# Joint Communication & Sensing – Antenna, Demo & Privacy Aspects

*Jan Adler, Maximilian Matthé, Mehrab Ramzan, Padmanava Sen, Prajnamaya Dass, Shahanawaz Kamal, Stefan Köpsell, Yevhen Zolotavkin*
**Barkhausen Institut gGmbH, Dresden, Germany**

KOMSENS 6G

barkhausen institut

## Role of BI in this Project

BI-sub project: **Full-duplex operation and security aspects in 6G communication**

WP2 : Analyze data protection and data security requirements , develop a secure architecture

WP3: Solve isolation issues between TX and RX antennas for device-to-device (D2D) integrated sensing and communication (ISAC).

WP6: Experimental analysis and demonstrators to showcase solutions developed in WP3 (self interference cancellation)

## Antenna Solutions Development (WP3)

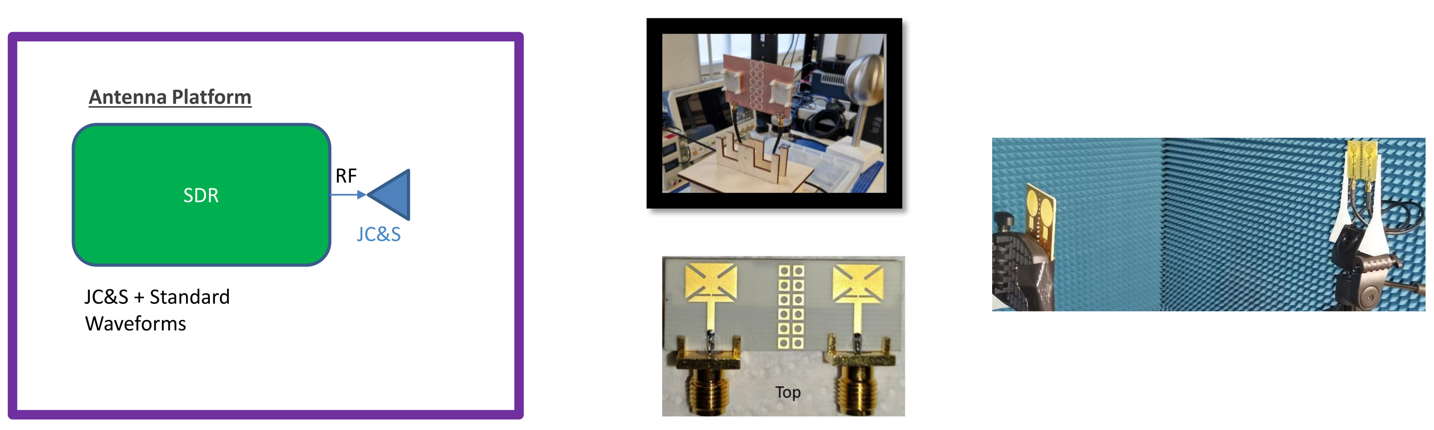
| Solution | Spectrum | Self-interference cancellation concept(s) | Meas. Peak Isolation [dB] | Antenna Gain [dBi] | Publication |
|---|---|---|---|---|---|
| **#1** Separate antennas | 802.11bf | EBG + DGS | 45 | 2.2 | [1] |
| | X-band | Antenna Array + DGS | 57 | 6.2 | [2] |
| | 5G NR | EBG | 50+ | 7.6 | [3] |
| **#2** Shared antennas using circulators or EBD | 802.11bf | Circulator | TBD | NA | NA |
| | X-band | Antenna Duplexed Beam Forming or Circulator | 30+ (initial) | NA | [4] |
| | 5G NR | EBD | TBD | NA | NA |

**802.11bf:** 5.9 GHz – 7.1 GHz
**X-band:** 8 GHz −12 GHz
**5G NR:** 24.25 GHz −27.5 GHz

**EBG:** Electromagnetic band gap
**DGS:** Defected ground structure
**EBD:** Electrically balanced duplexer
**TBD:** To be determined
**NA:** Not applicable

**[1]** M. R. Hossen, M. Ramzan, and P. Sen, "Slot-loading based compact wideband monopole antenna design and isolation improvement of MIMO for Wi-Fi sensing application," *Microwave and Optical Technology Letters*, 2023.
**[2]** M. T. Yalcinkaya, P. Sen and G. P. Fettweis, "High Isolation Novel Interleaved TRX Antenna Array with Defected Ground Structure for In-Band Full-Duplex Applications," *2023 17th European Conference on Antennas and Propagation (EuCAP)*, pp. 1-5, 2023.
**[3]** M. Ramzan, A. N. Barreto and P. Sen, "Meta-surface Boosted Antenna to achieve higher than 50 dB TRX Isolation at 26 GHz for Joint Communication and Radar Sensing (JC&S)," *2022 16th European Conference on Antennas and Propagation (EuCAP)*, pp. 1-5, 2022.
**[4]** M. Umar, P. Sen, "Antenna-Duplexed Passive Beamforming Front-end for Joint Communication and Sensing," *2023 IEEE 3rd International Symposium on Joint Communications & Sensing (JC&S)*, pp. 1-6, 2023.

## BI Focus in this Demo (WP3/WP6)




Antenna Evaluation Platform

- Passive Isolation using defected ground structure in MIMO antenna
- Integrate them with Hermes Py (BI) and NI X410 for JC&S Antenna Evaluation Platform
  - 250 MHz
  - Single carrier with raised cosine filter

## Link Level Evaluator integrated with Hardware (WP6)

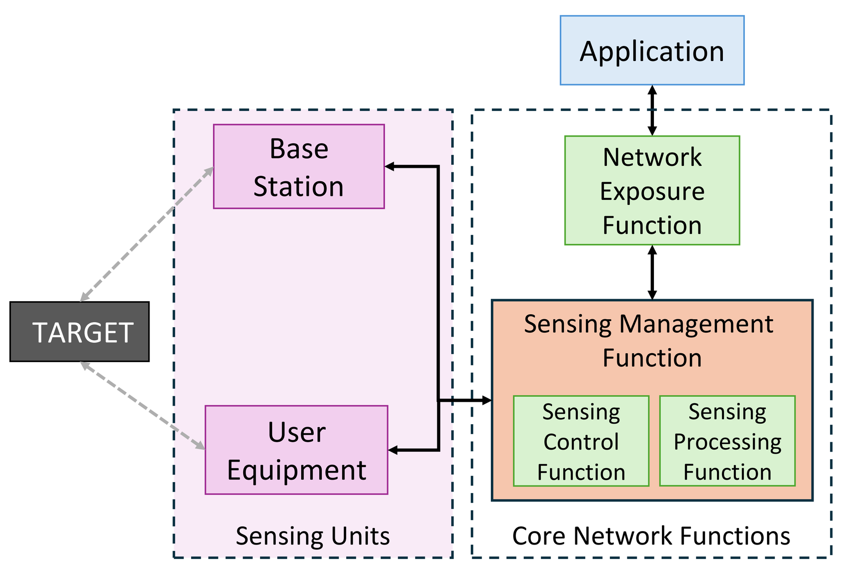
HermesPy: An Open-Source Link-Level Evaluator for 6G

JAN ADLER, TOBIAS KRONAUER, AND ANDRÉ NOLL BARRETO, (Senior Member, IEEE)

https://hermespy.org/

J. Adler, T. Kronauer and A. N. Barreto, "HermesPy: An Open-Source Link-Level Evaluator for 6G," in IEEE Access, vol. 10, pp. 120256-120273, 2022, doi: 10.1109/ACCESS.2022.3222063.

## Privacy Issues with Emergent JCAS Architecture (WP2)



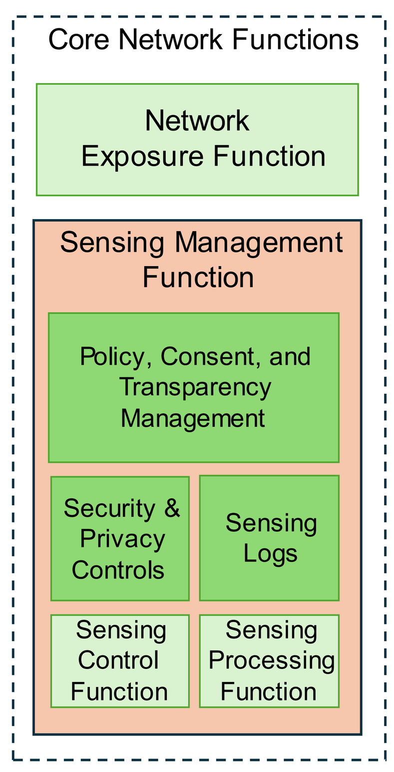
The emergent JCAS architecture

- **Collection of personal data through sensing**
- **Monitoring individual movements and interactions**
- **Profiling and discrimination**
- **Data sharing and third-party access**
- **Lack of Consent and Transparency**

## Proposal for a Privacy Architecture for JCAS (WP2)

[Dass et al.: "Addressing Privacy Concerns in Joint Communication and Sensing for 6G Networks: Challenges and Prospects"]

- **Access control** regarding sensing data
  - sensing policy, consent, and transparency management **Transparency** regarding data collection and processing
  - considering bystanders
- **Users are in control** of the sensing behaviour of their devices
- **Privacy controls** enforce the principle of **data minimisation**




SPONSORED BY THE

Federal Ministry of Education and Research

www.komsens-6g.com

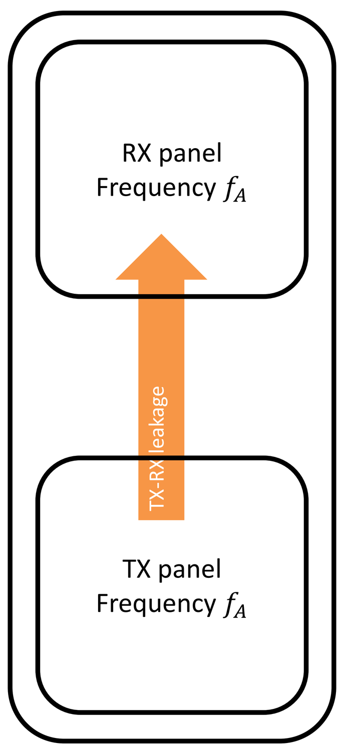
# Antenna Systems for integrated sensing and communication

Philipp Karl Gentner [1], Lucas Nogueira Ribeiro [1], Casimir Ehrenborg [1], Tobias Mann [1]

[1] Ericsson Antenna Technology Germany

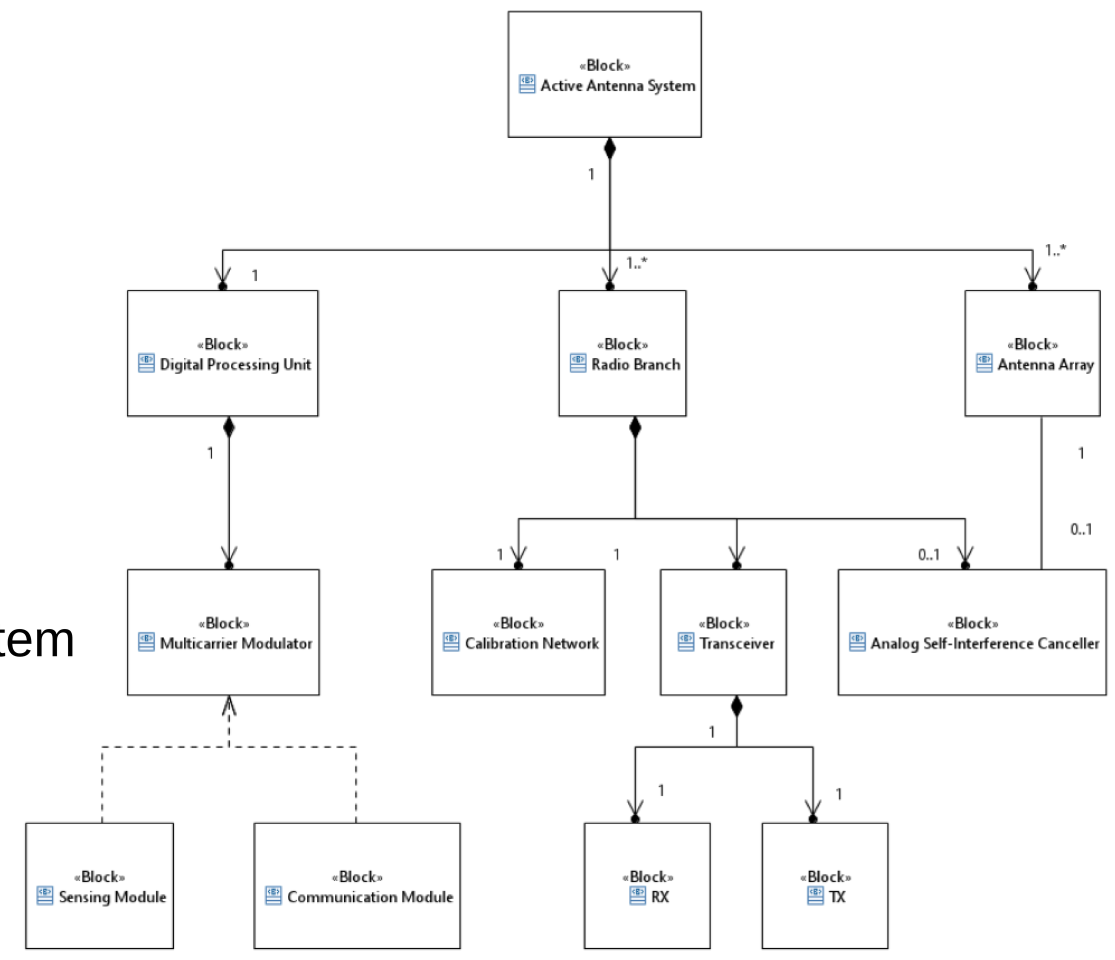
## Sensing and communication

- Focus on a monostatic ISAC antenna system
- Monostatic sensing relies on full-duplex-like systems
  - Simultaneous in-band transmit and receive
  - E.g., 3GPP Rel. 18: sub-band full duplex (SBFD)
  - Feasible in middle- and low-power scenarios, e.g., indoor → Passive isolation requirements
- Radio Frontend Design for various subarray configurations




## MBSE

- Model Bases System Engineering approach utilizing SysML notation of system components.
- Example Block diagram of Advanced Antenna System (AAS)




## ICAS Antenna Design

**Antenna Element**

- Patch radiator element fed by Gamma probe
- Slotted structure for increased polarization isolation.

**Subarray**

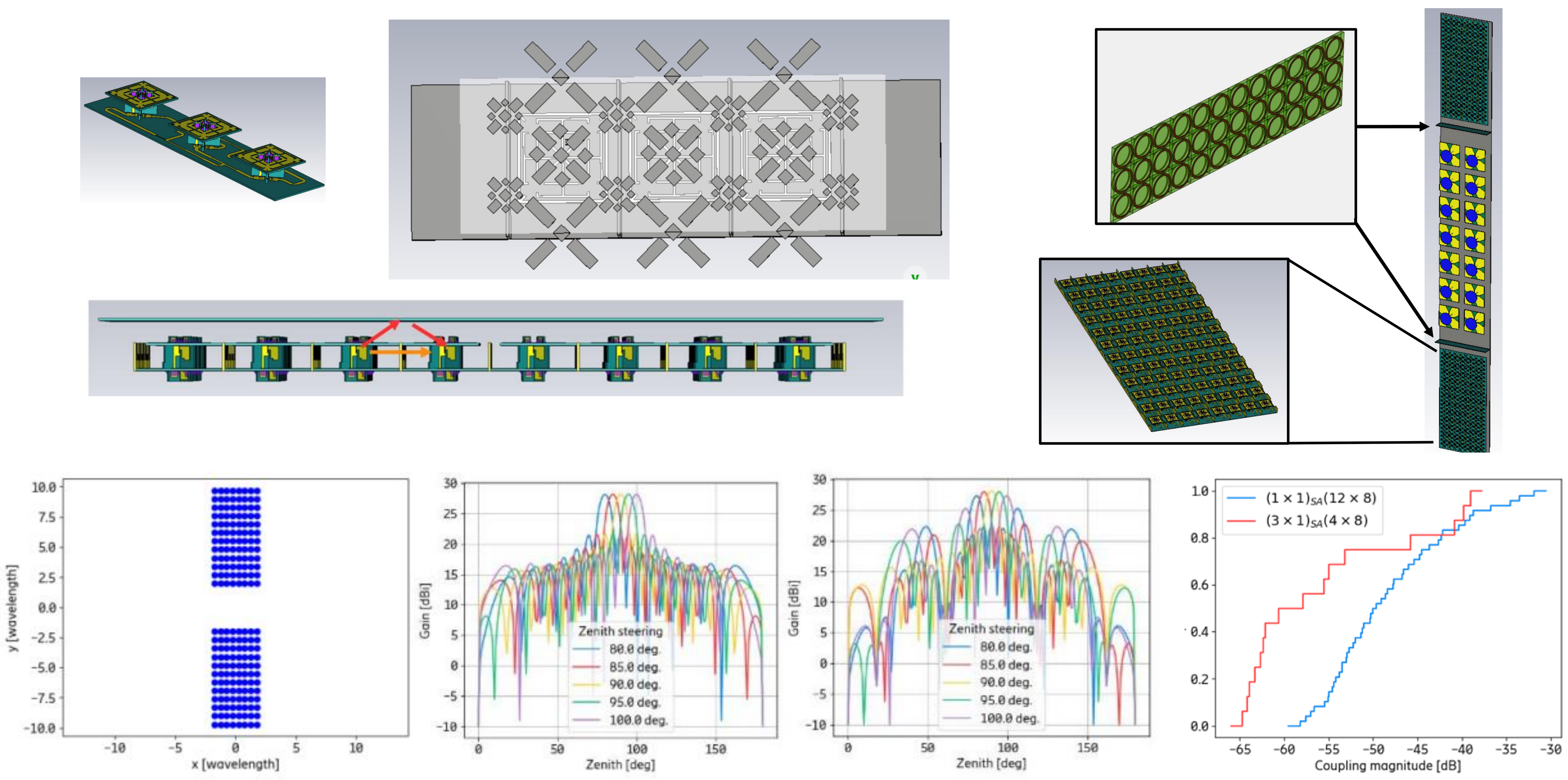
- 3x1 sub-array
- 0.7 $\lambda$ vertical distance at 7.1 GHz
- 0.5 $\lambda$ horizontal distance at 7.1 GHz

**Array Decoupling Structures**

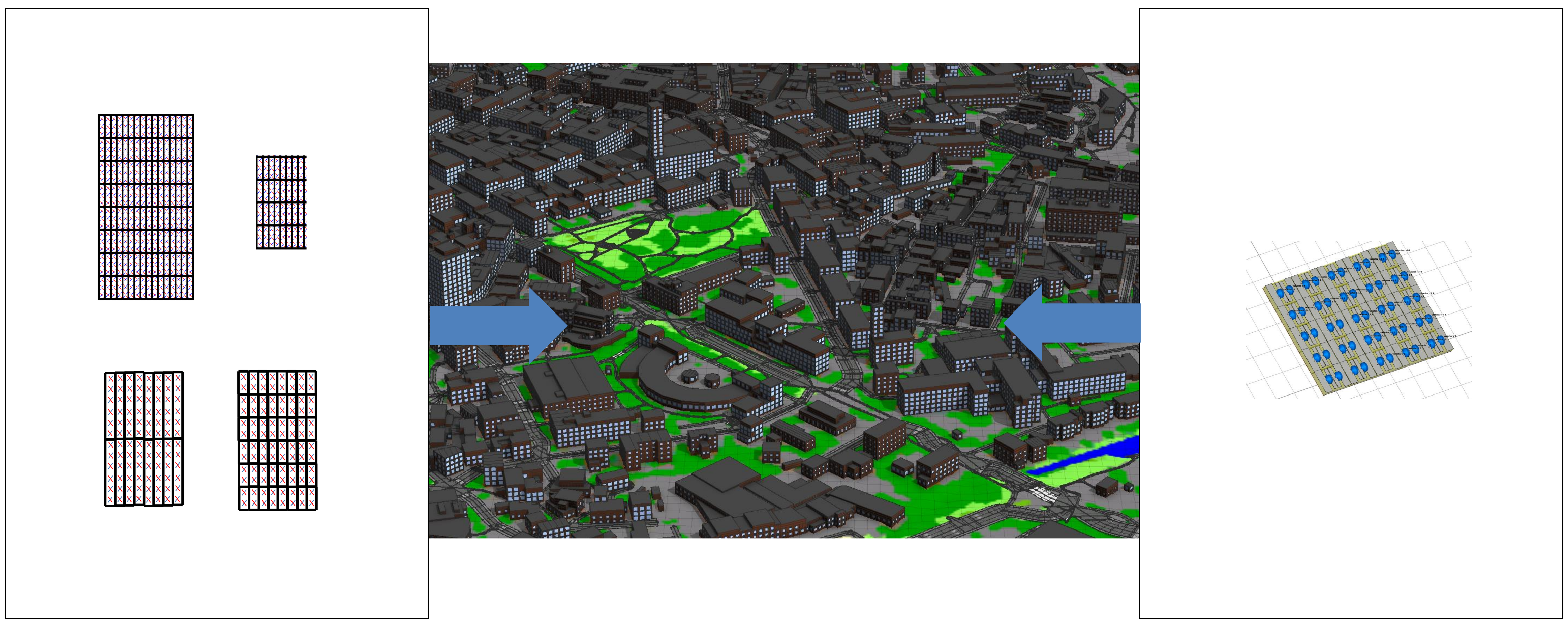
- Sidewalls to decouple horizontal sub-arrays
- Non-resonant passive elements
- Diffracted waves from the surface cancel coupled waves.

**Array Design**

- Evaluation of different 3x1 sub-array configuration for optimal mutual coupling
- Physically separated TX/RX modules for further increased isolation




## Signal Processing



Suitable TX or RX array layout for sensing

Parasitic passive structures (RIS)

- Definition and development of deterministic scenario specific reference models (6G sensing use cases)
- Full virtual representation, digital twin of a monostatic sensing system, which allows to swap the possible antenna layouts.
- RIS or any artificial passive antenna system have the capability to customize the propagation environment, which can further improve the sensing accuracy.

www.komsens-6g.com

SPONSORED BY THE

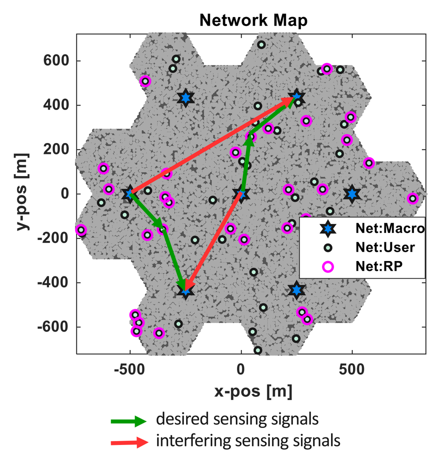
Federal Ministry of Education and Research

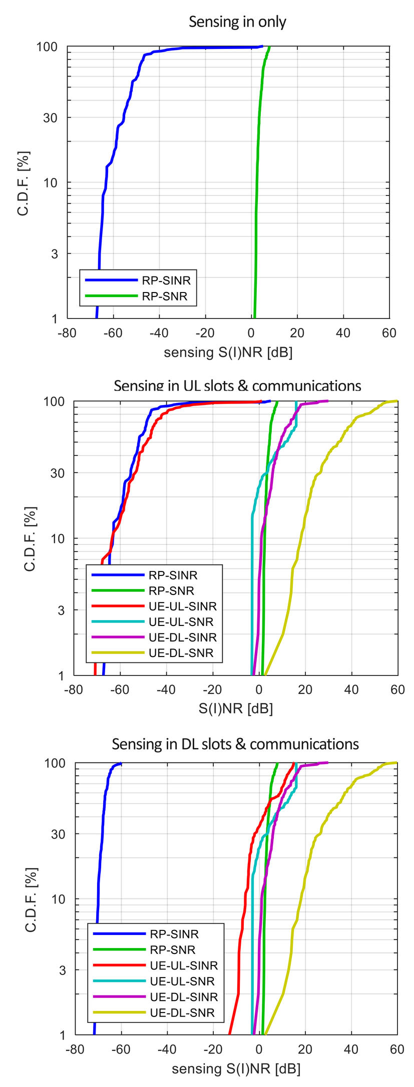
# BS to BS Sensing Interference and Coordination

Ericsson

## BS-BS Bistatic sensing baseline SINR evaluation

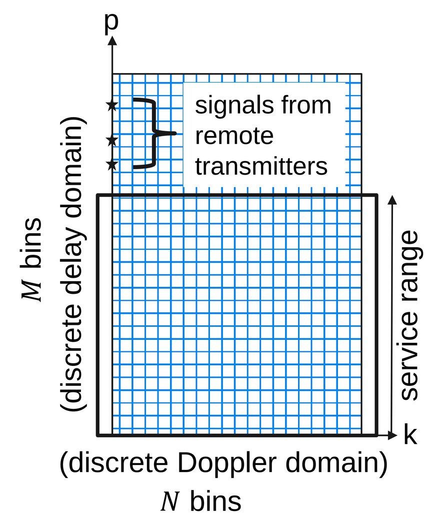
- BS to BS bistatic sensing avoid the self-interference challenge of monostatic sensing.
- Still BS to BS interference is a serious challenge.
  - BS above roofs often have LOS to many remote BSs.
- Investigated SINR for uncoordinated sensing-only and for simultaneous sensing and communications using separate signals for both.
- First step: sensing signal interference impact modelled as AWGN..
- For 5% random sensing resource utilization, very high probability of having at least 1 interferer active.
- In order to significantly reduce interference power, not only adjacent BS have to be muted but many tiers of BSs.
- Sensing in uplink (UL) symbols creates high interference to UL comms -> inacceptable
- Sensing has to happen in downlink (DL) symbols.



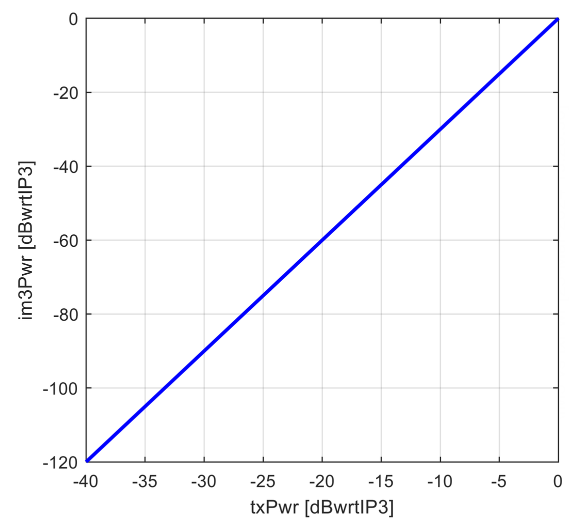

## Sensing signal principal coordination scheme

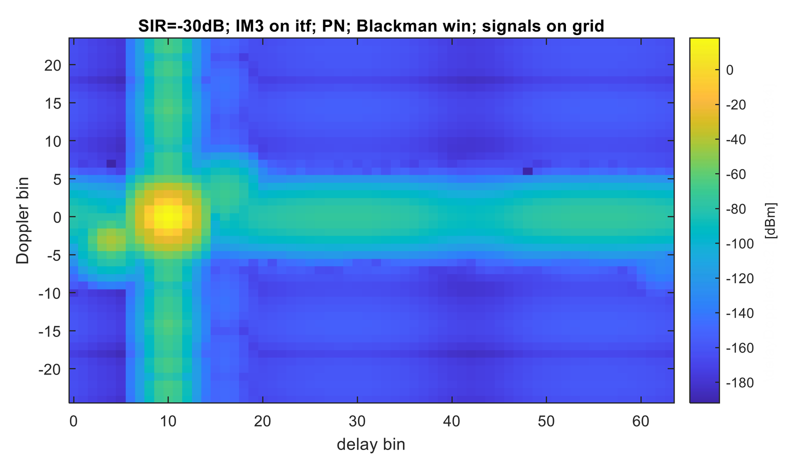
- Assume now dedicated sensing signals, not reusing the communications signals for sensing.
- Tailor the sensing signals to mitigate their interference impact.
- Exploit that each BS is responsible for sensing only objects up to a certain distance, e.g. where the distance is the shortest among all BSs.
  - This defines a sensing service range.
- Proposed coordination scheme
  - All BS are synched.
  - Identical signals applied between BSs that are sufficiently far away such that the signal from the remote BS appears in the delay-Doppler profile at a delay larger than the service range and can therefore be distinguished from objects of interest and be discarded.
    - Requires that the remote signal is still within the CP.
    - Likely to require multi-symbol sensing signal, where 2. and further symbols are cyclic repetition of the 1. symbol
  - Within a cluster of cells where interfering signals arrive within service range of considered cell:
    - Apply a resource and signal coordination scheme.




## Interference leakage in delay/Doppler

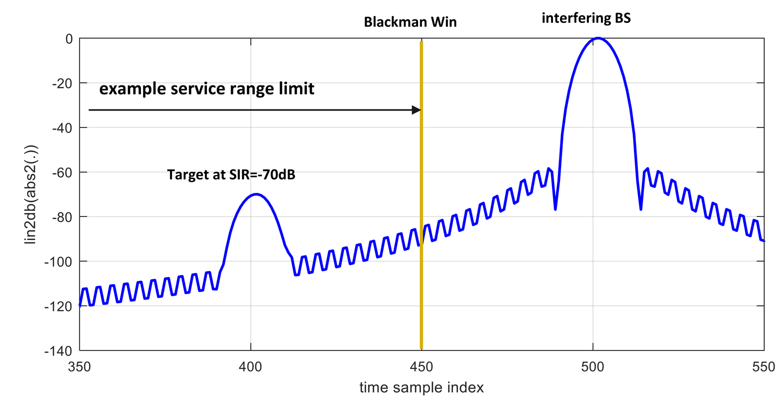
- Hardware impairments
  - IM3, EVM
    - IM3=-60dBc requires carrier power at -30dB from IP3
  - Phase noise
    - Leakage in Doppler domain
  - ADC
- Delay/Doppler windowing functions

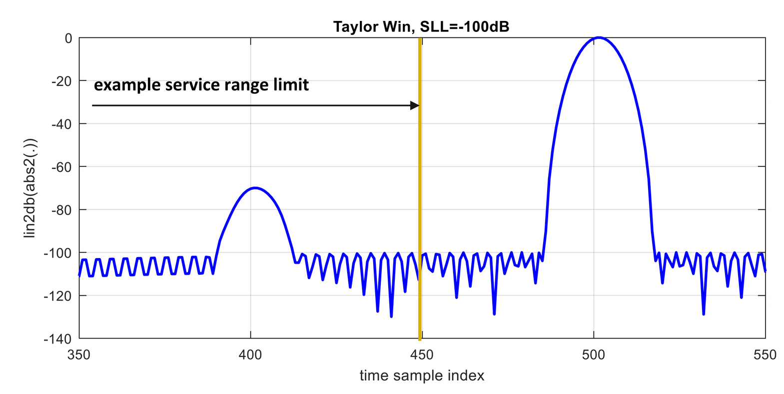



## Impact of windowing functions

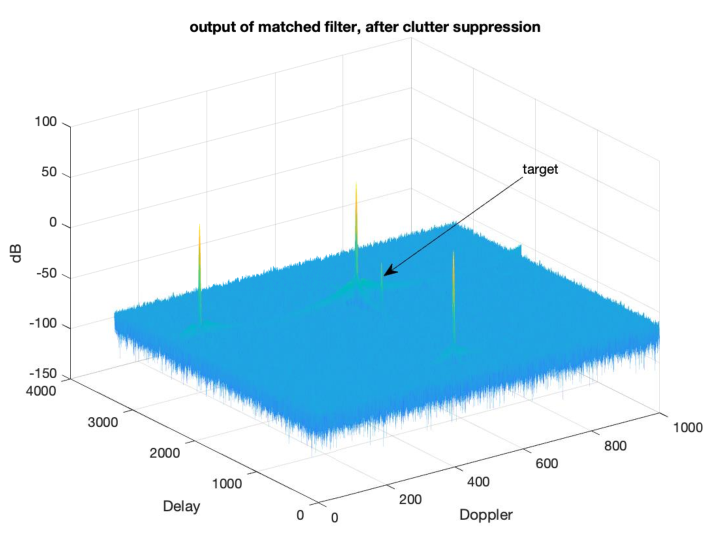
- SIR=-70dB, desired reflected signal in service area vs interfering BS signal, worst case from SINR CDF.
- Blackman window vs Taylor with -100dB max. sidelobe level.
- ZC signal, 1024 subcarriers, 4x oversampling to 4096 SC.
- Blackman with SLL=-60dB: interference sidelobes could trigger false alarms within the service range.
- Taylor with Sidelobe SLL=-100dB: interference unlikely to trigger false alarms.
  - Taylor main lobes accordingly slightly wider than Blackman.

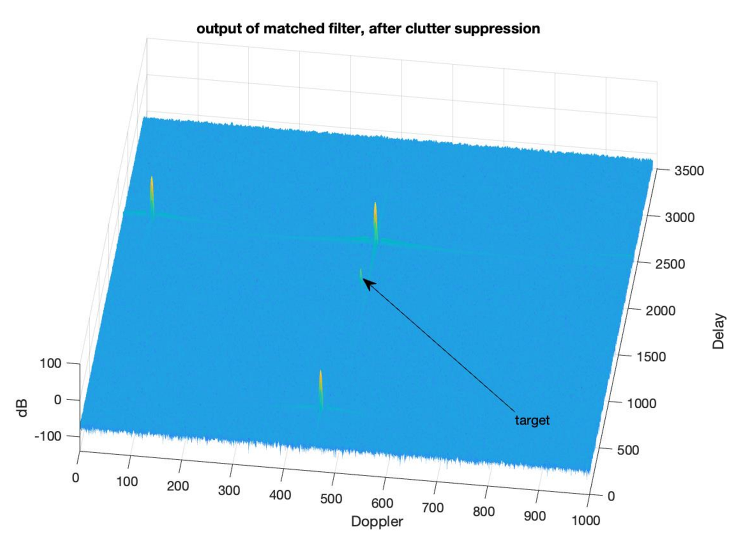



## Options for signal coordination

- Arranging interference in delay and Doppler domain
  - ZC with cyclic delays in t-domain and/or Doppler shifted, i.e. constant phase offset per subcarrier between symbols.
    - E.g. Cell k in K-cell reuse cluster applys cyclic shift k/K*CP
  - 2D ZC with e.g. cyclic delay in f-dom and t-dom
  - OTFS, directly defining shifts in delay and Doppler domain
- If moving all interference to delay beyond service range is too resource costly:
  - Allow some interference within service range but make it hop around either within or between radar frames...
  - ...in order to prevent constant masking of targets.
- Orthogonal in t-dom and/or f-dom, e.g. combs
  - Or non-comb, e.g. random, but coordinated such that overlap between cells is avoided.
    - Could avoid the ambiguities arising if combs were used.
    - Compressed Sensing to handle the non-equidistant t/f sampling.




## Conclusion

- Inter-site pathgain to closest sites is with -80dB very high!
  - Muting only a few tiers of surrounding BS is not sufficient because of free space propagation.
- Sensing in downlink slot appears to be preferrable, to protect the communications uplink in own and other network.
- Interference coordination is necessary to limit BS-BS interference into sensing RX.
- Use sensing signals at each BS that appear to victim BS like yet another radar target (of very high RCS), localized in periodogram.
  - Coordinate the locations in the periodogram
- Hardware impairments and windowing cause leakage in delay-Doppler domain that can be relevant despite many -10th dBc. Manageable by combination of:
  - Proper signal power configuration and resource coordination
  - TX-side (and RX-side) beamforming
  - Digital interference cancellation

SPONSORED BY THE

Federal Ministry of Education and Research

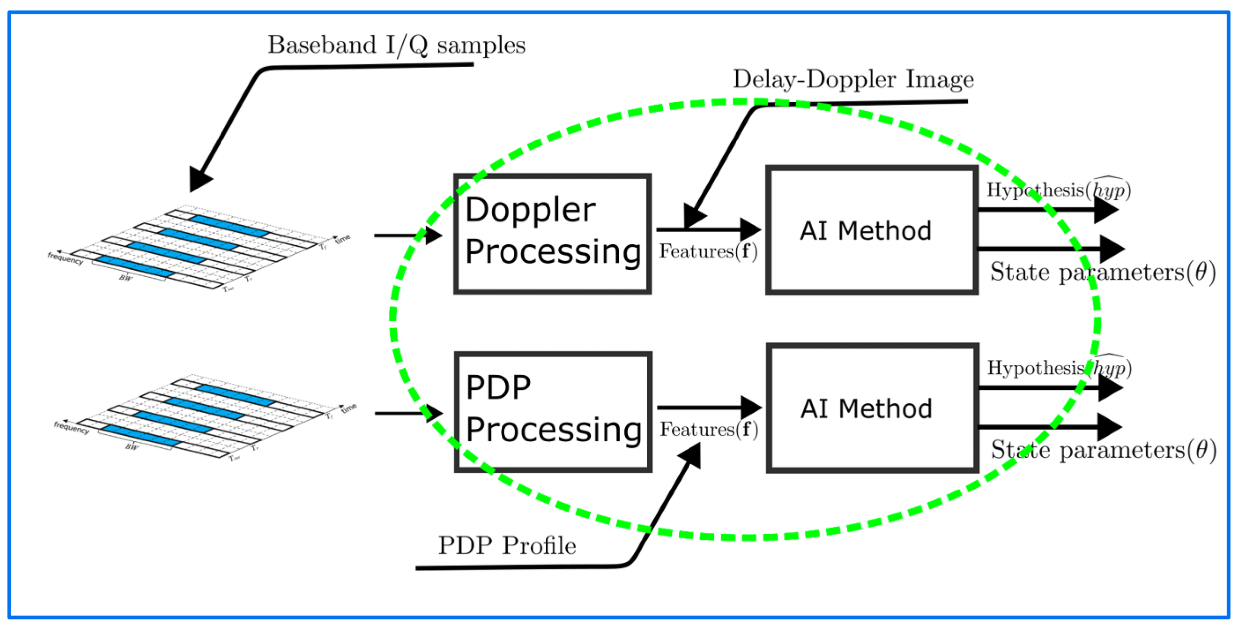
www.komsens-6g.com

# ML-based Passive Object Detection

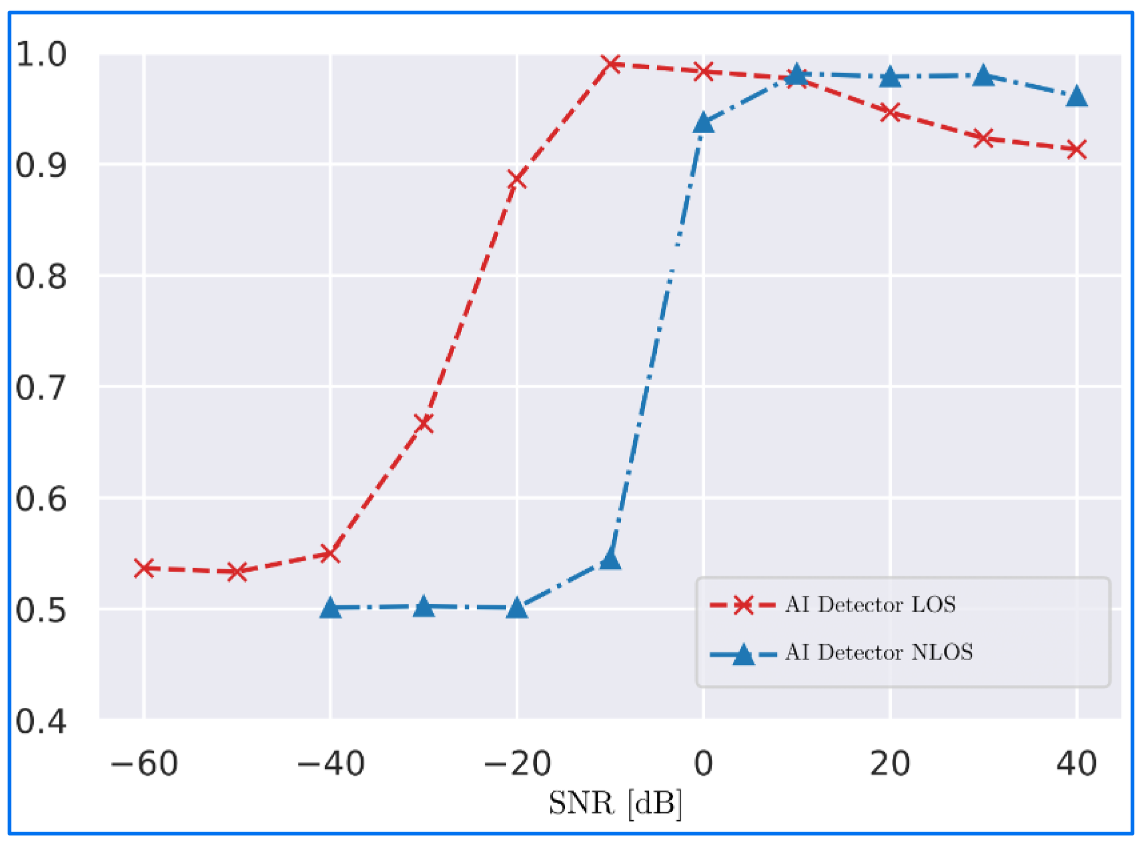
Ericsson

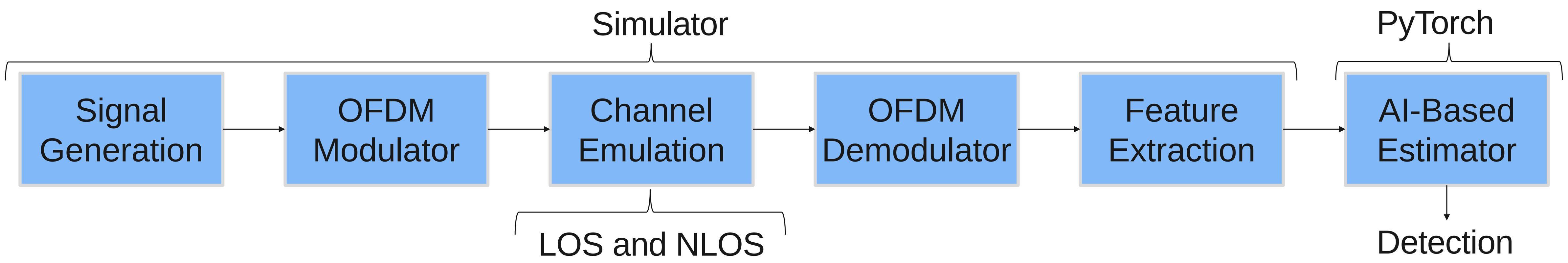
## Bi-Static Sensing in OFDM Wireless Systems

- OFDM system for integrated sensing and communication for passive object detection
- Delay-Doppler profile and power delay profile are used to train an ML-based detector



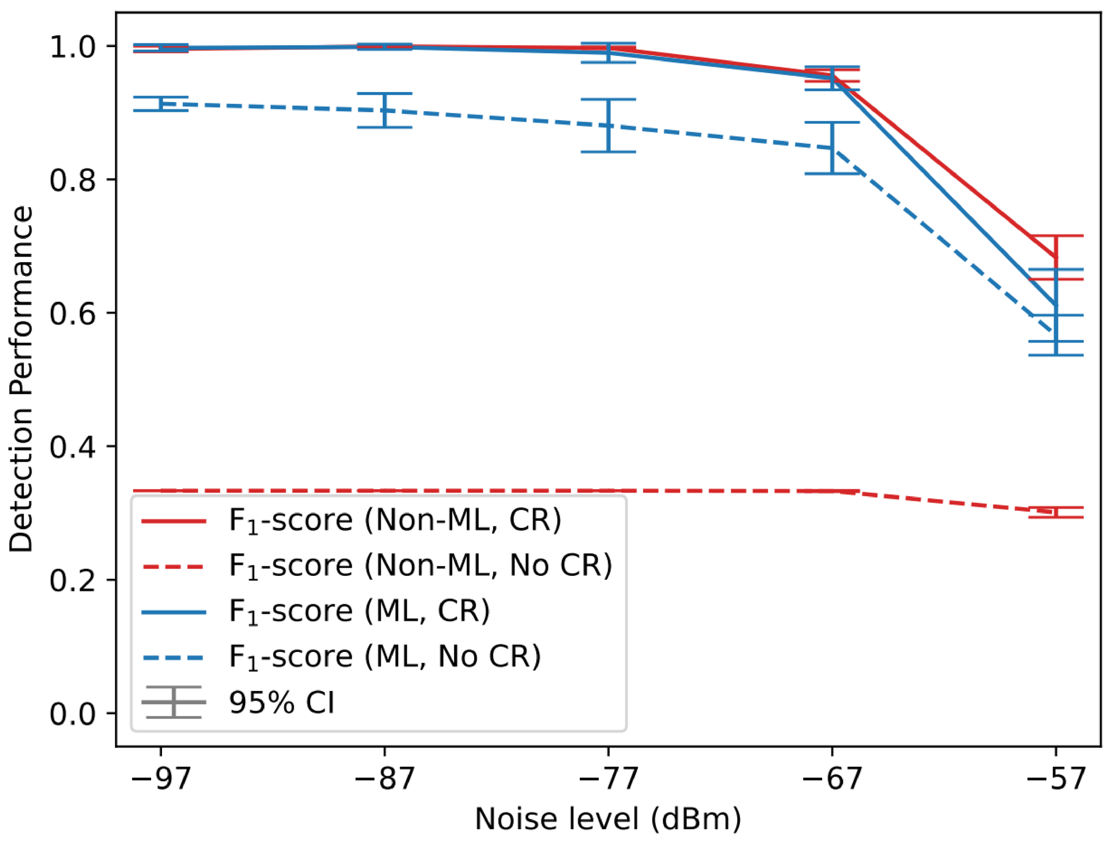

### Detection Accuracy



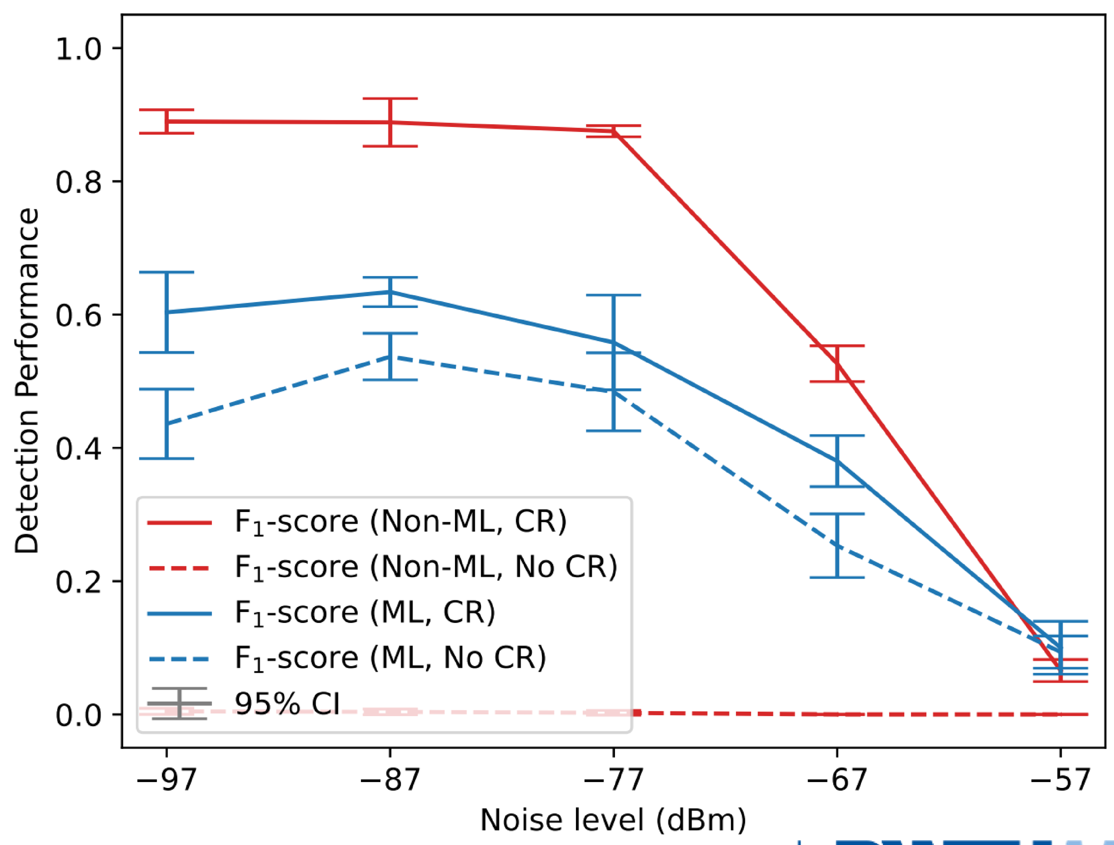




## ML-based Multi-Object Detection

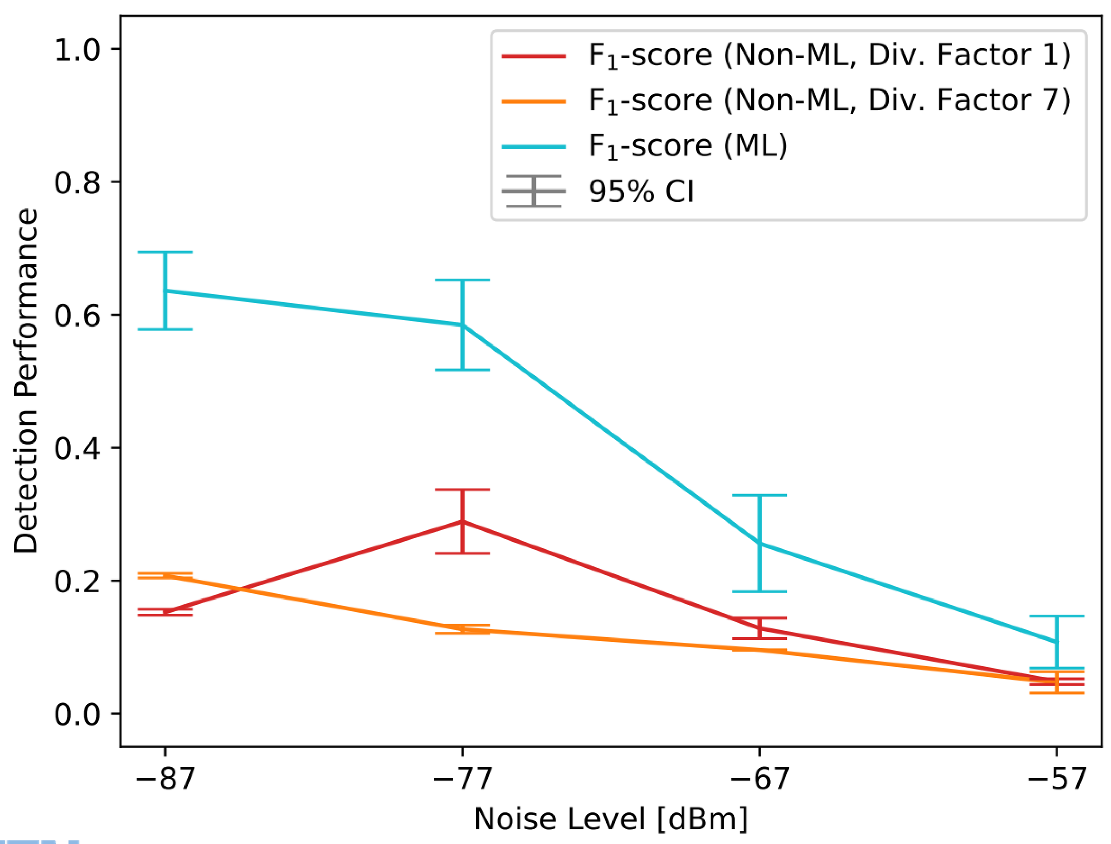
### Binary Detection




### Multi-Object Detection
Simple Scenario



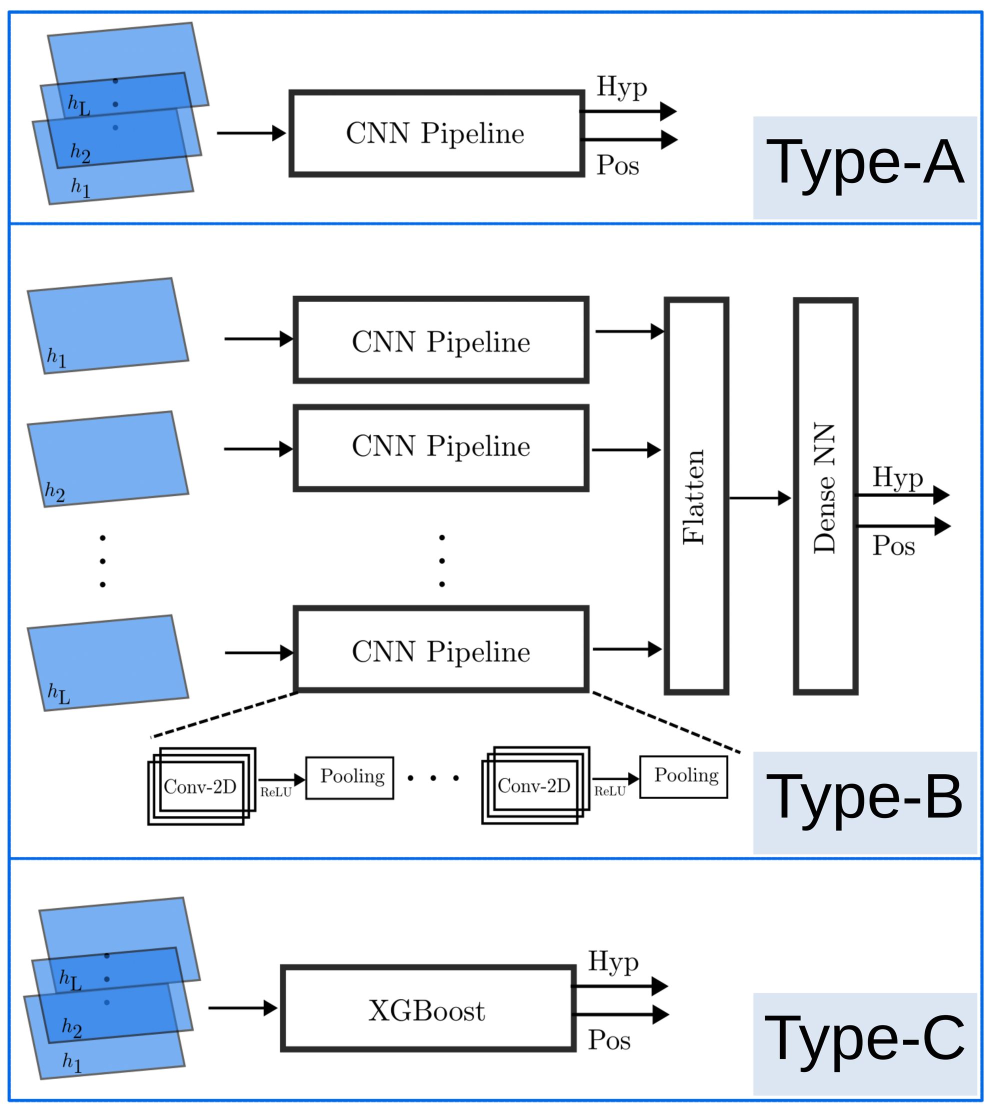

### Multi-Object Detection
Complex Scenario



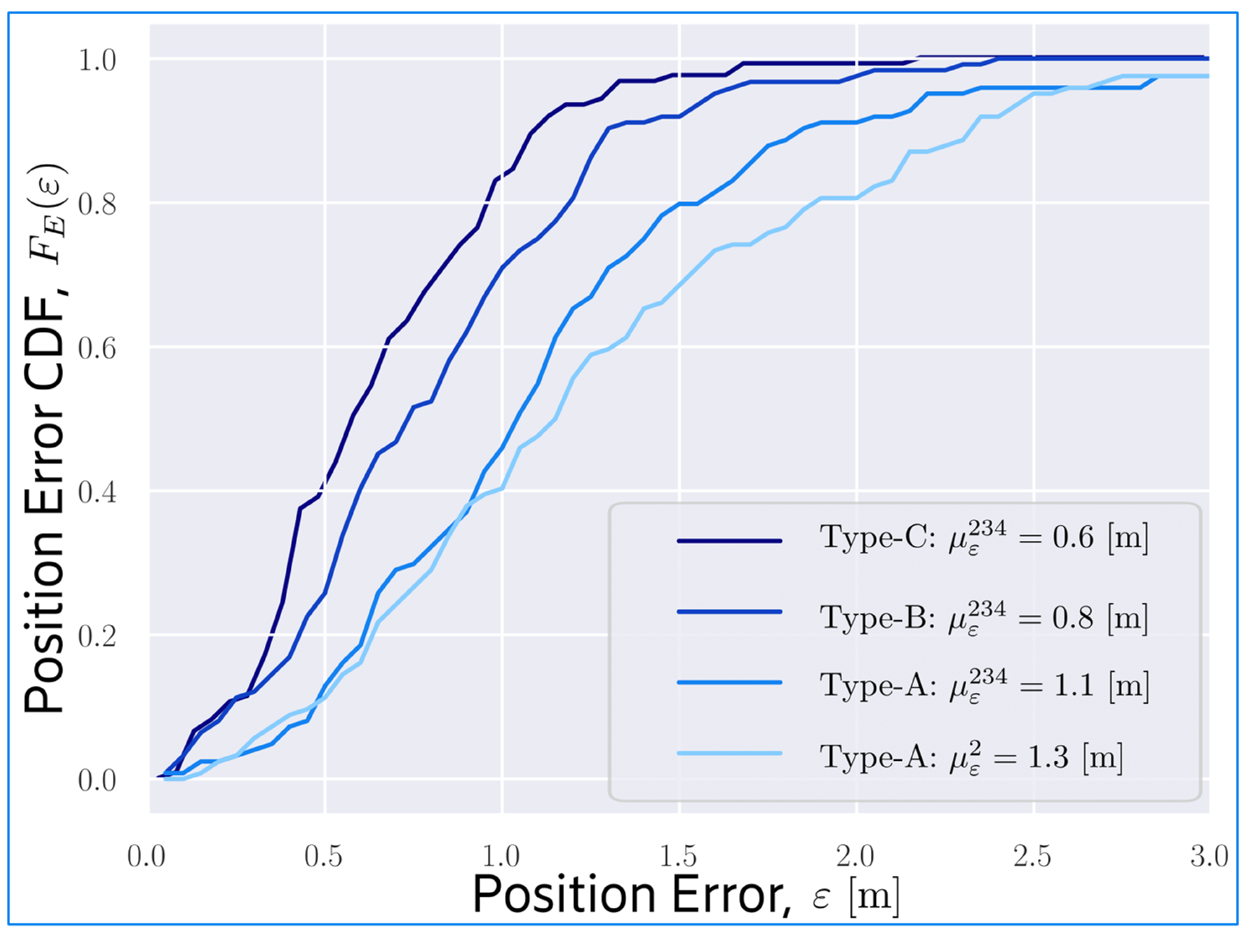

in collaboration with MCC Mobile Communications and Computing | RWTH AACHEN UNIVERSITY

## Indoor Sensing based on Measurements

- Detection based on multi-static measurements from indoor deployment
- ML-based sensing algorithms using channel state information (CSI) of the dynamic indoor environment can provide improved performance in terms of passive target detection and position estimation.
- Three different architectures in terms of varying requirements for compute, memory and training are explored.




### Localization Performance



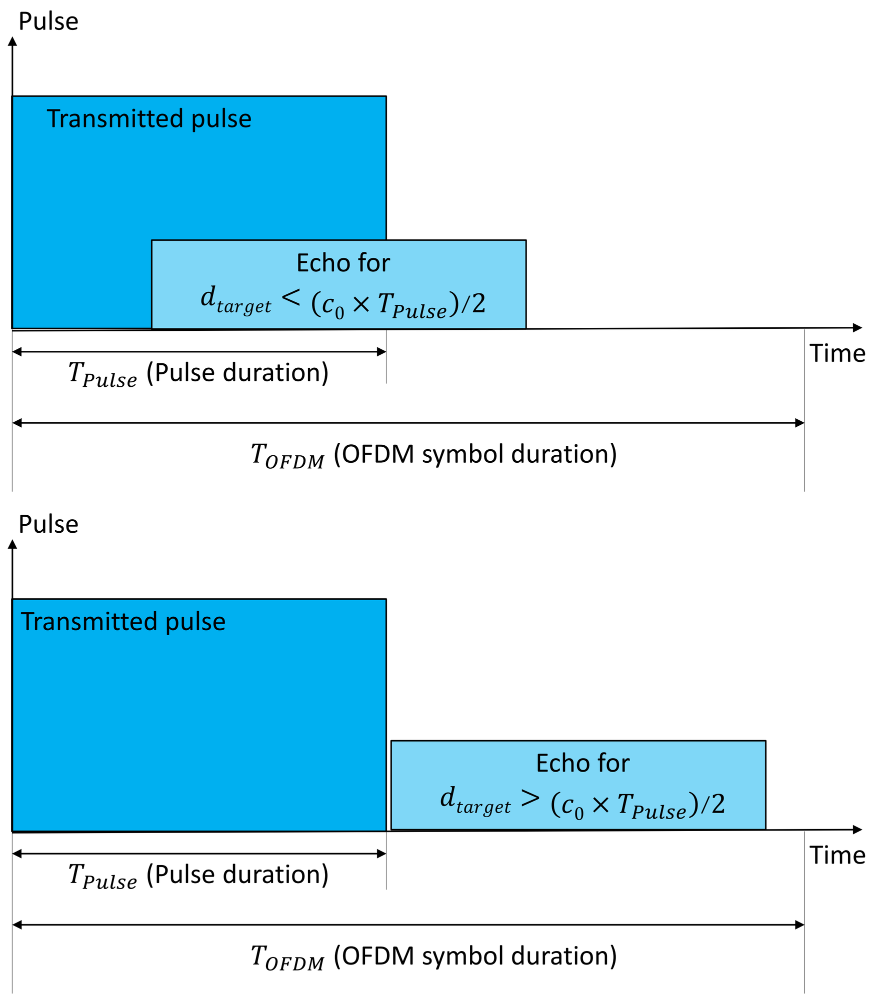

SPONSORED BY THE
Federal Ministry of Education and Research

www.komsens-6g.com

# Monostatic short pulse OFDM radar

Ericsson

## Monostatic radar



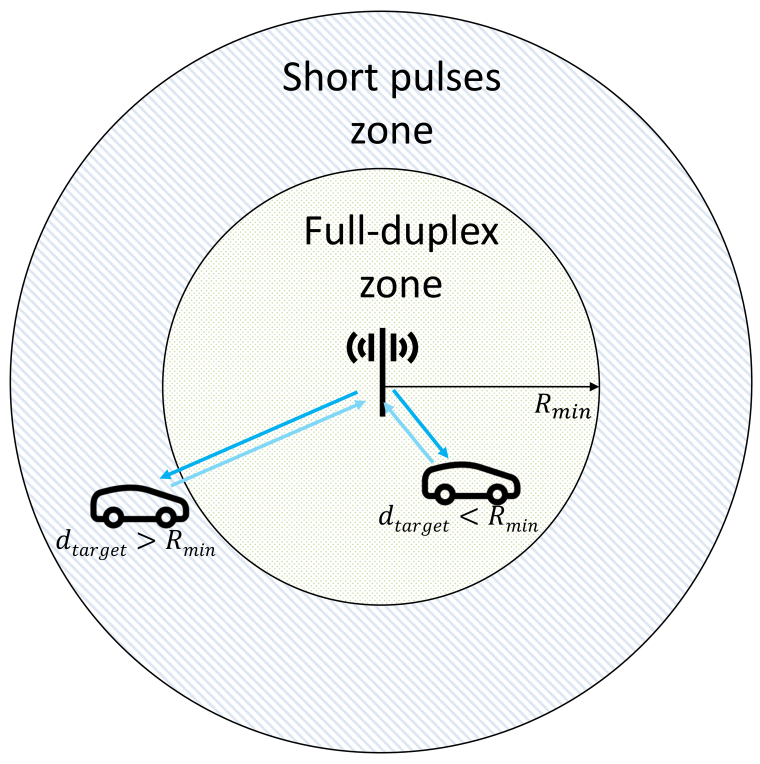

To design a monostatic radar with relaxed requirement on same-frequency full-duplex,

we avoid the strong self-interference (for sufficiently large $d_{target}$)

by transmitting short pulses within the OFDM symbol ($T_{Pulse}$ << $T_{OFDM}$)

so that echoes are received:
- after the pulse transmission
- during the OFDM symbol

## Half and full-duplex zones



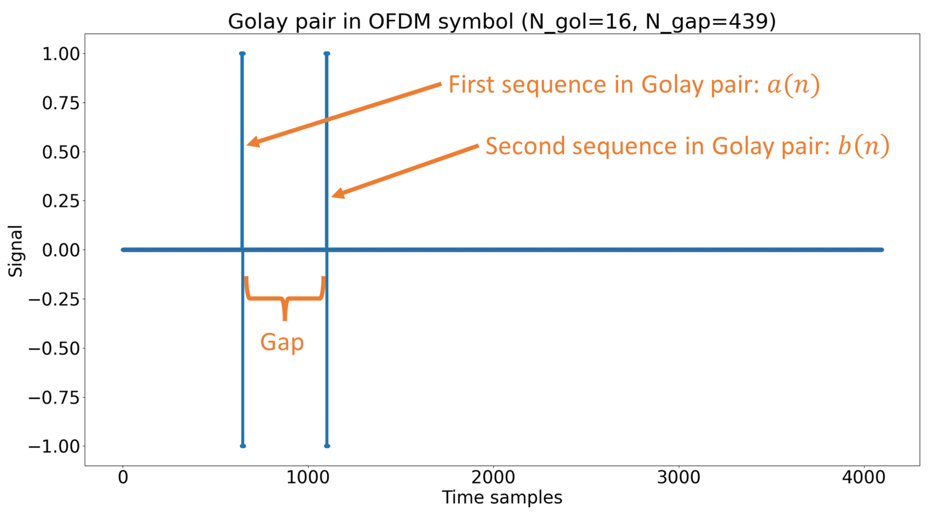

$T_{Pulse}$ determines a delimitation radius around the sensing node:

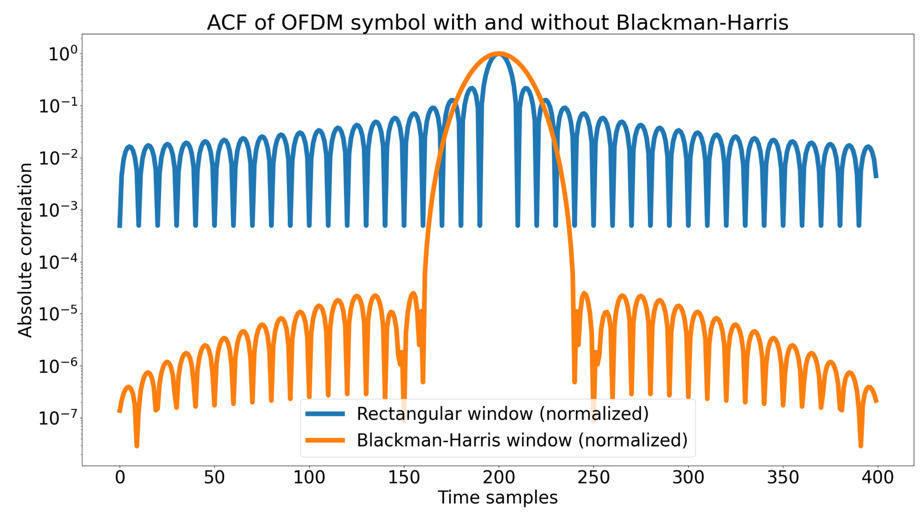
$$R_{min} = (c_0 \times T_{Pulse})/2$$

For $d_{target} < R_{min}$ self-interference but easier to handle because lower $d_{target}$ needs lower transmit power and leads to comparatively stronger echoes

For $d_{target} > R_{min}$ no self-interference makes it easier to receive echoes. It is the focus of this poster

## Golay complementary pairs for aperiodic ACF



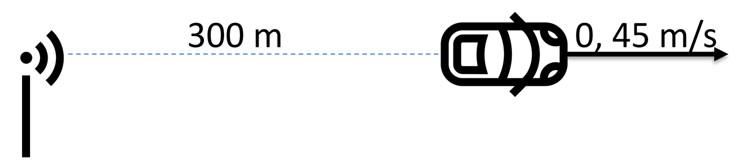




Because $T_{Pulse}$ << $T_{OFDM}$, convolution between matched filter and received signal can be viewed as linear (even if cyclic prefix)

For Golay complementary pairs: the sum of the aperiodic ACFs of sequences $a(n)$ and $b(n)$ is $\delta(n)$

We compared Golay complementary pairs (good aperiodic ACF) to Zadoff-Chu sequences (good periodic ACF)

## Simulation scenario

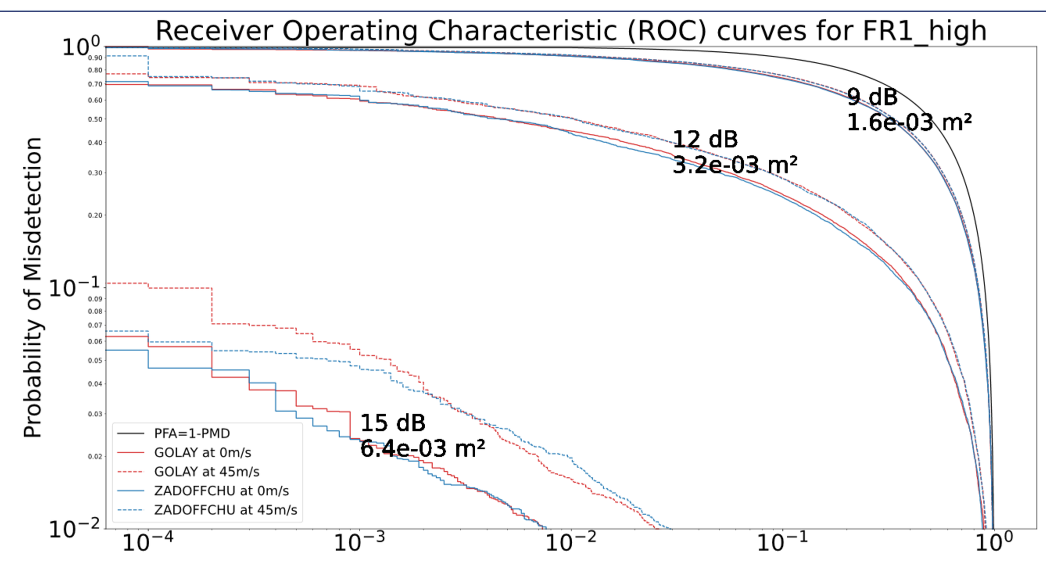


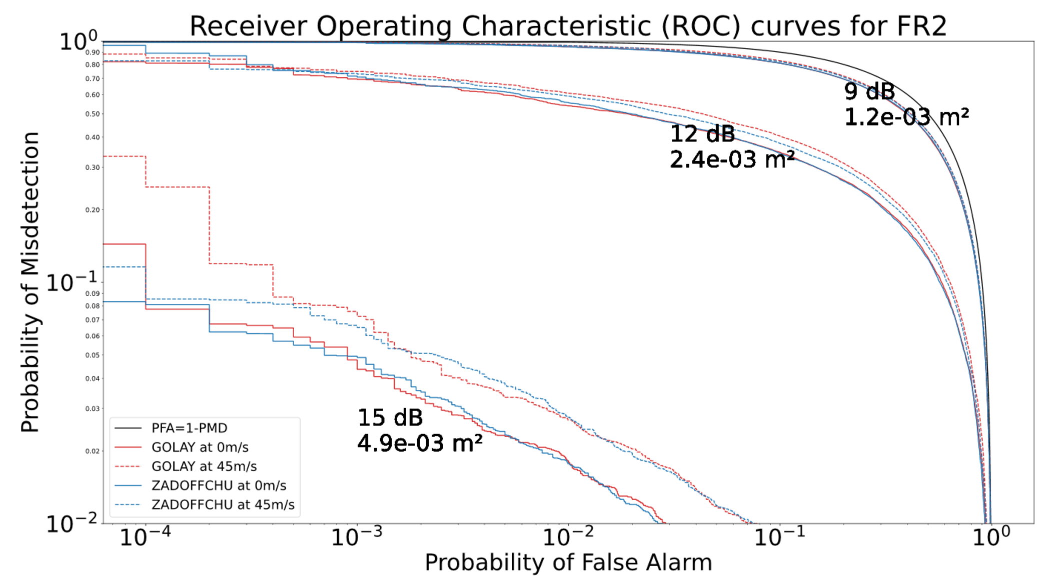

| | FR1 | FR2 |
|---|---|---|
| One-way distance to target $d_{target}$ [m] | 300 | 300 |
| Radial speed of target $v_{target}$ [m/s] | 0 or 45 | 0 or 45 |
| Radius of exclusion zone $R_{min}$[m] | 50 | 50 |
| Maximum target distance $R_{max}$[m] | 500 | 500 |
| Tx antenna elements $M$ | 16 | 16 |
| Rx antenna elements $N$ | 64 | 128 |
| FFT size | 16384 | 16384 |
| Oversampling factor | 4 | 2 |
| Cyclic prefix length [samples] | 1152 | 1152 |
| Subcarrier spacing $\Delta f$ [kHz] | 30 | 120 |
| Carrier frequency $f_c$ [GHz] | 3.5 | 39 |
| Bandwidth $BW$ [MHz] | 100 | 800 |
| Transmit power $P_{tx}$[dBm] | 50 | 38 |
| Number of pulses $N_{symbols}$ | 51 | 54 |
| Pulse Repetition Interval $PRI$ [µs] | 856.25 | 71.35 |
| $PRI/T_{OFDM}$[ ] | 24 | 8 |

## Results

The plots show PMD vs PFA for FR1 and FR2
The black curve on top right shows worst possible result (PMD = 1 − PFA)
There are 3 SINRs in 3 curve clusters (Set using RCS to indicated $m^2$ value)
In each cluster, four curves: Golay or ZC sequences, and 0 or 45 m/s target velocities

➔ Reaching a PMD close to 0 for a relatively small PFA is achievable
➔ No significant difference between Golay and Zadoff-Chu sequences




www.komsens-6g.com

SPONSORED BY THE

Federal Ministry of Education and Research

Friedrich-Alexander-Universität Erlangen-Nürnberg
KOMSENS 6G

# Code-Orthogonal PMCW ISAC System

Yanpeng Su, Maximilian Lübke, Norman Franchi

Friedrich-Alexander-Universität Erlangen-Nürnberg, Chair of Electrical Smart City Systems, Cauerstr. 7, 91058 Erlangen, Germany

## Introduction

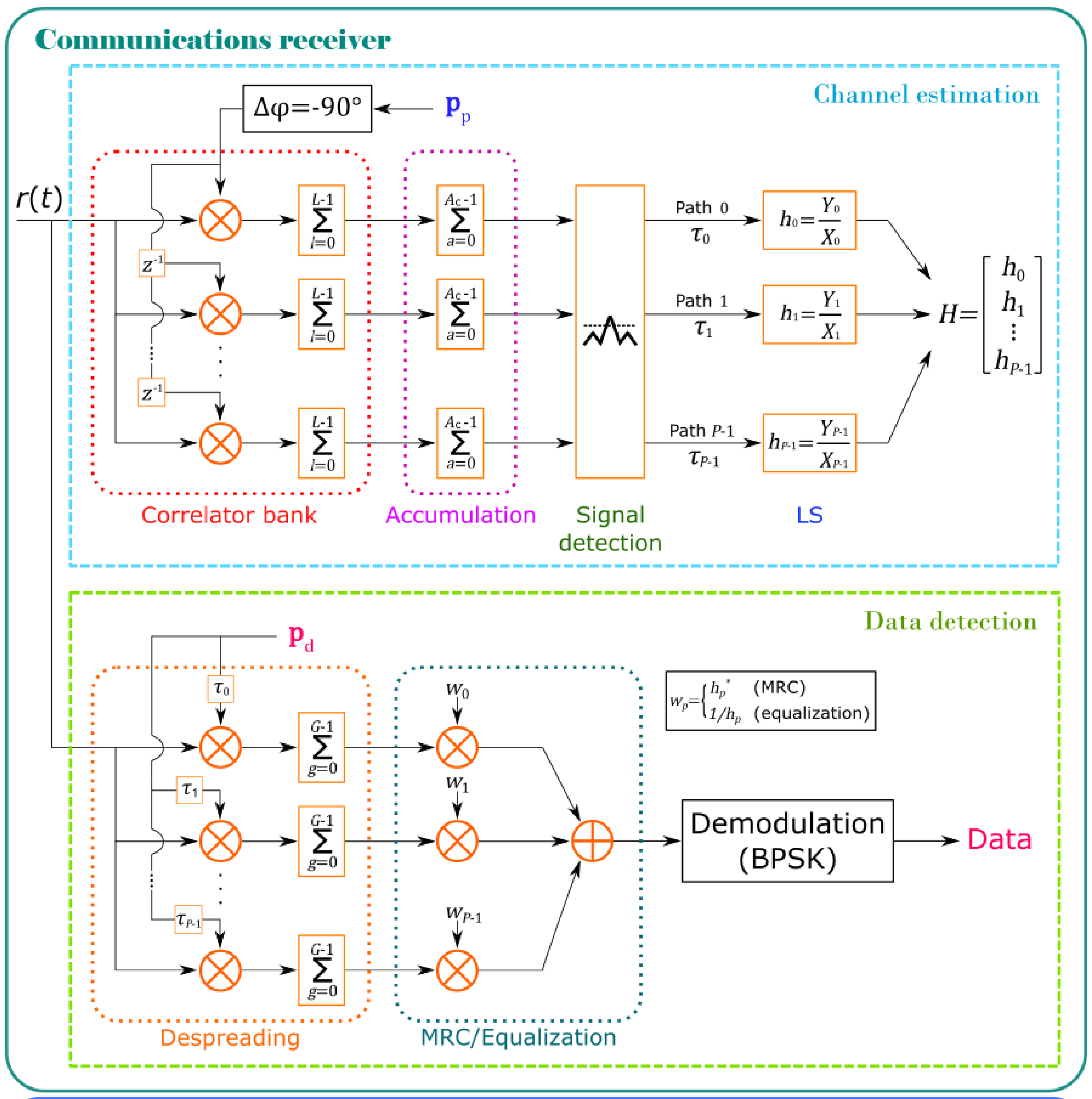
- Phase-modulated continuous waveform (PMCW) is attractive for the 6G ISAC system due to its favorable sensing capability.
- However, PMCW suffers from low communications functionality such as low throughput and poor performance in fast fading channels.
- We proposed a code-orthogonal PMCW (CO-PMCW) approach to improve the throughput and performance in dynamic environments.

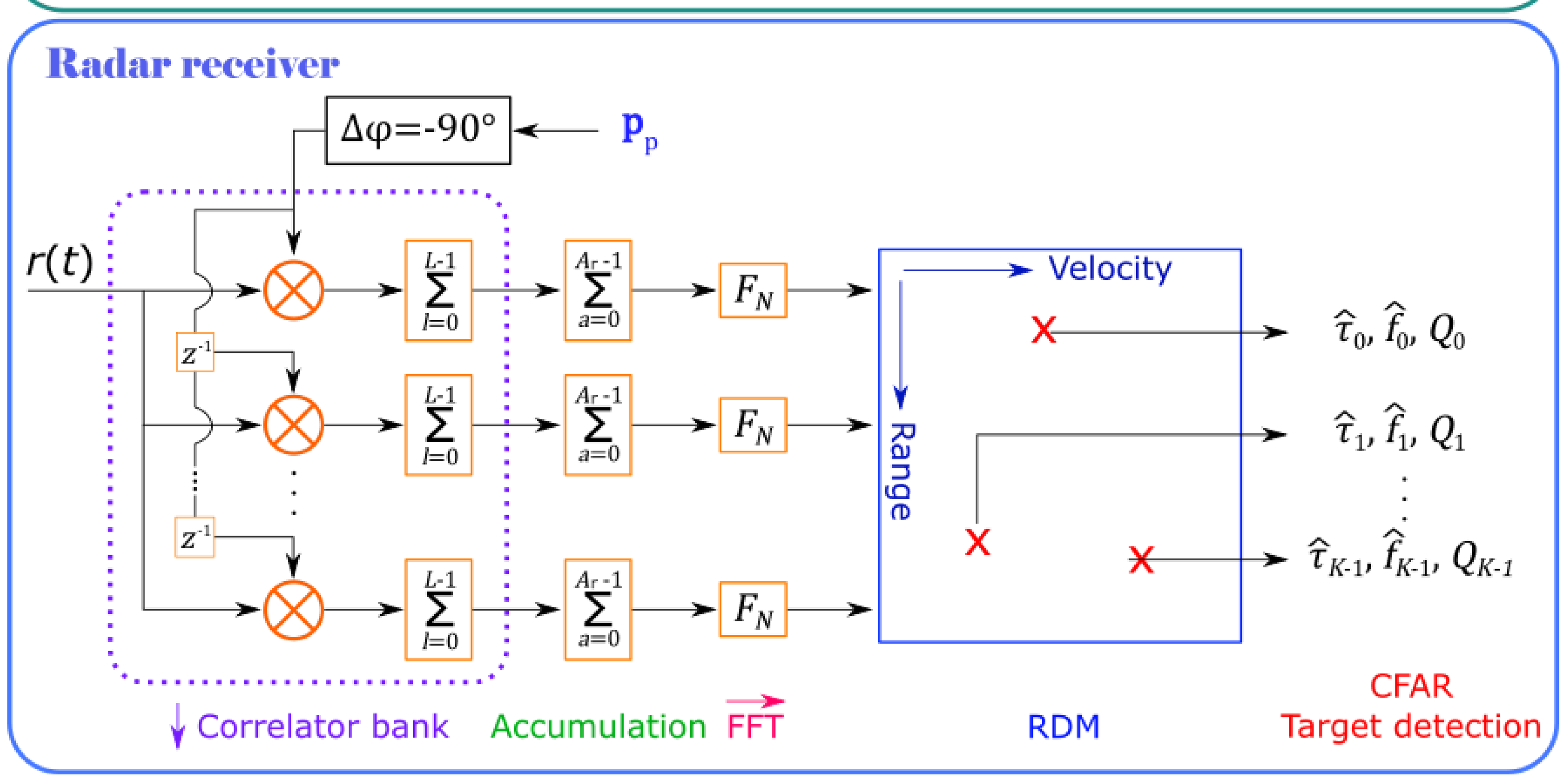
## Receiver

Communications receiver: simultaneously and continuously implemented channel estimation and data detection.

- Allowing the receiver to track the CSI in time.

Radar receiver: no change.

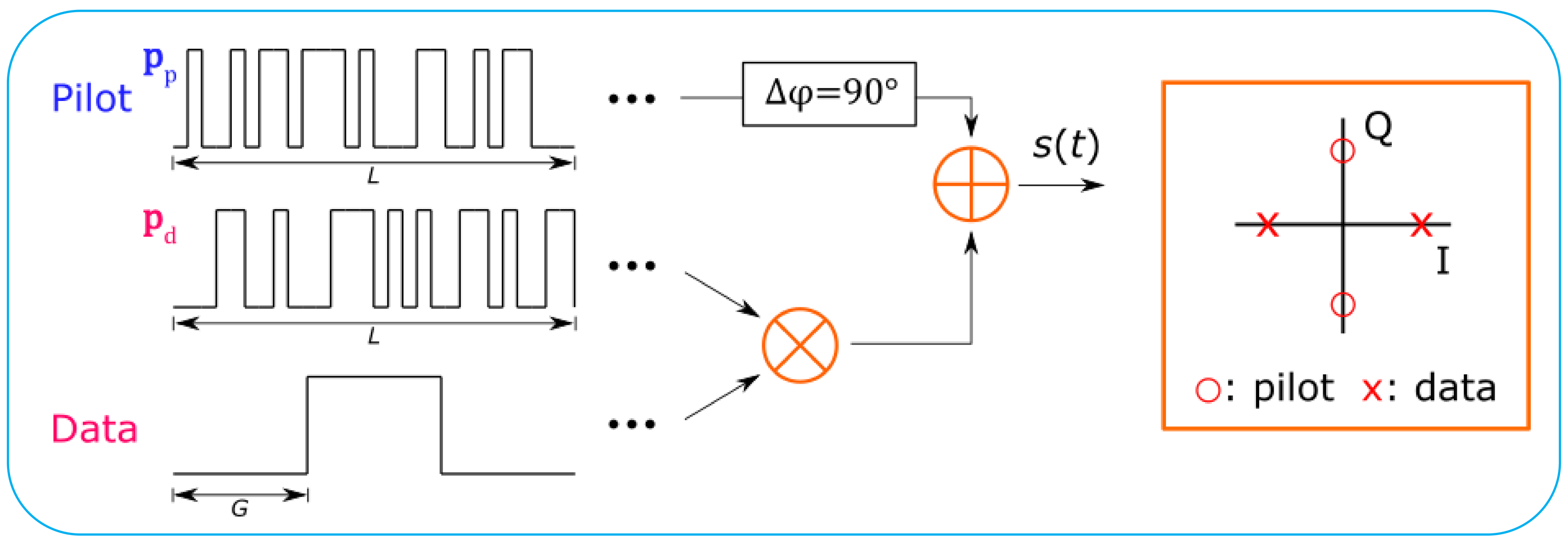



## Transmitter & Signal Structure

The pilot and data symbols are spread by different sequences.

- Enabling higher data rate.
- Leading to interference between the pilot and data.




## Pros & Cons

Pros:

- Extremely improved data rate.
- Better communications performance in dynamic environments.

Cons/Limitations:

- Increased peak-to-average power ratio without BPSK.
- Interference between the pilot and data sequences:
- Data rate is still limited due to multipath fading.

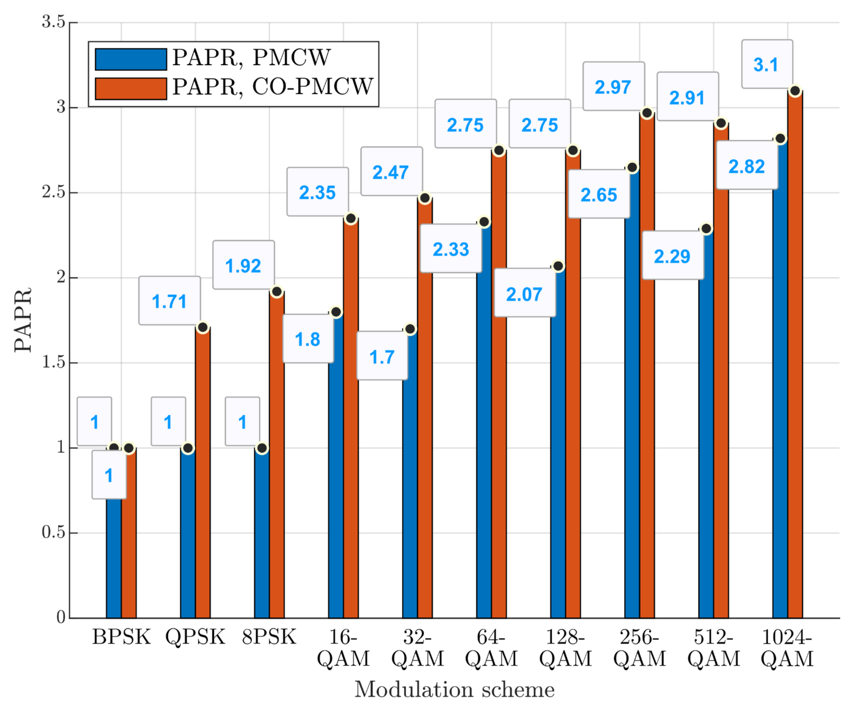



Fig. PAPR of PMCW & CO-PMCW

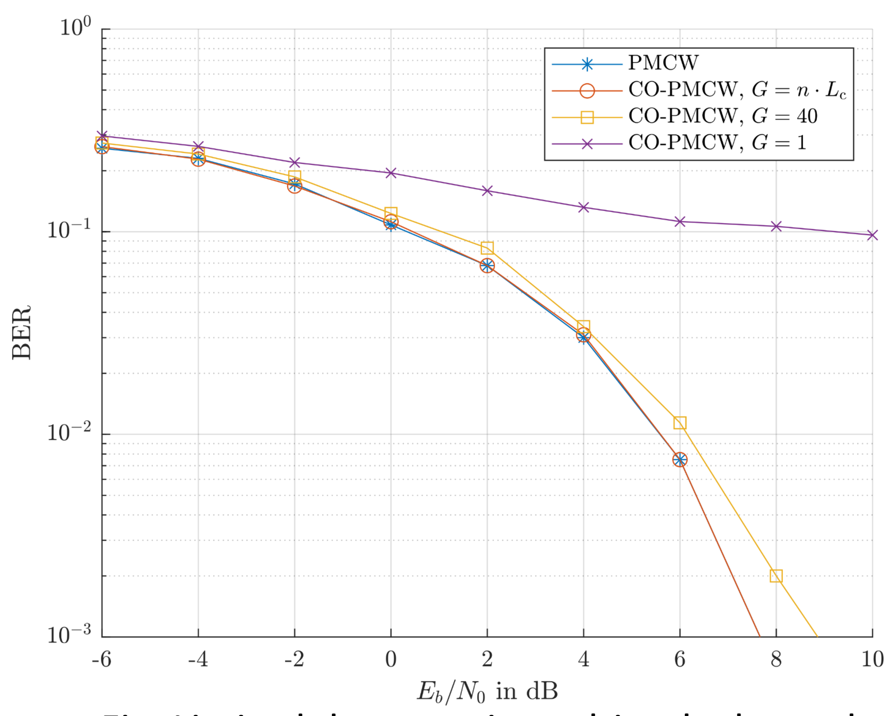



Fig. Limited data rate in multipath channel

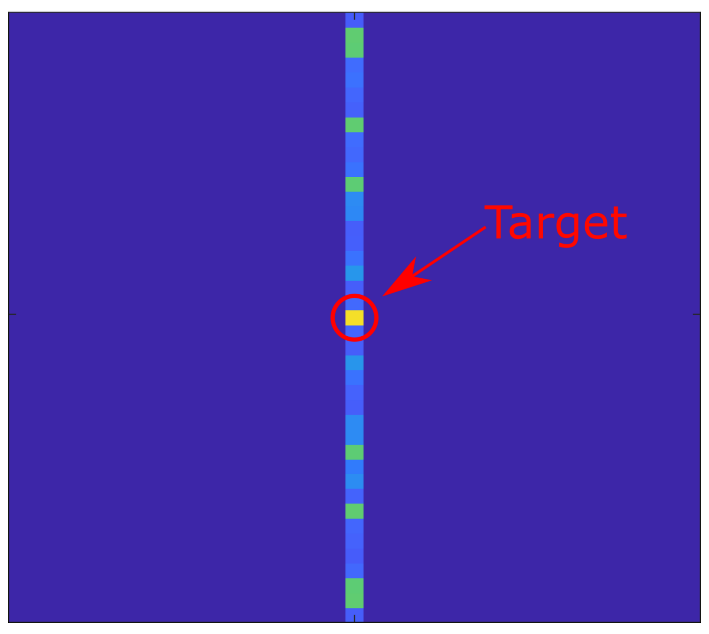



Fig. RDM of PMCW

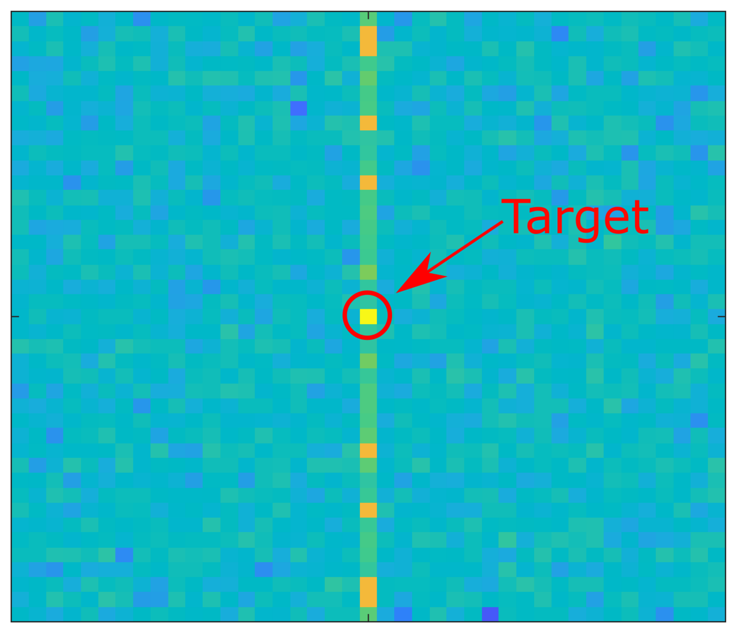



Fig. RDM of CO-PMCW

## Outlook

- Suppressing noise on the RDM produced by:
  - Non-ideal correlation properties
  - Doppler intolerance
  - Interference from the data sequence
- Improving the communications functionality by:
  - Reducing the interference between the two sequences
  - Improving communications reliability in fading channels

SPONSORED BY THE
Federal Ministry of Education and Research

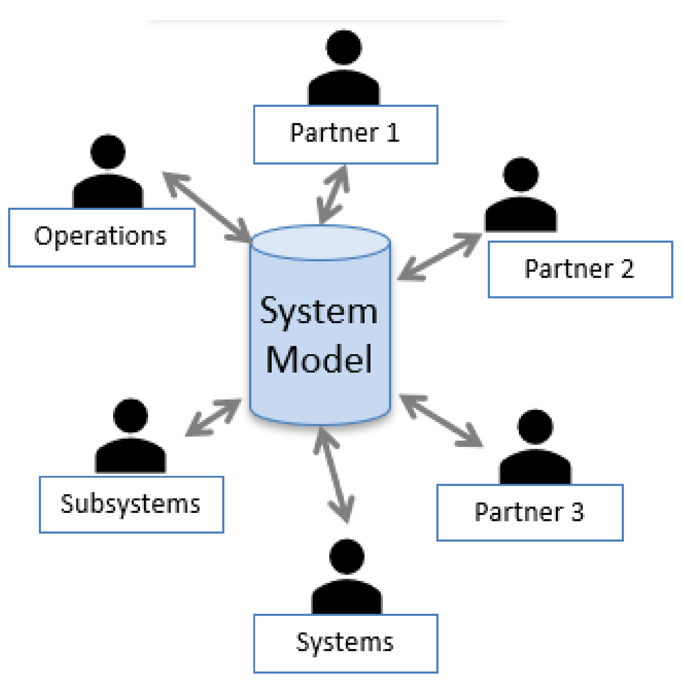
www.komsens-6g.com

# Modelling 6G-Networks

## Model-based System Engineering for Architecture & Design

by GPP Communication GmbH & Co.KG

## Objective




- The Architecture Group works jointly on one system model for ISaC.
- Central model server hosted by GPP to maintain access for the group
- Single point of truth.

## Methodology

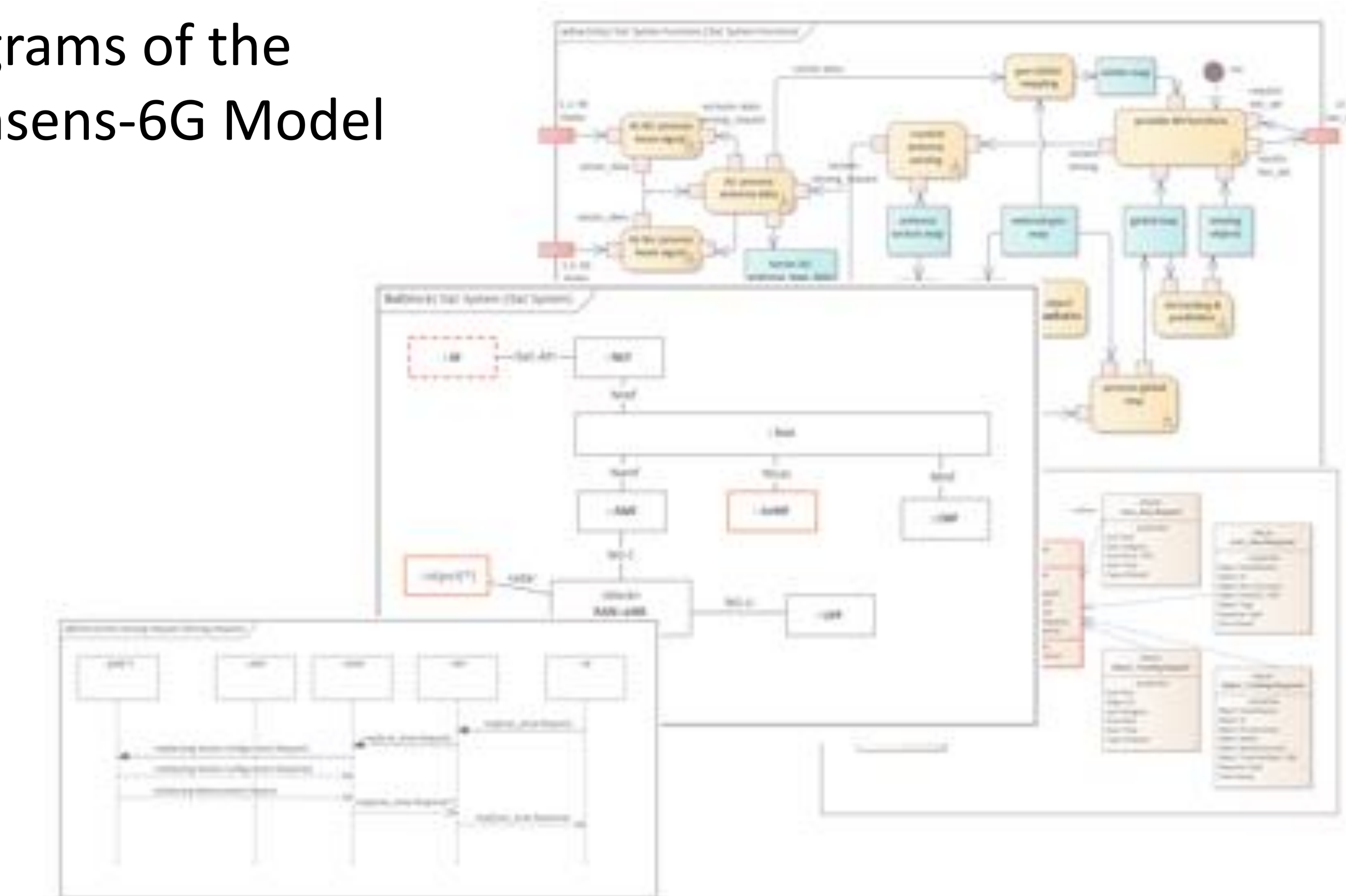
- Standardized modelling language used – SysML
- Standard by OMG https://www.omgsysml.org/

Specifying

- Structure of System, Subsystems and Components
- Interfaces and Protocols
- System Behavior

## 6G Network Architecture for ISaC

Diagrams of the Komsens-6G Model



Contents of the Komsens-6G SysML Model

- Activity Diagrams for the functional system specification
- Block Diagrams to specify product trees
- Internal Block Diagrams to define the architecture
- Message Sequence Diagrams to define protocols
- Interface Block Diagrams to define the interfaces
- State Diagrams to define modes of the components

## Results

- One single point of truth reflecting  the results of all system architecture discussions
- Set of diagrams for different views on the model – common source for re-use in other documents
- Consistency in formats and names of components and interfaces
- Basis for discussion always UpToDate

SPONSORED BY THE

Federal Ministry
of Education
and Research

www.komsens-6g.com

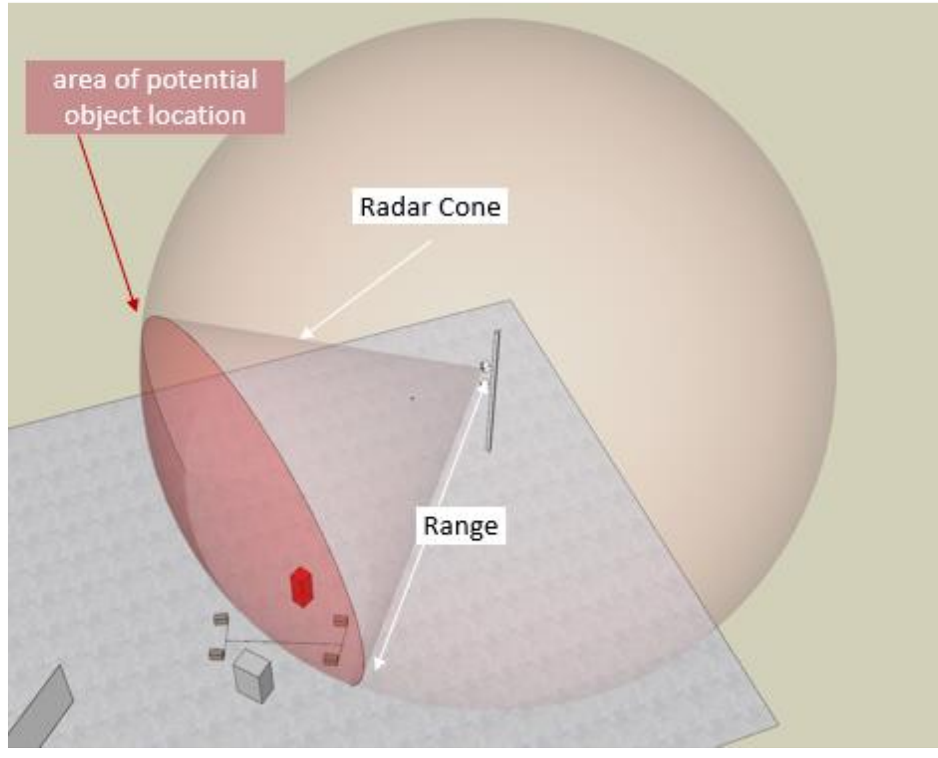
KOMSENS 6G

# 6G GeoMap Fusion

## turning SENSING into a valuable 6G service

by GPP Communication GmbH & Co.KG

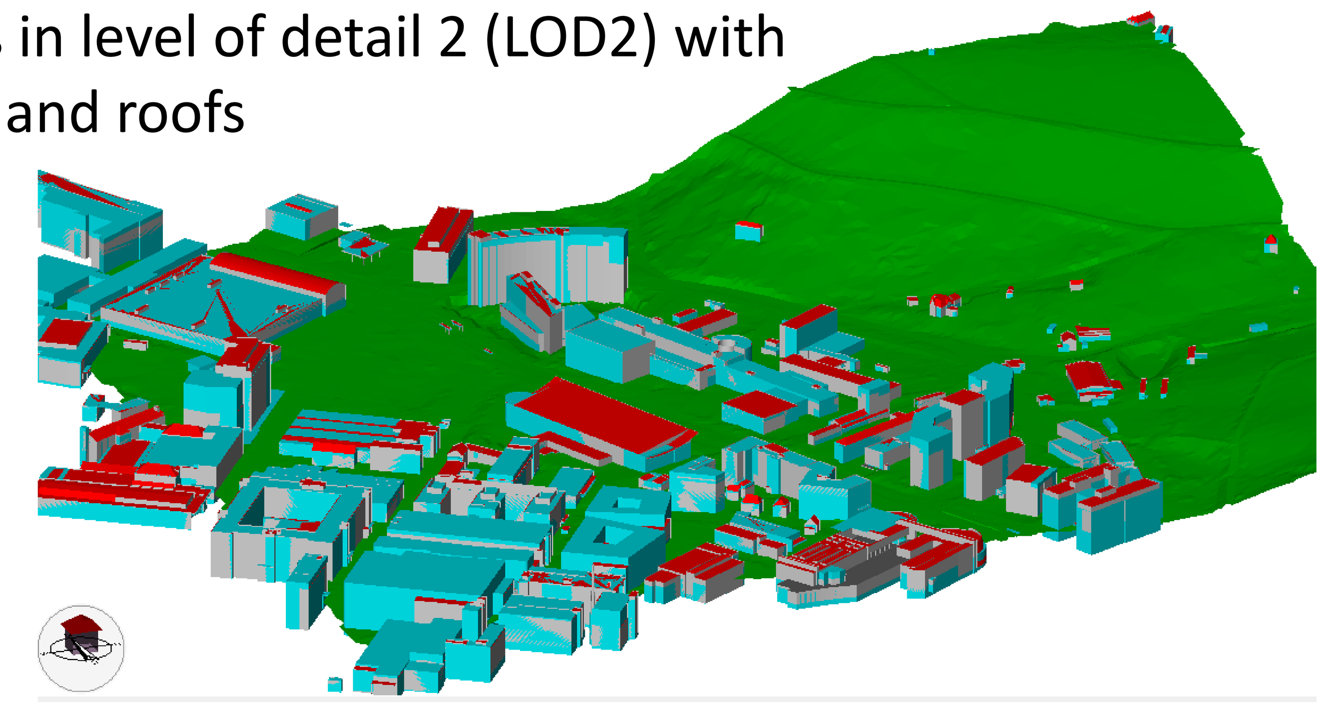
## Objective




- Improve the detection and classification of objects by fusing sensing information with existing 3D models

## Methodology

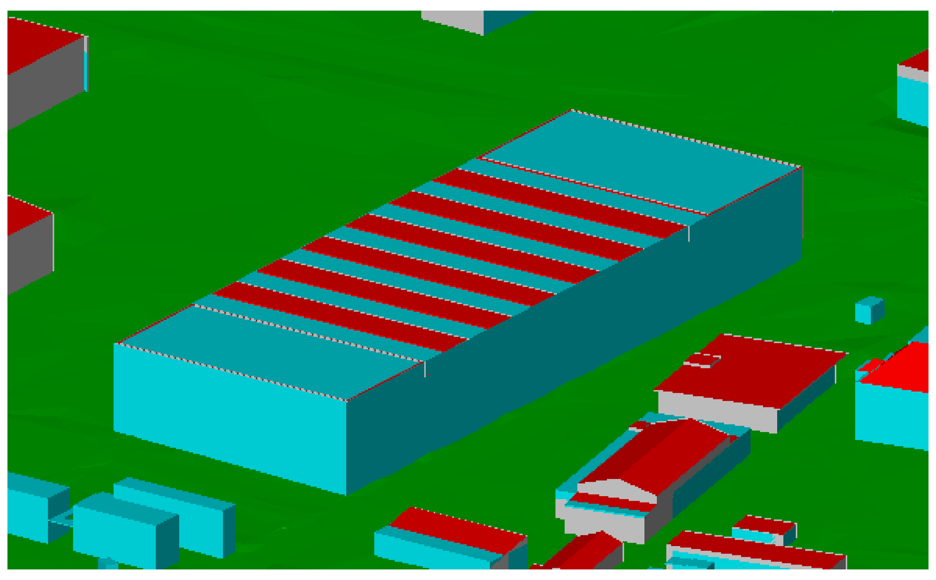
- Use semantic 3D models of the environment to identify known objects in the vicinity of the 6G antenna
- CityGML is a format providing semantics of landscape and cities in level of detail 2 (LOD2) with buildings and roofs



- CityGML (LOD4) provides details of building interior - e.g. for manufacturing

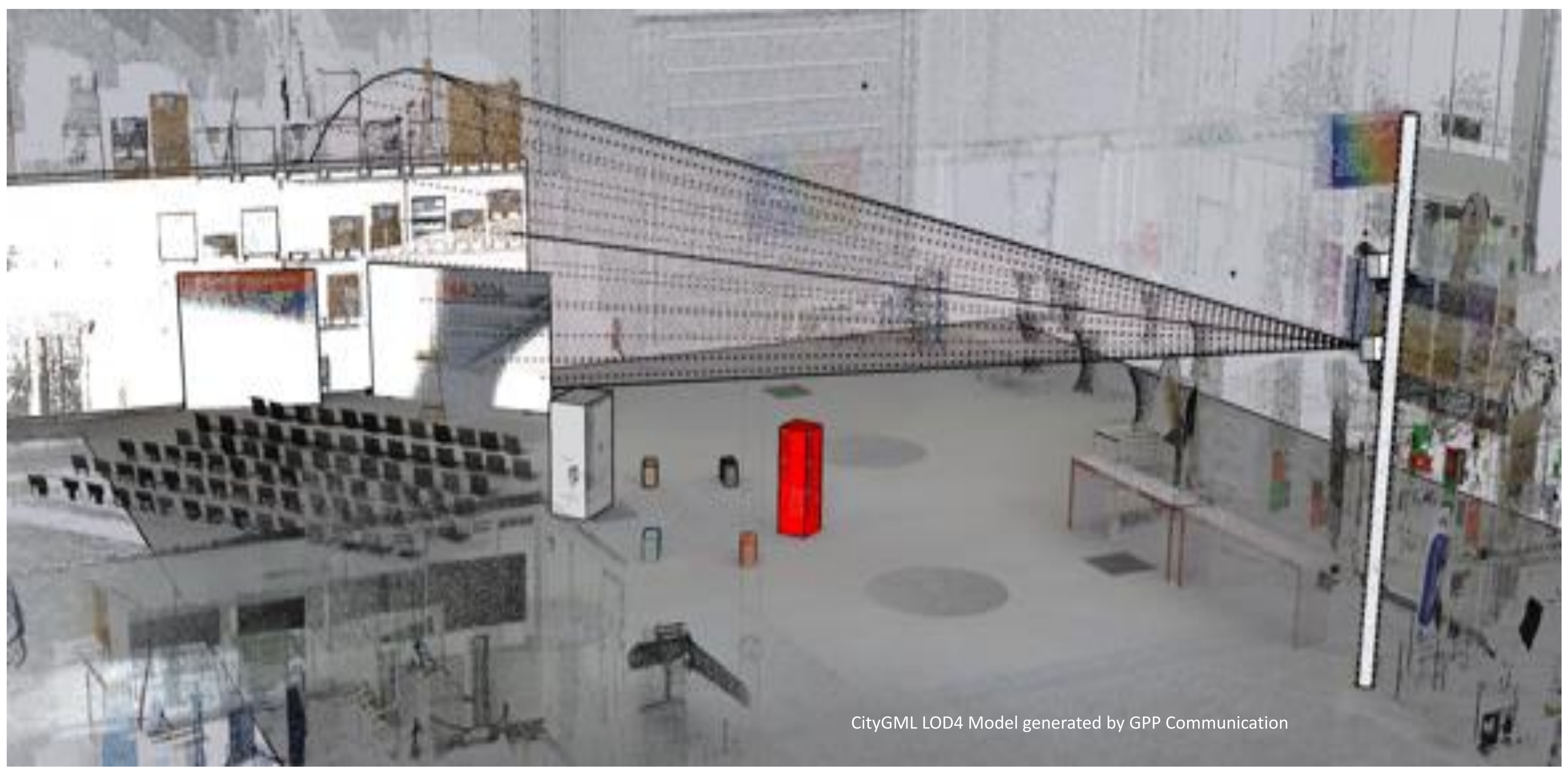
## PoC

Outdoor CityGML LOD2 model of and industrial environment (Arena2036)



Source: City of Stuttgart

- Demonstrated position detection of objects with a single 6G-SENSING beam and GeoMap Fusion




Created indoor CityGML LOD4 model with static and moving objects

## Results

- GeoMap Fusion improves object location detection and classification of 6G sensing measurement
- 3D models in CityGML are widely available for outdoor and can be detailed for indoor scenarios
- Applicable for outdoor sensing of e.g. traffic, trains, drones as well as for indoor for industrial environments e.g. logistics, robots, …

SPONSORED BY THE

Federal Ministry of Education and Research

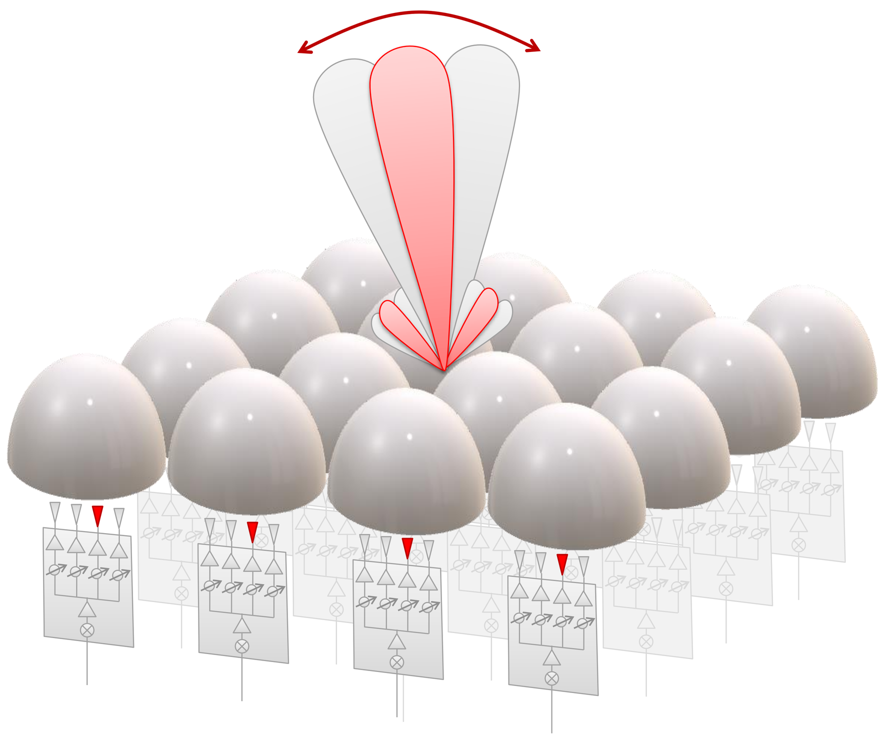
www.komsens-6g.com

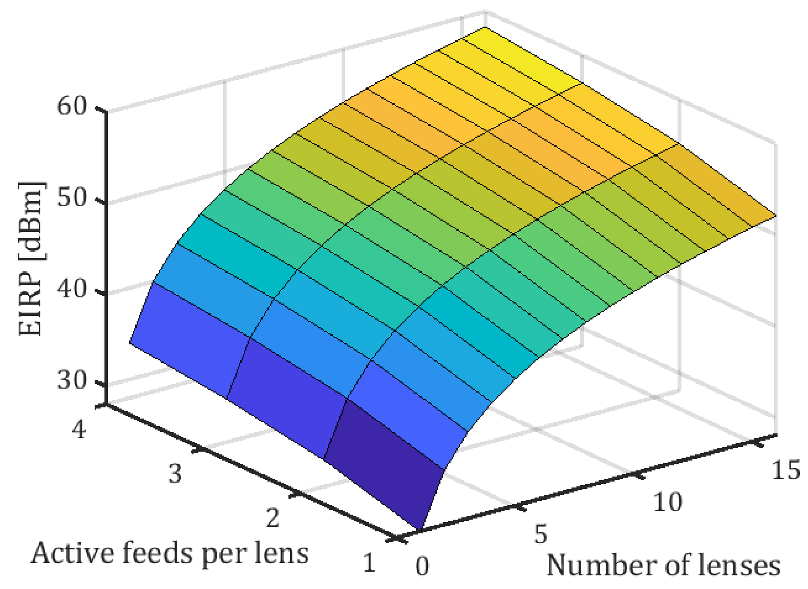
# D-band Lens Array for ICAS: Front-End Development

Marta Arias Campo [1], Simona Bruni [1], Ulrich Lewark [1], Olaf Kersten [1]

[1] IMST GmbH, Germany

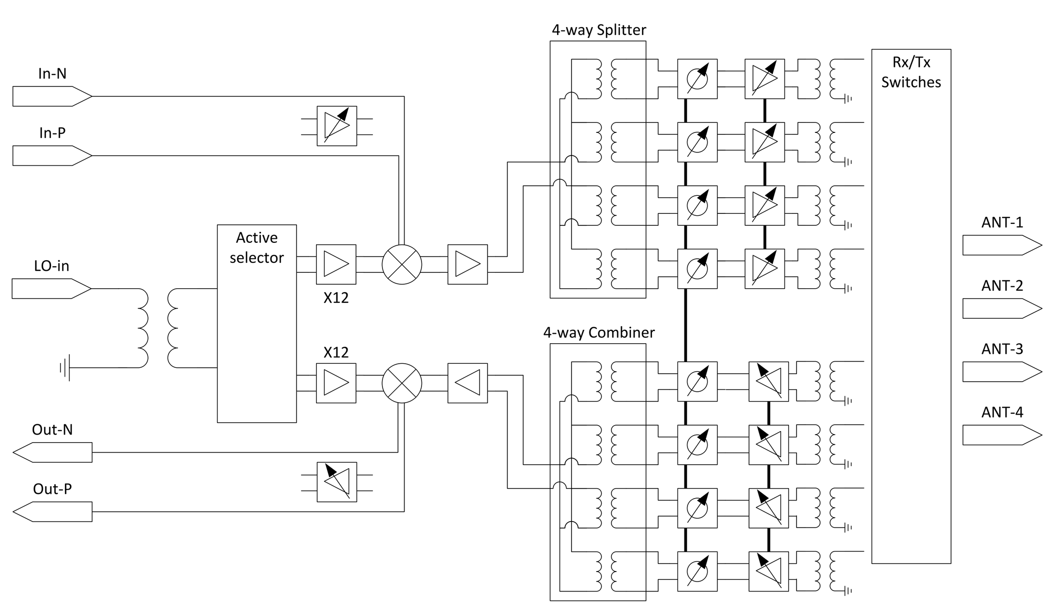
## Phased Lens Array Concept

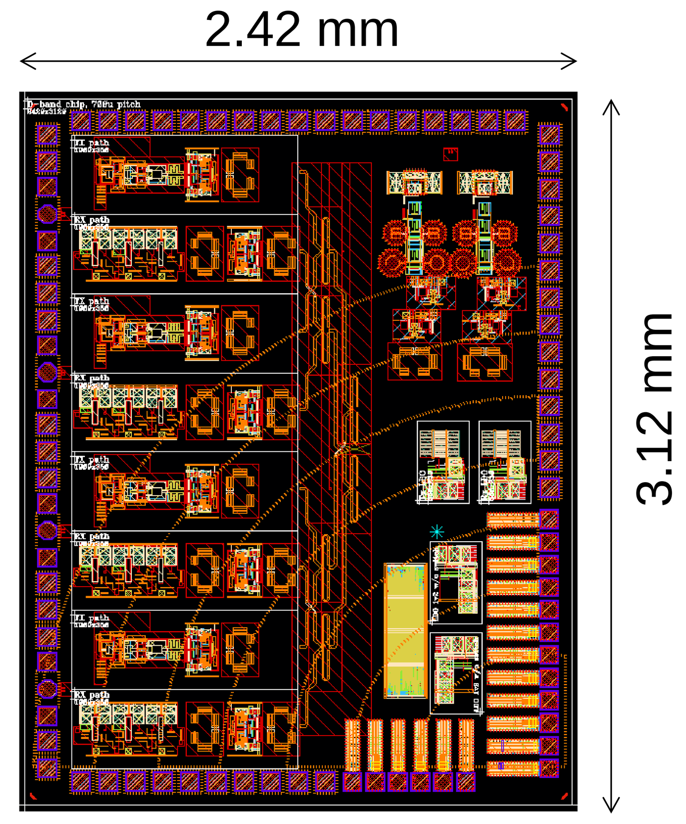





- Multiple, high EIRP beams with relaxed level of integration
- Hybrid beam-forming: quasi-optical and analogue
- Both switched beam or mechanical translation of the lenses possible to perform beam steering

## D-band Transceiver MMIC



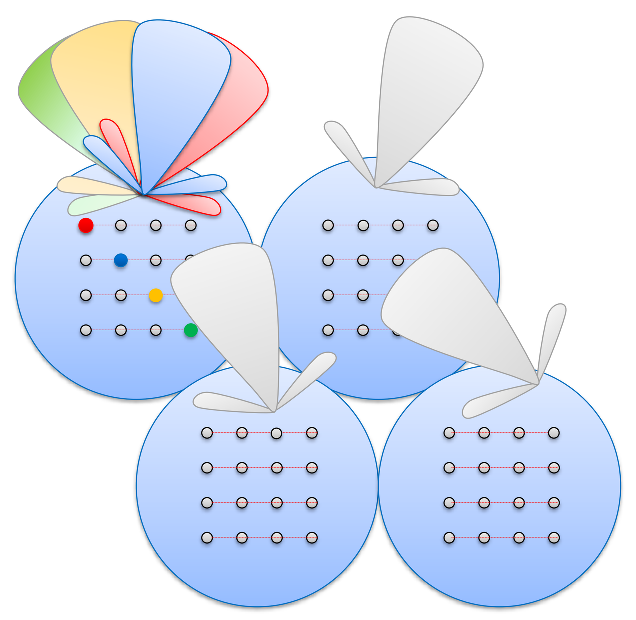




Preliminary design

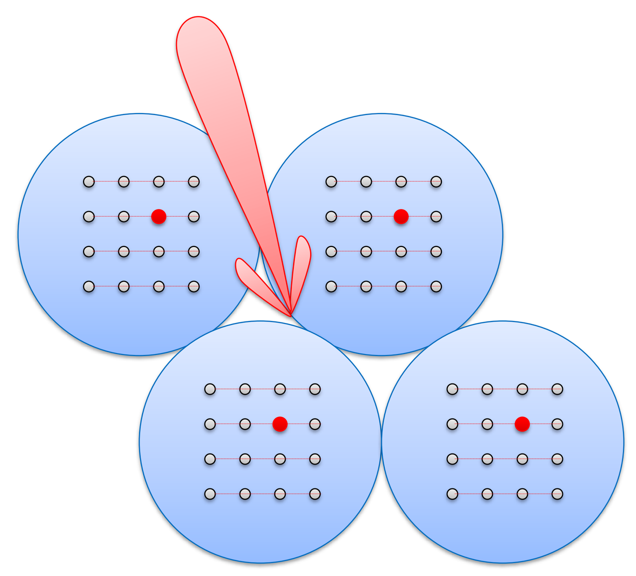
- 4-Channel Transceiver MMIC
- Switching function suitable for focal plane array
- Vector modulator enables lens phased array

## Modular Front-End Architecture

Enables adaptability to different scenarios or ICAS requirements

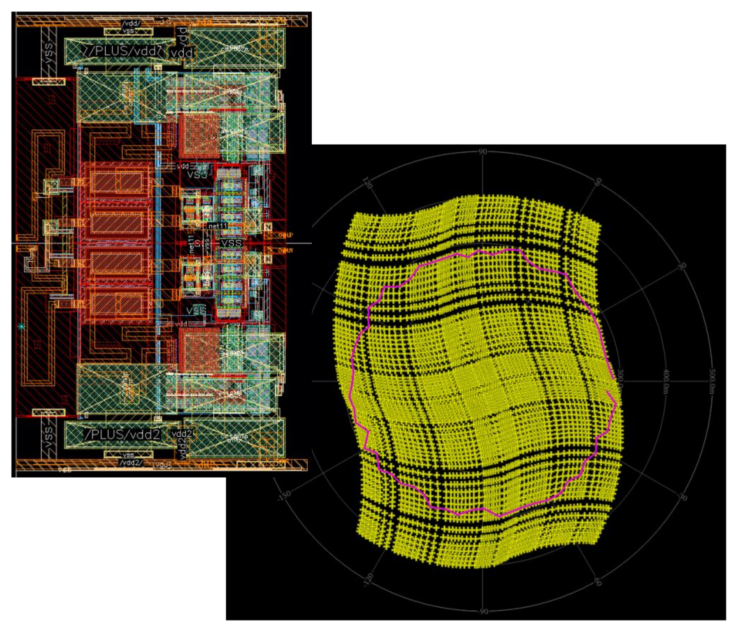


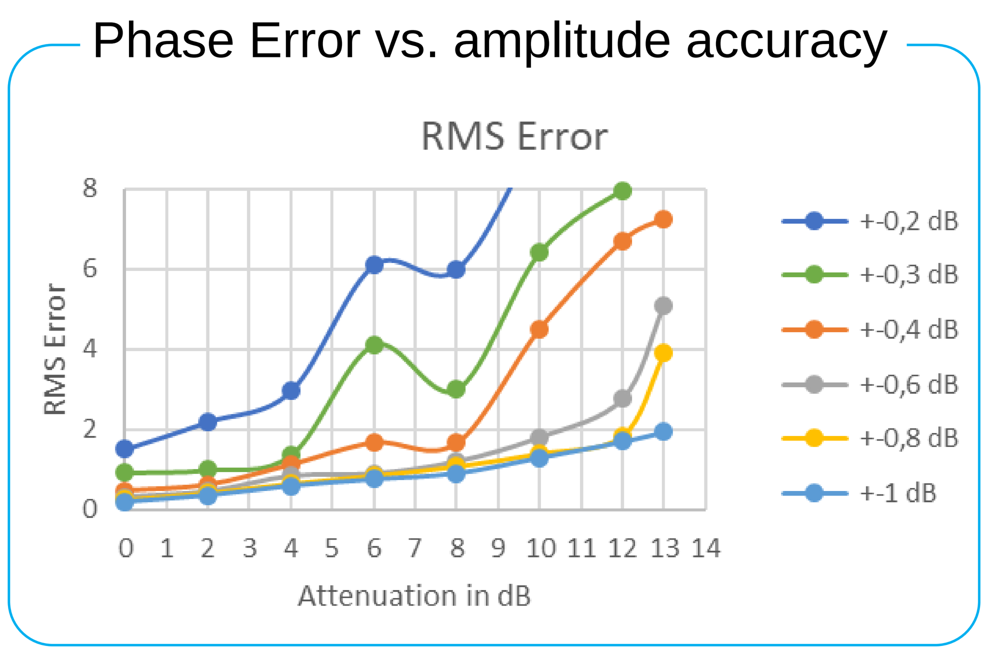
Multiple independent beams covering wide field-of-view



Single high-EIRP directive beam

## 140 GHz Vector Modulator

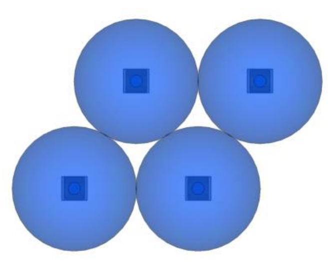




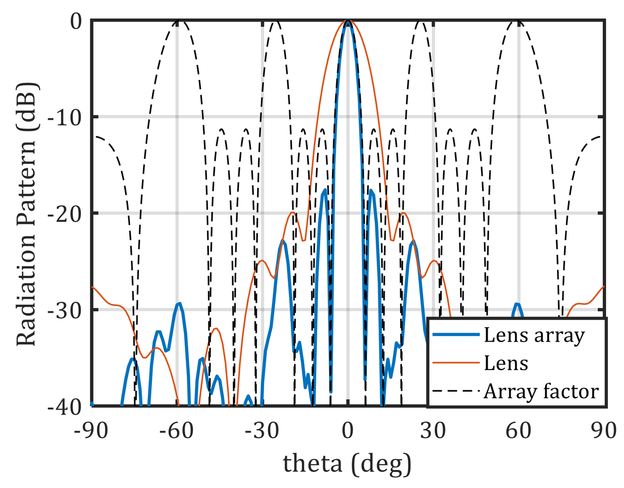

- Current mirror to steer attenuation/gain of a VGA
- 130 - 150 GHz bandwidth

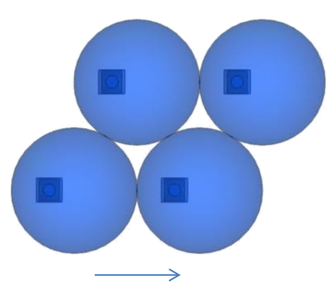
## Lens Array Simulations

Lens ∅ = 1 cm (4.6$\lambda$ @ 140 GHz)

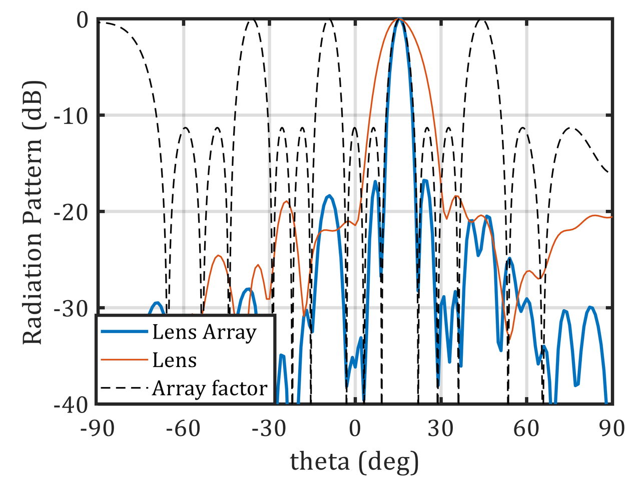


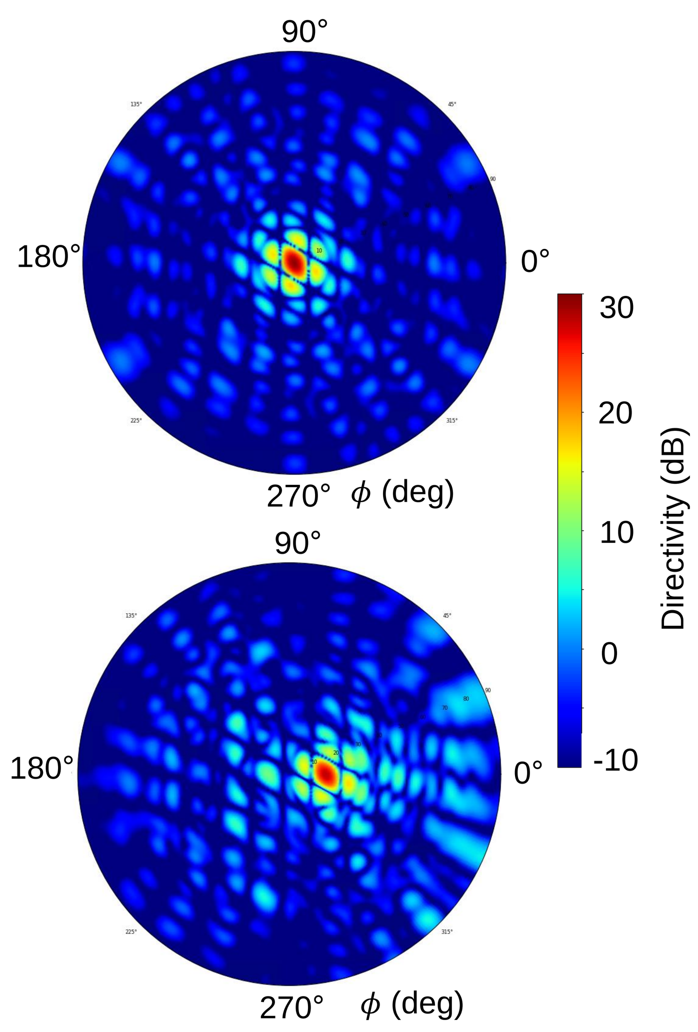
0° phase shift



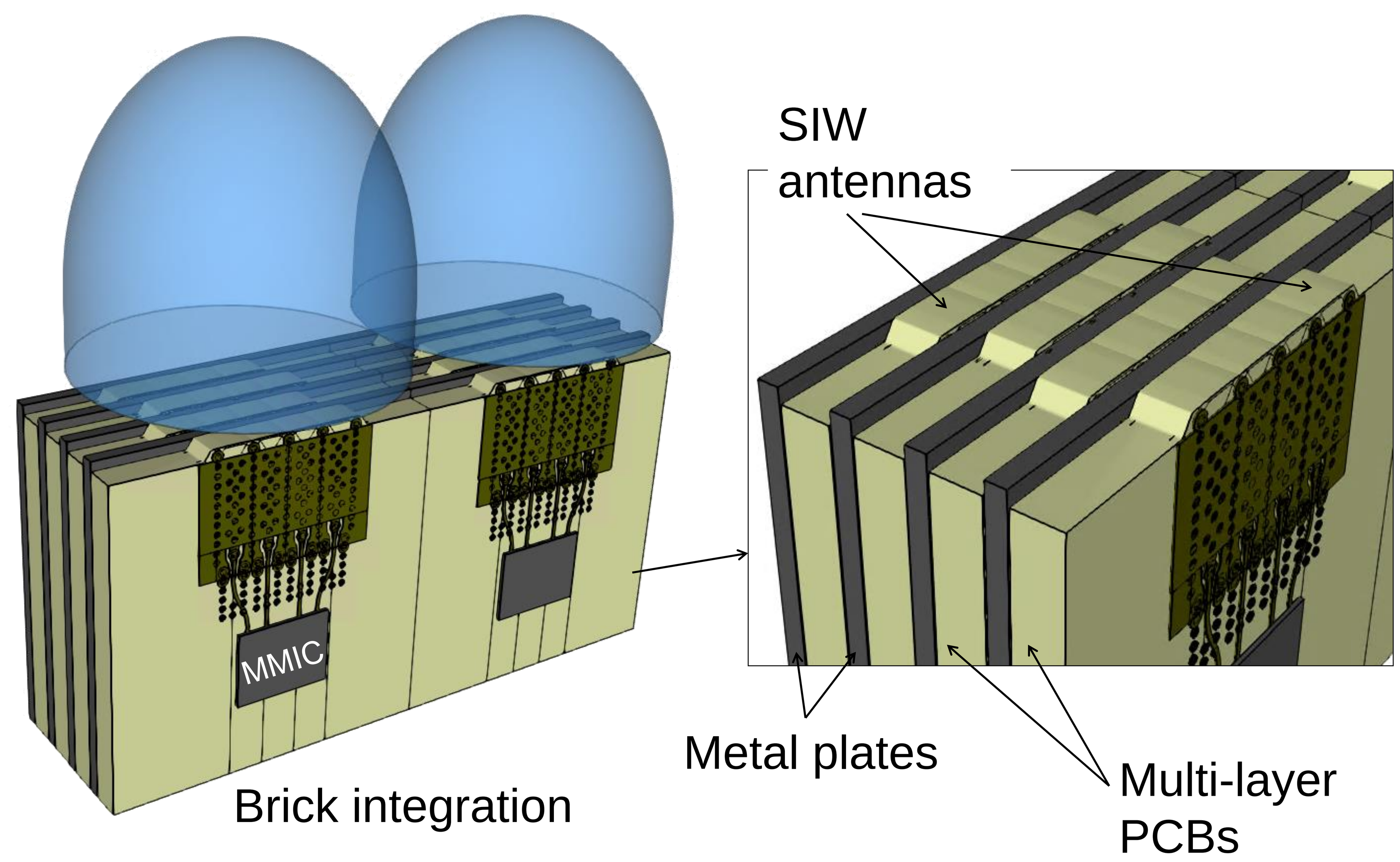



225° phase shift




## Front-End Brick Integration Concept




www.komsens-6g.com

SPONSORED BY THE
Federal Ministry of Education and Research

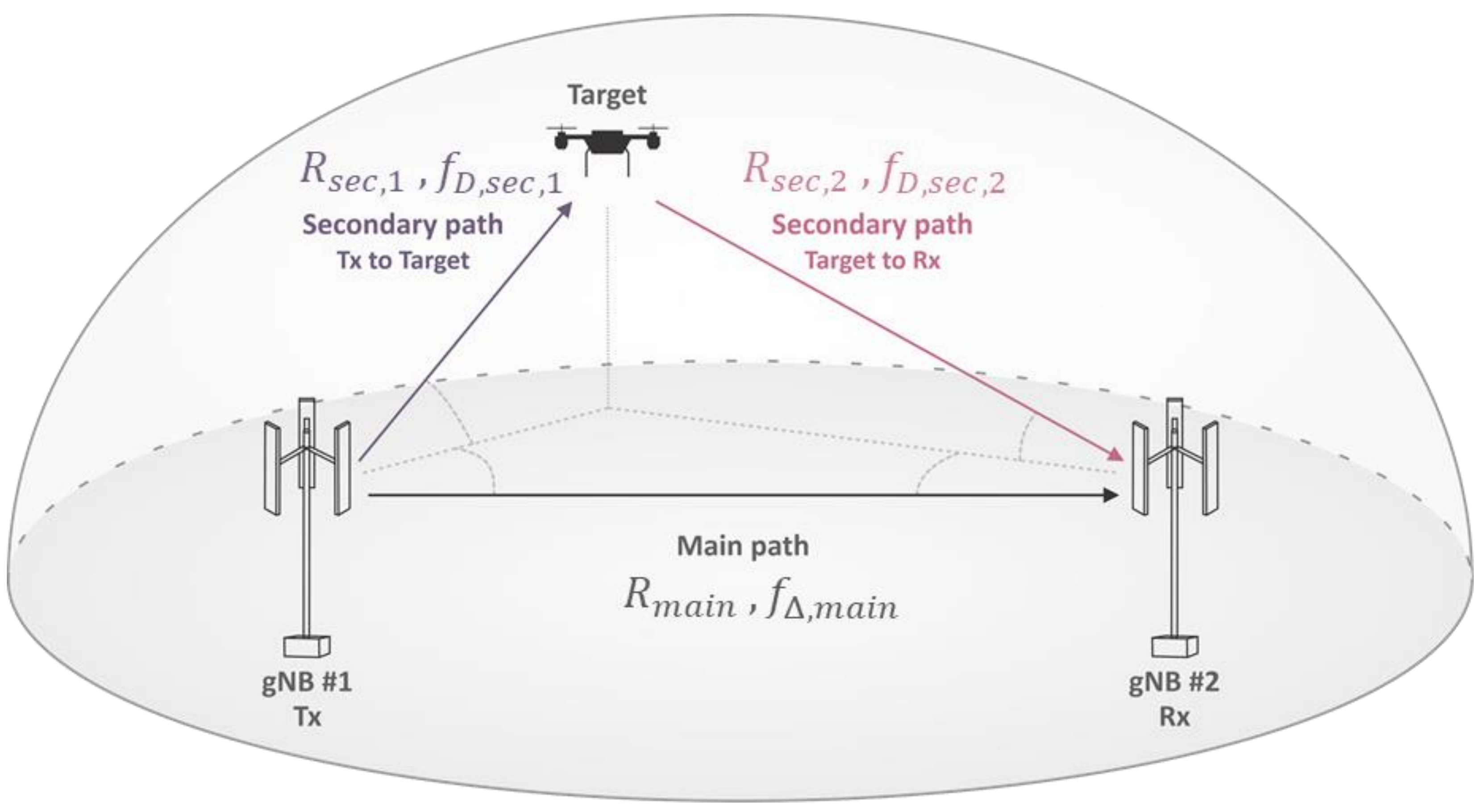
# Bistatic OFDM-based ISAC


Lucas Giroto de Oliveira and Benjamin Nuss

Institute of Radio Frequency Engineering and Electronics (IHE), Karlsruhe Institute of Technology (KIT)

{lucas.oliveira, benjamin.nuss}@kit.edu


## Objective




To perform radar sensing between two gNBs. In a single-target scenario, beams are pointed in two directions:

- Between Tx and Rx, creating a main path with range $R_{main}$ and Doppler shift $f_{\Delta,main} = 0$ since the gNBs are static. This path is used for synchronization, communication and sensing reference.
- Towards a radar target. The measured target's range and Doppler shift will respectively be:

$$R_{sec,1} + R_{sec,2} - R_{main}$$

and

$$f_{D,sec,1} + f_{D,sec,2} - f_{\Delta,main}$$

## Main Aspects of Bistatic OFDM-based ISAC

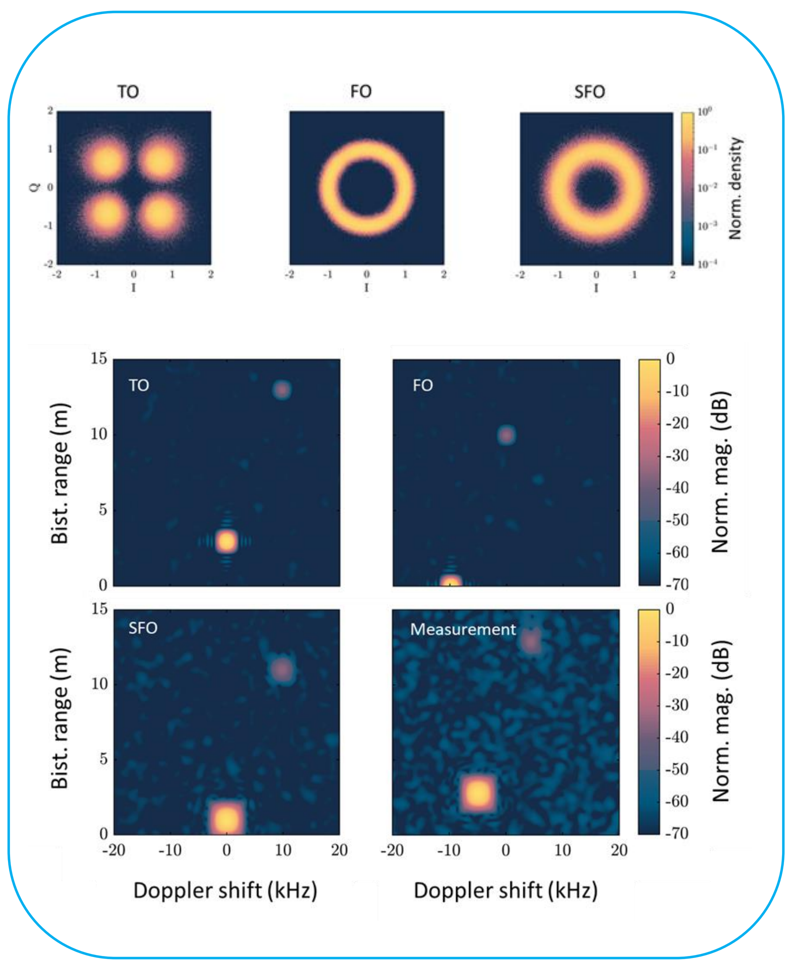
👍 Inherently distributed nature of cellular networks better exploited for radar measurements.

👍 Requirements imposed by full-duplex operation in monostatic ISAC (i.e., high isolation between Tx and Rx arrays and analog/digital interference cancellation) are avoided.

👎 More strict synchronization required to avoid sensing bias in target parameter estimates.

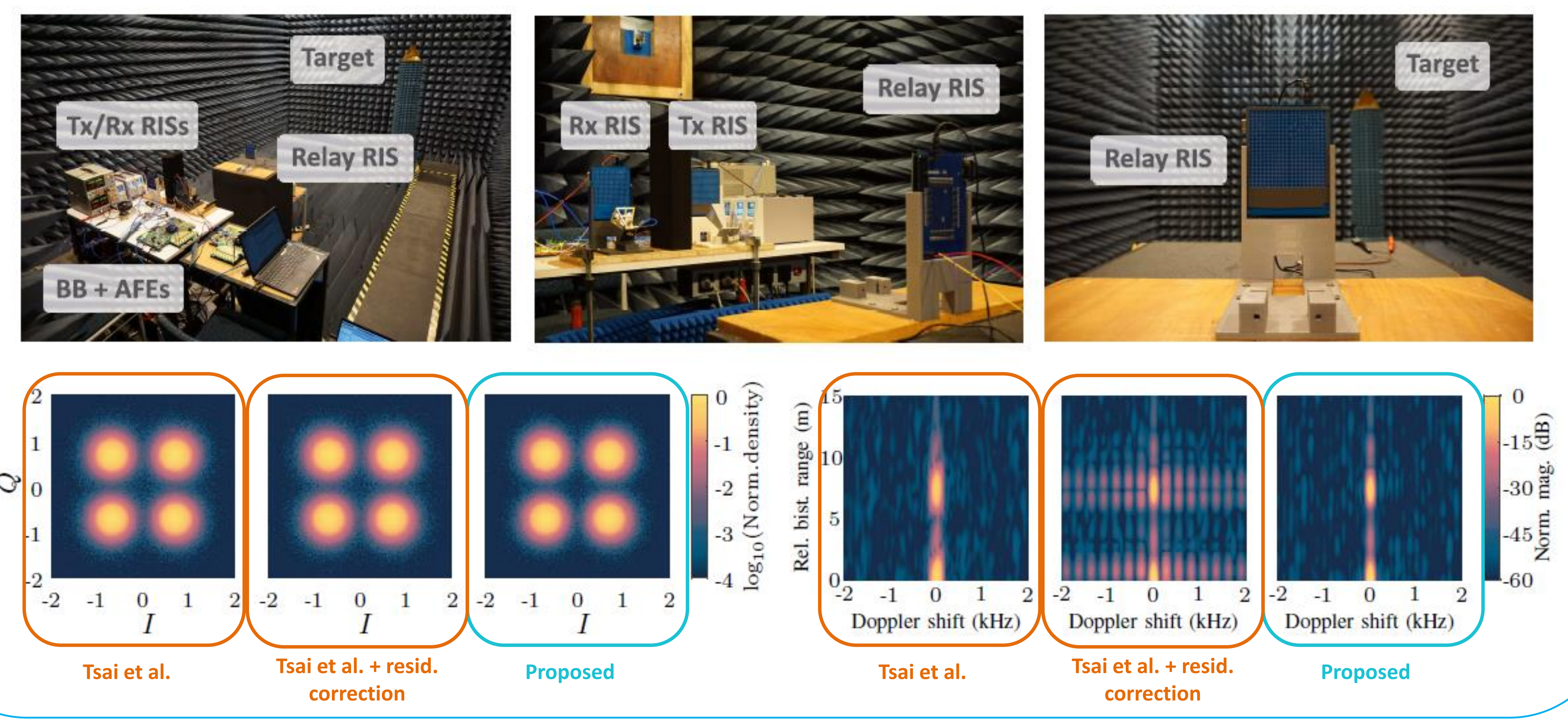
👎 Full comm. processing required to estimate Tx data and enable sensing with full processing gain and unamb. ranges for range and Doppler shift.

## Synchronization




Estimation and correction of time offset (TO), frequency offset (FO) and sampling frequency offset (SFO) are investigated. To meet the strict synchronization accuracy requirements for bistatic sensing, new algorithms for bistatic OFDM-based ISAC have been developed.

## Proof-of-Concept Measurements




Proof-of-concept measurements at 26.2 GHz with a main path created by a relay reflective intelligent surface (RIS).

Developed synchronization algorithms and processing strategies for communication data reconstruction and sensing processing adopted.

Similar communication performance, but considerably more accurate sensing than with state-of-the-art techniques achieved.


SPONSORED BY THE

Federal Ministry of Education and Research

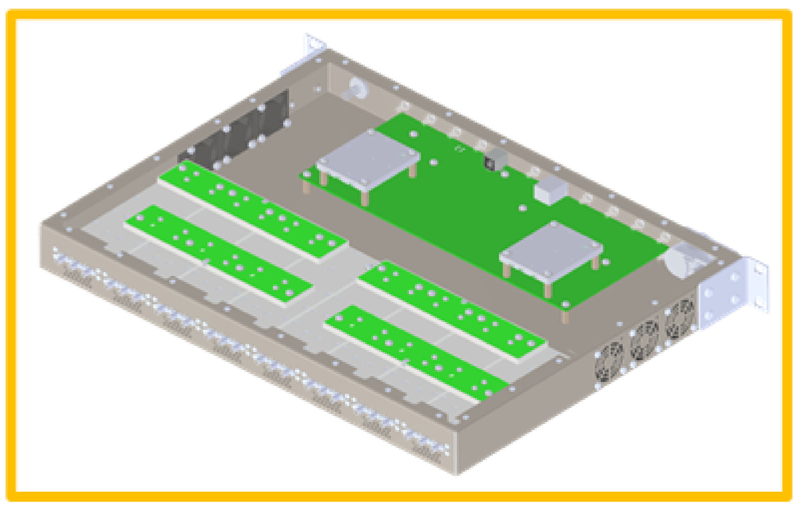

www.komsens-6g.com

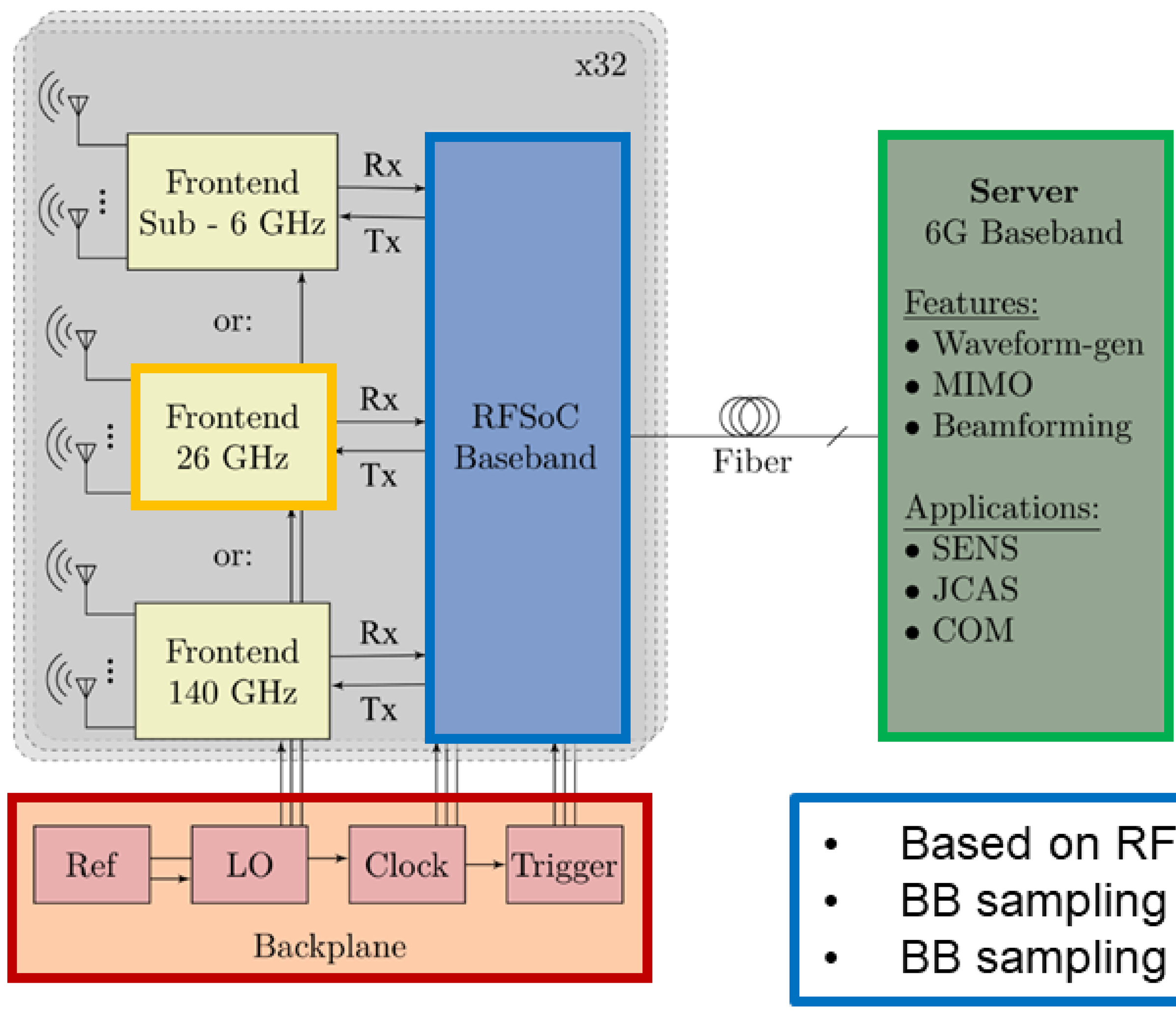
# Broadband Massive MIMO Testbed

Benjamin Nuss [1], Christian Karle [2], Marc Neu [2], Lukas Witte [3], Andre Scheder [3]
[1] Institute of Radio Frequency Engineering and Electronics (IHE), Karlsruhe Institute of Technology (KIT)
benjamin.nuss@kit.edu
[2] Institute for Information Processing Technology (ITIV), Karlsruhe Institute of Technology (KIT)
[3] Institute of Microwaves and Photonics (LHFT), Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)

## System Concept

- TDD, FDD, and FDX operation supported
- RF frequency from 24 GHz to 30 GHz
- 2 GHz instantaneous BW

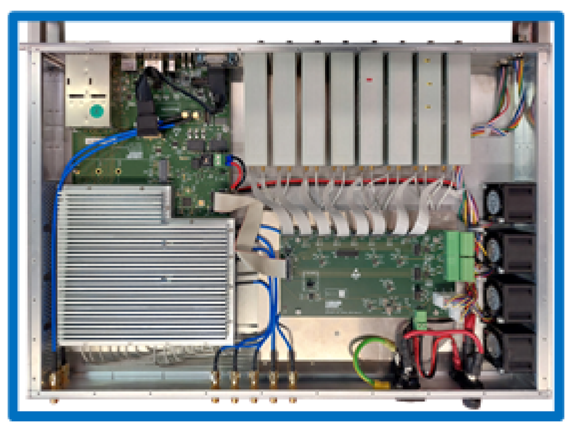





- Operation mode 1: Play + record
  → backed by storage and processing servers
- Operation mode 2: Real-time signal processing
- 2 servers per baseband module (8 ch.)
- Interfacing: 100 Gbit/s per server over QSFP28
- Data source and sink into RAM (128 GB)

- Generates LO, clock and trigger signals
  - LO/4 from 5.5 GHz to 7.5 GHz
  - Clock from 100 MHz to 500 MHz
  - Trigger as M-Seq with clock frequency
- All signals derived from one reference
  → full coherency

- Based on RFSoC XCZU47DR (8 ADCs, 8 DACs)
- BB sampling rate of 1 GSPS (8 Tx + 8 Rx channels useable)
- BB sampling rate of 2 GSPS (4 Tx + 4 Rx channels useable)



The Broadband Massive MIMO Testbed is developed and built in the Open6GHub and used in multiple projects, e.g., in KOMSENS-6G.

Open6GHub

**Visit the testbed at the Open6GHub booth!**

## Testbed Demonstrations

- **EuMW 2023**
  Exhibition & 5G to 6G Forum
  "Open6GHub – An Open Hardware Testbed for 6G Addressing Sub-6GHz to THz Spectrum"
- **Mobile World Congress 2024**
  Demonstrator at the booth of Rohde & Schwarz
- **Workshop on Smart Antennas 2024**
  Presentation of Open6GHub & Talk on Broadband MIMO Testbed
- **EuMW 2024 (Outlook)**
  Exhibition at the Open6GHub booth

EuMW 2023 EUROPEAN MICROWAVE WEEK Messe Berlin hub27 BERLIN, GERMANY 17th–22nd SEPTEMBER 2023 www.eumweek.com WAVES BEYOND WALLS

MWC GSMA February 26-29, 2024 Fira Gran Via, Barcelona

27th International Workshop on Smart Antennas March 17-19, 2024 | Dresden, Germany

## Applications

**Research Questions Addressed With the Testbed in KOMSENS-6G**

- Massive MIMO multistatic sensing
  - Over-the-air synchronization
    - Time offset
    - Carrier frequency offset
    - Sampling frequency offset
  - Data fusion
  - Clutter removal
  - Target classification
- Alternative waveforms
- Mutual interference cancellation
  - Simultaneous mono- and bistatic sensing

KIT Karlsruhe Institute of Technology · IHE · ITIV · FAU · LHFT

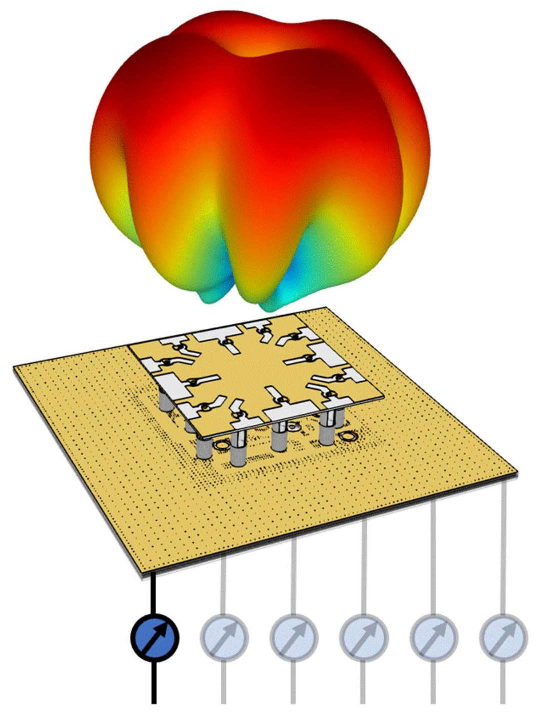
SPONSORED BY THE
Federal Ministry of Education and Research

www.komsens-6g.com

# Multi-Mode Multi-Port Antennas

Tim Hahn, Hendrik Jäschke, Dirk Manteuffel
Institute of Microwave and Wireless Systems, Leibniz University Hannover, Germany

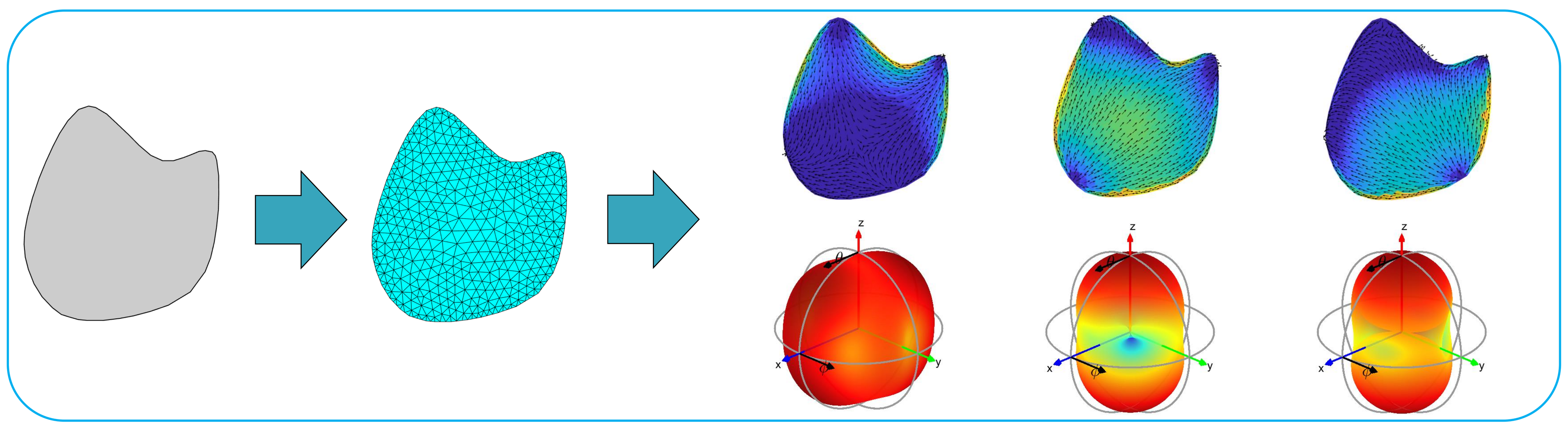
## What is a Multi-Mode Multi-Port Antenna (M³PA)?



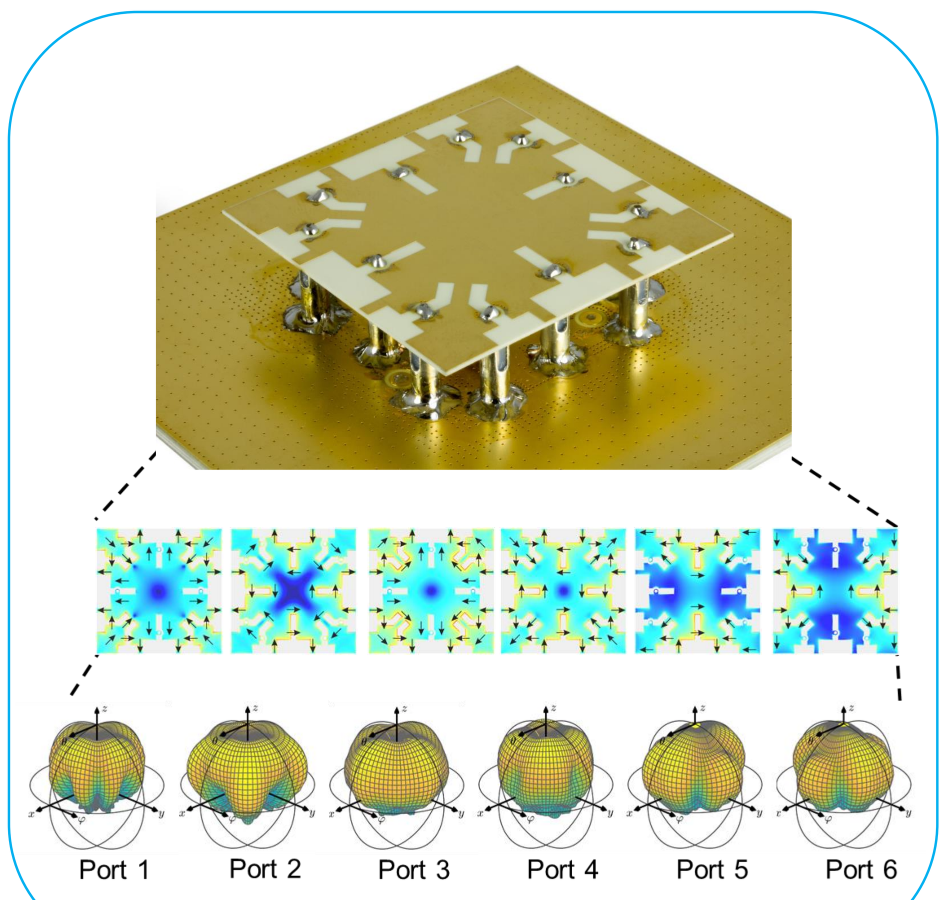
- One physical element
- Multiple isolated antenna ports
- Each port excites different current distributions on the element
- The port radiation patterns are uncorrelated to each other
- Angular diverse radiation patterns
- MIMO

## Theory behind M³PAs: Characteristic Modes

- Analyze antenna structure
- Inspect characteristic modes (eigencurrents)
- Identify feed points based on surface current distribution
- Define ports to excite different eigencurrents
- Excite structure per port



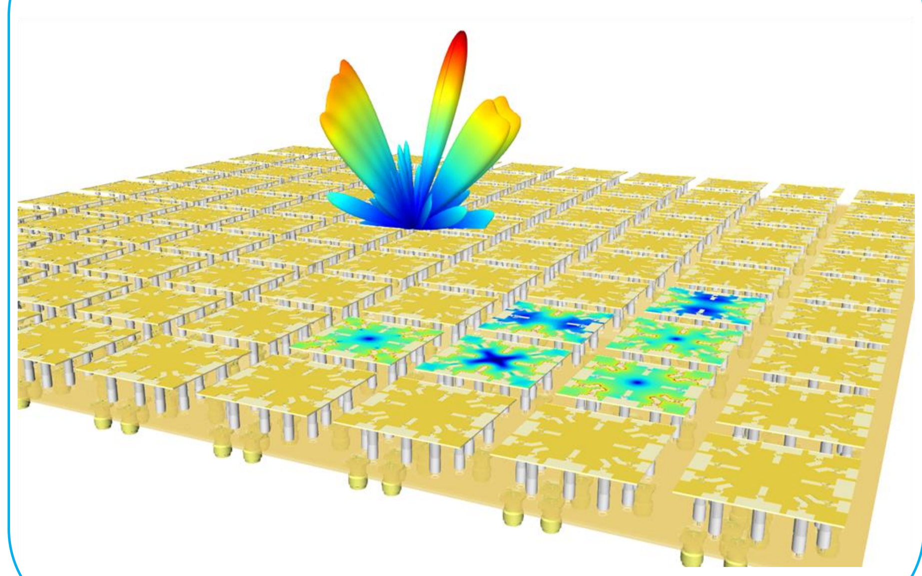
## Patch M³PA




Patch M³PA for MIMO Applications

- Six-Port Antenna Demonstrator
- Essentially combines six antennas within one structure
- Designed for broadband (UWB) applications
- Operating in the frequency band 6 < *f* [GHz] < 8.5

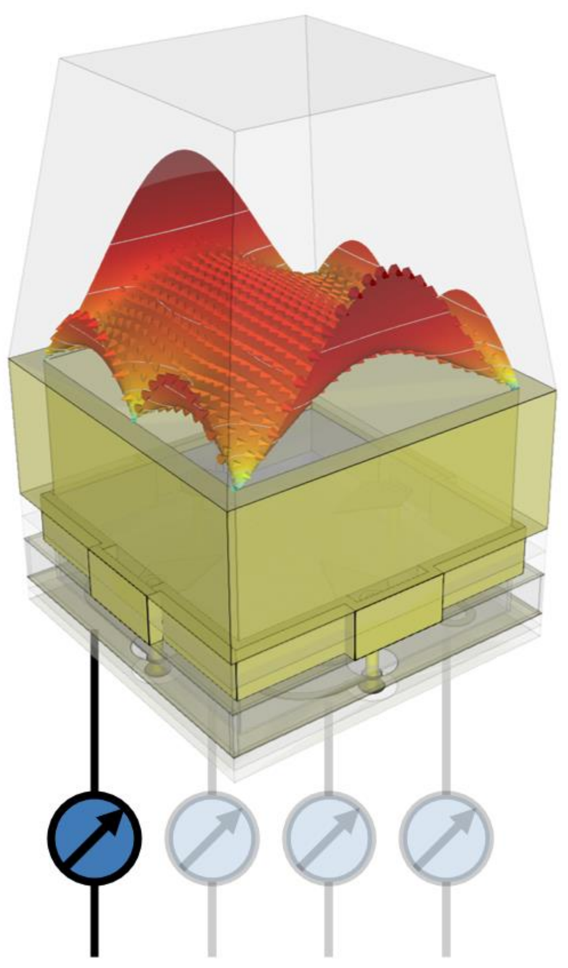
## Patch M³PA Array Beamforming



M³PA Arrays offer:

- Higher degrees of freedom for pattern shaping
- Large angle steering
- Grating lobe suppression
- Single element beamforming
- Application in single or multi beam scenarios

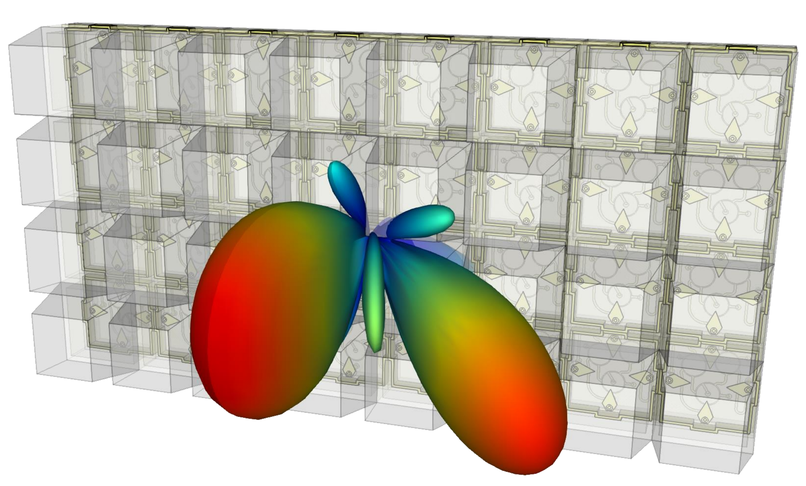
## Aperture M³PA



Aperture M³PA array for Integrated Sensing and Communication Applications

- Four-Ports per single radiator
- Orthogonal far-fields per port
- Aperture-based radiator design
- Aperture dimensions $0.53\ \lambda_0 \times 0.53\ \lambda_0$
- Designed for mmWave frequency band n257 and n258 $24.25 < f\ [\text{GHz}] < 29.5$

## Aperture M³PA Array Beamforming



- Initial demonstrator of an aperture radiator-based M³PA array
- Integrated Sensing and Communication (ISAC) applications
- Assign communication and sensing tasks to different ports
- Potential for simultaneous transmission and reception

SPONSORED BY THE
Federal Ministry of Education and Research

Institute of Microwave and Wireless Systems
Leibniz University Hannover
Hannover, Germany
www.imw.uni-hannover.de

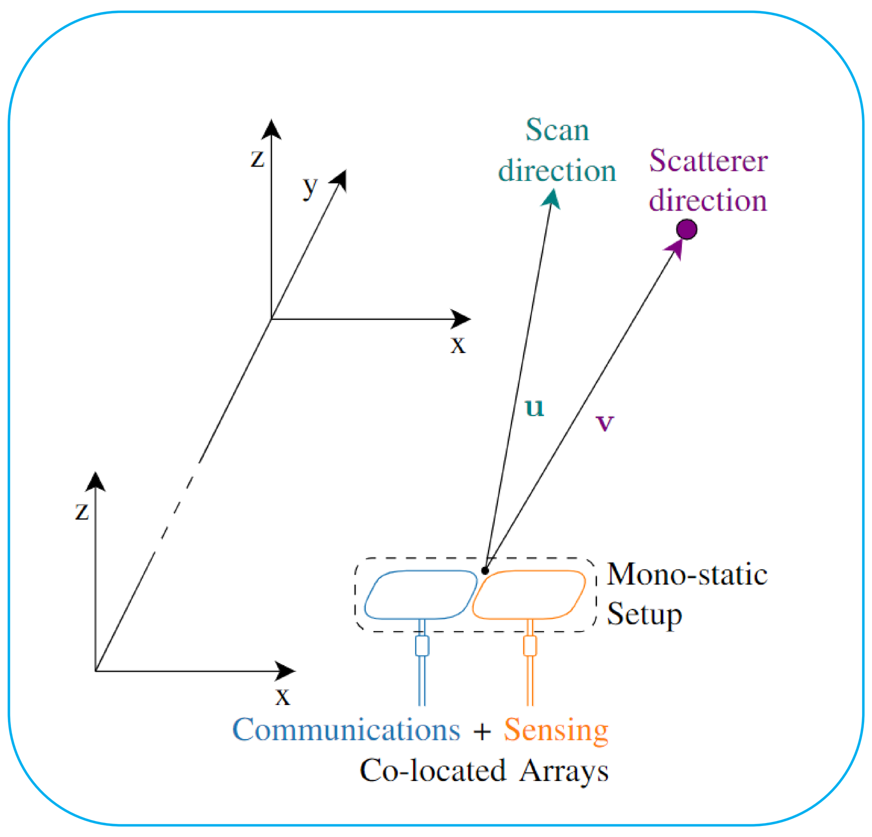
# Antenna Array Design for Monostatic ISAC

Alexander Felix[12], Silvio Mandelli[1], Marcus Henninger[12], and Stephan ten Brink[2]

[1] Nokia Bell Labs Stuttgart, 70469 Stuttgart
[2] Institute of Telecommunications, University of Stuttgart, 70569 Stuttgart
E-mail: alexander.felix@nokia.com

KOMSENS 6G

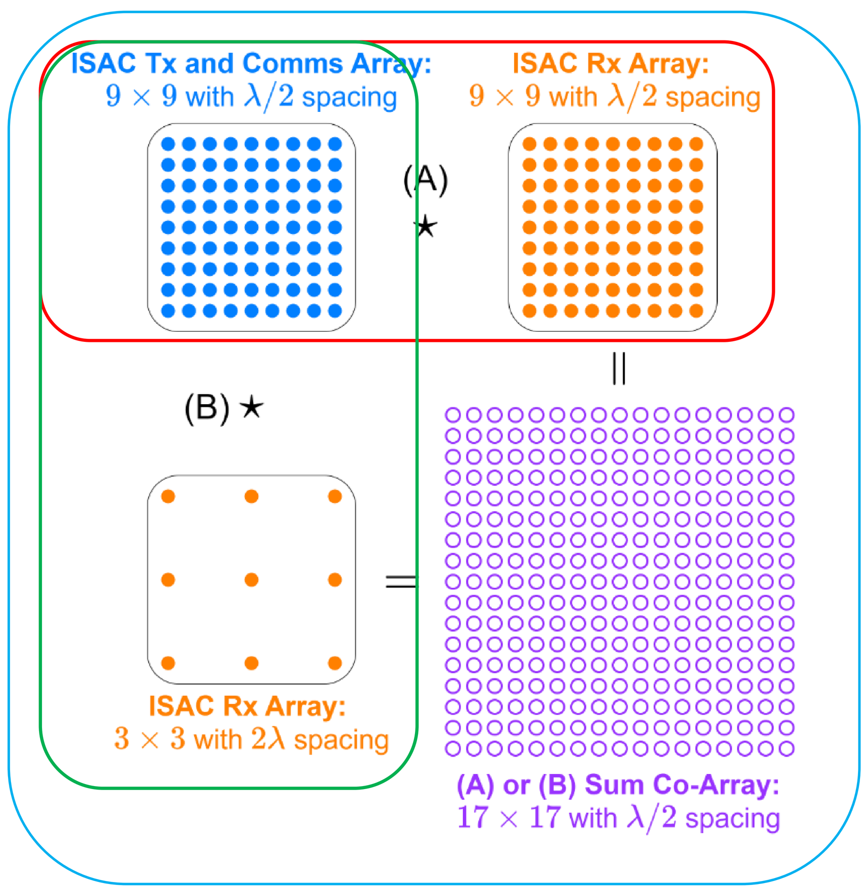
## Monostatic ISAC setup




- First ISAC operations will likely be mono-static
- 5G radios will be half-duplex, they can either transmit or receive
- One device (e.g., ISAC Tx / Communications Array) primarily defined by communications based on latest 5G NR hardware

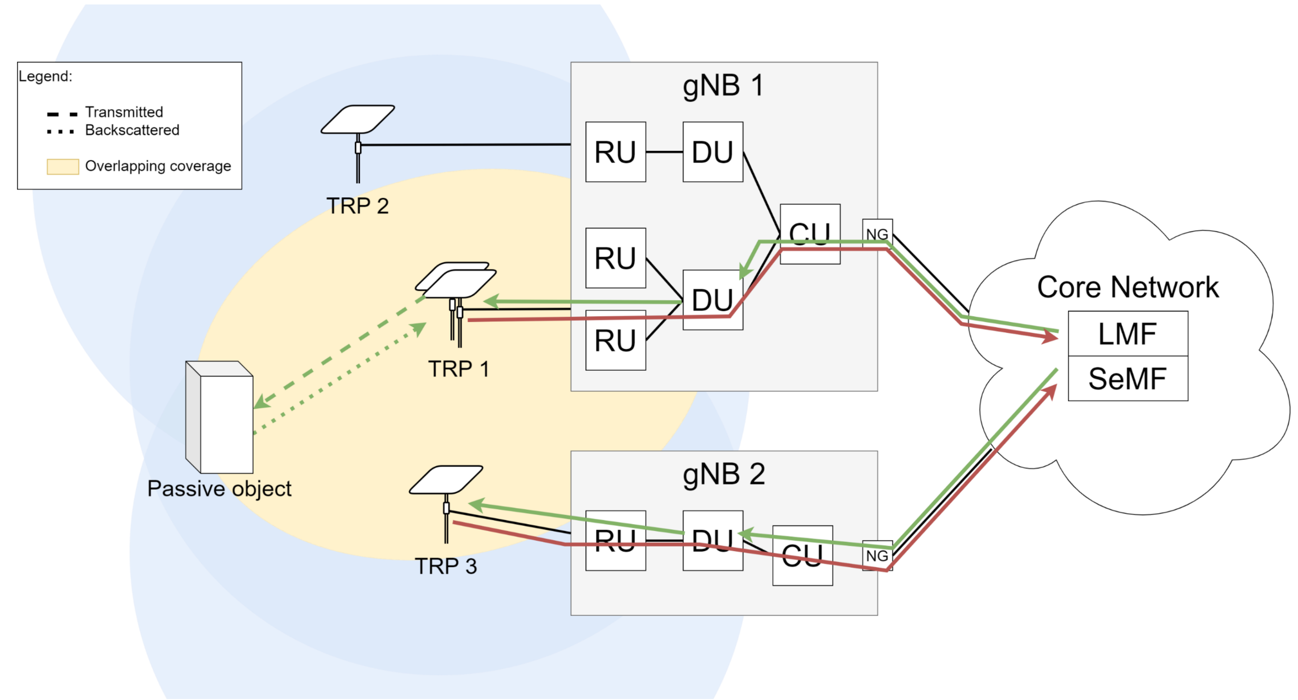
- Freedom in the design of 2nd device (e.g., ISAC Rx / Sensing Array)


## Improving the design of ISAC radios



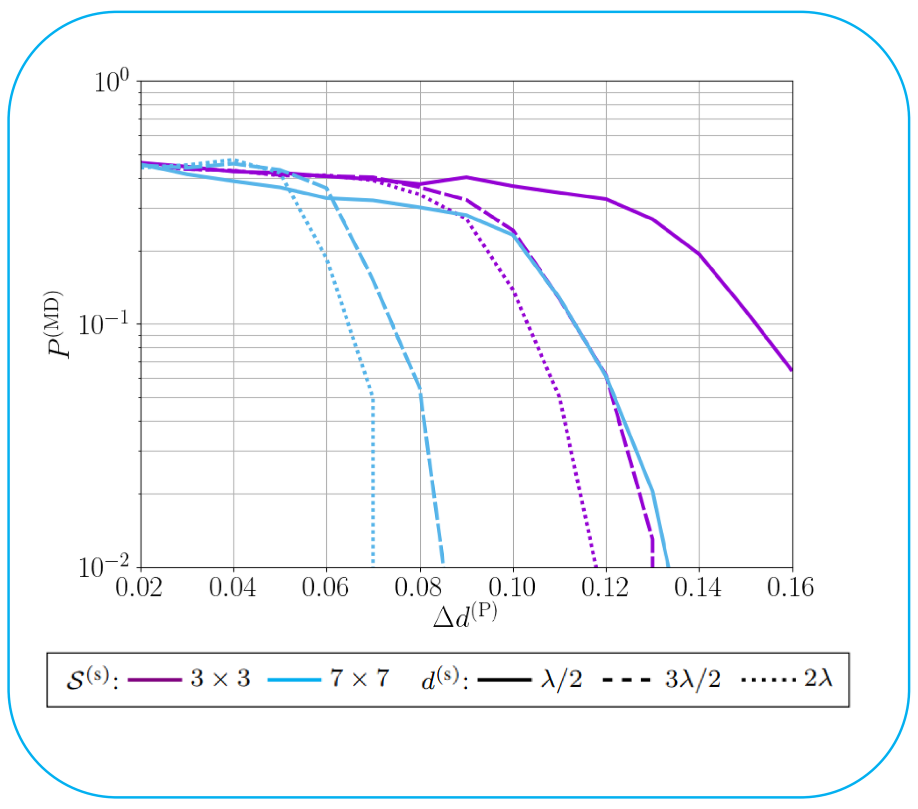

- Joint beamforming for dissimilar arrays
- What matters is the co-array structure
- Communications array as legacy URA with $d \approx \lambda/2$
- Sensing array can be designed in many ways, e.g., with sparse distant elements, reducing its costs

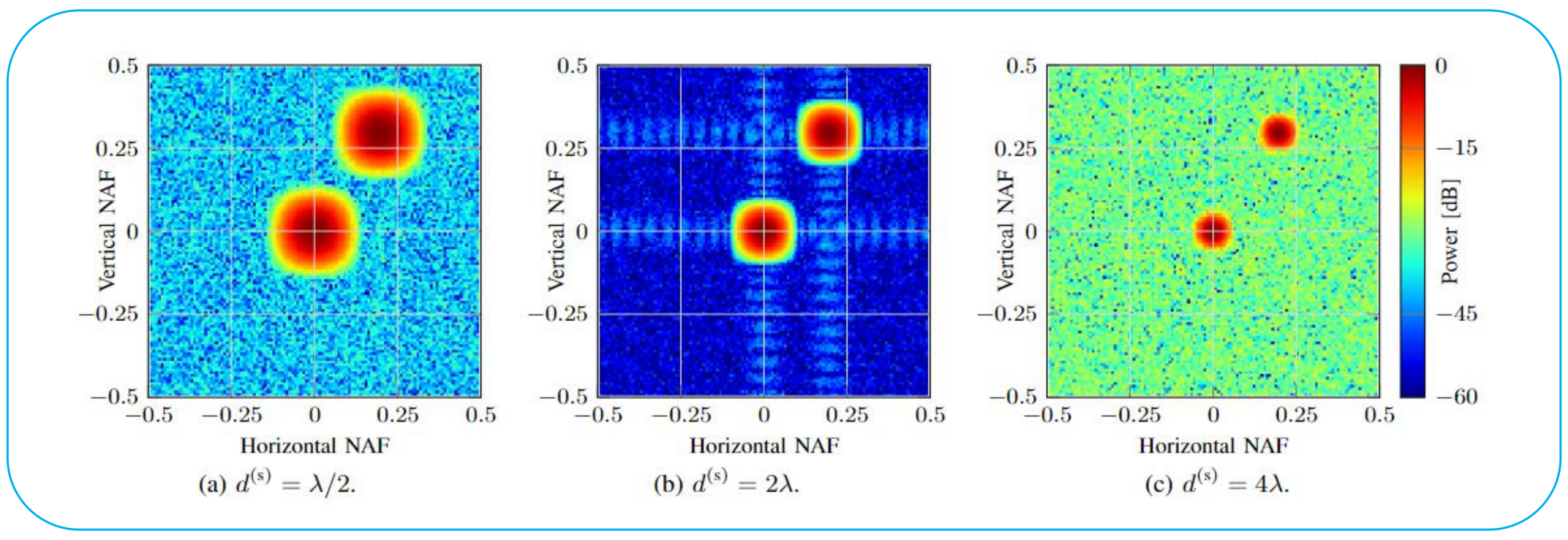
## Signaling and network evolution

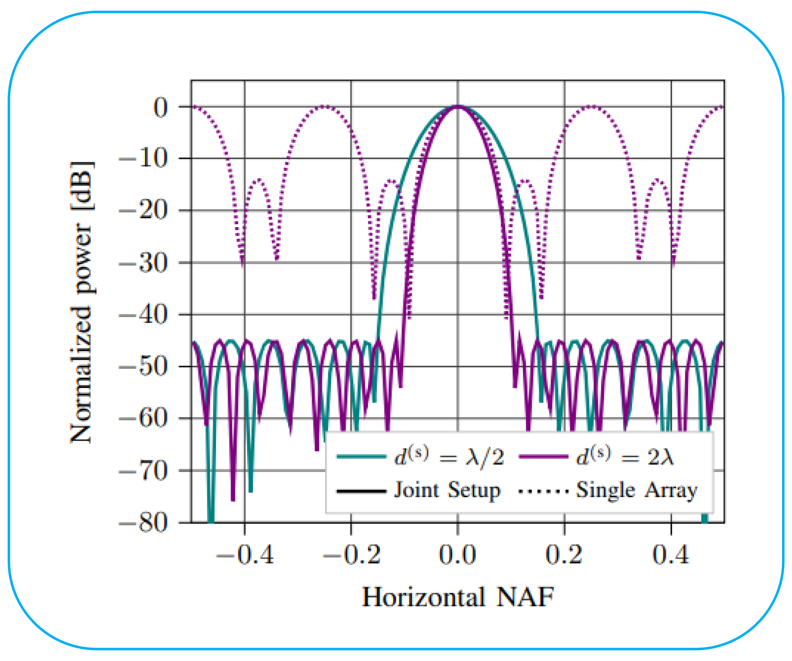



- Extension to New Radio Positioning Protocol a (NRPPa) to characterize joint beamforming of monostatic setups
- Coordination of sensing tasks in core network by SeMF

## Monte-Carlo evaluation




**Less elements, same aperture** leads to **same resolution with cheaper hardware**

NOKIA BELL LABS

SPONSORED BY THE
Federal Ministry of Education and Research

www.komsens-6g.com

# Cooperative Multi-Monostatic Sensing for Object Localization in 6G Networks

Maximiliano Rivera Figueroa, Pradyumna Kumar Bishoyi, and Marina Petrova

Mobile Communications and Computing, RWTH Aachen University, Aachen, Germany.

## Introduction

- The upcoming 6G network is expected to locate passive targets having no communication capabilities and are not registered in the network. For that, the base station (BS) needs to act as a monostatic radar, relying on reflected echo signals from the target for localization.
- The accuracy of the localization depends on the BS-target-BS propagation environment and degrades in **multi-path rich environment** as shown in Fig. 1.
- To mitigate the multipath effect, in this work we employ **multi-monostatic sensing**, in which multiple BSs independently localize the target and then combine their information to improve the position accuracy. It operates in two stages:
    - BSs estimate their distance to the target and share it with a CPU.
    - The CPU **fuses these estimates** to determine the target's position and enhance sensing accuracy.

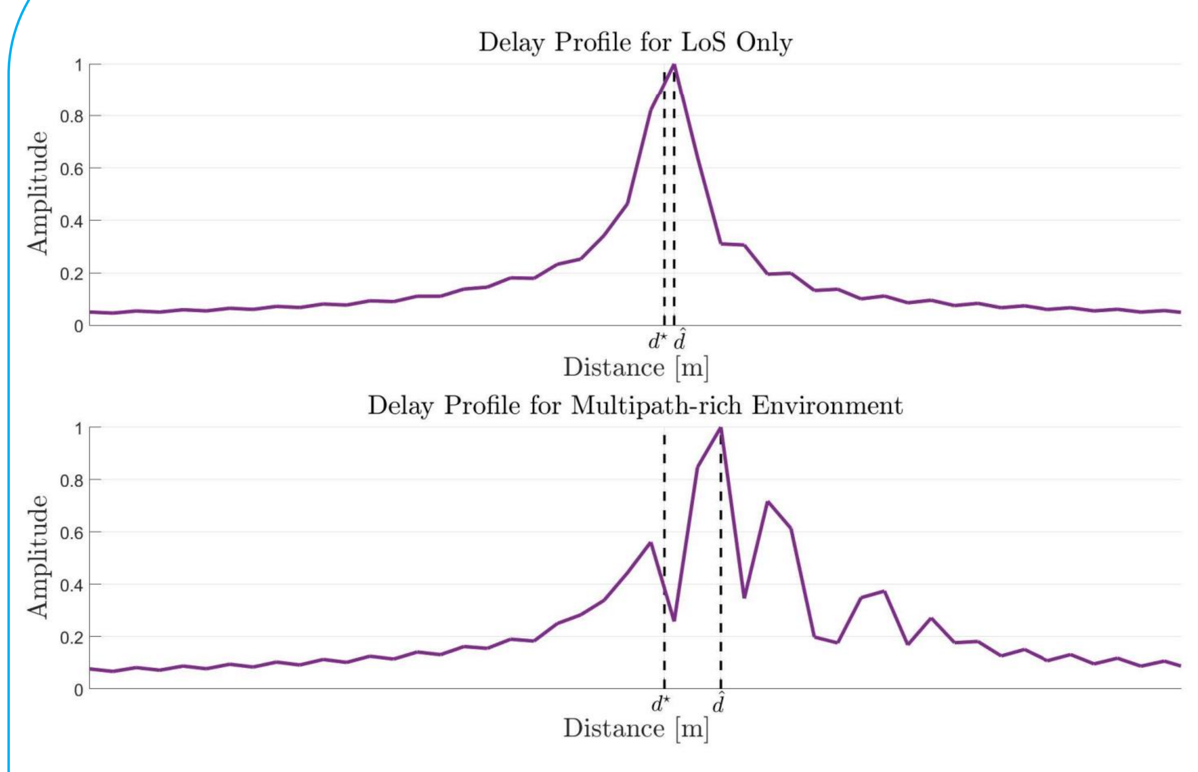



**Figure 1**: Effect of multipath. Difficult to spot the real target due to multiple peaks. $\hat{d}$: estimated distance, $d^*$: true distance

## Fusion Mechanisms

- Maximum Likelihood (ML):

$$\hat{\mathbf{x}}_{LL} = \arg\max_{\mathbf{x}} \sum_{k\in\mathcal{K}} w_k \cdot \ln\left(\frac{1}{\sqrt{2\pi}} \cdot \exp\left[-\frac{(\hat{d}_k - ||\mathbf{x}_k - \mathbf{x}||)^2}{2\,\sigma_k^2}\right]\right) = \sum_{k\in\mathcal{K}} w_k \cdot \ln\left(p_k(\mathbf{x})\right)$$

- Maximum a Posteriori (MAP):

$$\hat{\mathbf{x}}_{MAP} = \arg\max_{\mathbf{x}} \sum_{k\in\mathcal{K}} w_k \left[\ln\left(\frac{1}{||\mathbf{x}-\mathbf{x}_k|| + \epsilon}\right) + \ln\left(p_k(\mathbf{x})\right)\right]$$

- Non-linear Least Square (NLLS):

$$\hat{\mathbf{x}}_{\text{NLLS}} = \arg\min_{\mathbf{x}} \sum_{k\in\mathcal{K}} w_k \left(\hat{d}_k - ||\mathbf{x}_k - \mathbf{x}||\right)^2$$

$\sigma_k^2$: Gaussian component of the k-th BS.
$w_k$: weight for the k-th BS.
$\widehat{d_k}$: estimated distance of the k-th BS.

## System Model

- We consider a system of K 5G NR BSs located in an urban area.
- Each BSs acts as a monostatic radar operating in the **FR1 band**.
- All the BSs are synchronized and connected to a CPU.
- The system aim to locate a target moving along the street by sending an OFDM signal and estimating the time-of-arrival.

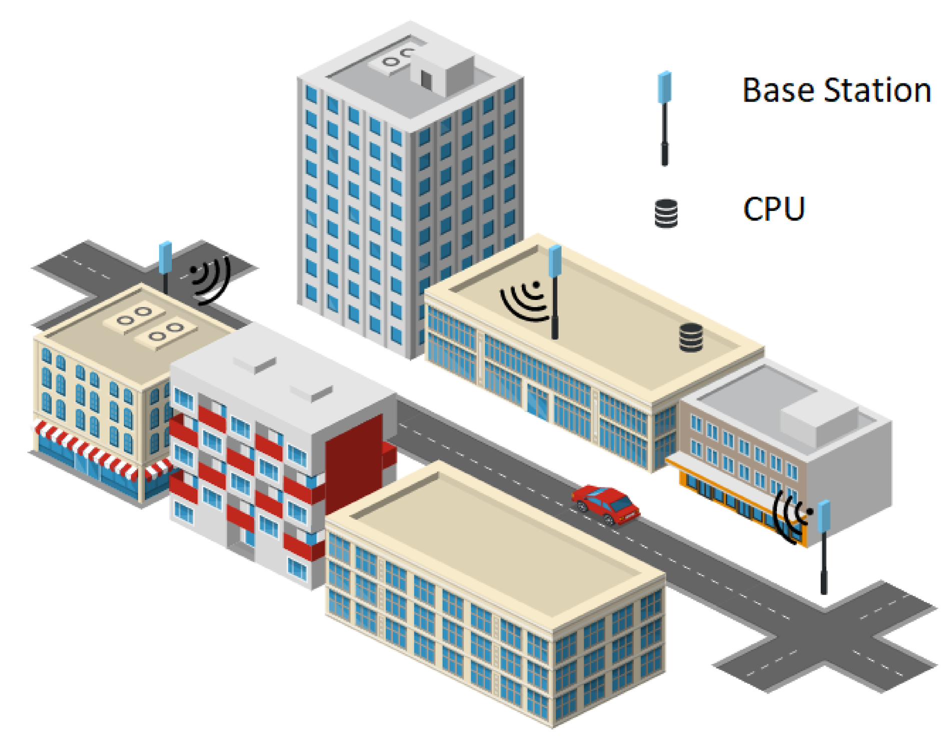



**Figure 2:** Considered scenario.

## Simulation Setup

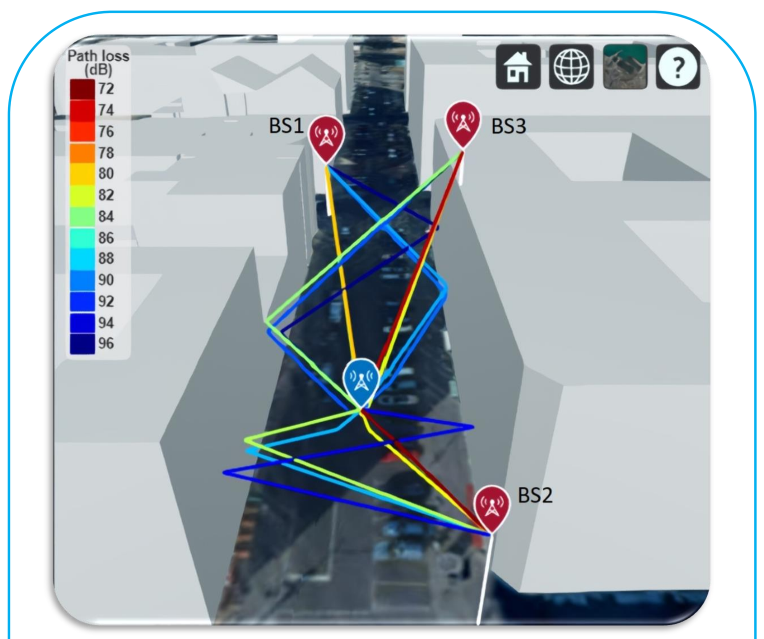



**Figure 3**: MATLAB Ray Tracer based on Berlin, PLZ 10969. Red: BSs. Blue: Target.

| | |
|---|---|
| Carrier Frequency | 3.5 GHz |
| Subcarrier Spacing | 30 kHz |
| Target Speed | 50 km/h |

## Results

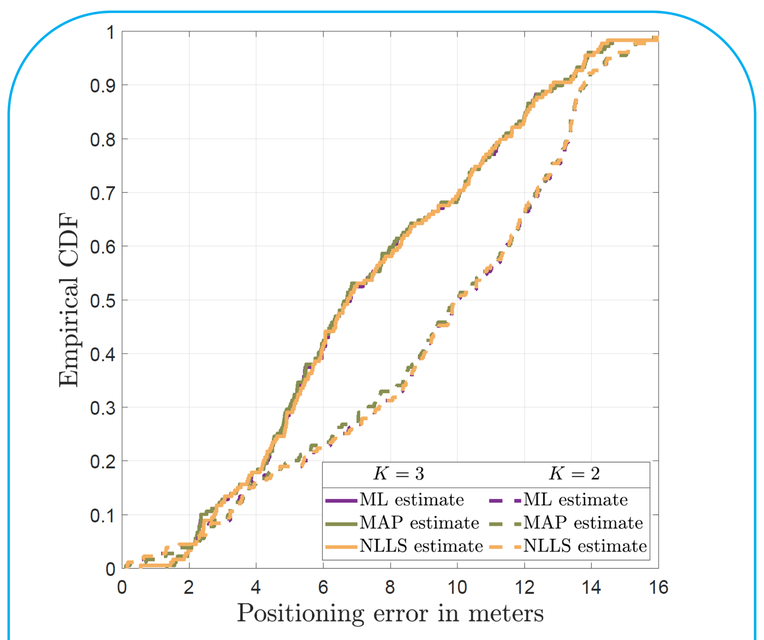



**Figure 4**: Positioning error for different number of BSs fused (K) under BW = 20 MHz.

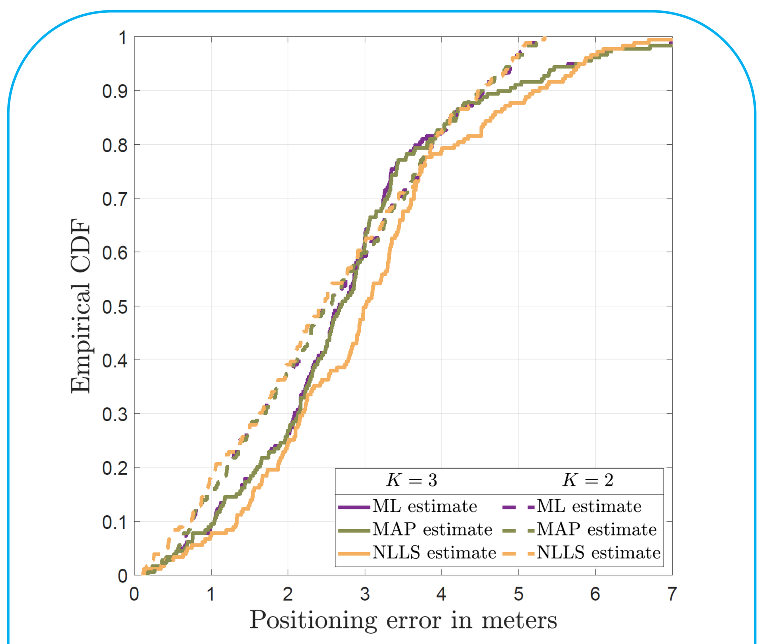



**Figure 5**: Positioning error for different number of BSs fused (K) under BW = 100 MHz.

- Fusing more base stations yields better position estimation in bandwidth limited scenario.
- However, under BW = 100 MHz, there is no improvement when adding an extra BSs.

## Conclusions

- Multi-monostatic sensing increases the accuracy of the estimation by combining the individual estimates of each BSs
- Increasing the BW leads to higher accuracy in distance and positioning estimation.
- The gain in the accuracy after fusion depends on the available BW used and the locations of the BSs, with each BS contributing differently based on multipath conditions.

www.komsens-6g.com

SPONSORED BY THE
Federal Ministry of Education and Research

**Paper Link**

https://arxiv.org/abs/2311.14591

# Grid-free Harmonic Retrieval and Model Order Selection using Convolutional Neural Networks

S. Schieler[1], S. Semper[1], R. Faramarzahangari[1], M. Döbereiner[2], C. Schneider[1,2], R. Thomä[1]

[1]Technische Universität Ilmenau, Institute of Information Technology, Helmholtzplatz 2, 98693 Ilmenau, Germany
[2]Fraunhofer Institute of Integrated Circuits, Am Wolfsmantel 33, 91058 Erlangen, Germany

## Introduction

- Harmonic retrieval arises in various applications such as **channel estimation, radar localization,** and **direction finding**
- Available solutions are roughly categorized into subspace-based, iterative maximum likelihood, Sparse Signal Recovery and **Machine Learning** algorithms
- We show a model-informed Machine Learning approach using a CNN, capable of estimating the **number of paths** $P$ (or sources) and their respective **delay** $\tau_p$ and **Doppler-shift** $\alpha_p$ according to the signal model

## Signal Model

- We model the wireless propagation channel as a superposition of specular paths via

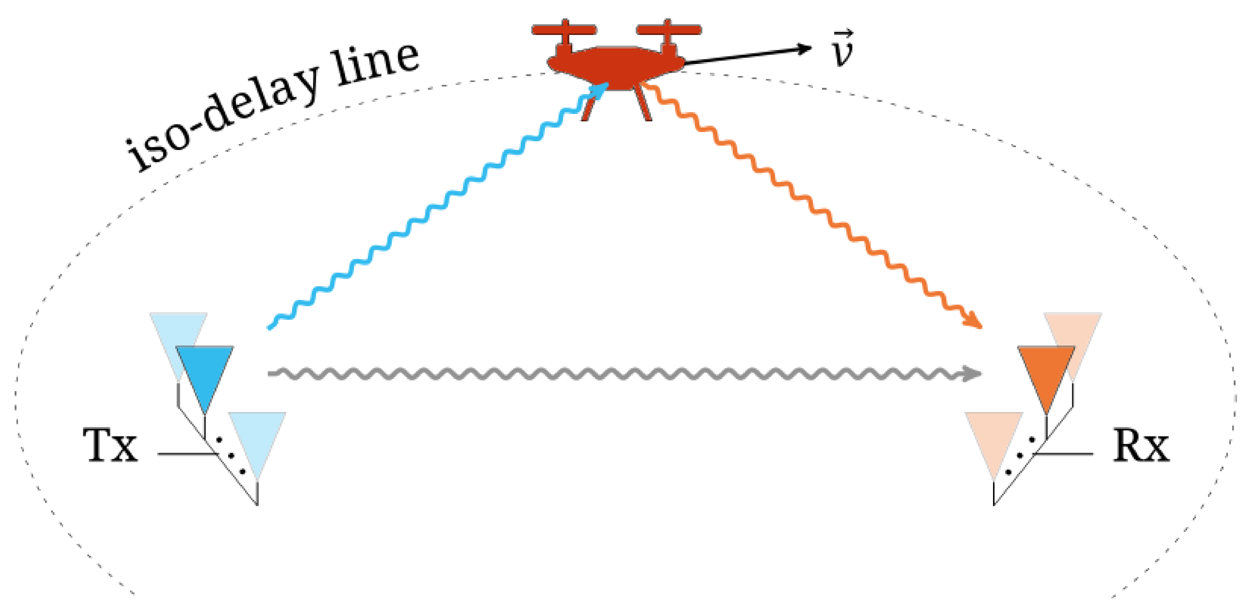
$$\boldsymbol{S}(\boldsymbol{\gamma}, \boldsymbol{\tau}, \boldsymbol{\alpha}) = \sum_{p=1}^{P} \gamma_p \cdot \boldsymbol{S}(\tau_p) \otimes \boldsymbol{S}(\alpha_p) \quad \in \mathbb{C}^{N_f \times N_t}$$

- We add AWGN, denoted by $\boldsymbol{N}$, and obtain the noisy channel measurement $\boldsymbol{Y}$ in frequency and time

$$\boldsymbol{Y} = \boldsymbol{S}(\boldsymbol{\gamma}, \boldsymbol{\tau}, \boldsymbol{\alpha}) + \boldsymbol{N} \quad \in \mathbb{C}^{N_f \times N_t}$$

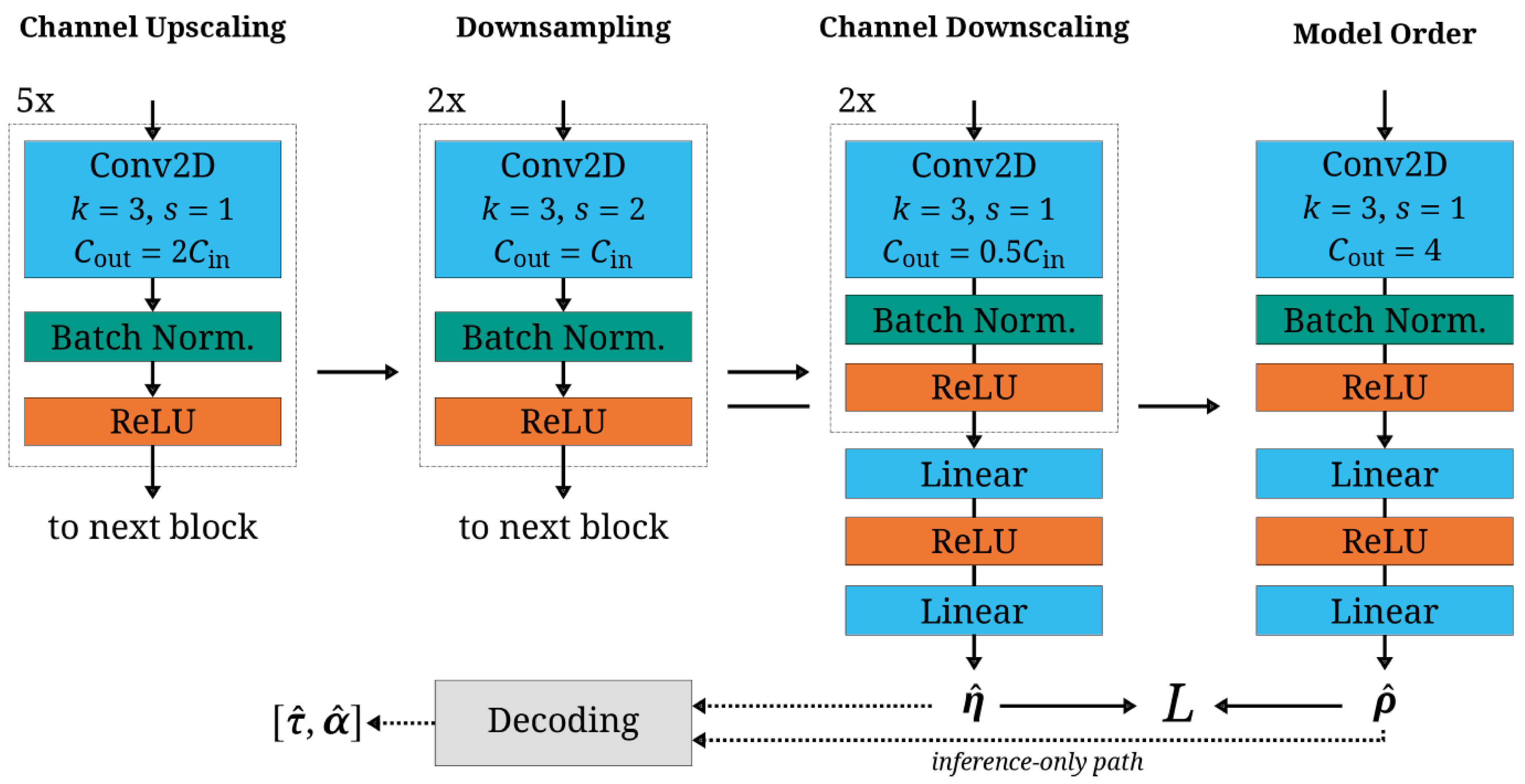
- The CNN is trained via supervised learning with synthetic data generated from the signal model as input and a grid-free encoding of the signal parameters $[\boldsymbol{\tau}, \boldsymbol{\alpha}]$ as labels

## Propagation Model




- Consider a scenario with a single-antenna Tx and Rx (SISO), or a single-link subset of a MIMO system
- The channel measurement $\boldsymbol{Y}$ contains an unknown number $P$ of specular paths and AWGN noise
- Each specular path is characterized by its delay $\tau_p$ and Doppler-shift $\alpha_p$
- The task at the Rx is to estimate the parameters $[\tau_p, \alpha_p]$ and the number of paths $P$ from the noisy measurement $\boldsymbol{Y}$

## Network Architecture



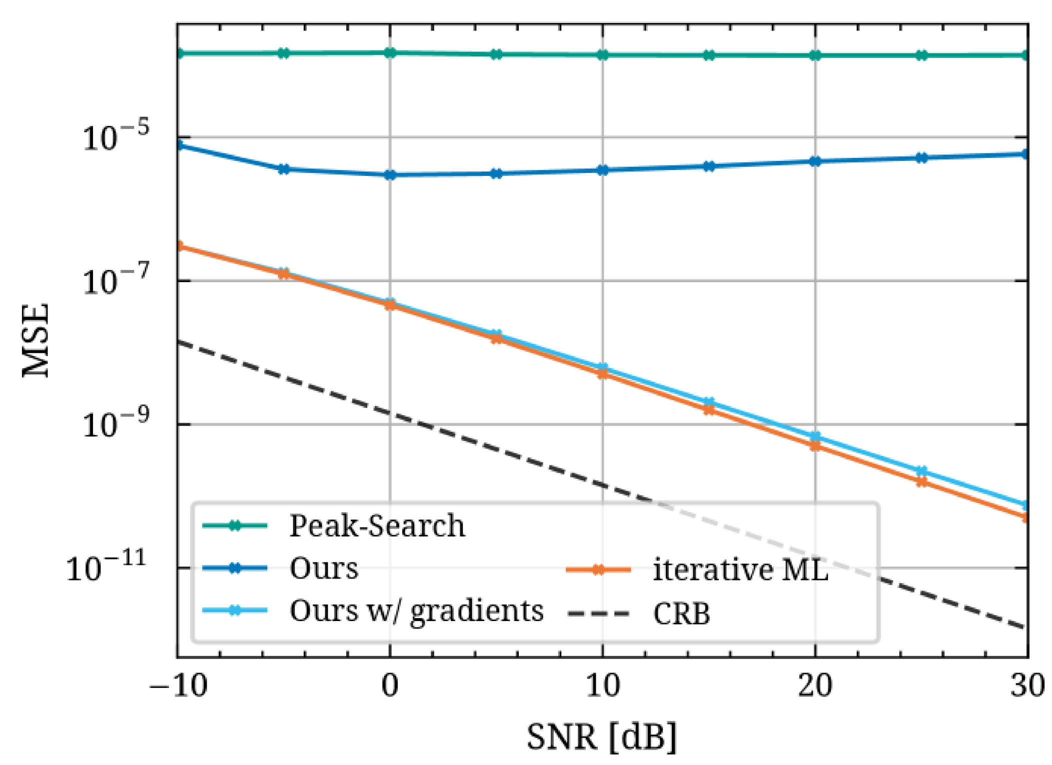

## Synthetic Datasets

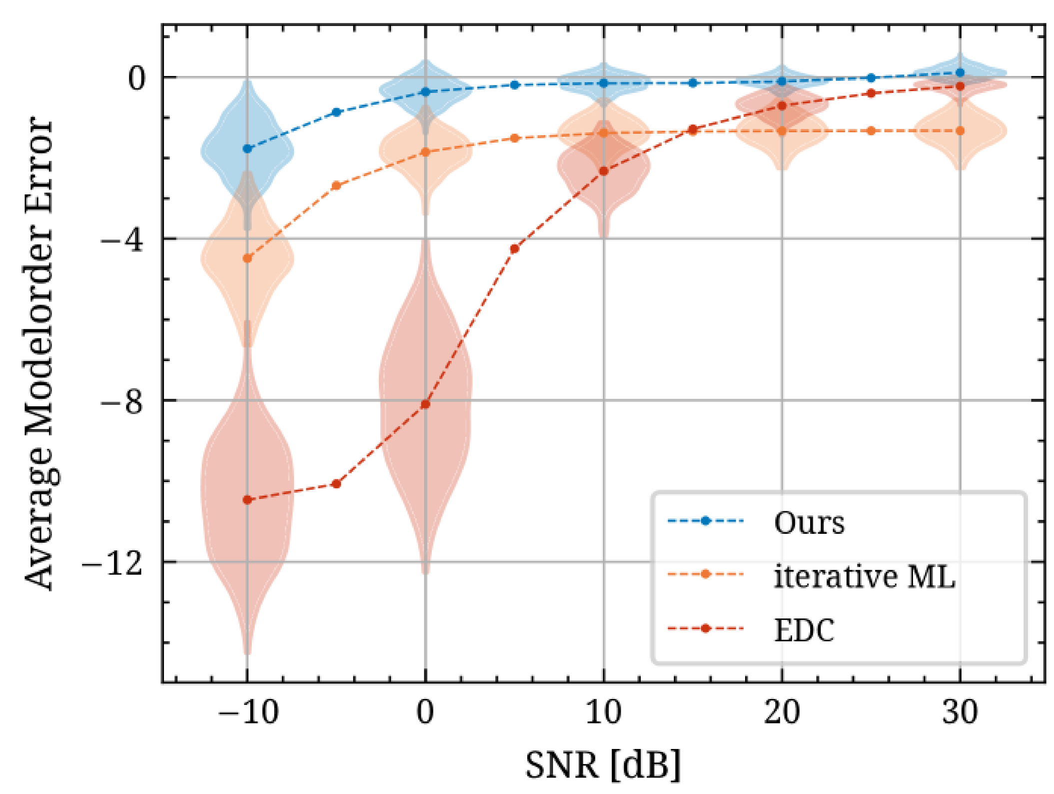
| Name | Value |
|---|---|
| **Datasets** | |
| Distribution $\tau_p$, $\alpha_p$ | $\mathfrak{U}_{[0,1]}$ |
| Magnitudes | $\mathfrak{U}_{[0.001,1]}$ |
| Phases | $\mathfrak{U}_{[0,2\pi]}$ |
| SNR | 0 dB to 50 dB |
| Number of Paths | $\mathfrak{U}_{[1,20]}$ |
| Trainingset Size | $400 \times 10^3$ |
| Validationset Size | 1000 |
| Testset Size | 4000 |
| **Training** | |
| Optimizer | Adam |
| Mini-Batchsize | 32 |
| Epochs | 20 |
| Trainable Parameters | $25 \times 10^6$ for $N_f = N_t = 64$ |

## Results and Outlook

### Results

- Compared to a conventional Peak-Search, our approach provides a (roughly) **tenfold** accuracy increase
- When using it to initialize a second-order gradient algorithm, our approach achieves similar results as an iterative Maximum Likelihood (ML) estimator
- Our approach provides the **best model-order estimates**, consistently outperforming conventional approaches, i.e., the Efficient Detection Criterion (EDC)
- The combined approach (Ours w/ gradients) requires ~60 ms, while the iterative ML requires almost ~10 s on average (on an identical host system), hinting at a **significant advantage in terms of computational complexity**




### Outlook

- The reason for the misaligned MSE results at higher SNRs must be determined
- An Ablation study of the network architecture is required to further reduce the number of trainable parameters
- Validating our approach on real-world measurement data can provide further insights, e.g., about the significance of the model-mismatch between the synthetic and measured data

BLOG

DEMO

Supported by the Federal Ministry of Education and Research of Germany and the DFG in projects "Open6GHub" (16KISK015), "KOMSENS-6G" (16KISK125), and HoPaDyn (TH 494/30-1).

TECHNISCHE UNIVERSITÄT ILMENAU

Technische Universität Ilmenau
FG Electronic Measurements and Signal Processing
steffen.schieler@tu-ilmenau.de