Practical Joint Communication and Sensing at Millimeter-Wave Frequencies

One6G - Open Lecture 3 on 6G testbed/simulation
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Developing the Science of Networks

Motivation

- Joint Communication and Sensing: more and more use cases depend on localization and sensing information
  - Lots of prior work over the past two decades, but only *now* the hardware capabilities are becoming sufficient for JCAS in more general settings

Smart factories, digital twins

Augmented/virtual reality, telepresence

Autonomous vehicles

- Experimental research is highly important
  - Actual performance depends critically on factors that are hard to model: real-world channel environment, hardware imperfections, calibration

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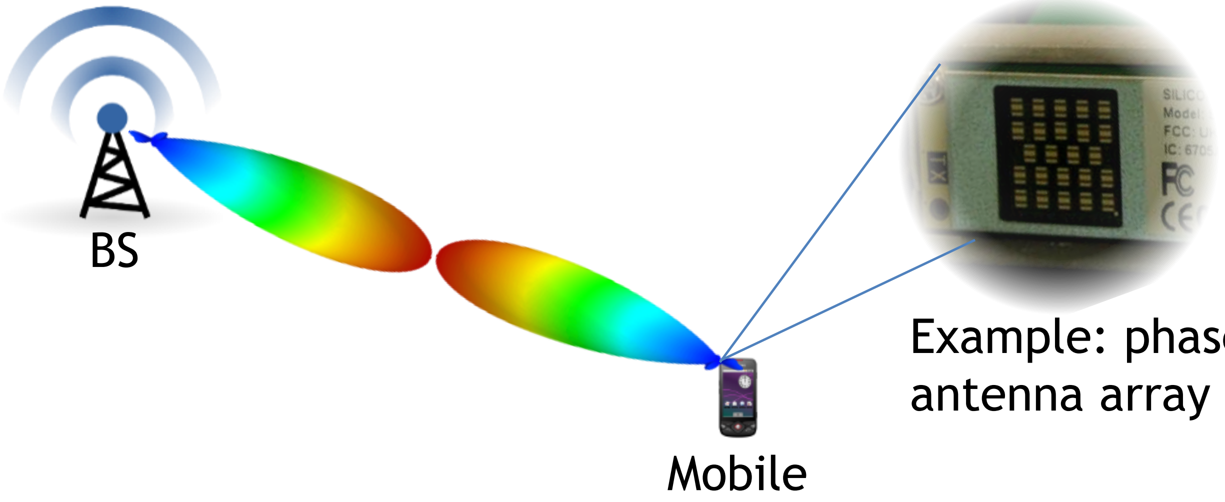
Millimeter-Wave (mmWave) Systems

- mmWave frequencies are particularly interesting
  - Many GHz of spectrum available for multi-Gbit/s per user data rates
  - Very high levels of spatial reuse through highly directional antennas
- The same properties also enable highly accurate localization and sensing
- But what real-world accuracy can be achieve with inexpensive off-the-shelf devices?



Example: phased antenna array

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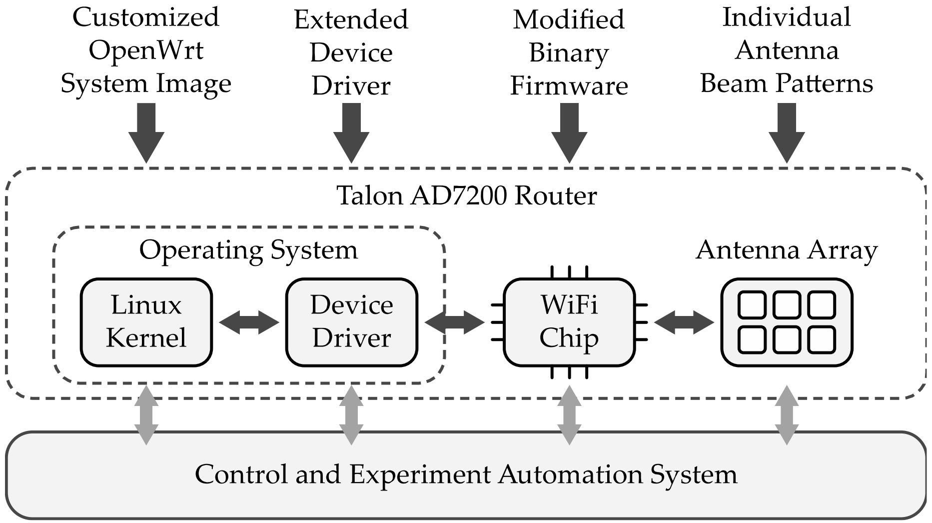
Off-the-Shelf Devices as Research Platform

- Research using off-the-shelf devices is highly important
- IEEE 802.11ad 60GHz devices: TP-Link Talon AD7200
- Ported OpenWRT to the routers
  - Custom embedded Linux OS (open source)
  - Extended 802.11ad Linux drivers
- nexmon framework for binary firmware patching
  - Custom extensions to the firmware
  - Modify beam training, beam forming, …
  - CSI extraction



Joint work with TU Darmstadt and University of Brescia
https://github.com/seemoo-lab/talon-tools
https://github.com/IMDEANetworksWNG/MultiLoc

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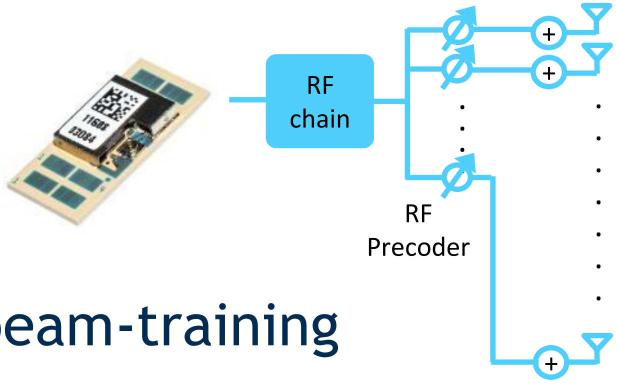
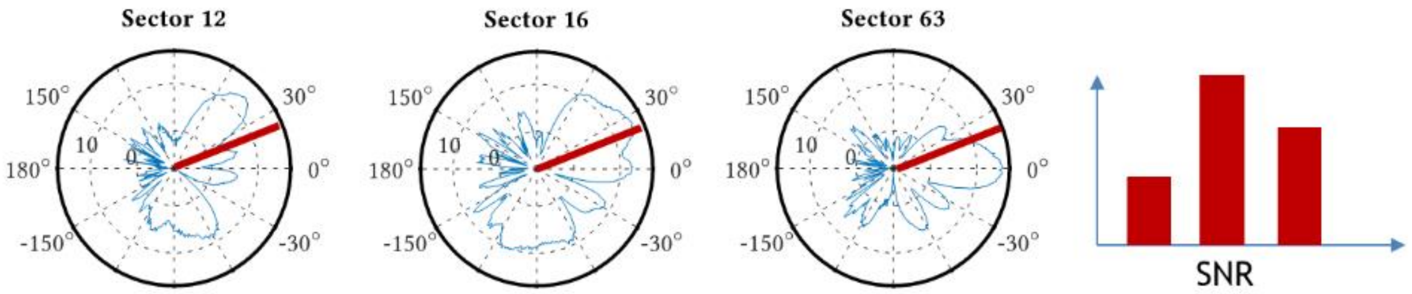
Fully Passive Angle-based mmWave Localization

- mmWave phased array with a single RF chain
  → approaches like MUSIC, etc. do not work directly

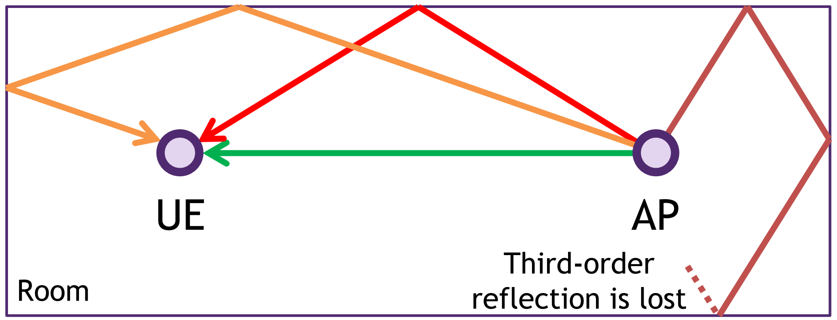


- Extract angle of arrival/departure information from the beam-training
  - **NO additional overhead for the location functionality**
  - Use compressive estimation to get accurate angles from coarse beam patterns
  - Probe subset of antenna patterns, record signal strength



Determine most likely angle from the sequence of SNR values

- Sparse multi-path channel
  - Trivial to locate a receiver using estimated angles (*known transmitter location and room geometry*)



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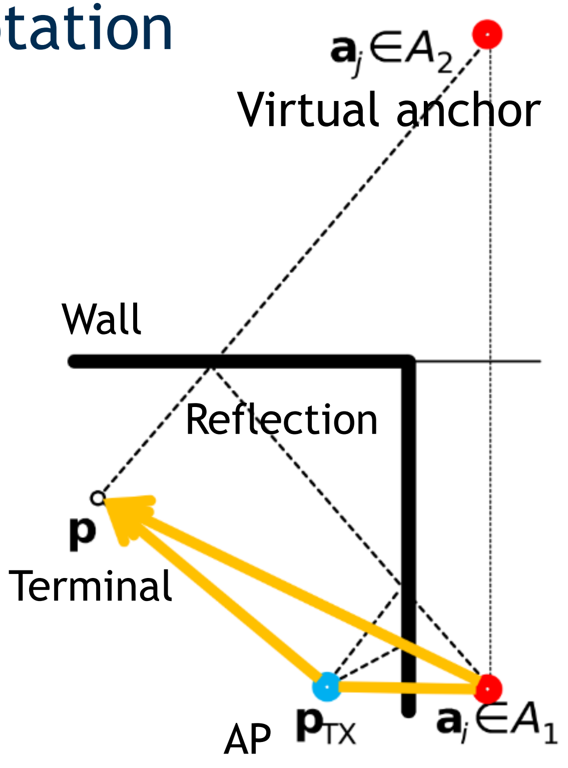
Zero-knowledge mm-wave Location System

- Unknown access point (AP) locations, unknown floor plan
- Location system based only on angle difference information
  - Using angle difference of arrival makes the problem rotation independent
- Several triangulation steps
  - Reflections are transformed into vectors departing from the position of the virtual anchor
  - Iterate over unknown position of terminal and unknown positions of (virtual) anchors
  - ***Needs user mobility over time***
- Learn: make use of history of locations for refinement



Joan Palacios et al., "JADE: Zero-knowledge device localization and environment mapping for millimeter wave systems", *IEEE Infocom*, May 2017

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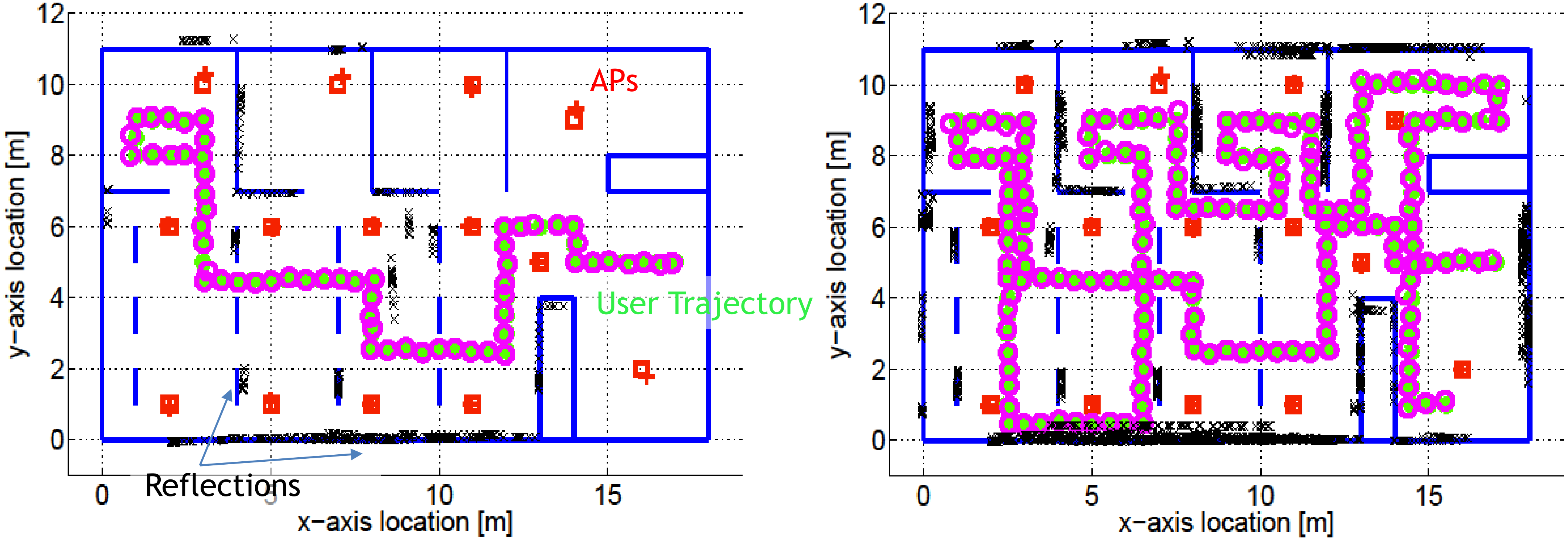
Simultaneous Location and Mapping

- Estimate the user and anchors' locations
- Infer the boundaries of the environment and of obstacles using the points from which reflections originate



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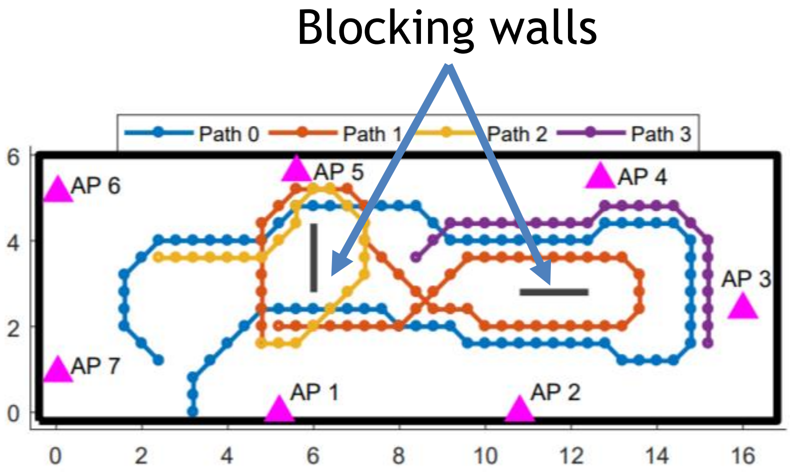
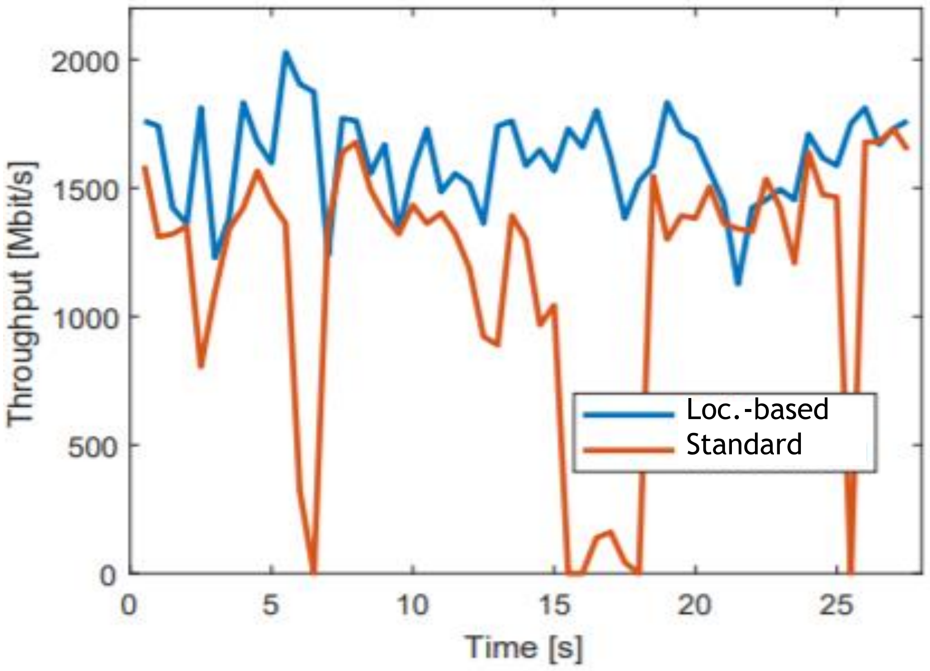
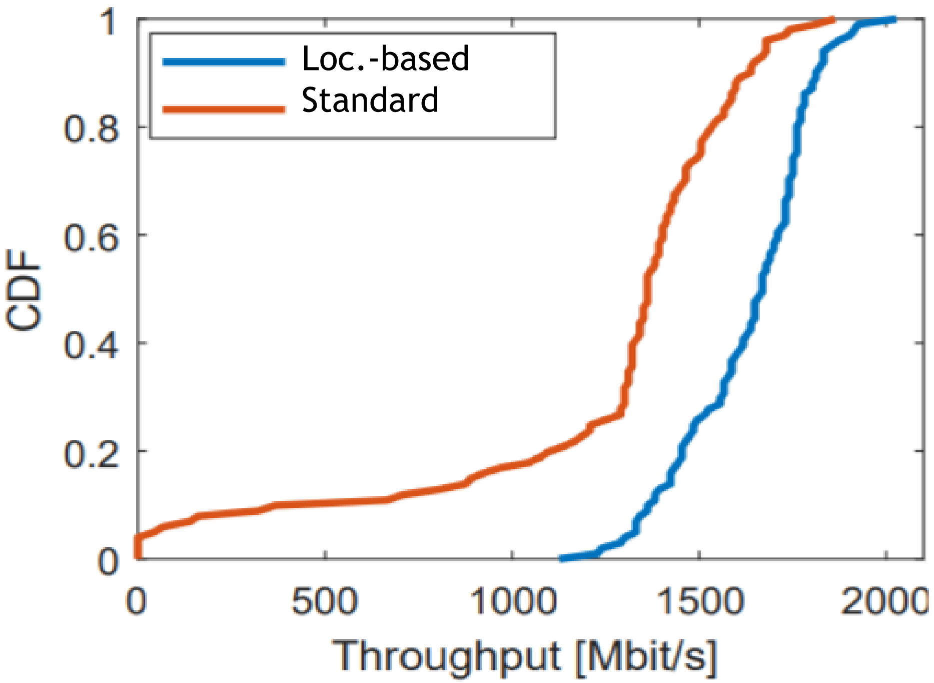
Location-Based Network Control for Resilience

- Evaluated in complex scenarios with walls
  - No outages and higher throughput







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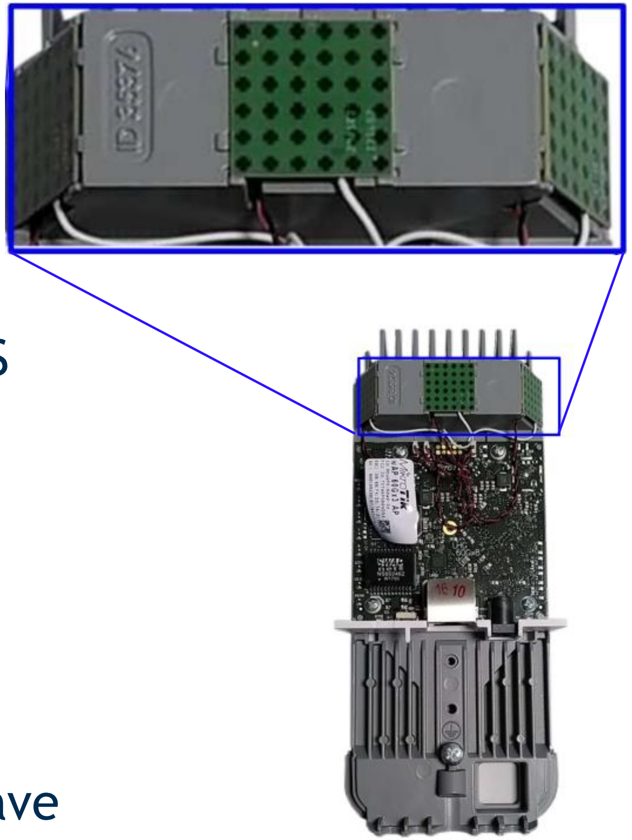
Mm-wave and Multi-band Localization



- Ported openWRT to more capable hardware (CSI+FTM)
  - Mikrotik wAP 60G: 32 element antenna arrays
  - Extremely **accurate AoA (~1 deg.) and ranging (~10 cm)** under LOS
  - BUT: very high error when no LOS path is present and an NLOS path is erroneously chosen
- Multi-band (mm-wave and sub-6 GHz) can help
  - Not to merge information (mm-wave is accurate enough), but
  - 1) To **distinguish mm-wave LOS from NLOS paths**
    OLOS paths available at sub-6 GHz which are not present at mm-wave
    → choose sub-6 GHz OLOS in case of NLOS at mm-wave
  - 2) To **choose the best mm-wave antenna array** (if multiple are present)
  - 3) And to provide localization when out of mm-wave coverage
- First open tool for CSI and FTM extraction for 802.11ad mmWave devices (https://github.com/IMDEANetworksWNG/MultiLoc)

Alejandro Blanco et al., "Augmenting mmWave Localization Accuracy Through Sub-6 GHz on Off-the-Shelf Devices", *ACM MobiSys*, June 2022

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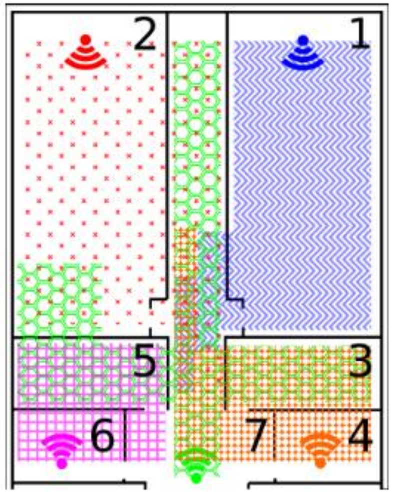
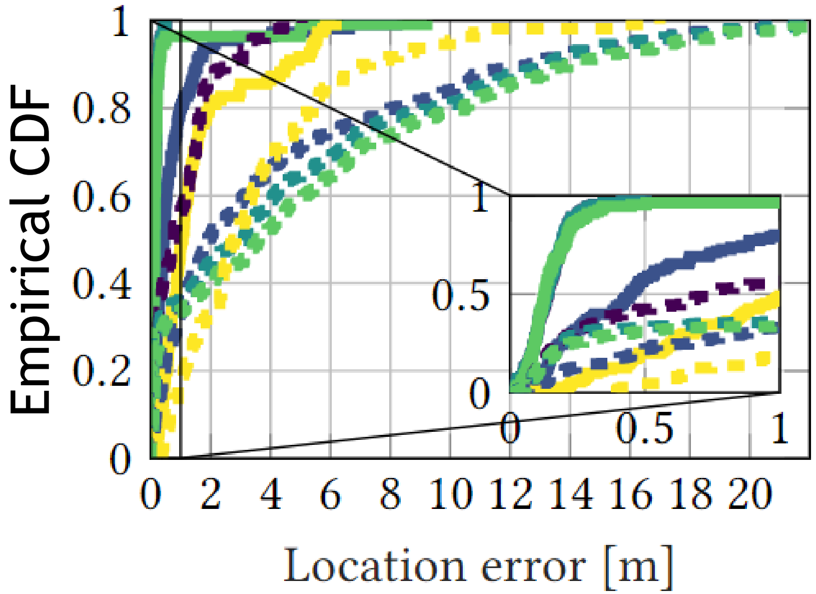
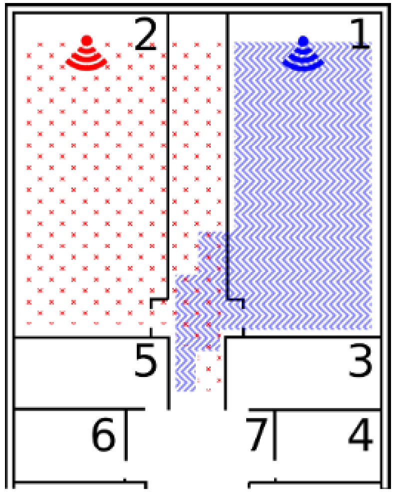
Multi-band Localization Performance

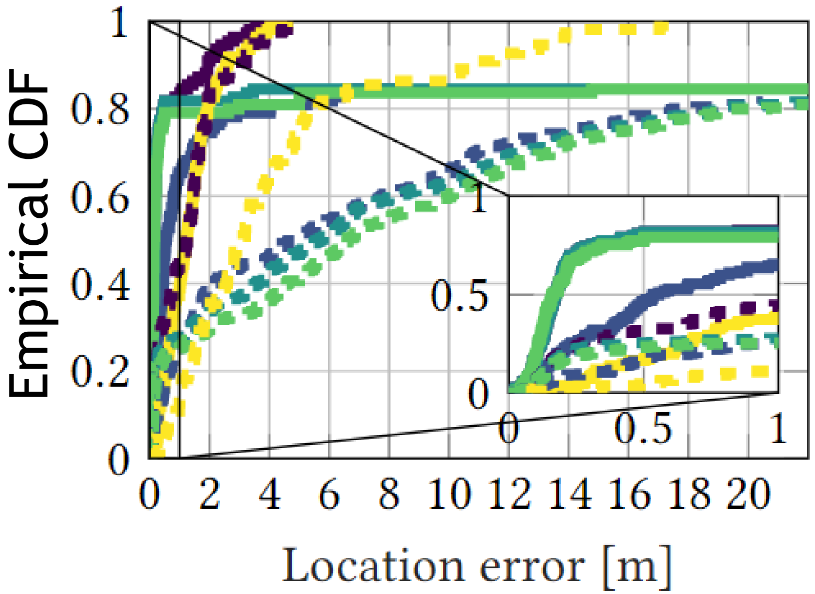
- Office scenario
- Measurements in 110 positions distributed over 7 different areas
- Significant NLOS mm-wave coverage
- **Median location error 10 cm with 5 APs (top) and 20 cm with 2 APs (bottom)**
- Sub-6 GHz information used wherever mm-wave is unavailable

Mm-wave coverage









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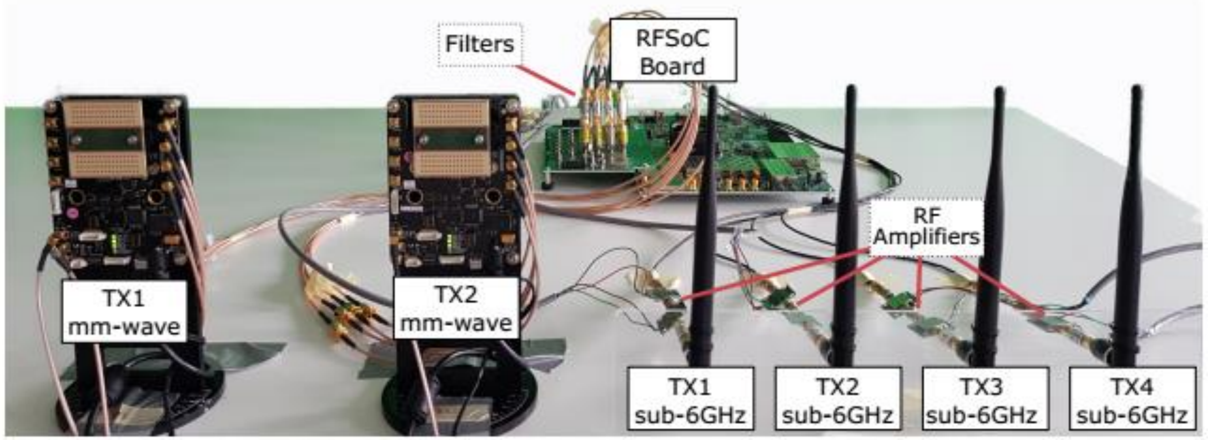
Platform for mmWave (and sub-6 GHz) Research

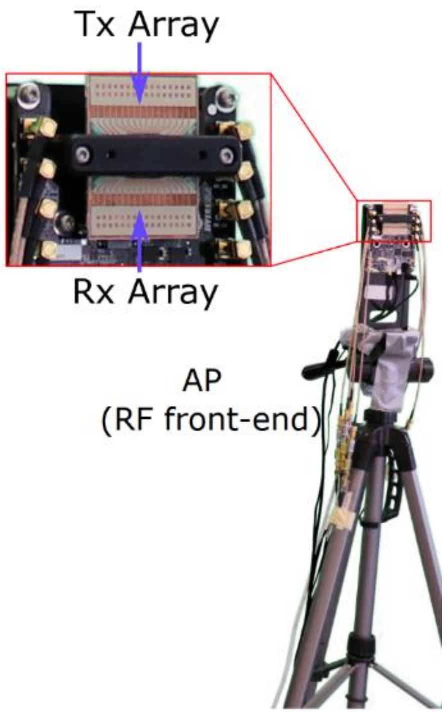
- COTS devices are a great experimentation tool, but PHY/signal processing research requires lower-level access to the waveforms
- Built open-source system based on Xilinx RFSoC board
  - Configurable data-paths for flexible bandwidth, MIMO-order
  - Memory-based design (to speed up prototyping), with hardware accelerators to support real-time functionality
  - Three basic modes of operation:
    - 8x8 MIMO at any sub-6 GHz frequency
    - 4x4 MIMO at mmWave via exchangeable RF frontends with up to 2 GHz of bandwidth per channel
    - Mixed configurations → multiple mmWave + sub-6 GHz interfaces

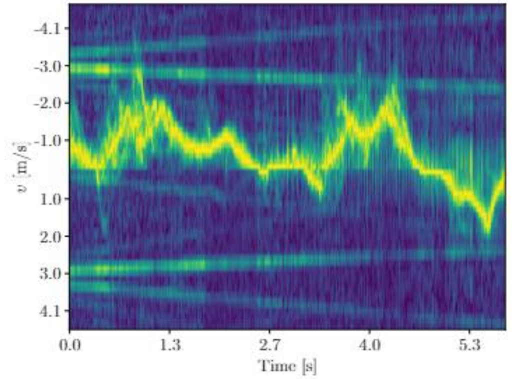


J. O. Lacruz et al., "A real-time experimentation platform for sub-6 GHz and millimeter-wave MIMO systems", *ACM MobiSys*, 2021

Mm-wave JCAS Micro-Doppler Estimation

- Wide bandwidth (0.4-2 GHz) required to track small movements
- Mono-static design: operate one MIMO RF chain as transmitter and one as receiver
  - Low self-interference due to directional mm-wave antennas
- Passive localization for multi-person tracking using beam training information (SLS, SSB)
- Micro-doppler extraction using a sequence of data packets with training fields (TRN, CSI-RS)
  - Phase estimation from Channel Impulse Response changes
  - Sparse estimation to deal with random packet inter-arrival times
  - Inter-arrival time determines maximum velocity, length of packet sequence determines velocity resolution
- ML-based activity recognition and person identification





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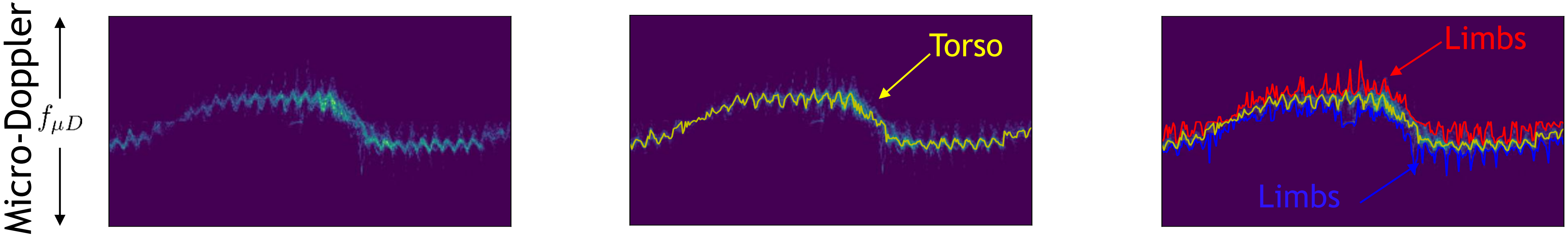
Activity Recognition and Person Identification

- Detect and identify multiple people performing ***different activities at the same time in the same area***
- Micro-Doppler signatures: frequency modulation on the returned signal that generates sidebands about the object's main Doppler frequency shift due to an object's micro-motion dynamics
- Well-known with a dedicated radar, difficult with data packets (ours is the first work to do this)



Walking example

$$f_{\mu D} = \frac{4 D_v f_v}{\lambda} \cos(2\pi f_v t)$$

Max vibration amplitude — Wavelength — Vibration frequency

Joint work with University of Padova

Jacopo Pegoraro et al. "SPARCS: A sparse recovery approach for integrated communication and human sensing in mmWave systems", ACM IPSN, May 2022

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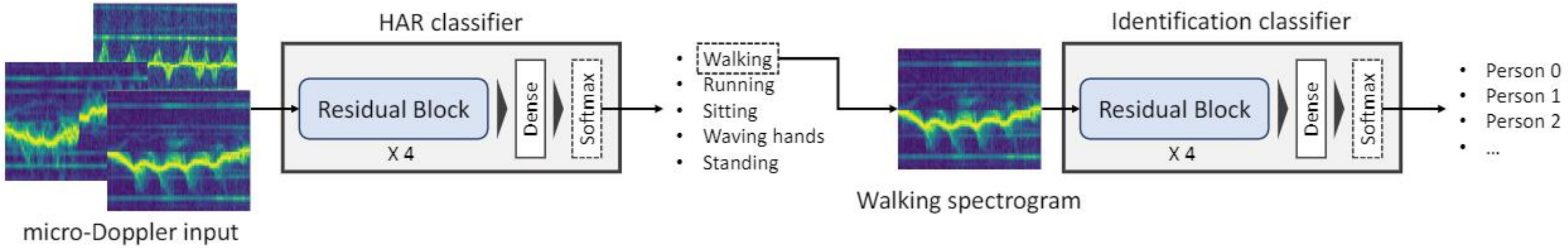
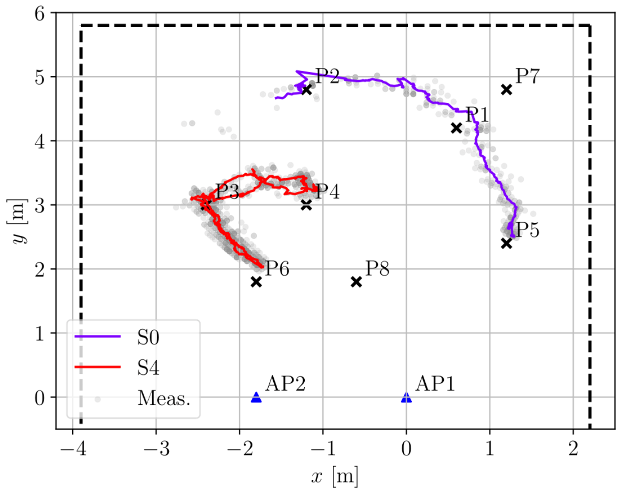
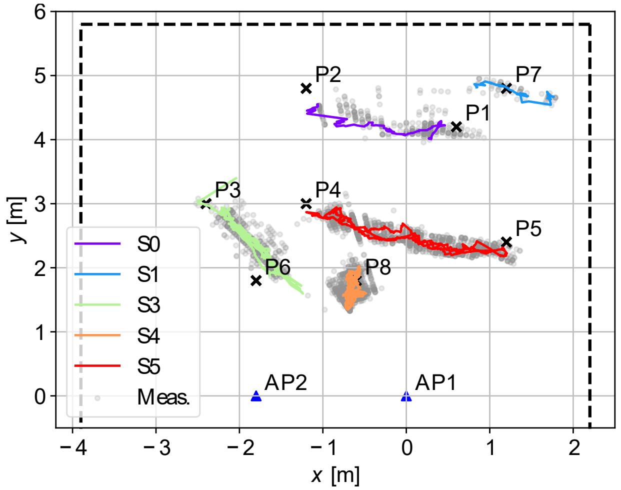
Activity recognition and person identification



ML-based design:

- Tracking of 1 to 5 subjects carrying out different activities
- Multi-AP view to deal with occlusion
- Accurate activity recognition
- Person identification with up to 7 subjects leads to 90-97 % accuracy





	Predicted [%]			
True [%]	Walking	Running	Sitting	Waving
Walking	**92.9**	0.8	6.2	0
Running	16.2	**71.6**	12.2	0
Sitting	0.2	0	**99.8**	0
Waving	3.3	0	6.8	**89.9**

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Open Research Problems

- Robustness
  - There are still many cases where sensing/localization is inaccurate or fails entirely → not good enough for some applications
  - Combining multiple systems/technologies may help
- Calibration
  - cm-level location accuracy requires that also the AP positions are known at cm-level accuracy
  - Phase calibration not relevant for communication but critical for angle estimation
  - Etc.

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Extensions towards a real-time 5G/6G experimentation platform

- Alternatives: OpenAirInterface, srsRAN
  - Standard compliant, but complex; *very* difficult/impossible to support high data rates in a stable way
- Plans for our platform: less functionality, not compatible with COTS smartphones, but much higher performance, better modularity
- Simple FR1/FR2 implementation based on the MIMORPH platform
  - Detect synchronization signals (SSB)→ PSS, SSS, PBCH
  - CFO compensation
  - Acquisition of timing information
  - Channel estimation
  - Full OFDM symbol decoding: fixed sub-carrier spacing, MCS, LDPC rate, BW (i.e., FFT length)
  - 5G standard-compliant timing and frame format
- Future:
  - Full initial access procedure
  - Multiple spatial streams
  - Standard compliant integration with upper layers → functional splits according to 3GPP

Conclusions

Practical Joint Communication and Sensing

- Not new topics by any means
- But very timely now, and of high practical relevance, especially in the context of 6G
  - Applications demanding both high rate data communication and accurate sensing information
  - Location information can help to deal with the increasing complexity mobile network control and the wireless physical layer
  - Intelligent reflective surfaces

Hardware is now just at the point where a lot of interesting applications become feasible (without too many limitations)
→ Requires ***flexible*, *high-performance experimental platforms***

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THANK YOU !

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