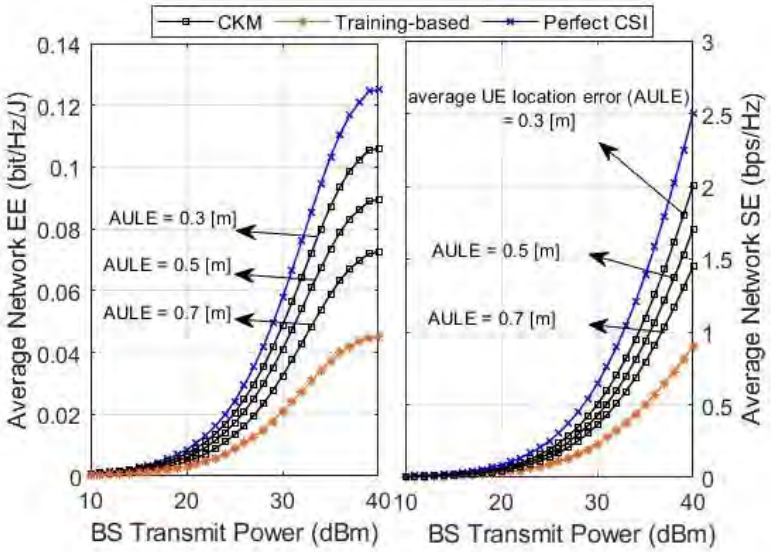
E2E throughput of the behind vehicle (UE2) as a function of transmit SNR

Energy efficiency in location-aided communications

- **Problem/ challenge to be addressed**
  - The interplay between communication and sensing with radio waves
  - The potential of localization and sensing to improve the communication aspects of the 6G systems
- **Initial proposed solution framework**
  - Environment-aware joint active/passive beamforming based on the new concept of channel knowledge map (CKM)
  - Location and environment information offered by CKM to achieve maximum spectral and energy efficiency
  - No real-time training is required



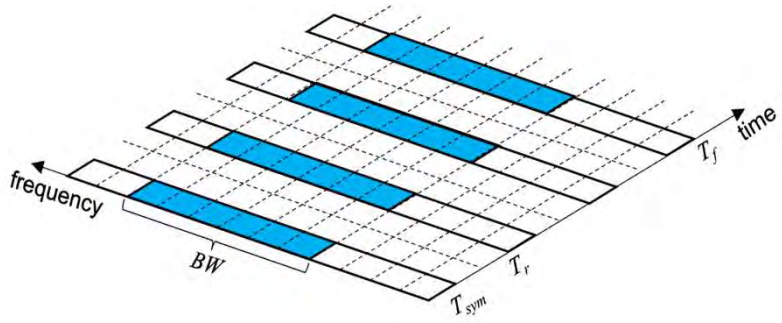
An illustration of CKM for enabling environment-awareness.



Average network EE and SE for CKM with different schemes

Time-frequency signal resource allocation for sensing

- **Problem/ challenge to be addressed**
  - Hardware and waveforms changes for reusing the communication spectrum for sensing
- **Initial proposed solution framework**
  - OFDM or a similar waveform that can be scheduled by the same algorithm and jointly with the ongoing communication



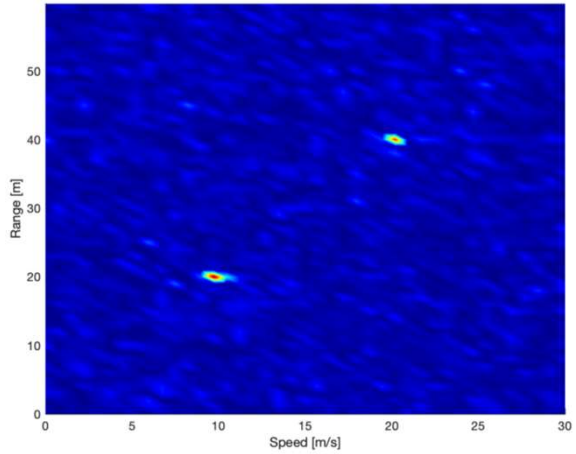
A train of OFDM symbols as a sensing signal.

An example illustration of parameterisation of sensing signal.

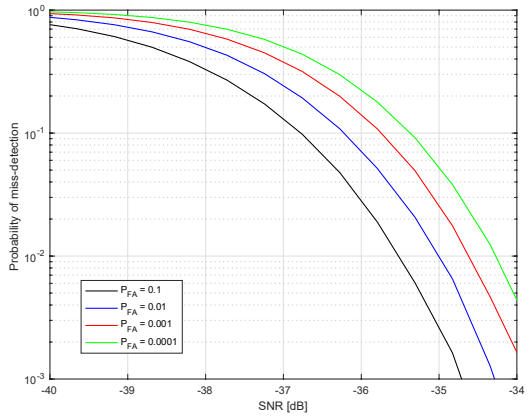
f_c [GHz]	SCS [kHz]	BW [MHz]	T_r [µs]	T_f [ms]	Overhead
3.5	30	300	1071	85.7	3.5%
6	30	300	625	50.0	7.1%
10	60	300	375	30 .0	7.1%
28	120	300	134	10.7	2.7%
60	480	300	62	5.0	0.7%
96	1920	300	39	3.1	0.2%

Sensing in a communication network

- **Problem/ challenge to be addressed**
  - Mono-static sensing: full-duplex capability
  - bi-static/multi-static sensing: high degree of synchronisation
- **Initial proposed solution framework**
  - Spectrum considerations:
    - Sensing accuracy and communication coverage trade-off
    - Sensing at high frequencies: advantage and disadvantage



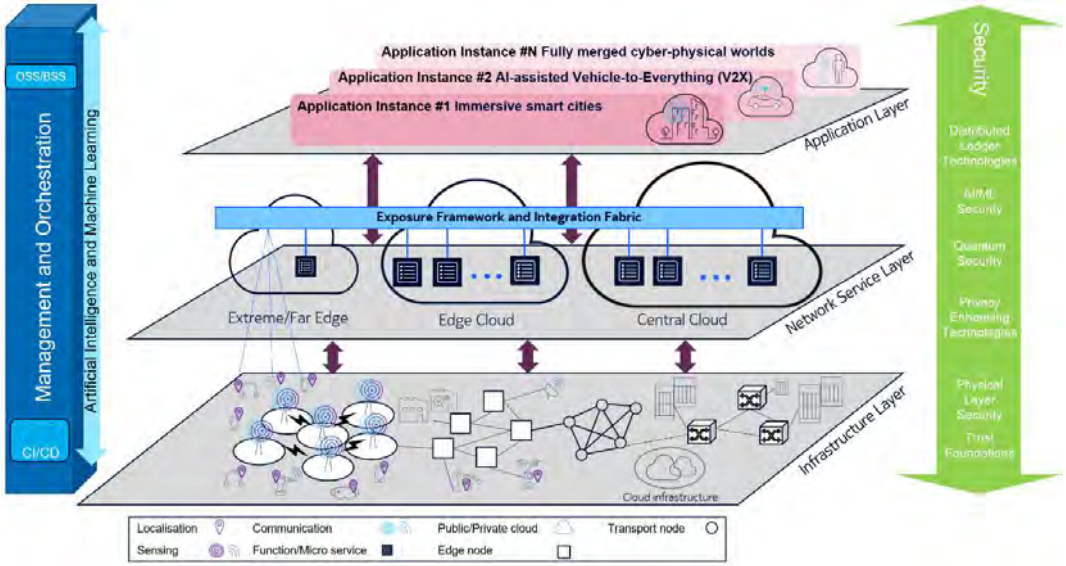
Detection of two objects with the range of 20 m and 40 m and speeds of 10 m/s and 20 m/s.



Probability of miss-detection as a function of SNR for different false alarm rates.

Implications and requirements for context-aware services

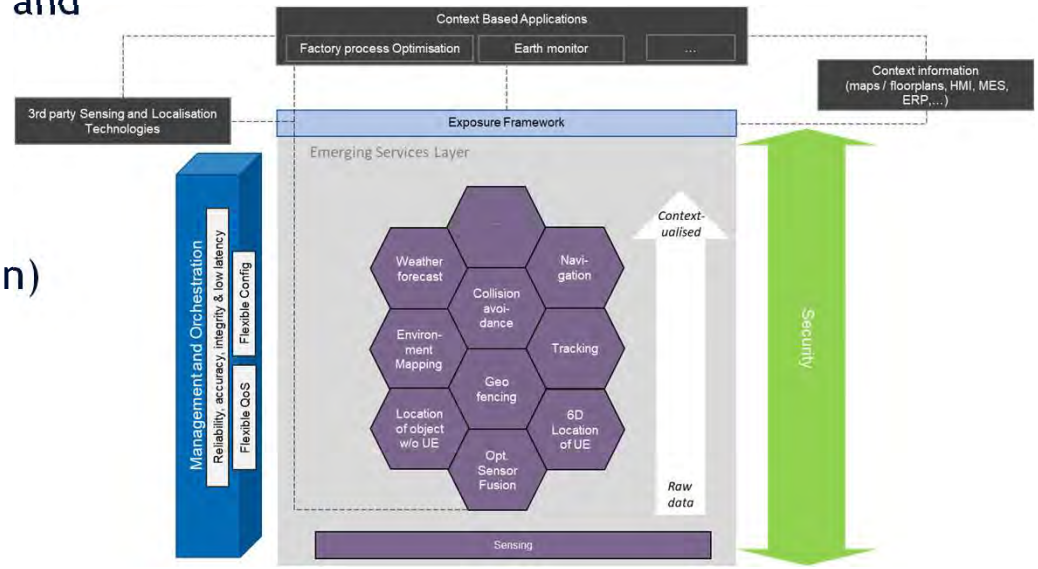
- **Problem/ challenge to be addressed**
  - Interaction between services creates an ecosystem for new and emerging services and applications
- **Initial proposed solution framework**
  - Future services and applications based on or integrating next-generation mobile networks will have many requests on each layer of the Hexa-X E2E 6G architecture view



6G E2E architecture overview.

Implications and requirements for context-aware services

- Enabling a flourishing ecosystem that can serve different scenarios and use cases will require flexibility, scalability, and ultra-low latency.
    - Configuration, flexible switching, and prioritisation
    - Exposure framework and data interpretation
    - Security (information access and information generation)
    - Flexible quality of service
    - Sensor and information fusion



First view on localisation and sensing ecosystem.

Summary, conclusion, outlook

- In 6G systems, localisation will no longer be a by-product of the communication development but integrated from the outset and thus must become one of the design targets.

- Integrating localisation and sensing with high accuracy and low latency are required to support many use cases identified in Hexa-X.

- Technical areas of focus are the following:
  - Our initial solutions in methods, signals, and protocols for localisation and mapping.
  - Location and sensing-enhanced services.

- Upcoming deliverable D3.3 (to be published in April 2023) will provide final models and measurements, performance evaluation of new signal designs, algorithms, and evaluation of location-based services.

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