Efficient Networking in Millimeter Wave Bands

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Developing the Science of Networks

IMDEA Networks

- International research center in network science and technology
  - Located in Madrid, Spain
  - ~50 researchers from 15 countries
  - Focus on top quality research with emphasis also on tech transfer
- Wireless Networking Group
  - 3 postdocs
  - 6 PhD students
  - 1 project administrator
  - 1 research engineer
  - Several interns

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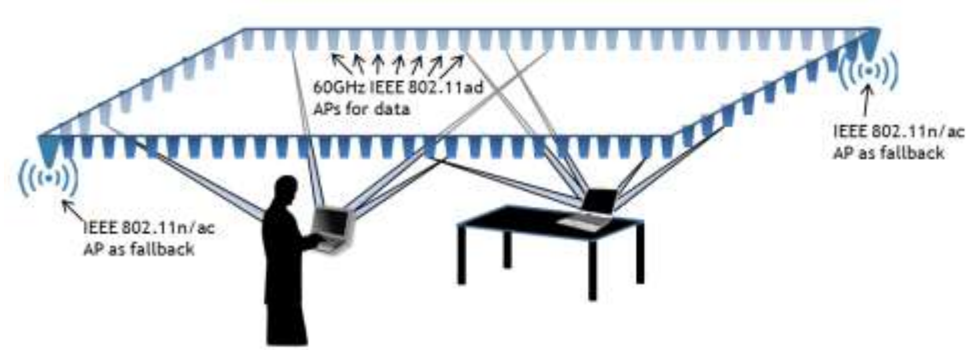
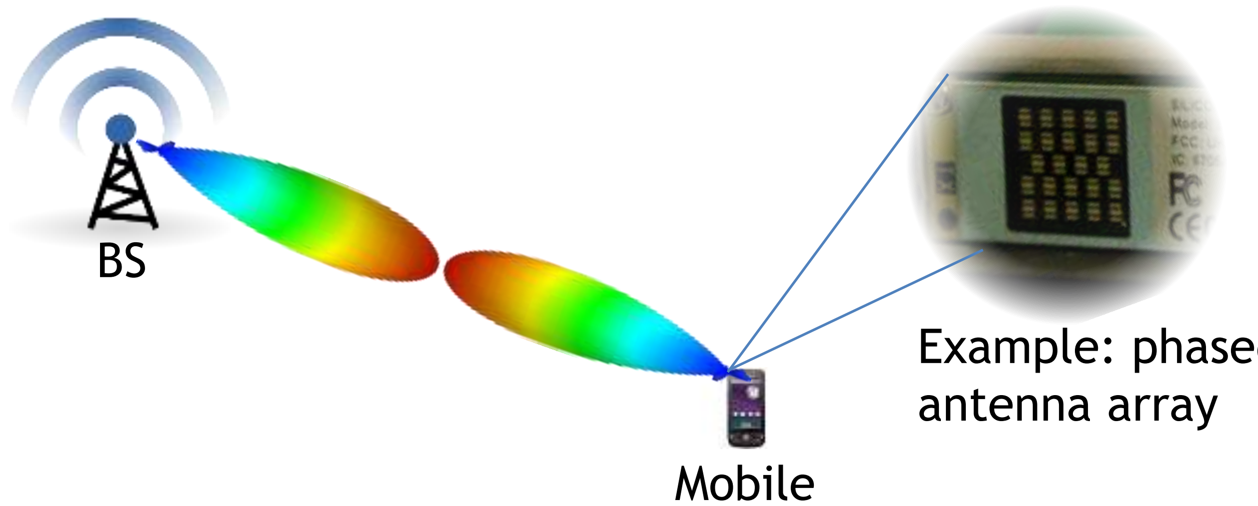
SEARCHLIGHT

- ERC Consolidator Grant (2014 – 2019)
- Focus on local area networks based on 60 GHz communication
  - Studies new communication paradigms for very high speed networks
  - Addresses spectrum scarcity and exponential growth of wireless data
- Challenging characteristics
  - High signal absorption often allows only for LOS channels
  - Directional communication using beamforming mechanisms
- Vision: many dedicated wireless point-to-point channels
  - Vast number of APs
  - Complex medium sharing
  - Accurate device tracking
  - Large managed deployments



Move to Higher Frequencies is Inevitable

- Many GHz of spectrum available at mm-wave frequencies
  - Multi-Gbit/s *per user* to support rapid increase in wireless traffic
  - Recent release of 7 GHz of unlicensed mm-Wave spectrum around 60 GHz
- Very high levels of spatial reuse
  - *Highly directional antennas* needed to achieve reasonable communication distance
  - Low interference (through side lobes)



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Mm-Wave Related Problems

Millimeter-wave communication is not easy

- High frequency related path loss
- Most materials block the signal
- Communication primarily line-of-sight
- Directional antennas need to be *aligned*
- RF design much harder at these frequencies

↓

- Mm-wave links are brittle and break easily
- *How to design fast, reliable, low latency networks?*

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Challenges

- Fast beam training
  - With many devices
- Quickly detect outage or blockage
- Support fast switching
  - Devices with multiple antenna arrays
  - Maintain multiple alternative mm-wave paths
  - Use multiple RF technologies (at different frequencies)
- *Without incurring excessive overhead!*
  - Many small cells, very frequent handovers between BS or technologies, Gbit/s streams, ms latency requirements

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Lack of Good Experimental Platforms

Available Off-the-Shelf Hardware

- TP-Link Talon AD7200 as research platform
  - Tri-band IEEE 802.11 router (2.4GHz, 5GHz, 60GHz)
- Ported OpenWRT/LEDE to Talon router and hacked the firmware of the 802.11ad mm-wave interface
  - Based on nexmon framework for binary firmware patching
  - Full access to the embedded Linux
  - AP, client, and monitor mode
  - Access to beam training
  - https://github.com/seemoo-lab/talon-tools

*Joint work with TU Darmstadt

Daniel Steinmetzer et al., "Compressive millimeter-wave sector selection in off-the-shelf IEEE 802.11ad devices", *ACM CoNEXT*, Dec. 2017

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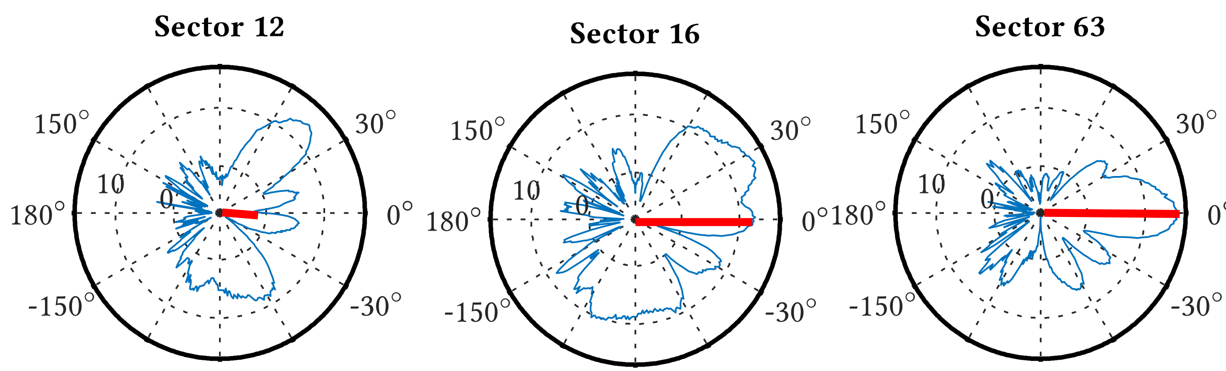
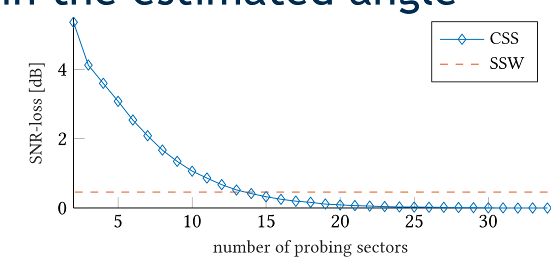
Implementing Compressive Beam Training

- 802.11ad beam-training probes 34 antenna patterns sequentially
- Instead: can exploit sparseness of mm-wave multipath channel
  - Sparse estimation problem, no need to train all possible antenna patterns
  - Probe subset of antenna patterns, record signal strength



  - Multiply received signal strength values with beam patterns and add them
  - Select the beam pattern that has the highest gain in the estimated angle
  - Probing 14 out of 34 sectors is sufficient
    → training time reduced by factor of 2.3



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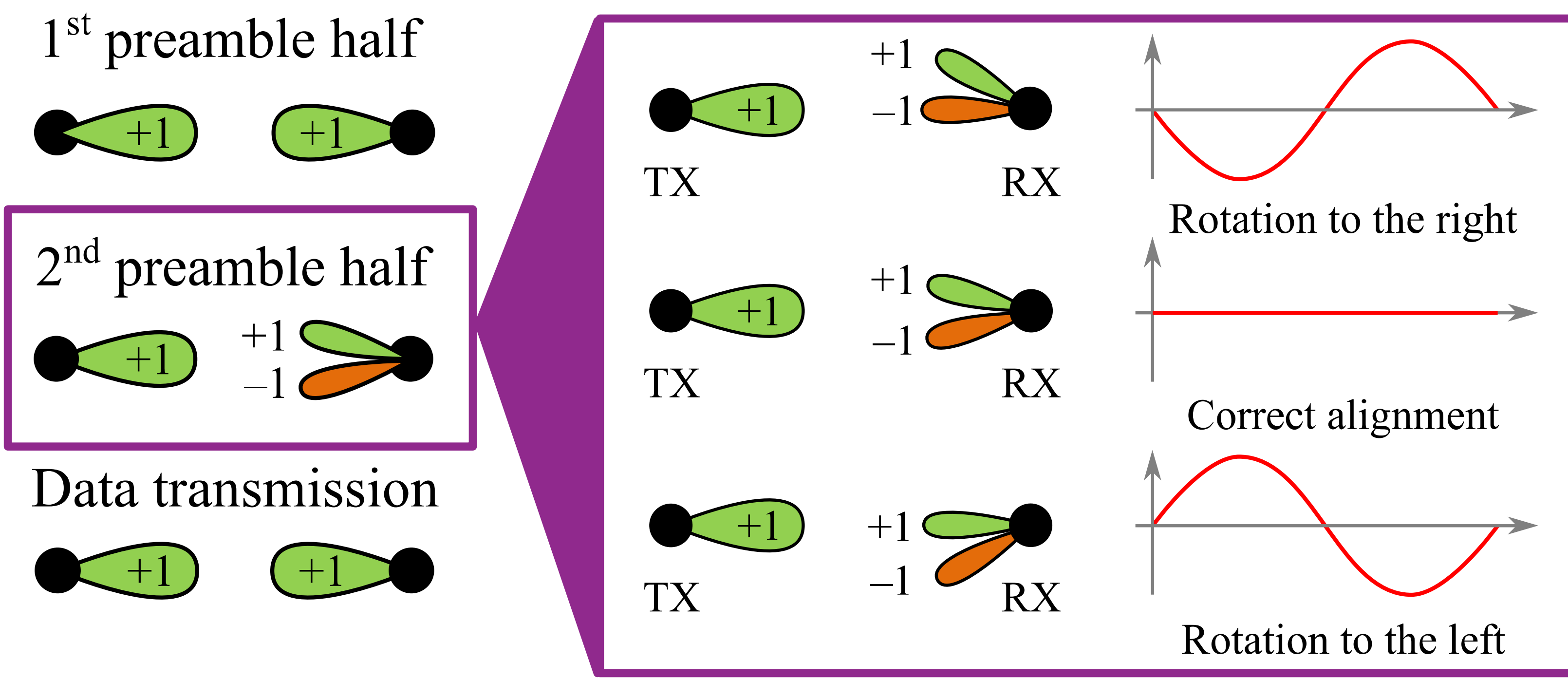
Zero Overhead Tracking

- Necessary to continuously maintain alignment after initial training
- Idea: **use two-lobe beam pattern with different phases per beam** during part of the packet preamble to detect movement and rotation
- Comparing first and second half of preamble reveals orientation



Adrian Loch et al., "Zero overhead device tracking in 60 GHz wireless networks using multi-lobe beam patterns", *ACM CoNEXT*, Dec. 2017

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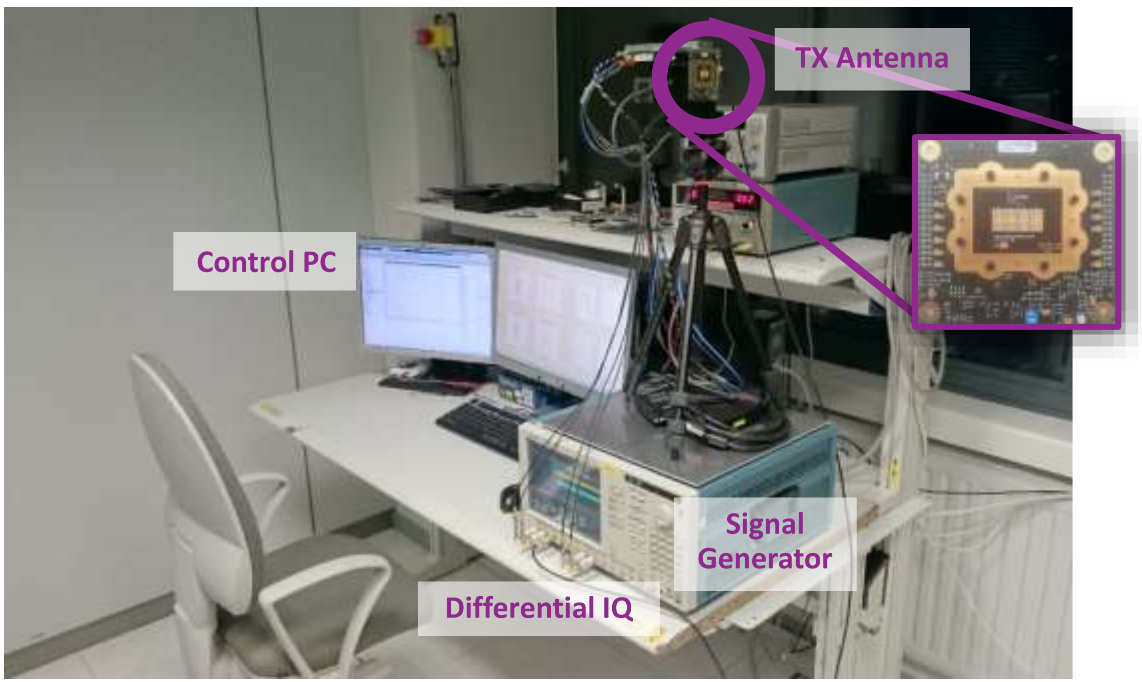
60 GHz Testbed Setup

- Collaboration with IMEC (Belgium)
- Signal generator, oscilloscope, IEEE 802.11ad compliant frontend, control PC



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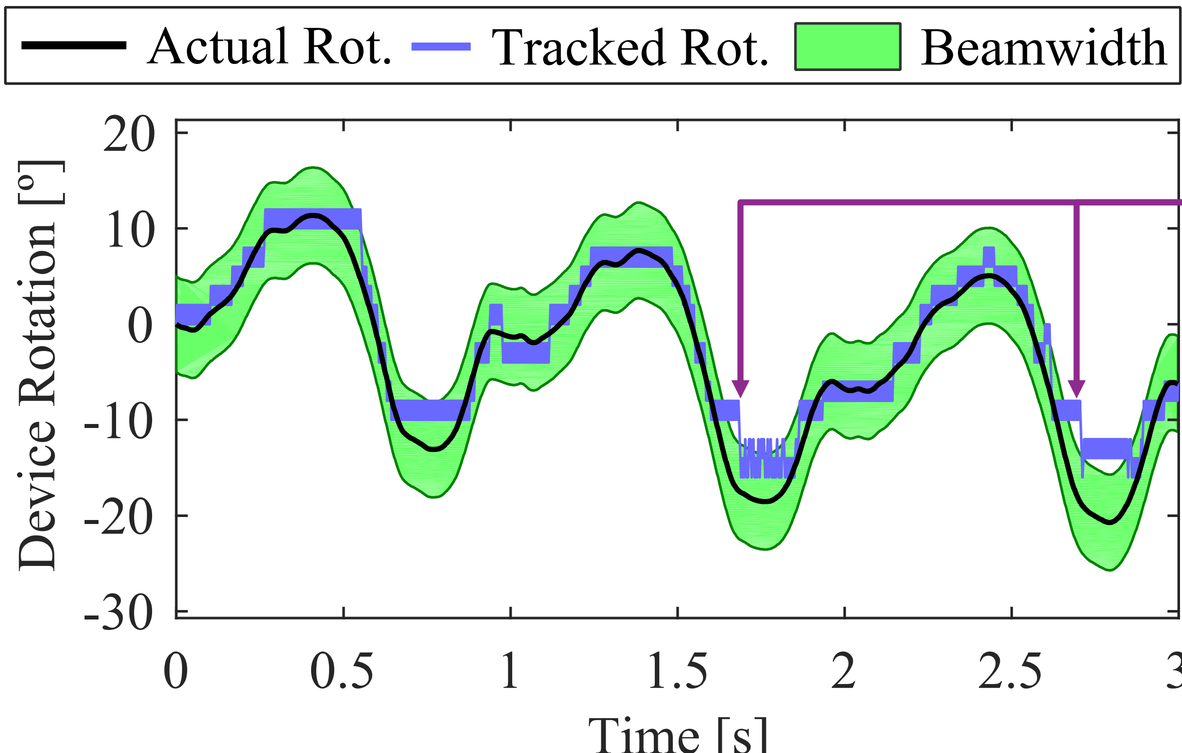
Evaluation Results

- One node rotates according to real-world gyroscope traces
- Automatic beam-steering adjustment based on correlation output
- Steering error always below 5° which results in up to 2x throughput gain



Seamless and fast error recovery

Walking movement at indoor speed

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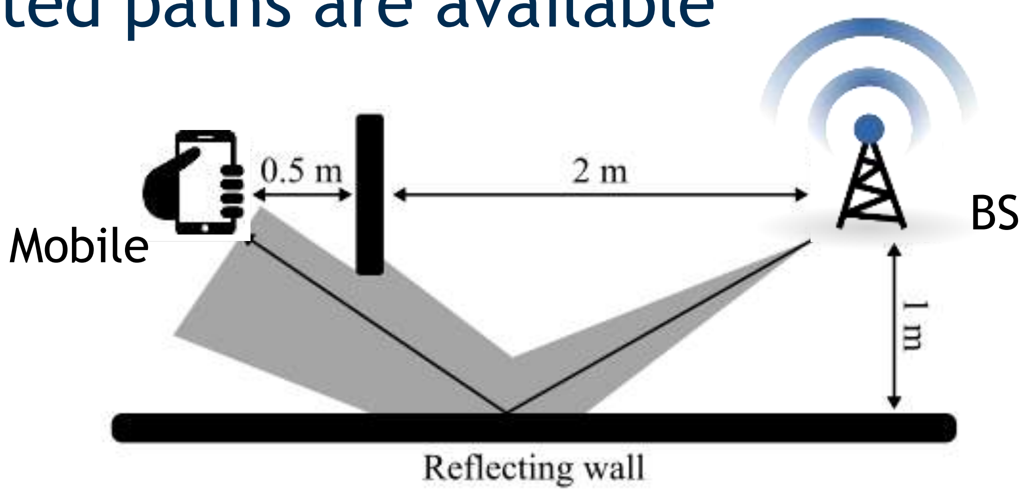
Adrian Loch et al., "Zero overhead device tracking in 60 GHz wireless networks using multi-lobe beam patterns", *ACM CoNEXT*, Dec. 2017

"Quasi-Optical" Mm-Wave Channels

- Sparse multi-path environment; LOS path, maybe 1st and 2nd order reflections (sometimes more)
- Position/movement of communication devices can be used to steer the antenna array
- Positions of obstacles allow to infer which paths are blocked
- Positions of obstacles/walls allow to infer which reflected paths are available



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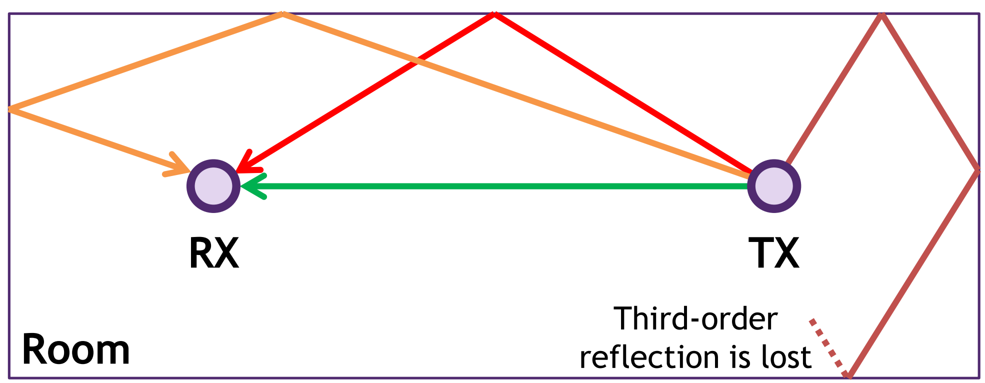
mmWave Location System

- Angle of arrival/departure information from the beam-training can be used for accurate location system
  - Use compressive beam training idea to get AoA from beam patterns
  - But: need to estimate multiple paths, not just the strongest
- Exploit sparse multi-path channel at mm-wave
  - High attenuation typically allows only for first- or second-order reflections
  - Signals arriving at a receiver can be easily traced back to transmitter



Alain Olivier et al., “Lightweight indoor localization for 60 GHz millimeter wave”, *IEEE SECON*, June 2016

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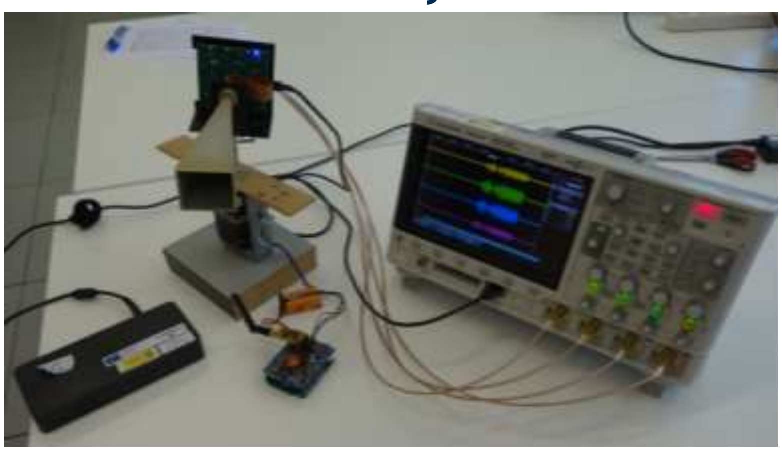
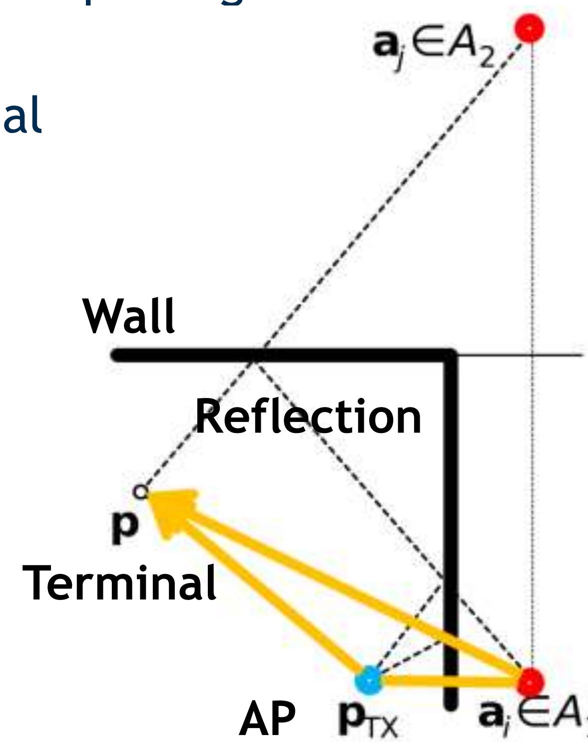
Localization Algorithm

- Joint Anchor and Device location Estimation (JADE)
  - Location system based only on angle difference information
- High level overview
  - Reflections are transformed into vectors departing from the position of the virtual anchor
  - Iterate over unknown position of terminal and unknown positions of anchors
  - Needs user mobility over time

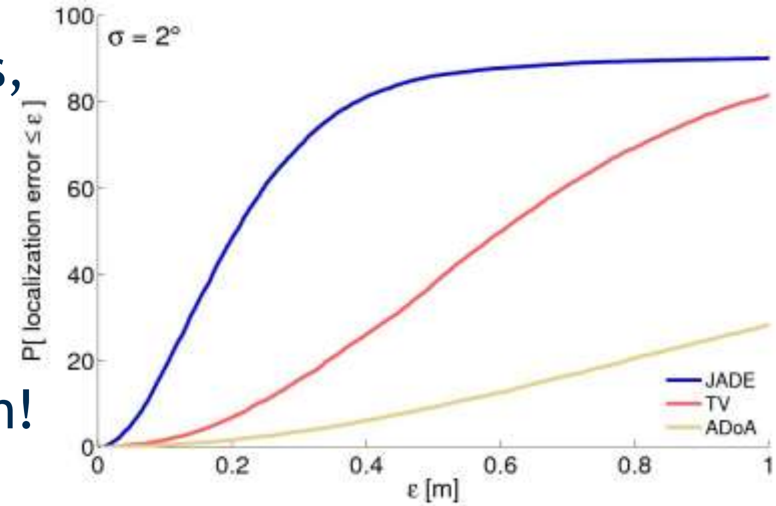




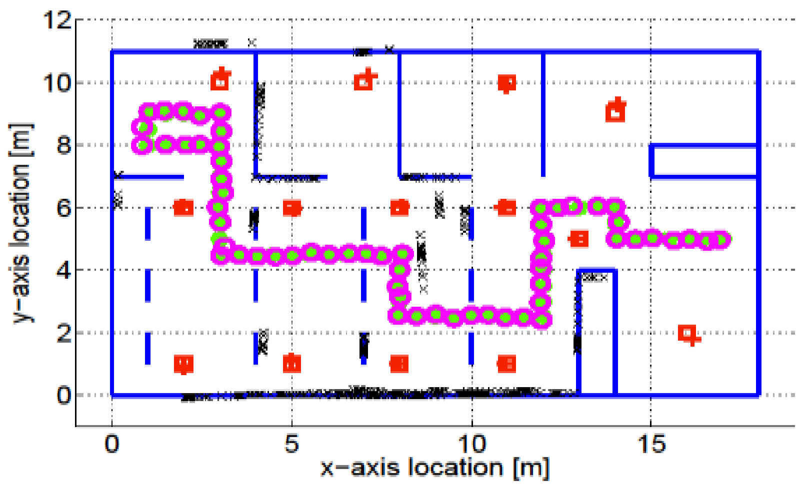
Joan Palacios et al., “JADE: Zero-knowledge device localization and environment mapping for millimeter wave systems”, *IEEE Infocom*, May 2017

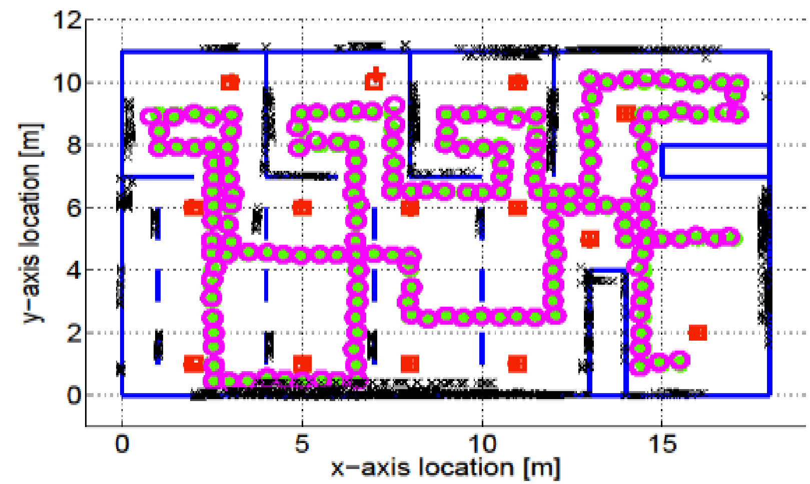
Localization Results

- *Unknown* access point (AP) locations, *unknown* floor plan, ***only* angle**
- Learn: make use of history of locations for refinement
- Outperforms even algorithms that assume floor plan and APs are known!



- Simultaneous Location and Mapping





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Preview: Custom Beamforming on COTS Devices

- IEEE 802.11ad uses a pre-determined codebook for beamforming (and brute-force beam training)
- Custom (SNR maximizing) beam patterns would significantly improve performance (as well as AoA estimation, etc.)
- Current 802.11ad routers allow to modify the codebook, but designing custom patterns requires CSI, which the routers do not provide
- Idea: generate a codebook that allows to measure the channel and then add custom CSI-based beam patterns to the codebook

Joan Palacios et al., "Adaptive Codebook Optimization for Beam-Training on Off-The-Shelf IEEE 802.11ad Devices", *ACM Mobicom*, October 2018

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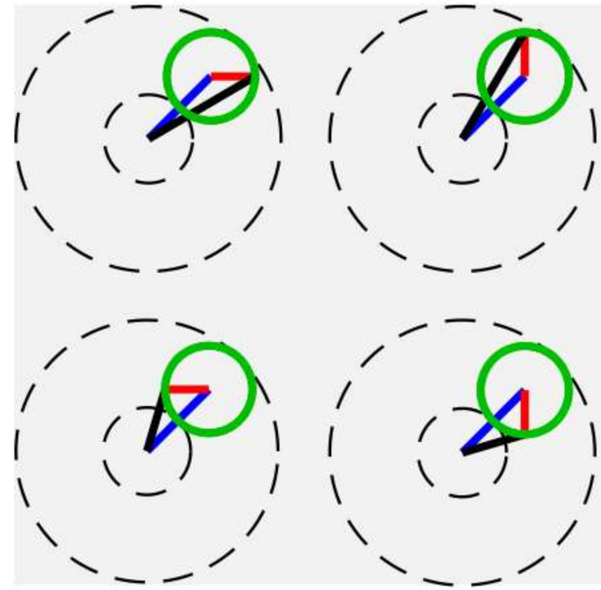
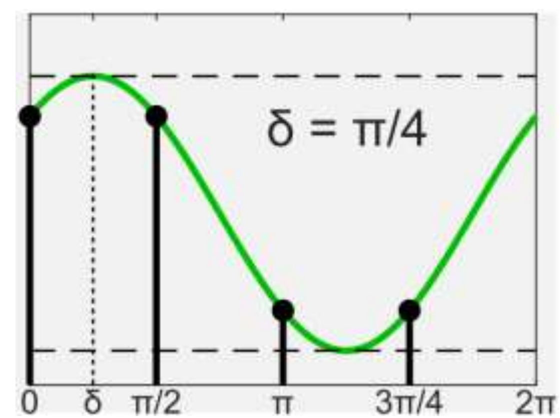
Amplitude and Phase of the Antenna Elements

- Use transmit antenna patterns which enable measured antenna element (red) with different phase shifts and an arbitrary reference element (blue)
- Requires four measurements
- Additional mechanism for low SNR (where signals from a single element cannot be decoded)
- To reduce overhead, determine the most important antenna elements and only measure those





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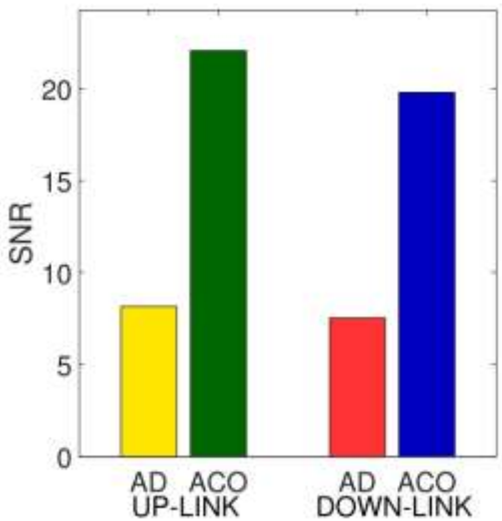
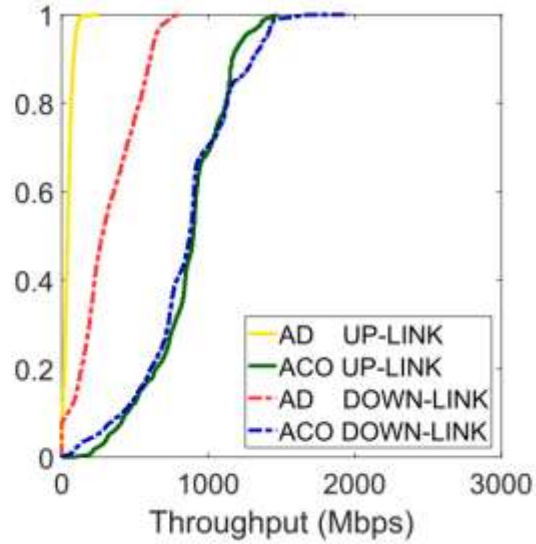
Performance Gains

- Average gains: 2.5× higher SNR, 2× higher throughput; much better NLOS coverage
- With the array factor we can generate fully custom beam shapes

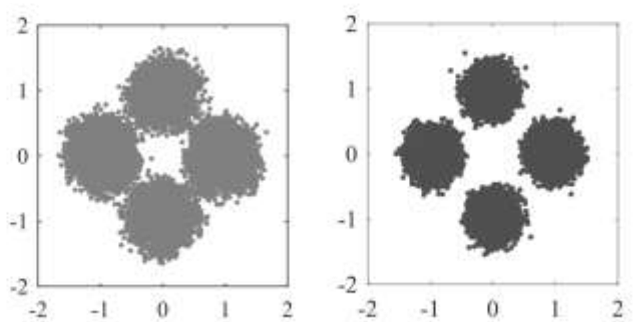
Average SNR gains



NLOS Example



Constellation diagrams (MCS8)



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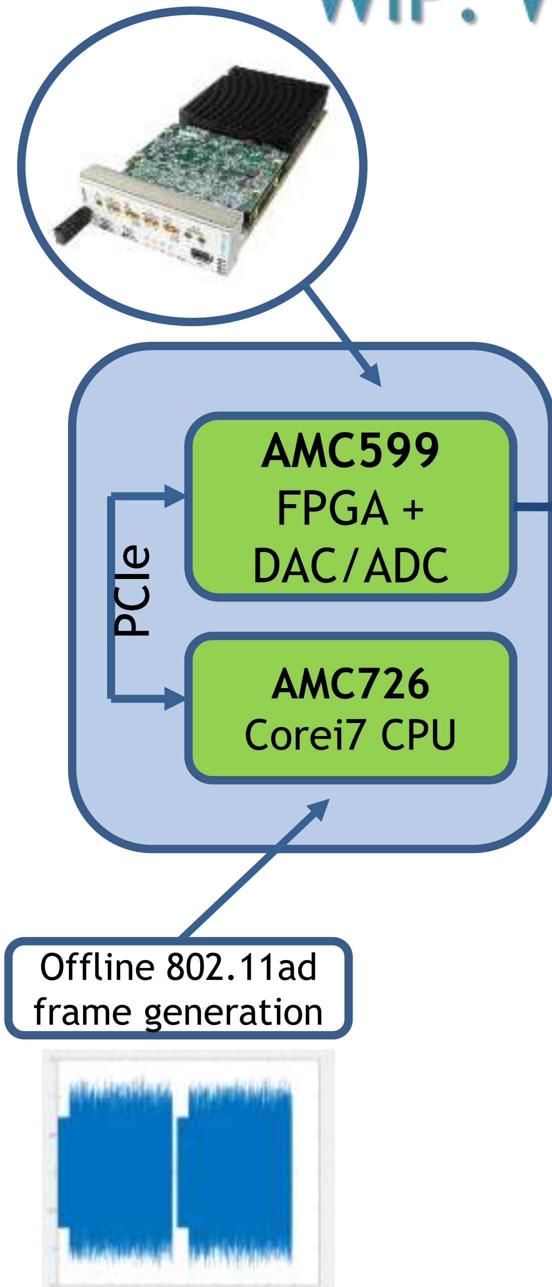
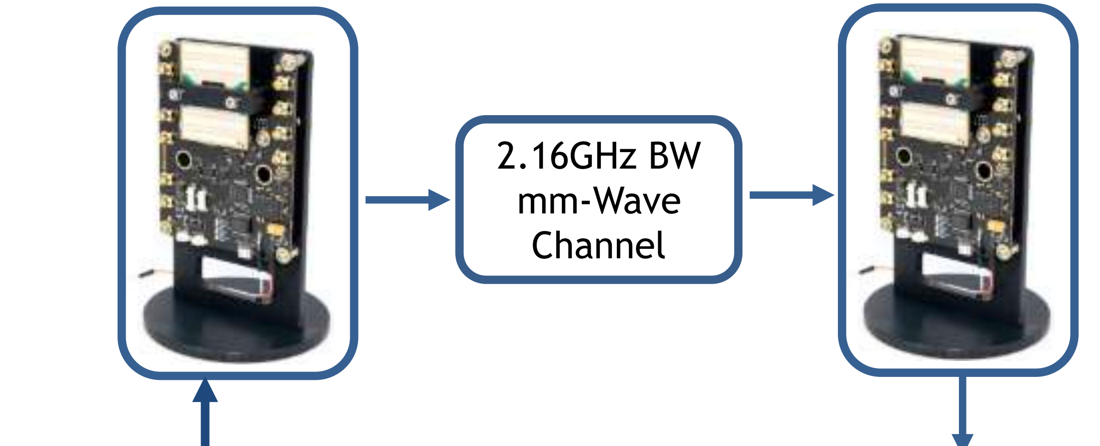
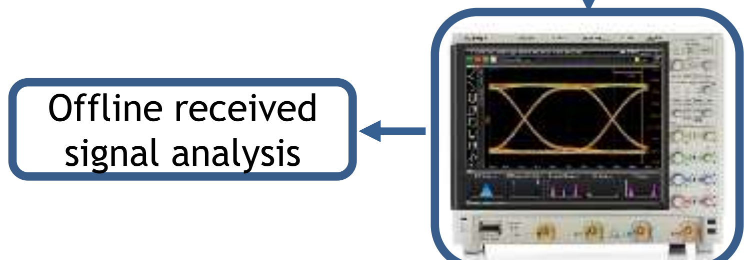
WIP: Wideband mmWave SDR System







Now:
- Offline 802.11ad-compliant frame generation in Matlab
- 60GHz Sivers up/down converters with phased arrays
- Decoding using Keysight Oscilloscope

Future:
- Fully 802.11ad-compliant transceiver
- Synchronization, channel estimation and decoding performed on the FPGA (in real time)
- Modular design

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Short Glance at Further Work

- Hybrid beamforming, beam pattern design, …
- MAC design, coordination, fairness, frame aggregation, …
- Efficient backhaul: quickly switching Gbit/s streams between base stations and/or technologies is not trivial
- Low latency mm-wave networks (bufferbloat!)
- Efficient transport (TCP issues with wireless)
- Network management and control in very large, very dense mm-wave AP deployments
- IEEE 802.11ad implementation in ns-3
- Full bandwidth 802.11ad on FPGA

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Final Remarks

- Extremely promising area, data rates of tens of Gbit/s feasible
  - In the future: >100 GHz to THz systems
- Conventional wireless network paradigms don't work well
  - Very directional, little interference, high levels of spatial reuse
  - Fragile links, very high network dynamics (for mobile networks)
- Mm-wave communication will become an integral part of mobile networks and WLAN
  - Single links more or less well understood
  - Managing large dynamic networks remains a challenge

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THANK YOU !