KOMSENS-6G

Milestone 1 Deliverable

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Executive summary

The objective of the BMBF-sponsored 6G Industry Project “KOMSENS-6G” is to explore – looking towards the anticipated next mobile network generation 6G – new *radio-based sensing capabilities,* that would possibly extend the current system’s main capability which supports *communication*. To achieve this objective, the project analyzes and adapts all relevant components of the mobile radio network system, in such a way, so that the sensing functionality will be deeply integrated in the overall system, which we here call “Integrated Communication and Sensing (ICaS)”.

The appending report is the Milestone 1 Deliverable of “KOMSENS-6G” which compiles the first outcomes of analyses that were conducted in four domains regarding the envisioned overall system.

WP2	Use cases & requirements
WP3	Radio frontend & baseband architecture: *State-of-the-Art (SotA) and gap analysis*
WP4	Protocols & functions in the Radio Access Network: *State-of-the-Art (SotA) and gap analysis*
WP5	Data processing for inferencing & applications: *State-of-the-Art (SotA) and gap analysis*

In WP2 potential use cases for ICaS have been compiled and consolidated. In many cases the use cases can be seen as instances belonging to wider application domain clusters that encompass various related use cases. The use cases are examined from various angles ranging from stakeholder demand, the actual sensing problem addressed, to privacy aspects and technical performance requirements incl. value ranges, among others. This use case list is a first base line that can be used to reflect the user demand situations against the achievable performance indicators that current (and projected) systems may provide (see other WPs). In a next step the performance requirements per use case shall be further detailed, then allowing possible groupings into ‘service’ clusters which can further inform the architecture work. The WP2 report also lists system function requirements and architecture basics that serve as a first baseline for developing an architecture that can realize ICaS.

In WP3’s document the state of the art and the gaps that will be addressed during the project are described, splitting the contribution according to the two streams of work active in WP3. At first, in T3.1 the radio frontend and antenna design topics are covered, while in T3.2 the baseband signal processing investigations and architecture definition are discussed. Each research topic active in WP3 corresponds to a paragraph in the document, highlighting the main baseline prior arts considered in it and the main gap that will be addressed.

In the WP4 domain the first 3 chapters provide an overview of the state-of-the-art in the areas of protocol design and signaling, resource allocation, network aspects and coordination, both in wireless communications systems and radars, that need to be taken into account when integrating both to an ICaS system. The final chapter collects those identified gaps on which WP4 will further focus the work.

The WP5 part of the deliverable focuses on the state-of-the-art and gap analysis in the area of *Data processing for Knowledge Extraction.* It is organized in three chapters corresponding to the tasks in the WP. The first chapter discusses data processing for distributed sensing, describing suitable fusion techniques and machine learning methods for parameter estimation. In the second chapter, knowledge extraction and representation methods are highlighted. Moreover, the architecture required for high-quality object localization and tracking and the methods for generating 3D environmental maps are discussed. In the third and final chapter, we point out the potential mutual performance gains that could be obtained by deeper integration of sensing and communication functionalities in an ICaS.

KOMSENS-6G

Work Package 2

Milestone 1
“Use cases and requirements”

KOMSENS-6G WP2: Milestone 1 Deliverable

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1 Introduction

This report is the first deliverable of the Work package 2 of KOMSENS-6G project, which focuses on use cases and their requirements, functional view on the architecture, standardization and regulation, and data protection. This report first describes identified use cases and their clustering based on application domains and privacy requirements. This is followed by a general view on the privacy protection in the ICaS and an initial view on the functional architecture. Furthermore, a regulatory view of the sensing is provided as well.

2 Use cases for ICaS including performance requirements and possible use case clustering

This section compiles and details a selection of possible use cases for ICaS that have emerged from discussions among the partners in the project. The diversity of the use cases reflects the variety of the project partners that have their own specific roles in the ecosystem. In order to have a structured description of the use cases that allows for later comparison in various feature dimensions, each use case is described along these dimensions – even if specific values cannot be provided (yet).

The detailing of the features – especially those regarding technical performance requirements – for all use cases will allow the identification of certain commonalities (or differences) which is useful information for developing certain functions of a to-be architecture for ICaS. It will also allow to discover significant differences when it comes to other feature dimensions (e.g., privacy requirements). In the end the detailing of the features will allow various clustering options for the use cases, depending on the specific feature dimensions considered. Being able to take these different perspectives with regard to ICaS should be helpful for deciding what will be really important for the to-be system architecture.

To start with an initial clustering of the use cases that locates the respective use cases in bigger conceptual “chunks”, we have used the feature dimensions “Application Domain” and “Privacy Requirement” as clustering criteria.

Application Domain clustering criteria

Application Domain refers to a field of activity where the referential context is quite similar. Referential context could be the phenomena encountered (e.g., road traffic participants, rain falling from the sky) or it could be effect/impact-oriented (e.g. public safety, logistics firms benefit, production firms benefit) or similar. Through the dialogues we have identified the following clusters (or classes) based on Application Domain (these are not mutually exclusive):

- Sensing-aided Communication
- Public Safety
- Smart Logistics
- Smart Factory
- Smart City
- Weather-related Sensing

The first cluster "Sensing-aided Communication" is the only cluster where the sensing capabilities of ICaS are used to further improve the communication – basically in a *self-referencing* fashion. The other five clusters use the sensing information rather to bring about an effect in a system *external* of the communication (e.g., warn a car driver or provide accurate rainfall information for farmers).

When looking from the angle of how sensing information (one could also say observations) are further processed, we can also roughly distinguish two uses (and following workflows). Firstly, many sensing use cases intend to detect the emergence of a certain pattern at the point in time when it appears (detecting a change in state). For instance, an intrusion or an anomalous pattern would create an event which typically should generate an alarm or warning that then goes to some controlling entity (that would trigger e.g., some kind of mitigation measure or other). Another cluster based on the sensing information processing dimension is, when based on the sensing data some sort of modeling (or mapping) is done (e.g. sensing free parking spots on a lot). Such model information can then be processed further, and various applications may make use of it. These two clusters are not mutually exclusive, however, one or the other characteristic is typically more dominant. For the use cases described later in the subsections, this aspect has not been explicitly detailed, however, from the initial descriptions it should already become clear which characteristic comes to the forefront.

Privacy Requirement clustering criteria

We have defined initially two clusters of privacy requirements: **Cluster 1** and **Cluster 2**.

Use cases in **Cluster 1** require coarse sensing capabilities (lower privacy intrusion), i.e., granularity of sensing (and subsequent post-processing) cannot go beyond a group of objects. Therefore, the degree of unlinkability (linking objects to specific persons or objects) is high and based on it, assurances, through modelling, should be developed as guarantees. This would allow stating that no additional privacy controls are needed.

Use cases in **Cluster 2** require fine sensing capabilities (higher privacy intrusion), i.e., granularity of sensing (and subsequent post-processing) can go beyond a group of objects and individual objects can be sensed (strict identification is not always necessary to possible). A degree of unlinkability should be calculated and in the fine sensing it will typically be low. The degree of unlinkability can be calculated via modelling (based on details of the use cases and their requirements). One of the precautions that may be taken to comply with privacy regulations without degrading sensing resolution is called consent (of user). For the consent a strong but privacy-preserving authentication may be demanded from the users.

Clustering of the use cases

The use cases that are described in the following subsections are listed as an overview in Table 1, as well as their allocation to specific clusters in the dimensions "Application Domain" and "Privacy Requirement".

Table 1. Specific use cases and allocation to clusters along dimensions "Application Domain" and "Privacy Requirement".

Use case (detailed, specific)	Application Domain cluster	Privacy Requirement cluster
Exploiting sensing information to improve communication services	Sensing-aided Communication	Cluster 2
Sensing support for EMF-related beam-specific power control of base station antennas	Sensing-aided Communication	Cluster 2
Monitoring and tracking of Unmanned Aerial Vehicles (UAV)	Public Safety	Cluster 2
Monitoring of suspicious patterns at highway parking lots	Public Safety	Cluster 2
Monitoring of patterns at railroad crossing	Public Safety	Cluster 1
Sensing-aided navigation of AGVs in logistics (outdoor)	Smart Logistics	Cluster 2
Sensing-aided navigation of AGVs in logistics (on yard)	Smart Logistics	Cluster 2
Sensing-aided navigation of AGVs in factory environment indoor	Smart Factory	Cluster 2
Detection of wrong-way drivers	Smart City; Public Safety	Cluster 2
Detection of road traffic congestion at intersections	Smart City	Cluster 1
Detection of rainfall and flooding	Environment related Sensing; Public Safety	Cluster 1

Technical parameter based clustering criteria

Technical and operational key performance indicators (KPIs) are important to make a judgement about the performance requirements of the ICaS solution we intend to design. It is important to know those KPIs upfront to provide guidance for design decisions and architecture. It is also very informative to estimate feasibility of defined use cases early on, i.e., considering the physical limitations and various regimes regarding the specific target use will reveal insights of whether an intended use case may be too far away from what is physically possible. Moreover, there could be certain required infrastructure needed to realize a specific use case (e.g., a certain degree of cell density) – which has cost and operational implications that could be prohibitively high due to too little demand that could not justify very complex extensions to the infrastructure setup.

The following shows some potential KPIs that can be appended to use cases and provide additional dimensions to identify clusters of use cases with common KPIs, and/or also allows to identify potential modules of performance requirements that could inform the design of core capabilities (or 'service clusters') that could reside in the 'center' of an ICaS architecture.

Potential KPIs from a demand/end user value perspective:

- Range resolution (level of detail sensed at distance) – (to meet application demand)
- Location accuracy – (to meet application demand)
- Orientation accuracy
- Angular resolution
- Motion rate accuracy
- Maximum link range (unambiguous range)
- Coverage area
- Value added apps integrating ICaS capabilities
- Service availability
- Update rate
- Maximal sensing service latency
- …

Potential KPIs from a network operator perspective offering ICaS based capabilities:

- Cost level for the network upgrade – (as low as possible)
- Monetary impacts of the service – (there must be significant demand from segments)
- Market size of potential user group – (as big as possible)
- Achievable market share – (considering competing technologies)
- Robustness of service – (to meet application demand)
- …

The more systematic list of KPIs to append to the use cases and the metric for each KPI will be specified in following phases. The desired target value of the indicator will also depend on the actual application. Sometimes value ranges will need to suffice as an initial estimate. The main objective is to populate the KPIs with more concrete values to get closer to the real technical requirements, as well as have a baseline from the use case/demand side that can be mirrored against the real – or projected, estimated – technical possibilities that can be delivered today and in the mid-term (see the other work packages in KOMSENS-6G).

The following subsections describe the selected use cases in more detail.

2.1 Exploiting sensing information to improve communication services (sensing-aided communication) (EDD, DTAG)

2.1.1 Objective

The Integrated Communication and Sensing (ICaS) paradigm enables Mobile Network Operators (MNOs) to optimize communication configuration and parameters from the sensed information. The sensed information provides information such as receiver location or even tracking of the receiver(s) trajectory [1]. This provides information necessary for optimization of beamforming, handovers, bandwidth allocation or assisted physical layer security. From the tracking of the receiver (or multiple receivers or even crowds of users with user equipments) location, this optimization can be extended to future via prediction [2] to predict communication channel quality [3]. The sensing enables detecting obstacles that will block the connection. Thus, based on the obstacle detection it is possible to avoid connectivity disruptions not just in user connectivity to base stations but in device to device connectivity between (autonomous) vehicles [4].

2.1.2 Use case description with an example

MNO operate mobile networks with many communicating devices. To provide high communication quality, beamforming is exploited to focus the antenna beams towards communicating devices (user devices, vehicles, etc.), as illustrated in Figure 1. The communicating devices may form crowds or areas with high traffic demand, that can be served by a single beam that needs to be selected. However, this requires a significant overhead, as the communicating device needs to be localized. The communication channel quality is also affected by obstacles, i.e., objects blocking or reflecting the propagation of the communication signal, which need to be detected to avoid communication through a blocked link.

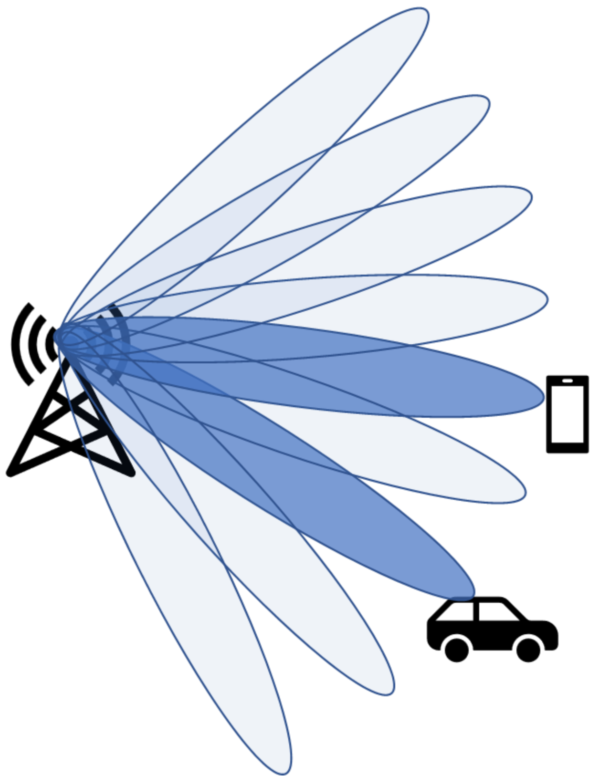


Figure 1. Beamforming optimization.

This use case can be illustrated in an example, where a user is travelling in a vehicle with many passengers, who want to enjoy interactive services. The mobile network can provide connectivity but as the vehicle is moving it needs to do beam search to find the best beamforming pattern (avoid blocked beams and ideally choose one with line of sight), which consumes the communication resources. However, the MNO has deployed ICaS and is able to localize and track the vehicle without additional overhead. Thus, the communication link is optimized, while overhead is decreased.

2.1.3 Current solutions / equivalent technology (if there are any existing)

What are current solutions that solve the same objective and what is their complexity/performance/cost? Currently to optimize the communication services via beamforming based on exhaustive or hierarchical beam search are used. To reduce the measurement overhead and latency beam prediction is exploited, primary based on supervised learning using neural networks. However, these face scalability issues due to complexity of training and deployment [5]. Therefore, solutions for beam prediction exploiting another type of sensor have been proposed, such as radar [6], camera [7] or combination of camera and GPS [7]. Even though exploiting additional type of sensor improves the performance, it requires additional sensor (hardware) increasing the cost and the complexity of the deployment.

What would be the expected benefit of replacing (combining) the current solution with ICaS? The ICaS provides a solution that leads to reduced overhead in terms of communication resource consumption and no need for additional sensors. The sensing capability vs communication capability can be adapted based on the need of the network. This provides the ability to pre-allocate communication resources and track the communicating device. A major question is whether sensing can really provide more benefits than dedicated radio resource management (RRM) related methods that exist in communication networks and can also be regarded as sensing methods, however here both the gNBs and the UEs are actively involved. In the evaluation of the benefit of new sensing methods the resource requirements for them need to be taken into account, which is often not done in literature. Furthermore, Non Line of Sight (NLoS) channels for the propagation between the gNB and the UEs should be taken into account, i.e., the sensing aided communications beam management should also perform well under such conditions. One possible outcome may be that additional sensing methods going beyond those that are currently part of 5G-NR RRM do have benefits, but some of the new sensing methods may get integrated into the RRM framework rather than with the sensing framework that is envisioned to be developed for sensing use cases that are not aiming at improving the communication service.

2.1.4 Related work

What are related works (research papers, SDOs, ...), their possible shortcomings with respect to the proposed use case and our use case novelty? Integrated sensing and communication for V2X in ultra-dense networks is a use case described in [4]. This use cases looks solely into the vehicular communication between two vehicles to maintain the communication link. Our use case is more generic as we look into communication enhanced by sensing.

In [8], antenna solutions for high-density scenarios are proposed, providing multiple fixed beams in sub-THz frequencies. Spatial and frequency division multiplexing is considered to minimize interferences. However, no reconfigurability is included to enhance the communication in case of changing conditions.

2.1.5 Difference to other projects/existing solutions (if there are any existing)

Are there other projects with similar goals? What are their approaches and selling points? What are their potential drawbacks? No related projects are known.

2.1.6 Customer demand & business potential

What type of customers might be interested in such a use case and how they can profit from the use case? MNOs would benefit from this use case by improving quality of communication service while reducing the overhead consuming communication resources. This leads to cost savings and improved customer satisfaction. Vendors providing RAN equipment would have a new RAN hardware to enhance their portfolio. End customers would benefit from the improved communication quality. Automotive industry would benefit from the ICaS by improved connectivity of the vehicles and also vehicular communication.

What is the expected growth of business cases related to the use case? The beamforming capabilities of communicating devices are increasing due to increasing number of antenna elements and also higher communicating frequencies requiring more focused beams. This leads to increased computation complexity and higher energy consumption. Therefore, there is already a need for lower computation demanding and energy consuming solutions, which will be even more important in the future.

What type of output would customer require, what is the demand and how to deliver it? Location/trajectory of object that can be leveraged for communication optimization in a privacy preserving manner.

Stakeholders – who would run such a business? MNOs that operate the RAN

2.1.7 Requirements

2.1.7.1 Sensing Performance & KPIs

Table 2. Sensing requirements for sensing aided communications - communication service improvement.

Name	Value	Comment
Sensing Type	Radar	
Accuracy	units to lower tens of meters	Either relative or absolute location can be used. The required accuracy depends on achievable beamwidth at given distance
2D/3D	2D/3D	3D based on specific requirements
Target Type	Communicating devices – smartphones, vehicles, machines.	
Update Rates	1-100 Hz	It depends on the application and channel dynamicity
Sensing Result	Device location	Can be relative or absolute. 2D or 3D.
Possible KPIs	- accuracy (distance and angular or location) - resolution	
Service Area	Tens of meters to hundreds of meters and lower units of kilometres.	Coverage area of the Sensing network.
Known Restrictions	Same as for Mobile Communication networks	
Requirements	- Data Fusion for Multistatic measurements - Full Duplex for Monostatic measurements	
Expected Clutter Type	Static and dynamic clutter, environment and the moving objects that are not target of the sensing.	Everything but the sensed devices are clutter. The main part is expected to be static clutter.

Unlinkability (Privacy)	Privacy aspect of the localization should be taken into account. The owners of the tracked devices need to provide consent (GDPR, ISO/IEC 29184 requirement) for localization.	The affected participating devices would be smartphones, vehicles, machines and their users. 2D/3D to provide more specific requirements. Tens of meters to hundreds of meters and lower units of kilometers. It is necessary to find the right balance between the localization precision and the communication efficiency.

2.1.7.2 Network (architecture, processing, etc.)

Who is expected to collect the sensing results? Is data fusion necessary? What are the latency requirements for the data fusion? The sensing data are expected to be collected at the RAN to enable real-time processing and adapting communication. Data fusion is not necessary but could be leveraged, based on the RAN deployment. For the useful data fusion it is necessary to achieve very low latency.

2.1.7.3 Privacy of the Sensing Data

Are humans (and their personal information) directly or indirectly involved in the use case? Yes, humans and their location/trajectory are collected but only from the device location. Personal details are not used and would increase the complexity of the solution. However, based on additional personal data, such as past user trajectories or habits it may be possible to do personal identification. However, the expected ICaS system itself will not be capable of this task.

What personal information might be potentially derived from the sensed data? From the ICaS data, no personal information can be derived. But, as mentioned, if other information from other sources about user is available, it may be possible to identify user based on the previous habits and tracking data.

What is the impact on the unintended sensed objects/users? By ICaS sensing, objects that are in the same area are sensed as well, therefore trajectory of other objects, devices and user can be sensed.

What is the impact of identification or tracking of people? High, in sense of tracking given object. However, no personal information is directly inferred from the sensed data.

2.1.7.4 Security of the Sensing Data

How important is the confidentiality (preventing unauthorized access to the data), integrity (preventing/detecting unauthorized modifications), authenticity/accountability (assurance regarding the source of the sensing data), availability (sensing data is available when and where needed) of the sensing data? The sensed data do not contain any personal information, but if combined with other data information sources, personal information, location and tracking could be exploited. From the perspective of the use case, integrity and authenticity/accountability of the data requirement is high, as modified data could disable the proper work of the network. In case of no sensing data availability, the network is able to operate with a slight performance reduction

Seeing the information derived from the sensed data as asset – how valuable is this asset? For a potential attacker, this data contains information about the movement of objects in the service area. By accessing additional data, persons can be identified and data can be used for malicious purposes.

What type of information could third-party actors (hackers, malicious actors, etc.) extract from the sensed data? Trajectories of objects and in combination with other available data person tracking may be possible.

2.1.7.5 Security & Privacy for the Sensing (general)

Describe in your own words against whom you want to achieve protection. The sensed data need to be protected from hackers or malicious actors, either trying to access the data or modify them.

What capabilities of the attacker do you assume, e.g., in terms of resources, knowledge, area of physical controls, roles in the system (insider, outsider, user, admin), manipulating or just listening etc.? Which type of attacker the system needs to withstand (script kiddies, insiders, professional hackers, cybercriminals, state-level attackers, etc.) All types of attackers with various knowledge.

Which stakeholders/entities are involved in the sensing data processing and what is you trust relation/trust assumption regarding these entities (e.g. mobile network operator – fully trusted; 3rd party sensing data processing service – honest but curious (will not manipulate the sensing data/result but might misuse the data) The sensed data collection will be done by the MNO, and as this use case's goal is to optimize the communication the processing of the sensed data will be done within MNO.

What are the stages for data collection and processing in the system? The first phase is obtaining sensing data from the low RAN layers (PHY), which then needs to be processed to determine locations of the communicating devices. After processing devices' locations the beamforming is optimized.

Describe some possible security/privacy of the sensing data threats/risks/attack scenarios. The most risks come from personnel with access to the infrastructure and the sensed data. Therefore, it is necessary to protect these data from perspectives of both data security and privacy.

2.2 Sensing support for EMF-related beam-specific power control of base station antennas (sensing-assisted communication) (DTAG)

2.2.1 Objective

The deployment of base stations and antennas needs to consider the environment to avoid transmitting to close objects. Therefore, sensing can be utilized to help with deployment by providing sensing-assistance in antenna systems of a mobile radio systems, allowing a dynamic adaption and shaping of antenna beam characteristics jointly optimizing the communication performance towards UEs and keeping at the same time safety margins set by EMF regulations around the antenna site.

2.2.2 Use case description with an example

At the set-up of base stations of a mobile radio network MNOs have, amongst others, to take care of requirements with respect to max transmit power (EIRP) in different beam directions at antenna sites to comply with EMF regulations (e.g., based on ICNIRP guidelines). Especially for time-varying and spatially distributed radiation of Massive-MIMO systems (power splitting between multiple beams for multiple users) corresponding measures have to be implemented to avoid that in the worst case one beam with full Tx power might cross the averaged power density limit in the safety zone around an antenna site where people may walk (see the example in Figure 2). Applying sensing functionalities, the occurrence of moving objects like human beings may be detectable (comparable to intruder detection) and countermeasures in the antenna beams via Tx power control could be performed (e.g., beams towards the object could be reduced in power and/or modified in their direction to fulfil regulatory EMF limits, in the extreme case the whole antenna could be switched off).

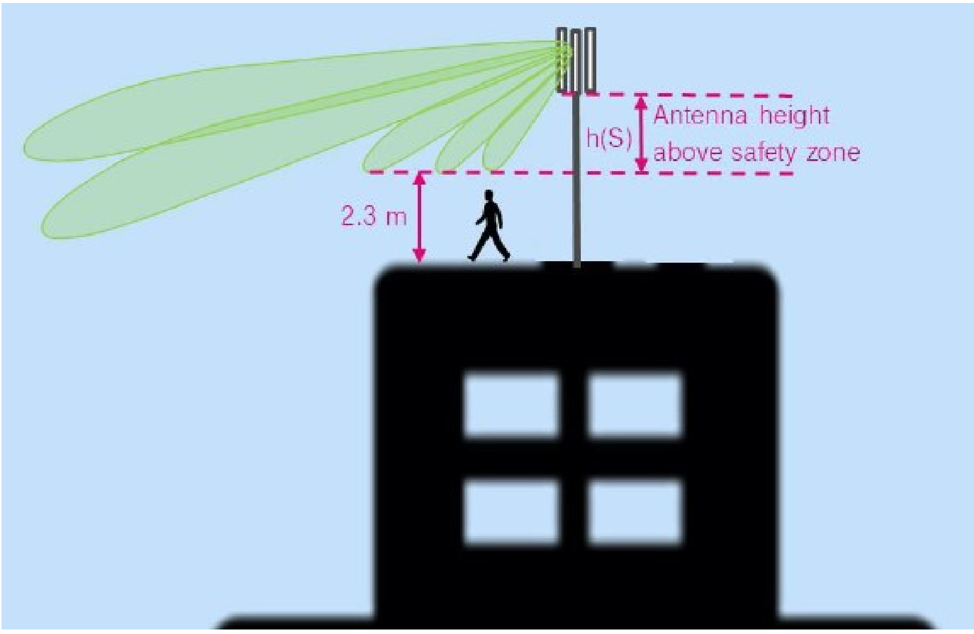


Figure 2. Exemplary deployment of a Massive-MIMO antenna system on a rooftop with related EMF safety zone.

With sensing functionalities in the antenna system, not only the zone directly below the antenna could be observed but the cell coverage area identifying especially main static obstacles/reflectors like buildings. Combined with the information from e.g., 3D city models used in radio network planning tools, potentially extended to a Digital Twin environment, the sensing information can be applied to dynamically adapt and shape the antenna beam characteristics (Tx power, beam direction, etc.) to optimize the communication performance towards users, but keeping at the same time the safety margins set by the EMF regulations around the antenna site. With the sensing approach, also temporary or remaining changes in the static environment which may not be immediately covered by the model in the planning tool or Digital Twin can be considered during a continuous operation of the antenna system informing also the OAM system via related messaging.

2.2.3 Current solutions / equivalent technology

What are current solutions that solve the same objective and what is their complexity/performance/cost? Current antenna deployment inclusive of beam characteristics requires a fixed set-up initially planned before the installation incorporating the related safety margins set by EMF regulation and tested after installation. Changes in the environment have to be typically explored by dedicated site visits and cannot be automatically adjusted in a planning tool and considered in antenna beam control.

2.2.4 Related work

What are related works (research papers, SDOs, ...), their possible shortcomings with respect to the proposed use case and our use case novelty? From a sensing perspective, there is a high similarity with intrusion detection considering any trespassing of the EMF safety zone around the antenna, but also identification of static objects/clutter is part of the sensing solution required for the described purpose.

2.2.5 Difference to other projects/existing solutions

Are there other projects with similar goals? What are their approaches and selling points? What are their potential drawbacks? See statement in Sec. 2.2.3.

2.2.6 Customer demand & business potential

What type of customers might be interested in such a use case and how they can profit from the use case? The customer of the solution is the MNO itself using the sensing functionality implemented by one or more network equipment vendors.

What is the expected growth of business cases related to the use case? With regard to business potential, such solutions may be applied at macro antenna sites, especially at installations on rooftops of buildings where several frequency layers are deployed inclusive of the use of Massive-MIMO antennas. Together with a Digital Twin of the mobile radio network, a highly autonomous operation of the antenna set-up should be feasible, ideally suited for zero-touch network deployments.

What type of output would customer require, what is the demand and how to deliver it? The customer would require information about presence of objects/persons in specified volumetric areas.

Stakeholders – who would run such a business? This use cases is specifically tailored to MNOs.

2.2.7 Requirements

2.2.7.1 Sensing Performance & KPIs

Table 3. Sensing requirements for sensing aided communications - beam specific power control.

Name	Value	Comment
Sensing Type	Radar	
Accuracy	Positioning accuracy for sensing objects: horizontal/vertical ≤ 1 m	Either relative (to the antenna position) or absolute location can be used
2D/3D	2D/3D	3D based on specific requirements

Target Type	- Human beings, potentially animals entering the safety zone around the antenna site. - Buildings, roof structures and similar static objects in the surrounding of the antenna site.	There is no need of object specific identification, just the presence of an object that occupies a given volume in the space.
Update Rates	≥1/s for EMF safety zone, 0.1-0.001/s for coverage area (identification of static objects like buildings/clutter)	It depends on the application
Sensing Result	Relative location per antenna sector (i.e., related to the antenna installation location) is to be measured; the absolute location can be estimated by incorporating the exact TRP location.	
Possible KPIs	- Positioning accuracy - Update rate - Missed detection rate for EMF safety zone: < 0.1%	
Service Area	EMF zone size in the range of up to several 10s of meters.	Up to coverage area of the Sensing network, depending on frequency band.
Known Restrictions	Compatibility with existing RAN.	
Requirements	Mandatory: - High detection rate for trespassing of EMF safety zone required.	
Expected Clutter Type	Static clutter, environment – buildings.	
Unlinkability (Privacy)	There is no need to identify a dedicated person but to identify that an object is entering the safety zone. It is not required to do any correlation with other data that may identify a human being.	As the primary target is only related to safety zones for macro cells, there is no intention to do further identification. There is certainly a possibility to combine such tool with cameras and/or access key sensors, e.g., to secure the

		building on which the antenna is located.

2.2.7.2 Network (architecture, processing, etc.)

Who is expected to collect the sensing results? Is data fusion necessary? What are the latency requirements for the data fusion? Sensing results will be evaluated in combination of RAN and sensing function. Raw sensing data as well as sensing results stay within the system of the MNO. Data fusion is not required but could be applied to achieve extreme reliabilities for EMF safety zone trespassing (video camera, motion sensors, etc.) with the drawback to increase the infrastructure cost.

2.2.7.3 Privacy of the Sensing Data

Are humans (and their personal information) directly or indirectly involved in the use case? Human beings only as possible objects entering the EMF safety zone. Personal identification is not required.

What personal information might be potentially derived from the sensed data? Personal information is not required.

What is the impact on the unintended sensed objects/users? No impact.

What is the impact of identification or tracking of people? Only seen as moving.

2.2.7.4 Security of the Sensing Data

How important is the <u>confidentiality</u> (preventing unauthorized access to the data), <u>integrity</u> (preventing/detecting unauthorized modifications), <u>authenticity/accountability</u> (assurance regarding the source of the sensing data), <u>availability</u> (sensing data is available when and where needed) of the sensing data? All high.

Seeing the information derived from the sensed data as asset – how valuable is this asset? High importance for network operation.

What type of information could third-party actors (hackers, malicious actors, etc.) extract from the sensed data? No relevant information for 3rd parties; but hackers should not be in a position to change those data (wrong action of system with risk for human health), i.e., data integrity and availability must be ensured.

2.2.7.5 Security & Privacy for the Sensing (general)

Describe in your own words against whom you want to achieve protection. The sensed data need to be protected from hackers or malicious actors, either trying to access the data or modify them.

What capabilities of the attacker do you assume, e.g., in terms of resources, knowledge, area of physical controls, roles in the system (insider, outsider, user, admin), manipulating or just listening etc.? Which type of attacker the system needs to withstand (script kiddies, insiders, professional hackers, cybercriminals, state-level attackers, etc.) All types of attackers with various knowledge.

Which stakeholders/entities are involved in the sensing data processing and what is you trust relation/trust assumption regarding these entities (e.g. mobile network operator – fully trusted;

3rd party sensing data processing service – honest but curious (will not manipulate the sensing data/result but might misuse the data) The sensed data collection will be done by the MNO, and as this use case's goal is to optimize the communication the processing of the sensed data will be done within MNO.

What are the stages for data collection and processing in the system? The first phase is obtaining sensing data from the low RAN layers (PHY), which then needs to be processed to determine locations or breaches of controlled areas of the communicating devices. Based on the detected area breaches, transmission power can be modified.

Describe some possible security/privacy of the sensing data threats/risks/attack scenarios. The most risks come from personnel with access to the infrastructure and the sensed data. Therefore, it is necessary to protect these data from perspectives of both data security and privacy.

2.3 Monitoring and tracking of Unmanned Aerial Vehicles (UAV) (TUIL)

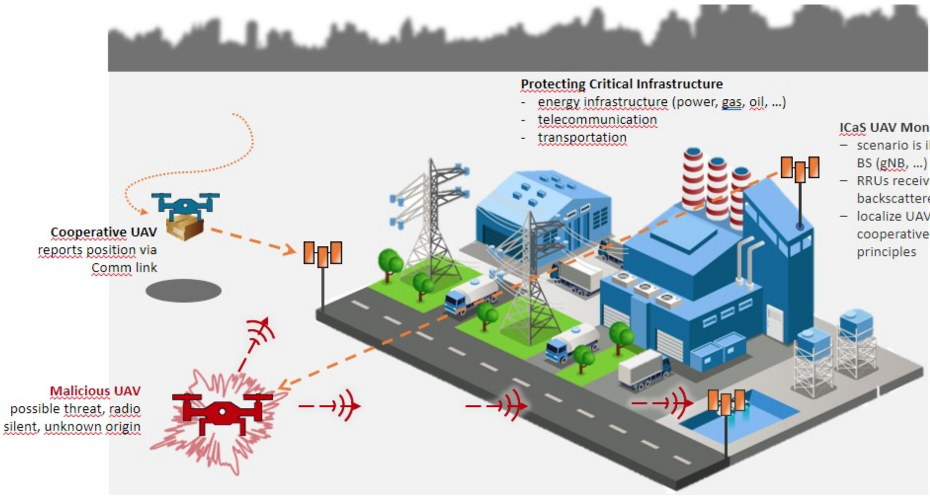


Figure 3. UAV monitoring via ICaS and Malicious UAV detection.

2.3.1 Objective

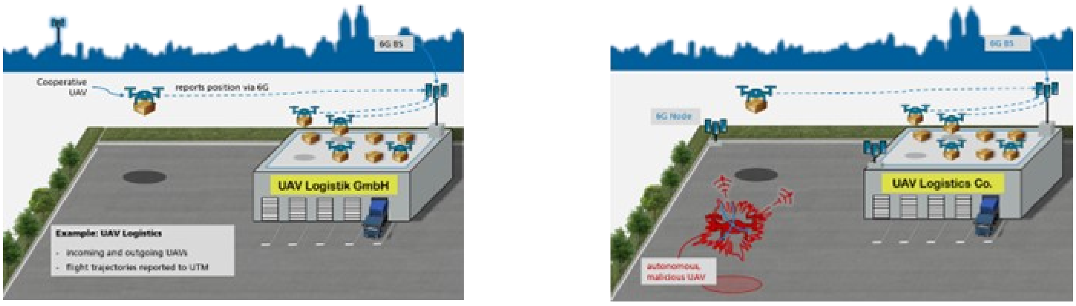
Large-scale UAV applications and business cases require close monitoring of the UAV positions in the lower airspace (< 200m, also called U-Space) to ensure safety, as illustrated in Figure 3. Currently available radar systems need to be more technically or economically viable. This use case aims to close the monitoring gap in the lower airspace using ICaS.

2.3.2 Use case description with an example

For the commercial use of low-altitude airspace by drones (also UAV, Unmanned Air Vehicles or UAS, Unmanned Aircraft Systems), a special airspace has been established as "U-Space", in which rules for safe use are defined (see also EU Drone policy 2.0).

In this context, 5G/6G is envisaged as a reliable and ubiquitous communication platform for controlling drones over longer distances. However, the UTM (UAS (Unidentified aerial system) Traffic Management) systems [9] planned on this basis alone are not sufficient to ensure safe flight operations, as they do not provide sufficient security against misuse or incorrect use of U-space or prevent possible collisions with other flying objects (birds, hobby drones, paragliders, etc.). In conventional air traffic control, dedicated radar and radio tracking systems are used for this purpose. Following the trust but verify principle, the dedicated systems allow independent verification of the information provided by the primary cooperative surveillance system (ADS-B) and timely detection of intruders and threat situations.

Existing air traffic control systems cannot be used for U-space, as they are neither technically designed for this purpose nor can be operated anywhere near economically. A mobile radio network with ICaS radar and emitter sensing capabilities (as envisioned for KOMSENS-6G) could be a solution for the detection of rule violations and unauthorized usage of the U-Space with comparatively low ubiquitous (area-wide). Re-using the existing mobile communication infrastructure ensures low installation costs and ubiquitous coverage. This can be further enhanced by distributed base stations and deploying data fusion to observe the radar scene from multiple angles.



(a) (b)

Figure 4. Commercial UAV monitoring in low-altitude airspace. In normal operation mode the UAVs are controlled via 6G communication links (a). With ICaS the network is used to close the surveillance gap using the existing infrastructure to detect malicious UAV (b).

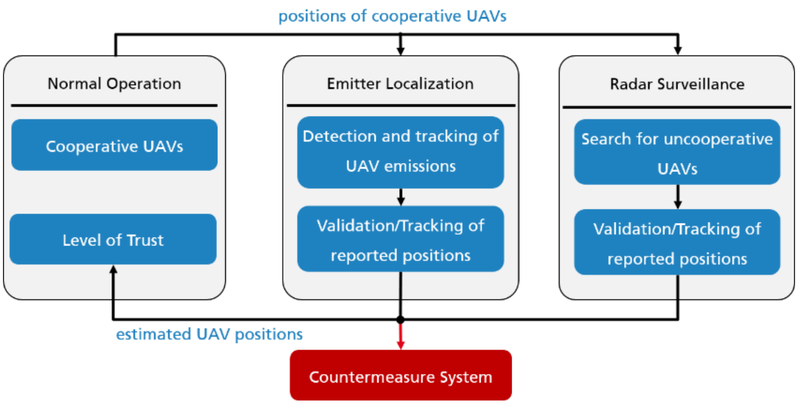


Figure 5. Operation modes of the proposed system. Surveillance is escalated from self-reported position monitoring to emitter localization (verify position reports) to radar surveillance (detect unknown UAVs. The results are forwarded to a countermeasure system (not part of KOMSENS-6G).

2.3.3 Current solutions / equivalent technology

What are current solutions that solve the same objective and what is their complexity/performance/cost? Emitter sensing systems can be used, but they have some drawbacks. For instance, UAVs can avoid detection by not transmitting wireless communication links, which they can do if they are able to fly autonomously. Additionally, using emitter sensing systems requires dedicated hardware, which can be costly, and it must cover a large frequency range as the carrier frequency is unknown a priori.

Radar sensing systems can also be used, which have some advantages over emitter sensing systems. For example, UAVs can only avoid detection by employing costly stealth measures that are typically military-grade. However, using radar sensing systems also requires dedicated hardware and deployment, which can be costly. Furthermore, achieving ubiquitous coverage would require a large-scale rollout of radar infrastructure, which is economically unfeasible.

What would be the expected benefit of replacing (combining) the current solution with ICaS? No need of additional hardware and ubiquitous coverage of sensing.

2.3.4 Related work

What are related works (research papers, SDOs, ...), their possible shortcomings with respect to the proposed use case and our use case novelty? 3rd Party companies have developed (costly) technologies to detect UAVs locally via a combination of emitter- and radar-sensing:

- Dedrone [10], uses a combination of emitter sensing and a dedicated radar system.
- Fraunhofer UAV fence [11], also uses a dedicated radar system to build a radar “fence” to detect incoming UAVs.

2.3.5 Difference to other projects/existing solutions

Are there other projects with similar goals? What are their approaches and selling points? What are their potential drawbacks? With ICaS, we can achieve almost ubiquitous coverage without installing costly dedicated systems. This is because we utilize the existing mobile communication network, making U-Space monitoring much more cost-efficient. Moreover, the approach provides a improved security because UAVs can't hide from radar detection.

2.3.6 Customer demand & business potential

What type of customers might be interested in such a use case and how they can profit from the use case? The types of customers interested in this use case include public safety and law enforcement organizations responsible for airspace monitoring, cooperations worried about industry espionage, specifically those involved in large-scale UAV operations, such as parcel or medical supply delivery.

What is the expected growth of business cases related to the use case?

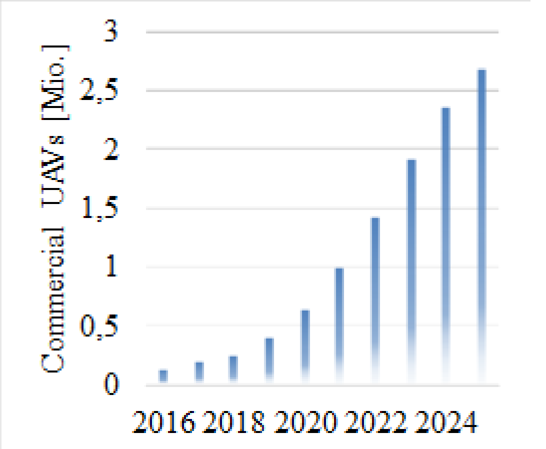


Figure 6. Worldwide predicted number of deployed commercial UAVs between 2016 and 2025 [12].

In addition, the data from the system could be used by 3rd party businesses to build additional services via an API, e.g., intruder detection for large rural areas.

What is the expected growth of business cases related to the use case? The number of commercial UAVs is expected to grow to almost 3 million by late 2024, indicating significant potential for this use case (see Figure 3).

What type of output would customer require, what is the demand and how to deliver it? Customers would require an API that provides access to the service, delivering information such as the presence or trajectory of objects and the probability of events. As lawfully operating UAVs must broadcast their location to confirm with regulation requirements,

Stakeholders – who would run such a business? Mobile communication operators would be the most likely stakeholders to run such a business.

2.3.7 Requirements

2.3.7.1 Sensing Performance & KPIs

Table 4.Sensing requirements for the UAV tracking.

Name	**Value**	**Comment**
Sensing Type	Radar	
Accuracy	~ 1-5 [m]	
2D/3D	3D	
Target Type	UAVs	In U-Space (< 200 m)
Update Rates	0.1-10 [Hz]	It depends on the application
Sensing Result	UAV location	Can be relative or absolute. 2D or 3D.
Possible KPIs	- sensing resolution: 1 [m] - maximum link range: 2 [km] - velocity range: 0 to 45 [m/s] - false alarm rate: 0.01 % - missed detections: 1 %	A high scalability is required to be able to expand the service area beyond the perimeters of the protected facility.

	- very high availability and high scalability -	
Service Area	Coverage area of the Sensing network	Depends on target RCS and signal processing parameters. The coverage area can be expanded by using multi-static sensing.
Known Restrictions	Same as for Mobile Communication networks	
Requirements	- Data Fusion for Multistatic measurements - Full Duplex for Monostatic measurements - RAN modifications to achieve system coverage via beamsteering (pointing beams upwards)	
Expected Clutter Type	Static clutter, moving objects that are not a UAV	Everything but the UAVs are clutter. The main part is expected to be static clutter.
Unlinkability (Privacy)	Identification of the ones responsible for the threat is relevant for this use-case, especially for law enforcement. However, the system may not be able to resolve this based on limited observations.	

2.3.7.2 Network (architecture, processing, etc.)

Who is expected to collect the sensing results? The sensing results are expected to be collected by a data fusion unit that can be installed in Multi-Access Edge Computing (MEC) nodes. This unit requires sufficient processing power and can be powered on and off on demand.

Is data fusion necessary? Whether data fusion is necessary depends on whether the system is set up for multistatic or monostatic sensing. For multistatic setups, data fusion is required, and multiple sensing units can boost detection probability. Data fusion is not necessary for monostatic setups, but instead full-duplex or quasi-monostatic setups are required.

What are the latency requirements for data fusion? The latency requirements for data fusion update rates are in the range of 0.2 – 5 Hz, which should be sufficient for the system.

2.3.7.3 Privacy of the Sensing Data

Are humans (and their personal information) directly or indirectly involved in the use case? Humans and their personal information are indirectly involved in the use case. If the detection algorithm mistakenly tracks a human instead of a UAV, they could be accidentally tracked, though this is unlikely to happen frequently.

What personal information could be derived from the sensed data? The personal information that could be potentially derived from the sensed data includes tracks of position.

What is the impact on the unintended sensed objects/users? The impact on unintended sensed objects or users is likely minimal. Even if an unintentional user is tracked, they would still have to be identified, which is not uniquely possible based on position data alone.

What is the impact of identification or tracking of people? The impact of identification or tracking of people includes the possibility of creating profiles. However, this use case does not deploy a system capable of uniquely identifying specific humans. But even in that case according to the regulations the drones must identify themselves using a Direct Remote Identification (DRI) code [13] which can be acquired even by smartphones. Since this use-case aims to protect critical infrastructure against threats, its goal is to specifically identify these UAVs that do not abide to the regulations (due to technical malfunction or unrightful intentions).

2.3.7.4 Security of the Sensing Data

How important is the confidentiality (preventing unauthorized access to the data), integrity (preventing/detecting unauthorized modifications), authenticity/accountability (assurance regarding the source of the sensing data), and availability (sensing data is available when and where needed) of the sensing data? Confidentiality, integrity, authenticity/accountability, and availability of sensing data are all very important. Reading the data can provide attackers insight into detected UAVs while modifying the data can allow an attacker to hide a specific UAV from detection. Sensing data is available at the sensing nodes, the data fusion node, and the server API.

Seeing the information derived from the sensed data as an asset – how valuable is this asset? When it comes to the value of the information derived from the sensed data as an asset, it could be more financially valuable.

What information could third-party actors (hackers, malicious actors, etc.) extract from the sensed data? Third-party actors such as hackers and malicious actors could potentially extract the position of UAVs and patterns of UAV activity for a sensing area from the sensed data.

2.3.7.5 Security & Privacy for the Sensing (general)

Describe in your own words against whom you want to achieve protection.

The system aims to protect against malicious UAV operators who wish to conceal their unmanned aerial vehicle (UAV) flights. The attackers are assumed not to be capable of manipulating the sensing data.

Which stakeholders/entities are involved in the sensing data processing and what is you trust relation/trust assumption regarding these entities.

Multiple stakeholders are involved in the sensing data processing, including the mobile network operator, who is considered fully trusted, and untrusted subscribers, who should only have read-only access.

What are the stages for data collection and processing in the system?

The system has three stages for data collection and processing, including the sensor stage, which estimates parameters such as delay, Doppler-Shift, and Direction of Arrival (DoA), the data fusion node stage, which estimates the position of UAVs in the area, and the server API stage, which provides the positions of all UAVs in the total coverage area.

Thinking about security/privacy of the sensing data – please describe some threats/risks/attack scenarios that come immediately to your mind. When it comes to the security and privacy of sensing data, there are various threats and attack scenarios to consider.

For instance, humans could potentially be tracked accidentally if they are mistaken for UAVs, but signal processing can minimize this risk through Micro-Doppler identification. Additionally, any moving object in the area can be positioned and tracked but identifying them requires additional data from sources such as cameras.

2.4 Monitoring of suspicious patterns at highway parking lots (TUIL, DTAG, GPP)

2.4.1 Objective

The objective of this use-case is to provide a reliable sensor network for detecting suspicious activities (e.g., burglaries) in a highway truck parking lot and circumvent them by alarming the law enforcement agencies. This is to the benefit of the parties that have financial interest in a safer transportation in highways, including governments, transportation companies, insurance companies, and private companies.

2.4.2 Use case description with an example

Organized cargo theft on German highways causes immense economic damage [14]. According to the Transport Asset Transportation Association (TAPA) and the European Union (EU), criminal gangs steal cargo worth more than 8.2 billion euros every year. Organized gangs act according to the following pattern, cited from [15]: "With five to eight people, they scout rest areas for lucrative vehicles and police presence. They act professionally in their thefts: Some of them are equipped with jammers. There is no cell phone, no radio, no alarm plan, not even police radio in the parking lot. They would park their vehicles next to the truck, cut open the tarp the size of the door, pull the goods to them and then take them to Poland."

The police are overwhelmed by the many possibilities and the resulting lack of area-wide surveillance around the clock. The resulting lack of presence and specialized police units is one part of the problem; the lack of a technical system to quickly detect a threat is another. Immediate driver response is usually prohibited to avoid putting oneself in danger. Secured highway parking lots are rare and very expensive to use. What is needed is an area-wide, networked sensor system that immediately detects a threat situation, reliably relays it and alerts the emergency services, as well as taking other supporting measures. This requires robust and intelligent radio and radar sensors that work together with additional video, infrared and sound sensors. This includes the detection of radio activity related to the threat situation, as well as the rapid detection and location of jammers. The ICaS capability embedded in a robust radio network would be a solution approach that requires little special installation effort.

A truck driver on a way from a city A to city B must take a mandatory stop along the way. Therefore, the driver looks for an available parking spot along the highway. Once the parking spot is found, the driver arrives, parks the truck, and takes a break. During the break time, burglars see the truck as a potential target. As the burglars are approaching the truck, the nearby base stations detect their presence via ICaS and the networks analyzes their behavior. If the burglars start using tools to illegally get into the truck (predictive–case - are deemed to proceed with the burglary), the truck driver, responsible authorities (and others) are informed. The act of burglars is disrupted, and the cargo is kept safely in the truck. (The burglars load the cargo to their vehicle but as they drive away, they are apprehended by the responsible authorities).

2.4.3 Current solutions / equivalent technology (if there are any existing)

What are current solutions that solve the same objective and what is their complexity/performance/cost? The existing monitoring solutions predominantly rely on cameras for detecting intrusion, which is not ideal due to optical limitations in shadows and weather conditions (such as rain and fog) and data privacy issues. A complement solution is deploying infrared sensors which will result in more costs and the blind spots in between the trucks would not be monitored.

The current solutions also lack in deploying advanced signal processing techniques and multi-modal sensing, which can significantly improve the performance of the intrusion detection.

What would be the expected benefit of replacing (combining) the current solution with ICaS? The existing intrusion detection systems for this case are usually installed separately from the other infrastructure of the parking site. ICaS provides the ability to integrate the intrusion detection system into the communication infrastructure. The ICaS system utilizes the radar sensing of the environment in parallel to radio surveillance, for detecting the radio equipment that the intruder may use. This can also reduce the deployment costs, as radio sensing and surveillance share the hardware platform with the communication infrastructure. To further enhance the reliability, sensor fusion techniques can be deployed (by using optical and other sensors) which is beyond the scope of ICaS systems.

2.4.4 Related work

What are related works (research papers, SDOs, ...), their possible shortcomings with respect to the proposed use case and our use case novelty? Too little research has been devoted to address this use-case, in which an ICaS system is used for radio surveillance to detect unauthorized access to highway parking lots. However, the basic building blocks of such system are already well-defined. The radar sensing is an essential part of this system and is included in ICaS systems. Another important part of such intrusion detection system would be radio emitter sensing, which has been addressed in many works including [16], [17]. The blind spot is however, the *sensor fusion techniques* that use *both* radar and emitter sensing outputs to detect an intrusion in the restricted parking lot area.

Secure track and trace [18]**:**

- In logistics, track and trace determine a' item's current and past locations (and other information). For example, suppose valuable goods, e.g., cash, is transported. In that case, the position of the used vehicles or transport containers can be tracked to verify whether the vehicle or transport container takes the expected route. Likewise, a robbery can be detected, e.g., if the vehicle is hijacked or the transport container is stolen.

Security gates [18]**:**

- This scenario is rather straightforward. Security gates, for example, at the entrance to factory premises or other restricted areas, e.g., in airports, offices, or data centers, require that each person be identified, and access rights verified before granting access. Truck (cargo) parking lots can be understood as a restricted area which should be accessed only by the truck driver and transportation (public safety) authorities.

UAVs/vehicles/pedestrians detection near Smart Grid equipment [3]**:**

- In the future, there will be more and more autonomous driving devices, such as drones and self-driving cars. These devices have a strong ability to affect the surrounding environment, which may have an impact on the operating equipment in Smart Grid. For example, vehicles, such as UAVs and engineering vehicles, may affect the operation safety of multiple links such as power generation, power transmission, and power transformation. In our case we detect persons near trucks and their activities.

Sensing for Parking Space Determination [3]**:**

- Sensing technology can improve the user experience in parking garage via enabling the vehicle and parking garage to get more information, e.g., information whether a parking space is available or not. In our case, we can provide information about availability of a suitable parking space.

Human Activity Detection [18]**:**

- The goal of human activity detection (HAD) is to identify common activities such as sitting, standing, walking, etc. In our case, we need to detect the act of forced entry into cargo.
- Human motion detection; Indoor; 5.32 GHz [19]

2.4.5 Difference to other projects/existing solutions (if there are any existing)

Are there other projects with similar goals? What are their approaches and selling points? What are their potential drawbacks? The parking lot monitoring using ICaS has not been directly addressed in the related flagship projects. In the Hexa-X project [18], Secure track and trace was proposed to track the containers of the goods. Another related in Hexa-X use-case is the Security Gates, that avoid the access of unidentified people to a protected area. In neither of these Hexa-X use-cases consider detecting the breach to the parking lot areas, where the valuable goods are extracted out of containers. The distinct difference of our approach to existing ones is that we consider breach cases besides hijacking the containers. Also, instead of controlling the access via security gates, the law enforcement will be alarmed in case of a suspicious activity.

2.4.6 Customer demand & business potential

What type of customers might be interested in such a use case and how they can profit from the use case? What is the expected growth of business cases related to the use case? The potential business use cases for this technology are extensive. For instance, logistics companies can use the system to safeguard valuable products and prevent theft. This can also be to the benefit of insurance companies and governmental institutions. Similarly, manufacturers can ensure the security of their equipment and prevent unauthorized access. Moreover, this system can be used to reduce vandalism, which can lead to decreased repair and maintenance costs.

What type of output would customer require, what is the demand and how to deliver it? The systems output to the customer can simply be the probability of an on-going breach and it`s suspected location, together with a time stamp in which the breach has been detected. The customer can then inform the local guards and law-enforcement agencies to evaluate the potential threat. Also, the customer can use the localization data for further inspections, using for example video surveillance systems, if available on site.

Stakeholders – who would run such a business? Stakeholders who would run such a business include security companies, technology providers, governments, and parking lot or storage facility owners. They would be responsible for the installation, maintenance, and management of the system, as well as the delivery of insights and data to customers.

2.4.7 Requirements

2.4.7.1 Sensing Performance & KPIs

Table 5 Sensing requirements for the high-way parking lot use case.

Name	Value	Comment
Sensing Type	Radar	
Accuracy	~ 1-5 [m]	In 3D Cartesian plane in a pre-defined coordination system.
2D/3D	3D	
Target Type	Vehicles, humans, suspicious radio activity.	In perimeters of the parking lot
Update Rates	0.1-1 [Hz]	It depends on the application
Sensing Result	Location of the suspicious activity (breaching, theft, vandalism) and suspicious radio activity (such as jamming)	Can be relative or absolute. 2D or 3D.
Possible KPIs	- sensing resolution: 0.1 [m] - velocity range: 0 to 25 [m/s] - false alarm rate: 0.01 % - missed detection: 1 % - very high availability and medium scalability is required.	
Service Area	Coverage area of the Sensing network	
Known Restrictions	Same as for Mobile Communication networks	
Requirements	- Data Fusion for Multistatic measurements - Full Duplex for Monostatic measurements	
Expected Clutter Type	Static clutter, moving objects that are not a potential threat.	A distinction between normal and threatful activity inside the perimeters is necessary. This can be done by deployment of other means of surveillance as a complement to ICaS.
Unlinkability (Privacy)	Identification of the peoples included in the breach can be relevant for law enforcement. But this needs to be done such that the non-breaching persons are not affected.	

2.4.7.2 Network (architecture, processing, etc.)

Who is expected to collect the sensing results? Is data fusion necessary? What are the latency requirements for the data fusion? The sensing data is collected in an MEC unit and would become accessible to the stakeholders. The data fusion process can be performed in the same node.

2.4.7.3 Privacy of the Sensing Data

Are humans (and their personal information) directly or indirectly involved in the use case? As the proposed system only senses the breach incidents in a highway parking lot, the identification of people would only occur when a potential threat is detected.

What personal information might be potentially derived from the sensed data? The exploited information in the case would be the coarse position of the incident and intercepted suspicious radio activity. In case of fusion with video-feed, the image of the breacher can also be provided. Again, it is noteworthy that the mentioned private data is only acquired in case of a potential breach and not in a continuous model.

What is the impact on the unintended sensed objects/users? TBD

What is the impact of identification or tracking of people? TBD

2.4.7.4 Security of the Sensing Data

How important is the <u>confidentiality</u> (preventing unauthorized access to the data), <u>integrity</u> (preventing/detecting unauthorized modifications), <u>authenticity/accountability</u> (assurance regarding the source of the sensing data), <u>availability</u> (sensing data is available when and where needed) of the sensing data? To ensure detecting of the breach cases, the authenticity of the provided of the alarms made by the system is essential. Also unauthorized access to the system information should be prohibited to prohibit the unauthorized access to the critical safety-related data.

Seeing the information derived from the sensed data as asset – how valuable is this asset? What type of information could third-party actors (hackers, malicious actors, etc.) extract from the sensed data? The information provided by this system are valuable in the sense that they can prevent financial and even intellectual properties and should be protected from malicious actors. If they can get access to the sensing data, they can potentially find a way to avoid law-enforcement agencies and proceed with their illegal activities.

2.4.7.5 Security & Privacy for the Sensing (general)

Describe in your own words against whom you want to achieve protection. Which stakeholders/entities are involved in the sensing data processing and what is you trust relation/trust assumption regarding these entities. What are the stages for data collection and processing in the system? Thinking about security/privacy of the sensing data – please describe some threats/risks/attack scenarios that come immediately to your mind. When it comes to the security and privacy of sensing data, there are various threats and attack scenarios to consider.

Similar to 2.3.7.5.

2.5 Monitoring of patterns at railroad crossing (GPP)

2.5.1 Objectives

Many mobile base stations and antennas are positioned along railway tracks to provide connectivity services for communication of train drivers (with the central services), collecting train information or providing connectivity to onboard train passengers. These base stations can be enhanced with sensing capabilities for two purposes: 1) to allow an easy way of monitoring the tracks within critical areas (crossings, forests, ...) for objects (obstacles) in the train tracks or in the near proximity, 2) to detect and track trains or other objects on the train track. The information about objects can be leveraged to inform train drivers ahead of time of dangerous areas and to take precautions. Similar can be done by providing information about the incoming train to the drivers or persons around the railroad crossings.

There are several types of objects that can be detected, such as persons whose lives can be saved by taking a timely action. Aside from persons, there are still occurring collisions with vehicles or obstacles (trees) in the tracks. Collisions due to train signal errors are still possible in cases of trains going in the wrong directions or being static on the wrong track. Detecting all these objects can save lives and avoid significant material costs. Even though there is an ongoing trend in decreasing collisions, there is still a long way to go [20].

The ICaS system could even observe trains, cars, people, or objects moving towards or around the crossing section without slowing down. The chance of a collision can be calculated. A warning can be sent to the train and vehicle drivers or even persons with smartphones to slow the train down or warn vehicles drivers and persons to move away from the railroad crossing. A local alarm can be implemented in addition, to warn people of critical situations.

For railroad safety we can think of multiple scenarios where the ICaS function could improve the situation. That is why a dialog with the stakeholder Deutsche Bahn, operating its own dedicated mobile communication system, will help to find the best Use Case and understand the customer needs.

2.5.2 Use case description with an example

The following scenario “Railroad crossing", illustrated in Figure 7 is an example for such a use case: There are sensing enhanced base stations near a railroad crossing monitoring crossing between a road and the railroad tracks. A train is approaching the crossing automatically triggers a sensing of the crossing area. This is done early enough to allow for a full stop of the train in case of detecting object at the railroad crossing. The sensing via ICaS system detects and reports a car blocking the train tracks in the crossing area. A warning is sent to the train driver to take a precaution of slowing the train. If the situation does not clear up, the train will come to a full stop.

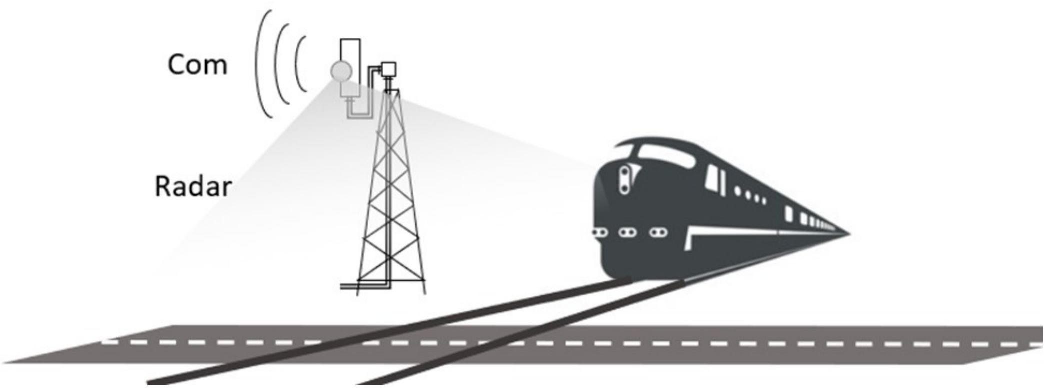


Figure 7. RADAR sensing of a Railroad Crossing to provide an early warning to the train driver.

The scenario has multiple users benefiting from the solution. Deutsche Bahn as the train operator saves lives and minimizes damages via continuous effort to increase the safety of the train transportation operation. People in the trains are safer by avoiding heavy collisions. People on the road are safer from coming into collision with trains. The train driver wellbeing is improved by avoiding shocking situations.

2.5.3 Current solutions / equivalent technology

What are current solutions that solve the same objective and what is their complexity/performance/cost? Currently the railroad crossing security is achieved via flashing lights at railroad crossings, to keep the people off the tracks when a train is approaching. Still, there are many situations where today just the attention of the train driver is the solution. In these cases, the reaction to stop the train comes in most cases too late.

What would be the expected benefit of replacing (combining) the current solution with ICaS? Mobile network antennas are available along the tracks illuminating large sections of the DB tracks. This existing infrastructure is ideal for an ICaS upgrade.

2.5.4 Related Work

What are related works (research papers, SDOs, ...), their possible shortcomings with respect to the proposed use case and our use case novelty? Solutions investigating integration of additional systems into trains are being researched. One option is to mount a camera to the front of the train and exploit computer vision (neural network based) via onboards cameras detecting obstacles [21]. This is also a part of Therefore, integration of additional systems into trains is being researched. One these systems is integration of computer vision (neural network based) via onboards cameras detecting obstacles [21]. This is also investigated in H2020 Shift2Rail project SMART (Smart Automation of Rail Transport) which aims at increasing the safety of rail transport by detecting obstacles on the rail tracks ahead of a moving train in order to reduce the number of collisions.

2.5.5 Difference to other projects/existing solutions

Are there other projects with similar goals? What are their approaches and selling points? What are their potential drawbacks? Other existing systems are primary based mounting a cameras [22], radars or Lidars to the trains [23], which bear additional costs to the trains and have limited range and area sensing capabilities. Therefore, it is not possible to detect incoming objects, such as vehicles near the railroad crossing. The ICaS system can provide a warning to the train driver for any object on the observed tracks ahead. The train can stop to avoid a collision. Different approach focused on vehicular security integrates driver warning system. The system warns driver if the vehicle is about to reach railroad crossroad while there is an approaching train SKODA auto has a system for warning car drivers about railway crossing. However, this solution works only for those who have the warning application and trains that share their location (which is not always the case). Moreover, the train is not informed about the vehicle [24].

2.5.6 Customer demand & business potential

What type of customers might be interested in such a use case and how they can profit from the use case? Railroad operators, automotive, people and all other participants in the transportation where there is a possibility of collision between two or more objects. Deutsche Bahn increases the safety of its operation in crossing sections and on illuminated parts of the tracks. People on the road enjoy a higher safety level when crossing tracks. When ICAS sensing capabilities become available with 6G network technology such safety scenarios for DB could be enabled with little extra effort to avoid collisions Figure 8. An associated partnership of Deutsche Bahn with the KOMSENS-6G consortium is desired to receive professional feedback to this case and potentially find additional cases for the railroad section.

What is the expected growth of business cases related to the use case? From the EU railroad study [20] it is clear that not all railroad crossings are properly secured and even in case when all the crossings are secured there is still possibility of object, such as a tree falling into the train tracks. Therefore, there is a large possible growth of securing railroad crossings and train tracks.

What type of output would customer require, what is the demand and how to deliver it? Presented of object to detect obstacles at the railroad crossing or trajectory of objects (vehicle, person or even train) to take collision avoidance precautions. This information could be delivered through infotainment systems in trains and vehicles or to user equipments.

Stakeholders – who would run such a business? There are multiple options for business models, e.g., a MNO who owns communication infrastructure along the track could offer "Sensing as a Service" to Deutsche Bahn. Additionally, sensor fusion, based on availability of other sensors, might add additional safety to the scenario for little extra costs (e.g., optical camera). The discussion with Deutsche Bahn will help to understand also the commercial side of the scenario and the solution.

Figure 8. Train Collision with a Car at a Railroad Crossing that could be avoided by sensing.

2.5.7 Requirements

2.5.7.1 Sensing Performance & KPIs

Table 6. Sensing requirements for monitoring railroad crossing.

Name	**Value**	**Comment**
Sensing Type	Radar	
Accuracy	Units of meters	The needed location accuracy is high, as the separating distance of trains and other objects at the railroad crossings are low (meters).
2D/3D	2D/3D	2D location should be sufficient but there may be other objects, such as UAVs or there could be over(under)passes for which 3D tracking may be necessary.
Target Type	People, vehicles, animals, trains	All participants that do not provide precise position.
Update Rates	Seconds to tens of seconds	System does not have to continuously track all objects but if

		object is moving to area near the track or crossing, update rate should increase.
Sensing Result	Detection of objects (actors) around the railroad crossing. Warning to train driver and the actors at the crossroad to avoid collision	
Possible KPIs	- accuracy - resolution -sensing range - false-alarm-rate – low required - missed detection – low required	
Service Area	Areas around railroad crossings, tens of meters to hundreds of meters.	
Known Restrictions	Line of sight to track the objects	Non-line of sight may not provide required results.
Requirements	Trajectory prediction	
Expected Clutter Type	Static clutter, moving objects that do not attend to reach railroad crossing.	
Unlinkability (Privacy)	No personal information is assumed if all actors are not actively participating. In this scenario only object detection and tracking is needed.	In case of active collaboration, e.g., vehicle sharing its position, these data need to be anonymized and not stored after vehicle moves out of area of interest.

2.5.7.2 Network (architecture, processing, etc.)

Who is expected to collect the sensing results? Is data fusion necessary? What are the latency requirements for the data fusion? The sensing results could be collected either by the railroad operators, MNO or 3rd parties providing service for this type of the use case. Data fusion should not be necessary but could improve the performance for detection of small objects. Latency requirements are not too strict due to need of issuing warning to participants ahead of time, i.e., latency in order of lower units of seconds may be sufficient.

2.5.7.3 Privacy of the Sensing Data

Are humans (and their personal information) directly or indirectly involved in the use case? Yes, humans are directly involved in this use case, both directly as the participants and indirectly as vehicle and train drivers. However, as the sensing output consists of detecting object at or near railroad crossing with insufficient accuracy to distinguish a specific person, no personal information should be possible to derive.

What personal information might be potentially derived from the sensed data? Presence of persons, but without sensor fusion it should not be possible to determine specific person.

What is the impact on the unintended sensed objects/users? Unintended objects/users are considered as clutter and are not sensed.

What is the impact of identification or tracking of people? Low, form the object presence or tracking in a very specific area it is not possible to identify person, as sensing resolution would be well above sensing specific person information.

2.5.7.4 Security of the Sensing Data

How important is the confidentiality (preventing unauthorized access to the data), integrity (preventing/detecting unauthorized modifications), authenticity/accountability (assurance regarding the source of the sensing data), availability (sensing data is available when and where needed) of the sensing data? Confidentiality of sensed data should be high, but from the simple camera deployment attacker or unauthorized person can obtain significantly more information. On the other hand, authenticity/accountability must be high, as any changes in the sensed data can have significant impact on the system and cause transportation delays and incur unwanted expenses due to false alarms. Availability should be high in case of ICaS being the sole and primary safety system in this use case.

Seeing the information derived from the sensed data as asset – how valuable is this asset? There are other easier ways to obtain more detailed information.

What type of information could third-party actors (hackers, malicious actors, etc.) extract from the sensed data? Presence of objects and their trajectory but without any personal information.

2.5.7.5 Security & Privacy for the Sensing (general)

Describe in your own words against whom you want to achieve protection. Primary protection in this use case would be against injecting malicious sensing data or modification of the sensed data, as any change could render the service unreliable.

What capabilities of the attacker do you assume (e.g., in terms of resources, knowledge, area of physical controls, roles in the system (insider, outsider, user, admin), manipulating or just listening etc.)? Which type of attacker the system needs to withstand (script kiddies, insiders, professional hackers, cybercriminals, state-level attackers, etc.). All possible capabilities should be assumed.

Which stakeholders/entities are involved in the sensing data processing and what is you trust relation/trust assumption regarding these entities (e.g., mobile network operator – fully trusted; 3rd party sensing data processing service – honest but curious (will not manipulate the sensing data/result but might misuse the data). MNO for sensing and processing and 3rd parties processing data. There needs to be trust towards MNO, otherwise it would not be possible to deploy such a service.

What are the stages for data collection and processing in the system? MNO receives the sensed data, transports these data and either does the processing or enables 3rd party to process the sensed data.

Thinking about security/privacy of the sensing data – please describe some threats/risks/attack scenarios which come immediately to your mind. Attacker deploying system capable of injecting malicious sensing data.

2.6 Sensing-aided navigation of AGVs in logistics (outdoor) (TUIL)

2.6.1 Objective

Autonomous guided vehicles (AGVs) can revolutionize logistics in urban logistics facilities by improving the efficiency and speed of transportation within logistic centers such as container ports and terminals. AGVs can navigate through complex and crowded environments, optimize routes, and reduce the need for human labor, ultimately enhancing the overall productivity and safety of these facilities.

2.6.2 Use case description with an example

The task of transporting goods in busy logistics centers (such as container ports) is a labor-intensive task. In a port, multiple workers operate forklifts and other heavy machinery to transport hundreds of containers in a day. With the introduction of AGVs, this process becomes much simpler and more efficient. The AGVs can be guided to automatically navigate through the logistics center, picking up and transporting containers to their designated terminals with the least human intervention. They can optimize their routes based on real-time traffic and demand data, avoiding congestion and delays. The use of AGVs not only simplifies the logistics process but also improves safety by reducing the risk of accidents involving human operators and heavy machinery. Additionally, it saves time and resources, allowing logistics centers to handle more containers with fewer resources and at a lower cost.

AGVs rely on various guidance information to navigate and operate efficiently. In addition to the data provided by the on-board sensors, they need accurate mapping of their environment that includes positions of other vehicles, humans, obstacles, and other important objects (such as the position of the containers that need to be transported). AGVs also need to be aware of their own precise position and information from a traffic control system that manages the movement of the vehicles inside the environment. This makes the deployment of AGVs and ideal use case of ICaS. The AGVs rely on a communication system for acquiring important guidance information and the same communication infrastructure can be used to provide the environment sensing information.

2.6.3 Current solutions / equivalent technology (if there are any existing)

What are current solutions that solve the same objective and what is their complexity/performance/cost? While AGVs are increasingly being discussed as a game-changer in factory automation, they have already been implemented in container ports and logistics centers. Several companies provide AGV-based solutions to move containers within the terminals and increase the efficiency of container handling operations [25, 26, 27]. However, they rely mostly on on-board sensors and the information provided by a traffic management unit. This both increases the load on the on-board processing unit and increases the dependency of AGVs to the central operator.

What would be the expected benefit of replacing (combining) the current solution with ICaS? ICaS can improve the performance of AGVs in container ports by providing a more extensive mapping of objects and other vehicles by providing them with sensing information (e.g., by providing a mapping of the environment). This can promote the autonomous operation of the AGVs and enhance their sensing accuracy. Furthermore, deployment of ICaS in container ports can reduce the costs of infrastructure that is needed for the operation of AGVs.

2.6.4 Related work

What are related works (research papers, SDOs, ...), their possible shortcomings with respect to the proposed use case and our use case novelty? Simultaneous Localization and Mapping (SLAM) [28] is a technology that enables autonomous guided vehicles (AGVs) to map their environment and determine their location within it. In ports and logistics centers, AGVs can use SLAM to optimize their movement, avoid collisions, and improve overall efficiency. Though SLAM techniques are reliable for mapping, AGVs currently use sensors such as lidars, cameras, and radars to detect and map their surroundings. The deployment of SLAM techniques can be investigated in the context of ICaS to provide a more extensive mapping of the environment using the sensing information provided by ICaS.

2.6.5 Difference to other projects/existing solutions (if there are any existing)

Are there other projects with similar goals? What are their approaches and selling points? What are their potential drawbacks? Environment mapping in smart cities and the role of SLAM algorithms has been discussed in the Hexa-X project. However, the main objective there is to perform traffic monitoring and the deployment of AGVs in outdoor scenarios is not relevant. Nevertheless, AGVs have been the subject of study in Hexa-X [18], yet only in industrial scenarios (mostly indoor).

2.6.6 Customer demand & business potential

What type of customers might be interested in such a use case and how they can profit from the use case? What is the expected growth of business cases related to the use case? Customers who are interested in deploying AGVs in container ports could include logistics and transportation companies, shipping lines, port authorities, and terminal operators. These customers would benefit from the increased efficiency and reduced costs that AGVs can provide in container handling operations. According to a report by Statista, the global market for AGVs is expected to grow at a CAGR of 13.2% between 2020 and 2025 [29]. Due to their efficiency and lower carbon emission, AGVs have already been deployed in multiple ports around the world [30].

What type of output would customer require, what is the demand and how to deliver it? Customers deploying AGVs in container ports would require real-time tracking and monitoring of the AGVs and containers, together with a map of environment that includes objects and obstacles. This would include the presence and location of the objects, as well as trajectory and velocity information.

Stakeholders – who would run such a business? Stakeholders to run this type of business are container ports could include logistics and transportation companies, shipping lines, port authorities, and terminal operators.

2.6.7 Requirements

2.6.7.1 Sensing Performance & KPIs

Table 7. Sensing requirements for Sensing-aided navigation of AGVs in logistics (outdoor).

Name	Value	Comment

Sensing Type	Radar	
Accuracy	~ 0.1 -1 [m]	
2D/3D	3D	
Target Type	Other AGVs, humans, obstacles, containers	On the ground.
Update Rates	0.1-1 [Hz]	
Sensing Result	A mapping of environment	Can be relative or global.
Possible KPIs	- sensing resolution: 0.1 [m] - maximum link range: 1 [km] - velocity range: 0 to 15 [m/s] - false alarm rate: 0.1 % - missed detections: 0.1 % - high availability and scalability	
Service Area	The area of the container port or logistic center	
Known Restrictions	Shadowing of targets due to large metallic containers	
Requirements	- Data Fusion for generating an extensive mapping of the environment	
Expected Clutter Type	Static clutter, moving objects that are not relevant	
Unlinkability (Privacy)	There is no need to identify present people in this use-case. However, humans can potentially be identified in the service coverage of the ICaS network.	- Identification of other AGVs or the transportees can be relevant. - For the logistics centers with restricted access, the identity of the ones inside the perimeters is already exposed to the security unit and in that case the privacy is not deteriorated.

2.6.7.2 Network (architecture, processing, etc.)

Who is expected to collect the sensing results? Is data fusion necessary? What are the latency requirements for the data fusion? The sensing information need to be gathered and continuously updated in a central management unit that provides the sensing information to all AGVs working in the port. The central unit can then end the local mapping information, along with other guidance information, to the AGVs. The latency for providing the guidance and mapping is critical to avoid collisions between AGVs and other objects and disruptions in service.

2.6.7.3 Privacy of the Sensing Data

Are humans (and their personal information) directly or indirectly involved in the use case? What personal information might be potentially derived from the sensed data? When it comes to privacy issues related to the sensing data, it is worth noting that the acquired information related to humans would be limited to human activities in the port. In fact, the positions of all humans in the port area are essential for effective route planning and safety reasons, but no identification is necessary for this. For collecting the data, from which the personnel can be identified a consent from the personnel would be essential. For this strong Multi-Factor Authentication (MFA) can be deployed.

What is the impact on the unintended sensed objects/users? TBD

What is the impact of identification or tracking of people? TBD

2.6.7.4 Security of the Sensing Data

How important is the <u>confidentiality</u> (preventing unauthorized access to the data), <u>integrity</u> (preventing/detecting unauthorized modifications), <u>authenticity/accountability</u> (assurance regarding the source of the sensing data), <u>availability</u> (sensing data is available when and where needed) of the sensing data? In the civil deployment of this use case, the sensing results don't have to be kept confidential. However, the availability of this data is necessary to ensure the continuous operation of AGVs.

Seeing the information derived from the sensed data as asset – how valuable is this asset? What type of information could third-party actors (hackers, malicious actors, etc.) extract from the sensed data? The sensed data is valuable because the entire AGV operation in ports relies on the acquired sensing information. If third-party actors breach the system, they can acquire guidance information and a constantly refreshed map of objects in the port area. Using this information, a hacker can potentially track containers at the port or redirect them to another location. Another threat is that a hacker can disrupt logistic activities in the port by manipulating guidance information.

2.6.7.5 Security & Privacy for the Sensing (general)

Describe in your own words against whom you want to achieve protection. Which stakeholders/entities are involved in the sensing data processing and what is you trust relation/trust assumption regarding these entities. What are the stages for data collection and processing in the system? Thinking about security/privacy of the sensing data – please describe some threats/risks/attack scenarios that come immediately to your mind. When it comes to the security and privacy of sensing data, there are various threats and attack scenarios to consider.

Same as 2.7.7.5.

2.7 Sensing-aided navigation of AGVs in factory environment (BOSCH, NOK, EDD)

2.7.1 Objective

The basic idea of the use case is to use the infrastructure-based ICaS capabilities to improve the autonomous transport solutions available nowadays in the industrial manufacturing domain. Especially, the aspects related to the collision detection with other participants on the shop floor incl. strategies for collision avoidance, advanced planning, management, and scheduling of transport tasks on the shop floor. Some specific objectives per partner that work on the use cases are as follows:

- Collision avoidance between AGV, robots and people (ERICSSON)BOSCH
- Replace safety-certified LIDAR (expensive) by using infrastructure sensing instead (mono-static or bi-/multi-static) (BOSCH)
- Required 5 mm accuracy in around 1 % of cases and 1-2 cm accuracy in 95 % of cases (BOSCH)
- Increase awareness of AGVs (BOSCH)
- Improve safety and job planning (BOSCH)

The most important benefits are the following:

- Increase of the safety and reliability of the transport solution on the shop floor,
- Reduction of the OPEX costs related to transportation due to replacement of human labor by autonomous transport systems and reduction of maintenance effort for, and increase efficiency of, the logistic system,
- Reduction of CAPEX because of less and cheaper sensor devices,
- Improvement of the transportation time, reliability and availability on the shop floor.

2.7.2 Use case description with an example.

Industry 4.0 (I4.0) represents the next step in the development of the industrial manufacturing. Although the fourth industrial revolution is known for some time already, the process is still ongoing and there is a lot to do. Moreover, the current state of the development towards the smart factory concept is rather modest.

There are many theories and initiatives about I4.0, which have not been implemented or tested. Solitary products and solutions dominate over massive rollouts of the I4.0 concepts. Even the Big Picture I4.0 shown by different companies is often too unspecific for clear use cases. The developments are rather technology-driven and not customer-driven. Newly built factories tend to implement many I4.0 concepts right away though the manufacturing process remains mostly fixed.

On the other hand, the customer requirements start to change more and more frequently showing a challenge to a fixed production concept. The large batch production principles tend to shift towards small and individual batch production. Such novel requirements like lot size 1 production at large-scale conditions, highly variable factories, reduction of set up times, significant reduction of investments and fast integration of the newest manufacturing technologies become the new standard.

To overcome these challenges, we consider several steps. The first step is a transition from fixed production lines to a flexible manufacturing process. This transition includes among many well-known I4.0 concepts the introduction of cyber-physical systems, autonomous mobile transport systems like AGVs (autonomous guided vehicles), digital twins, artificial intelligence, and massive connectivity including mobile technologies to the shop floor (see Figure 9.). These techniques enable a higher level of variability and flexibility of the production.

The following step should result in a highly flexible factory. Such a factory offers complete variability. Although the walls, the floor, the ceiling will all be fixed, everything else will be mobile. Assembly lines will be modular, and their constituent machines will move and reorganize themselves into new lines for new purposes. They'll communicate wirelessly with one another and with other process functions via mobile networks, and they will be powered through the floor via an inductive charging system. A very important aspect is the need for a mutual awareness of components on the shop floor. Here, ICaS can provide the basis. The factory of the future is going to be highly adaptable, flexible and fully connected.

The idea of the use case is to use the infrastructure-based ICaS capabilities to improve the autonomous transport solutions (Figure 9.) available nowadays in the industrial manufacturing domain. Especially, the aspects related to the collision detection with other participants on the shop floor incl. strategies for collision avoidance, advanced planning, management, and scheduling of transport tasks on the shop floor.

Figure 9. Factory of the future vision of the company Robert Bosch GmbH [Pictures: Bosch].

2.7.3 Current solutions / equivalent technology (if there are any existing)

What are current solutions that solve the same objective and what is their complexity/performance/cost? The current solutions provide environmental awareness of AGVs by using onboard sensors like ultrasonic, radars, lidars, video cameras, odometers, IMUs, etc. The processing of the data coming from the sensors requires high-power computers, which are carried by the AGVs. Currently, AGVs are still very expensive because of the expensive onboard components required to guarantee the awareness and safe functioning.

What would be the expected benefit of replacing (combining) the current solution with ICaS? Increase of the safety and reliability of the transport solution on the shop floor, improved awareness of the surrounding, eventual reduction of the CAPEX costs related to transportation due to replacement of the expensive onboard hardware through infrastructure sensing capabilities, improvement of the transportation time, reliability and availability on the shop floor, increased flexibility by modular concepts enabled by wireless communication, network slicing and edge computing.

2.7.4 Related work

What are related works (research papers, SDOs, ...), their possible shortcomings with respect to the proposed use case and our use case novelty? There exist similarities between this use case and other products (e.g., conventional radar and lidar systems) as well as other proposals ("Robots to Cobots" described in EU project Hexa-X [31]; 3GPP "AGV detection and tracking in factories" and "AMR collision avoidance in smart factories" [3]). Our use case envisions integration of the sensing capability inside of the communication sub-system of AGVs. The major benefits are the reduction of CAPEX and OPEX costs as well as the simplification of the system architecture for AGVs.

2.7.5 Difference to other projects/existing solutions (if there are any existing)

Are there other projects with similar goals? What are their approaches and selling points? What are their potential drawbacks? Not known to the best of our knowledge.

2.7.6 Customer demand & business potential

What type of customers might be interested in such a use case and how they can profit from the use case? Large manufacturing companies, which apply autonomous transport systems (e.g., Bosch, Siemens, BMW, Daimler, VW, Tesla). Also, vendors and providers of autonomous transport systems (e.g., Bosch Rexroth). In general, following business use cases could profit from the use case: Flexible industrial manufacturing and Indoor logistics.

What is the expected growth of business cases related to the use case? We expect a continuous growth as shown in Figure 10.

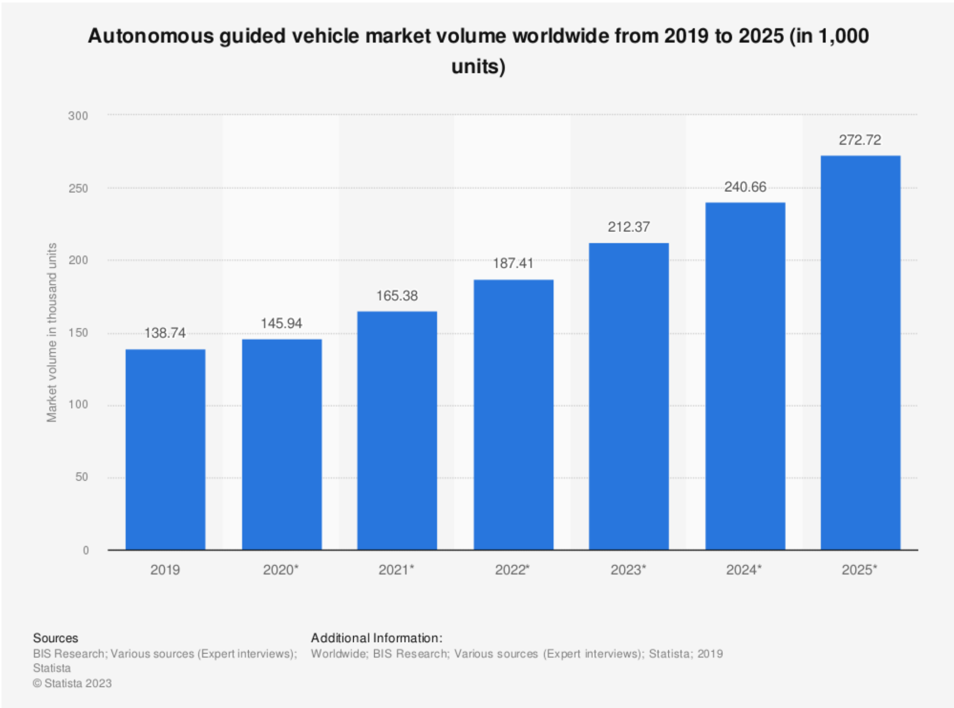


Figure 10. AGV global market prediction [29].

What type of output would customer require, what is the demand and how to deliver it?

Absolute position of an AGV and all other participants on the shop floor on the trajectory of the same AGV in 2D, (optional) in 3D. Optionally distances to the close objects and prediction for possible collisions on the defined trajectory

Stakeholders – who would run such a business? Large manufacturing companies, which apply autonomous transport systems (e.g., Bosch, Siemens, BMW, Daimler, VW, Tesla). Providers/operators of autonomous transport systems (e.g., Bosch Rexroth). Logistics solution for supply chains and warehousing provider, e.g., [32].

2.7.7 Requirements

2.7.7.1 Sensing Performance & KPIs

We list some selected KPIs for this use case in Table 8.

Table 8. Sensing requirements for Sensing-aided navigation of AGVs indoor.

Name	**Value**	**Comment**
Sensing Type	Radar (mono- and/or multi-static)	
Accuracy	cm-dm range depending on the exact situation (e.g., down to sub-cm accuracy for docking scenarios, dm range for normal movement along the corridors)	
2D/3D	2D (3D is nice to have)	
Target Type	- Large (e.g., 1 m3 onwards) (semi-)permanent objects/structures in the environment (boxes, stands, supermarket boxes, pillars, production cells, parts of production line) - Large (e.g., 1 m3 onwards) mobile objects in the environment (transport vehicles like forklifts, milkruns, large AGVs) - Middle size (< 1 m3) mobile objects (workers, other AGVs) - Small size (< 20 x 20 x 20 cm3) (semi-)permanent object in the environment (docking station, product pieces or other small object on the floor)	
Update Rates	10-100 Hz	
Sensing Result	2D map of the environment, with relative/absolute positions of objects	
Possible KPIs	Localization accuracy, range resolution, false alarm probability for object detection, velocity accuracy, update rate	

Service Area	Indoor industrial environment, industrial campuses (several buildings)	
Known Restrictions	Because of safety and security requirements there exist restrictions on utilization of components from trusted vendors only.	
Requirements	Mandatory: - Absolute position of an AGV - Position of close objects relative to a particular AGV	
Expected Clutter Type	- Walls and floor - Inner elements of production cells - Objects, which are not located along the trajectory of the AGV	
Unlinkability (Privacy)	In industrial environments, entropy on the shop floor is by design rather low (e.g., there are only few workers at a time present). So, the events tent to be easily linkable. Furthermore, there is intentional time accounting for all workers at work. So, privacy is already harmed by design. In this use case, our goal is, however, not to degrade the level of privacy even more and instead preferably improve it if possible.	

2.7.7.2 Network (architecture, processing, etc.)

Who is expected to collect the sensing results? Is data fusion necessary? What are the latency requirements for the data fusion? The sensing result is expected to be collected and fused by the AGV management system that controls the AGV movement. AGV itself needs to be informed about the results of the sensing to control its movement.

2.7.7.3 Privacy of the Sensing Data

Are humans (and their personal information) directly or indirectly involved in the use case? Yes. Humans are part of the use cases and are not allowed to be identified using the sensing information.

What personal information might be potentially derived from the sensed data? Body size, type of clothes.

What is the impact on the unintended sensed objects/users? No crucial impact in case identification of a user isn't possible.

What is the impact of identification or tracking of people? No crucial impact in case identification of a user isn't possible. In such an industrial environment, entropy on the shop floor is by design rather low (e.g., there are only few workers at a time present). So, the events tent to be easily linkable. Furthermore, there is intentional time accounting for all workers at work. So, privacy is already harmed by design. In this use case, our goal is, however, not to degrade the level of privacy even more and instead preferably even improve it if possible.

2.7.7.4 Security of the Sensing Data

How important is the confidentiality (preventing unauthorised access to the data), integrity (preventing/detecting unauthorized modifications), authenticity/accountability (assurance regarding the source of the sensing data), availability (sensing data is available when and where needed) of the sensing data?

- Confidentiality: "medium" till "high". Sensed data may be used to reconstruct machines applied in the production process, their parts, product pieces, etc. This may indirectly harm the company. Here, sensed data represents the final results of the sensing process after data pre- and post-processing. The raw sensing data remain in the sensor only and have very limited lifetime.
- Integrity: "high". Unauthorized modifications of data created in the sensing process (e.g., positions of obstacles on the way of an AGV) may result in a crash that may lead to a hazardous situation in the factory or even in the region around factory.
- Authenticity/accountability: "high". Sensing is done in the infrastructure. The communication of the sensed result to a corresponding UE must follow after proper authentication and authorization steps ensuring the trustfulness of the data.
- Availability: "high". Not availability of the sensing data results in an interruption of the production process on the shop floor being very expensive for the company. Unscheduled downtimes must be avoided.

Seeing the information derived from the sensed data as asset – how valuable is this asset? This asset has a very high value in case no other parallel sensing system is in operation

What type of information could third-party actors (hackers, malicious actors, etc.) extract from the sensed data? Positions of AGVs and factory personnel. Factory activity and load of the factory by statistical data from positions.

2.7.7.5 Security & Privacy for the Sensing (general)

Describe in your own words against whom you want to achieve protection. Hackers that want to extract data from the sensing result. Here, sensing result represents the final results of the sensing process after data pre- and post-processing. The raw sensing data remain in the sensor only and have very limited lifetime. Hackers that want to distract the operation on the shop floor by manipulating the sensing result.

What capabilities of the attacker do you assume (e.g., in terms of resources, knowledge, area of physical controls, roles in the system (insider, outsider, user, admin), manipulating or just listening etc.)? Which type of attacker the system needs to withstand (script kiddies, insiders, professional hackers, cybercriminals, state-level attackers, etc.). All types mentioned in the question are thinkable. Usually, the attackers represent outsider that apply high performance computers and reach to the system over a network. Most frequent are the attacks that result in stealing of data/information. Manipulation of data is rather difficult for attackers. The system should withstand such attacker types like script kiddies, professional hackers, and cybercriminals.

Which stakeholders/entities are involved in the sensing data processing and what is your trust relation/trust assumption regarding these entities (e.g., mobile network operator – fully trusted; 3rd party sensing data processing service – honest but curious (will not manipulate the sensing data/result but might misuse the data). In-house cooperate IT department – fully trusted. 3rd party AGV vendor and operator, mobile network operator – honest but curious (will not manipulate the sensing data/result but might misuse the data). 3rd party sensing data processing service – honest but curious (will not manipulate the sensing data/result but might misuse the data).Radio Equipment directive 2014/53/EU Article 3 [33] (3) e,f: (e) radio equipment incorporates safeguards to ensure that the personal data and privacy of the user and of the subscriber are protected; (f) radio equipment supports certain features ensuring protection from fraud;

What are the stages for data collection and processing in the system? Sensing data collection in a local data storage (provided by a local IT department and considered to be secured enough for this use cases), pre-processing of data in a local edge cloud (the most power consuming step that results in an object list), transmission of results to involved AGVs and corresponding AGV management system (controls the overall transport service on the shop floor and is considered to be secure for this use case), post-processing of data in AGVs and/or AGV management system.

Thinking about security/privacy of the sensing data – please describe some threats/risks/attack scenarios which come immediately to your mind. External hacker wants to intercept the sensing results (sensing data after processing) to be able to monitor the mobility on the shop floor. External hacker wants to manipulate the sensing results (sensing data after processing) to negatively impact the manufacturing process on the shop floor.

2.8 Sensing-aided navigation of AGVs in logistics (on yard) (BOSCH)

2.8.1 Objective

The deployed communication infrastructure (base stations) is used to collaboratively sense the environment around them. Infrastructure sensing could be supplemented by dedicated sensing equipment to improve accuracy. A digital map of the 3D environment in the sensed area is developed, in a format where any interested (3rd party) application can use it for various use cases.

2.8.2 Use case description with an example

As shown in Figure 11.. the base stations on top of buildings in an urban/industrial environment transmit sensing signals in a coordinated manner to develop a 3D model of the (semi-) permanent objects (such as buildings, billboards, parked vehicles etc.) in the environment. For Yard Management using autonomous vehicles in industrial/production environments or Automated Valet Parking (AVP) scenarios, the 3D environmental model could be used to provide backbone information for route planning. The generated environmental model could be used to improve the sensing/ communication performance by assisting for e.g. (predictive) beamforming.

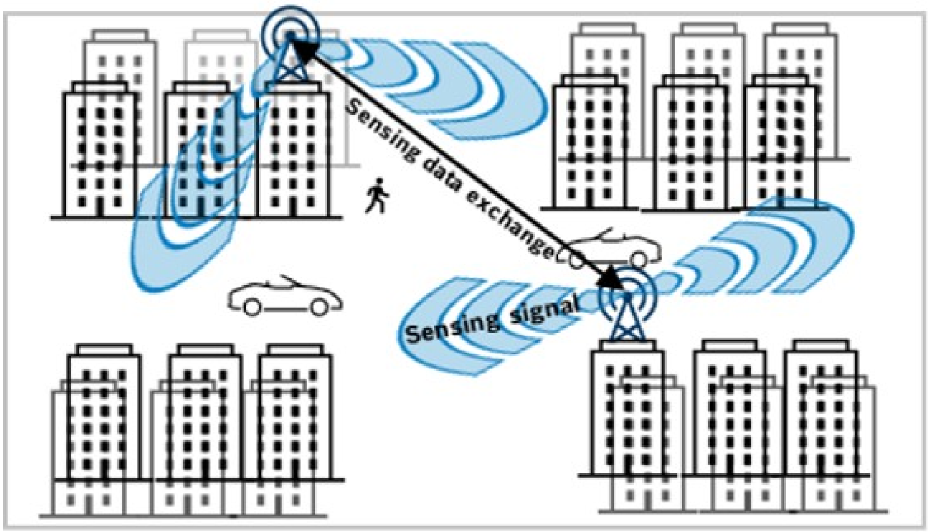


Figure 11. Sensing aided navigation on yard.

2.8.3 Current solutions / equivalent technology (if there are any existing)

What are current solutions that solve the same objective and what is their complexity/performance/cost? Currently, dedicated sensors such as LiDAR or cameras are used to develop perceptions of the environment. Each device/vehicle performs own (distributed) sensing, and there does not exist a centralized solution.

What would be the expected benefit of replacing (combining) the current solution with ICaS? Existing solutions cannot create a unified model of the environment. Distributed sensing is however an important component, as objects in the environment are *viewed/fused* from multiple viewpoints to improve model accuracy

2.8.4 Related Work

What are related works (research papers, SDOs, ...), their possible shortcomings with respect to the proposed use case and our use case novelty? The basic building blocks for such use cases exist for proprietary radar systems. However, the use case envisions integration of devices of various vendors with varied capabilities (hardware/software/power consumption). This requires that the architecture and signaling mechanisms are standardized, as well as the type and format of data to be shared between network nodes for fusion.

2.8.5 Difference to other projects/existing solutions (if there are any existing)

Are there other projects with similar goals? What are their approaches and selling points? What are their potential drawbacks? Not known to the best of our knowledge.

2.8.6 Customer demand & business potential

What type of customers might be interested in such a use case and how they can profit from the use case? Industrial and/or logistics management centers might be interested to utilize reliable maps of the environment. It might be possible to realize the targeted use cases in private networks.

What type of output would customer require, what is the demand and how to deliver it?

Absolute position of an AGV and all other participants on the trajectory of the same AGV in 2D, (optional) in 3D. Optionally distances to the close objects and prediction for possible collisions on the defined trajectory.

2.8.7 Requirements

2.8.7.1 Sensing Performance & KPIs

Table 9. Sensing requirements for Sensing-aided navigation of AGVs in logistics (yard).

Name	Value	Comment
Sensing Type	Radar	
Accuracy	1 m^3	
2D/3D	3D	
Target Type	Large (e.g. 1m^3 onwards) (semi-) permanent objects/structures in the environment	
Update Rates	1 Hz	
Sensing Result	3D map of the environment, with relative/absolute positions of objects	
Possible KPIs	Accuracy, resolution, false alarm probability etc.	
Service Area	Urban/industrial environment	
Known Restrictions		
Requirements	- Coordination between sensing signal Tx/Rx entities. - Data fusion frameworks	
Expected Clutter Type	- Smaller objects in the environment - Moving objects (people, AGVs)	
Unlinkability (Privacy)	Degree of uncertainty, entropy	

2.8.7.2 Network (architecture, processing, etc.)

Who is expected to collect the sensing results? Is data fusion necessary? What are the latency requirements for the data fusion? Are humans (and their personal information) directly or indirectly involved in the use case? (Note: Example for indirect involvement: sensing of a car à possibility of derivation of personal data regarding the driver (style of driving etc.)). What personal information might be potentially derived from the sensed data? See section 2.7.7.2.

2.8.7.3 Privacy of the Sensing Data

Are humans (and their personal information) directly or indirectly involved in the use case? What personal information might be potentially derived from the sensed data? What is the impact on the unintended sensed objects/users? What is the impact of identification or tracking of people?

See section 2.7.7.3

2.8.7.4 Security of the Sensing Data

How important is the <u>confidentiality</u> (preventing unauthorized access to the data), <u>integrity</u> (preventing/detecting unauthorized modifications), <u>authenticity/accountability</u> (assurance regarding the source of the sensing data), <u>availability</u> (sensing data is available when and where needed) of the sensing data? Seeing the information derived from the sensed data as asset – how valuable is this asset? What type of information could third-party actors (hackers, malicious actors, etc.) extract from the sensed data? See section 2.7.7.4

2.8.7.5 Security & Privacy for the Sensing (general)

See section 2.7.7.5

2.9 Detection of road traffic congestion at intersections (NOK)

2.9.1 Objective

Target of this use case to improve the traffic flow at major city crossings (the same functionality can be used for other means as well such as to provide info to fun-park visitors or tourists in general about congested areas in the fun-park and the touristic spots, respectively).

In the particular example covered in this section the sensing system provides measurements about the level of congestion for the different directions heading towards the street crossing.

The benefit of this use case is a better traffic flow and all related advantages (less fuel consumed, happier traffic members, …).

2.9.2 Use case description with an example.

The ICaS system is able to determine traffic density in all directions of a street crossing being handled by a traffic light system (e.g., through measuring the dimensions of the sensed cluster, no need for accurate numbers).

Based on the outcomes the traffic-light control system is informed about congested directions (and eventually the grade of congestion – e.g., based on the size of the detected clusters). This information can be used by the traffic-control system to modify the time-windows of green-light phases in favor of the congested directions.

The benefit would be to have green-light phases better fit to the actual traffic densities from the different directions (and no phases where a direction has green, but nobody is coming from that direction, while other directions are congested).

2.9.3 Current solutions / equivalent technology

What are current solutions that solve the same objective and what is their complexity/performance/cost? Currently green-light phases are fixed and pre-configured (to the best of our knowledge). Some crossings have sensors embedded into the street that can determine, if a car is close to the crossing in that direction, but the system is not aware of the situation behind. So, this solution can be used to trigger the switch to green-light but is not able to adjust the timing of the green/red-phases as a whole. Alternative solutions to determine traffic density and congestion are available based on other solutions (radar, camera, …). However, those systems are requiring dedicated infrastructure and have in same countries privacy barriers (e.g., cameras).

What would be the expected benefit of replacing (combining) the current solution with ICaS? Advantage of doing this as part of a ICaS system is that there is no additional infrastructure needed beyond the communications system (like given in the former point). Obviously, this advantage is only a real advantage, if this can be either realized with the regular base station grid used to offer communication services or at most with little additional infrastructure (e.g. FR2 nodes deployed near the street crossing being able to oversee the crossing) that has also further use (e.g. there are high-capacity communication needs that can be handled by those nodes, there are further sensing use cases those nodes can take, etc.).

2.9.4 Related work

What are related works (research papers, SDOs, ...), their possible shortcomings with respect to the proposed use case and our use case novelty? Not known to the best of our knowledge.

2.9.5 Difference to other projects/existing solutions (if there are any existing)

Are there other projects with similar goals? What are their approaches and selling points? What are their potential drawbacks? Not known to the best of our knowledge.

2.9.6 Customer demand & business potential

The service as such would be offered by the CSP owning the infrastructure. The customer is the (smart-) city administration (municipalities, traffic management entities).

The output of the sensing system would be directly fed into the traffic-light control system. Based on the level of congestion for the various directions reported to the traffic-light control system by the ICaS system the red/green-timing can be adjusted.

A CSP could offer this service towards, e.g., the city administration as part of a complete smart-city package.

2.9.7 Requirements

2.9.7.1 Sensing Performance & KPIs

The ICaS system needs to be able to detect the presence of clusters and associate them to the respective traffic line heading towards the street-crossing. There is no need for exact number but a rough differentiation between cluster dimensions and the associated doppler vectors (to get an understanding about the traffic-flow) would be required.

The requirements are not too high as only a rough assessment of the traffic in the different directions needs to be determined, but it may even be sufficient to “rank” the directions based on the size of the detected clusters. Alternatively, the size of the clusters can also be used to determine the green-light schedule. For this the granularity can be rather rough (no cluster, small cluster, big cluster, …).

An update rate of once every few minutes/seconds following the traffic-flow dynamics should be sufficient.

There is no need to apply this service to any street-crossing. Instead, it is proposed to support major (and problematic) city crossings.

As mentioned earlier optimally the regular FR1 (and potentially FR3, if available in 6G) grid of communication nodes should suffice to offer the service. Eventually if a given street crossing is not well covered not allowing for LoS coverage of this area additional infrastructure at the street crossing (e.g., FR3-based) may be useful. Optimally, those extra nodes would enhance the local communication quality as well.

Table 10. Sensing requirements for detection of road traffic congestion at intersections.

Name	**Value**	**Comment**
Sensing Type	Radar	
Accuracy	Few meters	
2D/3D	2D	
Target Type	Cluster of cars or people	For each direction of the street crossing
Update Rates	Every few minutes	
Sensing Result	Dimension/size of the cluster and embedded doppler vectors	
Possible KPIs	Cluster size, length of the congestion general direction of the cluster and rough speed of it (traffic jam, slow moving traffic, fast moving traffic)	
Service Area	Major street crossing	
Known Restrictions	shadowing of surrounding buildings (assuming the wide-area network to perform the action)	
Requirements	Interface to the traffic light system	
Expected Clutter Type	Static clutter (buildings, poles), moving objects (pedestrians)	
Unlinkability (Privacy)	Only clusters are sensed.	

2.9.7.2 Network (architecture, processing, etc.)

Who is expected to collect the sensing results? The CSP owning the deployment is collecting the raw data. Either this raw data is exposed to a third party implementing the post-processing or the CSP implements this software functionality within his network and exposes the concrete readings related to the traffic-characteristics.

Is data fusion necessary? Data fusion with further sensor systems may be useful (e.g., outcomes from another nearby crossing also being handled like this or with other systems like cameras, etc.).

What are the latency requirements for the data fusion? Latency is not critical and should match the traffic flow dynamics which are rather slow.

2.9.7.3 Privacy of the Sensing Data

Are humans (and their personal information) directly or indirectly involved in the use case? In this use case no individual cars/humans are detected. Instead, only clusters of cars/groups of people are sensed. The sensing system needs only to be active in case of high traffic times.

What personal information might be potentially derived from the sensed data? In the case of only a single car being present at the street crossing, it could be detected individually. So, in this case someone could combine the sensing outcomes with another source of information and this way privacy could be violated. Thus, respective dedicated protections means need to be integrated into the system.

What is the impact on the unintended sensed objects/users? Combining the sensing outcome "individual car detected" with another source of information makes it possible to relate the detected car with an actual person and thus the presence of this person at the street crossing and its behavior can be detected/tracked.

What is the impact of identification or tracking of people? Someone can follow the movement patterns and behavior of the tracked person.

2.9.7.4 Security of the Sensing Data

How important is the confidentiality (preventing unauthorized access to the data), integrity (preventing/detecting unauthorized modifications), authenticity/accountability (assurance regarding the source of the sensing data), availability (sensing data is available when and where needed) of the sensing data? Seeing the information derived from the sensed data as asset – how valuable is this asset? What type of information could third-party actors (hackers, malicious actors, etc.) extract from the sensed data? The system should be protected so that nobody can extract information about the traffic flow characteristics and even worse inject wrong data to modify the traffic-light control system in a wrong way. Attacks can happen both during the basic sensing action in the radio network (i.e., the step at which the radio system detects the presence of clusters and their characteristics such as size and related doppler vectors) and during post processing steps on application layer (i.e., the step at which the system translates the measured levels of congestion for the various directions into reasonable time windows for the green-phases of the traffic-light system). The former is less likely as the radio access network using dedicated hardware resources and not having direct links to e.g., the internet is much harder to be accessed than the latter. Also, the extracted information is rather abstract and would require sophisticated means to extract useful information for the intruder. Attacking the application layer is less complex and involves more sophisticated information (e.g., the configuration of the traffic-light system such as the selection of the lengths of the green-phases depending on the congestion level of the different directions) and thus the system requires dedicated protection mechanisms.

2.9.7.5 Security of the Sensing Data (general)

Describe in your own words against whom you want to achieve protection. What capabilities of the attacker do you assume (e.g., in terms of resources, knowledge, area of physical controls, roles

in the system (insider, outsider, user, admin), manipulating or just listening etc.)? Which type of attacker the system needs to withstand (script kiddies, insiders, professional hackers, cybercriminals, state-level attackers, etc.). Which stakeholders/entities are involved in the sensing data processing and what is your trust relation/trust assumption regarding these entities (e.g., mobile network operator – fully trusted; 3rd party sensing data processing service – honest but curious (will not manipulate the sensing data/result but might misuse the data). What are the stages for data collection and processing in the system? Thinking about security/privacy of the sensing data – please describe some threats/risks/attack scenarios which come immediately to your mind. TBD

2.10 Wrong-way driver detection (NOK, BOSCH)

2.10.1 Objective

The target of this use case is to have a system being able to identify wrong way drivers on the high-way and issue a warning to other drivers and responsible public safety organizations. The general benefit of such a system is to automatically identify potentially dangerous situation and issue a warning reducing the potential of a hazardous situation.

2.10.2 Use case description with an example

In order to implement the use case, the sensing system needs to be able to determine the area of a highway (in particular it needs to be able to distinguish between the two directions) and to detect the cars running on it. In particular it needs to be able to assess their doppler vectors and what direction are the correct ones (Figure 12a).

The sensing systems regularly scans for the doppler vectors travelling on the high-way and their associations to the directions. From the sensing, there are three sensing possible outcomes:

- All doppler vectors per direction are as they are supposed to be Figure 12a. In this case no action required from the warning system.
- The system detects a doppler vector not matching the correct direction (Figure 12b, red arrow). This means a potential wrong-way driver has been detected and a warning should be issued (e.g., towards the local radio station, the local highway security agency, or through a local digital infrastructure such as digital infrastructure signs at the highway)
- The system detects an object with zero doppler shift (Figure 12c, no doppler component at the bottom). This means either a potential accident or another misplaced object/person has been detected and a warning should be issued as described above.

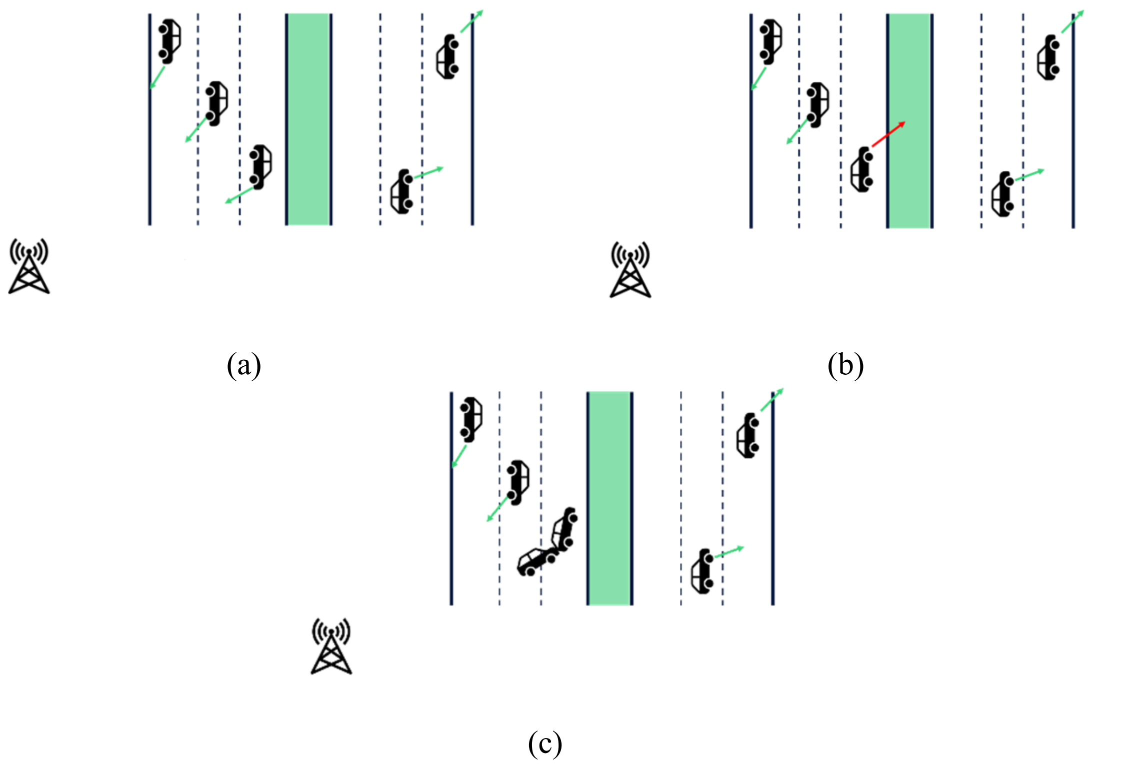


Figure 12. Possible sensing outcomes: a) all vehicles moving in the correct directions, b) there are vehicles moving in incorrect direction, c) there is a collision detected.

2.10.3 Current solutions / equivalent technology (if there are any existing)

What are current solutions that solve the same objective and what is their complexity/performance/cost? Currently people driving on the highway becoming aware of the situation are calling the local police or radio station. With automating this reporting system the warning can be issued quicker/earlier.

2.10.4 Related work

What are related works (research papers, SDOs, ...), their possible shortcomings with respect to the proposed use case and our use case novelty?

This use case can be related to the Hexa-X use case on fine localisation of vehicles [31] and the use case covered in 3GPP TR-22837 - Sensing Assisted Automotive Maneuvering and Navigation, sensing at crossroads with/without obstacle [3]. In particular it provides a more concrete scenario for this kind of use cases.

2.10.5 Difference to other projects/existing solutions (if there are any existing)

Are there other projects with similar goals? What are their approaches and selling points? What are their potential drawbacks? Not known to the best of our knowledge.

2.10.6 Customer demand & business potential

What type of customers might be interested in such a use case and how they can profit from the use case? Local/regional/national administration being in charge of the high-way system.

What is the expected growth of business cases related to the use case? Limited once the complete set of high-ways of the targeted market is covered accounting for the fact, that new high-ways are built rarely.

What type of output would customer require, what is the demand and how to deliver it? Warning message about the presence of a wrong-way driver in a given part of the high-way running a given direction.

Stakeholders – who would run such a business? The provider of this service is the CSP owning the infrastructure. With applying this use case traffic safety on highways can be increased. A CSP would offer this service towards e.g., the city administration as part of a complete smart-city/smart-urban/smart-countryside package.

2.10.7 Requirements

2.10.7.1 Sensing Performance & KPIs

In order to implement the use case the sensing system needs to be able to detect the Doppler vectors of the cars driving on the highway and their association to the set of lines they are riding on.

The required accuracy depends on the targeted miss-detection (should be as low as possible) and false-alarm rate (can be traded of, but should not be too high also, as otherwise regular actual false-alarms are issued). NB: the cars do not need to be accurately assigned to a single line. They only have to be correctly associated to either half of the high-way.

The update rate of the detection mechanism can be in the range of a few seconds?

In order to configure the use case someone needs to decide for the update-rate, the tolerated false-alarm and miss-detection-rates (both are depending on the quality of the system in determining the doppler and its correct association to the highway-direction).

Regarding deployment optimally there is no need for adding new sites beyond the grid of communication nodes rolled-out for communications means. The highway does not need to be supervised on all of its parts, but optimally all areas where cars are entering the highway are supervised. As the measured doppler vectors are only the components towards/away from the sensing direction the network nodes must not be looking towards the highway in an orthogonal direction. If there is room for additional radio nodes for this particular use case the optimal placement is between the lines of the highway looking along the highway.

Table 11. Sensing requirements for detection of wrong-way driver.

Name	**Value**	**Comment**
Sensing Type	Radar	
Accuracy	~ 1 - 2 [m]	
2D/3D	2D	
Target Type	Cars	
Update Rates	0.01 – 0.1 [Hz]	
Sensing Result	Car driving in the wrong direction, I.e. misaligned doppler vector	

Possible KPIs	False-alarm and misdetection-rate	
Service Area	High-ways	
Known Restrictions	Availability of basestation being able to oversee the selected part of the highway (assuming no dedicated installation targeted)	
Requirements	Interface towards either a radio station, a rescue squad or the digital infrastructure of the high-way (digital signs)	
Expected Clutter Type	Static clutter (trees, walls), moving objects (other cars)	
Unlinkability (Privacy)	Individual cars are detected.	

2.10.7.2 Network (architecture, processing, etc.)

Who is expected to collect the sensing results? Is data fusion necessary? What are the latency requirements for the data fusion? The owner of the 6G wide-area network is collecting the sensing results through his infrastructure. No dedicated data fusion required but fusing the outcomes of different base stations being able to oversee the high-way can be beneficial.

2.10.7.3 Privacy of the Sensing Data

Are humans (and their personal information) directly or indirectly involved in the use case? Yes, individual cars are detected.

What personal information might be potentially derived from the sensed data? The presence of the car and thus of the car driver at this particular position and his driving behavior.

What is the impact on the unintended sensed objects/users? Nothing directly, but someone could track the car through the flow of the high-way, if the sensing outcome can be combined with further sources of information making it possible to connect the sensor readings with an actual individuum. So respective privacy protection mechanisms are required.

What is the impact of identification or tracking of people? The driving behavior of the individual person can be tracked.

2.10.7.4 Security of the Sensing Data

How important is the confidentiality (preventing unauthorized access to the data), integrity (preventing/detecting unauthorized modifications), authenticity/accountability (assurance regarding the source of the sensing data), availability (sensing data is available when and where needed) of the sensing data? Seeing the information derived from the sensed data as asset − how valuable is this asset? What type of information could third-party actors (hackers, malicious

actors, etc.) extract from the sensed data? Attacks can happen both during the basic sensing action in the radio network (detection of the cars and their doppler vectors) and during post processing steps on application layer (identification of a misaligned doppler vector). The former is less likely as the radio access network using dedicated hardware resources and not having direct interfaces to e.g., the internet is much harder to be accessed than the latter. In general, the system should be protected so that nobody can inject wrong data. One potential attack vector is to have the system constantly issue warnings or the other way around not issuing any warnings at all by hacking into the application layer.

2.10.7.5 Security & Privacy for the Sensing (general)

Describe in your own words against whom you want to achieve protection. What capabilities of the attacker do you assume (e.g., in terms of resources, knowledge, area of physical controls, roles in the system (insider, outsider, user, admin), manipulating or just listening etc.)? Which type of attacker the system needs to withstand (script kiddies, insiders, professional hackers, cybercriminals, state-level attackers, etc.) Which stakeholders/entities are involved in the sensing data processing and what is you trust relation/trust assumption regarding these entities (e.g., mobile network operator – fully trusted; 3rd party sensing data processing service − honest but curious (will not manipulate the sensing data/result but might misuse the data) What are the stages for data collection and processing in the system? Thinking about security/privacy of the sensing data − please describe some threats/risks/attack scenarios which come immediately to your mind. TBD

2.11 Detection of rainfall and flooding (DTAG)

2.11.1 Objective

The density of the deployed mobile network base stations provides an option do a real-time monitoring of weather and its impact on the environment (fields, rivers, etc.). The ICaS enables providing communication services while sensing environment information, such as precipitation by measuring wireless link communication quality or reflection of the earth (soil, rivers, roads, …). This information is then passed to entities such as meteorological institutes, agriculture workers, or governmental bodies to provide early flooding detection and warning.

2.11.2 Use case description with an example

The MNO infrastructure that provides connectivity is capable of measuring channel quality between two base stations. These base stations can be located near agricultural field, as illustrated in Figure 13. In this scenario, channel quality is affected by the rain precipitation, which is measured and processed. The processed information is then provided to a farmer who grows crops and can plan when to sow or harvest the crops. Another way, how to leverage base stations is to detect flooding. The flooding detection can protect lives if the flooding is detected early. Rainfall quantities are also valuable input for water observation data collection which is a prerequisite for different forms of water management activities. The denser the ICaS infrastructure is (e.g., urban areas), the better, probably, the chances for more accurate rainfall quantity measurement as well as finer spatial resolution.

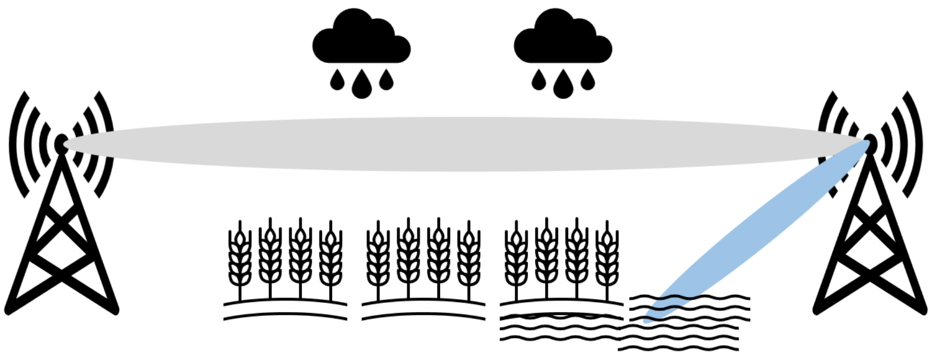


Figure 1314. MNO's infrastructure measuring channel quality to sense rain precipitation.

- What objects will be involved in the use case?
  - Air, soil, rain drops
- Provide an example story to illustrate the sensing benefit. (beneficial to clustering)
  - Farmer needs to start sowing (harvesting) for which rainfall prediction is necessary. The farmer thus utilizes the capability of mobile network to get a detailed information about rainfall prediction, which goes beyond the commonly available weather data. This data can be provided on-demand in a real-time fashion.

2.11.3 Current solutions / equivalent technology (if there are any existing)

What are current solutions that solve the same objective and what is their complexity/performance/cost? The weather or more specifically rain monitoring has been commonly done via ground weather radars or satellites. To obtain a more precise information in area of interest, local weather stations are deployed. With the need to get denser sensor measurements, wireless sensor networks are utilized by placing sensors in the soil and wirelessly collecting measurements. The precipitation monitoring can be done with microwave wireless communication links, which are affected via the precipitation [34]. In the wireless precipitation sensing, it is generally used a mixture of different frequencies and polarizations to get more detailed information. Moreover, data from multiple radars are combined to minimize potential impact of untrusted and malicious data. The current solution requires either deployment of specialized infrastructure or do microware link monitoring whether the precipitation effect is unwanted as it degrades the communication performance.

What would be the expected benefit of replacing (combining) the current solution with ICaS? The main benefit of replacing or combining current solutions would be leveraging existing mobile network infrastructure (RAN) that is capable of providing on-demand real-time data. Moreover, the RAN infrastructure is deployed even in urban areas, where it is generally hard to do weather monitoring with the weather radars.

2.11.4 Related work

List related works (research papers, SDOs, ...) from outside the project or other project partners. Use cases similar to the one presented are considered in Hexa-x as novel weather monitoring applications [18] and 3GPP as Sensing for flooding in smart cities, Rainfall monitoring [3].

Formulate the possible shortcomings with respect to the proposed use case and our use case novelty.

2.11.5 Difference to other projects/existing solutions (if there are any existing)

Are there other projects with similar goals? What are their approaches and selling points? What are their potential drawbacks? There is OpenSense project [35] which brings together scientists investigating different opportunistic sensors, experts from national weather services, owners of sensor networks, and end-users of rainfall products to build a worldwide reference opportunistic sensing community. The OpenSense project [35] relies on existing technologies, whereas the presented use case exploiting ICaS goes beyond the state of the art.

2.11.6 Customer demand & business potential

What type of customers might be interested in such a use case and how they can profit from the use case? Meteorologists, hydrologists, agriculture, farmers, government, weather services, public safety organizations.

List business use cases that can profit from the availability of the use case: Harvesting, flood protection

What is the expected growth of business cases related to the use case? The impact of the weather on daily life if growing due to the weather extreme events increasing frequency. Therefore, it is expected to see a significant growth in this weather monitoring business. [36]

What type of output would customer require, what is the demand and how to deliver it? Rain presence (prediction) and time development on a grid.

Stakeholders – who would run such a business? MNO will probably be able to provide "raw" levels of data. Further capabilities will be needed to infer specific quantities such as rainfall quantities from this data. Such expertise lies typically with hydrometeorologists or similar.

2.11.7 Requirements

2.11.7.1 Sensing Performance & KPIs

Table 12. Sensing requirements for detection of rainfall and flooding.

Name	Value	Comment
Sensing Type	(Weather) Radar	
Accuracy	Tens of meters to hundreds of meters (even km level may be sufficient)	
2D/3D	2D may be sufficient	3D to provide more specific requirements
Target Type	Water droplets	
Update Rates	Seconds to minutes	

Sensing Result	Rainfall quantity, possibly other precipitation quantities	
Possible KPIs	- accuracy - resolution - false-alarm-rate - …	
Service Area	Fields, cities	The sensed area depends on the range of the sensing system
Known Restrictions	tbd	
Requirements		
Expected Clutter Type	Objects, such as buildings, persons or vehicles.	
Unlinkability (Privacy)	By sensing only the rain drops the privacy of involved parties will be assured	Sensing of the ground could potentially reveal persons or other objects in the sensed area, but this is clutter for this use case

2.11.7.2 Network (architecture, processing, etc.)

Who is expected to collect the sensing results? Is data fusion necessary? What are the latency requirements for the data fusion? Meteorologists, agricultural workers, farmers. Data fusion may not be necessary but merging camera data may be advantageous to provide better service.

2.11.7.3 Privacy of the Sensing Data

Are humans (and their personal information) directly or indirectly involved in the use case? No, this use case aims at water droplet monitoring.

What personal information might be potentially derived from the sensed data? Potentially location of person if present on the field.

What is the impact on the unintended sensed objects/users? Minimal.

What is the impact of identification or tracking of people? Minimal/Negligible.

2.11.7.4 Security of the Sensing Data

How important is the <u>confidentiality</u> (preventing unauthorized access to the data), <u>integrity</u> (preventing/detecting unauthorized modifications), <u>authenticity/accountability</u> (assurance regarding the source of the sensing data), <u>availability</u> (sensing data is available when and where needed) of the sensing data? Medium to high. Sensing data must be highly available when it comes to public safety related impacts, e.g., in the case of critical floods, very heavy rainfalls, etc. Also, in these cases the integrity should be high as manipulated data could lead to inactivity with severe consequences.

Seeing the information derived from the sensed data as asset – how valuable is this asset? Very valuable but with limited geographical impact, I.e., data would be valuable to the entity being locally affected ty the rain fall.

What type of information could third-party actors (hackers, malicious actors, etc.) extract from the sensed data? Rain fall information.

2.11.7.5 Security & Privacy for the Sensing (general)

Describe in your own words against whom you want to achieve protection. Competitors in agriculture trying to damage agriculture producers. Malicious actors that want to disturb the emergency protocols of responsible institutions, e.g., lead them to believe there is an emerging flood, while there is not (false alarms initiating costly mitigation actions), or lead them to believe there is little rain, while there is a flood emerging – this is very critical.

What capabilities of the attacker do you assume (e.g., in terms of resources, knowledge, area of physical controls, roles in the system (insider, outsider, user, admin), manipulating or just listening etc.)? Which type of attacker the system needs to withstand (script kiddies, insiders, professional hackers, cybercriminals, state-level attackers, etc.). We would assume professional hackers. The assumption is that in case of higher-level attackers, there would be other safeguards in place (like plausibility checks, other sensing sources for validation) that could be leveraged. Needs to be further assessed.

Which stakeholders/entities are involved in the sensing data processing and what is you trust relation/trust assumption regarding these entities (e.g., mobile network operator – fully trusted; 3rd party sensing data processing service – honest but curious (will not manipulate the sensing data/result but might misuse the data). MNO to provide the sensing and collect the sensing data, then processing can be either done withing MNO, 3rd party or on-site at the customer.

What are the stages for data collection and processing in the system? MNO to provide the sensing and collect the sensing data, then processing can be either done withing MNO, 3rd party or on-site at the customer.

Thinking about security/privacy of the sensing data – please describe some threats/risks/attack scenarios which come immediately to your mind. The precipitation monitoring does not contain private data, as same can be achieved by deploying other types of sensors. However, it is necessary to filter out all unwanted clutter which may contain information about location of people.

3 Privacy protection (3GPP TR 22.837 - Protection of Sensing Information) (BI)

Data privacy is a function of Personally Identifiable Information (PII). In turn, PII can be defined through 'identity' and 'unlinkability'. The following definitions clarify the matter of PII, including links to ISO/TS:

Data privacy (information privacy) – rights and obligations of individuals and organizations with respect to the collection, use, retention, disclosure and disposal of personal information – (ISO/TS 17573-2:2020).

Personally identifiable information (PII, personal information) – information that a) can be used to establish a link between the information and the natural person to whom such information relates or b) is or can be directly or indirectly linked to a natural person – (ISO 31700-1:2023).

Privacy requirements, namely Anonymity, Pseudonymity, Unlinkability of operations and Unobservability, can be defined by their characteristics specifications, as shown in Table 13. The Table 13 provides some of the practical considerations. 'Sufficiency' refers to the confidence in satisfying the strictest privacy demands under the corresponding 'privacy characteristic'.

Table 13. Privacy requirements characteristics.

Privacy characteristic	Difficulty of achieving	Sufficiency
Pseudonymity	Medium	Low
Anonymity	High	Medium
Unlinkability	High	Medium
Unobservability	Very High	Very High

Anonymity – a user may use a resource or service without others being able to determine the user's identity – (ISO/IEC 15408-2:2020).

Pseudonymity – a user may use a resource or service without disclosing its user identity but can still be accountable for that use – (ISO/IEC 15408-2:2020).

Unlinkability of operations – users and/or subjects are unable to determine whether the same user caused certain specific operations in the system – (ISO/IEC 15408-2:2020).

Unobservability – a user may use a resource or service without others being able to observe that the resource or service is being used – (ISO/IEC 15408-2:2020).

Assurance is one of the central definitions for security and privacy in complex systems.

Assurance – grounds for justified confidence that a Target of Evaluation (TOE) meets the Security Functional Requirements (SFRs) – (ISO/IEC 15408-1:2009).

Unlinkability assurance is shown in Figure 15, and explains its rationale.

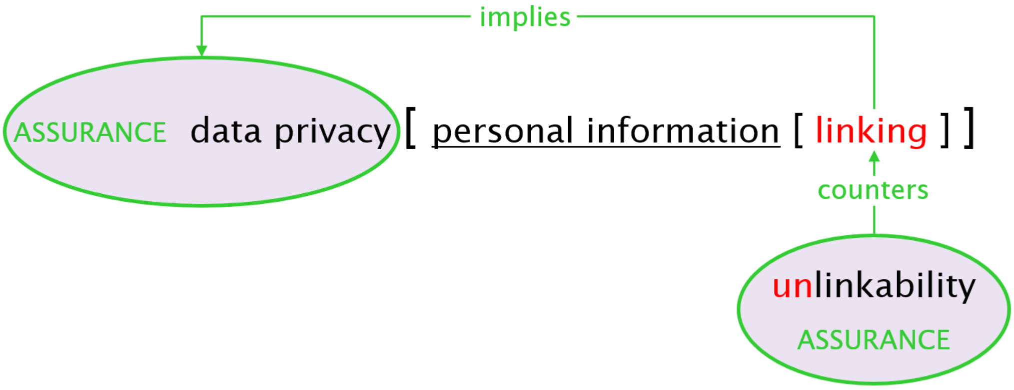


Figure 15. Data privacy and unlinkability.

Knowledge about the context and assumptions of the system are paramount to specify privacy requirements and to develop corresponding assurance arguments.

4 Mobile network infrastructure circumstances and potential trajectories

4.1 Functional requirements (DTAG, EDD, NOK, BOSCH, GPP)

In this section we provide functional requirements on the mobile network infrastructure to provide ICaS. The functional requirements are divided into mandatory and optional in the following text.

Mandatory requirements

- Enabling applications to request sensing information
    - Includes receiving desired target (e.g., location or sensing service area) and type of data needed.
- Authorizing application's requests
    - Collection, processing, and exposure of sensing data is subject to operator's policy and national or regional regulation. Therefore it is necessary to verify if the request is from genuine client which has agreed to pay for ICaS (charging functionality for Sensing-as-a-Service). This includes an authorization check for the application and for the type of data. In the authorization of the application request both cases, where user and/or sensing object consent can or cannot be obtained, have to be considered. Furthermore, it is necessary to includes assurance that privacy is not violated if the request is fulfilled.
- Determining what network sensing is required for fulfilling the requests
    - The starting point is the collective sensing requests from different applications, that may be served in parallel. These requests need to be mapped to what radio observations are required to achieve the desired output data (possibly multiple targets need to be sensed). The format of the desired output data is mainly determined by the diverse application services individually addressing the use cases described in Section 2. What should be noted is that failing to fulfill the request have to be considered as a valid sensing output.

  - The network may serve various degrees of sensing qualities, for instance given by sensing area, accuracy, precision, resolution, update rate. The quality provided is determined by the applications' service requests, the respective radio's sensing capabilities and the resource allocation strategy applied. Sensing can be provided on both licensed and unlicensed frequency bands and its specifics need to be considered. Based on availability of sensing resources and sensing requirements an optimal sensing mechanism should be selected based on, e.g., optimizing energy, minimal RF resource usage, or other criteria.
- Enabling the network to transmit and receive radar-like sensing signals
  - This needs to be done in a coordinated fashion with communication (e.g., scheduled appropriately considering a common QoS framework, reusing communication signals where possible, etc.) and other systems, such as radars that may be affected. The coordination approach shall consider a sustainable operation of the ICaS system, i.e., ICaS transmissions and receptions are adjusted in an energy efficient way by extending energy saving features introduced for the communication network infrastructure and UEs also to sensing purposes.
- Processing the received information to convert it to the desired sensing information
  - The sensing input consists of received raw observations, which need to be further processed to provide the required output. The processing steps include filtering, merging, peak analysis, segmentation, 3D analysis, object recognition, and producing the output information. The level of required processing and created sensing result objects may differ between applications leading to processing chains of varying complexity. In each step of the processing, encryption, integrity protection, and privacy of sensing data have to be supported and guaranteed.
- Exposing the retrieved information
  - The received and processed information has to be provided to the applications requesting sensing service. If the sensing request cannot be fulfilled, the network needs to provide an indication to avoid delay and user experience degradation. The processes sensing data, can be exposed internally (e.g., for network performance optimization purposes like sensing-assisted communication) or external applications. The processed data can be also exposed to applications running on UEs (but this may not look any different, but in certain applications an optimized direct "broadcast" might be needed).

Optional requirements

- Criticality control
  - Applications may make Network Reliability, Availability and Resilience (NRAR) like or Quality of Service (QoS) like statements about their level of criticality , e.g., response time (delay, latency) to prioritize between sensing and communication.
- Indirect sensing location support
  - Involves interaction with location-based network services or other location determining mechanisms on UEs. This indirection is required if sensing requests from applications can be expressed by referring to a location of a particular UE.
- Coordinating UE-assisted sensing

  - Includes determining which UEs are in the area of interest, can and should be involved in addition to the involved network nodes, their willingness, capability, and legality to participate. The participating UEs are then provided instructions from the network on sensing, and retrieval of results (if needed). If UE-based sensing is needed, the UEs need to be coordinated as well.
- Support roaming
  - Based on operator policy, support of Sensing-as-a-Service should be also feasible in case of roaming.
- Transmitter and receiver synchronization
  - Includes synchronization of transmitters and receivers, e.g., a base station sending a signal and another one receiving it. This would be mandatory if multi-static sensing is needed. Synchronization with UEs when UE-based sensing is needed may be required.
  - Synchronization is required if multi-static sensing is needed
- Validation and privacy check of the data to be exposed
  - In some designs, privacy checks may have to be performed before data goes out to the consumers – but this could also be done by construction, as part of the processing (e.g., removing identifiable persons).
- Additional processing support
  - There should be a possibility for data fusion from other sensors like cameras, etc. via a suitable interface if authorized.
- Enabling the creation of additional services
  - Programmability - new services can be created on top, but letting applications control processing tasks may bring performance benefits via reducing dataflows. Here are some examples: (1) application provides an AI model that is used by the network to detect desired conditions, (2) letting an enterprise application determine data access control rules, and (3) letting application specify when sensing is triggered.

4.2 Architecture basics

Due to similarities, between the architectural work in KOMSENS-6G for ICaS and location-based services (LCS), the ICaS architecture may be initially oriented to the existing positioning architecture defined by 3GPP for 5G-Advanced. Details on current state-of-the-art of that architecture and potential gaps that have to be filled for integrating sensing functionalities are described in "SOTA & Gap Analysis" of the Work Package 4 Deliverable part.

Dependent on service and functional requirements for introduction of "Sensing as a Service" via ICaS in a future 6G system, the existing 5G architecture has to be modified or even new architecture may be constructed. Considering novel technology trends under discussion for 6G such as intelligent networking based on native AI/ML, RAN-CN convergence, and programmable cloud-native platforms, the design on new architecture may be necessary.

4.3 Cellular Mobile Network Pre-Conditions

When addressing realization of ICaS services by a Communication Service Provider (CSP), several perspectives have to be considered. In order to address the various use cases and their requirements (discussed in the Section 2), different aspects and challenges of a cellular mobile radio network need to be regarded [37]. From the CSP perspective, ICaS can provide two major benefits:

- "Sensing as a Service" for private and business customers beyond traditional location-based services.
- Enhancement of radio network performance and operation.

A CSP's cellular mobile network infrastructure is typically composed of various types of radio cells served by distinct radio network technologies, see Figure 16. Depending on the radio environment to be covered, respective network density, coverage areas and frequencies are used:

- Sub-urban / rural: sparse network density, some km coverage range, sub-6GHz down to sub-1GHz
- Urban: rather dense network, some 100m coverage range, sub-6GHz
- Campus / indoor: dense network, some 10m coverage range, sub-6GHz up to mmWave

Figure 16. Cellular Network Infrastructure.

Note: With network density the number of radio transmitter received at a specific location is considered. Hence, it is assumed the more radio transmitter cover a specific area, the more and diverse sensing results can be obtained.

The cellular mobile radio network is traditionally optimized for communication services. When addressing sensing services in ICAS, additional needs for network planning and infrastructure set-up will arise, for instance, precise information of site geometries or even the demand for further network densification. Future analysis within KOMSENS-6G will provide insights on further optimization demand.

The core of sensing functions and radio processing will be found in an ICAS system in the radio access network. This can be divided into several areas of integration of sensing with communication functions:

- Integrated radio design and antenna types
    - The ICaS will have impact on integration of the radio frontend and transceiver design (including FR1 typically using Frequency Division Duplex (FDD)), leading to questions such as which types of antennas will be required.

- Baseband architecture and joint medium access control (MAC)
    - At the MAC level, radio resource management (RRM) needs to be optimized jointly for communication and sensing, considering also QoS requirements of each. The joint communication and sensing RRM has to work even in scenarios of on demand requests. The sensing overhead has non negligible impact on the communication system, which can be elevated by use of separated systems instead of a joint one.
- Sensing data fusion across RAN nodes and network elements
    - The data fusion from multiple sensing data sources opens various possibilities and challenges, such as which level of processing should be done on separate data, where to do the processing of fused data, selection of inference techniques (method vs ML based) or should the network elements follow protocol/signaling based design known from communication or should they be fully software based?

In ICaS-enabled mobile broadband networks Sensing-as-a-Service, especially object sensing, will be provided not as a stand-alone service but rather within a communication and sensing service portfolio. Accordingly, common resources and network functions will be shared between communication and sensing, as it cannot be anticipated that sensing service is continuously operating at highest service level in the entire cellular network as known from stand-alone-applications. Sensing-as-a-Service in ICaS should be rather provided on demand, based on the needs of the application and the resource consumption in an ICaS-enabled mobile broadband network.

Functions and procedures for servicing diverse application demands have to be considered while taking into account the current capabilities of the sensing radio system (Figure 17). Looking into the use case categories Sensing-aided Communication, Public Safety, Smart Logistics, Smart Factory, Smart City and Weather-related Sensing, each has different requirements and produced outputs. Therefore, the ICaS system should be rather general than a very specialized solution requiring deployment of multiple ICaS systems. This has an impact on the processing of the data, where inference should be done through a chain of steps providing the desired output. What should be noted, is that sensing clutter from one application can contain useful information. Therefore, requests from multiple applications can be satisfied at the same time.

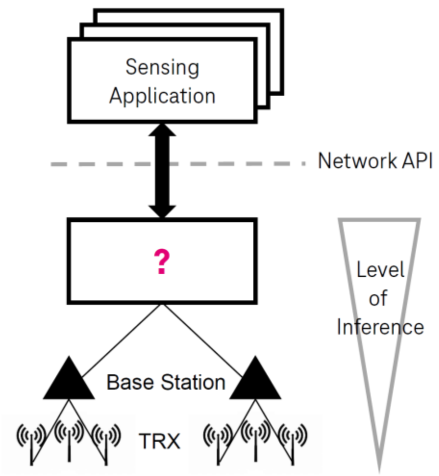


Figure 17. ICaS sensing radio system.

In this respect, cascading of sensing data inference is one option to serve this demand as illustrated in Figure 18. It will make use of the hierarchical and service-oriented architecture of a cellular mobile broadband network. Thereby, for each inference step best-of-bread methods can be applied. Open interfaces are provided in between. This provides benefits:

- Raw data inference can be carried out at the receivers in real time.
- Deep insights into radio specific functionalities are hidden.
- The amount of data to be provided to the next inference step is limited.
- Cellular data fusion is supported when combining processed sensing data from relevant neighboring receivers.
- Open architecture allows reuse and optimization of cascading process.
- Application servers for specific use cases can build on generalized extracted insights provided by APIs.

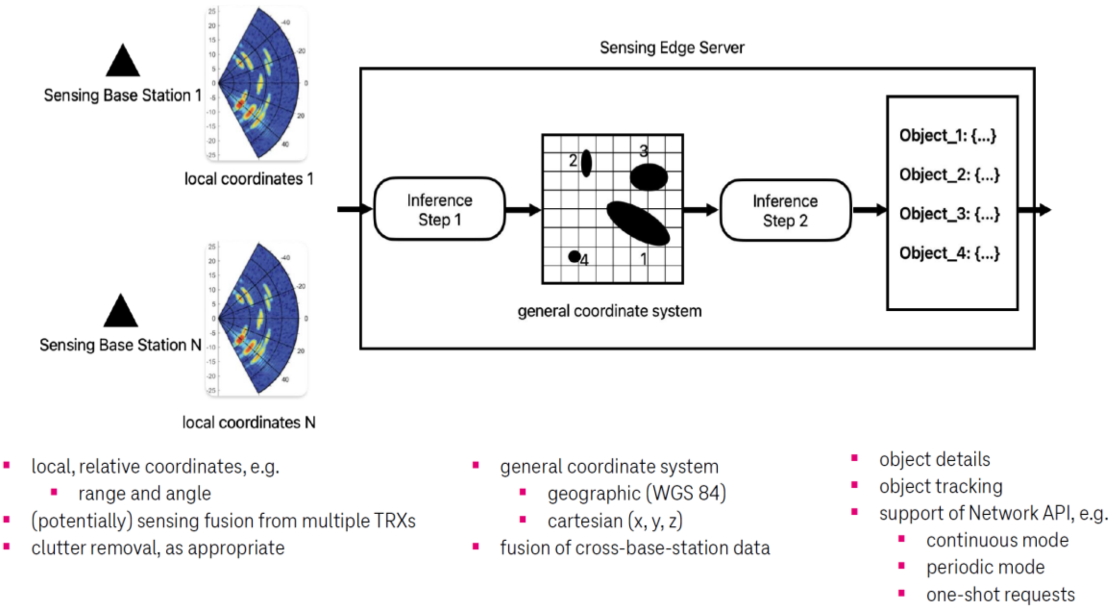


Figure 18. Split of Sensing Inference Steps.

4.4 Functional Architecture – High Level - GPP

A basic functional model of the overall ICaS system has been discussed to better understand the state-of-the-art technology and gaps for each system function. The system functions should be sufficient to serve the chosen use cases of Section 2.

The Figure 19 shows a “Functional View” on the preliminary system model.

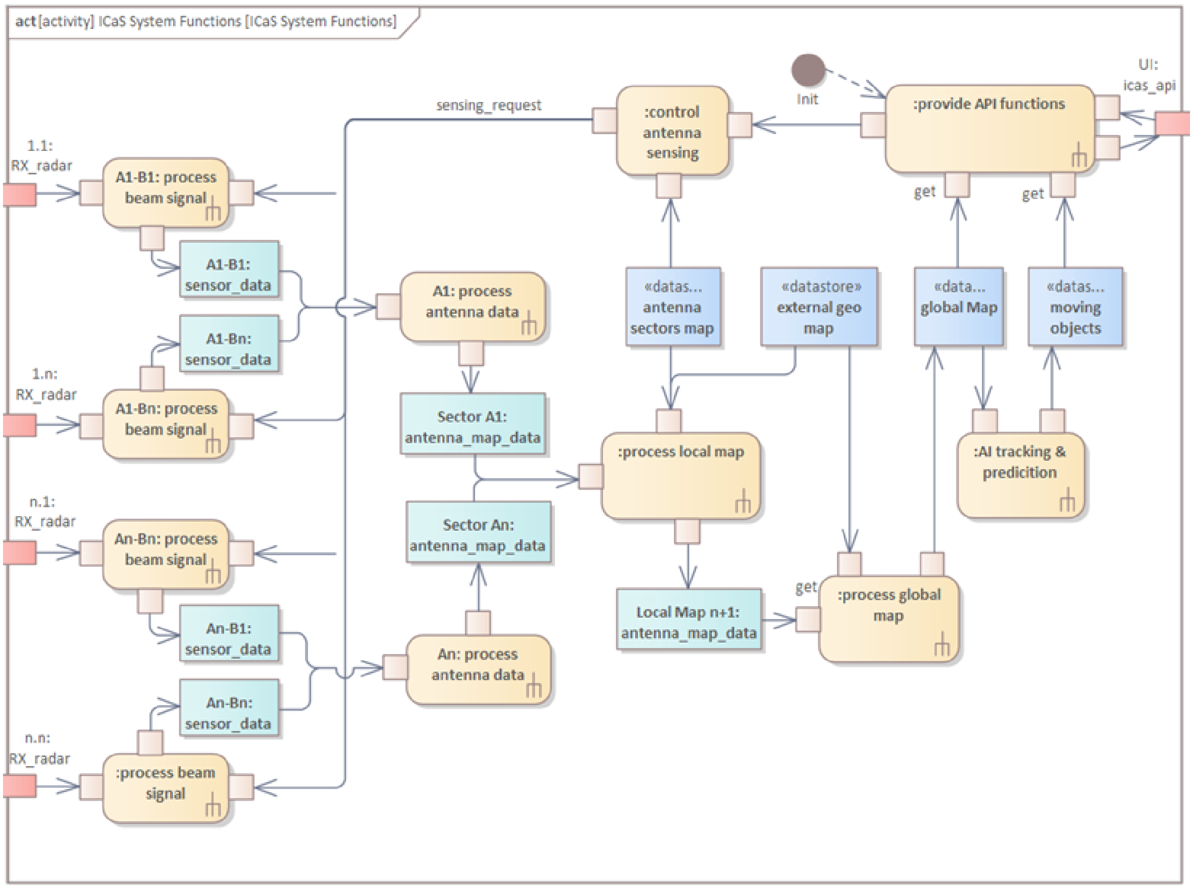


Figure 19. ICaS Functional System Architecture Concept.

The following text is a walk through the system functions discussing the technical aspects of each step as far as it can be envisioned today.

- The “ICaS_api” receives a request for sensing.
  - It is not yet clear how a complex network functionality like sensing will be exposed to the user to answer questions such as: Is the timing and quality of the expected result part of the request?
- The system function “provide_API_functions” analyses how to serve the API most efficiently.
  - Can multiple requests for the same area be combined? (datastore “Global Map”)
  - Is a prioritization required to avoid communication network overload by sensing requests?
- The function “control_antenna_sensing” activates the sensing of those antennas (TRPs), which cover the requested area.
  - How are those resources being managed which are also being used for communication?
  - How will new concepts look like for triangulation or multi-static sensing between antennas?
  - How to synchronize control across multiple antennas?
- The activation triggers the function “process_beam_signal” to receive reflected (radar) signals and evaluate them to provide the output “sensor_data” (e.g., object distance, angle, velocity).

    - How much analysis of the raw sensor data should be done already in the radio unit (RU)? (Especially the cost for processing power is a concern.)
    - How much control is possible -
        - To influence the sensing process (e.g., dedicated DL signals for sensing)?
        - To adjust the amount of processing by the RU (e.g., clutter removal Y/N)?
- The function "process antenna data" receives all sensor data of a single antenna. It needs to be decided what data processing is possible at that point, such as:
    - Mapping the sensor data to geo information.
    - Geo position of objects, velocity only in the direction of the antenna.
    - Consolidating information of overlapping antenna sections.
    - Tracking objects moving across multiple sections of the antenna (might be processed in the next step).
- The function "process local map" receives the data from multiple antennas. This position allows more complex processing of the sensor data, such as:
    - Consolidating the geo information of multiple antennas to one lager area.
    - Calculating the velocity vector over ground.
    - Tracking moving objects across multiple antennas.
    - Increase the accuracy of the location by triangulation.
    - Combining multiple antenna data for multi-static scenarios.
    - Apply AI algorithms to provide more valuable results from the sensed data (e.g., predict movement of objects).
- The function "process global map" aggregates the information from multiple local maps. This will enable sensing services for larger areas including:
    - Consolidating geo information of larger areas.
    - Tracking moving objects across multiple local maps.

This functional model just supports the analysis of the technical topics which need to be resolved during further activities of the KOMSENS-6G project. It is supposed to show those gaps which need to be addressed in the next steps, before starting the architectural concepts for the ICaS system.

4.5 ICaS Hardware System Model and Requirements (EAG)

ICaS is envisioned to support various use cases and satisfy different requirements. Each use case has its own assumptions on the hardware and supported features, and it can make the requirement analysis more challenging. Furthermore, the combination of communication and radar features into a single solution creates interdependencies and competing system parameters that can be challenging to analyze. Model-based system engineering (MBSE) is known to be quite helpful in modeling and optimizing complex multi-domain systems [38]and it should help the use case and requirement specification in this report.

An ICaS hardware model based on SysML [39] is presented in this report. Its structure is outlined in the diagram of Figure 20. The system structure model consists of four main packages:

1. 6G Site: the structure and behavior of an abstract 6G site are described.
2. Use Cases: use cases of interest and their stakeholders are specified.
3. Requirements: the requirements for each use case of interest and their connection to the 6G site structure are presented.

4. System Assumptions: the main system assumptions that help defining the system boundaries are outlined.

The EAG focus lies on the antenna structure to be detailed in the 6G Site.

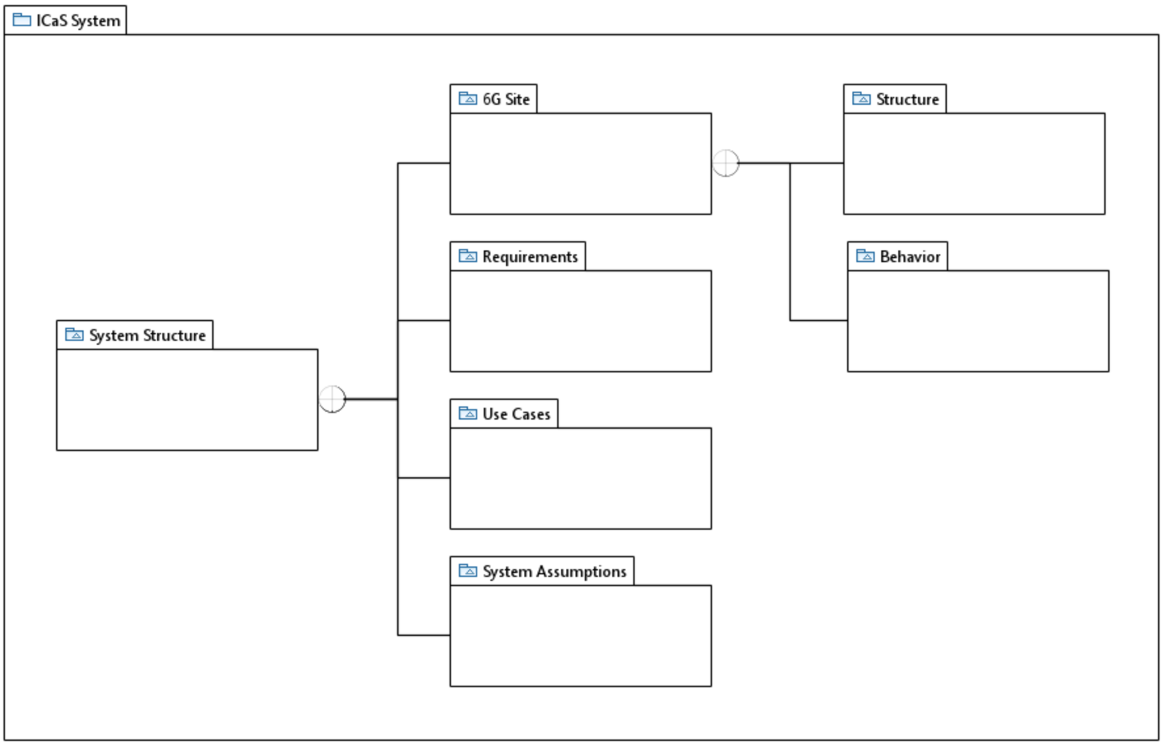


Figure 20. ICaS system structure.

The 6G Site model structure is presented in the block definition diagram (BDD) of Figure 21. The model includes one or more base stations, mobile terminals, sensing targets, and one wireless channel that connects all of them. The wireless channel block comprises, for example, the whole wireless medium including the communication links between all base stations and mobile terminals. Note that mobile terminals are not necessarily the sensing target. The base station block is itself modeled as a baseband unit that is connected to the core network, and some active antenna systems (AAS). The AAS and the baseband unit are connected for example through eCPRI interface.

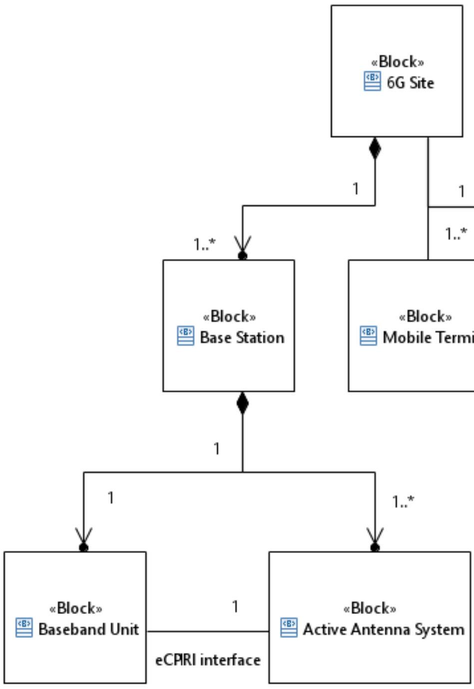


Figure 21. 6G Site Block Definition Diagram (BDD).

The Active Antenna System block structure is detailed in the BDD of Figure 22. It consists of three sub-systems: digital process unit, the radio front-end, and the antenna array. The radio front-end comprises various radio branches that connect the digital processing unit to the antenna array. The most relevant sub-system of the digital process unit is the Multicarrier Modulator. It offers key features to the Sensing and Communication modules. The interconnection between the AAS components is illustrated in the internal block diagram (IBD) in Figure 23. As seen in this diagram, the digital information is carried by Bitstream tokens while bandpass information is modeled by Bandpass signal tokens.

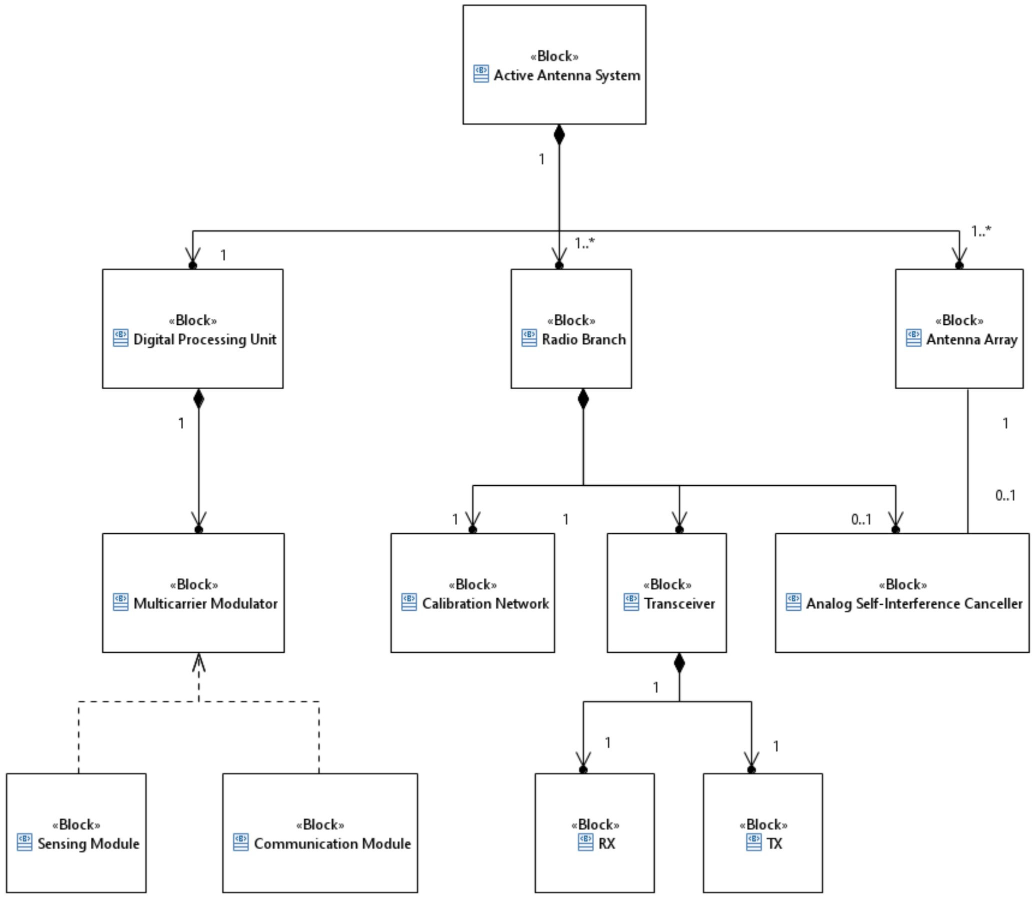


Figure 22. Active Antenna System BDD.

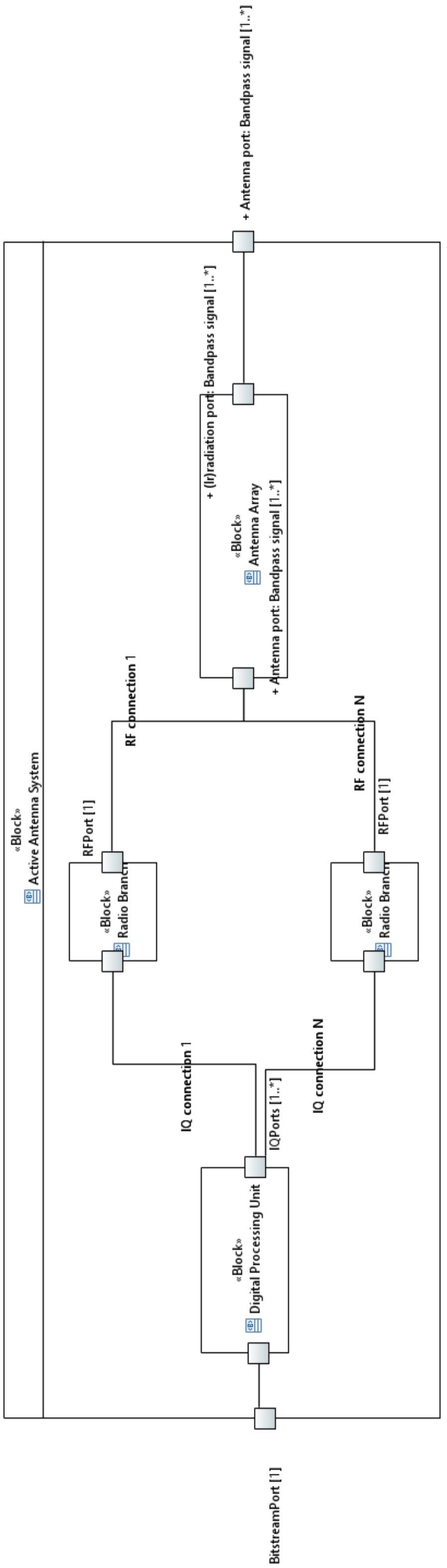


Figure 23. Active Antenna System Internal Block Diagram (IBD). The interconnect of the system parts is illustrated in this diagram.

Active Antenna System BDD. A more detailed Active Antenna System BDD is presented in Figure 24. There, the block attributes are also described. Furthermore, the communication part is organized in the left-hand part while the sensing part is arranged in the right-hand part of the diagram. The shared resources are placed in the central part of the diagram. Important performance indicators for the communication and sensing modules are also written as block constraints and shall be used to specify system requirements. Note that the presented antenna model is general enough to explore new concepts, e.g., multi-layering with multi-mode multi-port antenna radiators.

System assumptions are outlined in Figure 25. Simplifying assumptions regarding the sensing environment and the antenna architecture are presented.

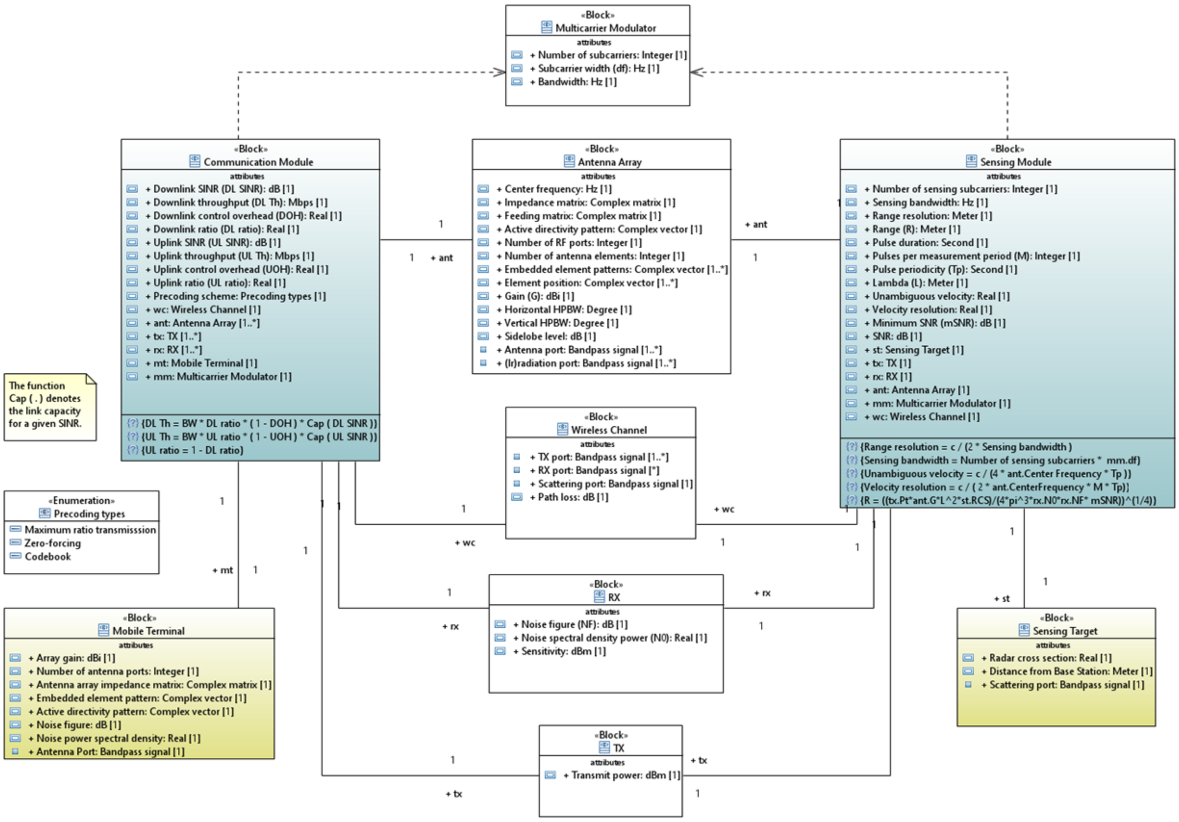


Figure 24. Detailed Active Antenna System BDD.

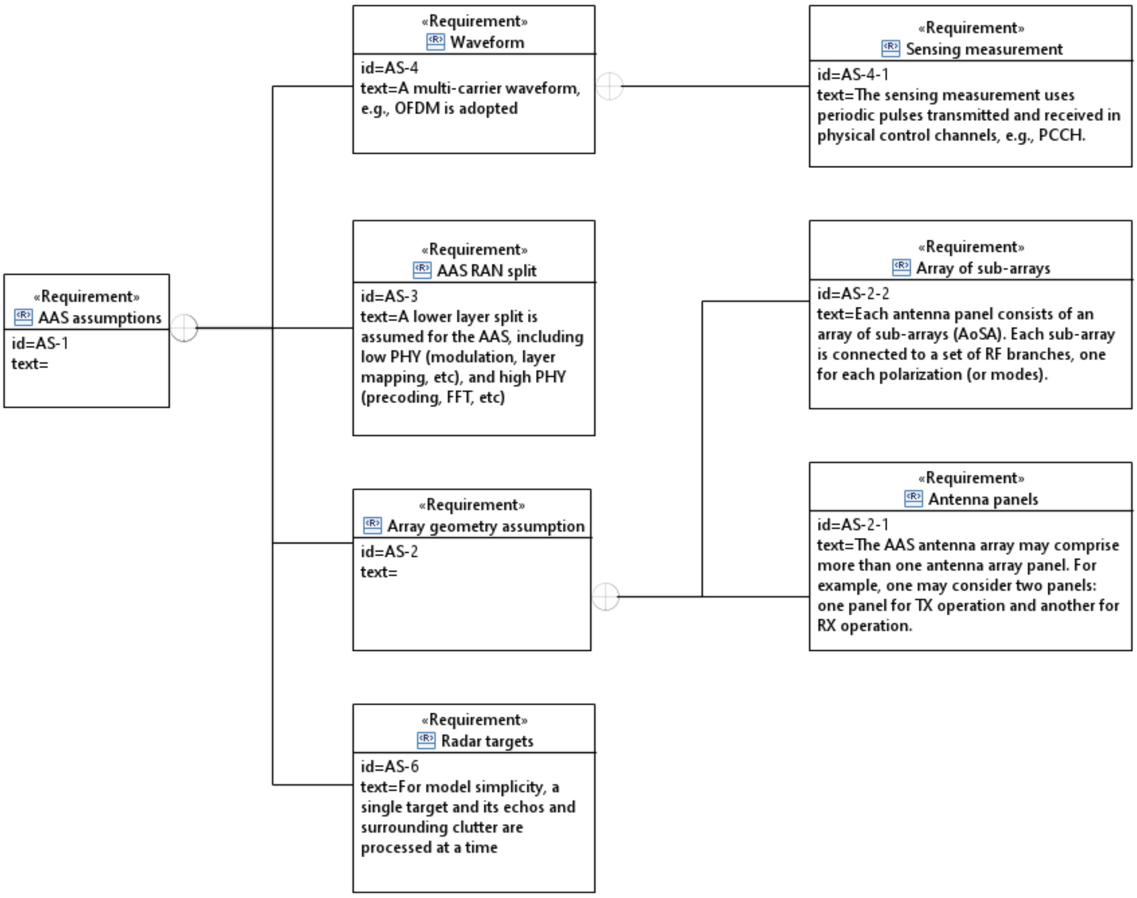


Figure 25. Active antenna system assumptions.

Detailed Active Antenna System Active antenna system assumptions. As an example of Use Case of Interest, the "Digital Twins for Manufacturing" use case [40] is considered. The corresponding use case diagram is shown in Figure 26. There, a Radio Access Technology (RAT) and a sensing API, as specified by GPP in Section 4.4, serve as system operators. While the RAT serves PHY channels and transmits reference signals to its user equipment, the sensing API uses the same reference signals to localize and sense scatterers. The requirements of this use case are illustrated in the Requirement diagram in Figure 27. They are organized in two groups: communications and sensing requirements. The communications requirement is merely illustrative and can be adapted or more detailed to better fit manufacturing requirements.

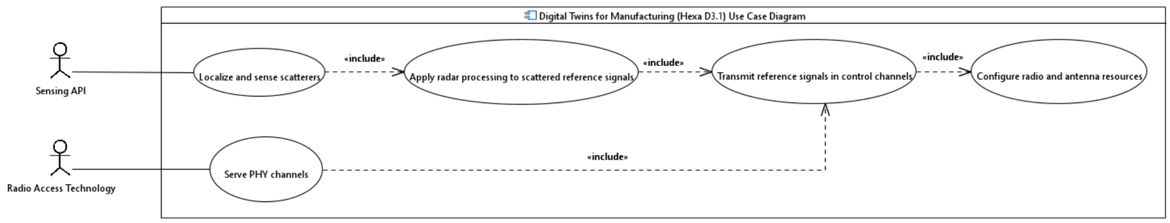


Figure 26. Use case diagram example.

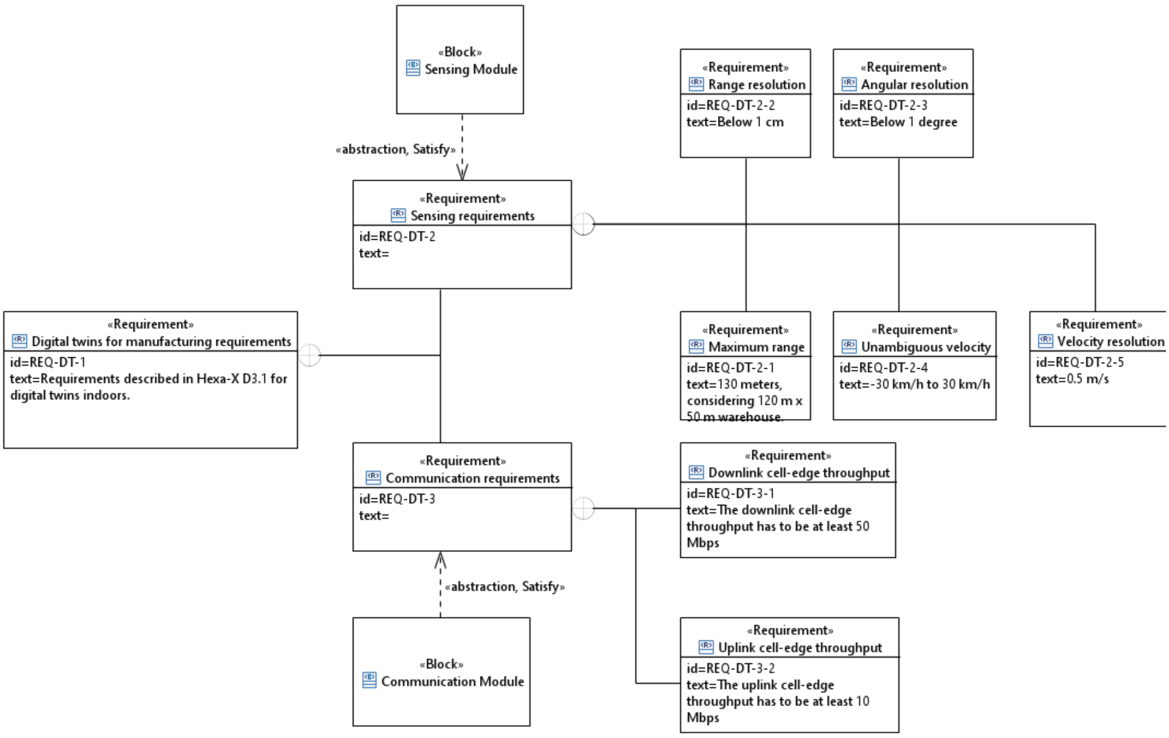


Figure 27. Use case requirements. Adapted from "Digital Twins for Manufacturing" from Hexa-X D1.3 [40].

Use case requirements. With the system model described in this section, it is now possible to have a holistic view on the ICaS hardware system interfaces and boundaries. Ongoing work focuses on implementing the hardware model in a numerical simulation environment to investigate the antenna parameter trade-off for the example use case. This investigation results shall be reported in WP3 of KOMSENS-6G.

5 Regulatory view on sensing

The usage of frequency bands licensed for mobile services are underlying the general provisions of the ITU-R Radio Regulations [41], respectively their national implementations (e.g., for Germany the "Frequenzverordnung") [42] and the provisions set by the national regulator as part of the dedicated frequency assignments. In Germany, the related assignment of frequency bands under consideration for integrated communication and sensing applications is for wireless network access to offer telecommunication services ("Drahtloser Netzzugang zum Angebot von Telekommunikationsdiensten"). In addition to telecommunication services also applications for network-internal operational and infrastructure purposes are allowed.

The ICaS approach envisages the usage of related frequency bands for both communication and sensing signals, ideally by signals that jointly support both purposes, e.g., reference signals that may be applied both for synchronization/demodulation/channel estimation across a DL/UL communication link as well as for sensing the environment of a base station and/or a UE. From that perspective, the incorporation of sensing in a mobile radio communication system is based on same principles as already used for positioning/localization services (LCS) specified by 3GPP, so there should be no restrictions for an MNO from a regulatory perspective, as long as the integrated sensing signals or jointly created ICaS signals comply with the operational and/or technical usage conditions, e.g., duplex frequency ranges, channel bandwidth, channel raster, out-of-band emissions, max allowed equivalent radiated power.

Based on that, the MNO may use the sensing operation for internal purposes, e.g., to improve the offered communication services (“sensing-assisted communication”) and/or may also offer commercial services based on the sensing operation aka “Sensing as a Service” (SaaS) for his communication customers or 3rd parties. Dependent on MNO’s policies and regulatory conditions that may impact the policies (considering applications offered e.g., in case of mission-critical services), the 6G network should be able to flexibly (de-)activate and configure sensing transmissions/receptions, ideally jointly incorporated with communication services, in a local area, i.e., for a single or some selected TRPs only, or in the whole coverage area under its responsibility.

Further aspects that need to be fulfilled are on confidentiality, integrity, and privacy (see also Section 3). Involving UEs for sensing purposes and/or combining UE-independent sensing with UE information requires an extension of the already existing user consent approach. Furthermore, dependent on the sensing use case, there may be the need for the MNO to encrypt and integrity protect the sensing data and/or results of sensing data processing within the network. Sensing results may also be offered to authorized and trusted 3rd parties via secured network exposure interfaces (e.g., APIs).

Figures

Tables

References

[1] A. J. Zhang, M. L. Rahman, K. Wu, X. Huang, Y. J. Guo, S. Chen and J. Yuan, "Enabling joint communication and radar sensing in mobile networks—A survey," *IEEE Communications Surveys & Tutorials,* pp. 306-345, 2021.

[2] F. Liu, Y. Cui, C. Masrouros, J. Xu, X. H. Tony, Y. C. Eldar and S. Buzzi, "Integrated sensing and communications: Towards dual-functional wireless networks for 6G and beyond," *IEEE journal on selected areas in communications,* 2022.

[3] 3GPP, "TR 22.837 Feasibility Study on Integrated Sensing and Communication," 2023.

[4] one 6G, "6G Vertical Use Cases," 2022.

[5] G. Yammine, G. Kontes, N. Franke, A. Plinge and C. Mutschler, "Efficient Beam Search for Initial Access Using Collaborative Filtering," in *IEEE Wireless Communications and Networking Conference (WCNC)*, 2023.

[6] U. Demirhan and A. Alkhateeb, "Radar aided 6G beam prediction: Deep learning algorithms and real-world demonstration," in *2022 IEEE Wireless Communications and Networking Conference (WCNC)*, 2022.

[7] G. Charan, A. Hredzak and A. Alkhateeb, "Millimeter Wave Drones with Cameras: Computer Vision Aided Wireless Beam Prediction," in *arXiv preprint arXiv:2211.07569*, 2022.

[8] A. M. Campo, "On the Design of Fly's Eye Lenses at Sub-THz Frequencies for Wideband Communications," 2021. [Online]. Available: https://doi.org/10.4233/uuid:a9bb41e0-3d2a-4028-a218-bd85f2053545.

[9] European Commussion, "Rolling Plan for ICT standardisation - U-SPACE," [Online]. Available: https://joinup.ec.europa.eu/collection/rolling-plan-ict-standardisation/u-space-0. [Accessed 15 June 2023].

[10] Dedrone, "Dedrone," [Online]. Available: https://de.dedrone.com/. [Accessed 15 June 2023].

[11] Fraunhofer FHR, "Drone in flight?," [Online]. Available: https://www.fhr.fraunhofer.de/en/businessunits/security/Drone-in-flight-jb2020.html. [Accessed 15 June 2023].

[12] Statista.com, "Prognose der Anzahl weltweit ausgelieferter kommerziell genutzter Drohnen in den Jahren 2016 bis 2025," [Online]. Available: https://de.statista.com/statistik/daten/studie/810172/umfrage/prognostizierte-auslieferungen-kommerzieller-drohen-weltweit/?locale=de. [Accessed 15 June 2023].

[13] European Commission, "A Drone Strategy 2.0 for a Smart and Sustainable Unmanned Aircraft Eco-System in," 2022.

[14] "Bundesverkehrsministerium gegen organisierte Kriminalität," Springer Fachmedien München - Verkehrs Rundschau, 24 October 2014. [Online]. Available: https://www.verkehrsrundschau.de/nachrichten/transport-logistik/bundesverkehrsministerium-gegen-organisierte-kriminalitaet-2998625. [Accessed 2023].

[15] M. Cordes, "Auf der Spur der Frachtdiebe," Springer Fachmedien München - Trucker, 30 May 2018. [Online]. Available: https://www.trucker.de/nachrichten/recht/auf-der-spur-der-frachtdiebe-2431897. [Accessed 2023].

[16] Y. Tao, H. Azril, S. Kentaro, I. Ryosuke, K. Ryouta, K. Yusuke, T. G. Khanh, T. Jun-ichi and S. Kei, "A Guide of Fingerprint Based Radio Emitter Localization Using Multiple Sensors," *IEICE Transactions on Communications,* vol. E101.B, pp. 2104-2119, 2018.

[17] J. M. Fresno, G. Robles, J. M. Martínez-Tarifa and B. G. Stewart, "Survey on the performance of source localization algorithms," *Sensors,* vol. 17, no. 11, p. 2666, 2017.

[18] Hexa-X , "Deliverable D3.2 Initial models and measurements for localisation and sensing," 2022.

[19] Y. Song, W. Taylor, Y. Ge, M. Usman, M. A. Imran and Q. H. Abbasi, "Evaluation of deep learning models in contactless human motion detection system for next generation healthcare," *Scientific Reports,* December 2022.

[20] European Union Agency for Railways, "Report on Railway Safety and Interoperability in the EU," Publications Office of the European Union, 2022.

[21] A. K. Kyatsandra, R. K. Saket, S. Kumar, K. Sarita, A. S. S. Vardhan and A. S. S. Vardhan, "Development of TRINETRA: A Sensor Based Vision Enhancement System for Obstacle Detection on Railway Tracks," *IEEE Sensors Journal,* vol. 22, no. 4, pp. 3147-3156, 2022.

[22] D. Ristić-Durrant, M. A. Haseeb and D. Nikolić, "SMART on-board multi-sensor obstacle detection system for improvement of rail transport safety," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit.,* vol. 6, no. 236, pp. 623-636, 2022.

[23] W. Zhangyu, Y. Guizhen, W. Xinkai, L. Haroan and L. Da, "A Camera and LiDAR Data Fusion Method for Railway Object Detection," *IEEE Sensors Journal,* vol. 21, no. 12, pp. 13442-13454, 2021.

[24] E. Ushakov, "Škoda cars now warn drivers of approaching trains at railway crossings," Autoua.net, [Online]. Available: https://autonews.autoua.net/en/novosti/32026-skoda-cars-now-warn-drivers-approaching-trains-railway-crossings.html. [Accessed 15 June 2023].

[25] Gaussin, "AGV PERFORMANCE," Gaussin, [Online]. Available: https://www.gaussin.com/agv-p. [Accessed 14 June 2023].

[26] Konecranes, "Automated Guided Vehicles," [Online]. Available: https://www.konecranes.com/port-equipment-services/container-handling-equipment/automated-guided-vehicles. [Accessed 14 June 2023].

[27] Hamburger Hafen und Logistik Aktiengesellschaft, "Strom statt Diesel," Hamburger Hafen und Logistik Aktiengesellschaft, [Online]. Available: https://hhla.de/innovation/batterie-agv. [Accessed 14 June 2023].

[28] H. Durarant-Whyte and T. Bailey, "Simultaneous localization and mapping: part I,," *IEEE Robotics & Automation Magazine,* vol. 13, no. 2, pp. 99-110, 2006.

[29] Statista, "Autonomous guided vehicle market volume worldwide from 2019 to 2025," [Online]. Available: https://www.statista.com/statistics/882706/global-agv-market-value/. [Accessed 14 June 2023].

[30] ABB, "ABB to electrify autonomous vehicles for new port in Singapore," ABB, 2019. [Online]. Available: https://new.abb.com/news/detail/35893/abb-to-electrify-autonomous-vehicles-for-new-port-in-singapore. [Accessed 14 June 2023].

[31] Hexa-X, "Deliverable D3.1 Localisation and sensing use cases and gap analysis," 2021.

[32] RHENUS, "RHENUS - YOUR LOGISTICS PROVIDER IN GERMANY," [Online]. Available: https://www.rhenus.group/de/en/. [Accessed 15 June 2023].

[33] European Parliament and European Council, "DIRECTIVE 2014/53/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 April 2014 on the harmonisation of the laws of the Member States relating to the making," 2014.

[34] C. Chwala and H. Kunstmann, "Commercial microwave link networks for rainfall observation: Assessment of the current status and future challenges," *Wiley Interdisciplinary Reviews: Water 6,* 2019.

[35] OpenSense - COST Action CA20136, "OpenSense - COST Action CA20136 - Opportunistic precipitation sensing network," [Online]. Available: https://opensenseaction.eu/. [Accessed 15 June 2023].

[36] European Environmnent Agency, "Economic losses from climate-related extremes in Europe (8th EAP)," European Environmnent Agency, [Online]. Available: https://www.eea.europa.eu/ims/economic-losses-from-climate-related. [Accessed 15 June 2023].

[37] A. Kadelka, G. Zimmermann, J. Plachy and O. Holschke, " A CSP's View on Opportunities and Challenges of Integrated Communications and Sensing," in *IEEE International Symposium on Joint Communications & Sensing*, 2023.

[38] J. A. Estefan, "Survey of model-based systems engineering (MBSE) methodologies," *Incose MBSE Focus Group,* vol. 25, no. 8, 2007.

[39] S. Fridenthal, A. Moore and R. Steiner, A practical guide to SysML: the systems modeling language, Morgan Kaufmann, 2014.

[40] Hexa-X, "Deliverable D1.3 - Targets and requirements for 6G - initial requirements," 2022.

[41] ITU-R, "Radio Regulations," [Online]. Available: https://www.itu.int/pub/R-REG-RR. [Accessed 15 June 2023].

[42] Bundesnetzagentur, "Frequenzverordnung," [Online]. Available: https://www.bundesnetzagentur.de/DE/Fachthemen/Telekommunikation/Frequenzen/Grundlagen/Frequenzverordnung/start.html. [Accessed 15 June 2023].

[43] VDE ITG, "Joint Communications & Sensing," 2022.

[44] G. Charan, A. Hredzak, C. Stoddard, B. Berrey, M. Seth, H. Nunez and A. Alkhateeb, "Towards Real-World 6G Drone Communication: Position and Camera Aided Beam Prediction," in *IEEE Global Communications Conference 2022*, 2022.

[45] Bundesnetzagentur für Elektrizität, Gas,Telekommunikation, Post und Eisenbahnen , "Frequenzzuteilung," [Online]. Available: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Telekommunikation/Unternehmen_Institutionen/Frequenzen/OffentlicheNetze/VergabeverfDrahtloserNetzzugang2010/Frequenzversteigerung2010/FreqZuteilung800MHz1010221.pdf?__blob=publicationFil. [Accessed 15 June 2023].

KOMSENS-6G

Work Package 3

Milestone 1
"State-of-the-Art (SotA) and gap analysis"

KOMSENS-6G WP3: Milestone 1 Deliverable

Table of Contents

Overview

Work package 3 is subdivided into two task groups, being T3.1 RF Design and T3.2 Baseband Signal Processing. Task group T3.1 is responsible for the Hardware decisions and concepts regarding the RF Front-End, while task group T3.2 is responsible for baseband signal processing such as waveform analysis, parameter estimation and tracking.

The following document will give an overview of the topics investigated by the task groups and partners. Each topic is introduced by prior art on the topic, followed by the gaps addressed and an overview of references.

T3.1 RF Design (LUH, IMST, EAG, BI, GPP, NOK, R&S)

1 Antenna Design and Architecture (LUH, IMST, EAG)

1.1 Modal Analysis and Design of M3PA Element (LUH)

The theory of characteristic modes [1], in detail the Characteristic Mode Analysis (CMA), allows the realization of multiple uncorrelated antenna ports per antenna element. In [2] a 6-port Multi-Mode Multi-Port Antenna (M^3PA) is realized, enabling 6 uncorrelated port patterns which can be used simultaneously for different tasks e.g., sending and transmitting communication and sensing signals. By utilizing this antenna concept for Joint Communication and Sensing (JCAS), it results in a wide range of possibilities regarding antenna array configuration and signal distribution due to the additional modal domain.

While in [2] a square patch antenna element of size $\lambda \times \lambda$ is used, the first research in this project is related to the miniaturization of the single antenna element. The influence of the substrate on the characteristic modes of a patch and mode selective frequency shifting techniques by modifying the antenna structure will be evaluated. In addition to patch antennas, also other types should be investigated, like slot or aperture antennas. An antenna catalog will be derived, listing the different antenna types with their advantages and disadvantages. Further, this catalog will present an overview of the investigated antenna types to assign them to the use cases derived by WP2. The individual antenna types are assigned based on their advantageous properties in the use cases.

<u>References:</u>

[1] R. Harrington and J. Mautz, "Theory of characteristic modes for conducting bodies," in IEEE Transactions on Antennas and Propagation, vol. 19, no. 5, pp. 622-628, September 1971, doi: 10.1109/TAP.1971.1139999.

[2] N. Peitzmeier, T. Hahn, and D. Manteuffel, "Systematic Design of Multimode Antennas for MIMO Applications by Leveraging Symmetry," in IEEE Transactions on Antennas and Propagation, vol. 70, no. 1, pp. 145-155, Jan. 2022

1.2 Antenna Architectures for Sensing and Communication (EAG)

The characteristic mode analysis can give more insights into the resonance and radiation behaviour of arbitrarily shaped structures. In the past we have followed the achievements in this domain, and have found it very useful in the industrial antenna design for base stations. Contributions to academic conferences focused on the antenna element [1], the array [2] and multiband array behaviour [3] have been made.

Modern 5G antennas are highly integrated and complex systems. The extension of their features to include radar capabilities in 6G is quite complex, therefore a methodological model-based system engineering (MBSE) approach can help to simplify the design of an integrated communication and sensing (ICaS) system. The application of MBSE methodologies to antenna design is rather unexplored. A phased-array design and optimization methodology that incorporates system requirements using MBSE methodologies is presented in [4]. However, this work does not provide an abstract antenna system model describing the antenna system structure and behavior and how it connects to the requirements. The full potential of MBSE for antenna systems remains to be investigated.

To exploit the existing and future antenna architectures for ICaS, it is of interest to determine which antenna modes shall be used for sensing and which ones for communication. On top of that, how a suitable partitioning of antenna modes can best cover both functionalities. Furthermore, it is yet unknown if additional modes can be utilized to increase the sensing performance. Within KomSens, we want to tackle the increasing number of modes for large antenna arrays, their possible and optimal combination in subarrays and subsequently their optimal feeding possibilities.

To describe the antenna architecture and behavior with state of the art model based system engineering methods, we develop a holistic ICaS antenna system model in WP2 together with GPP. In WP3, we intend to implement the ICaS antenna system in computational simulation environment, e.g., Modelica, Simulink. This will allow us to experiment with the multi-mode partitionining idea, optimize the antenna system and quickly verify its conformance to the requirements specified in WP2.

References:

[1] J. E. Bauer and P. K. Gentner, "Characteristic Mode Analysis of a Circular Polarised Rectangular Patch Antenna,"*13th European Conference on Antennas and Propagation (EuCAP)*, Krakow, Poland, 2019.

[2] P. K. Gentner, "On the Use of Characteristic Mode Analysis for the Design of Antenna Arrays," *14th European Conference on Antennas and Propagation (EuCAP)*, Copenhagen, Denmark, 2020.

[3] P. K. Gentner and M. Pietzka, "Base Station Antenna Array Design with Characteristic Mode Analysis," *15th European Conference on Antennas and Propagation (EuCAP)*, Dusseldorf, Germany, 2021.

[4] Pyry Salonpää, "Model-based systems engineering approach in phased antenna array design and optimization", Master Thesis, University of Oulu, July 2021.

1.3 D-Band Antenna and Front-End Integration (IMST)

The large bandwidth available at sub-THz frequencies enables high-speed communications as well as high-resolution sensing [1]. However, high propagation spreading and low output power in the active devices at these high frequencies need to be compensated with antennas providing high gain. The resulting small antenna opening angles lead as well to the necessity of antennas with steering and/or multi-beam capabilities.

Classical arrays with half-wavelength spacing are mostly used at Ku- and Ka-band to tackle high Equivalent Isotropic Radiated Power (EIRP) [2]. However, the required integration density is not reachable at sub-THz. While passive structures scale down with smaller wavelengths, the size of active devices does not follow this trend. Lens arrays have been proposed in the literature to address this problem [3], but no integrated active front-end has been presented yet at frequencies higher than 100 GHz, following this concept.

In this project, an active lens array at D-band (110-170 GHz) with beam steering and beam forming capabilities will be developed for the first time, supporting communication and sensing. The antenna front-end will allow the generation of multiple simultaneous beams pointing at different angles, with adjustable opening angle and EIRP values. The integration concept for the active front-ends of the multi-feed lenses as well as the thermal management will be some of the main challenges.

References:

[1] Guangjian Wang et al., “Terahertz Sensing and Communication Towards Future Intelligence Connected Networks”, *Communications of Huawei Research*, September 2022.

[2] W. Simon et al., "Highly Integrated Ka-Band Frontend Module for SATCOM and 5G," *2019 IEEE Asia-Pacific Microwave Conference (APMC)*, Singapore, 2019, pp. 441-443.

[3] S. Bosma, N. Van Rooijen, M. Alonso-Delpino, M. Spirito and N. Llombart, "First Demonstration of Dynamic High-Gain Beam Steering With a Scanning Lens Phased Array," *in IEEE Journal of Microwaves*, vol. 2, no. 3, pp. 419-428, July 2022.

2 Antenna Decoupling and Self-Interference Cancellation (BI, LUH, GPP, NOK)

2.1 Antenna Element Decoupling Using Electromagnetic Bandgap Structures (BI)

The mutual coupling issue between antennas has been comprehensively addressed in the literature with respect to E- and H-plane coupling [1] which can be tackled using active circuitry solutions. However, active elements will be inefficient and difficult to deploy in battery-driven devices for future 6G joint communication and sensing (JC&S) because they tend to increase the complexity of the entire system while consuming more power. Therefore, BI will focus on passive solutions first that will eliminate the need for external power to achieve relatively higher isolation between transmitting (TX) and receiving (RX) antennas. BI has extensively studied numerous techniques based on passive elements to mitigate the mutual coupling between antennas and derived the advantages and disadvantages of each technique [2]. Recently, integration of the electromagnetic bandgap (EBG) based metasurfaces has become increasingly important because of their capacity to boost the isolation by 20 dB or more in narrowband antennas.

In our research, we will discuss the feasibility of passive EBG antennas to achieve relatively higher TX-RX isolation. Particularly, we will thoroughly investigate different EBG as well as other passive structures to achieve isolation ≥30 dB for narrowband and wideband operation in the 802.11bf (5.9-7.2 GHz), X-band (8-10 GHz) and 5G NR bands (26-28 GHz) with bandwidths ranging 100 MHz -1 GHz. Another important aspect that will be taken into consideration is the fabrication tolerance because in our recent study, the simulated and measured isolation results depicted notable differences as the designed metasurface-based passive antennas were dependent on a particular parameter value. Single antenna solutions, where the transmitter and receiver share a single antenna through electrical balance duplexers (EBD) are another alternative for the full duplex system implementations [3]. Single ended and differential EBD structures in combination with different wideband antennas will be designed and implemented. PCB solutions will be provided to enable the low-cost implementation of numerous approaches in X-band. A comparison of their advantages and disadvantages with two-element antennas will follow. Finally, the developed designs will be used to estimate the system-level simulations showing the effect of low and high isolation. As part of work package 6, these antennas will be used in JC&S demonstrators/testbeds to evaluate the enhancement of key performance indicators for communication and object detection use cases.

References:

[1] D. M. Pozar, "Input impedance and mutual coupling of rectangular microstrip antennas," IEEE Transactions on Antennas and Propagation, vol. 30, no. 6, pp. 1191–1196, 1982.

[2] M. T. Yalcinkaya, P. Sen, and G. Fettweis. "Comparative analysis of antenna isolation characteristic with & without self-interference reduction techniques towards in-band full-duplex operation." IET Microwaves, Antennas & Propagation (2023).

[3] B. van Liempd et al., "2.2 A +70dBm IIP3 single-ended electrical-balance duplexer in 0.18um SOI CMOS," 2015 IEEE International Solid-State Circuits Conference - (ISSCC) Digest of Technical Papers, San Francisco, CA, USA, 2015, pp. 1-3, doi: 10.1109/ISSCC.2015.7062851.

2.2 Antenna Array Decoupling (LUH)

Antenna elements placed in an array couple to each other, due to near-field and far-field coupling as well as surface wave coupling [1-2]. At small distances between the antenna elements, near-field coupling should be considered, while at larger distances far-field coupling becomes more important due to the lower decrease of the field amplitude with increasing distance ($\sim \rho^{-1}$). At even larger distances, and especially with thicker substrates and higher permittivity, surface wave coupling becomes dominant [1-2]. These are some of the main problems that occur with conventional antenna arrays and need to be compensated to not decrease the performance of the array. Previously, decoupling techniques have been derived for mobile handset antennas, which can be adopted for base station antenna arrays [3].

In a first step the mutual coupling of conventional antenna arrays will be investigated and compared to literature results. In addition to this research and initial classification of the dependencies of the various coupling mechanisms, the coupling of M^3PA-arrays will be considered and advantages and disadvantages for certain use cases will be shown. In a next step, parameters and bounds of the investigated arrays will be summarized and added to the antenna catalog.

References:

[1] C. Wang, E. Li and D. F. Sievenpiper, "Surface-Wave Coupling and Antenna Properties in Two Dimensions," in IEEE Transactions on Antennas and Propagation, vol. 65, no. 10, pp. 5052-5060, Oct. 2017, doi: 10.1109/TAP.2017.2738030.

[2] C. A. Balanis, "Antenna Theory - Analysis and Design," 3rd Edition. John Wiley & Sons, 2005, ISBN: 9780471667827.

[3] Y. Chen and D. Manteuffel, "A Tunable Decoupling and Matching Concept for Compact Mobile Terminal Antennas," in IEEE Transactions on Antennas and Propagation, vol. 65, no. 4, pp. 1570-1578, April 2017.

2.3 Array Partitioning and Beamforming (LUH)

Besides the studies of mutual coupling, the beamforming behavior of the array to be designed is of major interest. While for decoupling purposes the elements distance should be increased, increasing the distance will worsen the beamforming behavior due to the occurrence of grating lobes [1]. In general, a tradeoff for both parameters must be selected.

To characterize conventional arrays with respect to their beamforming performance, the array factor using pattern multiplication can be used (neglecting coupling). This allows a first approximation of the number of required antenna elements to realize a defined gain, Half-Power Beamwidth (HPBW) and angular coverage.

While for conventional arrays the array factor is an important quantity to characterize the beamforming performance, for M^3PA-arrays this kind of array factor is not sufficient. Besides the separation in the spatial domain, due to the spatial arrangement of the antenna elements, M^3PA-arrays offer a higher degree of freedom by additionally using the modal domain. An important step towards this topic will be the expansion and extension of the array factor to a more generalized definition also including the modal domain and taking mutual coupling into account.
Furthermore, partitioning the array by defining sub-arrays as well as virtually layered arrays will be investigated e.g., to decrease coupling between sensing arrays in transmit and receive mode. For different arrays the beamforming performance and partitioning will be summarized and added to the antenna catalog.

References:

[1] R. C. Hansen, "Phased Array Antennas," 2nd Edition. John Wiley & Sons, 2009, ISBN 0470401028.

2.4 Wideband Hybrid Self-Interference Cancellation (GPP)

Wideband Self-Interference (SI) should be efficiently mitigated to enable joint communication and sensing. Due to wideband frequency-selective fading, dynamic propagation reflections exist. There is a need for the interpretation of which reflections to adaptively delete and how to capture the useful echo reflection for the sensing information (e.g., distance, velocity). In the sequel, the state-of-art and its limits are analyzed:

- The state-of-art is about narrow band Self-Interference Canceller (SIC) for joint communication and sensing
- The existing wideband solution (e.g., Kumu) may not preserve the useful echo reflection
- Wideband (e.g., >=100 MHz) RF SIC canceller is critical for 6G

By analyzing self-interference and sensing echo, crucial SIC challenges are:

- High ADC dynamic range should be considered
  - E.g., the dynamic range of 14 bits AD 9683 is (11-2)*6.02 = 54 dB, where the efficient bits are 11
  - Thus, practical ADC 9683 can handle signal below -59 dBm w.r.t. 5 dBm Tx power
- Similarly, practical LNA can handle signals below -30 dBm in general
- How many taps should be experimentally calibrated for efficiently wideband reflection mitigation
  - Kumu K6 has 11 taps
  - 4 taps for 10 MHz flat fading channel in Kumu K6
  - More taps for increasing signal bandwidth
- In order to reduce the interference below the noise floor, we need additional digital cancellation

To address the problems, the main SIC requirements and main contributions are expressed as

- Design digitally control (math- and AI-based) algorithms for the wideband RF SIC
- Investigate hybrid (i.e., RF and digital) SIC canceller solution for better SIC
- Reflections must be deleted by SIC while sensing echoes are preserved
- Analog SIC must fall in ADC dynamic range
    - Approximately 60 dB self-interference should be removed in the analog domain to prevent saturation of 14 bits AD 9683
    - Isolation between Tx and Rx antennas is 30 dB and 50 dB for FR1 and FR2, respectively
- Define efficient calibration procedures for Kumu K6
- Design of 2x2 MIMO SIC Testbed
- Concept study for wideband RF SIC circuit (opt.)

References:

[1] Bharadia, Dinesh, Emily McMilin, and Sachin Katti. "Full duplex radios." ACM SIGCOMMComputer Communication Review 43.4 (2013): 375-386.

[2] Kumu Networks. " K6 Cancellation Module Product Brief v9." https://kumunetworks.com/wp-content/uploads/2022/06/K6-Analog-Cancellation-Module-Product-Brief-v9.pdf

2.5 System Analysis for Full-Duplex Concepts (FD) for Sensing (NOK)

Full duplex operation mode is frequently discussed in standardization for sub band full duplex SBFD considering only sub band FD is reflecting the enormous isolation challenges of concurrent transmit and receive operational mode in telecommunication context. This applies for FR1 and FR2 frequency region.

ICAS requires by concept FD in a monostatic radar approach without a considerable increase in HW costs.

The sensing approach may offer different HW architectures and concepts which are evaluated, and minimum isolation requirements/assumptions are defined to outline a plausible TX/RX isolation budget for wideband channels. Knowing the exact transmit signal may be leveraged while additional feedback receiver is considered in the architecture for a hybrid linear/nonlinear SIC approach. FR2 region may have the advantage to use a different TX / RX antenna array or panel concept for further RF isolation. Considering intelligent RX beamforming nulling towards dominant and saturating echo's is a further idea towards a required minimum isolation.

The isolation concept study is preparing Nokia's WP6 experimental research where in particular SIC requirements and market options are studied.

References:

[1] https://www.microwavejournal.com/articles/37607-boosting-5g-network-performance-using-self-interference-cancellation

[2] XIANGHUI HAN "Interference Mitigation for Non-Overlapping Sub-Band Full Duplex for 5G-Advanced Wireless Networks" https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9992227

[3] https://www.microwavejournal.com/articles/32394-kumu-networks-announces-ku1500-rfic-evaluation-board-availability

3 ICaS Antenna System Performance Evaluation and Antenna Characterization (EAG, R&S)

3.1 Raytracing-Based Evaluation of ICaS Antenna System Performance (EAG)

System-level evaluation of mobile communication systems has been traditionally done using stochastic simulators. Besides providing an analytical tractable framework, stochastic simulators, such as [1], can simulate large-scale networks and provide fairly good models for the most important electromagnetic propagation mechanisms. Deterministic approaches, e.g., raytracing simulations [2], [3], are more suited for radar-based technologies like ICaS. This is because the ICaS model quality strongly depends on fine details of virtual maps, e.g., terrain, buildings, and foliage. Therefore, the development of accurate system-level evaulation methodologies of ICaS system remains an open challenge.

In order to benchmark ICaS antenna systems, it is necessary to build up a digital twin based on reference scenarios. The reference scenarios are chosen from the use case analysis, where we focus on the detection of large objects such as trains and buses. High-quality maps and an accurate description of the environment are needed to build the foundation of an ICaS digital twin. Proprietary software tools so far cover the quality-of-service aspect for a given antenna and scenario, but not the quality-of-sensing.

In addition, the environment cannot be considered static anymore and an evaluation of the dynamic behavior of ICaS systems is necessary.

References:

[1] M. K. Müller and F. Ademaj and T.Dittrich and A. Fastenbauer and B. R. Elbal and A. Nabavi and L. Nagel and S. Schwarz and M. Rupp, “Flexible multi-node simulation of cellular mobile communications: the {Vienna 5G System Level Simulator”, EURASIP Journal on Wireless Communications and Networking, 2018

[2] Ansys 2023 R1, HFSS, SBR+, https://www.ansys.com

[3] Feko 2022 – WinProp, https://altair.com/feko

3.2 Antenna Characterization (R&S)

Antennas are a fundamental part of communication systems on the device and radio infrastructure side to enable data transmission over the air. The same applies for sensing applications known from current automotive radar implementations. Enabling both within the same technology resonates with new antenna development approaches, such the potential of using multi-mode multi-port antennas (M^3PA).

Any new antenna technology performance needs to be objectively measured and evaluated in order to access the potential in particular with focus on a joint support for communication and sensing applications. Antenna performance will be assessed in terms of antenna pattern verification for multiple target configurations and potentially for multiple frequency bands.

4 Demonstrator Concepts and Component Design (LUH, IMST)

4.1 Demonstrator Concept Based on Application Specification (LUH)

A non-negligible step towards constructing the final demonstrator(s) is the realization and design of a feed network. This design can be a challenging task due to the high number of available antenna ports [1,2]. Depending on the use case, different specifications and requirements need to be fulfilled, resulting in different feed topologies and methods. Some of the most relevant configuration methods are individual port configuration of the total array to offer the highest amount of configurability or hard wiring to decrease complexity of the feed structure.

In this topic the feed topology depending on the use case will be investigated. Further, the setup of the radio frequency (RF) link chain will be elaborated. The control signals will be generated using Universal Software Radio Peripherals (USRPs). For higher frequencies of interest, depending on the use case, mixers are used for upconverting the RF signals. The RF frontend is followed by the signal distribution network, whereby in this topic concepts for the signal distribution will be evaluated. Based on the fundamentals derived from the above topics and the created antenna catalog concepts for the design of the final demonstrator(s) will be elaborated.

References:

[1] N. Peitzmeier, T. Hahn, and D. Manteuffel, "Systematic Design of Multimode Antennas for MIMO Applications by Leveraging Symmetry," in IEEE Transactions on Antennas and Propagation, vol. 70, no. 1, pp. 145-155, Jan. 2022

[2] D. Manteuffel and R. Martens, "Compact Multimode Multielement Antenna for Indoor UWB Massive MIMO," in IEEE Transactions on Antennas and Propagation, vol. 64, no. 7, pp. 2689-2697, July 2016, doi: 10.1109/TAP.2016.2537388.

4.2 D-Band Multi-Channel Transceiver Chip (IMST)

The use of sub-THz frequencies brings many advantages, but also many challenges arise in the development and integration of active devices. In order to enable the integration of two-dimensional array front-ends, multi-channel chips are needed, which reduce the overhead area required by the interfacing pads. There are no multi-channel chips available commercially at frequencies higher than 100 GHz. Besides, sub-THz active devices suffer from low power density or efficiency. This fact magnifies the importance of achieving low-loss transitions to the antenna [1], as well as a good thermal management in the front-end.

In this project, a multi-channel transceiver chip will be developed at D-band. The concept will be partly based on the upscaling of lower frequency multi-channel core chip concepts carried out at IMST [2, 3]. The high-frequency interconnection technology between the chip and PCB antenna will be as well investigated, in order to minimize the losses over a wide frequency band.

References:

[1] M. Arias Campo et al., "H-Band Quartz-Silicon Leaky-Wave Lens With Air-Bridge Interconnect to GaAs Front-End," *in IEEE Transactions on Terahertz Science and Technology*, vol. 11, no. 3, pp. 297-309, May 2021.

[2] Follmann, R. and Berben, J. (2018) *PROWILAN – Entwicklung von neuartigen drahtlosen Kommunikationslösungen für den industriellen Einsatz* (https://www.forschung-it-sicherheit-

kommunikationssysteme.de/projekte/prowilan) [Bundesministerium für Bildung und Forschung]

[3] Follmann, Rüdiger / Berben, Jörg / IMST GmbH (2018), *PROWILAN: Professionelles Wireless Industrie LAN : Abschlussbericht IMST – Version 1.0,* (https://www.tib.eu/de/suchen/id/TIBKAT:1026813514/PROWILAN-Professionelles-Wireless-Industrie-LAN?cHash=3f6b46d4f6b3c268e28df34eebe9297b), TIB

T3.2 Baseband Signal Processing (NOK, KIT, TUD, EDD, TUIL, R&S)

5 Waveforms and Signal Design (KIT, TUD, EDD, R&S)

5.1 Waveforms for Joint Communication and Sensing (KIT)

OFDM is extensively studied as a waveform for JCaS in the form of OFDM radar. It performs well in most types of channels [1], yet very high mobility channels or impairments at high-frequency bands may decrease its performance [2] and some features of it such as PAPR are not ideal. Other waveforms addressing these impairments have been proposed such as GFDM, OTFS and chirp-based or delay-Doppler domain waveforms. Research concerning their performance in sensing is, as of now, incomplete.

Our research will focus on the suitability of alternative waveforms for Joint communication and sensing. We will analyze possible synchronization and other base band processing algorithms attached to the use of certain waveforms and will especially focus on the complexity attached to implementing these algorithms, since even if throughput increases, a higher complexity might inhibit a waveform from being used.

References:

[1] L. Gaudio, G. Colavolpe and G. Caire, "OTFS vs. OFDM in the Presence of Sparsity: A Fair Comparison," in *IEEE Transactions on Wireless Communications*, vol. 21, no. 6, pp. 4410-4423, June 2022, doi: 10.1109/TWC.2021.3129975.

[2] A. Bemani, G. Cuozzo, N. Ksairi and M. Kountouris, "Affine Frequency Division Multiplexing for Next-Generation Wireless Networks," *2021 17th International Symposium on Wireless Communication Systems (ISWCS)*, Berlin, Germany, 2021, pp. 1-6, doi: 10.1109/ISWCS49558.2021.9562168.

5.2 Linear Waveforms for Joint Communication and Sensing (TUD)

Many systems, including Wi-Fi, LTE, and more recently 5G, have embraced the orthogonal frequency division multiplexing (OFDM) waveform due to its efficient use of the spectrum, simple channel equalization over frequency selective channels and its simple implementation using FFT techniques. However, on doubly dispersive channels, which also exhibit high Doppler shift and temporal selectivity in addition to frequency selectivity, OFDM performance deteriorates significantly. Other waveforms, such as the Orthogonal time Frequency and Space (OTFS), have been proposed for these channels. In situations involving doubly dispersive channels with high mobility, OTFS performs efficiently [1]. One generic framework to produce linear waveforms was proposed by Vodafone Chair for Mobile Communications Systems - TU Dresden. This generic framework offers a broad perspective on how to spread the transmitted symbols over time and frequency with the use of generation matrices of orthogonal transforms like OFDM and Walsh-Hadamard. Furthermore, OFDM can be seen as special case of this generic framework, where OFTS can be considered as a pre-coded OFDM [2,3].

For use in future communication systems, like 6G, there may be significant benefits to employing other linear waveforms than ODFM. Our plan to develop the use of linear waveforms under our generic framework for JCaS applications.

References:

[1] Hadani, Ronny, Shlomo Rakib, Michail Tsatsanis, Anton Monk, Andrea J. Goldsmith, Andreas F. Molisch, and R. Calderbank. "Orthogonal time frequency space modulation." In *2017 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1-6. IEEE, 2017.

[2] Bomfin, Roberto, Ahmad Nimr, Marwa Chafii, and Gerhard Fettweis. "A robust and low-complexity walsh-hadamard modulation for doubly-dispersive channels." *IEEE Communications Letters* 25, no. 3 (2020): 897-901.

[3] Bomfin, Roberto, Marwa Chafii, Ahmad Nimr, and Gerhard Fettweis. "A robust baseband transceiver design for doubly-dispersive channels." *IEEE Transactions on Wireless Communications* 20, no. 8 (2021): 4781-4796.

5.3 Golay Complementary Sequences for OFDM-Based Radar Systems (EDD)

Complementary sequences are a family of sequence pairs where the sum of aperiodic autocorrelation functions (ACF) of sequences in the pair is perfect, i.e. non-zero at time lag zero and otherwise zero. While it is easy to find sequences with perfect periodic ACF (e.g. Zadoff-Chu sequences) it is impossible to find sequences (not sequence pairs) with this property. The most famous family of complementary sequences are Golay complementary sequences. The perfect aperiodic ACF sum property makes them suitable in applications requiring good timing detection using non-cyclic signal processing. Golay complementary sequences are for example used in 802.11ad and 802.11ay as reference signals for channel estimation.

In this work Golay complementary sequences are used to generate short pulses with very good aperiodic ACF properties in an OFDM-based radar system. The short pulses are synthesized such that the resulting signal is limited to the allocated number of subcarriers. Limiting the short-pulse signal to the number of allocated subcarriers implies a bandwidth limitation which results in time-domain ringing. To obtain radar pulses that are 1) effectively short in time (majority of energy concentrated in short time interval); and 2) maintain the good aperiodic ACF sum of Golay complementary sequences, the bandwidth limitation is performed with a suitable window function in frequency-domain. The perfect ACF sum is only obtained if no cross-correlation terms between sequences of the pair appear at the correlator output, the sequences must therefore be transmitted with a time-separation corresponding to at least the sequence duration. To avoid also cross-correlation terms between sequences of the pair received as reflections from different targets, a separation corresponding to the two-way propagation difference between nearest and furthest away target is needed. We will therefore focus on assessing the suitability of Golay sequences in a short pulse OFDM-based radar system and evaluate the cross-correlation issue in various scenarios.

References:

[1] IEEE Standard for Information technology—Telecommunications and information exchange between systems, Local and metropolitan area networks—Specific requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band, IEEE Std

802.11ad™-2012 (Amendment to IEEE Std 802.11™-2012, as amended by IEEE Std 802.11ae™-2012 and IEEE Std 802.11aa™-2012), New York, 2012

[2] IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems, Local and Metropolitan Area Networks—Specific Requirements, Part 11: Wireless LAN Medium Access Control(MAC) and Physical Layer (PHY) Specifications, Amendment 2: Enhanced Throughput for Operations in License-exempt Bands above 45 GHz, IEEE Std 802.11ay™-2021 (Amendment to IEEE Std 802.11™-2020 as amended by IEEE Std 802.11ax™-2021), New York, 2021

5.4 Waveform and Reference Signal Design Impact on T&M (R&S)

OFDM based and other alternative waveforms are researched as part of this joint communication and sensing research project. Reference signal parts within the designed waveform are of importance for test and measurement applications, since test devices need to conduct channel estimation and synchronization tasks to determine a measurement result.

The work will review the researched waveforms in terms of impact to measurement applications tasks. Specifically, for alternative waveform approaches next to determine JCAS KPIs, the assessment in terms of complexity to derive such measurements results as well as the possible best accuracy of such measurement results will be reviewed.

6 Parameter Estimation, Tracking, and Beamforming (KIT, TUIL)

6.1 Joint Beamforming and Parameter Tracking (KIT)

In order to save hardware and increase energy efficiency, hybrid beamforming is commonly used instead of digital beamforming [1]. Beamforming methods are mainly implemented as beam codebooks, calculating the connected beamforming vectors offline, and the application of machine learning methods has led to further improvements [2]. Concerning simultaneous sensing, we need in addition to beams toward communication receivers some radiated energy toward the sensing objects. The direction and power needs of this beam highly depend on the object's position.

Our research needs to focus on ways how to inject the results of parameter estimation or tracking into the beamformer to obtain control of the beam illuminating the sensing objects while still serving a communication receiver in the same time instance, but different place. With this, we can analyze the trade-off concerning sensing beam energy and the accuracy of estimation of the sensing parameters. We will address classical beamforming codebooks, as well as machine learning (aided) beamforming. In this context, mono- and bistatic arrangements in scenarios with extended targets will be considered assuming 4D sensing, that is, encompassing range, Doppler shift, azimuth and elevation measurements. As opposed to the assumption of knowledge of a first target state estimation in most studies in the literature, initial target estimation will be also considered in the aforementioned beamforming strategies. Finally, the sensing coverage will be estimated both considering the achieved beampatterns and via thorough link budget calculations considering relevant baseband and RF hardware aspects.

References:

[1] I. Ahmed *et al.*, "A Survey on Hybrid Beamforming Techniques in 5G: Architecture and System Model Perspectives," in *IEEE Communications Surveys & Tutorials*, vol. 20, no. 4, pp. 3060-3097, Fourthquarter 2018, doi: 10.1109/COMST.2018.2843719.

[2] M. S. Aljumaily and H. Li, "Machine Learning Aided Hybrid Beamforming in Massive-MIMO Millimeter Wave Systems," *2019 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, Newark, NJ, USA, 2019, pp. 1-6, doi: 10.1109/DySPAN.2019.8935814.

6.2 High-Resolution Channel Parameter Estimation and Tracking (TUIL)

A radio channel is the physical wave propagation medium between two points (Transmitter and Receiver) that typically consists of multiple propagation paths. Though raytracing is the most accurate way of modelling such an environment, parametric models are often preferred due to their simplicity and demonstrating power, as the position of the reflecting objects can be acquired by exploiting the parameters of such models. The parameters of these models are often estimated using advanced signal processing methods. Due to the real-time constraints of sensing applications, the most convenient methods typically include the use of periodograms in combination with a detection algorithm such as the Constant False Alarm Rate (CFAR) algorithms [1]. However, the accuracy of this method is bound to the resolution of the acquired spectrum from the channel impulse response measurements (CIR). Another category of parameter estimation algorithms (often called “high-resolution parameter estimation”) can perform beyond the limitations introduced by the grid. Maximum likelihood methods [2-3] for example, can achieve a performance close to the Cramer-Rao Bound but require longer computation times. The next step is to translate the estimated parameters into the position of the reflecting objects of interest. To extract the positions, state-space models, and tracking algorithms (such as Kalman filters) can be deployed. Though the Kalman filter was developed around linear models, its non-linear variations (e.g., extended Kalman filter (EKF)) can be used for non-linear problems such as channel parametric models. Deployment of EKF can become challenging in the existence of multiple propagation paths that change in time. This challenge is addressed in multiple object tracking (MOT) algorithms [4-5].

The problem with maximum likelihood methods is that they are often too complicated and slow to be deployed in real-time, which is a key requirement for the sensing services in ICaS. We attempt to develop parameter estimation methods using Deep Learning (DL) [6] that can achieve a significantly lower run-time with comparable accuracy in parameter estimation. Furthermore, tracking algorithms need to be applied to the output of parameter estimators to extract the sensing information. The high complexity and increased run-time of these methods are also a known issue when using accurate tracking algorithms (such as PMBM [5]). To this end, DL methods can also improve the performance of tracking but are not yet closely examined for ICaS scenarios.

References:

[1] M.A. Richards, Fundamentals of radar signal processing, McGraw-Hill Education, 2014.

[2] B. H. Fleury, M. Tschudin, R. Heddergott, D. Dahlhaus and K. I. Pedersen, "Channel parameter estimation in mobile radio environments using the SAGE algorithm", IEEE J. Sel. Areas Commun., vol. 17, no. 3, pp. 434-450, Mar. 1999.

[3] A. Richter, Estimation of radio channel parameters: Models and algorithms, May 2005,

[4] Vo, B. -T, and W. K. Ma. "The Gaussian mixture Probability Hypothesis Density Filter." IEEE Transactions on Signal Processing, Vol, 54, No, 11, pp. 4091–4104, 2006.

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

7 NLoS Sensing, Clutter Removal, and Multistatic Sensing (NOK, KIT)

7.1 NLoS Sensing (NOK)

Non-line-of-sight (NLoS) sensing is an interesting potential application due to the possibility of detecting/localizing targets behind corners, thereby offering additional capabilities over camera-based systems. Prior art has mainly focused on the optical approach (e.g., using LIDAR), which is costly, limited to short ranges, and susceptible to environmental conditions such as fog. The few existing works on RF-based NLoS sensing typically consider simple L-junction or T-junction scenarios with a mono-static radar illuminating the environment. For instance, the localization of a target behind a corner using a UWB Radar has been investigated in [1]. More recent RF approaches have also applied deep learning techniques, e.g., in [2], where data obtained from FMCW radars has been fed to a neural network for NLoS detection and tracking.

As RF-based NLoS sensing is a very challenging problem, initial research will have to address some fundamental questions to better assess its feasibility. In that regard, we plan to leverage our mmWave ICASC PoC to conduct measurements in a factory-like environment to give us insights into whether higher-order reflections can be detected. These measurements may also allow drawing conclusions about feasible deployments (mono-static, bi-static) and scenarios. Later research will likely investigate possible algorithms for NLoS sensing, such as Simultaneous Localization and Mapping (SLAM), but will be tailored based on insights gained from the measurement campaigns.

7.2 Clutter Removal (NOK)

Clutter removal algorithms are required to remove the influence of reflections that are not of interest for the sensing task. As radar has existed for decades, also various clutter removal techniques are available, such as Space-Time Adaptive Processing (STAP) [3] or Extensive Cancellation Algorithm (ECA) [4]. Most legacy radar operations, however, are typically only interested in (fast) moving targets, which allows the adoption of cancelation techniques removing information at zero Doppler components. This can clearly not be assumed for most envisioned ICAS use cases, as also slowly moving (or even static) targets – such as humans – must be detected. Moreover, the radar systems considered in most prior art on clutter removal techniques differ in their limitations from classical communication setups.

In view of the previously described differences of conventional radar operations with respect to ICAS applications, our research will focus on developing algorithms that take the peculiarities of communication systems, as well as the anticipated use cases into account. For instance, clutter removal techniques developed for ICAS should be robust against phase noise, which is likely non-negligible if TX and RX do not share the same local oscillator (e.g., in bi-static setups). During our investigations, we will also place a particular emphasis on the computational complexity of the algorithms, since use cases such as pedestrian tracking require a low latency at runtime.

References:

[1] R. Zetik, M. Eschrich, S. Jovanoska and R. Thomä, "Looking Behind a Corner Using Multipath-Exploiting UWB Radar" in *IEEE Transactions on Aerospace and Electronic Systems*, vol. 51, no. 3, pp. 1916-1926, Jul 2015.

[2] N. Scheiner et al., "Seeing around street corners: Non-line-of-sight detection and tracking in-the-wild using doppler radar" in *Proceedings of the IEEE/CVF Conference on Computer Vision and (CVPR)*, pp. 2068-2077, Jun 2020.

[3] S. Sen, "OFDM Radar Space-Time Adaptive Processing by Exploiting Spatio-Temporal Sparsity" in *IEEE Transactions on Signal Processing*, vol. 61, no. 1, pp. 118-130, Jan 2013.

[4] F. Colone et al., "A Multistage Processing Algorithm for Disturbance Removal and Target Detection in Passive Bistatic Radar" in *IEEE Transactions on Aerospace and Electronic Systems*, vol. 45, no. 2, pp. 698-722, Apr 2009.

7.3 Multiple gNBs as a Multistatic Radar System (KIT)

The use of multiple gNBs or UEs for bi- and multistatic sensing is expected to significantly increase the capability of detect targets with aspect-dependent radar cross sections, as well as increase the coverage of observation areas of interest in complex scenarios. In this context, several aspects of bi- and multistatic sensing with modern cellular infrastructure have become subject of investigation in recent literature. Those include evaluation of accuracy of mono- and bistatic range measurements [1] as well as coverage analysis [2]. Most studies, however, do not address synchronization issues and consider rather simple scenarios, usually only with point targets and/or absence of clutter. Furthermore, only 2D sensing with AoA estimation for azimuth [1-2] is considered, as also mentioned in topic 2.

Assuming that no physical infrastructure such as optical fiber is available to enable hardware-level synchronization, our research will focus on the use of the OFDM-based JCaS signals to enable over-the-air synchronization of sensing nodes. In this context, compensation of time, frequency and sampling frequency offsets will be performed. This will not only enable bi- and multistatic sensing, but also reconstruction of incoming signals from gNBs and/or UEs to enable mutual interference cancellation for appropriate monostatic sensing at all sensing nodes. Furthermore, distributed sensing in scenarios with extended targets with aspect-dependent radar cross sections and clutter will be investigated assuming 4D sensing. The coverage of multistatic networks will be then estimated building upon the investigations from topic 2. A further investigation topic is the fusion of signals from different sources and bands, which will be more closely addressed in WP5.

References:

[1] O. Kanhere, S. Goyal, M. Beluri and T. S. Rappaport, "Target Localization using Bistatic and Multistatic Radar with 5G NR Waveform," 2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring), Helsinki, Finland, 2021, pp. 1-7, doi: 10.1109/VTC2021-Spring51267.2021.9449071.

[2] V. Yajnanarayana and H. Wymeersch, "Multistatic Sensing of Passive Targets Using 6G Cellular Infrastructure," arXiv preprint arXiv:2211.05340v2 [cs.IT], Apr. 2023.

KOMSENS-6G

Work Package 4

Milestone 1
“State-of-the-Art (SotA) and gap analysis”

KOMSENS-6G WP4: Milestone 1 Deliverable

Table of Contents

1 Introduction

This report provides in the first 3 chapters an overview of the state-of-the-art in the areas of protocol design and signalling, resource allocation, network aspects and coordination in wireless communications systems and radars that need to be taken into account when integrating both to an ICaS system. The final chapter collects those identified gaps on which the project will focus the further work.

2 Protocol design and signaling

2.1 Wireless communications networks [DTAG, EDD, HHI]

2.1.1 3GPP networks [DTAG, EDD]

The current 3GPP 5G NG-RAN architecture with the interconnection points to the 5G CN (5GC) is shown in the following figure (for details see TS 38.300 [15] and related specifications; details on the overall 5G system architecture incl. 5GC are given in TS 23.501 [12]).

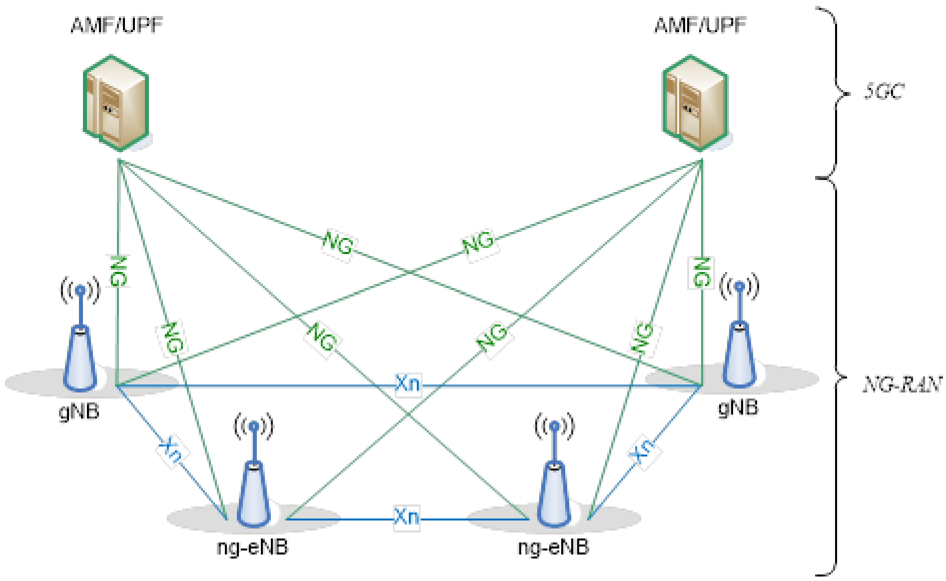


Figure 1: Overall NG-RAN architecture (see TS 38.300[15])

The NG-RAN nodes (gNBs or ng-eNBs) are connected to the 5GC via the NG interface (split into NG-C and NG-U for Control Plane (CP) and User Plane (UP)) [21] and may be interconnected between each other via the Xn interface (split into Xn-C and Xn-U for CP and UP) [22]. The next figure shows the UP and CP protocol stacks for the NG-RAN.

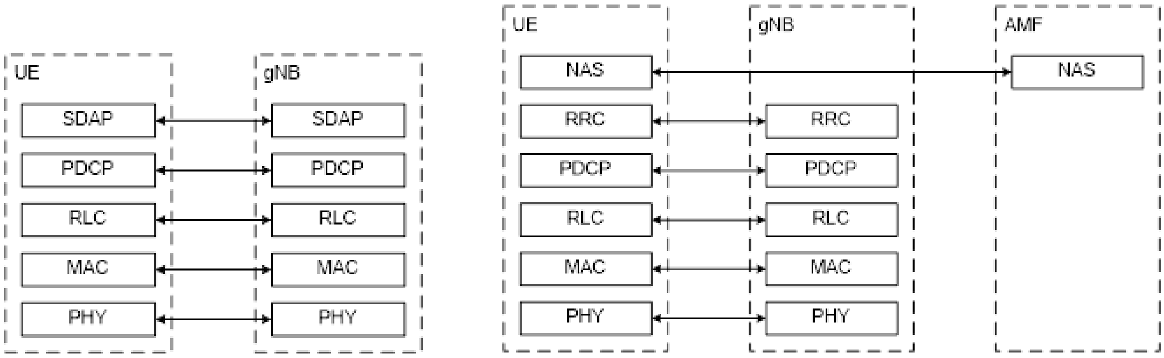


Figure 2: UP (left) and CP (right) protocol stack layers for the NG-RAN (see TS 38.300 [15])

The CP protocols are, among other things, responsible for connection setup, mobility, and security. The Non-Access Stratum (NAS) CP functionality operates between the Access and Mobility Management Function (AMF) in the 5GC and the UE. It includes authentication, security, and different idle mode procedures such as paging. It is also responsible for assigning an IP address to a UE.

The Radio Resource Control (RRC) CP functionality operates between the RRC located in the gNB and the UE (see TS 38.331 [19]). RRC in the gNB is responsible for handling the RAN related CP procedures over the Uu interface, including:

- Broadcast of System Information necessary for the UE to be able to communicate with a cell. Paging initiated by 5GC (AMF) or NG-RAN to notify the UE about incoming connection requests. CN Paging is used in the RRC_IDLE state when the device is not connected to a cell.
- Establishment, maintenance and release of an RRC connection between the UE and NG-RAN including addition, modification and release of Carrier Aggregation (CA) as well as of Dual Connectivity (DC) in NR or between E-UTRA and NR.
- Security functions including key management.
- Establishment, configuration, maintenance and release of Signalling Radio Bearers (SRBs) and Data Radio Bearers (DRBs).
- Mobility functions including handover and context transfer, control of UE cell (re-)selection, and Inter-RAT (Radio Access Technology) mobility.
- Quality of Service (QoS) management functions.
- UE measurement reporting and control of the reporting.
- Detection of and recovery from radio link failure.
- NAS message transfer to/from NAS from/to UE.
- Handling of UE capabilities; when connection is established the device will announce its capabilities as not all devices are capable of supporting all the functionality described in the 3GPP specifications.

RRC messages are transmitted to the UE using SRBs, using the same set of lower protocol layers (PDCP, RLC, MAC, and PHY (details see TS 38.300 [15]) as also used for the UP. CP and UP data can be multiplexed in the MAC layer and transmitted to the UE in the same time slots, i.e., Transmission Time Intervals (TTIs). The MAC control elements can also be used for control of radio resources in some specific cases where low latency is more important than ciphering, integrity protection, and reliable transfer. More information about radio resource management (RRM)/allocation is given in Section 3.

An NG-RAN node as shown in Figure 3 may be further disaggregated into one Central Unit (CU) and one or more Distributed Units (DUs) connected via the F1 interface (split into F1-C and F1-U for CP and UP) [24]. The CU is hosting the PDCP, SDAP, and RRC layers, whereas the lower layers are hosted by the DU. In addition, a CU could be further split into a CU-CP and one or more CU-UPs connected via the E1 interface (CP only) [14]. Details on the disaggregated architecture as shown in the next figure (here only for a gNB) can be found in TS 38.401 [20].

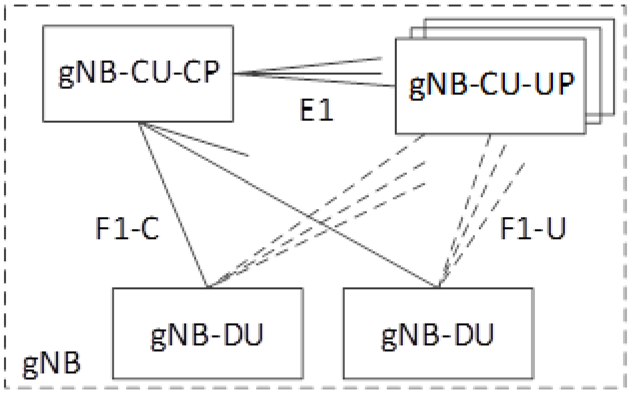


Figure 3: gNB-split architecture (see TS 38.401 [20])

The 3GPP 5G RAN architecture as presented before is complemented by specifications of the O-RAN Alliance allowing a higher degree of network function disaggregation and supporting the operation of the RAN in a virtualized/cloudified multi-vendor environment. The corresponding architecture designed by O-RAN with main functional blocks and interfaces in between is shown in the next figure. Note that the Uu interface as defined by 3GPP between a UE and the O-RAN radio unit (O-RU) and/or the O-eNB is not explicitly shown in that figure as it is not impacted by O-RAN.

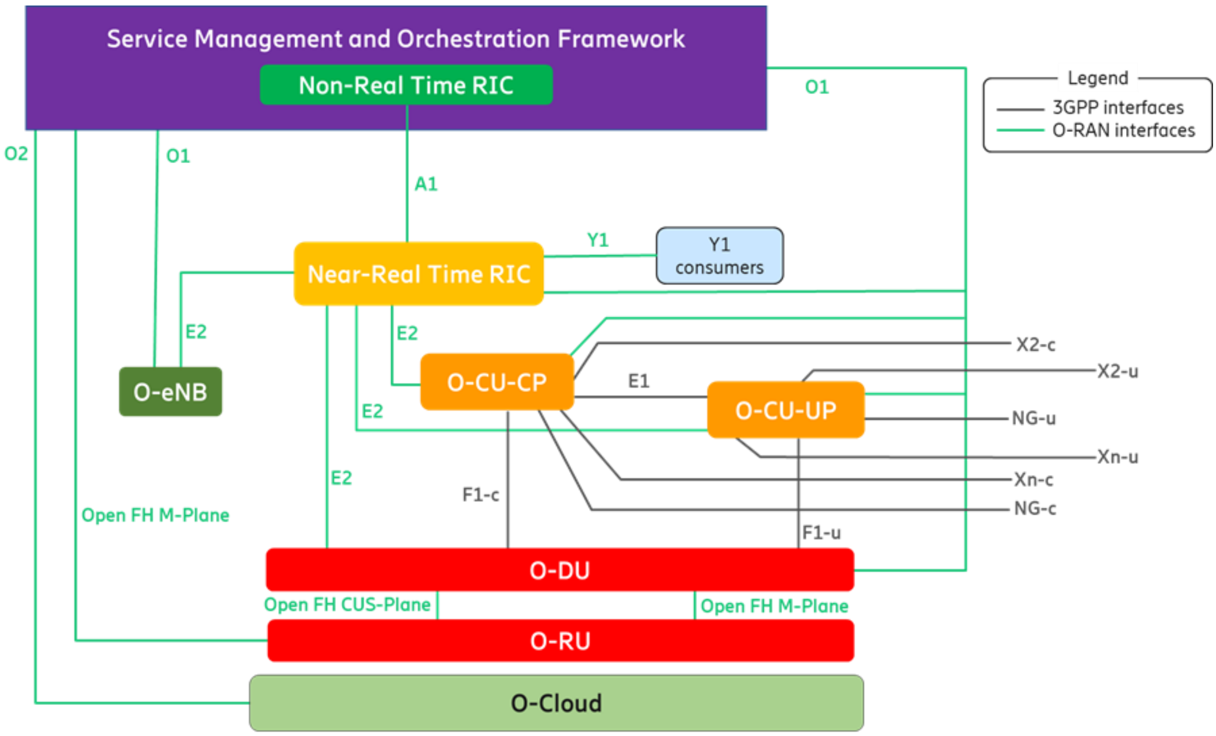


Figure 4: Logical O-RAN architecture (see TS O-RAN.WG1.OAD [25])

The logical DU node as specified by 3GPP has been split into the O-DU and the O-RU nodes with the Open Fronthaul (FH) interface in between the 2 components (see TS O-RAN.WG4.CUS [26]). For the definition of the Open FH interface the so-called 7-2x split in the PHY layer has been applied so far and the packet-based data transport over the interface is realized based on the eCPRI specification.

O-RAN has introduced a new logical RAN node called Near-real time Radio Intelligent Controller (Near-RT RIC) which is connected via the newly defined E2 interface (CP only) with the other logical RAN nodes (except of O-RU), the so-called E2 nodes. The Near-RT RIC builds upon interaction with the Non-RT RIC via the A1 interface (policy-based guidance). The Non-RT-RIC is part of the OAM system called Service Management and Orchestration (SMO) in O-RAN context. Benefits from Near-RT RIC deployment are seen in higher degree of flexibility and programmability in RAN domain allowing enhanced RRM optimization across RAN nodes based e.g. on (potentially 3rd party) artificial intelligence/machine learning (AI/ML) applications that can be on-boarded on Near-RT RIC's cloud-native platform (so-called xApps). RRM functional allocation between Near-RT RIC and E2 nodes is subject to the capability of E2 nodes to expose corresponding functions by means of the E2 Service Model (E2SM). Via those functions the Near-RT RIC, respectively the xApps, may e.g. monitor, suspend/stop, override or control the behavior of E2 nodes via related policies. From a logical point of view the Near-RT RIC may be seen as an extension of the CU-CP as defined by 3GPP and both logical nodes may be hosted together e.g. in case of a centralized deployment.

The O-Cloud shown in the figure represents a cloud computing platform comprising a collection of physical infrastructure nodes that meet O-RAN requirements to host the relevant O-RAN functions (logical RAN nodes), the supporting SW components (such as operating system, container runtime, etc.) and the appropriate management and orchestration functions. The O1 and O2 interfaces are Management Plane (MP) interfaces to OAM/SMO.

As a basis for the work on integrating sensing capabilities into a cellular communication network, KOMSENS-6G may initially orientate towards the architectural set-up of 3GPP for location and positioning services (LCS) in the 5G system which was firstly introduced in Rel-16 and enhanced in following releases (see TR 21.916 [7] and TR 21.917 [8]).

Service requirements for LCS were defined by 3GPP in TS 22.261 [10] and TS 22.071 [9] addressing also KPIs like accuracy, availability, response time, coverage (indoor, outdoor, 5G (enhanced) positioning service area, etc.) assigned to 7 Positioning Service Levels, with accuracy ranging from 10 m for Service Level 1 down to 0.2 m for Service Level 7. In principle, also different LCS QoS classes were defined which may be optionally fulfilled by the system during operation for immediate location request response (see TS 22.071 [9]). Stage 2 descriptions of the underlying architecture and protocol approaches are captured primarily in TS 23.273 [11] and TS 38.305 [16]. Details on Stage 3 positioning protocols can be found in TS 37.355 (LTE Positioning Protocol (LPP); applicable for E-UTRAN and NG-RAN) [13] and TS 38.455 (NR Positioning Protocol A (NRPPa); applicable for NG-RAN) [23].

The LPP is used as a point-to-point protocol between a location server (Enhanced Serving Mobile Location Centre (E-SMLC), Location Management Function (LMF) or Secure User Plane Location (SUPL) Location Platform (SLP)) and a target device (UE or SUPL Enabled Terminal (SET)) in order to achieve location information of the target device using position-related measurements obtained by one or more reference sources (NG-RAN nodes, global navigation satellite systems (GNSS), …). The

NRPPa describes the CP radio network layer signalling procedures between a NG-RAN node and the LMF for positioning purposes.

The following figure shows the UE positioning overall architecture applicable to NG-RAN. The NG-RAN nodes (gNB or ng-eNB) are connected to the AMF in the 5GC via the NG-C interface which forwards LPP or NRPPa messages between LMF and the NG-RAN nodes.

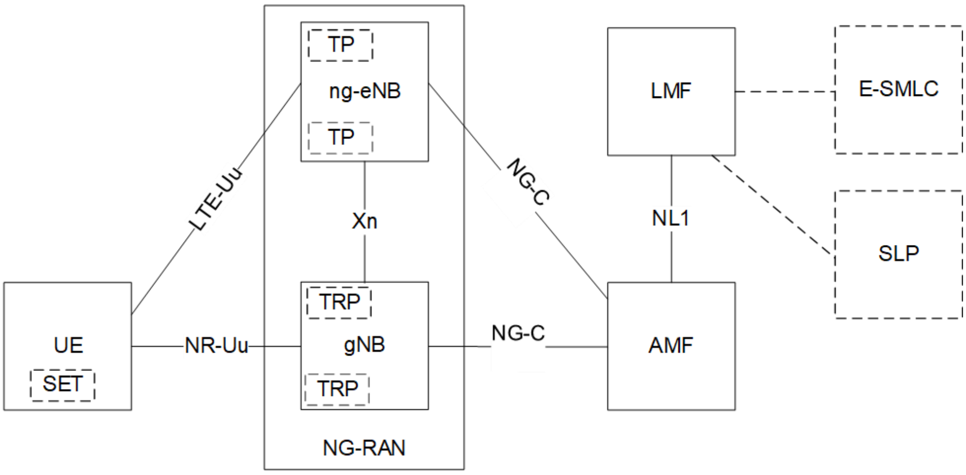


Figure 5: UE positioning overall architecture applicable to NG-RAN (see TS 38.305[16]) (note: for 5GC only a limited set of NFs was shown; a more detailed description is covered in TS 23.273 [11])

The signaling flow for the LCS support via the NG-RAN is shown in Figure 6 (see TS 38.305 [16]). After getting a request for a LCS associated with a particular target UE from another entity (e.g., Gateway Mobile Location Centre (GMLC) or UE) or if the AMF itself decides to initiate a LCS on behalf of a target UE (e.g., for an IMS emergency call from the UE; see TS 23.273 [11]) the AMF sends a LCS request to an LMF. The LMF processes the LCS request which may include transferring assistance data to the target UE to assist with UE-based and/or UE-assisted positioning and/or may include positioning of the target UE. The LMF then returns the result of the location service back to AMF (e.g., a position estimate for the UE). In the case of a location service requested by an entity other than the AMF (e.g., GMLC or UE), the AMF returns the location service result to this entity. An LMF may have a proprietary signalling connection to an E-SMLC which may enable an LMF to access information from E UTRAN or to an SLP which is the SUPL entity responsible for positioning over the UP.

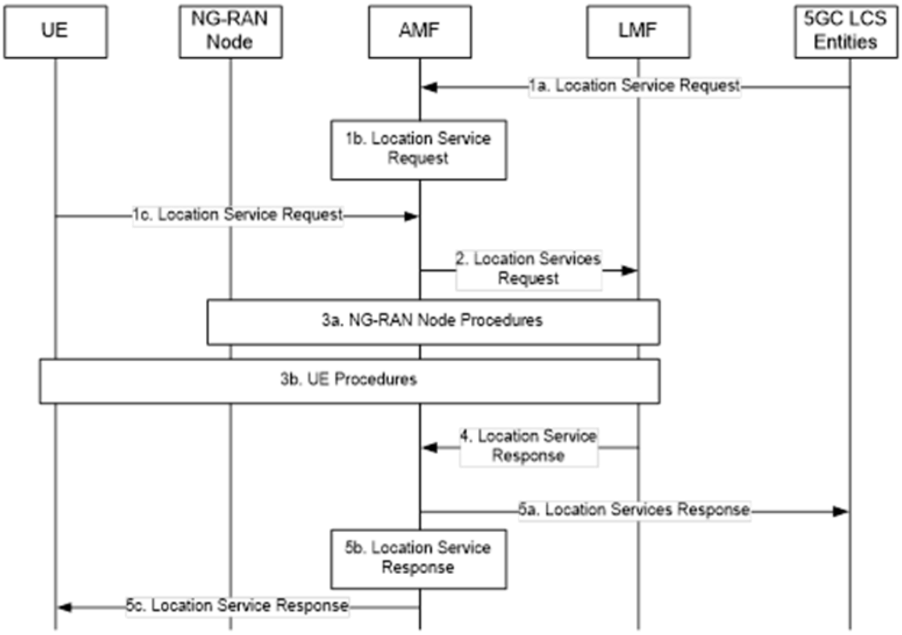


Figure 6: LCS support by NG-RAN (see TS 38.305 [16])

The following 2 figures show the protocol stacks for the LPP between LMF and UE (a LPP Packet Data Unit (PDU) is carried in NAS PDU between AMF and UE) as well as for NRPPa between LMF and an NG-RAN node. The AMF routes the NRPPa PDUs transparently based on a Routing ID which corresponds to the involved LMF node over the NG interface without knowledge of the involved NRPPa transaction. It carries the NRPPa PDUs over NG interface either in UE associated mode or non-UE associated mode.

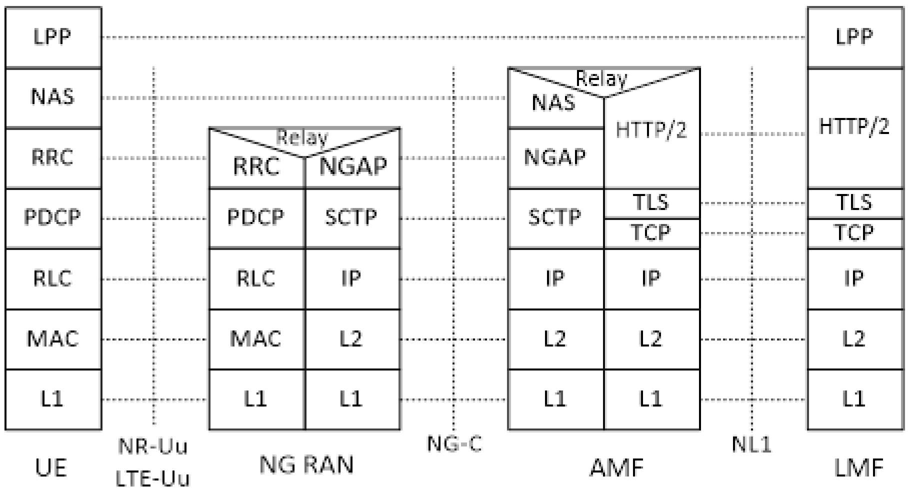


Figure 7: LPP protocol stack between LMF and UE (see TS 38.305 [16])

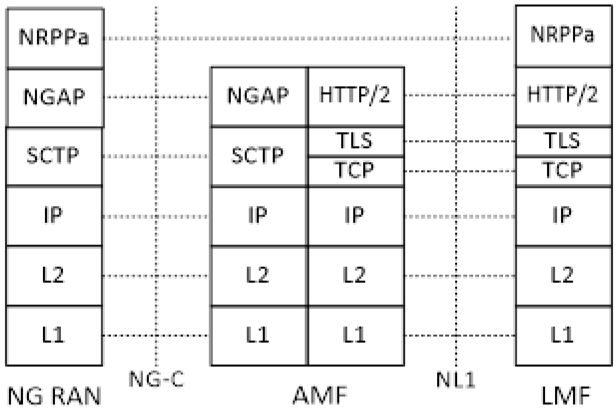


Figure 8: NRPPa protocol stack between LMF and NG-RAN (see TS 38.305 [16])

An NG-RAN node may control several Transmission-Reception Points (TRPs)/ Transmission Points (TPs)/ Reception Points (RPs), such as remote radio heads, or Downlink Positioning Reference Signal (PDL-PRS)-only TPs for support of PRS-based Terrestrial Beacon System (TBS). In case of split gNB architecture, a gNB-DU may include TRP functionality where the TRP functionality may support functions for a TP, RP or both TP and RP. A gNB-DU which includes TRP functionality does not need to offer cell services. For the split gNB architecture the application protocol of the F1 interface (F1AP) between gNB-CU and gNB-DU (see TS 38.473 [24]) was extended to support the positioning procedures.

The RRC protocol terminated between the gNB or ng-eNB and the UE provides the transport for LPP messages over the Uu interface. It also supports transfer of measurements that may be used for positioning purposes through the existing measurement systems specified in TS 38.331 [19] as well as broadcasting of assistance data via positioning System Information messages. It is also used to configure UEs with a Sounding Reference Signal (SRS) in RRC_CONNECTED and RRC_INACTIVE modes to support NG-RAN measurements for NR positioning, provide pre-configured measurement gap configuration(s) and pre-configured PRS processing window for DL-PRS measurement and report the UE TxTEG (Tx Timing Error Group) for UL-TDOA.

Positioning methods supported by 5GS may be differentiated according to RAN-assisted and RAN-based methods:

- For RAN-assisted methods the State-of-the-art outdoor positioning is performed by the UE making use of GNSSs, like GPS, Galileo or GLONASS, whereby 3GPP systems support "Assisted GNSS" functionality to improve operational performance. With improved GNSS hardware and network-based services GNSS positioning accuracy performance can be improved down to cm level accuracy as known by legacy RTK (Real Time Kinematic) solutions.
- RAN-based positioning methods specified in NG-RAN are based on
    - DL TDOA – Downlink Time Difference of Arrival
    - DL AoD – Downlink Angle of Departure
    - UL TDOA – Uplink Time Difference of Arrival
    - UL AoA – Uplink Angle of Arrival (Azimuth and Zenith)

- Multi-RTT – Multi Round Trip Time
- NR E-CID – NR Enhanced Cell ID

For the RAN-based positioning methods the following reference signals and new physical layer measurements were specified [7][8]:

- Reference signals (see TS 38.211 [17]):
  - DL PRS
  - UL SRS for positioning
- Physical layer measurements (see TS 38.215 [18]):
  - UE measurements:
    - DL PRS-RSRP (downlink positioning reference signals – reference signal receiver power): Applied for DL AoD, DL TDOA, Multi-RTT
    - DL RSTD (downlink reference signal time difference): Applied for DL TDOA
    - UE Rx – Tx time difference: Applied for Multi-RTT
  - NG-RAN (gNB) measurements
    - UL RTOA (uplink relative time of arrival): Applied for UL TDOA
    - UL SRS reference signal received power (UL SRS-RSRP): Applied for UL TDOA, UL AoA, Multi-RTT
    - gNB Rx – Tx time difference: Applied for Multi-RTT
    - UL AoA (uplink angle of arrival): Applied for UL AoA and E-CID
- For NR E-CID support the following existing RRM measurements were reused: CSI-RSRP, CSI-RSRQ, SS-RSRP, SS-RSRQ.

DL PRS are allocated and transmitted periodically with configurable periodicity and time offset with respect to SFN0 (System Frame Number). The DL PRS configuration is done per DL positioning frequency layer that defines multiple DL PRS resource sets associated with different TRPs and characterized by the same DL PRS subcarrier spacing, transmission bandwidth, cyclic prefix length, DL PRS Point A and offset with respect to DL PRS Point A. The DL PRS resource set may contain multiple DL PRS resources, where each DL PRS resource is associated with certain spatial transmission direction of DL PRS from a given TRP (beam) and characterized by configurable number of symbols, resource element pattern, initial comb-offset, offset in slots, symbols and DL PRS sequence ID. The DL PRS is single port signal that can be configured as quasi-collocated with SSB index or other DL PRS resources. The configuration of DL PRS is provided as a part of UE assistance information. DL PRS transmissions can be muted according to configured bitmaps for each DL PRS resource set that control the DL PRS resource set transmission period or DL PRS resource repetition transmission within a DL PRS transmission period.

UL SRS for positioning are defined based on NR UL SRS with modified staggered RE pattern and disabled frequency hopping. Each configured UL SRS resource set for positioning may contain multiple UL SRS resources for positioning characterized by number of symbols, transmission bandwidth, RE pattern, time offset and may be associated with UE TX beam. They can be spatially related with SSB indexes or DL PRS resource index as well as reference signal for UL open loop power control towards serving and neighbor cells (defined for UL SRS for positioning). The LMF may recommend the spatial relation and pathloss reference to the gNB for SRS configuration and may also request (de-)activation of non-periodic SRS transmission to the gNB.

The following figure exemplarily shows the signaling flows for different RAN-based positioning methods between UE, gNB and LMF.

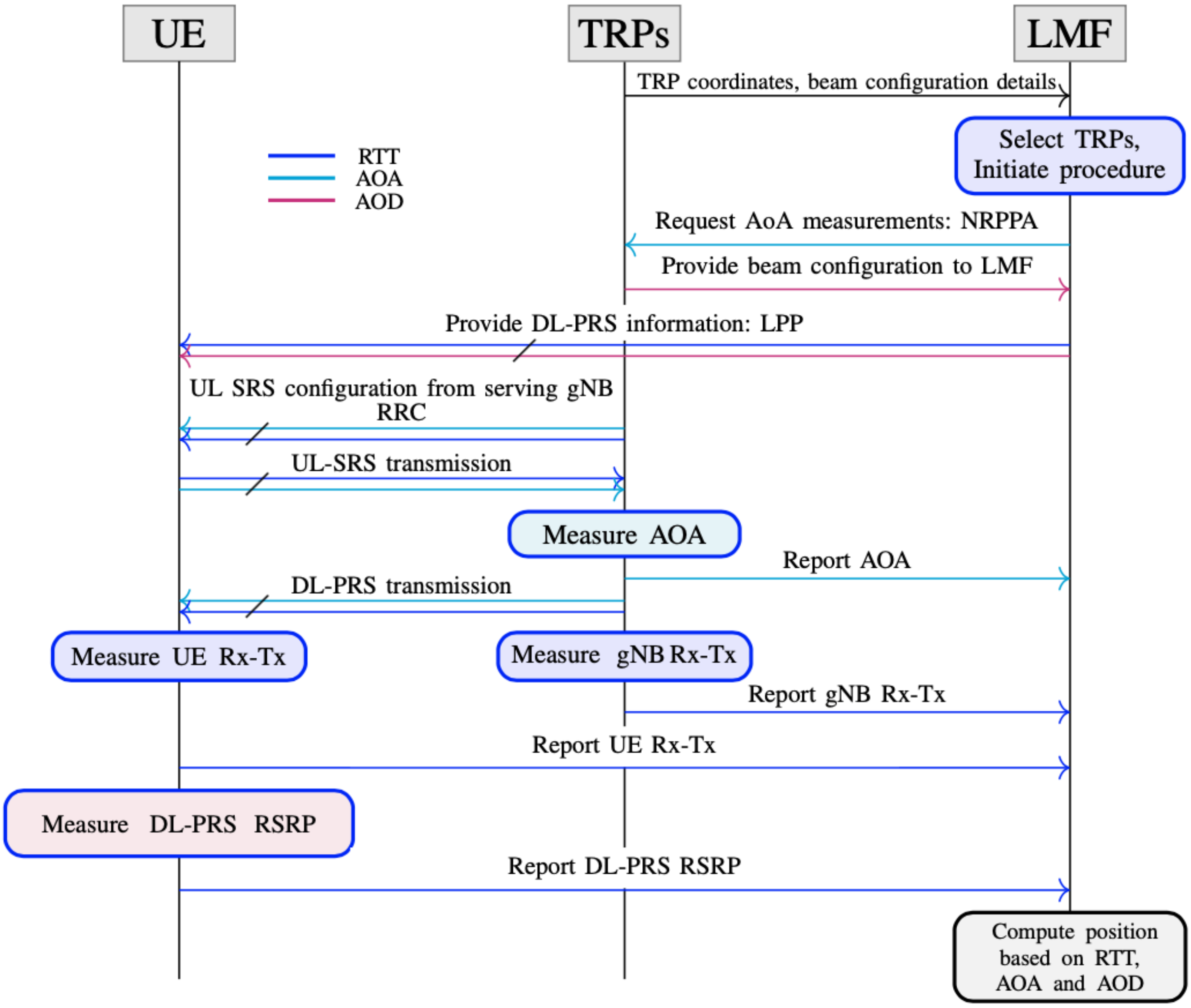


Figure 9: Message sequence chart for different RAN-based positioning methods in 5G (please note that the term "TRPs" stands here for the related NG-RAN node(s) to which the TRPs belong, see Figure 5 above)

Gap analysis:

Contrary to LCS purposes which address procedures to evaluate positions of UEs connected to the 5GS, the sensing approach to be considered in KOMSENS-6G is not expected to primarily rely on UE measurements, but the focus is rather on RAN node transmission and receptions at the same or a neighboring node (the use of UE for sensing purposes is not excluded). Nevertheless, approaches specified for positioning methods for setting up the measurement timing and related resource control can be used in a similar way also for sensing purposes. In addition, it could be feasible to use results of the sensing process also for improving the positioning accuracy which in that case would only fit for UEs connected to the 6G system.

Instead of the LMF a network function with related capabilities for sensing is expected to be implemented in the CN, here preliminary called Sensing Function (SF). The main properties of the SF are:

- Initiation and parametrization of related sensing measurements in the RAN based on sensing service requirements from a (Sensing) Application Function ((S)Af) triggered by the mobile network operator (MNO) or 3rd parties.
    - Based on (S)AF requirements and related use cases the SF will consider the initiation of sensing measurements at RAN nodes PLMN-wide, in a certain area, or only for one or more dedicated TRPs. RF resources to be triggered at TRP(s) for the measurements will be strongly dependent on requested sensing QoS classes and the interrelation with RRM for communication services. The exchange of information about sensing signal schedules may happen via Xn interface between different RAN nodes to avoid interference impacts or centrally via the SF if synchronized coordination between TRPs from neighboring RAN nodes is required.
    - (S)Afs working on results of SF could be directly involved in case of a trusted function or via the Network Exposure Function (NEF) in the 5GC in the untrusted case.
    - It is expected that the CN is furthermore responsible for sensing service authorization and fulfilment of data integrity/ encryption (dependent on use case). In addition, procedures allowing to charge “Sensing as a Service" (SaaS) have to be specified.
- Final processing of sensing data and preparation of results to be offered to (S)Afs for SaaS.
    - The final processing demand in the SF depends on the split of processing stages across the different logical nodes in the service chain inclusive of RAN.
    - Ideally, any feasible pre-processing should happen as early as possible to save data rate over interfaces towards the CN, i.e., the transfer of raw sensing measurement data (e.g., I/Q samples) generated by TRPs (O-RUs) should be avoided. Initial pre-processing steps may be performed in the gNB-DU baseband processing (O-DU) or in case of centralized deployment in the gNB-CU (O-CU) or alternatively in the Near-RT RIC taking care of its AI/ML functionalities in xApps. The latter two logical nodes are more appropriate for joint processing of data from several DUs or gNBs, respectively.
    - An open issue is if sensing data transfer is handled via CP as it is the case in the 5G system or if a dedicated data plane with related processing functionalities will be introduced (not to be mixed with the UP in 5GS).

To allow running both positioning and sensing procedures in parallel over the same TRPs, coordination between LMF and SF is required, especially in the case that same Tx RF signals are jointly used for both purposes. Based on analysis to be done within KOMSENS-6G this may finally lead even to the requirement of having an integrated function of LMF and SF.

For the case that there is no active communication link for sensing purposes between the RAN and the UE, LPP-like procedures between SF and UEs are not needed to be considered, i.e., the focus in this case should be on a signalling protocol between the SF and the RAN nodes similar to NRPPa allowing the transfer of sensing related information and supporting corresponding interface management functionalities, e.g., set up and error handling.

For sensing information transfer procedures via a new Sensing Protocol (SP) at least following functions should be considered:

- TRP information transfer: This function allows the SF to obtain TRP related information from a RAN node for sensing purposes.
- Sensing measurement (de-)activation: This function allows the SF to trigger or stop sensing transmissions/receptions at one or several RAN nodes down to TRP level. Sensing may happen periodic, on-demand or event-based.
- Sensing measurement reporting: This function allows to transfer sensing results from NG-RAN nodes to the SF. Which results are transferred is use case dependent and needs further discussion during the KOMSENS-6G project runtime. Data pre-processing steps that may be potentially handled already in the NG-RAN (within a single RAN node and/or in cooperation between nodes) and their impact on the protocol structure needs also further clarification.

Additional functions can be further explored during next phases in KOMSENS-6G.

In case that TRPs from different NG-RAN nodes are jointly involved in sensing measurements, corresponding signaling e.g. on detailed resource allocation and timing is required, if not already fully adjusted via the SF. Details on network aspects and inter-node coordination can be found in Section 4.

It has to be mentioned that the 5GS description given before is seen as a baseline for further work in KOMSENS-6G. We may also take into account new approaches coming up from other research projects and industry fora and addressing novel topics to be potentially incorporated in a 6G system like intelligent networking based on native AI/ML, RAN-CN convergence, and programmable cloud-native platforms. That means that function definitions inclusive of functional splits, computation of network and application functions, and the related signaling in the ICaS context may further change with gradual project runtime.

2.1.2 IEEE WiFi aspects [RWTH, GPP]

Today's communication services are offered on "converged networks". When introducing new services in the core network the design should consider the different technologies of the access networks. That is why WiFi is of interest for KOMSENS-6G in two aspects:

- How is WiFi adressing sensing capabilities technically?
- How will ICaS core services connect to WiFi access points in the future?

Even though these solutions are out of scope for the KOMSENS-6G project, it will be interesting to observe the progress in this area when designing ICaS solutions.

The IEEE 802.11 WiFi working group has recently established a new Task Group, 802.11bf [67], to specify the essential modification to the existing physical and medium access control (PHY and MAC) layers to enhance sensing capability and facilitate easy implementation. More specifically, 802.11bf will operate in both sub-7 and 60 GHz frequency bands and is expected to provide backward compatibility and coexistence with existing WiFi standards such as IEEE 802.11n/ac/ax (in sub-7 GHz) and IEEE 802.11ad/ay (60 GHz). The research on this new standard is still in its infancy and is expected to be commercialized by the end of 2024.

The main focus points are

- To analyze how the sensing framework and procedure in WiFi is different from cellular networks?
- What are the variety of candidate technical features that have been proposed in the literature to enhance the sensing functionality in WiFi

IEEE 802.11bf sensing framework and procedure:

Waveform and Channel: IEEE 802.11bf utilizes the existing 802.11 waveform and channels to support WiFi sensing in sub-7 GHz and 60 GHz mmWave bands. In the sub-7GHz band, waveforms based on orthogonal frequency division multiplexing (OFDM) are utilized, whereas single carrier modulated waveforms are utilized for mmWave frequencies. The signal (pulses) used for sensing are PHY Protocol Data Units (PPDUs) specified by the IEEE 802.11 standard. In addition, each sub-7GHz channel has a bandwidth of 20 MHz and can aggregate up to 320 MHz. In contrast, each channel in the mmWave band is 2.16 GHz wide and can be aggregated up to 8.64 GHz. Having wider bandwith makes mmWave WiFi a suitable technology to enable applications requiring high resolution and high accuracy sensing.

Transceiver roles: The standard specifies two sets of roles for the sensing procedure. First, the station (STA) initiating the sensing is referred to as *sensing initiator* and the STA participating in sensing procedure in response to the requests of sensing initiator in called *sensing responder*. Further, depending on who transmits the sensing signals, two other types of roles are defined. One is *sensing transmitter* and the other is *sensing receiver.* Note that, a sensing initiator can be either a sensing transmitter or a sensing receiver, both or neither, during the sensing procedure [69]. If the sensing initiator is also sensing receiver, it will start the sensing process and will obtain the results by itself, which is similar to monostatic radar. In contrast, if the sensing initiator is the sensing transmitter, it relies on the sensing receiver to take the measurements, which is similar to bi-static/multi-static radar.

Sensing procedure: The sensing procedure of IEEE 802.11bf standard follows five phases [68], as shown in Figure 10.

- *Sensing session setup*: In this phase, sensing-capable devices discover each other. More specifically, sensing initiators establish connection with sensing responders and exchange basic sensing capabilities, which builds the initial steps necessary to for initiating subsequent sensing measurements.
- *Sensing measurement setup*: This phase is a setup for the sensing initiator and sensing responder to negotiate and agree on operational parameters associated with a specific sensing application.
- *Sensing measurement instances*: In this phase the actual sensing process goes on, where the PPDU pulses are transmitted, and the corresponding measurements are done at the sensing receiver end.
- *Sensing measurement termination*: In this phase, corresponding sensing measurement setups are terminated, and the sensing initiator and responder releases the allocated resources to store the sensing measurement setup.
- *Sensing session termination*: In this phase, STAs stop performing sensing measurement and terminate the sensing session.

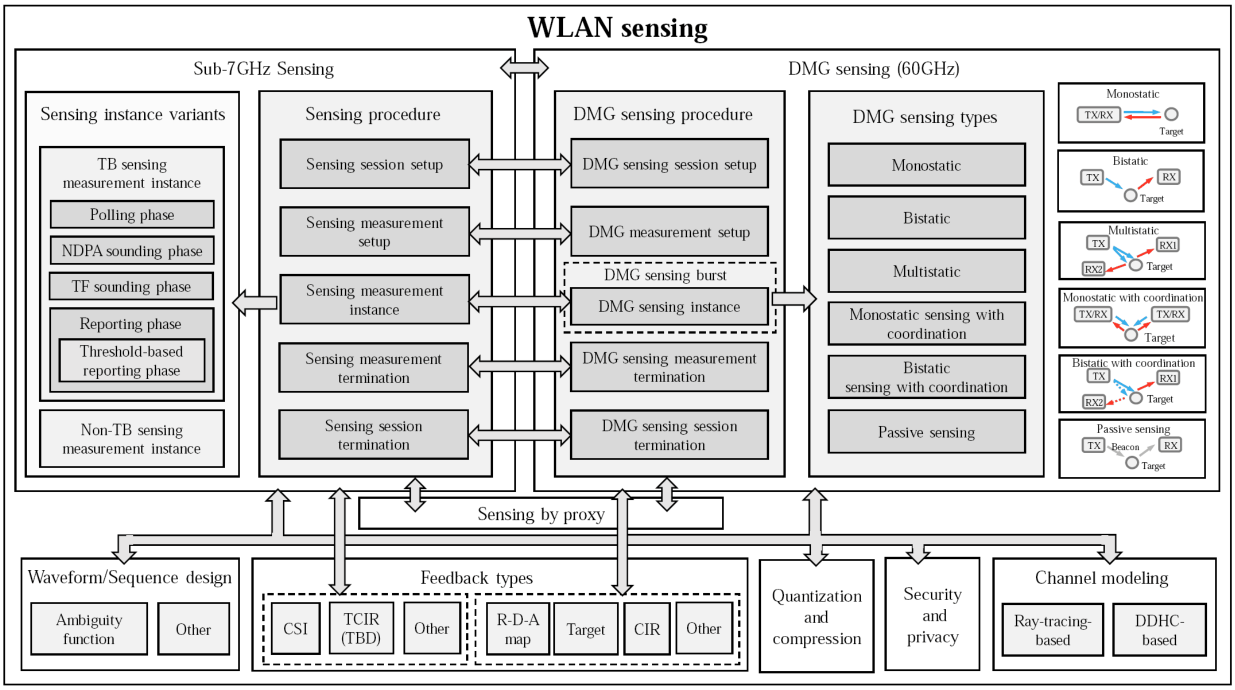


Figure 10: Sensing procedure of IEEE 802.11bf [68]

Sensing measurement report format: The sensing measurement report corresponds to the collected measurement results reported by the sensing receiver. In order to implement various sensing applications, it is critical to provide appropriate sensing measurement results in the feedback. IEEE 802.11bf specifies different measurement report format depending on the application requirements at sub-7GHz and 60 GHz. For sub-7GHz, sensing measurement report includes full channel-state information (CSI), partial CSI, power-delay profile (PDP), truncated power-delay profile (TPDP)/truncated channel impulse response (TCIR). For 60 GHz, the measurement report includes full CSI, range-doppler-angular (R-D-A) information per detected target.

Regarding sensing in WiFi 802.11 bf, concepts of WiFi Station roles, from the sensing procedure as well as the sensing feedback types and compression schemes may be partly applicable also to 3GPP 6G ICaS mobile networks and will be further explored in the project.

Sensing in spectrum-sharing bands: WiFi-devices will share spectrum with incumbents in the 6 GHz band, such as 5G NR-Unlicensed. Coexistence between 6G mobile ICaS technology and WiFi technology will however not be studied in the project.

2.1.3 IEEE Standard for Low-Rate Wireless Networks (IEEE 802.15.4z) [BOSCH]

The standard of IEEE 802.15.4z comes as an enhancement of the previous standards for the Impulse Radio Ultra-Wideband (UWB) technology. The main improvements provided by IEEE 802.15.4z are increasing ranging capabilities, reduced power consumption and more security. To achieve these improvements the standard, that was published as an amendment IEEE 802.15.4z [47], provides changes in the MAC layer and the support of new settings for the PHY layer have been suggested. Furthermore, the optional insertion of a cryptographically-generated scrambled timestamp sequence (STS) in the UWB frame was proposed. In the following, we present a brief discussion of some aspects of this standard.

Four different packet configurations are defined by IEEE 802.15.4z, namely SP0 to SP3 as shown in Figure 11. These different configurations enable either to entirely omit the STS (SP0), or to insert it in the frame at different locations (SP1 to SP3). The SP3 option allows to reduce the airtime during ranging by avoiding the transmission of payload altogether, i.e., no communication is performed in this case. The physical header (PHR) provides necessary information to the receiver about the data rate and the length of the payload field.

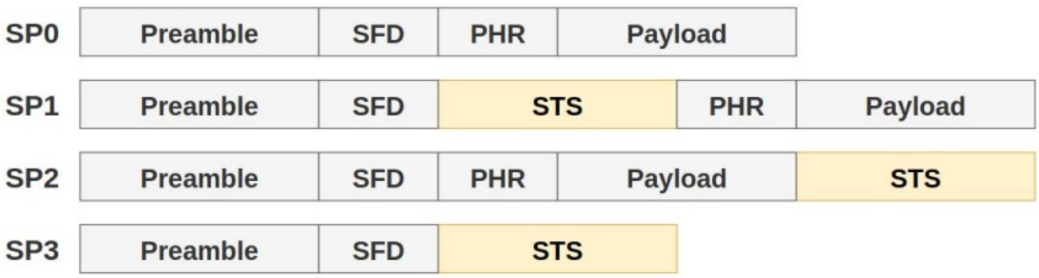


Figure 11: IEEE 802.15.4z-compliant frame configurations [48]. Note that SFD stands for Start of Frame Delimiter, PHR for Physical Header and STS for Scrambled Timestamp Sequence

One of the most noteworthy features supported by IEEE 802.15.4z is the employment of two-way ranging (TWR) time of flight (ToF) which can yield precise estimates of the relative distance, i.e., range between two devices, namely the fixed location sensor (anchor) and the mobile device (tag). To obtain the required measurements, a transmitted frame and response frame are used. Overall, the following relative positioning methods for the time difference of arrival (TDOA) are supported:

- Single-sided two-way ranging (SS-TWR)
- Double-sided two-way ranging (DS-TWR)
- One-way ranging (OWR)

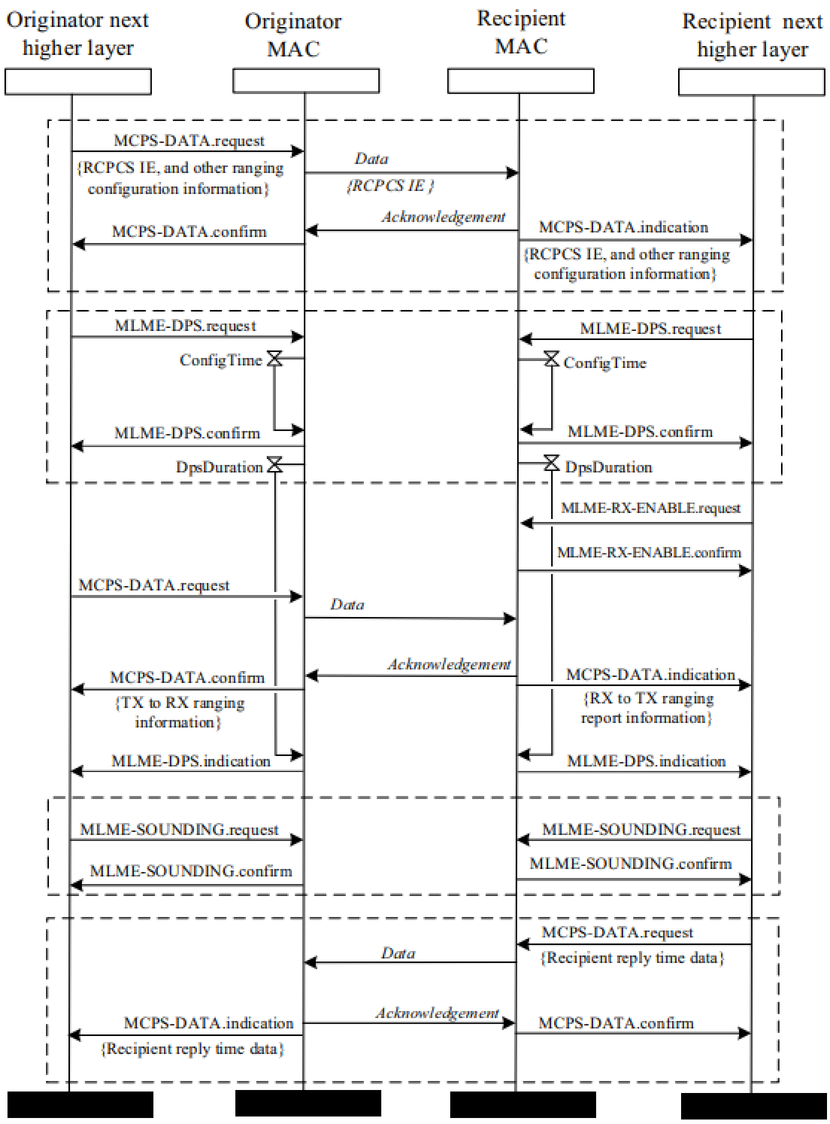


Figure 12: An example of a message sequence for ranging as defined by IEEE 802.15.4z [47]

An example of message sequence that might be used for TWR is shown in Figure 12**.** Note that the messages within the two top dotted boxes are only suggestions clarifying how communications capability of the Ranging Capable Device (RDEV) can be used to set up the ranging activities. Similarly, the messages in the bottom dotted box are also only suggestions showing how the communications capability of the RDEV can be used to accomplish the ranging finish-up activities. For more details on this topic, we refer the reader to Section 6.9 of the standard [47].

As IEEE 802.15.4z is a point-to-point radio system, the aspect of resource allocation is rather trivial and the aspect of coordination between multiple nodes does not exist. For this reason this technology is not considered in chapters 3 and 4.

2.2 Radar systems [BOSCH]

Protocol design in radar systems inherently plays a smaller role than for communication networks, as protocol aspects like communication error detection and correction do not exist in radar. Some other aspects depend on whether the radar is monostatic or bi-/multistatic and whether there is coordination among radars for interference management of for executing the sensing itself, as in bi-/multistatic sensing, or for mobility support, e.g. tracking targets while they're moving across the reach of multiple radar stations. Here we provide an overview on the physical layer, in the form of radar waveforms, and briefly address the MAC layer, or the absence thereof.

2.2.1 Radar Waveforms [BOSCH]

In radar systems, the waveform is the specific pattern of transmitted signals that is used to extract information about the target. Different types of waveforms are used for different radar applications, such as detecting moving targets or measuring the distance and speed of targets.

Here we discuss the most relevant waveforms for radar systems. The main ones are:

- **Pulse-Doppler:** Used for detecting moving targets. This protocol involves transmitting a series of short pulses, each with a specific frequency, and then measuring the frequency of the echo that is reflected back from the target. By analyzing the frequency shift of the echo over time, the radar can determine the velocity and distance of the target [35].
- **FMCW (and variations thereof):** Frequency-Modulated Continuous Wave (FMCW) is a continuous wave signal with a modulated frequency to measure the range and velocity of objects. In FMCW radar, the transmitted signal is characterized by a linearly increasing or decreasing frequency over time, creating a frequency sweep or "chirp." As this chirp signal interacts with targets, the received signal is mixed with the transmitted signal, resulting in a beat frequency proportional to the target's range and Doppler shift [40]. By analyzing the beat frequency, the radar system can accurately determine the range and velocity of objects, offering advantages such as high range resolution, immunity to certain types of interference, and the ability to simultaneously track multiple targets. Other variations of FMCW such as the fast-chirp FMCW are also well described in [40].
- **OFDM:** Orthogonal Frequency-Division Multiplexing (OFDM)-based radar is a radar system that utilizes the principles of OFDM modulation commonly employed in communication systems. In OFDM-based radar, the radar waveform is divided into multiple orthogonal subcarriers, each with its own narrow bandwidth. These subcarriers are transmitted simultaneously and independently, allowing for efficient utilization of the available bandwidth. The radar system exploits the inherent orthogonality between the subcarriers to achieve high spectral efficiency and robustness against multipath interference. The received signal is then processed using advanced signal processing techniques such as fast Fourier transform (FFT) to extract range and Doppler information from individual subcarriers, see for example [41]. Note that for radar-applications other variations of OFDM have also been studied, such as the stepped-carrier OFDM [42].
- **PMCW:** Phase-Modulated Continuous Wave (PMCW) is the second main digital modulation scheme along OFDM (in automotive context also known as PN radar). The main idea behind this scheme is mapping sequences of binary symbols onto 0°- and 180°-degree phase shifts of a continuous radio frequency carrier [43]. This approach dramatically reduces the risk of interference. However, this approach requires an entirely new radar architecture. "*Uhnder*" has demonstrated a bi-phase coded system that has proven efficient in mitigating interference. The noise and power consumption of the overall system will necessarily increase with such systems.

2.2.2 Access Methods [BOSCH]

The protocol layer in radar systems refers to the set of rules and procedures that govern the transmission and reception of the waveform. This includes aspects such as when and how often to transmit the waveform, how to process the received signals, and how to manage access to the radar resources.

Time-Division Multiple Access

Radar systems typically use a time-division multiple access (TDMA) scheme, where multiple radar units take turns transmitting and receiving signals. This helps to prevent interference between radar systems and allows for efficient use of the available bandwidth. In TDMA, the available time is divided into equal time slots, and each radar unit is assigned a specific time slot for transmitting and receiving signals. This ensures that each radar unit has exclusive access to the resources during its assigned time slot, and reduces the likelihood of interference with other radar systems.

Frequency-Division Multiple Access

Another access method used in some radar systems is frequency-division multiple access (FDMA), where each radar unit is assigned a specific frequency band for transmitting and receiving signals. This helps to reduce interference between radar systems that are operating in close proximity to each other.

2.2.3 Communication vs. Radar Technology

Communication networks has long been established for dealing with resource allocation problem for treating interference. For this purpose, a medium access control layer (MAC) has been established responsible for allocating orthogonal resources such that the users do not experience interference. The schemes like TDMA, FDMA, CDMA, SDMA are the realizations of interference avoidance strategies in time, frequency, code. space domains.

However, current radar technology suffers from the absence of MAC layer, which in turn impedes the coordination between users for achieving interference avoidance. Hence, current radar technology deals with interference cancellation via signal processing. If radar technology tends to adopt interference management schemes from communication technology, a MAC layer needs to be integrated in radar systems. This can be directly implemented as an extra layer, which facilitates coordinated radar problem as well.

In the following section, we explain how interference between radars can be mitigated in spite of the non-existence of signaling protocols.

3 Resource Allocation

3.1 3GPP networks [NOK]

Radio resource allocation is concerned with allocating the dimensions of time, frequency and space (and possibly further ones like polarization) to different users and services.

First a brief overview of the NR radio resource structure is provided here.

In the time domain, NR transmissions are organized into frames of length 10 ms, each of which is divided into 10 equally sized subframes of length 1 ms. A subframe is in turn divided into slots consisting of 14 OFDM symbols each, that is, the duration of a slot in milliseconds depends on the numerology as illustrated in Figure 13. On a higher level, each frame is identified by a system frame number (SFN). [1]

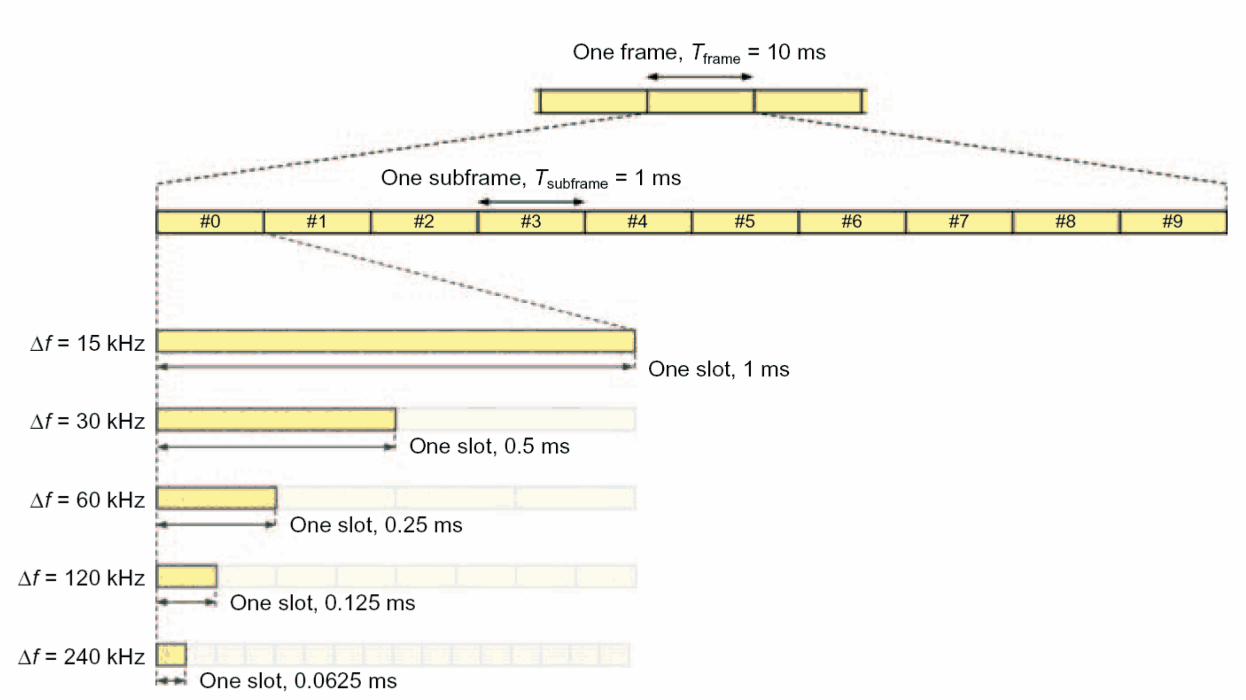


Figure 13: Time structure of NR for different subcarrier spacings

A resource element, consisting of one subcarrier during one OFDM symbol, is the smallest physical resource in NR. Furthermore, as illustrated in Figure 14, 12 consecutive subcarriers in the frequency domain are called a resource block. [1]

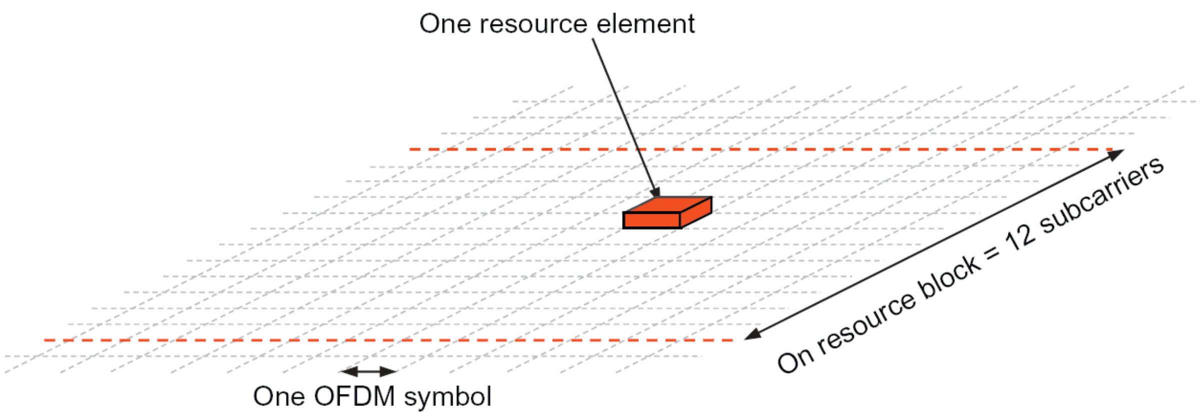


Figure 14: Relation between resource element, resource block, subcarrier and OFDM symbol

Gap discussion

For radars two methods are known to limit the interference from the transmit signal into the receiver: Full Duplex (FD) operation, with analog/digital interference mitigation in combination with antenna separation, and time-division duplex (TDD), where the radar signal consists of only a short pulse and the transceiver is switched from TX to RX. For TDD operation to work, the pulse needs to be shorter than the round trip time from the closest target. Figure 15 shows the relation between pulse duration and distance R_{min} to the closest target. Noting that the shortest NR OFDM symbol duration is 62.5us, it becomes clear that pulses extending over an OFDM symbol period cannot be used for TDD operation.

A candidate solution is to generate shorter pulses, which can be achieved even with the established NR OFDM transceiver structure, by properly precoding the input to the OFDM modulator, as outlined in the Work Package 3 part of this report.

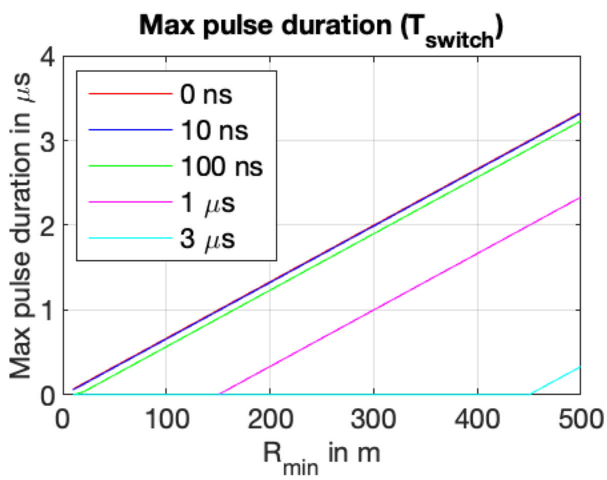


Figure 15: Maximum pulse duration vs distance to closest target for different TX/RX switching durations

If the method of FD is used, i.e. radar pulses of any duration can be used, the following resource allocation aspects need to be taken into account for a ICaS concept.

The minimum pulse repetition time of a monostatic radar is given by:

$$T_r > 2R_u/c$$

for a given unambiguous range R_u and c the speed of light. The unambigous range can be regarded as the maximum range of the radar system.

- Reception requires FFT across subcarriers
  - Received copy of transmitted radar signature involves terms like $s(n-\tau_l)$with τ_l the RTT of scatterer l
  - After application of FFT, this delay becomes $\exp(-j2\pi \cdot k \cdot \Delta f \cdot \tau_l)$ (substituting $N \cdot \Delta f \cdot \tau_l = n_l$ leads to classical DFT formula)
    - Normalized distances (RTT) $\Delta f \cdot \tau_l$ and $\Delta f \cdot \tau_l + m$ (m any integer cannot be distinguished from each other) →Unambiguous range $R_u = \frac{c_0}{2 \cdot \Delta f}$
    - Δf is the frequency separtion between two subcarriers used for radar (i.e. either OFDM subcarrier spacing or comb width in Hz)
  - If all subcarriers are used the RTT delay needs to be more than one OFDM symbol →not a serious limit.

$$\frac{2R}{c_0} < \frac{1}{\Delta f} \rightarrow R_u = \frac{c_0}{2 \cdot \Delta f}$$

- If a comb is used the signal becomes periodic within a symbol duration and above RTT limit is reached when the RTT exceeds the repetition duration. For a comb using every mth subcarrier (symbol is repeated m times within $\frac{1}{\Delta f}$ in time domain):

$$\frac{2R}{c_0} < \frac{1}{m\Delta f} \rightarrow R_u = \frac{c_0}{2m\Delta f}$$

- Another range limit is the CP length: For standard per-symbol OFDM processing the latest echo needs to arrive within the CP →This limit is typically more stringent than the unambiguous limit above
  - If latest echo arrives outside CP more advanced signal processing is likely needed, but smooth degradation

PRS frequency stitching

GPP Communication investigates the concept of PRS frequency stitching within WP 4. The initial investigations are presented as follows.

PRS frequency stitching is a mechanism where DL PRSs [32],[33] are processed over aggregated DL PRS resources (e.g., 2 frequency layers in Figure 16) for the enhanced positioning, that is:

- the mechanism to support the coherent reception [31] of the DL PRS from multiple frequency layers
- the mechanism to study DL PRS bundling in the frequency domain, with considerations for “PRS stitching” in both intra-band and inter-band scenarios.

Figure 16: PRS frequency stitching, where CC means component carrier and θ random phase offset between both CCs*from* [32],[33]

Further, the below crucial points can be checked for their realistic applicability in sensing.

- The scenarios and performance benefits of aggregating multiple DL positioning frequency layers
- Analysis of coherent and non-coherent frequency stitching methods (structure of the frequency spectrum)
- Analysis of imperfect synchronicity between different nodes
- The impact of channel spacing, timing offset, and power imbalance among *component carriers (CCs*) on the positioning performance for intra-band and inter-band scenarios

Regarding the state-of-the-art, the frequency stitching has been identified in previous 3GPP studies as one promising positioning enhancement technique. Specifically, in Rel-17, to increase the bandwidth for transmission and reception of PRS, bandwidth aggregation for intra-band carriers is briefly investigated. So far, the Rel-18 work will also consider the frequency stitching technique as positioning enhancement, with a focus on intra-band carriers [34].

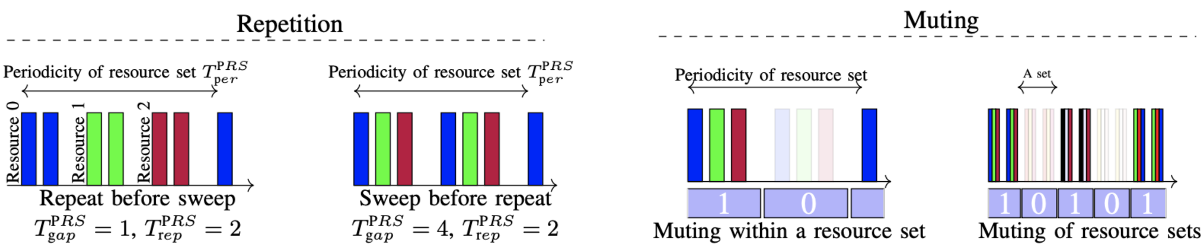
In conclusion, even though the PRS with frequency stitching concept is under study in 3GPP, the application of frequency stitching realistic sensing scenarios may be analyzed in KOMSENS-6G project.

The preceding discussion highlights several design options in the resource allocation for sensing that should be further explored in the project.

The ICaS resource allocation can learn from that of the Positioning Reference Symbols (PRS) that are used for positioning in NR. A good introduction to the PRS resource allocation is given in [2]:

"PRS are transmitted in certain positioning subframes grouped into positioning occasions. A positioning occasion is characterized by its length and periodicity. These two parameters describe the PRS configuration, which is a part of the assistance data signalled to the UE. Since LTE release 9, a positioning occasion can be 1, 2, 4, or 6 consecutive positioning subframes, which occurs periodically with a 16, 320, 640, or 1280 ms interval. Since release 14, some UEs also support new positioning occasion lengths, which can be any number between 2 and 160, and new periodicities of 5, 10, 20, 40, and 80 ms.

Within each positioning occasion, PRS are transmitted with a constant power. PRS can also be transmitted with zero power, or muted, which can be utilized to avoid measuring in the presence of the strongest interferers. The PRS muting configuration of the serving and neighbor cells are to be decided by the network and signalled to the UE over the LPP protocol."



T_{gap}^{PRS} = Gap between resources
T_{rep}^{PRS} = Number of resource repetition
T_{per}^{PRS} = Period of resource set

Figure 17: PRS time domain resource allocation parameters

Dynamic resource allocation in wireless communications networks

There are very many different resource allocation algorithms based on a wide variety of scenarios and environments, however, the design of these algorithms basically requires consideration of the following elements. [27]

- Spectral efficiency, which aims to maximize the system data throughput with the help of channel quality indicators (CQI).
- Fairness, which guarantees minimum performance of each user, especially for the users with bad channel conditions, e.g., the cell-edge users.

- QoS provisioning, which considers the requirements of different services, the metric could refer to minimum guaranteed bitrate, maximum delivering delay, or packet loss rate.
- Complexity and scalability: considering more metrics could bring better performance regarding the spectral efficiency and fairness, but high complexity brings high computational costs, making it impossible to achieve real-time processing in deployment.

Requirements of a radio communication system towards a MAC scheduler are the following:

- Enforce policies defined by the network operator.
  Policies are consequences of a network operator's business model. Assuming e.g., a railway company that operates a wireless network to ensure safety of its operations and increases the comfort of passengers by providing a free communication service. A reasonable policy of this hypothetical company network would always prioritize safety over the comfort of its passengers. Another example for policies could be from the context of public network operators that share a base station in a rural environment. They could agree at a minimum share of their respective resources. It is the MAC schedulers task to enforce constraints resulting from these policies [3] [4].
- Exploit the time-, frequency- and space- variant nature of radio propagation.
  Fast Fading is an essential property of radio channels. It expresses the fact that the channel capacity between two communicating entities is not constant but varies over time and frequency [4]. Therefore, a scheduling gain can be collected, if transmissions are scheduled to a time and frequency resource that has a relatively better than that channel's average capacity. This corresponds to the working principle of the well-established proportional fairness. MIMO techniques extend this principle into the channel's spatial domain. In support for this technique, current radio communication networks are allowing for supporting measurements.
- Efficient use of resources

A scheduler can only take reasonable decisions in a stable system. In general, radio communication systems therefore control which connections are admitted to the network.

The term scheduling can refer to both: the allocation of resources and the mechanisms to obtain the information required to take the allocation decision. Beyond the task to allocate resources for communications payload, the scheduler is also responsible to allocate resources for control signalling including the one required for control information acquisition .

Since there are plenty of resource allocation algorithms based on different considerations, we cannot cover them all, so here we only introduce some basic algorithms.

- Round Robin (RR): are used when CQI is unaware. RR uses the amount of time that the users are served in history as metric to make sure that each user will be served. In this context, the fairness in occupancy time is maximized but the system throughput is not optimal.
- Generalized Proportional Fair (GPF): [28] It is a typical way to find a trade-off between fairness and spectral efficiency. Proportional Fairness means the ratio of throughputs among users is equal to the ratio of CQI, where the throughput metric is typically taking into account multiple previous scheduling events. In Generalized Proportional Fairness, the importance of system throughput and fairness can be adjusted by setting a parameter.

- Schedulers for Guaranteed Data-Rate: [29] this considers the priorities of different services. First, in the time domain users are sorted according to their urgency (to meet the QoS requirements), and then in frequency any variant of the PF algorithm can be applied to guarantee the throughput and fairness among high-priority users.
- Schedulers for Guaranteed Delay Requirements: for example, Modified LWDF (M-LWDF) [30]. It is a CQI-aware extension of LWDF and provides bounded packet delivery delay.

5G networks are offering a wide range of services based on complex mechanisms. The task of MAC scheduling is to coordinate different parts of these systems such that a service is provided to network users. The decisions of a MAC scheduler in these systems are ruled by channel capacity. More concisely, the scheduler compares different resource options (e.g. time, frequency, beams or layers) of the current radio channel to a user and decides under considerations of the limits set by the higher layers and the capabilities of the involved devices.

With the introduction of localization and sensing services in 5G and 6G networks, this situation changes. In contrast to the communication services, these new services need new performance metrics, and the scheduler needs new ways to trade off the performance between sensing and communication needs.

For ICaS resource allocation we can distinguish the cases

1) Communication signal is also used for sensing

2) Communication and sensing signals are multiplexed

For 1), the sensing requirements in terms of bandwidth, energy, susceptibility to interference and repetition rate need to be inputs to the scheduling algorithm. At times when there is no data for communications into a direction of interest for sensing, but a sensing signal needs to be transmitted to fulfill the above requirements, a sensing-only signal has to be scheduled.

For 2), for sensing a resource allocation pattern that is at least short-term fixed appears to make sense. The existing semipersistent scheduling framework may be reusable. Communications would then be scheduled around the sensing resources. For Ultra-reliable Low latency communication (URLLC), preemption or postponing of sensing resources that are then repurposed for URLLC should be considered.

For comparison: In NR positioning the PRS transmission is not dynamically scheduled and is not (short term) adaptive to the channel between the transmitter(s) and the receiver(s). Such adaptivity could be investigated in the second phase of the project. Adaptivity to characteristics of the sensing target should be taken into account, e.g. the velocity, and possibly also adaptivity to the clutter characteristics.

3.2 Radar systems [GPP]

Radar Resource Management (RRM) is an important part of radar systems whenever the radar resources are not sufficient to perform all required function tasks, like surveillance, tracking, confirmation, etc. In such cases, some tasks might need to be performed using a degraded performance or even dropped, due to insufficient available resources. Each function task implies a different requirement with respect to the three major resources of a radar system,

- Time

- Energy
- Computation

While the energy and the computational resources are limited by the transmitter energy and the processing unit of the system, time is characterized by the mission requirements. These limitations have impacts on the performance of the RRM and therefore on the performance of the whole radar system.

In case of a network of radar systems, the RRM has the additional task to synchronize and distribute the radar tasks between the different nodes of the network, e.g. the distribution of surveillance and tracking tasks in case of overlapping Field of View (FoV) of several nodes, or a proper synchronization for the extension of the FoV of several network nodes.

The model of a general RRM system is shown in Figure 18. It performs the following steps:

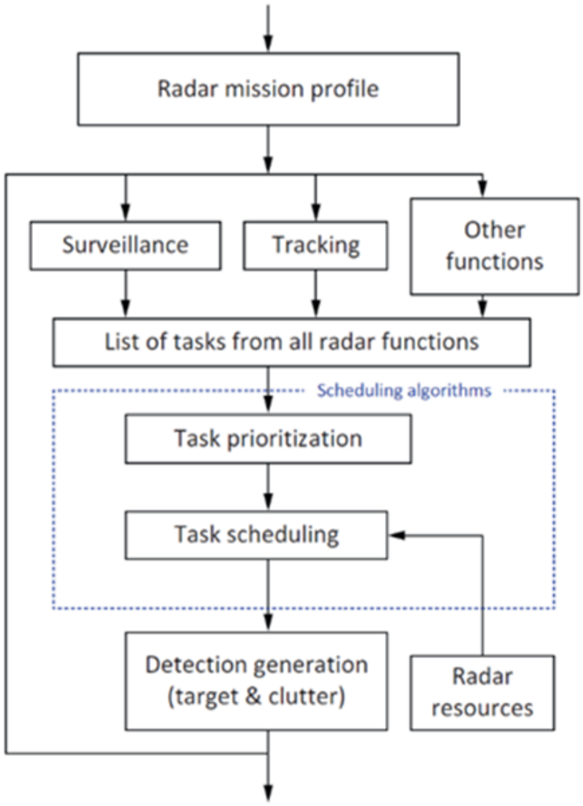


Figure 18: General model of a radar resource management [54].

- Obtain a radar mission profile or function setup.
- Generate radar tasks.
- Assign priorities to tasks by using a prioritization algorithm.
- Manage available resources using a scheduling algorithm, such that the system can meet the requirements of all radar functions.
- For non-surveillance tasks, schedule a re-look if a target was not detected or confirmed. This will depend on the task priority and elapsed time since the last scheduling of the same task.

3.2.1 Overview of RRM Techniques

Several innovations focus on the improvement of the RRM performance. Some of them are still experimental, others are implemented in state-of-the-art products in operation.

Perception-Action Cycles

In the last decades several techniques based on perception-action cycles were developed [53]These methods use lists of predefined waveforms and parameter setups, from which actions are chosen, depending on the previous measurement (perception). The following list of techniques increases in adaptivity [53]:

- Track-while-Scan
- Alert-Confirm
- Active Tracking
- Adaptive Tracking
- Adaptive Searching

Most of these perception-action cycles have been demonstrated in experimental and implemented in operational systems [53].

Artificial Intelligence Algorithms

The usage of Neural Networks (NN) for RRM is proposed in several scientific publications [54][55]. A list of publications, sorted by RRM tasks and AI techniques can be found in [55]. Mainly classification neural networks are used for task prioritization, task scheduling and track classification. No reports have been found that such algorithms are implemented in any prototype or operational radar system. The generation of meaningful training data is a big challenge, since this will dictate the effectiveness of NN algorithms.

The Expert System approach, which is proposed in some scientific publications, uses a knowledge-based system for Parameter Selection, Task Prioritization and Task Scheduling. No report has been found that such a system is currently implemented in a real radar system.

The use of fuzzy logic to resolve the conflicts of an adaptive scheduler are reported in several publications. Moreover, it allows for adaptive prioritization and was used for waveform selection and energy management. With Adapt_MFR a fuzzy logic controller was implemented in a phased array radar simulator, which showed to be able to prioritize targets, such that they could be scheduled accordingly. “The processing speed of the fuzzy controller is fast, making it useful in real radar systems” [54].

The proposal of an Entropy Algorithm is found in literature, which is based on the concept of information entropy and provides an additional approach for track prioritization. It heavily depends on modeled target dynamics, which are unknown in a real application. An implementation in a current system is not reported.

Dynamic Programming Algorithms

The Dynamic Programming (DP) approach is a nonlinear optimization method, using statistical models e.g. Multi-arm bandit problem involving hidden Markov models. It serves for both, task prioritization and task scheduling. This approach is in the research stage and needs further studies with more realistic constraints.

Q-RAM Algorithms

Q-RAM algorithms are based on the QoS concept, which uses a cost function of performance and tries to maximize the global system utility. It solves both task prioritization and task scheduling simultaneously. Currently the Q-RAM algorithms in radar applications are in a research stage.

Waveform-Aided Algorithms

Waveform-Aided algorithms assume a given task prioritization and scheduling module. They focused on improving radar resource requirements by reducing time, energy, and processing budgets using waveform selection. Waveform diversity is well known in the radar and communication community. The usage of different waveforms is realized in several operational system, where the waveforms are chosen from a fixed library. In future the waveforms should be generated adaptively, taking into account the mission profile as well as the environment.

Adaptive Update Algorithms

Adaptive update algorithms are mainly focusing on the optimization of traditional trackers, by optimizing Kalman filter update intervals to save resources. These algorithms have been used in many radar systems, but the optimal adaptive rate is still an ongoing topic, due to the complexity of formulating motion noise models for adaptive tracking.

Adaptive Scheduling Techniques

The Time Balancing Scheduler (TBS) is a simple and efficient method, which was implemented for the MESAR system and is often implemented in operating systems. It keeps a time balance for all functions and picks the function with the maximum time balance for scheduling, at any scheduling time. Linear programming is used to find the optimal schedule, considering cost functions for data link, tracking and searching [61].

3.2.2 Radar Resource Management for Networked Radars

Resource Management in a radar networks extents the RRM of a single radar by the additional task to distribute multiple tasks between multiple network nodes.

In general, two different architecture concepts of resource management in radar networks are considered, which are depicted in Figure 19. A distributed or decentralized RRM is managing the resources of the single nodes locally at the network node, while a centralized RRM manages the resources at a central node. In both cases a communication between the different nodes is required.

The relationship between coverage areas of network nodes as important characteristic in RRM for radar networks. In areas with overlapping FoV, tasks must be assigned between nodes while in non-overlapping areas the assignment is naturally defined, since the nodes act as in the single radar case. When coverage areas of nodes extent each other, tracking tasks can be handed over or surveillance tasks need to be synchronized. These considerations add further complexity to the network RRM.

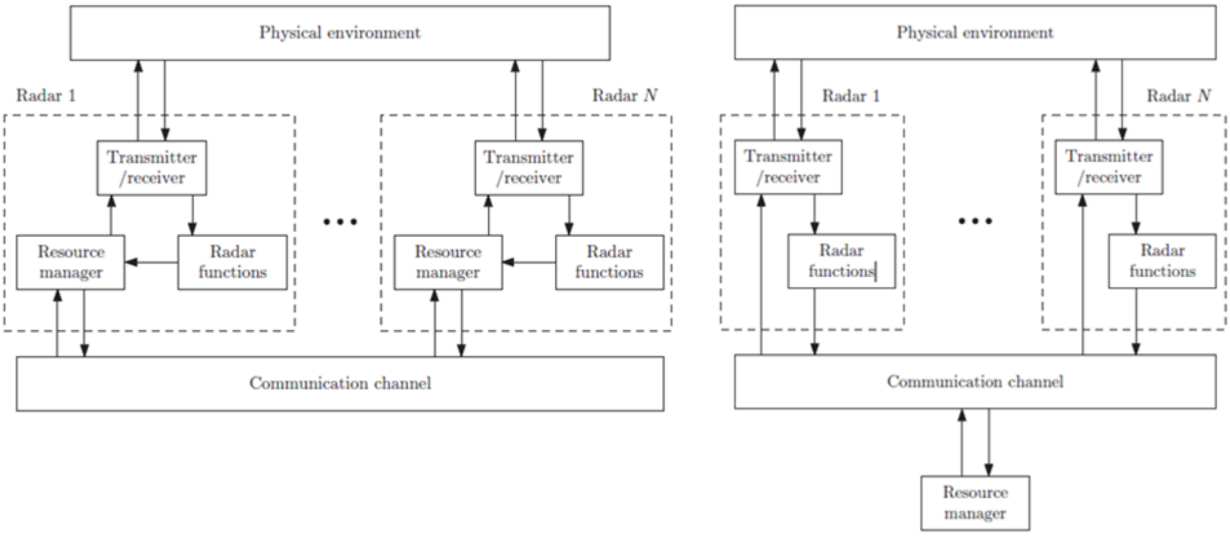


Figure 19: Resource management architecture in a radar network. Left: distributed management architecture. Right: centralized management architecture [54]

Scheduling approaches for RRM for radar networks are part of the current research. Here several different techniques are proposed, like the modelling of track scheduling as a partial observable Markov decision process and formulating a scheduling solution based on particle filtering [63]. Other approaches
model track scheduling by using a modified Quality-of-Service Resource Allocation Model [65] or use a minimization of sensor loading [62]. The latter considers the scheduling of both tracking and surveillance tasks for networked radars and quantifies both tracking and surveillance performance. All these methods are not reported to be implemented in currently operating systems.

Distributed Tracking is another important management aspect in radar networks, with data association being a key problem. In general, three types of distributed tracking can be considered:

- independent tracking.
- distributed track fusion (track-to-track data association)
- distributed track maintenance (measurement-to-track data association)

Current systems for space surveillance use some hybrid form of the two latter types. Here the orbits of space objects are catalogued and different sensors (not really a network) create independent measurements and tracks, correlate these with the information from the catalogue, and update tracks in case of measurements of known objects. However, this is performed offline, and the sensors do not need to be in a network with communication between the nodes.

For the prioritization of targets and surveillance tasks in radar networks, the literature proposes adaptations of known RRM techniques for single systems. These include fuzzy logic prioritization, time-balancing scheduling or the usage of adaptive track update intervals. No reports are found that these are used in currently operating systems.

A very rudimentary form of resource management in a radar network is the example of the so called “Radar Tango” in the German C-band weather radar network [64]. Here the different weather radar nodes are synchronized with respect to their view angle to avoid interference between neighboring radar nodes.

4 Network aspects and coordination of multiple nodes

4.1 3GPP networks [EDD, FAU, TUIL, GPP]

In wireless communication networks, the concept of Coordinated Multipoint (CoMP) is well known. A good overview is provided in [1]

"The first release of LTE included specific support for coordination between transmission points, referred to as Inter-Cell Interference Coordination (ICIC), to control the interference between cells. However, the support for such coordination was significantly expanded as part of LTE Rel-11, including the possibility for much more dynamic coordination between transmission points.

In contrast to Rel-8 ICIC, which was limited to the definition of certain messages between base stations to assist coordination between cells, the Rel-11 activities focused on radio-interface features and device functionality to assist different coordination means, including the support for channel-state feedback for multiple transmission points. Jointly these features and functionality go under the name Coordinated Multi-Point (CoMP) transmission/reception. Refinement to the reference-signal structure was also an important part of the CoMP support, as was the enhanced control-channel structure introduced as part of Rel-11, see below.

Support for CoMP includes multipoint coordination—that is, when transmission to a device is carried out from one specific transmission point but where scheduling and link adaptation are coordinated between the transmission points, as well as multipoint transmission in which case transmission to a device can be carried out from multiple transmission points either in such a way that that transmission can switch dynamically between different transmission points (Dynamic Point Selection) or be carried out jointly from multiple transmission points (Joint Transmission) (see Figure 20).

A similar distinction can be made for uplink where one can distinguish between (uplink) multipoint coordination and multipoint reception. In general, uplink CoMP is mainly a network implementation issue and has very little impact on the device and very little visibility in the radio-interface specifications.

The CoMP work in Rel-11 assumed "ideal" backhaul, in practice implying centralized baseband processing connected to the antenna sites using low-latency fiber connections. Extensions to relaxed backhaul scenarios with non-centralized baseband processing were introduced in Rel-12. These enhancements mainly consisted of defining new X2 messages between base stations for exchanging

information about so-called CoMP hypotheses, essentially a potential resource allocation, and the associated gain/cost."

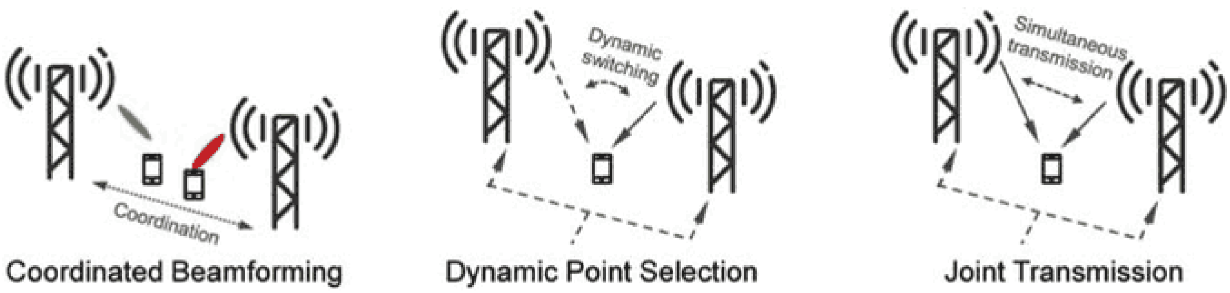


Figure 20: 3 main CoMP operating methods [1]

Multiple Transmission-Reception-Points (multi-TRP)

In NR, transmission to and reception from a UE is supported with up to 2 TRPs. Control information (PDCCH, PUCCH) and thereby scheduling can be provided separately from both TRPs. PDSCH transmissions may overlap in time-frequency domain. So, multi-TRP does not necessarily involve coordinated resources between TRPs, at least not in the sense that overlap is totally avoided.

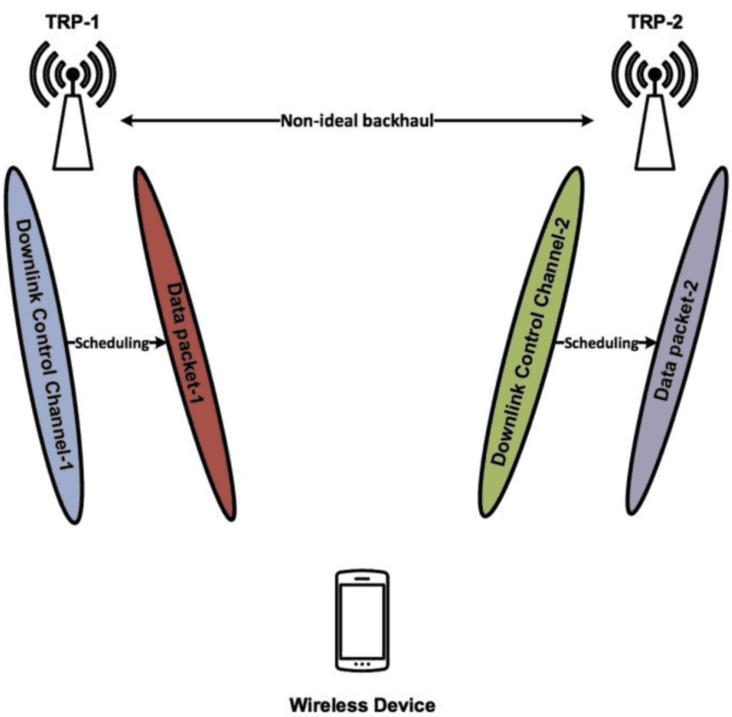


Figure 21: Multi-TRP operation principle, retrieved from https://ofinno.com/article/multiple-transmission-reception-architecture-5g/

The multi-TRP framework should be kept in mind when designing protocols for bi-/multistatic sensing. For example, for the calculation of sensing target positions, it needs to be signaled which of the TRPs has actually been transmitting and/or which one has been receiving. Also, the resource allocation coordination option of multi-TRP may be extendable to bi-/multistatic sensing.

PRS transmission coordination across multiple cells

A good introduction to the Positioning Reference Symbols (PRS) resource allocation is given in [2]:

"To further improve hearability of PRS, positioning subframes have been designed as low-interference subframes (LIS), that is, with no or low transmission activity on data channels. As a result, ideally in synchronous networks PRS are interfered by other-cell PRS with the same PRS pattern index, that is, the same frequency shift, but not by data transmissions. To achieve good positioning performance, interference coordination for PRS is crucial in these subframes. Therefore, configuring aligned positioning subframes over cells is a justified PRS planning strategy giving synchronized positioning occasions in subframe-synchronized LTE networks and up to half-subframe-aligned positioning subframes in asynchronous LTE networks."

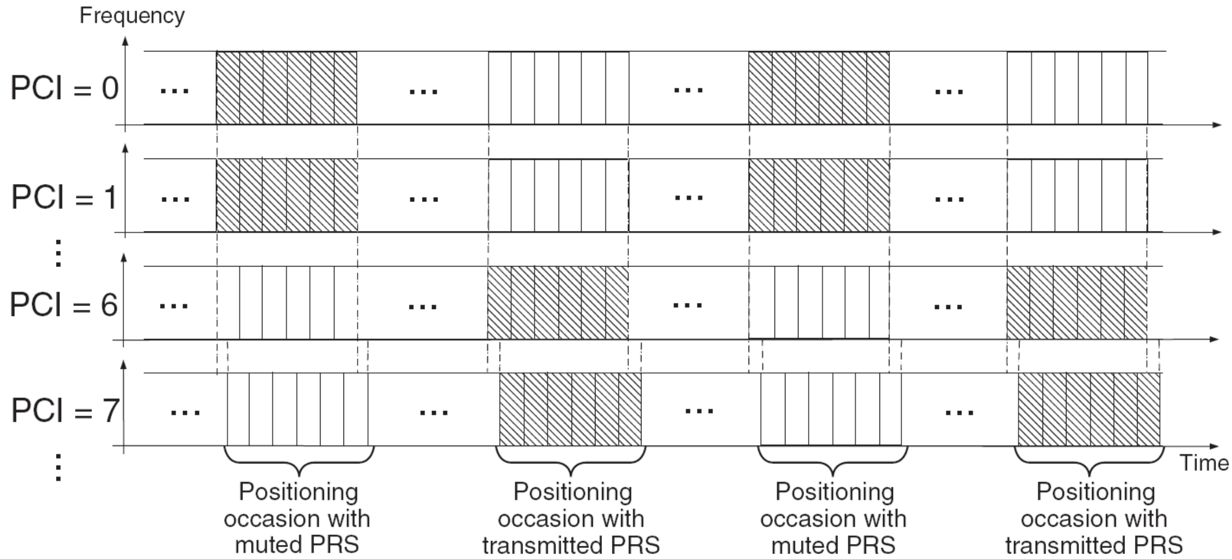


Figure 22: A PRS configuration example for three subframe-synchronized cells that are half-subframe-aligned with the fourth cell. The dashed rectangles are the positioning occasions with transmitted PRS that are otherwise muted in other positioning occasions. A positioning occasion comprises six consecutive PRS subframes

The interference to PRS can be further minimized, for example, by allowing simultaneous PRS transmissions for groups of cells with either orthogonal PRS patterns or low mutual interference. A PRS configuration example for four cells is illustrated in Figure 22. In OTDOA, the UE receiver has to deal with PRS from neighbor cells, much weaker than those received from the serving cell. Furthermore, without the approximate knowledge of when the measured signals are expected to arrive in time and what is the exact PRS pattern, the UE would need to search the signals blindly, which would impact the time and accuracy of the measurements. To facilitate UE measurements, the network transmits assistance data to the UE [8], including, among the others, neighbor cell list with PCIs, the number of antenna ports, the number of consecutive DL subframes per positioning occasion, PRS transmission bandwidth, expected RSTD, and the estimated uncertainty."

Synchronization

Several bi-/multistatic sensing methods rely on precise synchronization, similarly to positioning methods. Sync methods based on the transmitted radar signal itself are mostly addressed in WP3 of KOMSENS-6G. Other sync methods may be considered in WP4. 3GPP mobile networks may operate unsynchronized or synchronized between gNBs, with various levels of synchronization accuracy. Synchronization methods that can be used are GNSS, NTP (Network Timing Protocol) and IEEE 1588 PTP.

In addition, Radio Interface Based Synchronization (RIBS) has been studied by 3GPP in [70]. The method is basically the same as an RTT based Time of Arrival (TOA) measurement in NR positioning: Each gNB transmits PRS to its peer, and measures the time delay between transmission and reception, or vice versa, and signals this measurement to its peer, as illustrated in Figure 23.

Thereupon the exact propagation delay can be calculated and one gNB can be instructed to adjust its time base accordingly.

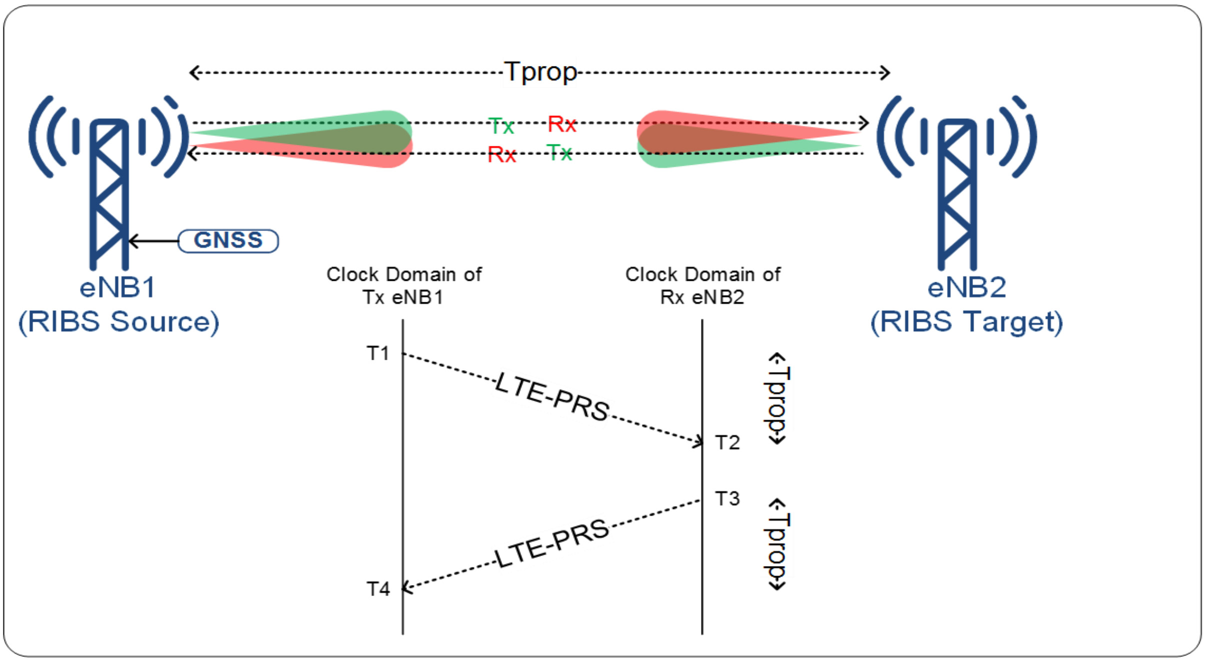


Figure 23: Illustration of RIBS principle

The signalling and procedure of RIBS can also be used without actually adjusting the timing of a gNB. The determined time offset can be used for timing monitoring purpose. Such feature is known as Radio Interface Based Time Monitoring (RIB-TM). The determined time offset can also be taken into account in standardized positioning methods. In the same way it can be taken into account in future sensing methods.

Table 1: Indicative accuracy of synchronization methods, from [70]. Actually achievable accuracy can be several order of magnitudes better, depending on scenario.

Sync Method	Freq Sync (Achievable on the radio interface)	Phase Sync (Achievable on the radio interface)	Comment
Synchronous PDH / SDH / Synchronous Ethernet (SyncE)	±0.05 ppm or better	—	SyncE must be supported on all nodes in the sync chain. See applicable ITU-T recc. (G.803, G.813, G.8261, G.8262, etc.)
IEEE 1588 PTP for freq only sync	±0.05 ppm	—	It does not require on-path support between Master and Slave. Performance depends on load of network. See applicable ITU-T recc. (e.g. G.8261.1)
IEEE 1588 PTP for freq/phase sync (partial timing support under study)	±0.05 ppm	250ns – 1.5µs	See applicable ITU-T recc. (e.g. G.8271.1)
Sattelite time reference (e.g. GPS)	< ±0.01 ppm	< 100ns	Receiver antenna and cabling installation can be expensive in indoor installations.
NTP (Network Timing Protocol)	±0.05 ppm	FFS	Depends on network characteristics (similar rules as for PTP apply in case of frequency sync; also in this case a specific clock recovery algorithm is required)
RIBS Radio Interface Based Synchronization (3GPP Rel-12)	±0.1 ppm	2.5µs	LTE-FDD: Requires capability to listen to sync source downlink frequency band

4.2 Radar systems [BOSCH]

Radar networks consisting of multiple transmitters and/or multiple receivers promise an improvement in terms of detection performance as well as the angular performance, in particular if the entire network spans a larger aperture than that of a single sensor. Such advantage is shown in Figure 24, where the angular resolution is drastically increased for network radar compared to a single-site radar even though it is using MIMO.

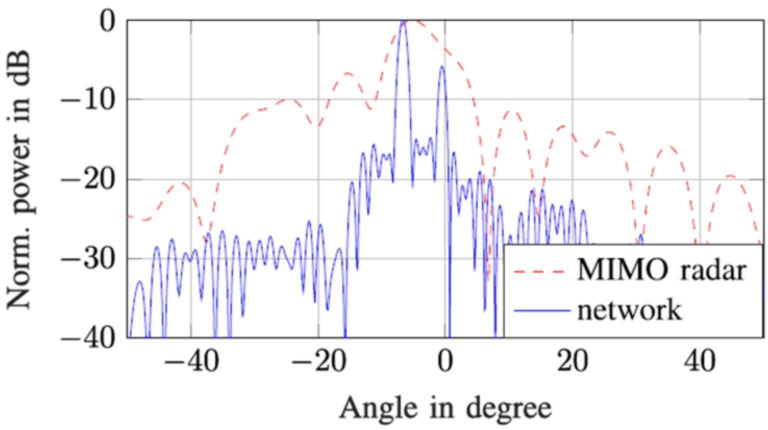


Figure 24: Measurement with a single MIMO radar (aperture 3 cm) in comparison to a coherent network (aperture 16 cm) of a scenario with two targets at 0° and -5.2° [45]

On top of improving the classic radar performance, networks allow also establishing totally new functions like ego-motion estimation [45], i.e., the motion of the vehicle equipped with the sensors, or improved grid-mapping. In literature, the term *radar networks* is used to refer to radar system concepts with several separated sensors or transmitters. These setups can be further refined into subclasses as we discuss in Section 4.2.1. Afterwards, the concepts of cooperative mono-static sensing and distributed multi-static sensing are explained in Section 4.2.2 and 4.2.3.

4.2.1 Classes of Radar Systems [BOSCH]

Here, we need to clearly define and distinguish between different classes of radars, namely:

- Distributed radars can be distinguished (with respect to Tx, Rx antenna) into:
  - Monostatic radars
  - Bi/Multi-static radars
- Collocated radars can be classified into (w.r.t. number of antennas)
  - Single antenna radars
  - Multiple antenna radars

Table 2 below provides the specific definitions of each of these terms.

Table 2: Classification of radar systems

Classification Criterion (w.r.t.)	Radar Classes			
Tx/Rx antenna Location	**Distributed Radars**		**Collocated Radars**	
	Radars which are installed on *different* devices. This term does not refer the signal processing and does not exclude cooperation between radars. Distributed radars can exchange information among each other to facilitate the data processing. In an extreme case, they can even forward their data to a central unit for a joint signal processing. More important is that in distributed radar the antennas have different views of the same scene.		Radars which are installed on the *same* device and thus observe the same scene from the same perspective.	
Number of Antennas	**Monostatic Radars**	**Bi-/Multi-static Radars**	**Single-Antenna Radars**	**Multiple-Antenna Radars**
	The radar system, in which the transmit and receive antennas are located close to each other compared to the expected target.	The radar system, in which the transmit and receive antennas are located close to each other compared to the expected target.	A radar system equipped with one antenna for transmitting and receiving. Notice that, the transmit and receive antennas can be physically the same or separated antennas.	A radar system with multiple transmit and receive antennas. Here, we distinguish between phased-array radar and MIMO radar. While in the phased-array radar, the antennas transmit the same signal with different phase shift, in the MIMO radar, the signals transmitted by different antennas are orthogonal to each other.

Another relevant criterion to classify radar systems is data synchronization. We namely distinguish between:

- **Non-coherent radars:** A radar system, in which no information regarding the waveform, timing, and phase noise of signals is available. There is no interface between radars for coordination and synchronization of data. Notice that this term does not only address the synchronization between sender and receivers but also among senders *or* receivers.

- **Waveform-coherent radars:** A radar system, in which the waveform and time-synchronization between radars are provided. This might be given by a common time basis (like GPS) or a protocol.
- **Phase-coherent radars:** A radar system, in which synchronization between radars is perfectly given. It means besides the wave form and time synchronization; the phase relationship is known between the radar nodes while the phase noise is either known or low enough to be neglected.

A cooperative radar system can be described as a system that consists of more than one radar sensor to evaluate a measurement scene based on the information provided by more than one sensor. By definition, the system does not have to be mounted on the same platform. In the following sections, we discuss different implementations of cooperative radar systems.

4.2.2 Cooperative Distributed Mono-static Sensing [BOSCH]

An important scenario for cooperative radar is the case when distributed mono-static radar sensors observe the same scenario and provide their data to a central unit for further processing or fusion. Depending on level of available data for fusion in central unit, we distinguish between different types, namely high-level and low-level data fusion.

High-Level Data Fusion

High-level data fusion involves the signal processing of sensor data at the local level, and thus, enabling the smart sensors to effectively turn raw data into meaningful object-level information, a.k.a *object-level sensor data*. By performing signal processing locally, more efficient and accurate fusion of the collected data can be achieved. Subsequently, an object list with the corresponding attributes is generated and transmitted to a central or distributed units for further processing and fusion. It is worth noting that this approach enables multi-modal sensor cooperation, i.e., cooperation between different types of sensors such as radar, camera and lidar. Further details on this topic are provided in the Work Package 5 part of this report.

Low-Level Data Fusion

In contrast to high-level data fusion, in this approach raw data provided from the sensors form the input to the fusion unit. The technical details of this technique are discussed in detail as well in the Work Package 5 part of this report.

4.2.3 Distributed Multi-static Sensing [BOSCH]

Another type of cooperative radar is the so-called distributed multi-static sensing. In this approach, the signals sent by various radars are used for sensing the environment. The separation between transmit and receive antennas in multi-static sensing setting provides additional benefits which cannot be achieved by the traditional mono-static approach. Nevertheless, multi-static sensing requires *coordination* and *synchronization* between geographically distributed radars which presents new challenges. This section provides a brief overview of some related results and publications.

A fundamental setup for radar sensor network has been described in [49]. The system model is shown in Figure 25, in which we have M sensors while each sensor illuminates a target and receives the reflection of its own signal and those of other sensors. Notice that in order to avoid potential interference, orthogonal waveforms are deployed by different sensors. For instance, in [49], the authors use FMCW with different center frequencies. Additionally, a model for phase fluctuation is included in the system model.

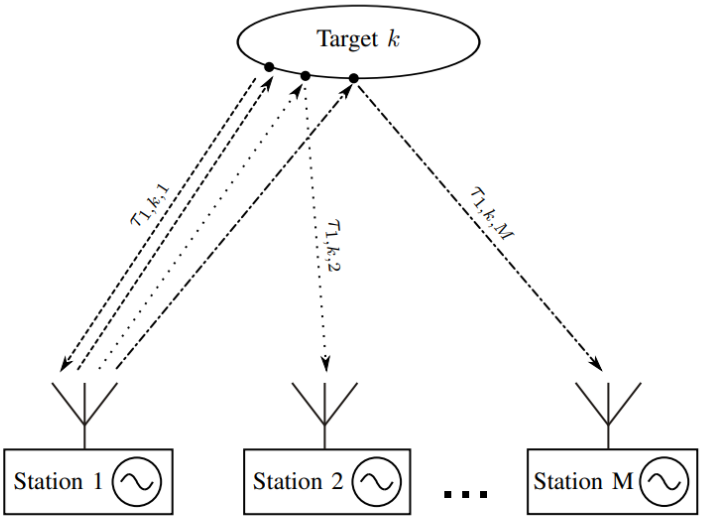


Figure 25: The system model in [49]

As illustrated in Figure 25, each sensor receives a superposition of all reflections from targets. After down-conversion of the received signal to baseband and mixing it with the own transmit signal, two components will appear which are mono-static and bi-static responses. While the former one can be processed as the conventional radar system, the second one is explained in details in [49]. The main challenge of bi-static signal processing addressed in the paper is determining the exact frequency offset between sensors due to imprecise synchronization between sensors. A robust signal processing technique to estimate the bi-static distance has been presented. The measurements done in the paper is with two radar sensors with a distance of 0.5 m from each other.

The major challenges of multi-static sensing are synchronization and calibration of sensors. In fact, to assume that the radars are coherent, an accurate time synchronization is required as shown in [50]. There are several papers that focus on synchronization of cooperative radars. For instance, the use of a communication link to synchronize cooperative radar sensors is proposed in [51]. The communication link is generated by radars. In order to determine the distance between radars, a LoS connection between the radar sensors is required. Another approach, that is proposed in [50], is based on a central processing. The authors of [50] show the feasibility of incoherent cooperative bi-static sensing when the post-processing is done at a central processor unit. This increases the latency and requires additional components in infrastructure.

A decentralized approach for localization and velocity estimation using bi-static sensing was proposed in [52]. The authors of [52] use FMCW radar sensors operating in mono- and bi-static fashion with non-coherent radar sensors for estimating the velocity vector and positioning. In the proposed setup, two independent radar sensors create independent FMCW with a frequency offset, which will be used to distinguish mono-static and bi-static responses. The local oscillator signal is used at each sensor for down-conversion of the received signal. The general system setup is depicted in Figure 26**.**

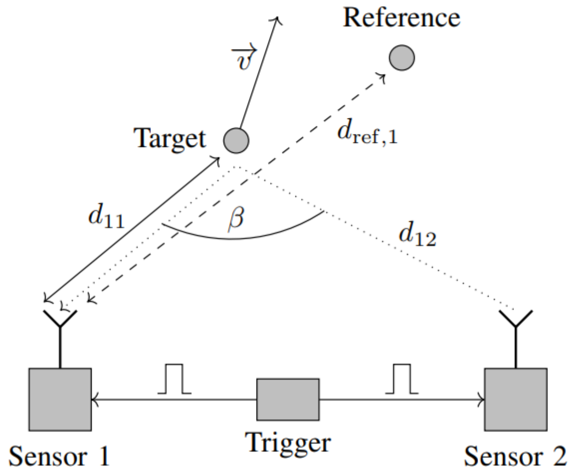


Figure 26: Schematic of the general system setup [52]

4.2.4 Interference Mitigation

The major advantage of radar is its robustness against changing environmental conditions, and hence, its ability to reliably detect objects. However, as there is currently *no regulation for coexistence in the 76-77 GHz frequency band*, and with the drastically increasing number of vehicles equipped with radars and increasing number of radars per vehicle (up to twelve), the environment becomes crowded with millimeter-wave signals, leading to a strong likelihood of interference between the different radar systems.

It is worth noting that interference between radars is a critical problem, as it leads to sensitivity deterioration, decreased measurement accuracy, or even sometimes to sensor blindness. For automotive applications, these problems are unacceptable for safety-related functions such as the automatic emergency brake or vulnerable road user protection. Therefore, there is a serious need to investigate how inter-sensor interference can be addressed.

As a matter of fact, interference mitigation between sensors can be classified as follows:

1. Detect and repair
2. Active avoidance
3. Cooperation

Detect and Repair

The principle of "Detect and Repair" consists of recognizing the affected received signals and reconstructing the waveform as close as possible to the original one [35, 36].

This approach has not only been shown to be effective for FMCW, but also for PMCW and OFDM as well [37]. Note that the detect and repair approach is standard for radar sensors on the market nowadays.

Active avoidance

Avoidance is a well-established concept in RF communication and deployed universally in lightly regulated frequency bands. By virtue of an analyze-before-measure scheme, the transmitter listens before sending and adapts its operational parameters such as transmit direction or center frequency to avoid conflicts (example in [38]).

The automotive industry is currently working on avoidance schemes.

Cooperation

The active avoidance technique can be leveraged by a cooperative interference mitigation approach that can be either [39]:

- Rule-based approach: Every radar sensor has a constant set of common rules that determine the reaction to interference.
- Communications-based approach: A central unit arbitrate between the sensors.

Note that cooperative operation is rather still a future topic. Some of the major challenges associated with the cooperative approach to mitigate against interference are:

- The design of efficient and robust algorithms for radar coordination and interference mitigation.
- Trade-off complexity vs. flexibility: The algorithms should have minimum computational complexity to be able to operate in real time while handling the challenges of dynamic and uncertain nature of the environment.

Trade-offs between cooperation and competition: In some scenarios, the interests of different radar systems may conflict, leading to a trade-off between cooperation and competition. For example, one radar may prioritize its own detection performance over the interference it causes to other radars. Finding the right balance between cooperation and competition is a complex problem that requires careful consideration of the system objectives and constraints.

5 GAP analysis

In this chapter we compile those identified gaps of the previous chapters on which the project will focus the further work.

Protocol design and signalling

Assuming a similar architectural approach for 6G as it is specified for 5G, instead of the LMF for LCS purposes a network function with related capabilities for sensing is expected to be implemented in the CN, here preliminary called Sensing Function (SF).

The sensing protocol will have to enable the control of the resource allocation across multiple TRPs and for UEs participating as sensing transmitters or receivers. Receiving and processing radar sensing signals should be only activated for areas and/or time periods of interest. Multiple TRPs might need to be activated and managed depending on the size of the requested area for sensing.

To allow running both positioning and sensing procedures in parallel over the same TRPs, a coordination between LMF and SF is required, especially in the case that same Tx RF signals are jointly used for both purposes. Based on analysis to be done within KOMSENS-6G this may finally lead even to the requirement of having an integrated function of LMF and SF.

From a protocol and signaling perspective, it is required to initially define the functional tasks of different processing steps for sensing purposes in DL and UL direction and to specify the data to be exchanged. In the next step the needed signaling and data flows for these tasks or blocks on a functional architecture level can be designed and then described on a protocol level taking into account existing protocols between RAN, CN, and/or OAM nodes or designing new ones adapted to the sensing use cases. Further modifications and adaptations are expected to inherently support communication services by sensing and vice versa taking into account synergies between both service types. This further requires a joint QoS framework that allows an appropriate handling of radio resources considering SLA-based policy settings from MNOs and/or triggered by 3rd parties interested in sensing services. For that purpose, also the related signaling framework has to be defined that can be incorporated between AF, SF, and RAN nodes.

The 5GS architecture description will be taken as an initial baseline for the signaling and protocol framework in KOMSENS-6G, but also new approaches coming up from other research projects and industry fora and addressing novel topics to be potentially incorporated in a 6G system like intelligent networking based on native AI/ML, RAN-CN convergence, and programmable cloud-native platforms will impact the further work, i.e., the content of the signaling and protocol framework may further change with gradual project runtime.

Regarding sensing in WiFi 802.11 bf, concepts of WiFi Station roles, from the sensing procedure as well as the sensing feedback types and compression schemes may be partly applicable also to 3GPP 6G ICaS mobile networks and will be further explored in the project.

Sensing in spectrum-sharing bands: WiFi-devices will share spectrum with incumbents in the 6 GHz band, such as 5G NR-Unlicensed. Coexistence between 6G mobile ICaS technology and WiFi technology will however not be studied in the project.

Resource allocation

At the level of resource management, joint consideration of communication and sensing may lead to the definition of new and even more complex multidimensional optimization problems, where not only conflicting key performance indicators (KPIs) of the communication part have to be balanced against each other, but also KPIs of the sensing part. One implication is that the coexistence of sensing and communication implies in practice sharing of the same time-frequency-spatial resources.

For ICaS resource allocation we can distinguish the cases

1) Communication signal is also used for sensing

2) Communication and sensing signals are multiplexed

For 1), the sensing requirements in terms of bandwidth, energy, susceptibility to interference and repetition rate need to be inputs to the comm scheduling algorithm. At times when there is no data for comms into a direction of interest for sensing, but a sensing signal needs to be transmitted to fulfill the above requirements, a sensing-only signal has to be scheduled.

For 2), for sensing a resource allocation pattern that is at least short-term fixed appears to make sense. Existing semipersistent scheduling framework may be reusable. Communications would then be scheduled around the sensing resources. For URLLC, preemption or postponing of sensing resources that are then repurposed for URLLC should be considered.

For comparison: In NR positioning the PRS transmission is not dynamically scheduled and is not (short term) adaptive to the channel between the transmitter(s) and the receiver(s). Such adaptivity could be investigated in the second phase of the project. Adaptivity to characteristics of the sensing target should be taken into account, e.g. the velocity, and possibly also adaptivity the clutter characteristics.

Time domain scheduling flexibility for sensing should be investigated, i.e. the impact of aperiodic sensing signals on performance. Some sensing methods in fact exploit aperiodic sampling, as in Compressed Sensing (CS). In general, the convergence of sensing and communication could have multi-fold implications on the system design, including, potentially, the (i) definition of sensing-related services classes; (ii) development of new medium access control (MAC) and radio resource management (RRM) protocols to allocate the radio resources according to the needs of different sensing and communication services; (iii) extension of the network slicing concept to support sensing-related services.

Regarding frequency domain resource allocation, we will investigate frequency stitching, considering the following aspects:

- The scenarios and performance benefits of aggregating multiple DL positioning frequency layers by UEs (i.e., active sensing) or gNBs (i.e., passive sensing)
- Analysis of coherent and non-coherent frequency stitching methods (structure of the frequency spectrum)
- Analysis of imperfect synchronicity between different nodes
- The impact of channel spacing, timing offset, and power imbalance among component carriers (CCs) on the positioning performance for intra-band and inter-band scenarios

Network aspects and coordination of multiple nodes

The main challenge in coordinating multiple sensing notes lies in interference control. Received sensing signals can be expected to be very weak, in general weaker than communications and positioning signals. Weak received power can compensated to some extent by processing gain, but on the expense of increased resource allocation. For communications systems the state-of-the-art is to largely rely on some kind of processing gain, e.g. achieved by Hybrid-ARQ. Whether this is a good solution also for sensing should be further investigated.

In particular in bi/multistatic sensing the TDD structure will be broken as one node is transmitting and another one receiving at the same time. A receiving node's antennas may be located in proximity to the transmit antennas of another node that is transmitting communications or sensing signals at the same time and may cause high interference unless such concurrent transmissions are avoided by coordination. The project will therefore investigate to what extent interference coordination is necessary and develop appropriate methods.

In a heterogeneous infrastructure, where nodes with different capabilities (communication, sensing, and/or both) need to coexist cooperatively and fairly with each other, how to optimize the channel access to minimize the probability of interference will be an interesting approach to study.

In particular methods for selecting the suitable network nodes for participating in the sensing procedure for a given target region of interest will be developed.

Regarding inter-node synchronization, the performance limits using standardized 5G synchronization methods, including over-the-air based bidirectional methods, should be evaluated and improved where necessary.

6 References

[1] Erik Dahlman; Stefan Parkvall; Johan Sköld, "5G NR: The Next Generation Wireless Access Technology"; Elsevier 2018

[2] Ari Kangas; Iana Siomina; Torbjörn Wigren: Positioning in LTE; book chapter Handbook of Position Location: Theory, Practice, and Advances, Second Edition; Editor(s):Seyed A. (REZA) Zekavat; R. Michael Buehrer; ©IEEE; 2019

[3] A. Lieto, I. Malanchini, S. Mandelli, E. Moro and A. Capone, "Strategic Network Slicing Management in Radio Access Networks," in *IEEE Transactions on Mobile Computing*, vol. 21, no. 4, pp. 1434-1448, 1 April 2022, doi: 10.1109/TMC.2020.3025027.

[4] S. Mandelli, M. Andrews, S. Borst and S. Klein, "Satisfying Network Slicing Constraints via 5G MAC Scheduling," *IEEE INFOCOM 2019 - IEEE Conference on Computer Communications*, Paris, France, 2019, pp. 2332-2340, doi: 10.1109/INFOCOM.2019.8737604.

[5] B. Sklar, "Rayleigh fading channels in mobile digital communication systems .I. Characterization," in *IEEE Communications Magazine*, vol. 35, no. 7, pp. 90-100, July 1997, doi: 10.1109/35.601747.

[6] Tanenbaum, Bos, “Modern Operating Systems”, Prentice Hall 2014, ISBN: 978-0-13-359162-0

[7] 3GPP TR 21.916: Release 16 Description; Summary of Rel-16 Work Items

[8] 3GPP TR 21.917: Release 17 Description; Summary of Rel-17 Work Items

[9] 3GPP TS 22.071: Location Services (LCS); Service description; Stage 1

[10] 3GPP TS 22.261: Service requirements for the 5G system; Stage 1

[11] 3GPP TS 23.273: 5G System (5GS) Location Services (LCS); Stage 2

[12] 3GPP TS 23.501: System architecture for the 5G System (5GS); Stage 2

[13] 3GPP TS 37.355: LTE Positioning Protocol (LPP)

[14] 3GPP TS 37.480: E1 general aspects and principles

[15] 3GPP TS 38.300: NR; NR and NG-RAN Overall Description; Stage 2

[16] 3GPP TS 38.305: Stage 2 functional specification of User Equipment (UE) positioning in NG-RAN

[17] 3GPP TS 38.211: NR; Physical channels and modulation

[18] 3GPP TS 38.215: NR; Physical layer measurements

[19] 3GPP TS 38.331: NR; Radio Resource Control (RRC) protocol specification

[20] 3GPP TS 38.401: NG-RAN; Architecture description

[21] 3GPP TS 38.413: NG-RAN; NG application protocol (NGAP)

[22] 3GPP TS 38.423: NG-RAN; Xn application protocol (XnAP)

[23] 3GPP TS 38.455: NR Positioning Protocol A (NRPPa)

[24] 3GPP TS 38.473: NG-RAN; F1 application `protocol (F1AP)

[25] O-RAN Working Group 1 (Use Cases and Overall Architecture): O-RAN Architecture Description (TS O-RAN.WG1.OAD)

[26] O-RAN Working Group 4 (Open Fronthaul Interfaces WG): Control, User and Synchronization Plane Specification (TS O-RAN.WG4.CUS)

[27] Capozzi F, Piro G, Grieco L A, et al. Downlink packet scheduling in LTE cellular networks: Key design issues and a survey[J]. IEEE communications surveys & tutorials, 2012, 15(2): 678-700.

[28] C. Wengerter, J. Ohlhorst, and A. von Elbwart, "Fairness and throughput analysis for generalized proportional fair frequency scheduling in OFDMA," in Proc. IEEE Veh. Tech. Conf., VTC-Spring, vol. 3, Stockholm, Sweden, May 2005, pp. 1903 – 1907.

[29] G. Monghal, K. I. Pedersen, I. Z. Kovacs, and P. E. Mogensen, "QoS oriented time and frequency domain packet schedulers for the UTRAN long term evolution," in Proc. IEEE Veh. Tech. Conf., VTC-Spring, Marina Bay, Singapore, May 2008.

[30] M. Andrews, K. Kumaran, K. Ramanan, A. Stolyar, P. Whiting, and R. Vijayakumar, "Providing quality of service over a shared wireless link," IEEE Commun. Mag., vol. 39, no. 2, pp. 150 – 154, Feb. 2001.

[31] K. Shi, E. Sillekens and B. C. Thomsen, "246 GHz digitally stitched coherent receiver," 2017 Optical Fiber Communications Conference and Exhibition (OFC), Los Angeles, CA, USA, 2017, pp. 1-3.

[32] 3GPP TS 38.133: NR requirements for support of radio resource management

[33] 3GPP R1-2008617: Considerations on Additional Scenarios for Evaluation

[34] 5G Americas white paper: Becoming 5G Advanced the 3GPP 2025 Roadmap

[35] J. Fink and F. K. Jondral, "Comparison of OFDM radar and chirp sequence radar," 2015 16th International Radar Symposium (IRS), Dresden, Germany, 2015, pp. 315-320, doi: 10.1109/IRS.2015.7226369.)

[36] Toth, P. Meissner, A. Melzer, and K. Witrisal, "Performance comparison of mutual automotive radar interference mitigation algorithms," in Proc. IEEE Radar Conf., 2019, pp. 1–6.

[37] J. Bechter, F. Roos, M. Rahman and C. Waldschmidt, "Automotive radar interference mitigation using a sparse sampling approach," 2017 European Radar Conference (EURAD), Nuremberg, Germany, 2017, pp. 90-93, doi: 10.23919/EURAD.2017.8249154.

[38] Roos, J. Bechter, C. Knill, B. Schweizer, and C. Waldschmidt, "Radar sensors for autonomous driving: Modulation schemes and interference mitigation," IEEE Microw. Mag., vol. 20, no. 9, pp. 58–72, Sep. 2019.

[39] Bechter, C. Sippel, and C. Waldschmidt, "Bats-inspired frequency hopping for mitigation of interference between automotive radars," in Proc. IEEE MTT-S Int. Conf. Microw. Intell. Mobility, 2016, pp. 1–4.

[40] J. Huang et al., "V2X-communication assisted interference minimization for automotive radars," in China Communications, vol. 16, no. 10, pp. 100-111, Oct. 2019, doi: 10.23919/JCC.2019.10.007.

[41] M. Kronauge and H. Rohling, “New chirp sequence radar waveform,” IEEE Trans. Aerosp. Electron. Syst., vol. 50, no. 4, pp. 2870–2877, Oct. 2014.

[42] C. Knill, B. Schweizer, S. Sparrer, F. Roos, R. F. H. Fischer, and C. Waldschmidt, “High range and Doppler resolution by application of compressed sensing using low baseband bandwidth OFDM radar,” IEEE Trans. Microw. Theory Techn., vol. 66, no. 7, pp. 3535–3546, Jul. 2018.

[43] B. Schweizer, C. Knill, D. Schindler, and C. Waldschmidt, “Stepped-carrier OFDM-radar processing scheme to retrieve high-resolution range-velocity profile at low sampling rate,” IEEE Trans. Microw. Theory Techn., vol. 66, no. 3, pp. 1610–1618, Mar. 2018.

[44] G. Hakobyan and B. Yang, “High-performance automotive radar: A review of signal processing algorithms and modulation schemes,” IEEE Signal Process. Mag., vol. 36, no. 5, pp. 32–44, Sep. 2019.

[45] C. Waldschmidt, J. Hasch and W. Menzel, "Automotive Radar — From First Efforts to Future Systems," in IEEE Journal of Microwaves, vol. 1, no. 1, pp. 135-148, Jan. 2021, doi: 10.1109/JMW.2020.3033616.

[46] D. Kellner, M. Barjenbruch, J. Klappstein, J. Dickmann, and K. Dietmayer, “Instantaneous ego-motion estimation using Doppler radar,” in Proc. 16th Int. IEEE Conf. Intell. Transp. Syst., 2013, pp. 869–874.

[47] "IEEE Standard for Low-Rate Wireless Networks--Amendment 1: Enhanced Ultra Wideband (UWB) Physical Layers (PHYs) and Associated Ranging Techniques," in IEEE Std 802.15.4z-2020 (Amendment to IEEE Std 802.15.4-2020) , vol., no., pp.1-174, 25 Aug. 2020, doi: 10.1109/IEEESTD.2020.9179124.

[48] Michael Stocker, Hannah Brunner, Maximilian Schuh, Carlo Alberto Boano, Kay Römer, "On the Performance of IEEE 802.15.4z-Compliant Ultra-Wideband Devices", 2022 Workshop on Benchmarking Cyber-Physical Systems and Internet of Things (CPS-IoTBench), pp.28-33, 2022.

[49] A. Frischen, J. Hasch and C. Waldschmidt, "Contour recognition with a cooperative distributed radar sensor network," 2015 IEEE MTT-S International Conference on Microwaves for Intelligent Mobility (ICMIM), Heidelberg, Germany, 2015, pp. 1-4, doi: 10.1109/ICMIM.2015.7117926.

[50] R. Feger, C. Pfeffer, C. M. Schmid, M. J. Lang, Z. Tong and A. Stelzer, "A 77-GHz FMCW MIMO radar based on loosely coupled stations," 2012 The 7th German Microwave Conference, Ilmenau, Germany, 2012, pp. 1-4.

[51] A. Stelzer, M. Jahn and S. Scheiblhofer, "Precise distance measurement with cooperative FMCW radar units," 2008 IEEE Radio and Wireless Symposium, Orlando, FL, USA, 2008, pp. 771-774, doi: 10.1109/RWS.2008.4463606.

[52] S. Edstaller and D. Mueller, "Vector Velocity and Position Measurement Using a 77-GHz Cooperative Radar System," 2019 IEEE MTT-S International Microwave Symposium (IMS), Boston, MA, USA, 2019, pp. 548-551, doi: 10.1109/MWSYM.2019.8700770.

[53] A. Charlish, F. Hoffmann, C. Degen und I. Schlangen, „The Development From Adaptive to Cognitive Radar Resource Management,“ IEEE Aerospace and Electronic Systems Magazine, Bd. 35, pp. 8-19, June 2020.

[54] P. Moo und Z. Ding, Adaptive Radar Resource Management, Academic Press, 2015.

[55] U. S. Hashmi, S. Akbar, R. Adve, P. W. Moo und J. Ding, „Artificial intelligence meets radar resource management: A comprehensive background and literature review," IET Radar, Sonar & Navigation, Bd. 17, pp. 153-178, 2023.

[56] VDE ITG, "Joint Communications & Sensing," 2022.

[57] Hexa-X , „Deliverable D3.2 Initial models and measurements for localisation and sensing," 2022.

[58] 3GPP, „TR 22.837 Feasibility Study on Integrated Sensing and Communication," 2022.

[59] Y. Song, W. Taylor, Y. Ge, M. Usman, M. A. Imran und Q. H. Abbasi, „Evaluation of deep learning models in contactless human motion detection system for next generation healthcare," Scientific Reports, December 2022.

[60] S. C. D. L. V. K. F. R. D. L. C. a. K. A. Krämmer A., „Providentia - A Large-Scale Sensor System for the Assistance of Autonomous Vehicles and Its Evaluation," Journal of Field Robotics, pp. 1156-1176, 2022.

[61] E. Winter und L. Lupinski, „On Scheduling the Dwells of a Multifunction Radar," in 2006 CIE International Conference on Radar, 2006.

[62] A. S. Narykov, O. A. Krasnov und A. Yarovoy, „Algorithm for resource management of multiple phased array radars for target tracking," in Proceedings of the 16th International Conference on Information Fusion, 2013.

[63] Y. He und K. P. Chong, „Sensor scheduling for target tracking in sensor networks," in 2004 43rd IEEE Conference on Decision and Control (CDC) (IEEE Cat. No.04CH37601), 2004.

[64] M. Frech, C. Hald, M. Schaper, B. Lange und B. Rohrdantz, „Assessing and mitigating the radar–radar interference in the German C-band weather radar network," Atmospheric Measurement Techniques, Bd. 16, p. 295–309, 2023.

[65] A. Charlish, „Tasking networked multi-function radar systems for active tracking," in 2013 14th International Radar Symposium (IRS), 2013.

[66] A. B. Charlish, „Autonomous agents for multi-function radar resource management" 2011.

[67] Chen, H. Song, Q. Li, F. Meneghello, F. Restuccia and C. Cordeiro, "Wi-Fi Sensing Based on IEEE 802.11bf," in IEEE Communications Magazine, vol. 61, no. 1, pp. 121-127, January 2023, doi: 10.1109/MCOM.007.2200347.

[68] R. Du, et al. "An overview on IEEE 802.11 bf: WLAN sensing." arXiv preprint arXiv:2207.04859 (2022).

[69] IEEE Draft Standard for Information Technology– Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks– Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Enhancements for wireless LAN sensing, IEEEp802.11bf/d0.5, 2022.

[70] 3GPP TR 36.89: Network Assistance for Network Synchronization; Technical Specification Group Radio Access Network; V14.0.0; 2017-01

KOMSENS-6G

Work Package 5

Milestone 1
“State-of-the-Art (SotA) and gap analysis”

KOMSENS-6G WP5: Milestone 1 Deliverable

Table of Contents

Introduction

This report is the first deliverable of the KOMSENS-6G project Work package 5, *Data processing for Knowledge Extraction and its Application* and focuses on the state-of-the-art and gap analysis. The document consists of three chapters. The first chapter discusses data processing for distributed sensing, describing suitable fusion techniques and machine learning methods for parameter estimation. In the second chapter, knowledge extraction and representation methods are highlighted. Moreover, the architecture required for high-quality object localization and tracking and the methods for generating 3D environmental maps are discussed. In the third and final chapter, we point out the potential mutual performance gains that could be obtained by deeper integration of sensing and communication functionalities.

T5.1 Data Processing for Distributed Sensing [NOK, KIT, TUD, BOSCH, TUIL]

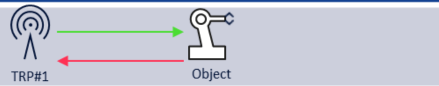
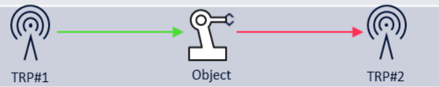
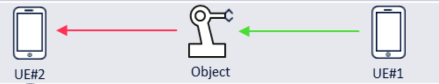
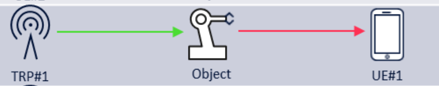
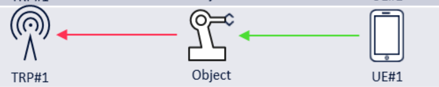
1 Primer on Data Processing Techniques for Localization, Tracking and Imaging

In the context of KOMSENS-6G, where sensing is to be integrated into a communication network, sensing refers to the detection of (physical) objects, called targets, by transmitting a known sensing signal and detecting what thereof objects (back-)scatter to the sensing receiver(s). Objects, respectively, the whole environment, do not participate in the sensing process, i.e., neither transmit nor receive the sensing signal itself. In contrast, the positioning service available in today's 4G and 5G communication networks refers to the process of determining the position (in the sense of coordinates) of an object, wherein the object actively participates by either transmitting or receiving the positioning signal. For positioning, the object, therefore, is required to have communication user equipment (UE), while for sensing, it may not.

Both sensing and positioning have many commonalities. The same signal may be used for both, the received signal may be described, compressed, and reported in the same way, and sensing may be used, like positioning to determine an object's (geographic) position. In 4G and 5G communication networks, both radio access network (RAN), respectively its transmission and reception points (TRP), and mobile (UE) can act as both sensing transmitter and sensing receiver. Depending on which role TRP and UE take and whether the same single TRP or UE takes both roles simultaneously, six alternatives can be distinguished, shown in Fig. 2.1.

The terms monostatic and bistatic (and multistatic with two and more receivers) stem from RADAR (radio detection and ranging). In monostatic, the transmitter and receiver use the same or closely co-located antennas for transmitter and receiver. In bistatic, the transmitter and receiver antenna are spaced (far) apart. Multistatic refers to a single transmitter and two or more receivers spaced far apart. Processing of the received/backscattered sensing signals is generally done within the network. Whenever a UE acts as a sensing receiver, processing may alternatively be done by the UE.

Sensing distinguishes between active and passive sensing. Active sensing itself illuminates the target, and passive sensing relies on external source(s) to provide the sensing signals. Communication networks generate their own sensing signal and therefore do active sensing. This is not to be confused with the active and passive "participation" of targets in the process of positioning, which can be active if positioning is done as in today and as detailed in the following subsection, or passive, when done via (active) sensing.

No.	Sensing type	Trans-mitter	Receiver	Figures	Where is measured data processed?
Alt.1	Monostatic	TRP#1	TRP#1		Network
Alt.2	Monostatic	UE#1	UE#1		Network or UE
Alt.3	Bistatic	TRP#1	TRP#2		Network
Alt.4	Bistatic	UE#1	UE#2		Network or UE
Alt.5	Bistatic	TRP	UE		Network or UE
Alt.6	Bistatic	UE	TRP		Network

Transmitted
Backscattered

Figure 2.1: Example for a drone detection use case of (a) monostatic SAP with a single gNB acting as a transmit/receive point (TRP), (b) bistatic SAP pair with one transmitting and one receiving gNB, and (c) fully multistatic SAP network with four gNBs, all acting as TRPs.

1.1 5G Positioning

For positioning, i.e., active localization of a mobile (UE), 3GPP has standardized dedicated physical layer signals and signalling protocols. Active positioning works through measuring and reporting either specific signals in downlink or in uplink. In downlink, base station(s) (gNB) respectively their transmission and reception points (TRP) transmit positioning reference signals (PRS) [1] that a UE measures and reports to the Location Management Function (LMF) through the LTE Positioning Protocol (LPP) [2]. In uplink, the UE transmits sounding reference symbols (SRS) that TRP(s) receive and report to the LMF through the New Radio Positioning Protocol A (NRPPa) [3]. The LMF is the core network function that configures and controls all positioning operations [4].
Multiple positioning methods are supported in 5G:

- Downlink time difference of arrival (DL-TDOA): The positioning reference signal (PRS) was introduced in Release 16. The UE performs downlink Rx signal time difference (DL RSTD) measurements for each Transmission Reception Point (TRP) and reports these measurements through the LTE Positioning Protocol (LPP) to the Location Management Function (LMF). The LMF estimates the position.
- Uplink time difference of arrival (UL-TDOA): The sounding reference signal (SRS) was enhanced for the purpose of positioning. Each TRP measures the uplink relative time of arrival (UL-RTOA) and reports the measurements to the LMF through the New Radio Positioning Protocol A (NRPPa). The LMF estimates the position.
- Downlink angle-of-departure (DL-AoD): The UE measures the PRS receive power (DL RSRP) per beam and TRP. Measurements are reported through the LPP to the LMF. The LMF estimates the position.
- Uplink angle-of-arrival (UL-AoA): Each TRP measures the angle-of-arrival of the SRS. Measurement reports are sent to the LMF through the NRPPa.

- Multi-cell round trip time (RTT): The gNB/TRP and UE perform Rx-Tx time difference measurement for multiple cells. Both gNBs/TRPs and UE report their measurements to the LMF.
- Enhanced cell ID (E-CID). This is based on Radio Resource Management (RRM) measurements (e.g. DL RSRP) of each gNB at the UE. The measurement reports are sent to the LMF.

The position estimation algorithms are explained, e.g., in [5]. The position estimation algorithms are explained, e.g., in [5]. To improve position estimation accuracy, both time and angle-based methods can be combined [6].

2 Distributed Sensing and Processing for Localization (KIT, TUD)

2.1 Distributed Sensing

In the context of distributed radar sensing with the inherently distributed infrastructure of cellular networks, where gNBs can act as sensing access points (SAPs), several configurations are possible. One of them, which relates to the simplest type of radar network, is having multiple gNBs acting as monostatic SAPs. In this specific case, no synchronization among the gNBs is required, and the target detections undergo incoherent fusion, e.g., at the track level [7]. Other possible configurations involve the use of bi- or multistatic SAPs. In bistatic SAP pairs, a non-collocated, and often non-synchronized, transmitter and receiver pair is used as opposed to the collocated, synchronized pair in a monostatic SAP. As for a multistatic network, it is assumed that at least two receivers can receive reflections from targets of a signal that was originally transmitted by a single transmitter. To enhance diversity in a network of sensing-capable gNBs, a fully multistatic network can be realized, in which all gNBs can receive monostatic reflections of their own signals and bistatic reflections of signals transmitted by the remaining gNBs in the network. An example is illustrated in Fig. 2.2.

Added to the beamforming capabilities enabled using massive MIMO gNBs, fully multistatic sensing can efficiently improve the coverage of an observation area with respect to the sole monostatic sensing with a single gNB. Furthermore, it can improve the multidimensional resolution (i.e., in range, Doppler shift and angular domains jointly) and enable more accurate estimation and tracking of 3D position and velocity of multiple targets. Furthermore, a higher probability of detection is experienced for targets with aspect-dependent radar cross section (RCS) such as drones, or detection of targets that are occluded, e.g., by large objects or buildings with respect to one or multiple sensing nodes in the multistatic network.

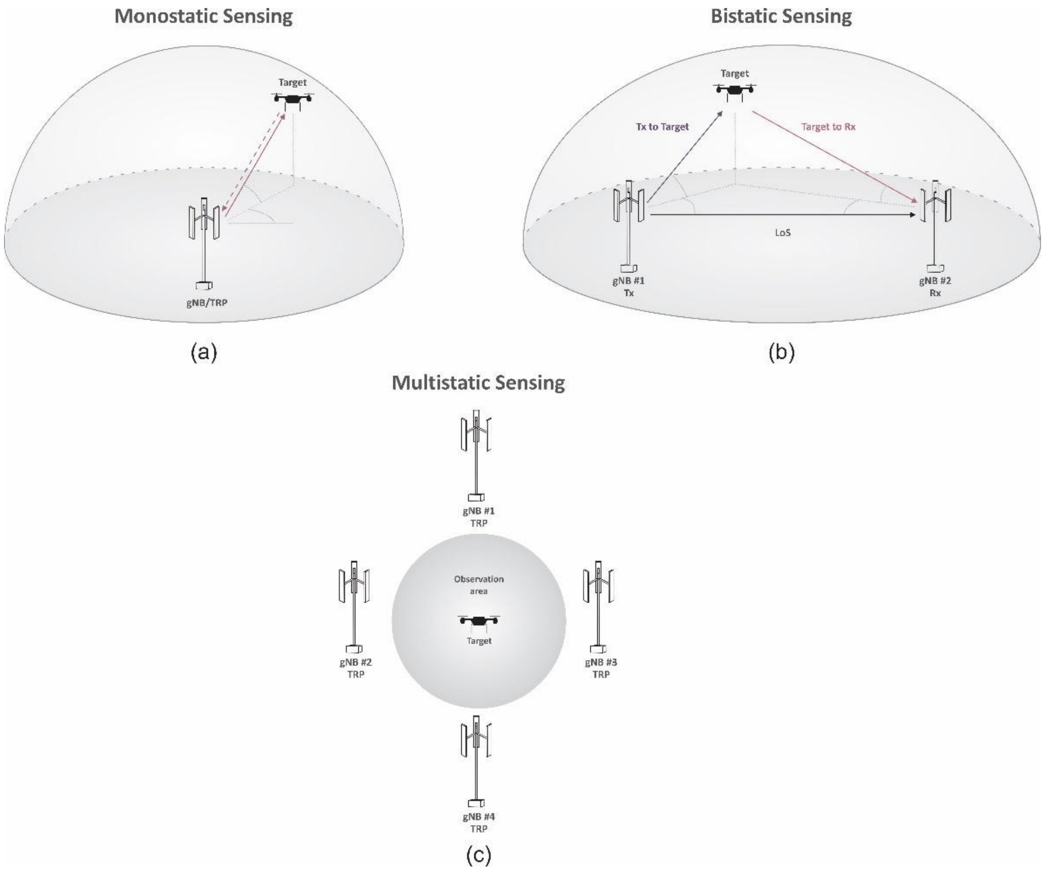


Figure 2.2: Example for a drone detection use case of (a) monostatic SAP with a single gNB acting as a transmit/receive point (TRP), (b) bistatic SAP pair with one transmitting and one receiving gNB, and (c) fully multistatic SAP network with four gNBs, all acting as TRPs.

To enable multistatic sensing, synchronization is needed to enable bistatic measurements and suppress mutual interference. The first point is paramount to enable accurate range, Doppler shift/velocity, and angular estimation in mono- or bistatic transmitting/receiving gNB pairs. While accurate synchronization of time, frequency, phase, and sampling clocks can be achieved with optical fibre links among gNBs, this additional infrastructure may not always be present. In such cases, over-the-air (OTA) synchronization using the integrated communication and sensing (ICaS) signal may become necessary, as the use of GPS can only provide sufficient frequency synchronization [8]. In its turn, the latter point becomes essential for mitigating mutual interference among sensing nodes in networks with multiple gNBs, yielding enhanced dynamic ranges in radar images, either monostatic or bistatic. Imperfect synchronization and interference cancellation among gNBs can yield bias in estimated mono- and bistatic radar images within the multistatic network. Such biased images will ultimately impair the performance of data fusion aiming to detect and estimate the position and velocity of extended targets. The performance of those two aspects is more closely addressed in WP 3, and preliminary and ongoing studies at the KIT have been reported in [9], [10].

Depending on whether phase synchronization is yielded, incoherent or coherent data fusion may be performed. In the first case, point target detections from mono- and bistatic images can be clustered and assigned to a hypothetical extended target at each receiver, similarly to what is done in [11] for the monostatic case. Then, either local data fusion can be performed at the same receiving gNB, or information on the detections can then be exchanged among the gNBs to perform centralized data fusion. Since the measurements are not coherent, data extracted from them is usually fused on the track level [7]. However, if highly accurate synchronization, e.g., via optical fibre, is adopted and phase synchronization is achieved among the gNBs, coherent data fusion can be performed considering the multistatic network as a distributed MIMO radar with widely separated groups of antennas [12]. In this case, point target detections are obtained from the coherent combination of all mono- and bistatic radar images and tracking will only be used to predict future target states instead of fusing detections from multiple transmitting and receiving gNB pairs. If, besides combining measurements from multiple gNBs, sensing data from multiple bands is used (e.g., mmWave and sub-6 GHz), even greater target detection capability and accuracy of position and velocity estimates can be achieved. Depending on the adopted data fusion strategy, dilution of precision (DOP) can be used for either network planning for sensing or evaluation of sensing capability of an existing network. This parameter can be used not only for range measurements but can also consider angles of departure and arrival (AoD and AoA) as well as Doppler shift or velocity measurements [13].

2.2 Data Processing for Localization

Following the scenario depicted in Fig. 2.2, the SAPs aim to measure position-related parameters, such as time-of-arrival (ToA), angle-of-arrival (AoA), and received signal strength (RSS). Moreover, the localization algorithms can be divided into ranging-based, angle-based, and fingerprinting matching [14].

Ranging-based techniques use the estimated distances between the source and SUs for calculating the corresponding transmitter position via geometric multilateration, and the angle-based techniques that use AoA for positioning are named multiangulation. For the case of ranging-based localization, distance estimation can be obtained in two ways: through RSS or with the wave propagation delay, i.e., ToA. The mathematical models for RSS have an exponential distance-dependent decay and statistical components depending on multipath propagation and environment-related shadowing noise. In contrast, for ToA, the models have a simpler structure that assumes that ToA measurements are affected by zero mean additive Gaussian noise. Therefore, localization based on ToA has been regarded as more accurate when compared to RSS in scenarios where LoS conditions are easily attained [15]. However, ToA estimation requires the transmission of a wide-band known sequence, while RSS can be blind to the transmission standard.

For the angle-based, each SU must have an antenna array for estimating the AoA, and the angular resolution depends upon the number of elements in the array, which increases SUs' size, cost, and complexity. Moreover, AoA estimation algorithms have a relatively large computation complexity compared with RSS and ToA [16]. Consequently, RSS is particularly interesting for simple and low-cost transmitter localization applications. Nevertheless, the performance of schemes based on RSS distance estimation is particularly affected by random propagation effects, shadowing noise and hardware nonlinearities [17]. For this reason, localization schemes based on measurement database search, i.e., fingerprinting matching, have been proposed as alternatives [18] and still have been gathering attention from the scientific community [19].

There are different algorithms for data processing for distributed sensing that work as multilateration, such as maximum likelihood (ML), maximum a posteriori (MAP), and non-linear least squares (NLLS). Different studies assume a particular probability density function (PDF) for the ML estimator [20] and a prior for the MAP [22] estimator. Other studies [21, 24] apply NLLS to the estimates due to insufficient information about the likelihood pdf. These studies present a central processing, where the APs are synchronised, and a central unit performs the data processing for distributed sensing. There are different forms to combine the information based on the estimated parameters. In [20], joint processing of distance and AoA estimates is done, whereas only TOA information is used in [21, 22, 23].

2.3 Gap Analysis

In the case of distributed localization, the sensing capabilities of the SPAs vary substantially, providing a variety of measurements that carry positional information, such as range, angle of arrival, and time of arrival. In addition, the measurement accuracy and sensing range of SAPs vary widely. Research challenges lie in the synchronization and processing of the hetergeoneous data from different sources.

Further, in case of high dense SPA scenarios, managing the coordination and scheduling of the SPAs for joint data processing will be an interesting aspect to study.

3 Data Fusion Techniques (BOSCH, TUD, NOK, RWTH)

3.1 Levels of Data Fusion

Based on the level of fusion, we distinguish between three levels, i.e., low-level, feature-level, and high-level fusion. These levels of fusion are explained in the following below.

Low-level fusion: In low-level fusion, the input is the raw data from sensors. In other words, the sensors forward the raw data without any processing to the fusion unit. At the fusion unit, a central tracking algorithm is applied [24], as depicted in Fig. 2.3. The advantage of low-level architecture is that the fusion unit has access to data in a very early stage. Therefore, the fused measurement has a high likelihood of being a valid measurement for the considered application [25]. However, low-level data fusion has a disadvantage. It requires high channel bandwidth for data exchange.

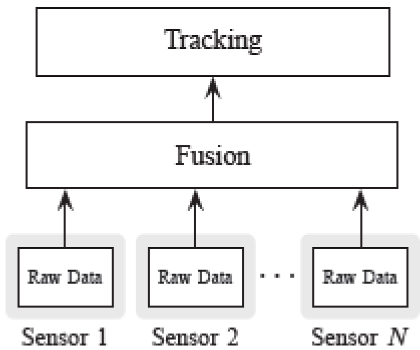


Figure 2.3: Low-level fusion architecture [25]

Moreover, the architecture's scalability in practical scenarios requires some additional effort due to the different data formats of sensors [25]. Furthermore, the requirements for time synchronization of low-level data fusion might be generally higher than other types. Nevertheless, low-level fusion can be applied even for time-critical with safety requirements. The feasibility of low-level data fusion architecture has been shown in [26] for automotive safety applications.

Signal processing for low-level data fusion is classified into measurement-to-measurement fusion and centralized measurement fusion [24].

In measurement-to-measurement fusion, the raw data provided by different sensors are associated with each other, and then the resulting data is further processed by the fusion. This type of signal processing requires high-time synchronization between sensors [24]. In Table 2.1, related works which use measurement-to-measurement fusion are summarized [24].

Table 2.1: Related works that use measurements-to-measurement fusion.

[26]	Laser scanner + short range radar	Detecting an unavoidable collision with a stationary object
[27]	Laser scanner + Camera	Vehicle detection
[28]	Laser scanner + Stereo camera	Moving Objects tracking in intersection scenario

In centralized measurement fusion, the raw data captured by sensors are directly provided to the tracking module. This approach requires the same time baseline for all sensors. If the sensors perform asynchronously, with different update rates or latency, the available data at the tracking module does not follow the same time baseline, known as out-of-sequence measurements [24]. Centralized signal processing of such measurements has been studied in the literature. Several out-of-sequence algorithms are developed in [29, 30]. Some investigations on centralized measurement are provided in Table 2.2.

Table 2.2: Related works that use centralized measurement fusion.

[31]	Radar, Camera, Lidar	Pre-crash and safety application
[32]	Radar +camera; belief network	Positioning of target vehicle

Mid-level fusion: In mid- or feature-level fusion, the sensors extract some features from raw data and provide them to the fusion module. Feature-level fusion requires sensors using a global object model and a specified feature for exchanging data [24]. The architecture of feature-level fusion is illustrated Fig. 2.4.

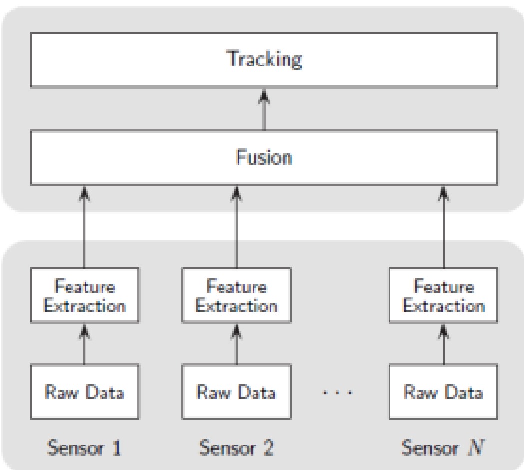


Figure 2.4: Architecture for feature-level fusion

An example of feature-level fusion in the context of cooperative radar is presented in [31], in which joint radar signal processing given target points provided by different sensors is introduced. The authors use the target points for generating the object-level data. In more detail, each sensor measures multiple target points belonging to one or several objects. For each target point, the range, velocity, and azimuth angle are measured and exchanged as extracted features. The measured data by sensors is illustrated Fig. 2.5.

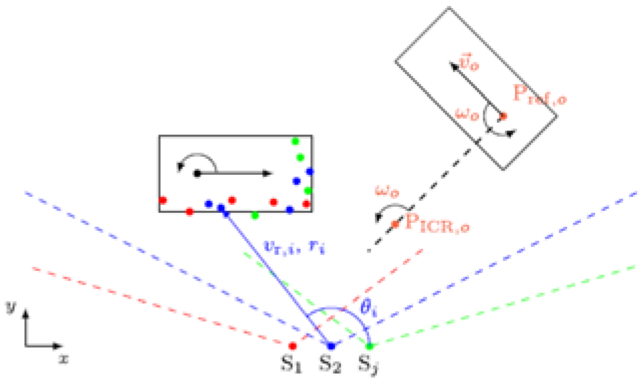


Figure 2.5: Measurement target point [31] and raw data description.

The set of measured target points by each sensor is provided to a central processor, which is called a fusion module (in our reference architecture) for further computations. The processing chain for generating the objects from raw data in a multiple radar sensor network is illustrated in Fig. 2.6. The data processing chain is described as follows:

- Clustering: In this step, the target points belonging to the same physical object should be grouped as clusters. There are several approaches for clustering the target points, which are addressed in [31]. Regardless of the applied approach, clustering becomes challenging if the density of object target points is low with only a few distinguished features. This can result in the so-called over-clustering. Using multiple sensors increases the density of the target points, and thus, the over-clustering problem can be overcome.
- Contour estimation: In this step, a convex hull of the target points assigned to a single object is determined. The goal is to estimate the bounding box for each detected target. The more dimensions of a target can be observed by the sensor, the easier robust contour estimation is. In the case that the target is located very close to a radar sensor, the problem of contour estimation is relevant since only one dimension of the object can be observed by a single radar sensor. Using spatially separated radar sensors which provide target points from different sides can increase the robustness of contour estimation.
- Motion estimation: The goal is to determine the motion model given the radial velocity of target points. Generally, an instantaneous estimation of non-linear motion requires more than one sensor unless a model-based algorithm is used. While two sensors are required for the estimation, further sensors improve the stability.

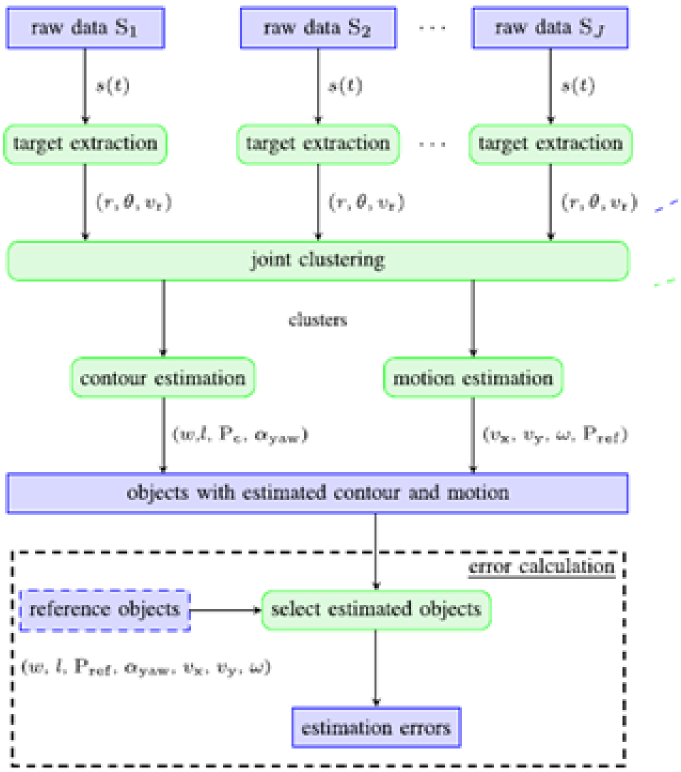


Figure 2.6: Complete processing chain for estimating extended objects using multiple radar sensors [31].

Subsequently, [31] focuses on single-frame multi-radar evaluation. In this context, a frame is a single simultaneous measurements done by different radars. Moreover, the authors of [31] evaluated their proposed approach based on practical measurements. The measurement setup is shown in Fig. 2.7. Three sensors installed on a linear rail measure in a monostatic fashion target point of objects. Their trigger inputs are created by a pulse-generating arbitrary waveform generator. AWG delivers a distributed trigger signal of repetition rate to allow for time-synchronous measurements [31]. The results of [31] show better coverage of objects and higher estimation quality using multiple sensor measurements.

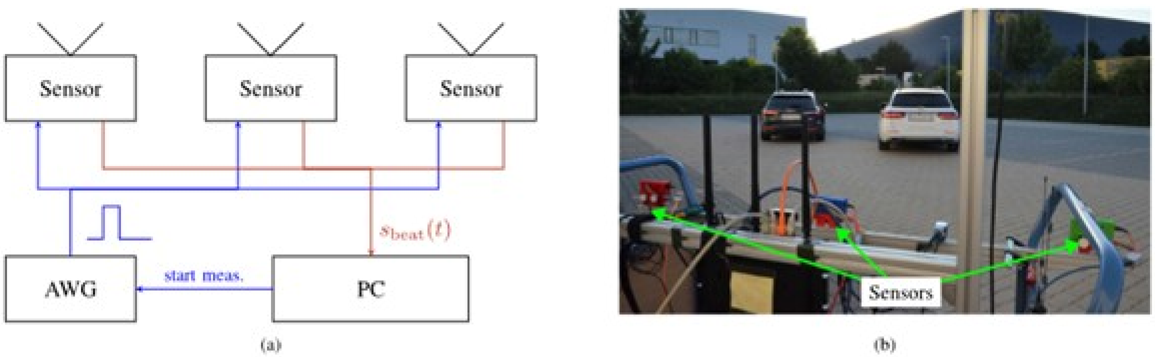


Figure 2.7: Measurement setup [31]

An analytical analysis of cooperation gain in feature level is investigated in [32]. This paper studies the accuracy of central sensor data fusion based on geometric parameters. The authors use a simple

Markov motion model for the target, i.e., constant velocity model with a zero-mean normal-distributed noise. In addition to the noisy measurement of target position, the detection probability and Poisson distributed sensed clutters are exchanged between sensors. The sensor fusion used in the paper is based on a particle filter at a central data fusion without considering any communication loss. Based on the simulation, the cooperation gain and the requirements on radar sensors are evaluated.

High-level fusion: In high-level data fusion, each sensor does the data processing and tracking on its own and provides the so-called object list. The object lists provided by different sensors are fused into a single object list. In this type of fusion, most of the signal processing is done locally in sensors, and the so-called object-level sensor data is exchanged between sensors. In this case, sensors process their perceived raw data to object level. An object list with the corresponding attributes is generated and provided to a central or distributed unit for further processing and fusion. There are many investigations in academia and industry dedicated to this type of cooperation. It is worth mentioning that this type of cooperation allows multi-modal sensor cooperation, for example, between different sensor types such as camera, radar, and lidar.

As an example, the authors of [33] studied infrastructure sensors (camera and radar) for highway scenarios. Fig. 2.8 and 2.9 show the infrastructure sensors and the architecture used in [33], respectively.

Figure 2.8: An example of the measurement points installed on the A9 highway near Munich, Germany. In addition to the visible radars in this picture (indicated by the red circles), two further radars directed towards the north are installed on the other side of the gantry and cannot be seen from this perspective [33]

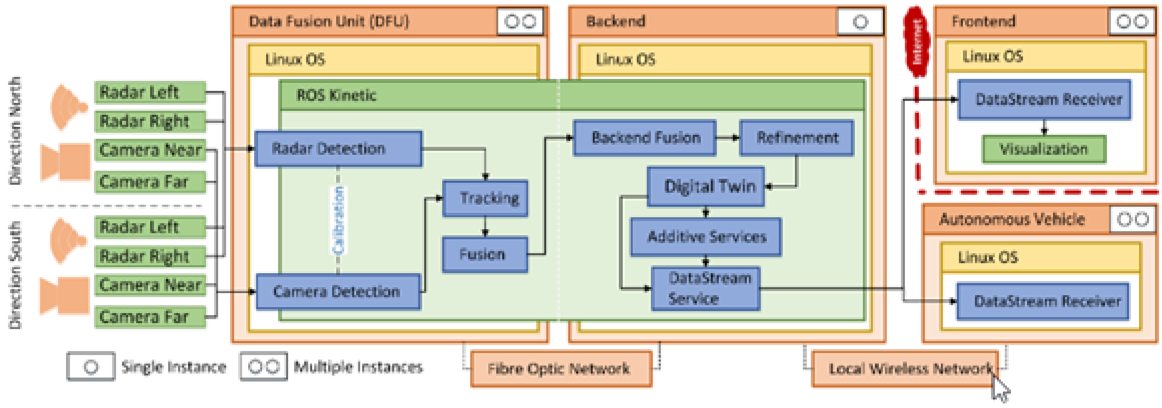


Figure 2.9: Platform architecture [33]

Clearly, object-level sensor data fusion requires a specified interface for exchanging data. In the domain of vehicular communication, the so-called cooperative awareness message (CPM) [34] is specified for exchanging data between different traffic members. This message is used for exchanging the object lists between vehicles and/or infrastructure. The possibility of exchanging information such as covariance matrix (used for determining the inaccuracy of measurements), and object class with its uncertainty increases the accuracy of object-level fusion. In project LUKAS (German: Lokales Umfeldmodell für das Kooperative, Automatisierte Fahren in komplexen VerkehrsSituationen) [35], the feasibility of using CPM for multi-modal data fusion is studied. Fig. 2.10 shows an overview of sensors and data processing modules used in LUKAS.

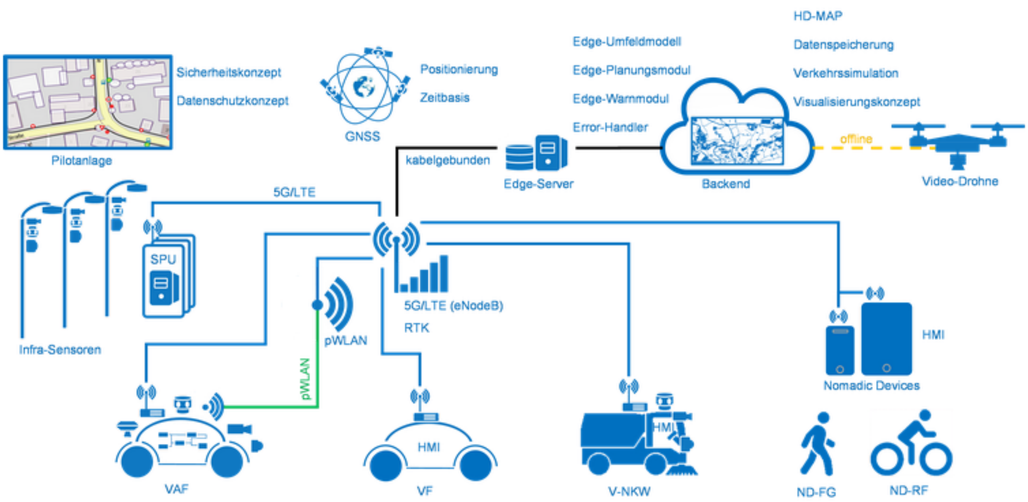


Figure 2.10: An overview of approach used in project LUKAS [35]

As shown in Fig. 2.10, vehicles and infrastructure are equipped with sensors. Hence, we have different environmental models (in vehicles and in infrastructure). Vehicles transmit their environment models to the infrastructure (using CPM). Infrastructure performs a fusion of environment models captured by its sensors and road users. Clearly, the resulting environment model has better accuracy with an extended field of view. The generated environment model is sent to vehicles and traffic members.

The advantage of high-level fusion is that the amount of data which should be exchanged between users is less than in low-level data fusion. Moreover, standardization of the interface for high-level fusion is easier and as mentioned, this has already been done for the automotive domain. The other advantage is distributed data processing. The main disadvantage of high-level data fusion is that the sensors need enough computation power to generate the object list. Reliability and trust are other things which need to be considered for high-level data fusion. Moreover, the high-level data fusion has a drawback in that the central fusion module does not have access to raw data, which might have an impact on the accuracy of perception.

Hybrid fusion: Each level of data fusion has its own advantages and disadvantages. Depending on the scenario and the data type, we might need different fusion levels. Hybrid fusion is an approach which allows different levels of fusion in a system. Thus, we can optimize and configure the system depending on the data demand, communication, and computation resources.

The authors in [36] use the concept of hybrid fusion for the automotive domain. The concept of this work is to use the sensor data information from infrastructure in a vehicle. To reduce the channel load for communication, the data fusion for generating an environment model is done in infrastructure, and the object list is transmitted to vehicles. In the vehicle, the object list from the infrastructure is fused with the raw data captured from sensors installed on the vehicle. Fig. 2.11 shows an overview of this scenario.

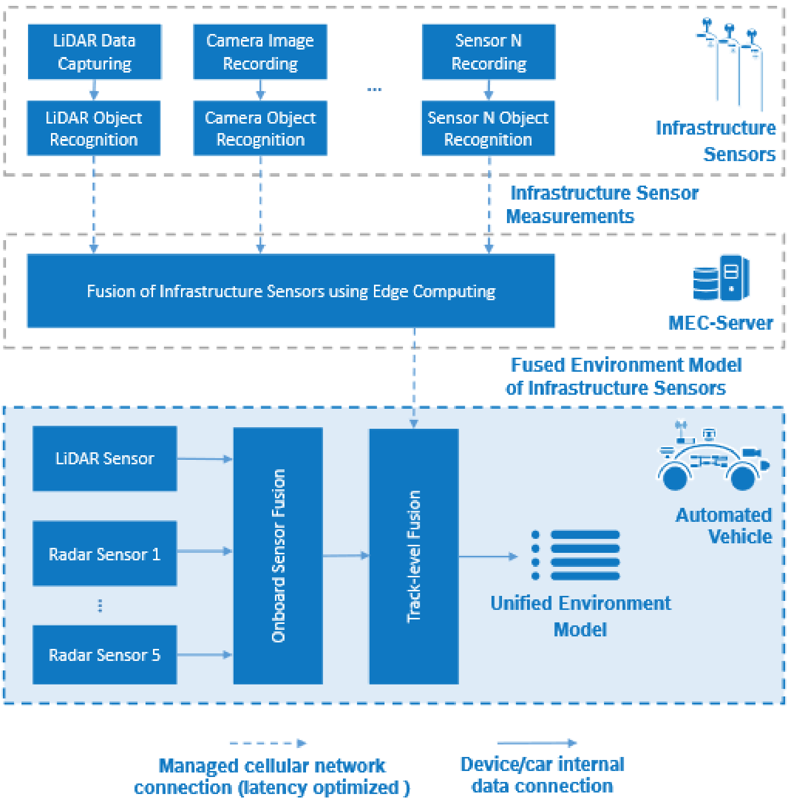


Figure 2.11: System overview of hybrid fusion studied in MEC-View project [36]

Despite the advantages of hybrid fusion, the complexity of the fusion module in practical applications may be very high. Additionally, the interface becomes quite complex since the requirements for communicating different data types need to be satisfied.

3.2 Gap Analysis

Our primary focus will be determining which fusion mechanism should be implemented across various network elements, such as base stations, baseband processing units, and cloud servers, in order to improve sensing and communication performance. We will analyze how to combine information from RF sensing with other sensing modalities that are likely to be available such as cameras, radars, Lidars. Even though fusion helps to increase the sensing accuracy, synchronization of all network elements is an essential requirement for fusion-based systems. In addition, the time required to combine the sensing data from various network elements contributes to the overall increase in latency. In this context, we analyze the impact of synchronization on the overall fusion process and quantify the trade-offs between timeliness and system fidelity/precision.

4 Machine learning methods for parameter estimation (TUIL)

4.1 State-of-the-Art

The parameter estimation stage in ICaS is responsible for extracting the necessary information for localization from the received signal. The first step is to estimate the wireless channel impulse response using pilot signals. This step is similar to the channel estimation in wireless communication systems, allowing both systems to share the signal processing step efficiently. There are different options for the next step. One is signal parameter estimation, and another is direct position estimation, as shown in Fig. 2.12, both outlined with their respective challenges below.

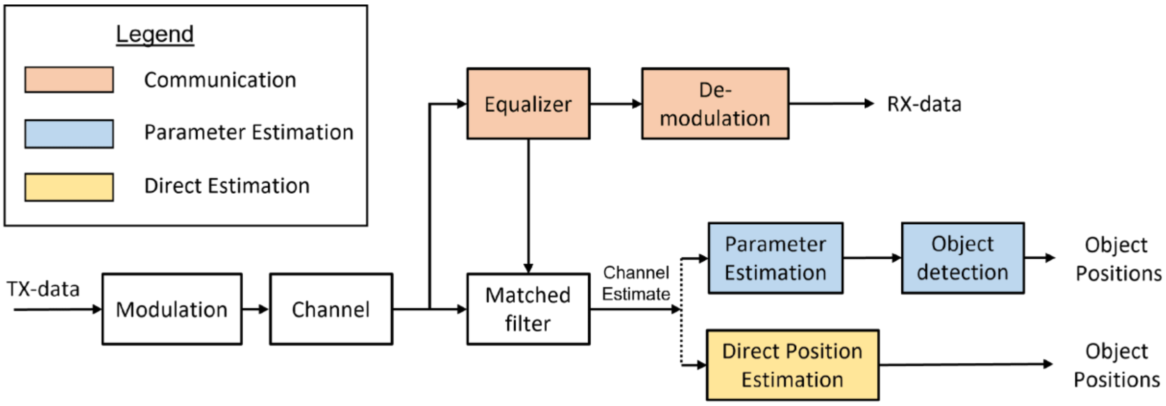


Figure 2.12: Block Diagram of the Signal Processing to obtain object positions via ICaS. Two different approaches exist to estimate the object positions. With signal parameter estimation (blue) the position is computed from the parameters using explicit geometry knowledge. With direct position estimation, the geometry is implicitely included into the algorithm

The goal of signal parameter estimation is to extract the target's parameters (i.e., delay, Doppler, Direction of Arrival) from the channel estimate using parameter estimation algorithms. Generally, the use of signal parameters in ICaS deployments has several advantages. Signal parameters are a low-bandwidth representation of the high-bandwidth measurement, minimizing the signalling overhead while preserving all information required for sensing. Moreover, they directly relate to the geometry of the wireless propagation environment, decoupling the scenario-specific geometry from the localization-relevant information acquisition.

Existing approaches for parameter estimation can be categorized into four groups: subspace methods, including Multiple Signal Classification (MUSIC) [37] and Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT) [38]; iterative maximum likelihood (ML) [39]; Sparse Signal Recovery (SSR) [40]; and, more recently, Deep Neural Network (DNN)-based techniques [41-43]. The latter techniques are being actively researched for their potential parameter estimation, given their predictable computation time and adaptability to complex data. For instance, in [41], a CNN is used to estimate frequencies and has shown improved performance compared to MUSIC, particularly in low-SNR situations. Further, other works have explored CNNs for Direction-of-Arrival (DoA) estimation, with some using denoising autoencoders and DNNs [42].

A more direct approach that circumvents the signal parameter estimation is the direct position estimation. In the context of this positioning (see Section 3.1), where an active transmitter is to be located, the problem of position estimation can also be solved using machine learning approaches. To this end, a straightforward approach is directly using the channel state information to estimate the transmitter's position via (deep) Neural Networks (NN).

In [44], various NNs to estimate the position of an active user in an indoor environment were compared. An interesting problem is the generalization capability of different NN architectures, i.e., the ability to create site-agnostic NNs. NNs can be applied to sensor fusion as well. In [45], raw data from different sensors are used as input to an NN, which directly estimates the position from the raw input data.

4.2 Gap Analysis

These classification-based methods for parameter estimation show performance enhancements in low-SNR domains but face estimation bias due to grid mismatch and poor scaling. Hence, Grid-free estimates are of interest, especially for high-resolution parameter estimation. Recently, such methods have been proposed [43] but are still of limited use, mainly due to their lack of supporting a sufficiently large number of propagation paths and the comparably high number of weights at higher dimensional tasks.

One promising approach to tackle these issues is to switch from a fully connected to a CNN-based architecture. This would reduce the number of parameters in the CNN and enable the simultaneous processing of multiple signal dimensions. The major challenges for signal parameter estimation that we try to address are:

- Severe multipath environment: Multipath propagation in wireless channels is a major challenge in ICaS systems, as received signals contain various propagation paths from clutter and (extended) targets. It is also connected to the open issue of efficient model order selection in parameter estimation.
- Resource allocation: ICaS systems necessitate efficient allocation of resources such as bandwidth, power, and time for both radar and communication functions.
- Hardware imperfections: ICaS system accuracy is impacted by hardware imperfections like phase noise, carrier frequency offset, and non-linear distortion.
- Synchronization: Accurate synchronization between radar and communication functions is crucial for efficient signal processing in ICaS systems.
- Interference: Interference from other sources, such as other ICaS systems or wireless communication systems, can significantly impact ICaS system performance.

References

[1] NR; Physical channels and modulation, 3GPP TS 38.211 version 17.4.0 Release 17, January 2023. https://www.3gpp.org/ftp/Specs/archive/38_series/38.211/38211-h40.zip

[2] LTE Positioning Protocol (LPP), 3GPP TS 37.355 version 17.4.0 Release 17, March 2023. https://www.3gpp.org/ftp/Specs/archive/37_series/37.355/37355-h40.zip

[3] NG-RAN; NR Positioning Protocol A (NRPPa), 3GPP TS 38.455 version 17.4.0 Release 17, April 2023. https://www.3gpp.org/ftp/Specs/archive/38_series/38.455/38455-h40.zip

[4] NG Radio Access Network (NG-RAN); Stage 2 functional specification of User Equipment (UE) positioning in NG-RAN, 3GPP TS 38.305 version 17.4.0 Release 17, March 2023. https://www.3gpp.org/ftp/Specs/archive/38_series/38.305/38305-h40.zip

[5] Mogyorósi, Ferenc, Péter Revisnyei, Azra Pašić, Zsófia Papp, István Törös, Pál Varga, and Alija Pašić. "Positioning in 5G and 6G Networks—A Survey" *Sensors* 22, no. 13: 4757, June 2022, DOI: 10.3390/s22134757.

[6] M. Henninger et al., "Probabilistic 5G Indoor Positioning Proof of Concept with Outlier Rejection," *Proc. IEEE Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, Grenoble, France, 2022, pp. 249-254, DOI: 10.1109/EuCNC/6GSummit54941.2022.9815663 (alt: DOI: 10.48550/arXiv.2207.08512)

[7] Z. Geng, "Evolution of Netted Radar Systems," *in IEEE Access*, vol. 8, pp. 124961-124977, 2020, doi: 10.1109/ACCESS.2020.3007774.

[8] M. Weiß, "Synchronisation of bistatic radar systems," *Proc. IEEE International Geoscience and Remote Sensing Symposium*, Anchorage, AK, USA, 2004, pp. 1750-1753 vol.3, doi: 10.1109/IGARSS.2004.1370671.

[9] Y. L. Sit, "MIMO OFDM radar-communication system with mutual interference cancellation," Ph.D. dissertation, Institute of Radio Frequency Engineering and Electronics, Karlsruhe Institute of Technology, Karlsruhe, Germany, 2017.

[10] L. Giroto de Oliveira et al., "Bistatic OFDM-based Joint Radar-Communication: Synchronization, Data Communication and Sensing," submitted to the 2023 20th European Radar Conf (EuRAD).

[11] T. Wagner, R. Feger and A. Stelzer, "Radar Signal Processing for Jointly Estimating Tracks and Micro-Doppler Signatures," *in IEEE Access*, vol. 5, pp. 1220-1238, 2017, doi: 10.1109/ACCESS.2017.2667720.

[12] A. M. Haimovich, R. S. Blum and L. J. Cimini, "MIMO Radar with Widely Separated Antennas," *in IEEE Signal Processing Magazine*, vol. 25, no. 1, pp. 116-129, 2008, doi: 10.1109/MSP.2008.4408448.

[13] O. Kanhere, S. Goyal, M. Beluri and T. S. Rappaport, "Target Localization using Bistatic and Multistatic Radar with 5G NR Waveform," *Proc. IEEE Vehicular Technology Conference (VTC2021-Spring)*, Helsinki, Finland, 2021, pp. 1-7, doi: 10.1109/VTC2021-Spring51267.2021.9449071.

[14] C. Laoudias, A. Moreira, S. Kim, S. Lee, L. Wirola, and C. Fischione, "A survey of enabling technologies for network localization, tracking, and navigation," *IEEE Communications Surveys Tutorials*, vol. 20, no. 4, pp. 3607–3644, 2018.

[15] N. Patwari, A. O. Hero, M. Perkins, N. S. Correal, and R. J. O'Dea, "Relative location estimation in wireless sensor networks," *IEEE Transactions on Signal Processing*, vol. 51, no. 8, pp. 2137–2148, 2003.

[16] S. A. (Reza) Zekavat, Handbook of Position Location: Theory, Practice and Advances, An Introduction to Direction-of-Arrival Estimation Techniques, ch. 9, pp. 303–341. John Wiley & Sons, Ltd, 2018.

[17] A. Zanella, "Best practice in RSS measurements and ranging," *IEEE Communications Surveys Tutorials*, vol. 18, no. 4, pp. 2662–2686, 2016.

[18] P. Bahl and V. N. Padmanabhan, "RADAR: an in-building RF-based user location and tracking system," *Proc. IEEE INFOCOM*, Tel Aviv, Israel, 2000, pp. 775-784 vol.2, doi: 10.1109/INFCOM.2000.832252.

[19] C. Zhou, J. Liu, M. Sheng, Y. Zheng and J. Li, "Exploiting Fingerprint Correlation for Fingerprint-Based Indoor Localization: A Deep Learning Based Approach," *in IEEE Transactions on Vehicular Technology*, vol. 70, no. 6, pp. 5762-5774, June 2021.

[20] T. E. Abrudan, Z. Xiao, A. Markham and N. Trigoni, "Underground Incrementally Deployed Magneto-Inductive 3-D Positioning Network," *in IEEE Transactions on Geoscience and Remote Sensing*, vol. 54, no. 8, pp. 4376-4391, Aug. 2016, doi: 10.1109/TGRS.2016.2540722

[21] Y. Ge, M. Stark, M. F. Keskin, F. Hofmann, T. Hansen, & H. Wymeersch, ʻʻAnalysis of V2X Sidelink Positioning in sub-6 GHzʼʼ. *Proc. IEEE International Symposium on Joint Communications & Sensing (JC&S)*, 1-6.

[22] F. Perez-Cruz, C. -K. Lin and H. Huang, "BLADE: A Universal, Blind Learning Algorithm for ToA Localization in NLOS Channels," *Proc. IEEE Globecom Workshops (GC Wkshps)*, Washington, DC, USA, 2016, pp. 1-7, doi: 10.1109/GLOCOMW.2016.7848849.

[23] I. Guvenc and C. -C. Chong, "A Survey on TOA Based Wireless Localization and NLOS Mitigation Techniques," *in IEEE Communications Surveys & Tutorials*, vol. 11, no. 3, pp. 107-124, 3rd Quarter 2009, doi: 10.1109/SURV.2009.090308.

[24] Michael Aeberhard, Object-Level Fusion for Surround Environment Perception in Automated Driving Applications, Dissertation

[25] Michael Aeberhard, Nico Kaempchen "High-Level Sensor Data Fusion Architecture for Vehicle Surround Environment Perception", *Proc. 8th Int. Workshop Intell. Transp*. Vol. 665. 2011.

[26] S. Pietzsch, T. D. Vu, O. Aycard, T. Hackbarth, N. Appenrodt, J. Dickmann, and B. Radig, "Results of a precrash application based on laser scanner and short-range radars," *in IEEE Transactions on Intelligent Transportation Systems*, December 2009, vol. 10, pp. 584–593

[27] H. Takizawa, K. Yamada, and T. Ito, "Vehicles Detection Using Sensor Fusion," *Proc. IEEE Intelligent Vehicles Symposium*, Parma, Italy, June 2004, pp. 238–243

[28] Q. Baig, O. Aycard, T. Dung Vu, and T. Fraichand, "Fusion Between Laser and Stereo Vision Data for Moving Objects Tracking in Intersection Like Scenario," *Proc. IEEE Intelligent Vehicles Symposium*, Baden-Baden, Germany, June 2011, pp. 362–367

[29] Y. Bar-Shalom, "Update with Out-of-Sequence Measurements in Tracking: Exact Solution," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 38, no. 3, pp. 769–778, July 2002.

[30] Y. Bar-Shalom, H. Chen, and M. Mallick, "One-Step Solution for the Multistep Outof-Sequence Measurement Problem in Tracking," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 40, no. 1, pp. 27–37, January 2004.

[31] J. Dickmann, F. Diewald, M. Mählisch, J. Klappstein, S. Zuther, S. Pietzsch, S. Hahn, and M. Munz, "Environmental Perception for Future Integrated Safety Systems," *Proc. 21st Int. Tec. Conf. Enhanced Safety of Vehicles*, Stuttgart, Germany, June 2009,

[30] B. Steux, C. Laurgeau, L. Salesse, and D. Wautier, "Fade: A Vehicle Detection and Tracking System Featuring Monocular Color Vision and Radar Data Fusion," *Proc. IEEE Intelligent Vehicles Symposium*, Versailles, France, June 2002, pp. 632–639.

[31] J. Schlichenmaier, M. Steiner, T. Grebner and C. Waldschmidt, "Clustering and Subsequent Contour and Motion Estimation of Automotive Objects Using a Network of Cooperative Radar Sensors," *in IEEE Transactions on Vehicular Technology*, vol. 72, no. 1, pp. 428-443, Jan. 2023, doi: 10.1109/TVT.2022.3204965.

[32] M. Ashury, C. Eliasch, T. Blazek and C. F. Mecklenbräuker, "Accuracy Requirements For Cooperative Radar With Sensor Fusion," *Proc. IEEE European Conference on Antennas and Propagation (EuCAP)*, Copenhagen, Denmark, 2020, pp. 1-5, doi: 10.23919/EuCAP48036.2020.9135378.

[33] A. Krämmer, C. Schöller, D. Gulati, V. Lakshminarasimhan, F. Kurz, D. Rosenbaum, C. Lenz, and A. Knoll, "Providentia - a large-scale sensor system for the assistance of autonomous vehicles and its evaluation," *arXiv preprint arXiv:1906.06789* (2019).

[34] Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Analysis of the Collective Perception Service (CPS); Release 2; ETSI TR 103 562

[35] https://www.projekt-lukas.de/project-00.html

[36] M. Gabb, H. Digel, T. Müller and R. -W. Henn, "Infrastructure-supported Perception and Track-level Fusion using Edge Computing," *Proc. IEEE Intelligent Vehicles Symposium (IV)*, Paris, France, 2019, pp. 1739-1745, doi: 10.1109/IVS.2019.8813886.

[37] R. Schmidt, "Multiple emitter location and signal parameter estimation," *IEEE Trans. Antennas Propag.*, no. 3, 1986. DOI: 10.1109/tap.1986.1143830.

[38] R. Roy and T. Kailath, "ESPRIT-estimation of signal parameters via rotational invariance techniques," *IEEE Trans. Acoust. Speech Signal Process.*, no. 7, 1989. DOI: 10.1109/29.32276.

[39] M. Haardt, R. Thomä, and A. Richter, "Multidimensional high-resolution parameter estimation with applications to channel sounding," *High-Resolution and Robust Signal Processing*. CRC Press, 2017. 253-338.

[40] D. Malioutov, M. Cetin, and A. Willsky, "A sparse signal reconstruction perspective for source localization with sensor arrays," *IEEE Trans. Signal Process.*, no. 8, 2005. DOI: 10. 1109/tsp.2005.850882

[41] G. Izacard, S. Mohan, and C. Fernandez-Granda, "Data-driven estimation of sinusoid frequencies," in *Advances in Neural Information Processing Systems*, 2019.

[42] G. K. Papageorgiou, M. Sellathurai, and Y. C. Eldar, "Deep networks for direction-of-arrival estimation in low SNR," *IEEE Transactions on Signal Processing*, 2021. DOI: 10.1109/TSP. 2021.3089927.

[43] A. Barthelme and W. Utschick, "A Machine Learning Approach to DoA Estimation and Model Order Selection for Antenna Arrays With Subarray Sampling," *IEEE Transactions on Signal Processing*, 2021. DOI: 10.1109/TSP.2021.3081047.

[44] Maximilian Arnold, Mo Alloulah, "Benchmarking learnt radio localisation under distribution shift", *arXiv e-prints*, October 2022, DOI: 10.48550/arXiv.2210.01930.

[45] M. Arnold and F. Schaich, "Indoor positioning systems: Smart fusion of a variety of sensor readings", *Proc. IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Lucca, Italy, November 2021, pp. 1-5, DOI: 10.1109/SPAWC51858.2021.9593158 (full version: DOI: 10.48550/arXiv.2105.05438).

T5.2 Knowledge Extraction and Representation [DTAG, RWTH, HHI, TUIL, BOSCH, EDD, NOK, GPP]

5 Architecture of an ICaS Data Processing Model

5.1 Overview

This section depicts the architecture of the data processing of an ICaS system in Fig. 3.1. This model consists of multiple stages, sensing requests, processing the beam signal, the antenna data, the local map, and the global map. An overview of these stages is presented in the sections below.

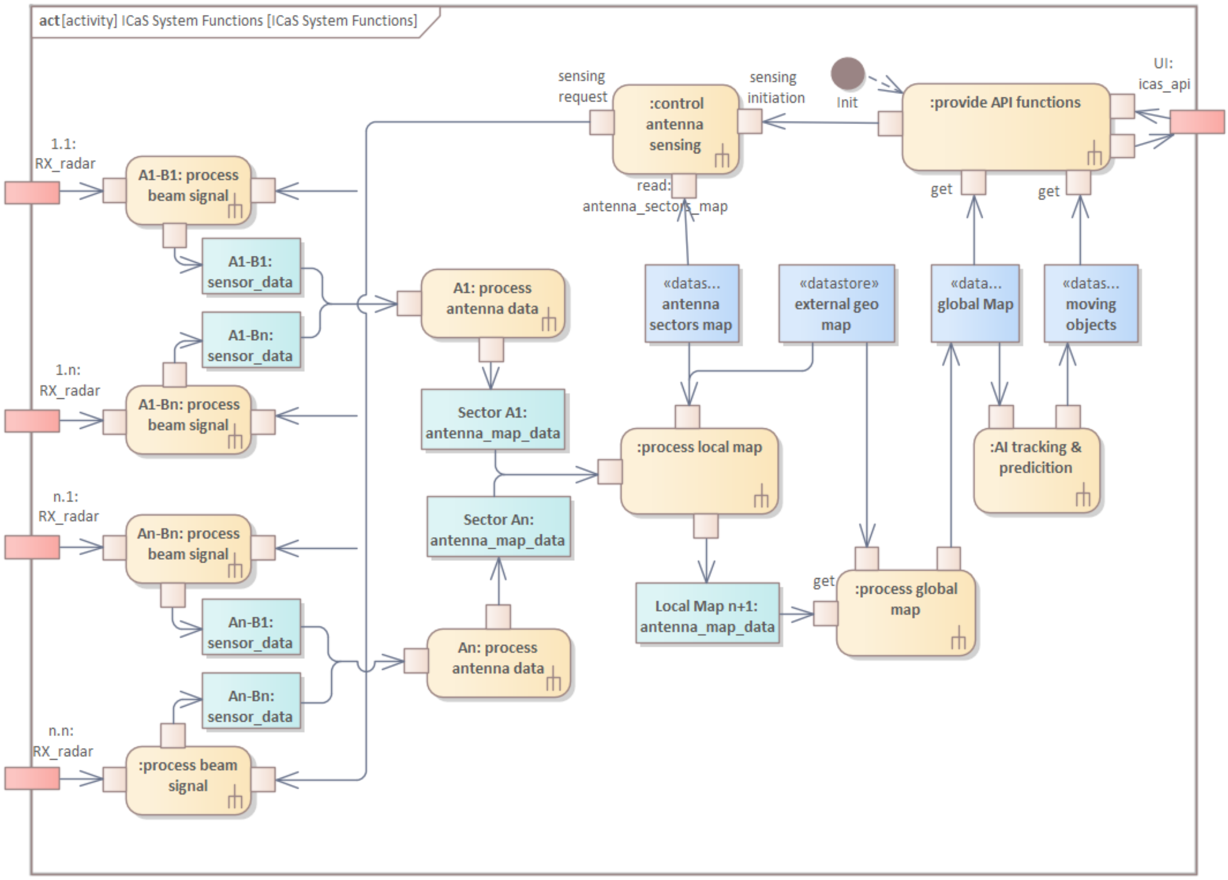


Figure 3.1: Functional Model of Data Processing

The first stage is the sensing request, where a request for sensing can be submitted via the API of the function "provide API function". In some cases, such requests might be directly served from the existing data stores "Global Map" and "Moving Objects". Those data stores are being maintained by regularly scheduled update services or other sensing requests. If more up-to-date information is required, the "control antenna sensing" function is activated. The function uses the antenna sector map to identify all antenna sectors which need to be activated for sensing. There are many sub-functions involved to orchestrate the sensing mechanisms in multiple antennas to retrieve the requested information for the user. The user can set several parameters to define the knowledge in which he is interested. Such parameters can be, but are not limited to:

- Geographical area of interest

- Time window of observation
- Type of object (static, moving, clutter)
- Quality of object classification
- Object properties (position, speed)

Once the sensing mechanism in the radio network is activated, the evaluation process starts to extract the knowledge from the received radar information.

The second stage is the process of the beam signal, where a radio signal (TX) is generated and transmitted (for transmission or explicit for sensing) and is reflected by objects in the vicinity of the antenna. The reflected signal is received on the same frequency and analyzed. Processing those received signals in comparison to the sent signal results in the following information about the observed object distance (based on the phase difference between the sent and received signal), direction of the object (based on the angle of the reflected signal), and velocity of the object in the direction of the beam (based on the received doppler information). The process uses filtering methodologies to identify an object from the received sensor data (e.g. removing clutter by ignoring received echoes with insufficient signal strength). The process would add for any identified object an Object ID, and a Timestamp, as this is essential for the following functions to uniquely identify each echo signal and combine information of multiple sensors of moving objects by interpolating movement according to the timestamp.

The third stage is to process the antenna data, in which a mobile network antenna provides data from multiple beams, sectors and antenna segments of different frequencies. Combining the information from multiple sensors (sensor fusion) can improve the identification of objects. The antenna also has a defined geological position. The potential information extracted on this level could be the Geo positions of multiple objects (longitude, latitude) and Velocity vectors in the direction of the antenna.

The fourth stage is to process the local map, where combining data from multiple antennas of a defined local area allows further extraction of information by triangulation and vectoring of object movements. Objects not seen by one antenna might be detected by another antenna from a different angle. This leads to a more precise geo-information of the whole local area, such as geo-position of all objects detected in the local area, higher accuracy of object position by triangulation, velocity vector over ground (combined from multiple directional Doppler velocities), and tracking of moving objects across antenna boundaries.

Additional geo-data map information of that area can support the process. State-of-the-art combines static maps with dynamic information as mobile devices send their GPS positioning data. The combination of radar data with mapping into static maps is also state-of-the-art in radar systems. However, the identification and classification of objects using additional map data containing static objects and radar-reflective surfaces is completely new, especially when applied to mobile network sensor data. Combination of static geo-data information with the ICaS sensor data allows extraction of additional information, for instance, geo-calibration of sensor map data, changes in static objects (e.g. house tear down), and improved object classification using static map information like the used roadway part. Geo-map information is available today in different formats maintained by different organizations. A life update of such information based on sensor data is unknown today. Applying AI/ML technologies to such data sets would open up a new area of predictive applications (e.g. predicting traffic jams before they happen). There is a wide range of opportunities to be explored.

The final stage is the processing of the global map. Map information of a larger area can be generated from multiple local maps. Stitching concepts for static map information are well-known (e.g. Picture stitching). It needs to be investigated how moving objects can be tracked across local area boundaries. This would be the knowledge extracted from the local maps to provide the feature of moving object tracking across local area boundaries.

5.2 Gap Analysis

Extending existing communication-oriented wireless networks to support sensing functionalities requires additional modules across different network elements. Our research will focus on methods for efficiently collecting sensing data across available dimensions, such as time, frequency, and space, and developing techniques for extracting information/knowledge, such as localization information, target type, and target movement, for various sensing use cases. To guarantee a good sensing performance, we will concentrate on the following main issues.

- Deciding what parameters need to be measured or extracted from the sensing data is the most critical step. Based on the sensing service requirements, one needs to decide what sensing parameters need to be extracted.
- When creating a global map of an area, it is not always advantageous to extract partial information from partial sensing data. In the ICas architecture, which network element will process the sensing data? Our focus will be on determining how to efficiently combine the sensing data from various network elements and extract relevant information to obtain precise environmental information.
- How to develop efficient sensing data processing algorithms to extract useful knowledge from the sensing data? What are the ways to realize appropriate data processing for distributed sensing scenarios? Further, how to modify the network infrastructure, e.g., antennas, radio units, and baseband processing units, to collect sensing data will be our research focus.

6 Object Localization, Identification and Tracking [DTAG]

6.1 State-of-the-Art

6.1.1 Radar-Based Object Sensing Framework

In this subsection, we focus on existing works on radar-based object sensing in automotive radar. First, we provide an overall architecture of the signal processing chain used in radar. We especially focus on the frequency-modulated continuous waveform (FMCW)-based radars, which are used in vehicles for object detection. In the case of FMCW radar, the transmitter first transmits a chirp signal towards the target and waits for the reflected echo signals. After dechirping of the received signal at the receiver end, the radar data matrix is generated from the sampled signal. Roughly speaking this matrix is obtained by reshaping the sampled data into a matrix. The number of rows and columns of the radar data matrix is the number of slow- and fast-time samples, respectively. Fig. 3.2 depicts the architecture for a signal processing chain of an FMCW radar.

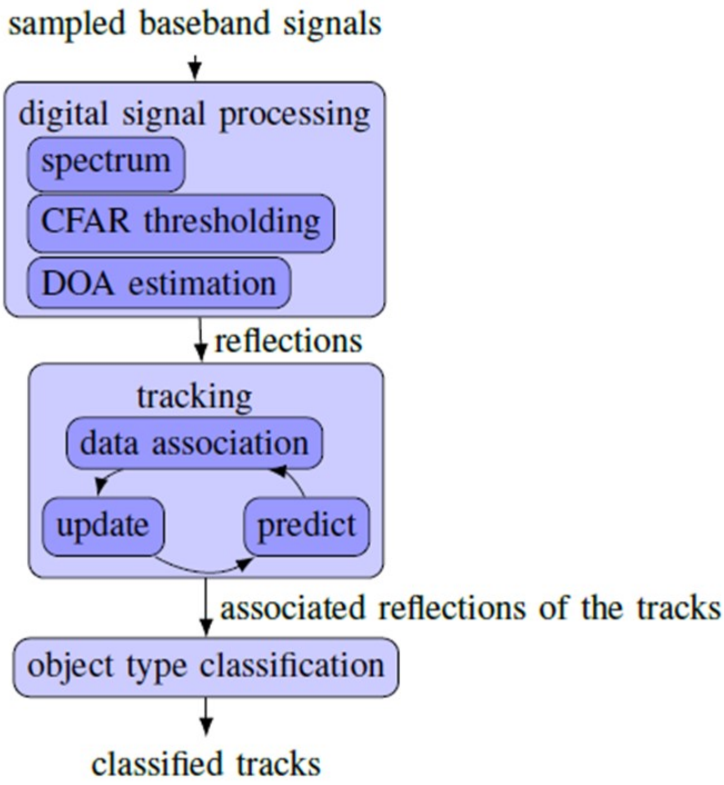


Figure 3.2: An over architecture of signal processing chain for automotive radar [1]

Doing the 2-dimensional DFT of the radar data matrix, we obtain the range-Doppler spectrum matrix, called spectrum in the Fig. 3.2. The rows and columns of this matrix represent the range and velocity, respectively.

Next step is the peak detection based on the range-Doppler matrix using radar constant false alarm rate (CFAR) detector. The main idea of CFAR is comparing the energy of the elements of the range-Doppler matrix with a constant threshold. This provides a fixed false alarm rate. For choosing the threshold optimally, the noise variance is needed. Assuming a white Gaussian noise for the measured range-Doppler spectrum, we obtain a Rayleigh distribution for the absolute value of the range-Doppler spectrum matrix. Given the noise variance, one can compute the probability density function (PDF) for the absolute value for entries of the range-Doppler matrix for the hypothesis that no object exists. Using this PDF one can easily write false alarm rates. Given the false alarm rate as a function of threshold, one can easily obtain the optimal CFAR threshold for a desired target false alarm rate. As mentioned above, this optimization required knowledge about noise variance. Estimating the noise variance can be done using other elements of the range-Doppler spectrum. Details are provided in [2].

After range and Doppler estimation, the direction of arrival (DOA) is estimated given different complex observations. To do this, the amplitude of range-Doppler is evaluated using different received spectra from different antennas. This is done mostly target-based and consists of two steps. In the first step, the signal is compressed given the estimated range and Doppler of the target. In the next step, the maximum Likelihood estimator is used for DOA estimation. The details of DOA estimation are presented in [2]. Generally, there are also other approaches for DOA estimation such as MUSIC (Multiple Signal Classification) and ESPRIT (Estimation of Signal Parameters via Rotational Invariance Techniques).

After DOA estimation, objects should be detected given the reflection points. Notice that one single object might have multiple reflection points. This is the task of tracker to do the association of the reflection point and determine which reflection points belong to the same object and then generate the object with a bounding box. The so-called Kalman-filter (with its different types such as extended Kalman-filter, unscented Kalman filter, constrained Kalman filter, …) is widely used as tracker. Generally, Kalman filter consists of two phases namely prediction and update. In prediction phase, the future state is predicted given previous states and a state transition model. In the update phase, the prediction is enhanced using new observations. Explaining details of Kalman-Filter is beyond the scope of this report. For more details, we refer readers to [3], [4].

In the context of object detection, a broad range of research activities on this topic for automotive use cases is ongoing whereby recent advances in ML techniques are applied [5, 6, 7, 8, 9, 10]. Cross-Modal supervised learning is applied in [5]. Thereby, imaging radars are mounted together with RGB cameras in a calibrated and time-aligned set-up. For the training phase labeled data is produced by object recognition and annotation from the camera images (range/angle localization and object classification: car, pedestrian, cyclist) and fused with radar data to increase localization accuracy. Bringing together image processing capabilities with radar data, a rather self-supervised learning approach is realized.

One additional outcome of this activity is a publicly available dataset [11] of driving scenarios, providing radar and camera images as well as object annotations for the machine learning training phase. Fig. 3.3, 3.4 and 3.5 depict the RGB images and the respective radar images for different scenarios. In Fig. 3.3 and 3.4 a static car scenario in a parking lot is shown. In Fig. 3.5 an image and the respective radar image from a scenario with a car in motion is shown.

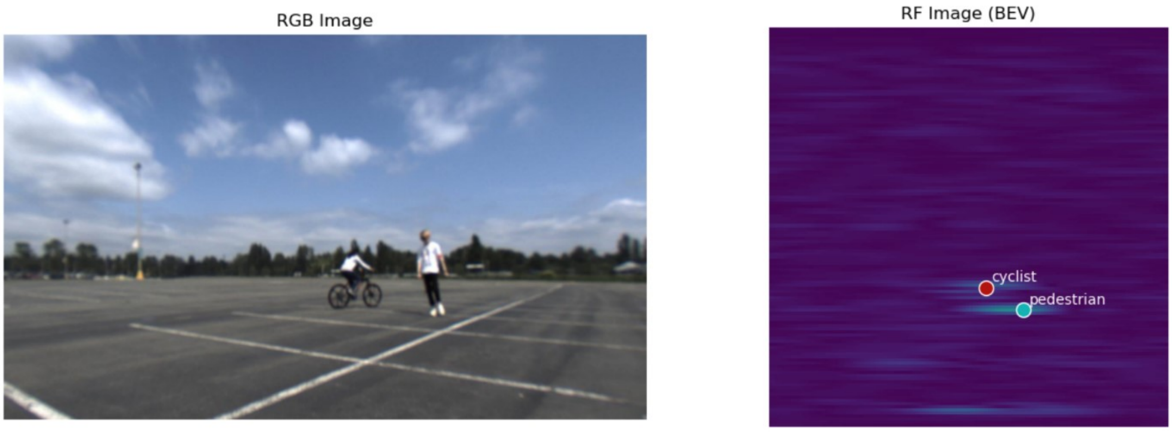


Figure 3.3: Cross-modal sensing with camera imaging and static FMCW radar, scenario A [11].

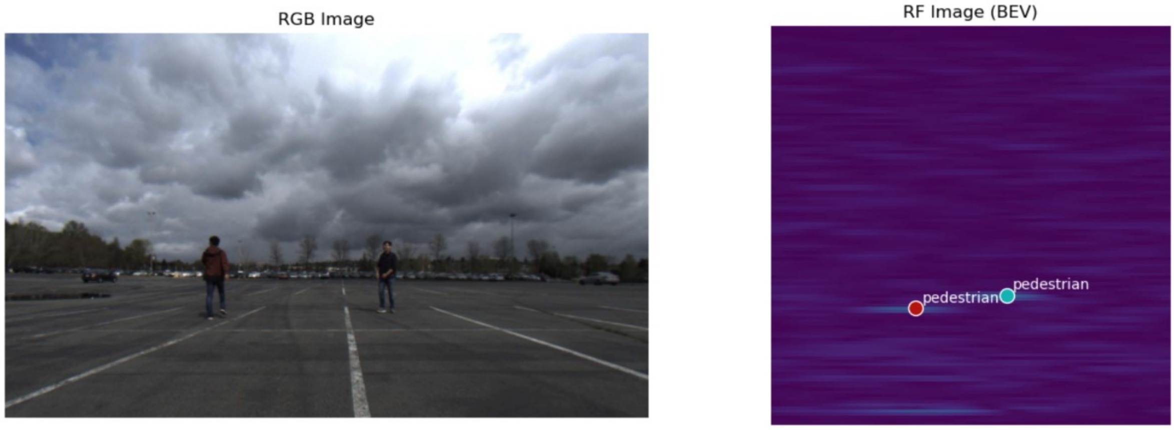


Figure 3.4: Cross-modal sensing with camera imaging and static FMCW radar, scenario B [11].

Figure 3.5: Cross-modal sensing with camera imaging and FMCW radar in motion, scenario C [11].

Radar data is provided in [11] in 3-dimensional arrays of size 128x128x2 resulting from internal pre-processing steps of the FMCW radar set-up, applying consecutive steps of FFT and low pass filtering. The frequency used is 77 GHz. From the physical parameters the range-angle information of the individual sequences and data points can be derived:

- map_size (range, angle): 128x128
- sampling frequency: 4 MHz
- frame rate: 30
- chirps per frame: 4
- min. angle: -90°
- max. angle: 90°

In this radar set up range information ranges from about 0.6 m up to 27.7 m and angular information from -90° to $+90^\circ$.

6.1.2 ICaS-Based Sensing Framework

Wireless sensing technologies have originated from the most widely used sensing technology known as Radar (radio detection and ranging), where radio waves are exploited to determine distance, angle, or instantaneous velocity of objects. Nowadays, this principle is exploited for example by Lidar (light detection and ranging) systems that are capable of obtaining an image of the environment around a sensor. The Lidar system may be either a stand-alone device or integrated in a mobile device or a vehicle. Typically, these stand-alone systems are designed for dedicated applications and use cases, e.g. autonomous driving. A lot of R&D work has been conducted to develop methods and algorithms for these specific application problems.

In contrast to these rather specific sensing applications, sensing in cellular mobile broadband networks differs in at least two dimensions [12]. First, the sensing service of mobile broadband networks needs to serve diverse use cases, not only one. Second, a mobile broadband network is built on cellular infrastructures applying a service-oriented architecture. Hence, instead of optimizing and aggregation of sensing (raw) data for specific use cases and/or stand-alone applications, sensing services in mobile broadband networks need to provide functions and internal services that serve multiple (and maybe diverse) use cases whilst building on a cellular system architecture.

In these respects, ICaS differs significantly from positioning in mobile broadband networks, as addressed for instance in [13]. One key difference is that sensing objects are not actively involved in the inference process. Hence, the algorithms defined for positioning cannot be applied to sensing. Further, every object in the environment can be a sensing target, whereas in case of positioning targets are defined only by the positioning capabilities of the collocated UEs, and a sensing object can be defined by much more features than only the location information in the case of positioning. Another difference is that due to the large variety of potential sensing use cases, a sensing solution should serve the various application demands accordingly. In respect to the positioning solution, UE detection/identification/tracking are inherently given since UEs are "known" to the system, whereas in a sensing approach, this information is not given a priori, it has to be "learned" from the measured data. Lastly, ICaS base stations have to serve both, communication and sensing. Due to the additional processing needs to infer these sensing features, base stations need to be relaxed from these application-driven tasks. These challenges in an ICaS-enabled mobile communication network have been discussed in [12].

In the context of object detection, applying AI/ML to solve object sensing and other sensing tasks on ICaS systems is a promising approach. Thereby, state-of-the-art ML/Deep Learning techniques rely heavily on annotated/labelled data during training [14, 15]. The efficient application of these techniques lacks in the availability of ICaS training data. The first approaches start with the commonly known approaches of transfer learning applying models already trained with huge available datasets [14]. Authors in [16] propose to apply the CRUW dataset [11] generated for radar-based object detection for autonomous driving [5]. Thereby, cross-modal sensing is applied: radar data labels are obtained by object detection in RGB images from a parallel running camera. This can be easily done since image-based object detection can build on well-established techniques applying Deep Neural Networks (DNN), for instance using the YOLO model [17] trained on a very large image data set. Fig. 3.3 and 3.4 show typical results from [13] for a static radar. In contrast to sensing base stations in the ICaS case, autonomous driving radars have to deal with "radars in motion" most of the time as shown in Fig. 3.5. Hence, for ICaS in mobile broadband networks only the stationary subset of training data can be used.

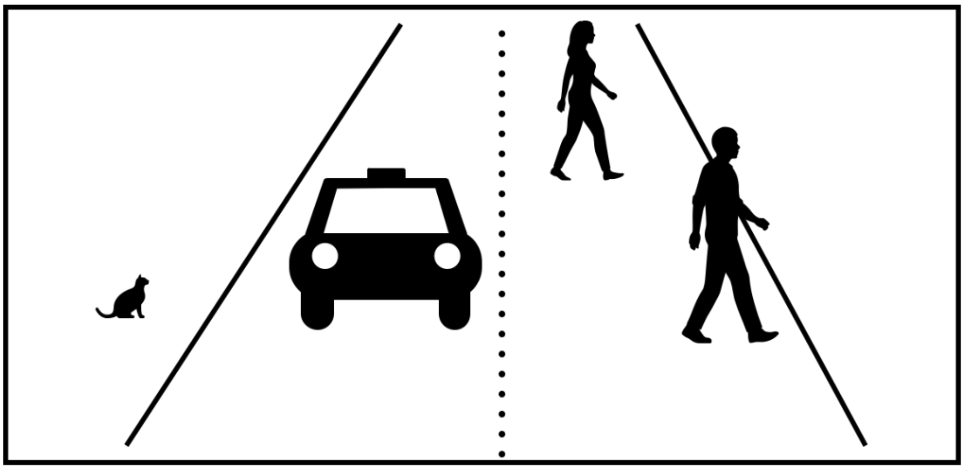


Figure 3.6: View of a car mounted FMCW radar

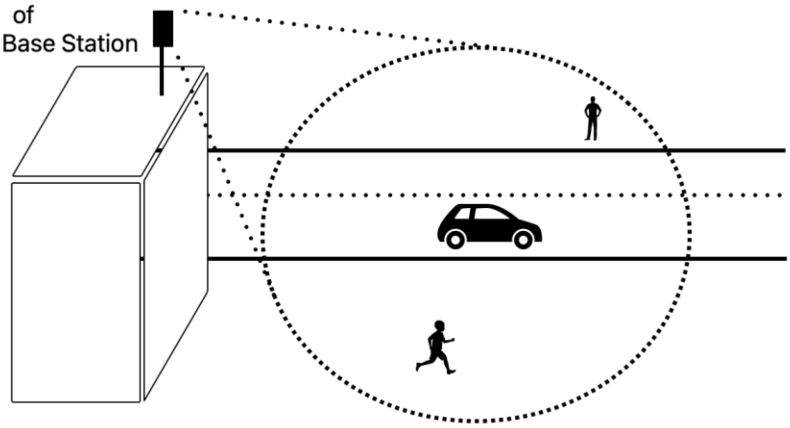


Figure 3.7: View of an ICaS TRX/antenna in dense urban environment

Another limitation of transfer learning from autonomous driving AI/ML is determined by the very different aspect ratio and visual plane of ICaS Sensing Base stations vs. car embedded radars as shown in Fig. 3.6 and 3.7, respectively. Models learned on objects detected from the front view of a car radar will show a degraded performance when transferred to ICaS systems, especially since Sensing Base Station antennas will experience a large variety of aspect ratios and visual planes - resulting from their diverse locations.

In [18] first attempts have been made to prepare a dedicated dataset for mobile radio. As in [5, 16] cross-modal sensors are considered, whereby training data can be produced by object detection in RGB images generated in parallel to the radio data. Although this attempt tends to be more realistic for ICaS systems, it goes along with a considerable effort to produce this data: only a very limited amount of test-beds and base station antenna scenarios can be produced in a certain amount of time. This approach may be applicable for a few selected base station installations but may fail in two aspects. First, it does not provide a huge dataset needed for advanced deep learning methods, and second, it does not cover the variance of base station antenna locations and environments expected in realistic sensing scenarios as required for the use cases defined in Work Package 2. Hence, the approach of [18] may be sufficient for specific scenarios but will not generalize easily.

6.2 Gap Analysis

The ICaS technology provides an excellent opportunity for integrating sensing functionality with communication and facilitating the development of novel sensing-related services for consumers. To achieve this, we must prioritize the efficient processing of sensing data and the inference of knowledge from the data based on the service requirements. In addition, there is a need for appropriate protocol design and signaling across existing cellular networks with regard to the processing of sensing data and the transfer of knowledge. How to coordinate between different cellular base stations for fusing sensing data and determining the achievable sensing performance in terms of use case requirements for accuracy, target misdetection, resolution, and precision of localization will be among the primary challenges to solve.

Splitting sensing inference: In this direction, one possible approach is splitting the sensing inference process into multiple steps as shown in Fig. 3.8, where cascading of sensing data inference is proposed, making use of the hierarchical and service-oriented architecture of a cellular mobile broadband network. Thereby, for each inference step, best-of-breed methods can be applied. Some of the benefits of this approach are: (i) raw data inference can be carried out at the receivers in real time; (ii) the amount of data to be provided to the next inference step is limited; (iii) cellular data fusion is supported when combining processed sensing data from relevant neighboring receivers; (iv) open architecture allows reuse and optimization of the cascading process.

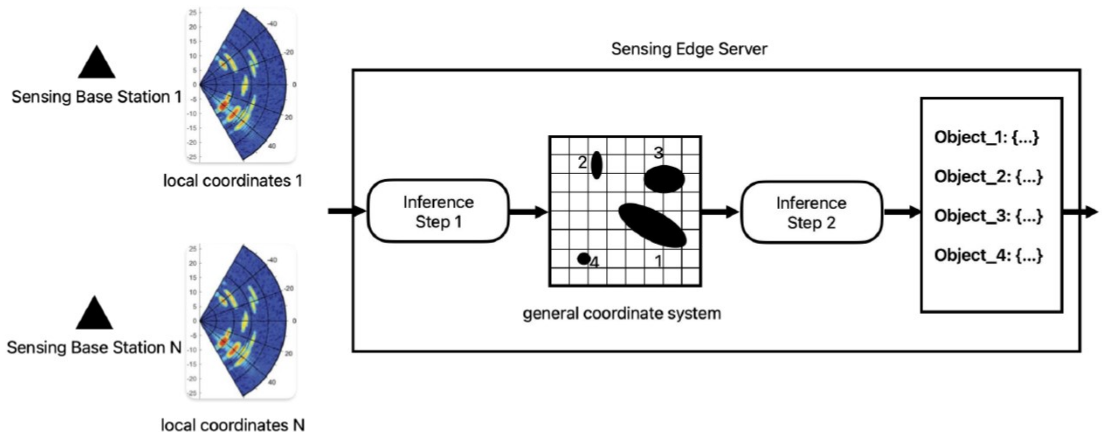


Figure 3.8: Split of object sensing inference steps

Sensing-as-a-Service: In ICaS-enabled mobile broadband networks, sensing-as-a-service and especially object sensing will be provided not as stand-alone service but rather within a communication and sensing service portfolio. Accordingly, common resources and network functions are shared between communication and sensing, it cannot be anticipated that sensing service is continuously maintained at highest service level in the entire cellular network as known from stand-alone applications discussed in the previous section. Sensing-as-a-Service in ICaS is rather provided on demand. Serving this application demand needs to respect the application requirements as well as the resource consumption in an ICaS-enabled mobile broadband network.

Functions and procedures for servicing diverse application demands have to be considered taking also into account the current capabilities of the sensing radio system, see Fig. 3.9.

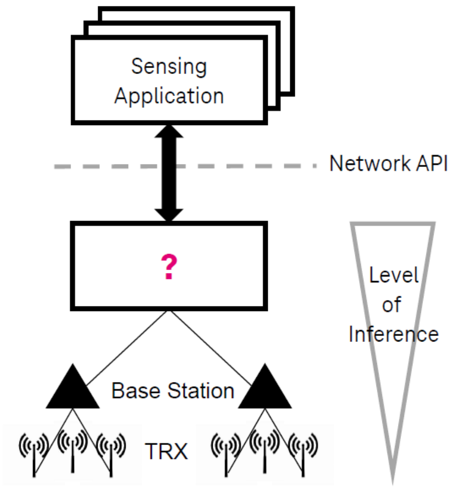


Figure 3.9: Challenges from service diverse sensing applications

Sensing-as-a-Service to support various applications and use cases. For example, (i) object detection/identification/tracking with KPIs on position, velocity, orientation, shape/type, precision/reliability; (ii) environment sensing with KPIs on static-state observation, anomaly/intrusion detection, state change detection; (iii) environment monitoring with KPIs on distinct measurements, like rain, flood. etc.

To facilitate sensing-as-a-service, our investigation will focus on the following aspects: How to manage the trade-off between specific application demands and generalization of radio's sensing capabilities? Since the base stations are heterogeneous in terms of sensing environment and data processing capacity, how to define proper policies for base station coordination and scheduling to achieve the sensing of the large-scale dynamic environment.

7 Environmental mapping [HHI, UST, GPP]

7.1 Channel Charting [HHI, UST]

7.1.1 Overview

Channel charting (CC) is a novel framework that maps each channel state information (CSI) sample of the transmitter to a corresponding point in a latent space in an unsupervised manner while preserving the relative sample distances in the CSI space. This approach is based on a large dataset of CSI samples acquired for a given environment. A key advantage of CC is its unsupervised, data-driven nature, which enables it to be applied without any knowledge of the user's location and without the need for a faithful geometric model of the user's environment. However, rather than providing exact localization, channel charting offers only relative localization or pseudo localization.

This approach can be seen as a relaxation of the classical localization problem, which reduces the need for geolocated CSI data or accurate propagation models, making it an attractive option for practical implementation in real-world scenarios. The potential applications of CC are numerous and range from context-based network management to enhanced localization. CC lends itself especially well to network management tasks in which in many cases only proximity information between UEs is sufficient. In such cases, absolute localization approaches provide more information than is actually needed. Furthermore, pseudo-location can also be seen as a privacy-protecting feature, allowing privacy-sensible applications such as contact tracing to be implemented without requiring the actual user position to be estimated.

An exemplary channel chart, obtained from real-world distributed massive MIMO channel measurements [19], is depicted in Fig. 3.10. It is clearly visible through the preserved colouring that neighbourhood dependencies from the ground truth positions are maintained to a large extent. In absolute terms, on the other hand, the positions in the channel chart do not match with the ground truth positions at all, which is, however, not necessarily required for many applications.

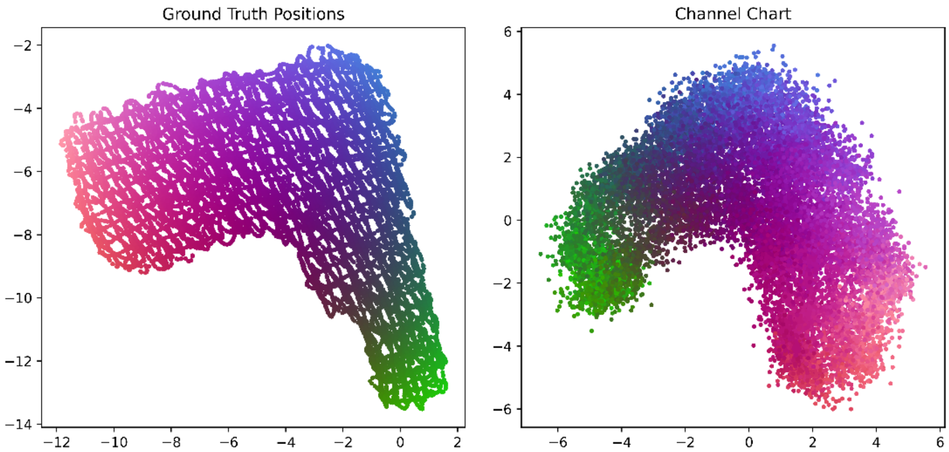


Figure 3.10: Exemplary channel chart (right-hand side) obtained from CSI data corresponding to the ground truth positions (left-hand side) with preserved coloring.

The range of applications for CC is vast and is for itself a subject of active research and development. Being a pseudo-localization framework, CC can be applied to any network management task in which localization, or proximity information between devices, may provide some benefits for reducing system complexity and/or improving system performance. It has been applied to various network management tasks such as, beam management [20], in which annotated multi-beam channel charts have been trained to select the best beam for a given channel chart location. Similar in spirit, SNR annotated channel charts have been utilized in [21] for hand-over optimization. In [22], channel chart locations have been leveraged to reduce complexity of statistical learning-based user scheduling models for sub-THz networks. In [23], CC has been used for the pilot assignment task in mMTC networks with pilot reuse. In [24] channel charts have been leveraged for the prediction of beamformers.

In addition to network management tasks, CC may be used for user localization in environments where GNSS systems, as well as classical localization approaches (TDoA, AoA), fail, which can be the case in environments with strong multipath propagation (e.g., indoor, street canyons). It remains to be seen whether advances in CC will not only preserve local geometric features but manage to reconstruct the global geometry of the radio environment. Global localization, if achievable, would also have great implications on the privacy aspects of Channel Charting, which need to be considered.

7.1.2 State-of-the-art

Learning channel charts, which provide a faithful spatial characterization of a considered network, require a suitable metric capable of providing a good estimate of spatial proximity between CSI from different locations. The task of designing a suitable metric greatly depends on system assumptions, architecture, parameterization and the assumption of the availability of side information. As CC is closely related to localization, the ability to extract a faithful representation of the global spatial geometry will greatly depend on available CSI bandwidth, antenna size, and network architecture in general. In [25], a convexly deployed indoor distributed antenna setup with high bandwidth UWB CIRs have been considered. By considering a high spatial sampling density, the authors approximate the global geodesic distance by interpolating the distances of closely located sample points using KNN interpolation. As a means of integrating time-stamp side information into CC, the authors of [26] trained a DNN model with a push-pull metric-learning objective, also known as triplet-loss. Furthermore, various direct metrics such as, covariance matrix distance [27], or phase-insensitive distance [28] have been applied to CC.

In addition to the choice of the distance metric, the quality of a channel chart also greatly depends on the employed dimensionality reduction technique. While the first publications on channel charting [29] focused on classical linear and nonlinear dimensionality reduction techniques, later work proposed to use of deep neural networks for this task, including Siamese neural networks [30], triplet neural networks [26], and various modifications to triplet neural networks [31]. Due to the ability to perform inference on previously unseen data, neural network-based approaches appear most promising for practical uses of Channel Charting; however, classical approaches remain relevant as a benchmark for distance metrics thanks to their enhanced reproducibility. Furthermore, suitable Feature Engineering for neural network-based Channel Charting and the incorporation of side information (e.g., some known “beacon” positions) remains an open research topic. As the approaches for channel charting have evolved over the past years, the resulting channel charts got more and more meaningful.

7.1.3 Gap analysis

Channel charting is in its infancy when it comes to reconstructing the complete geometry of a dynamic environment. Future research on CC must therefore consider the following issues. How to enhance the framework for pseudo-location even for mobile users and environments with intense scattering. How to develop a distributed framework for multi-point channel charting to generate enhanced environment maps and refine the mapping using distributed machine learning algorithms. Another aspect to investigate is the privacy aspect. Since building the CC the access point/base station has a much finer-grained understanding of the user's location, it can trace the user's precise location without its knowledge.

Both learning (charting) and inference in CC applications must be accomplished with strict real-time and storage restrictions. This opens numerous challenges related to the real-time implementation of ML algorithms for the physical layer in future wireless systems.

7.2 Generating 3D Maps by Accessing Geospatial Information [GPP]

7.2.1 Overview

Combining wireless sensing results with existing geospatial information will add significant value to the generation of high-definition maps, which can capture the near real-time dynamics of the surroundings and present the 3D environment. This can facilitate navigation, tracking, and location-based services even in a global navigation satellite system (GNSS)-denied environment. Making use of geospatial information requires access via standardized interfaces. The OGC (Open Geospatial Consortium) for example fosters the standards for geospatial information interoperability. The Level of detail (LOD) is defined by the OGC standard CityGML 2.0 [32] and is intended to represent different scales of semantic 3D city models as shown in Fig. 3.11.

Figure 3.11: Standardized Level of Detail

Further, sensing of active objects by cellular base stations and the combination of results from multiple base stations will generate a dynamic 3D map of the surrounding environment. The experimental demo collection from TUM-University [33] includes simulations of traffic on top of such geo-maps as shown in Fig. 3.12.

Figure 3.12: Simulation of moving objects on geo-map

7.2.2 Gap Analysis

In general, sensing finer details of surrounding objects requires an enormous quantity of sensing bandwidth and overhead. However, the current cellular standard might not meet the stringent requirements. The primary emphasis of the research will be on the suitability of alternative sensing data acquisition methods for the precise localization of active and passive objects in scenarios with limited bandwidth. In addition, the analysis will concentrate on the complexity of implementing the various data processing algorithms and learning methods associated with different scenarios, such as outdoor and indoor environments.

References

[1] Michael Ulrich, Claudius Gläser, and Fabian Timm; DEEPREFLECS: Deep Learning for Automotive Object Classification with Radar Reflections", *2021 IEEE Radar Conference (RadarConf21)*, Atlanta, GA, USA, 2021, pp. 1-6, doi: 10.1109/RadarConf2147009.2021.9455334.

[2] Michael Ulrich, Radar Signal Processing and Sensor Fusion with Thermal Infrared for Firefighting

[3] Reza Zekavat; R. Michael Buehrer, ``An Introduction to Kalman Filtering Implementation for Localization and Tracking Application", *in Handbook of Position Location: Theory, Practice, and Advances, IEEE*, 2019, pp.143-195, doi: 10.1002/9781119434610.ch5.

[4] A. Kamann, J. B. Bielmeier, S. Hasirlioglu, U. T. Schwarz and T. Brandmeier, "Object tracking based on an extended Kalman filter in high dynamic driving situations," *Proc. IEEE International Conference on Intelligent Transportation Systems (ITSC)*, Yokohama, Japan, 2017, pp. 1-6, doi: 10.1109/ITSC.2017.8317851.

[5] Wang, Z. Jiang, X. Gao, J. Hwang, G. Xing, H. Liu: "RODNet: Radar Object Detection using Cross-Modal Supervision", Proc. *IEEE Winter Conference on Applications of Computer Vision (WACV)*, Waikoloa, HI, USA, 2021, pp. 504-513, doi: 10.1109/WACV48630.2021.00055.

[6] M. Meyer, G. Kuschk: "Automotive Radar Dataset for Deep Learning Based 3D Object Detection", in Proc. *IEEE European Radar Conference (EuRAD)*, Paris, France, 2019, pp. 129-132.

[7] H. Jha, V. Lodhi, D. Chakravarty: "Object Detection and Identification using Vision and Radar Data Fusion System for Ground-based Navigation", Proc. IEEE *International Conference on Signal Processing and Integrated Networks (SPIN)*, Noida, India, 2019, pp. 590-593, doi: 10.1109/SPIN.2019.8711717.

[8] T. Lim, S. Markowitz, M. Do: "RaDICaL: A Synchronized FMCW Radar, Depth, IMU and RGB Camera Data Dataset with Low-Level FMCW Radar Signals", in *IEEE Journal of Selected Topics in Signal Processing*, vol. 15, no. 4, pp. 941-953, June 2021, doi: 10.1109/JSTSP.2021.3061270.

[9] A. Manjunath, Y. Liu, B. Henriques, A. Engstle: " Radar Based Object Detection and Tracking for Autonomous Driving", *Proc. IEEE MTT-S International Conference on Microwaves for Intelligent Mobility (ICMIM)*, Munich, Germany, 2018, pp. 1-4, doi: 10.1109/ICMIM.2018.8443497

[10] N. Meegan, H. Liu, et al.: "ViFiCon: Vision and Wireless Association Via Self-Supervised Contrastive Learning", preprint arXiv:2210.05513v1 [cs.CV] 11 Oct 2022

[11] CRUW dataset and code are available at: https://www.cruwdataset.org/

[12] Arndt Kadelka, Gerd Zimmermann, Jan Plachý, Oliver Holschke: "A CSP's View on Opportunities and Challenges of Integrated Communications and Sensing", in Proc. *IEEE 3rd International Symposium on Joint Communications & Sensing (JC&S)*, 5-7 March 2023

[13] S. Sun, A. Petropulu, H. Poor: "MIMO Radar for Advanced Driver-Assistance Systems and Autonomous Driving", *IEEE Signal Processing Magazine*, vol. 37, no. 4, pp. 98-117, July 2020, doi: 10.1109/MSP.2020.2978507.

[14] Aurélien Géron: "Hands-On Machine Learning with Scikit-Learn, Keras & TensorFlow", O'Reilly, 2022

[15] Next G Alliance: "6G - Next G Alliance Report: AI-Native Wireless Networks", https://www.nextgalliance.org/

[16] M. Alloulah, A. Singh, M. Arnold: "Self-Supervised Radio-Visual Representation Learning for 6G Sensing", in proceedings of International Communication Conference (ICC) 2022

[17] Joseph Redmon, Santosh Divvala, Ross Girshick, Ali Farhadi: "You Only Look Once: Unified, Real-Time Object Detection", arXiv:1506.02640, 2015

[18] A. Alkhateeb, G. Charan, et al.: "DeepSense 6G: A Large-Scale Real-World Multi-Modal Sensing and Communication Dataset", arXiv:2211.09769v2, 2023

[19] F. Euchner and M. Gauger, 'CSI Dataset dichasus-015x: Indoor Line of Sight, Lab Room', 2021, available at: https://darus.uni-stuttgart.de/dataset.xhtml?persistentId=doi:10.18419/darus-2202

[20] P. Kazemi, T. Ponnada, H. Al-Tous, Y. -C. Liang and O. Tirkkonen, "Channel Charting Based Beam SNR Prediction," *Proc. IEEE Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit)*, Porto, Portugal, 2021, pp. 72-77, doi: 10.1109/EuCNC/6GSummit51104.2021.9482548.

[21] P. Kazemi, H. Al-Tous, C. Studer and O. Tirkkonen, "SNR Prediction in Cellular Systems based on Channel Charting," *Proc. IEEE Eighth International Conference on Communications and Networking (ComNet)*, Hammamet, Tunisia, 2020, pp. 1-8, doi: 10.1109/ComNet47917.2020.9306087.

[22] P. Agostini, Z. Utkovski and S. Stanczak, "Channel Charting for Beam Management in Sub-THz Systems," *Proc. IEEE Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, USA, 2023.

[23] L. Ribeiro, M. Leinonen, H. Djelouat and M. Juntti, "Channel Charting for Pilot Reuse in mMTC with Spatially Correlated MIMO Channels," *Proc. IEEE Globecom Workshops (GC Wkshps)*, Taipei, Taiwan, 2020, pp. 1-6, doi: 10.1109/GCWkshps50303.2020.9367434.

[24] L. L. Magoarou, T. Yassine, S. Paquelet and M. Crussière, "Channel charting based beamforming," *Proc. IEEE Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, USA, 2022, pp. 1185-1189, doi: 10.1109/IEEECONF56349.2022.10051826.

[25] M. Stahlke, G. Yammine, T. Feigl, B. M. Eskofier and C. Mutschler, "Indoor Localization with Robust Global Channel Charting: A Time-Distance-Based Approach," in *IEEE Transactions on Machine Learning in Communications and Networking*, doi: 10.1109/TMLCN.2023.3256964.

[26] P. Ferrand, A. Decurninge, L. G. Ordoñez and M. Guillaud, "Triplet-Based Wireless Channel Charting," *Proc. IEEE Global Communications Conference*, Taipei, Taiwan, 2020, pp. 1-6, doi: 10.1109/GLOBECOM42002.2020.9322643.

[27] P. Agostini, Z. Utkovski and S. Stańczak, "Channel Charting: an Euclidean Distance Matrix Completion Perspective," *Proc. IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Barcelona, Spain, 2020, pp. 5010-5014, doi: 10.1109/ICASSP40776.2020.9053639.

[28] L. Le Magoarou, "Efficient Channel Charting via Phase-Insensitive Distance Computation," *in IEEE Wireless Communications Letters*, vol. 10, no. 12, pp. 2634-2638, Dec. 2021, doi: 10.1109/LWC.2021.3109295.

[29] C. Studer, S. Medjkouh, E. Gonultaş, T. Goldstein and O. Tirkkonen, "Channel Charting: Locating Users Within the Radio Environment Using Channel State Information," *in IEEE Access*, vol. 6, pp. 47682-47698, 2018, doi: 10.1109/ACCESS.2018.2866979.

[30] E. Lei, O. Castañeda, O. Tirkkonen, T. Goldstein, and C. Studer, “Siamese Neural Networks for Wireless Positioning and Channel Charting,” *Proc. IEEE Annual Allerton Conference on Communication, Control, and Computing (Allerton)*, Monticello, IL, USA, 2019, pp. 200-207, doi: 10.1109/ALLERTON.2019.8919897.

[31] B. Rappaport, E. Gönültaş, J. Hoydis, M. Arnold, P. K. Srinath, and C. Studer, “Improving Channel Charting using a Split Triplet Loss and an Inertial Regularizer,” *Proc. IEEE International Symposium on Wireless Communication Systems (ISWCS)*, Berlin, Germany, 2021, pp. 1-6, doi: 10.1109/ISWCS49558.2021.9562215.

[32] Open Geospatial Consortium (OGC), „CityGML Overview - OGC Standards,“ [Online]. Available: https://www.ogc.org/standard/citygml/.

[33] TUM, „Online Demo Collection, 3D City Model New York City,“ [Online]. Available: https://wiki.tum.de/display/gisproject/Online+Demo+Collection.

T5.3 Mutual Benefits [RWTH, EDD, NOK, BOSCH, DTAG, HHI, KIT]

A key advantage of ICaS networks is the mutual benefit that communication and sensing will bring, either improving communication through sensing or improving sensing through communication. The following sections discuss these two topics.

8 Improved Communication Through Sensing [EDD, HHI, NOK, RWTH.]

8.1 State-of-the-Art

To improve communication through sensing, it is important to notice that communication systems already use sensing to improve their performance, as discussed in [1]. For instance, CSI estimation by sending pilots before the data is transmitted and Spectrum sensing in cognitive radio applications [2]. In these examples, however, the target is also communicating and not a passive target, such as for usual radar or lidar detection. The following paragraphs discuss how this kind of "radar-like" sensing can be used to improve communication in different aspects.

In the context of mobility management, [1] proposes sensing as a powerful tool for sensing-assisted cell handovers, with the examples of vehicular communication with roadside units, where frequent handovers are needed due to high mobility. In this case, sensing could be used to estimate the time and location at which vehicles enter another RSU's coverage.

In the context of beamforming and beam alignment, directional beamforming is needed in mmWave communication systems, while the overhead of beam training should be kept to a minimum. An exhaustive beam search of the optimal beam pair can result in large overheads and high latency [1]. [3] and [4] propose more efficient codebook-based beamforming protocols and channel estimation algorithms. [5] introduce the concept of using radar signals in a different frequency band to improve the beam alignment for the communication signal in vehicular communication and show some simulation results. Once the communication link is established, beam tracking and prediction are used to keep the communication link. In [6], the authors propose ISAC-based beamforming and -tracking techniques which outperform communication-only schemes in their numerical results, while [7] propose an ISAC-based Bayesian predictive beamforming scheme. The authors of [8] develop a CNN-based beam prediction approach which they validate with a real-world dataset [9]. The same dataset is used to evaluate radar-aided blockage prediction approaches in [10], including an LSTM-based solution.

8.2 Gap Analysis

A major question is whether sensing can provide more benefits than dedicated radio resource management (RRM) related methods that exist in communication networks and can also be regarded as sensing methods. However, here, both the gNBs and the UEs are actively involved. In the evaluation of the benefit of new sensing methods, the resource requirements for them need to be considered, which is often not done in the literature. Furthermore, NLoS channels for the propagation between the BS and the UEs should be considered, i.e., the sensing aiding of the communications beam management should also perform well under such conditions. One possible outcome may be that the additional sensing methods going beyond those that are currently part of 5G-NR RRM do have benefits, but some of the new sensing methods may get integrated into the RRM framework rather than with the sensing framework that is envisioned to be developed for sensing uses cases that are not aiming at improving the communication service.

In case of monostatic ICaS systems, mutual interference caused by communication and sensing signal sharing the same antenna can degrade the performance of both the systems. Existing works assume full-duplex systems for ICaS but implementing them in practice is extremely difficult. In this context, our research focuses on analyzing mutual interference between communication and sensing signal. We try to analyze how the communication load of a base station influences its sensing performance. In addition, in a scenario where multiple cellular base stations conduct sensing operations, we will analyze the impact of sensing signal(s) interference on communication performance and develop interference mitigation techniques that optimize sensing performance while satisfying communication SINR requirements.

Our research will focus on developing energy-saving techniques for ICaS systems and will analyze the overall energy footprint as a result of the integration of two functionalities. How does the integration of sensing functionality affect the overall energy consumption of the existing cellular network, and how are the sleep modes or discontinuous transmission/reception modes modified to maintain the energy efficiency of the ICaS system, these are among the most important questions we seek to answer.

9 Improved Sensing Through Communication [TUIL, EDD, NOK, RWTH]

9.1 State-of-the-Art

In the previous section, it was discussed how communication could be improved by sensing. Similarly, it can also be examined how sensing could be improved by communication. One exemplary use case could be to coordinate sensing between different entities, e.g., in the automotive domain. As stated in [11], there is no standard defining interference rejection or performance for automotive radar specifications. The authors also show that a decrease of up to 30 dB SNR occurs in their test environment without interference cancellation [11]. Similar findings can be found in [12], where it is also stated that with increasing use, the probability of interference becomes an issue. Different mutual interference mitigation techniques are developed and listed in [13]. An alternative approach to traditional interference mitigation is proposed in [14] based on a CNN-based autoencoder, which shows promising results with respect to SINR. In [15], a cooperation system between radar and communication was designed for automotive radar, showing an example of how sensing was improved by communication.

Another approach is by Cooperative Passive Coherent Location (CPCL) [16]. CPCL leverages the existing radio frequency (RF) signals from mobile communication networks as illuminators of opportunity in a cooperative radar sensing system. Due to its strong integration into the mobile communication network, CPCL can efficiently exploit existing features of the mobile communication system, such as MAC scheduling, resource allocation mechanisms, and parts of signal processing. The most resource-efficient operation mode for ISAC is to reuse the signals originally transmitted for communication purposes for object illumination, resembling the well-known passive radar principle and extending it with cooperative features.

Regarding resource allocation mechanisms for cooperative sensing, future 6G networks are expected to have large amounts and densities of base stations (BSs), greater antenna array sizes, as well as wider bandwidth usage when compared to present-day cellular systems. It will be appealing for communication systems to systematically integrate wireless sensing capabilities, which in turn aids in distributed cooperative network sensing [17-19]. To achieve a comprehensive and accurate view of a large-scale complex environment, cooperative sensing from different network nodes (such as BSs, WiFi APs) collocated in the same geographical location can be fully exploited. In [17], the authors discussed the possible technology enablers for facilitating joint positioning and location-aware communication services in a dense 5G network. In addition, the authors proposed a fusion-based method for improving the accuracy of outdoor positioning by combining the estimation of distinct positioning parameters (DoA and AoA) of distributed access networks.

9.2 Gap Analysis

To improve the performance of cooperative sensing, we intend to focus on the following aspects.

- Developing efficient and robust communication protocols for coordinated sensing that can cope with the dynamic and heterogeneous nature of the sensing environment.
- Improving the performance of cooperative sensing algorithms in terms of accuracy, latency, and computational complexity, particularly in the presence of clutter, noise, and interference.
- Enhance the target classification accuracy by observing micro-Doppler properties and movement patterns from multiple angles.
- Deploying data fusion methods to create an online map of the sensed objects from multiple nodes. This can partly be done using existing methods such as Radar-SLAM [2].
- Developing joint resource allocation algorithms to provide optimal distributions in frequency, time, and (beam-)space for the individual requirements of communication UEs and joint sensing tasks. Providing UEs with internal data fusion algorithms to enable data fusion with onboard sensors such as camera and lidar.
- Investigating the security and privacy implications of cooperative sensing and developing appropriate countermeasures to protect the system against potential threats.

References

[1] F. Liu, Y. Cui, C. Masouros, J. Xu, T. X. Han, Y. C. Eldar und S. Buzzi, ''Integrated Sensing and Communications: Toward Dual-Functional Wireless Networks for 6G and Beyond, " *IEEE Journal on Selected Areas in Communications*, Vol. 40, No. 6, p. 1728–1767, 2022.

[2] T. Yucek und H. Arslan, ''A survey of spectrum sensing algorithms for cognitive radio applications, " *IEEE Communications Surveys & Tutorials*, Vol. 11, pp. 116-130, 2009.

[3] J. Wang, Z. Lan, C.-w. Pyo, T. Baykas, C.-s. Sum, M. A. Rahman, J. Gao, R. Funada, F. Kojima, H. Harada und S. Kato, ''Beam codebook based beamforming protocol for multi-Gbps millimeter-wave WPAN systems, " IEEE *Journal on Selected Areas in Communications*, Vol. 27, pp. 1390-1399, 2009.

[4] A. Alkhateeb, O. El Ayach, G. Leus und R. W. Heath, "Channel Estimation and Hybrid Precoding for Millimeter Wave Cellular Systems," *IEEE Journal of Selected Topics in Signal Processing*, Vol. 8, pp. 831-846, 2014.

[5] N. González-Prelcic, R. Méndez-Rial und R. W. Heath, ''Radar aided beam alignment in MmWave V2I communications supporting antenna diversity," *Proc. IEEE Information Theory and Applications Workshop (ITA)*, La Jolla, CA, USA, 2016, pp. 1-7, doi: 10.1109/ITA.2016.7888145.

[6] F. Liu, W. Yuan, C. Masouros und J. Yuan, ‘’Radar-Assisted Predictive Beamforming for Vehicular Links: Communication Served by Sensing,“ *IEEE Transactions on Wireless Communications*, Vol. 19, pp. 7704-7719, 2020.

[7] W. Yuan, F. Liu, C. Masouros, J. Yuan, D. W. K. Ng und N. González-Prelcic, ‘’Bayesian Predictive Beamforming for Vehicular Networks: A Low-Overhead Joint Radar-Communication Approach,“ *IEEE Transactions on Wireless Communications*, Vol. 20, pp. 1442-1456, 2021.

[8] U. Demirhan und A. Alkhateeb, ‘’Radar Aided 6G Beam Prediction: Deep Learning Algorithms and Real-World Demonstration,“ *Proc. IEEE Wireless Communications and Networking Conference (WCNC)*, Austin, TX, USA, 2022, pp. 2655-2660, doi: 10.1109/WCNC51071.2022.9771564.

[9] A. Alkhateeb, G. Charan, T. Osman, A. Hredzak, J. Morais, U. Demirhan und N. Srinivas, ‘’DeepSense 6G: A Large-Scale Real-World Multi-Modal Sensing and Communication Dataset,“ 2022.

[10] U. Demirhan und A. Alkhateeb, "Radar Aided Proactive Blockage Prediction in Real-World Millimeter Wave Systems," *Proc. IEEE International Conference on Communications*, Seoul, Korea, Republic of, 2022, pp. 4547-4552, doi: 10.1109/ICC45855.2022.9838438.

[11] S. Heuel, ‘’Automotive radar interference test,“ *Proc. IEEE International Radar Symposium (IRS)*, 2017, pp. 1-7, doi: 10.23919/IRS.2017.8008119.,

[12] G. M. Brooker, ‘’Mutual Interference of Millimeter-Wave Radar Systems,“ *IEEE Transactions on Electromagnetic Compatibility*, Vol. 49, pp. 170-181, 2007.

[13] M. Kunert, „Project Final Report MOSARIM, MOre Safety for All by Radar Interference Mitigation,“ 12 2012. [Online]. Available: https://cordis.europa.eu/docs/projects/cnect/1/248231/080/deliverables/001-D611finalreportfinal.pdf.

[14] J. Fuchs, A. Dubey, M. Lübke, R. Weigel und F. Lurz, ‘’Automotive Radar Interference Mitigation using a Convolutional Autoencoder,“ *Proc. IEEE International Radar Conference (RADAR)*, Washington, DC, USA, 2020, pp. 315-320, doi: 10.1109/RADAR42522.2020.9114641.

[15] C. Aydogdu, M. F. Keskin, N. Garcia, H. Wymeersch und D. W. Bliss, ‘’RadChat: Spectrum Sharing for Automotive Radar Interference Mitigation,“ *IEEE Transactions on Intelligent Transportation Systems*, Vol. 22, pp. 416-429, 2021.

[16] R. S. Thoma et al., "Cooperative Passive Coherent Location: A Promising 5G Service to Support Road Safety," in *IEEE Communications Magazine*, vol. 57, no. 9, pp. 86-92, September 2019, doi: 10.1109/MCOM.001.1800242.

[17] M. Koivisto, A. Hakkarainen, M. Costa, P. Kela, K. Leppanen and M. Valkama, "High-Efficiency Device Positioning and Location-Aware Communications in Dense 5G Networks," *in IEEE Communications Magazine*, vol. 55, no. 8, pp. 188-195, Aug. 2017, doi: 10.1109/MCOM.2017.1600655.

[18] K. Witrisal et al., "High-Accuracy Localization for Assisted Living: 5G systems will turn multipath channels from foe to friend," *in IEEE Signal Processing Magazine*, vol. 33, no. 2, pp. 59-70, March 2016, doi: 10.1109/MSP.2015.2504328.

[19] Y. Xiong, N. Wu, Y. Shen and M. Z. Win, "Cooperative Localization in Massive Networks," *in IEEE Transactions on Information Theory*, vol. 68, no. 2, pp. 1237-1258, Feb. 2022, doi: 10.1109/TIT.2021.3126346.