Joint Communication and Sensing (JCAS) for 6G Wireless Systems

Keynote Presentation

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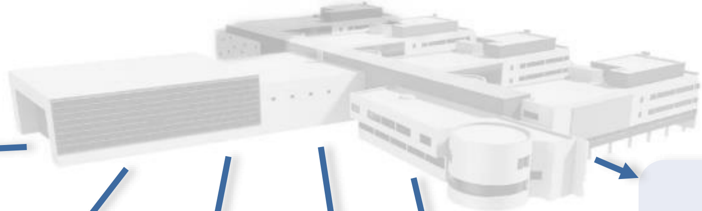
IHP – Leibniz-Institut für innovative Mikroelektronik

Leibniz Institute for high performance microelectronics

About IHP: Profile and strengths of the IHP



Vertical research concept from materials research and technology to circuits and systems

International leadership and visibility

in all research areas

Unique selling point of a **200mm pilot line** for state-of-the-art BiCMOS technologies, operated under **industry-oriented conditions**, **24/7**, for the provision of prototypes and small batches

Qualified technological platform with direct access for science and industry

Approx. **350** employees

Third-party funds (2020, without FMD): € 17. 3 million

Institutional funding (2020): €33.5 million (of which €21 million operating budget, €12.5 million investment funds)

Bridging the gap between basic research and application through close cooperation with universities and industry

Joint Communication and Sensing (JCAS) - Outline

1. Introduction
2. Early Work (Ranging, Localization, …)
3. Potential Applications of JCAS
4. Some Info on JCAS – techniques
5. Selected Experimental Results
6. Conclusions

Introduction: RADAR – Communication – JCAS

JCAS = JC&S = ICAS = JSAC = ...

Differences between communication- and sensing signals

- Sensing signals:
  - High localization and tracking accuracy
  - Low peak-to-average power ratio (PAPR)
  - Long Range operation
- Communication signals:
  - Maximize information carrying capabilities
  - High PAPR (e.g. OFDM)
  - Packet based and modulated (time, frequency and spatial domain)
  - Complex signal structure

Categories of joint communications and sensing (JCAS) systems:

- Radar-centric
- Communication-centric
- Joint design

JCAS – Early Work & State of the Art

- Use of communication systems for ranging such as two-way ranging (TWR)
- Use of communication systems for localization
- Use of communication system for synchronization
- Use of communications system for Line-of-Sight detection

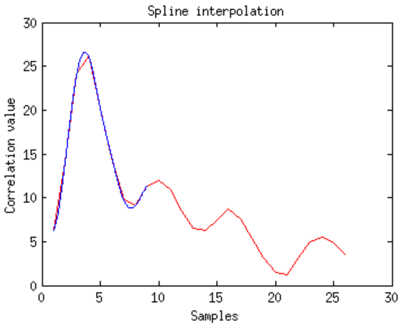
- Ranging (time of flight) ToF: $\Delta x = c * \Delta t$
  - c: speed of light
  - t: time of flight
  - x: distance

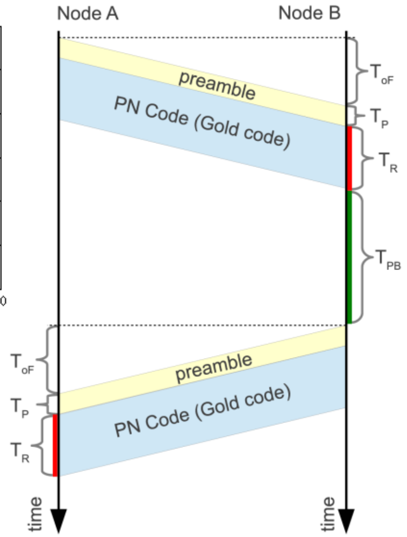
  - Δt: inverse of sampling rate (of ADC) -> range binning

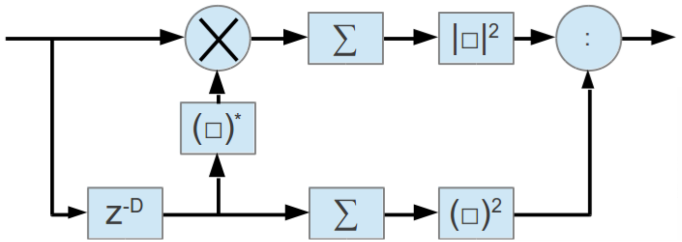
 | |

Two Way Ranging (TWR)

- TWR typically uses PN-Sequences
  - T_{PB} has to be know and stable
  - Time critical tasks and precise time measurement is implemented on FPGA available in the SDR platform
  - Non time critical tasks, e.g. distance estimation from obtained samples, is implemented in software on a host computer
- Localization is achieved by performing TWR with 3 anchor nodes + trilateration
  - TWR is performed with each anchor node in a round robin fashion
  - Using trilateration and the obtained distances, the position of the node is estimated

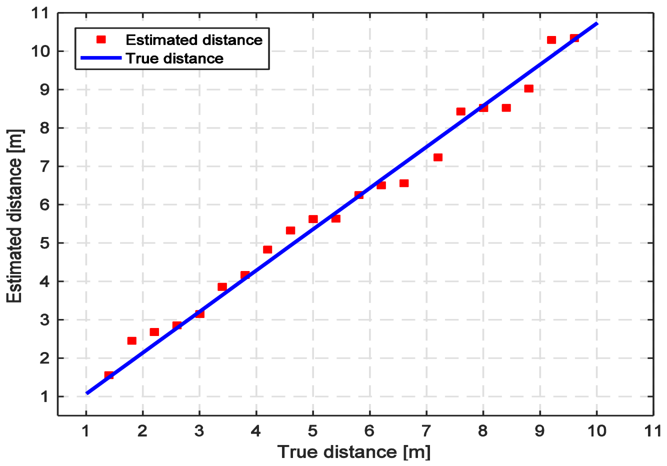


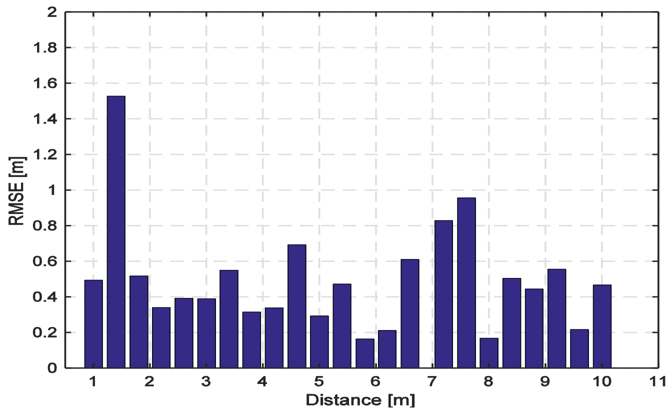




Two Way Ranging – using WiFi @ 5 GHz

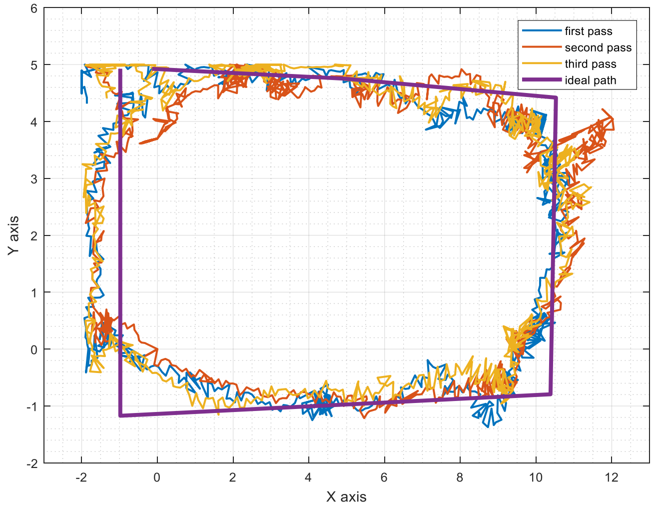
- Ranging tested in a long and narrow hallway
  - Bandwidth, carrier frequency, and modulation: 25 MHz @ 5.75 GHz; BPSK modulation
  - Accuracy of 0.5-1 meter achieved





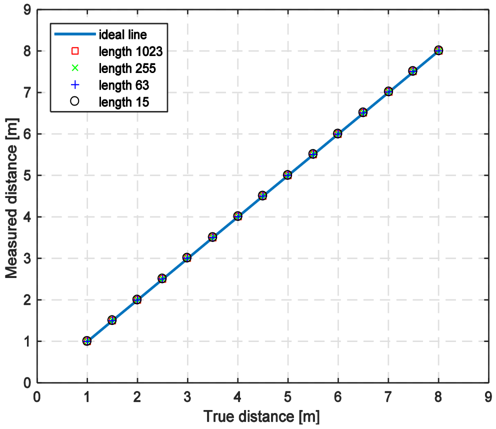
Localization using n-Way Ranging @ 5 GHz

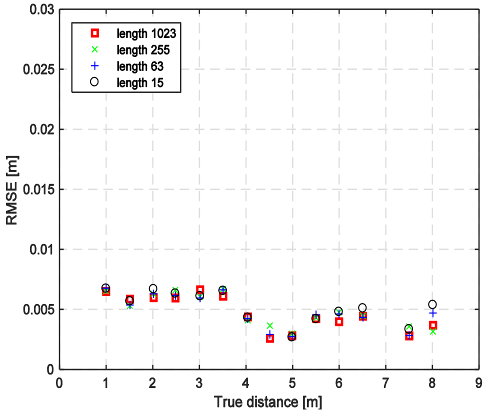
- Positioning area: 20x20 meters
  - 3 anchor nodes
  - Average positioning error 1-2 meters due to low number of anchor nodes

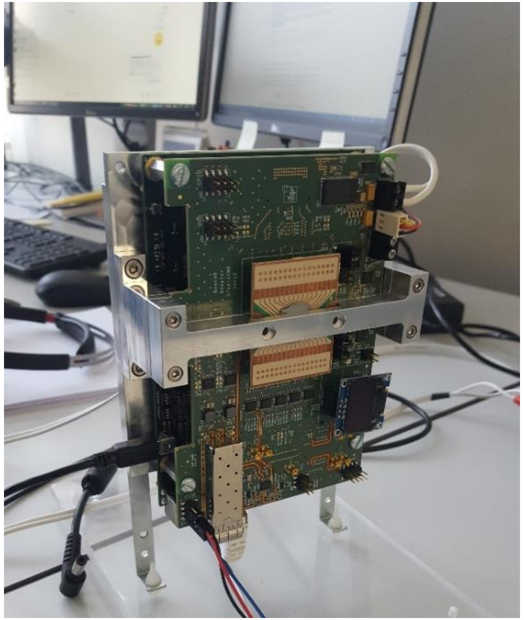


Two Way Ranging @ 60 GHz (ca. 2 GHz Bandwidth)

- IHP-developed ‘DigibackBoard’
  - A system for wireless data transmission in the 60 GHz band
- Analog frontend
  - 60 GHz SiversIMA
- Improved ranging precision – better than 1 centimeter



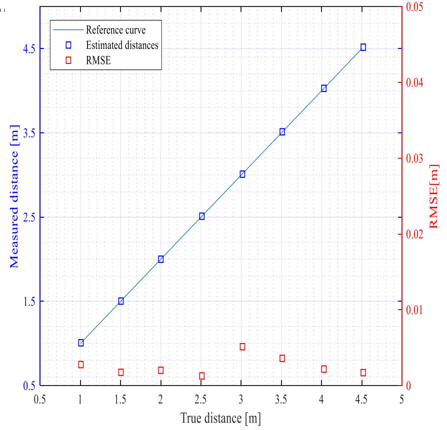


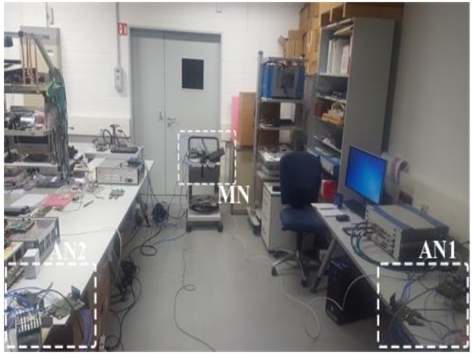


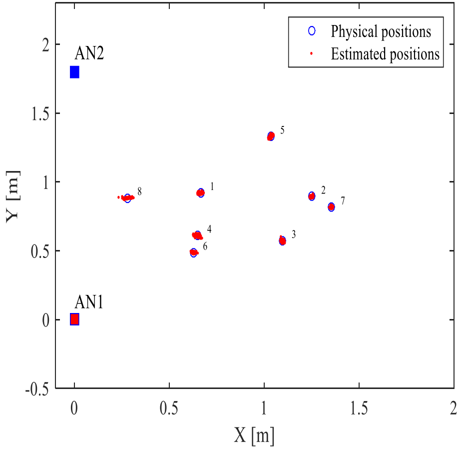
Localization using n-Way Ranging @ 60 GHz

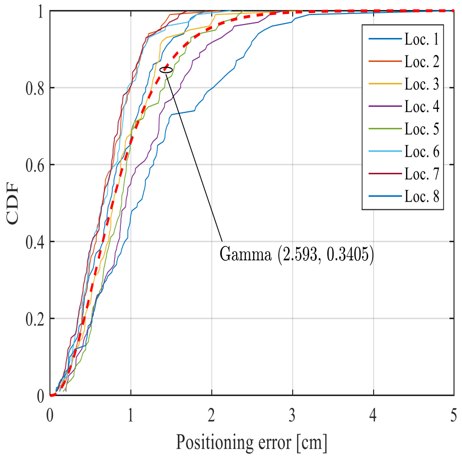
- First ranging experiments at 60 GHz

- Results on the 60GHz localization
  - Setup with two anchor nodes (total 3 digibackBoards)
  - <5cm positioning error in the lab environment









Cramer Rao Lower Bound (CRLB)

$$var(\hat{r}) = \sigma_{\hat{r}}^2 \geq \frac{c^2}{(2\pi B)^2 E_s/N_0}$$

c – speed of light

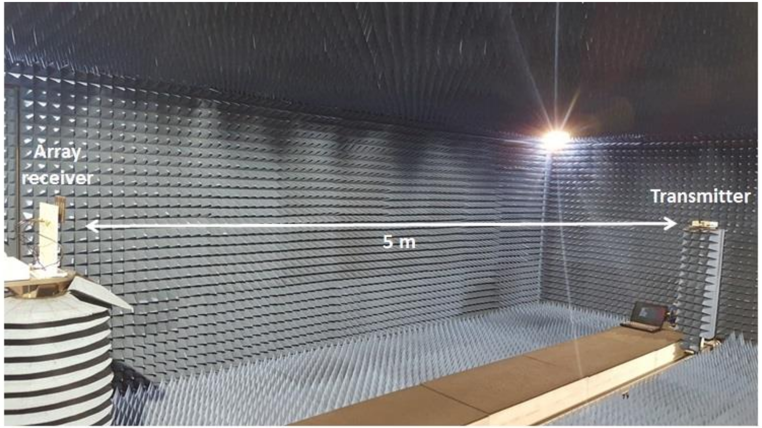
r – distance estimation

B – bandwidth

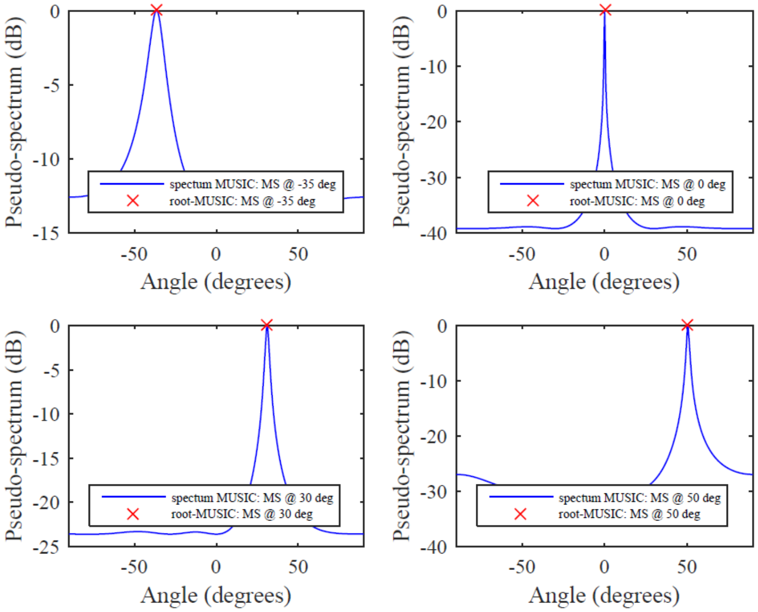
E_s/N_o – signal energy to noise density ratio

-> Large bandwidth and high SNR needed for precise localization

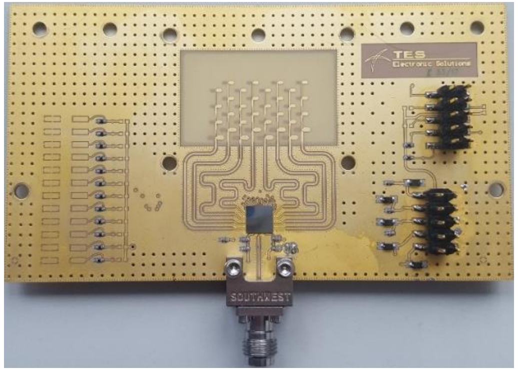
Angle based positioning (1/2)

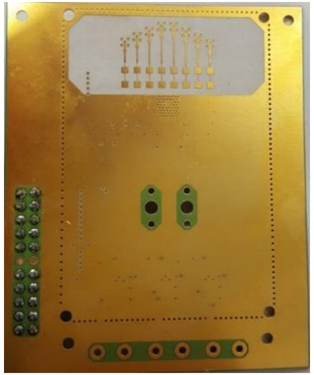


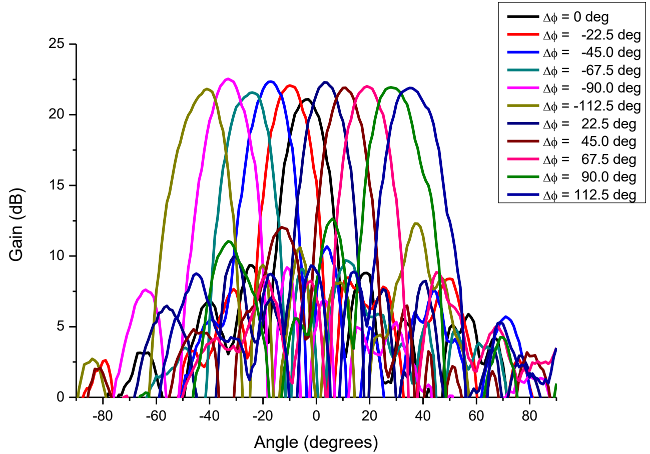
MUSIC (MUltiple SIgnal Classification)

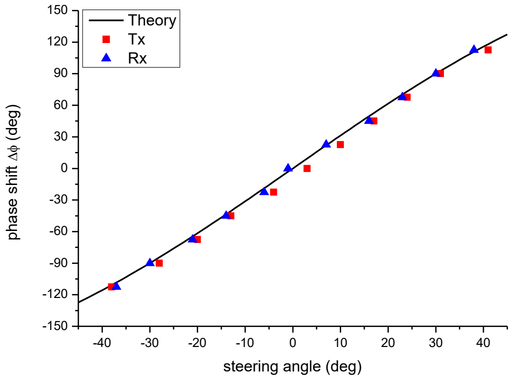


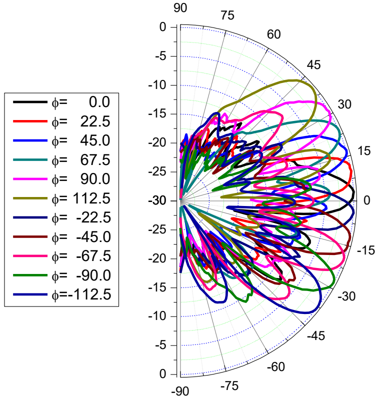
Angle based positioning (2/2)





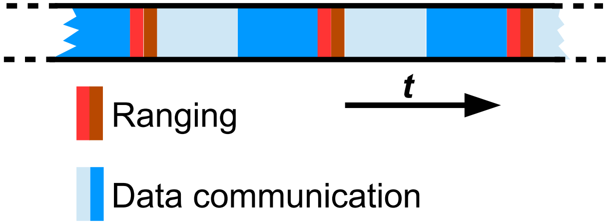


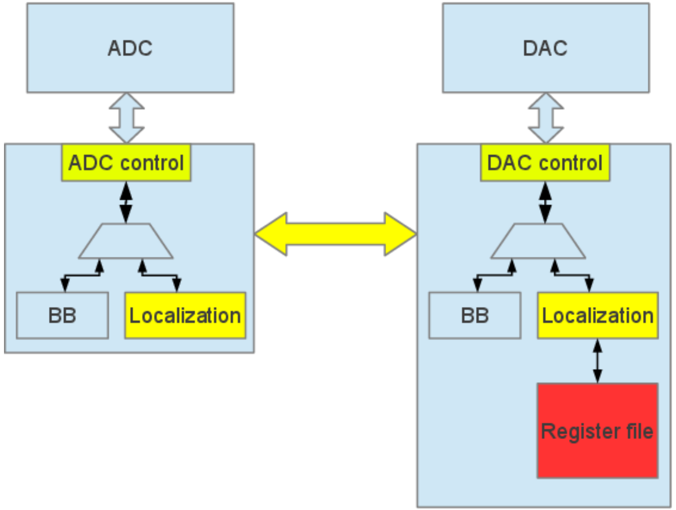




Combined High Speed Data Communication and High Precision Ranging in the 60 GHz Band

- Main focus: seamless data transmission and ranging
- Integration of data transmission and ranging performed on 60 GHz system
  - Available standalone cores for data transmission and ranging
- Time division multiplexing (TDM) used to multiplex data transmission and ranging
  - MAC schedules the time slots





Hardware/Technology Developments Supporting JCAS

- With ***higher frequencies*** (mmWave, sub-THz) RF becomes similar to LIDAR (***pencil beams***)
- ***High angular resolution*** of beams possible due to large number of elements
- Very ***high bandwidth*** allows good spatial resolution (Cramer-Rao lower bound)
- ***High sampling rates*** of Baseband signals reduce the issue of range-binning (high distance resolution possible)
- ***Full duplex***/TDD – monostatic/bistatic (with full duplex transceivers a combination of monostatic and bistatic radar is possible)
- Systems with ***high quality broadband receivers*** allow for ***passive sensing*** functions (receiver only, backscatter receivers).

Applications

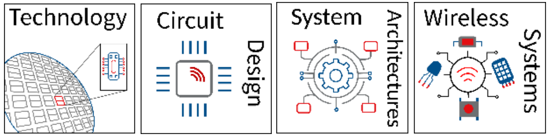
- Room reconstruction (E. Sedunova)
- “Mona Lisa Scenario” - Intrusion / Anomaly detection (L. Wimmer)
- Gesture recognition (Y. Zhao)
- Network Optimization (P. Geranmayeh)

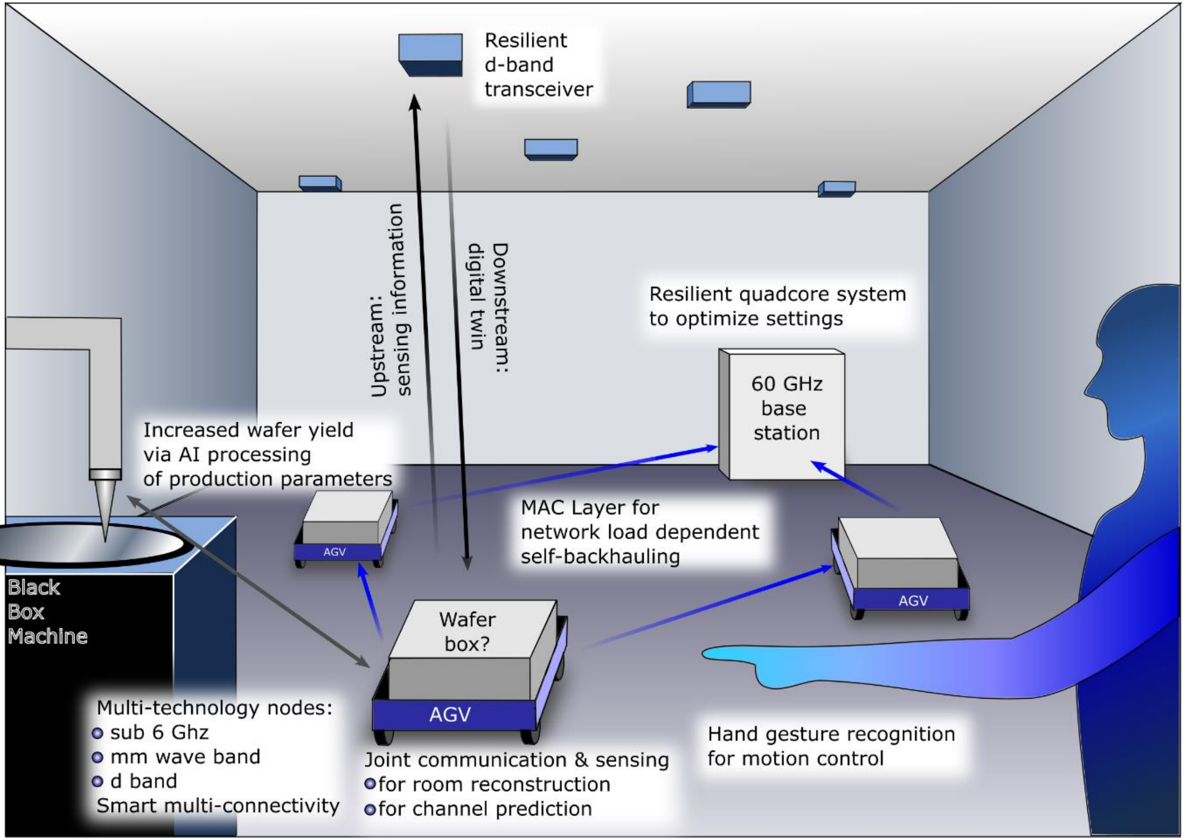
- … also:
  - Autonomous driving (Simultaneous Detection and Mapping – SLAM)
  - Detection of radio transmitters
  - Industrial automation – navigation, proximity/status detection
  - Security and safety in various sectors
  - …

Open 6G Hub: Industrial Application Scenario

A resilient communication & sensing system with multi-technology nodes

- Self-awareness & awareness of local surrounding
- Dynamic nodes & dynamic environment
- Resilience by Design in all layers

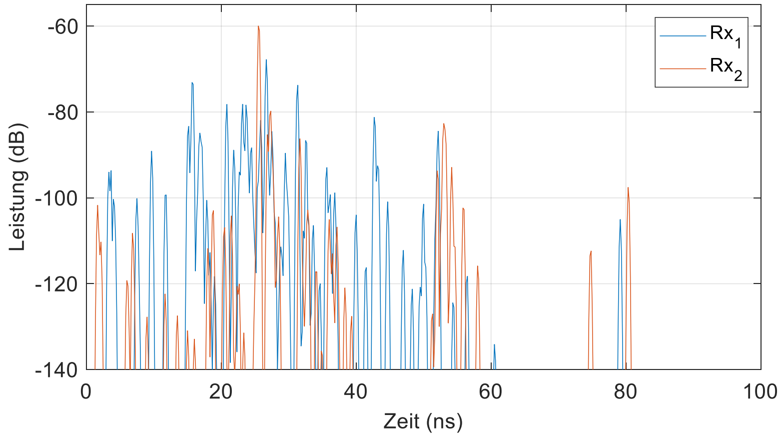




Funded by BMBF

L. Wimmer

Room reconstruction in 3D

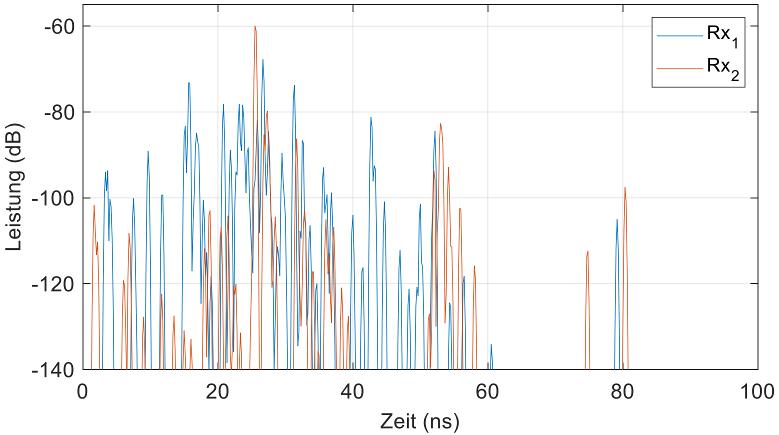


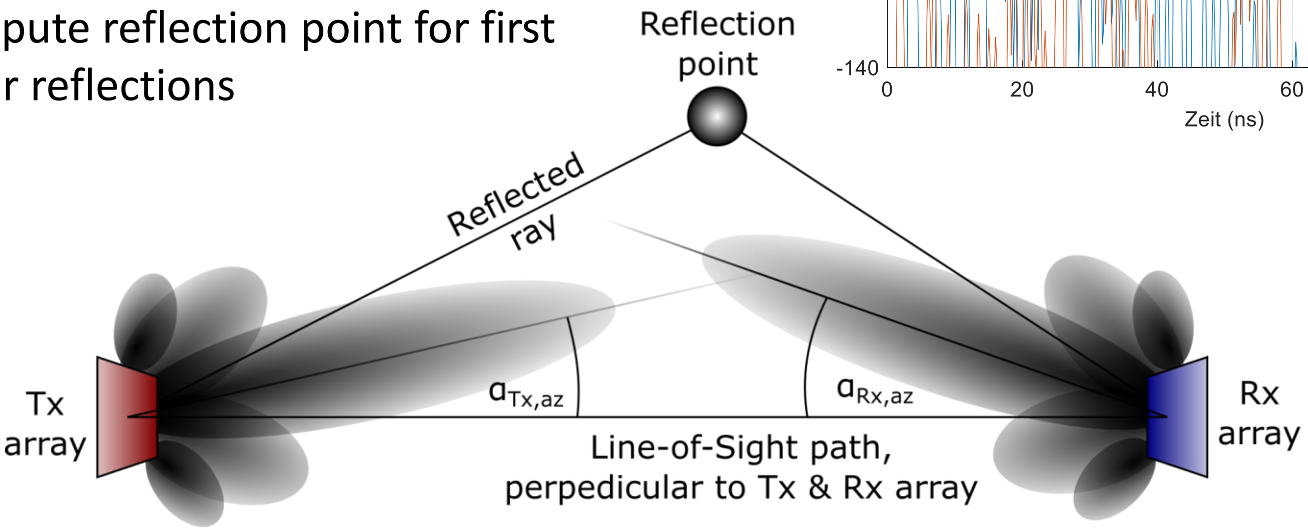
- Raytracing simulation (here: office room) to generate channel impulse responses.
- Simulation for comparison with reconstruction results.

L. Wimmer

Room reconstruction in 3D: How to do it?

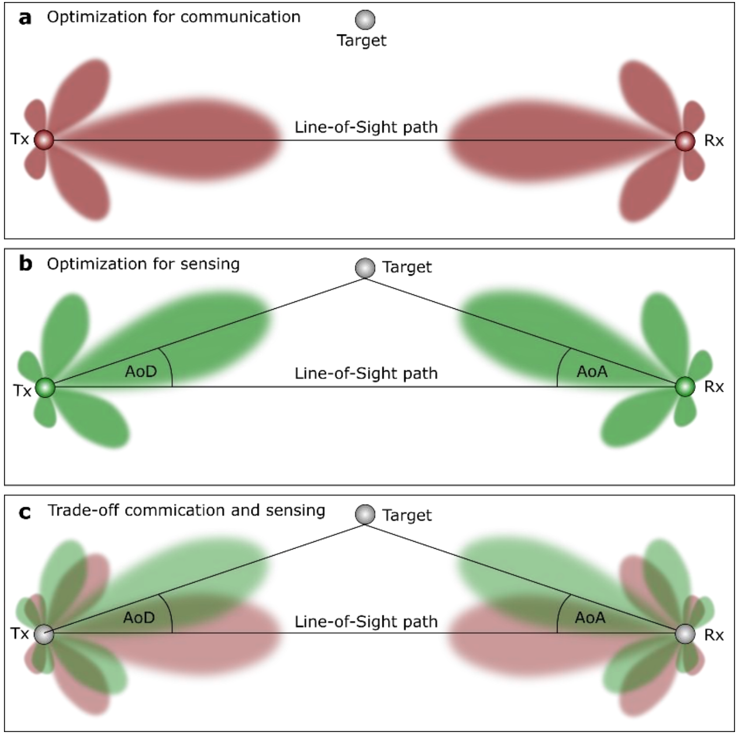
- Scan room in azimuth and elevation direction
- Classify multipath components as
  - Line of Sight
  - First reflection
  - Higher order reflection
- Compute reflection point for first order reflections





L. Wimmer

Physical Limitations of Joint Communication & Sensing



Trade-off communication and sensing on physical layer:

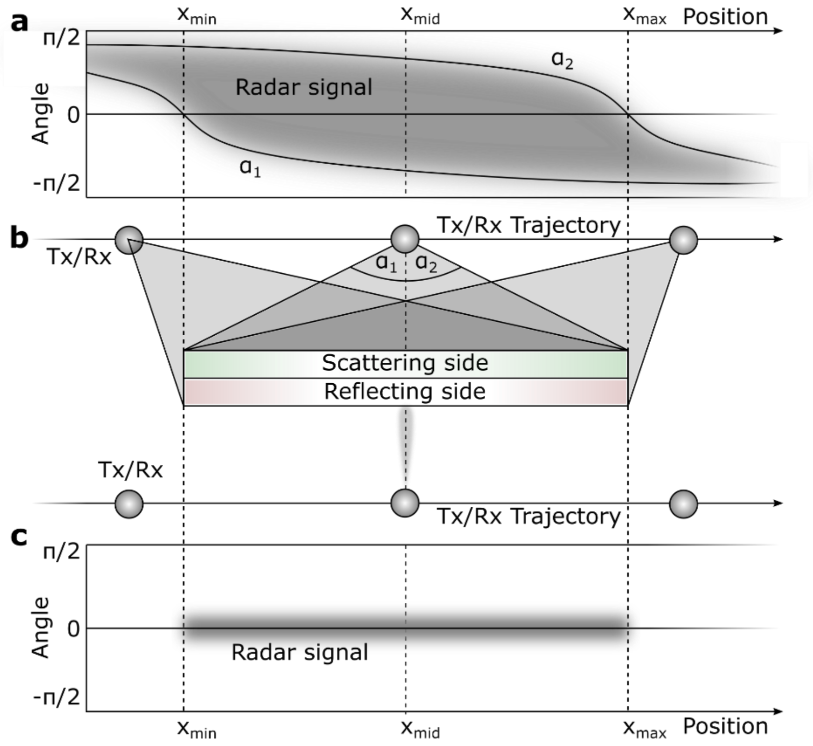
Both cannot be optimized simultaneously

- Option: Adaptive system
- Option: Time-division duplexing
- Option: Sensing beam & communication beam separately

- **Monostanic radar:** power used for sensing or communication
- **Bistatic radar:** multipath components as part of the channel impulse response appears energy efficient. Consider system view

L. Wimmer

Surface & material characterization using JCAS



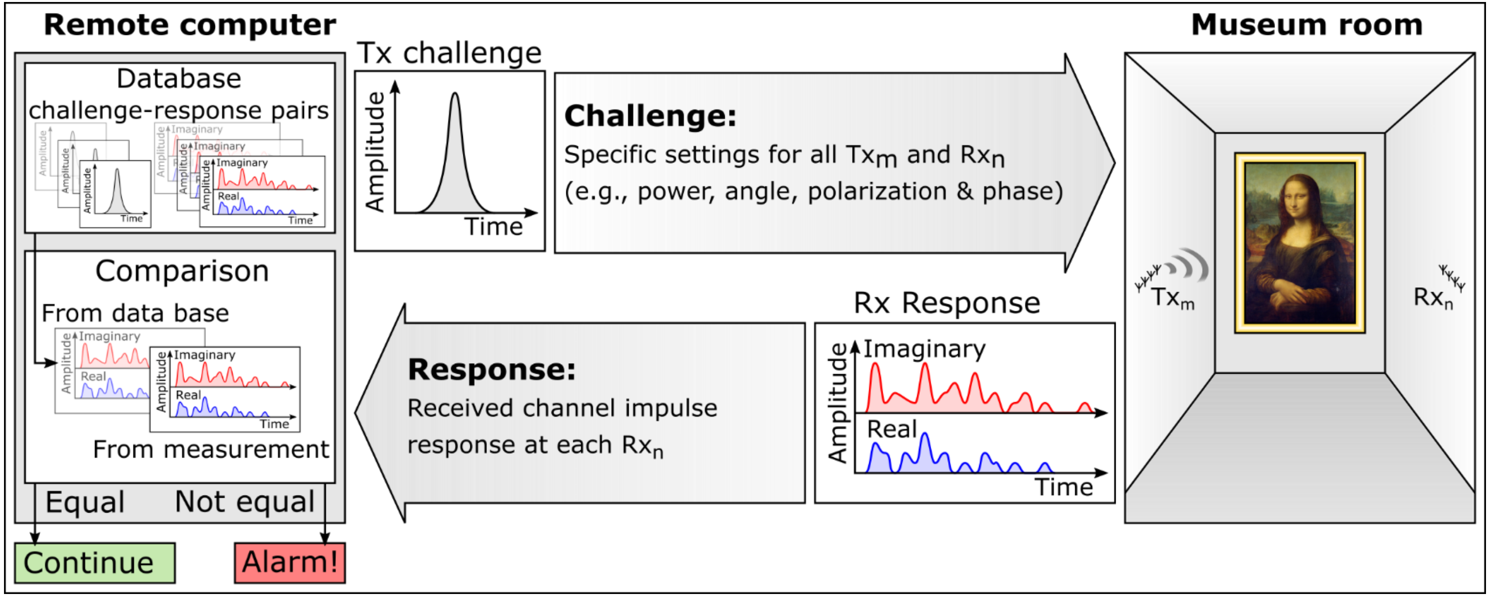
Scattering vs Reflection:

- **Scattering**: scattered signal independent from incident angle
  Reconstruction of scattering areas
- **Reflection:** incident angle = reflecting angle
  Reconstruction of reflection points
- **Mixed case:** „angle dependent scattering“

Object recognition & material characterization improved by dynamic Tx-Rx constellation

L. Wimmer

Mona-Lisa Scenario: Physical Unclonable Functions (PUF)



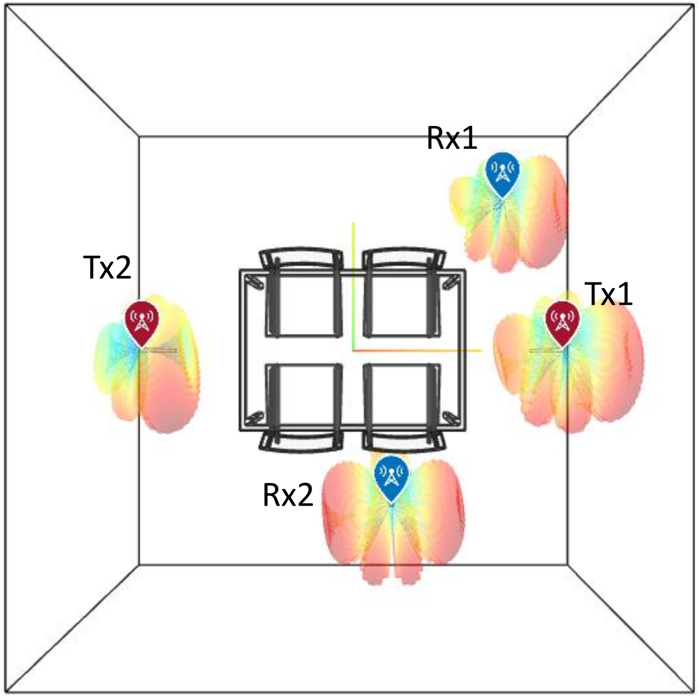
Superposition principle of electromagnetic waves: $R(C_1 + C_2) = R(C_1) + R(C_2)$

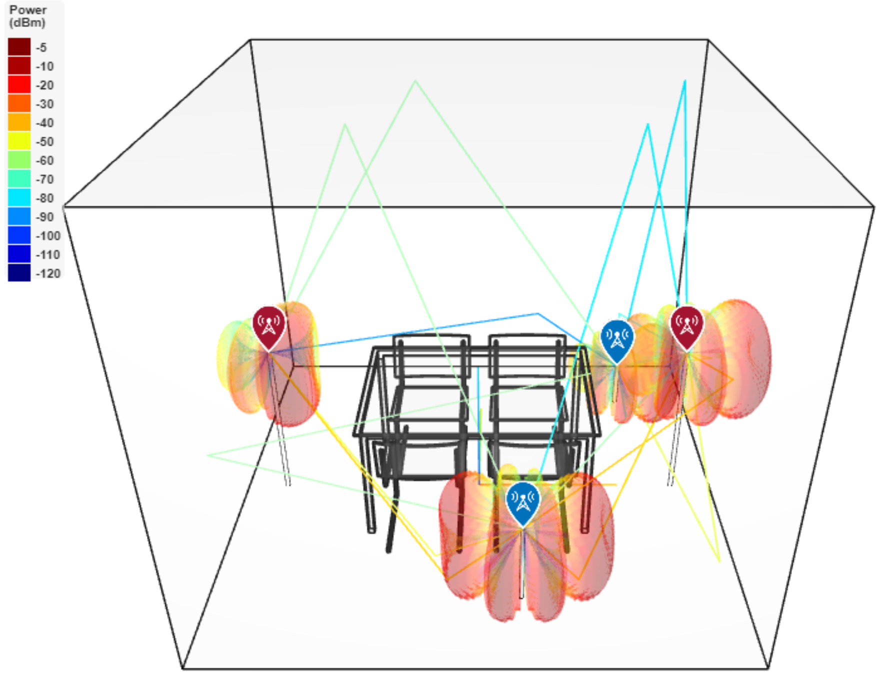
IB 1627 -01 EP (*application submitted*): Active targets alter the reflection characteristics of the room depending on the challenge characteristics

U. Rührmair, L. Wimmer

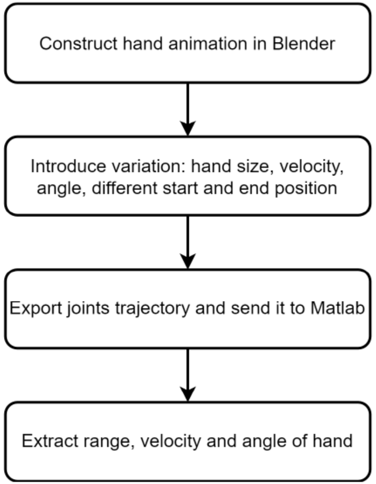
Optimisation Beam Patterns for Minimized Interference

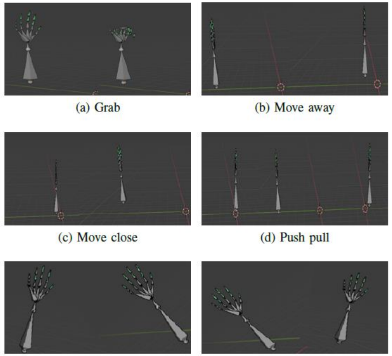
Adjustment of beam patterns for all TX- and RX- beams such that SINR and total network capacity are maximized



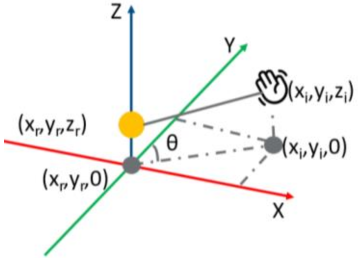


Hand Gesture Recognition - Synthetic Data Generator





(a) Grab (b) Move away (c) Move close (d) Push pull (e) To left (f) To right



Algorithm 2: Synthetic feature extraction.

Data: Trajectories: Target_pos
Result: Range, velocity and angle feature vectors
initialisation;
for $frame\_counter = 1, 2, \ldots, 32$ **do**
  if $frame\_counter == 1$ **then**
    $v(1) = 0;$
    $d(frame\_counter)$ = Euclidean distance(Target_pos($frame\_counter$,:), Rad_pos);
    $\theta(frame\_counter) = \frac{180}{\pi} \arctan\left(\frac{\text{Target\_pos}(frame\_counter,1)}{\text{Target\_pos}(frame\_counter,2)}\right).;$
  else
    $d(frame\_counter)$ = Euclidean distance(Target_pos($frame\_counter$,:), Rad_pos);
    $v(frame\_counter) = \frac{d(frame\_counter) - d(frame\_counter-1)}{T_m};$
    $\theta(frame\_counter) = \frac{180}{\pi} \arctan\left(\frac{\text{Target\_pos}(frame\_counter,1)}{\text{Target\_pos}(frame\_counter,2)}\right).;$
  end
end

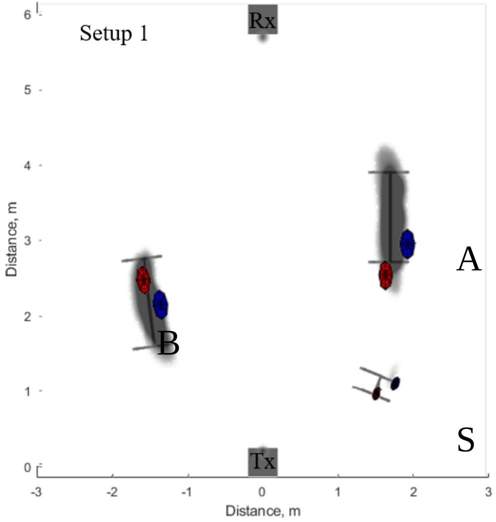
Challenges for Joining Communications and Sensing

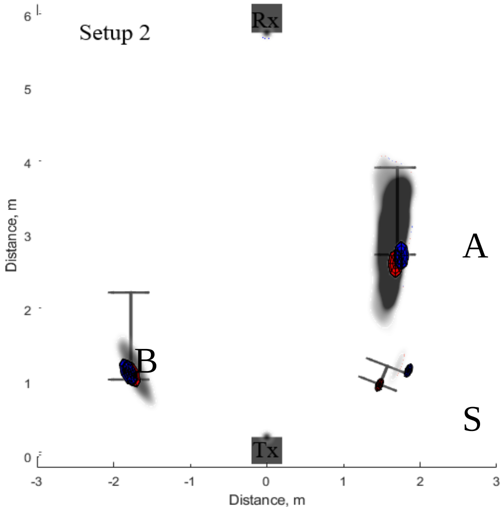
- Sampling rate limitations -> range binning
- Angular resolution of beams -> precision of object position
- Change / calibration / stability of antenna pattern
- Processing requirements / complexity / deployment of AI / power dissipation
- Availability of channel sounding data
  (traditional, statistical channel models are not suitable)
- Legal issues as well as security and privacy

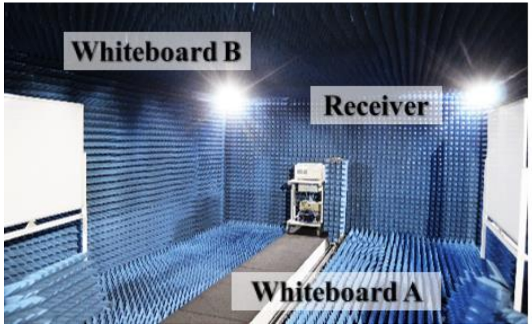
Some Results of Experimental Work

- Room reconstruction (E. Sedunova, L. Wimmer)
- Gesture recognition (Y. Zhao)

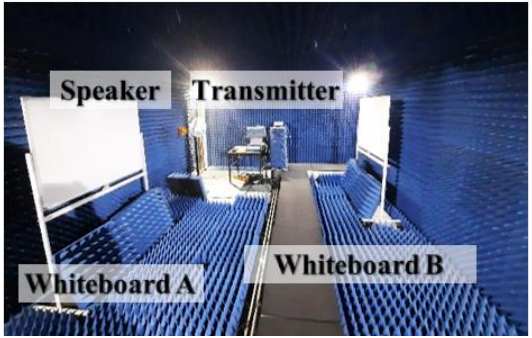
Room Reconstruction Results from Experimental Data







Setup 1

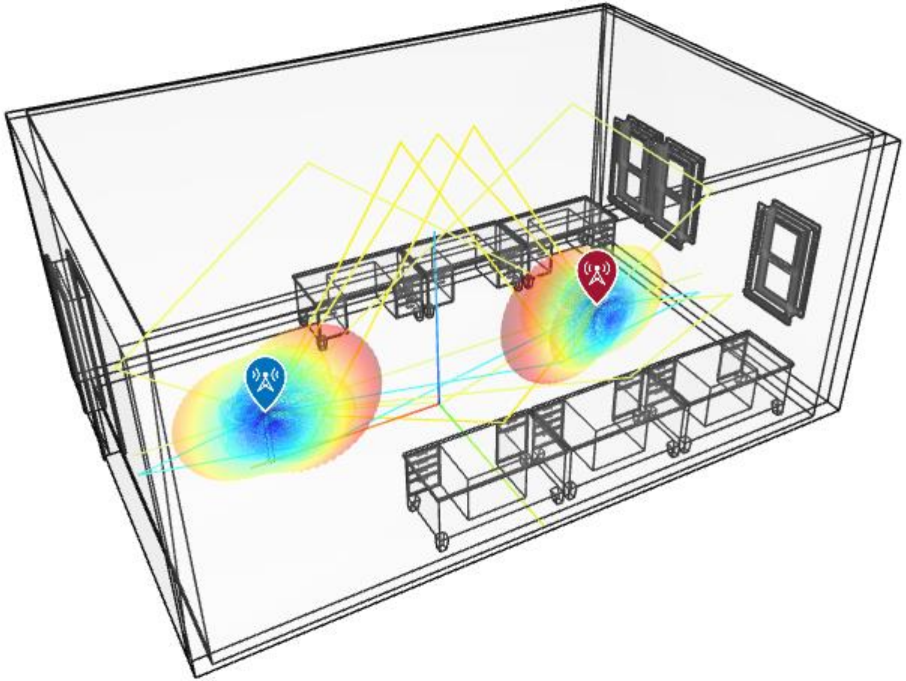


Setup 2

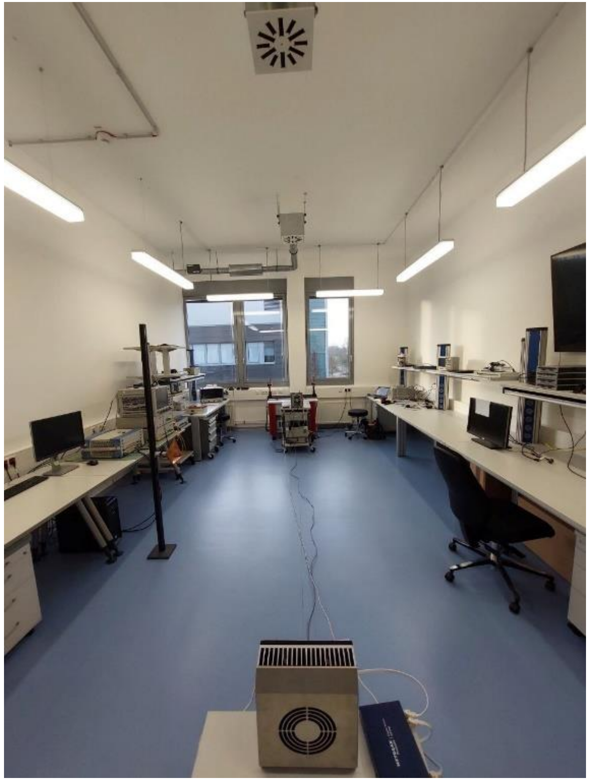
- The figures show the results of different methods based on the two measurements setups in an anechoic chamber.
- The red and blue ellipses represent the power map and enhanced method [1]
- The area represented by shadows are based on the approach that is inspired by bistatic radars.

[1] E. Sedunova, N. Maletic, L. Wimmer, D. Cvetkovski, E. Grass, and B. Lankl, “Utilizing Beamsteering at Millimeter Waves for Indoor Object and Room Geometry Detection,”

Simulation using Ray-Tracing Channel Model



Simplified real lab room environment built using Autodesk Revit



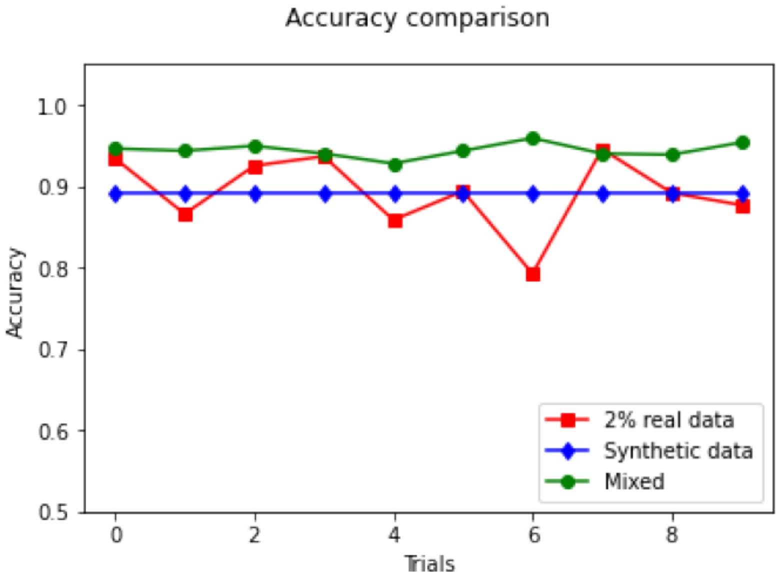
Measurements in the lab

Gesture Recognition – Low Complexity Approach

- Classifier
  - SVM with linear kernel
- Scenario I
  - A random selection of 2% of the real data as the training set and the rest of the real data are used as the test set.
- Scenario II
  - Training set: Synthetic dataset; Test set: real dataset
- Scenario III
  - 2% of the real data + synthetic data set as the training set
  - The remaining 98% of the real data set as the test set.

Gesture Recognition – Experimental Results for Low Complexity Approach

- Accuracy of test set



Scenarios	Average Accuracy	Standard Deviation
Scenario I: 2% real data	89.21%	4.43%
Scenario II: Synthetic data	89.13%	0.00%
Scenario III: Mixed	94.43%	0.82%

Some Learnings

1. Reconstructing basic features of a room is possible using angular resolved CIRs
2. The varying antenna patterns of beamsteering systems represent a significant additional challenge for processing the measurement data
3. Wide beams and complex antenna patterns can be compensated using deconvolution, if the angular step-size of the measured CIRs is small
4. The unavailabilty of suitable experimental channel sounding data is a significant obstacle for developing efficient algorithms
5. The unavailability of objective quality measures for the results of room reconstruction etc. is a major problem of optimising the algorithms
6. As yet, it is unclear if classical signal processing or AI techniques are best for processing the obtained CIRs (in terms of complexity and quality of results)

6G-Technologies and their Potential (Very Personal!)

- Reconfigurable Intelligent Surfaces (RIS, IRS)	(0)
- (sub-)THz Communications	(+)
- openRAN / disaggregated Architectures	(0)
- Joint Communication and Sensing (JCAS)	(++)
- Cell-free communication network	(+)
- Joint Access and Transport	(+)
- Quantum Communications (Security)	(+)
- Post-Shannon Communications (identification channel)	(0)
- ML and AI for PHY-Layer processing	(0)
- ML and AI in Network Control and Optimisation (includ. dig. Twin)	(++)
- Visible Light Communications / Free space optical comms.	(0)
- Orbital Angular Momentum Multiplexing (OAM)	(+)
- Backscatter Communications/sensing (using ambient RF signals)	(+)

Future Work & Acknowledgments

- Room Reconstruction using deconvolution of the power maps for varying antenna patterns (as common for beamforming nodes)
- Based on the angular resolved CIRs, establishing a digital twin of a room using signal processing AND AI-methods
- Based on lateral movement of nodes and obtained CIRs, establishing a digital twin of a room using AI-methods
- Material characterisation based on the obtained CIRs
- Sensor fusion and collaborative sensing
- Investigation of potential security / privacy issues coming from JCAS (and mitigation techniques)

Acknowledgements:

1) *The authors acknowledge the financial support by the Federal Ministry of Education and Research of Germany in the project "Open6GHub" (grant number: 16KISK009).*
2) *Parts of this work is supported by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) within the AgileHyBeams project № 673121)*

Thank you for your attention!

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