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

• Experimental research is highly important
  – Actual performance depends critically on factors that are hard to model: real-world channel environment, hardware imperfections, calibration
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 achieved with inexpensive off-the-shelf devices?

Example: phased antenna array
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

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

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

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

![Graph showing throughput comparison between location-based and standard methods](chart.png)

![Graph showing cumulative distribution function (CDF) of throughput comparison](CDF.png)
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
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
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
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)

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Walking example

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

Max vibration amplitude \quad Wavelength \quad 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
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

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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.
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
THANK YOU!