Subproject: RISC-6G

Reconfigurable Intelligent Surfaces and Low-power Technologies for Communication and Sensing in 6G Mobile Networks

February 12, 2023

Joerg Widmer

Research Professor and Research Director

IMDEA Networks, Madrid, Spain

[Developing the Science of Networks]

Wireless Networking Group (WNG)

- Group leader
  - Dr. Joerg Widmer
- Senior Researcher
  - Dr. Claudio Fiandrino
- Postdoc
  - Dr. Syed Waqas Haider
- Research Engineers
  - Dr. Jesus Omar Lacruz
  - Rafael Ruiz
- PhD Students
  - Sai Pavan Deram
  - Nina Grosheva
  - Serly Moghadas Gholian
  - Bei Ouyang
  - Salil Sharma
- Project Administrator
  - Francisco Javier Hervas

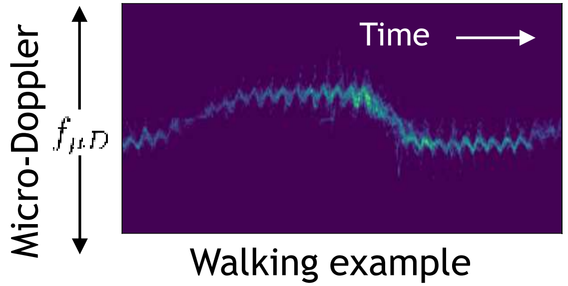
- Current projects: MINTS (ITN), LOCUS (H2020), TAPIR-CM (regional), CONTACT-CM (regional), RISC-6G (national), MAP-6G (national)

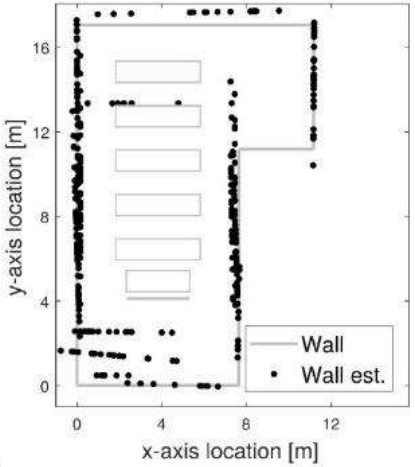
https://networks.imdea.org/team/research-groups/wireless-networking-group/

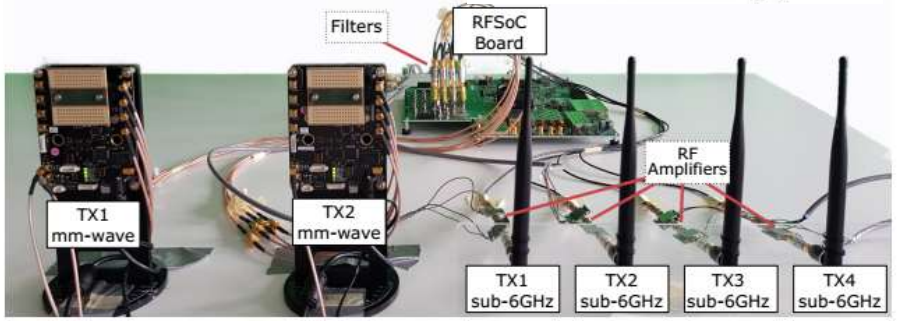
institute imdea networks

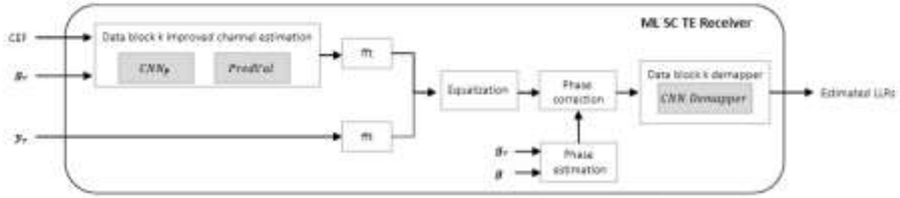
Wireless Networking Group Topics

- Wireless (mmWave and sub-6 GHz)
  - Joint communication and sensing
  - Localization and environment mapping
  - (Memory-based) SDR-based experimentation platform
  - 5G network performance measurements (FR1+FR2)
- Millimeter-wave networks
  - Mm-wave (MU-)MIMO efficient channel estimation, beam training, precoding
  - Low-latency networks
  - Ultra-dense deployments
  - ML-based PHY design
  - Intelligent reflective surfaces
  - Soon: THz communications
- Other work: edge computing, explainable AI and adversarial ML in the context of mobile network management and control









RISC-6G Overview

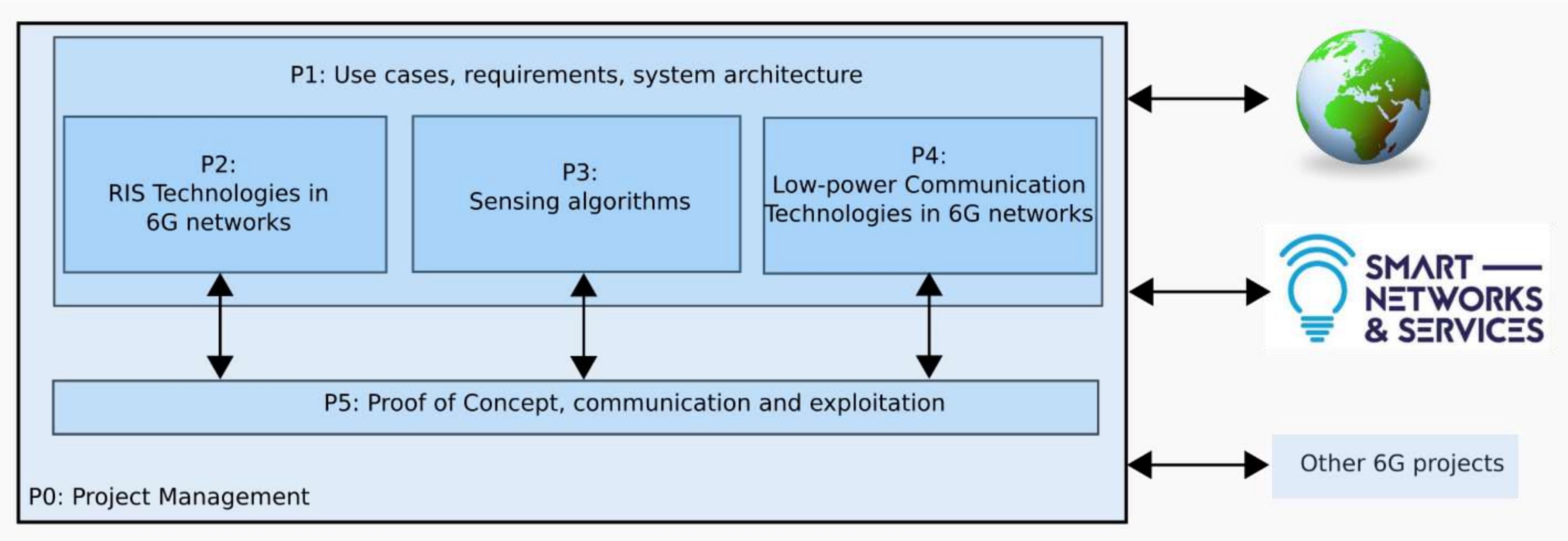
- Target: 6G mobile networks
  - Vastly larger number of connected devices
  - Significantly higher performance requirements
  - Support for detailed object and environment sensing in addition to communication
- Approach:
  - Integrate crucial new technologies to improve wireless communications
  - Provide environmental sensing
  - Significantly lower the per-device energy footprint
  - Harness reconfigurable intelligent surfaces, visible light communication, and RF backscatter
- Demonstrator in collaboration with industry partners of the consortium, integrating communication, sensing and low-power design for the use case of the Internet of Everything

General Objectives

- Define detailed use cases and the overall architecture
- Native integration of reconfigurable intelligent surfaces in 6G systems, addressing their main research challenges and practical implementation aspects
- Design of high-accuracy sensing capabilities jointly with communication
- Novel green radio technologies, integrating low-power devices that can both communicate, sense and harvest visible light waves
- Demonstrate the capabilities of the core technologies investigated in the project in key 6G scenarios
- Exploit and communicate project results to involve external players and inform the general public

institute imdea networks

Work Package Structure



Effort Overview

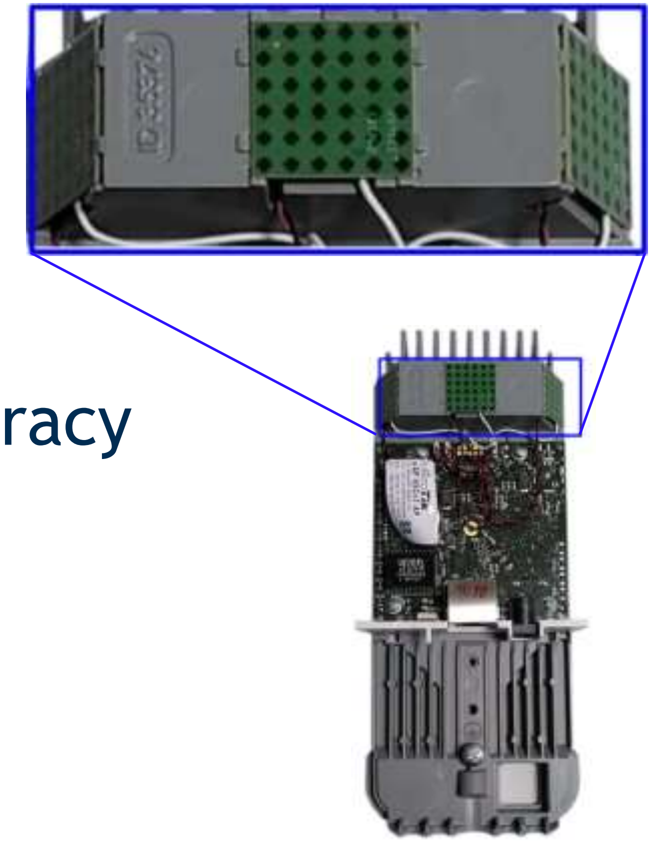
EFFORT TABLE AT THE TASK LEVEL		1	2	3	4	5	
	Leader	IMDEA	Ind1	Ind2	Sme1	Sme2	TOT
P0: Project Management		7	0	0	0	0	7
A1: Project management	IMDEA	7	0	0	0	0	7
P1: Use Cases, Requirements, System Architecture		4	0	0	0	0	4
A2: Use cases and requirements	IMDEA	2	0	0	0	0	2
A3: Overall architecture	IMDEA	2	0	0	0	0	2
P2: RIS Technologies in 6G networks		11	27	8	0	0	46
A4: RIS network integration in 6G networks	NEC	0	27	0	0	0	27
A5: RIS control plane in 6G networks	Telefonica	0	0	8	0	0	8
A6: Communicating and sensing support for RIS networks	IMDEA	11	0	0	0	0	11
P3: Sensing algorithms		12	0	0	9	0	21
A7: Activity recognition	IMDEA	12	0	0	0	0	12
A8: Object detection and environment mapping	Sme1	0	0	0	9	0	9
P4: Low-power Communication Technologies in 6G networks		20	0	0	0	0	20
A9: Wireless harvesting for 6G networks	IMDEA	10	0	0	0	0	10
A10: Low-power communication	IMDEA	10	0	0	0	0	10
P5: Proof of Concept, communication and exploitation		0	14	0	0	10	24
A11: Proof of concept	NEC	0	11	0	0	0	11
A12: Communication	Bluspecs	0	0	0	0	10	10
A13: Exploitation	NEC	0	3	0	0	0	3

Deliverables

Cod.	Entregable	Descripción	Clasificación	Paquete de trabajo	Fecha
E1	Project plan	Revision of the project vision, taking into account first results generated within the project, other relevant scientific, technological or market developments, including scenario and use case definitions, requirements, KPI and evaluation criteria.	Document	P1, P2	31/08/2022
E2	Initial report on RIS network integration, joint communicating and sensing	Initial specification of RIS network architecture and solutions for 6G communicating and sensing, including RIS network integration and control plane concepts.	Document	P2, P3	30/04/2023
E3	Initial report on novel low-power communication technologies and energy harvesting	Initial specification of low-power wireless communication technologies with specific focus on energy harvesting for 6G networks.	Document	P4	30/06/2023
E4	Final report on RIS concepts, network integration, joint communicating and sensing algorithms and low-power communication	Report including all the final algorithms and developed technologies in the technical activities on RIS, sensing and low-power communication.	Document	P2, P3, P4	30/04/2024
E5	Performance evaluation report	Extensive report on the performance evaluations of RIS-based solutions for 6G communicating, sensing, and low-power communications, including the RIS-based network performance improvements, achieved sensing accuracy, and possible energy savings.	Document	P2, P3, P4	31/10/2024
E6	Proof of Concept, dissemination, communication and exploitation	Report and software for the final proof of concept, as well as overview of dissemination, communication and exploitation actions.	Document+ Software	P1, P5	31/12/2024

Mm-wave Localization

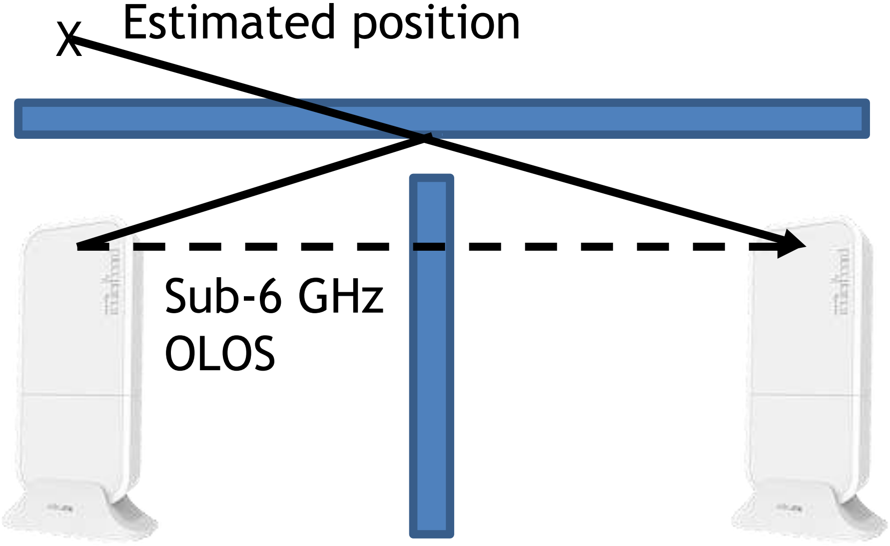
- Mikrotik wAP 60G particularly interesting for localization
  – Good time resolution due to 2 GHz of bandwidth
  – Planar array (6x6) with 32 antenna elements (Mikrotik wAP 60Gx3 even has 3 such arrays)
  – Hacked the device to enable WiFi Fine Time Measurement
- Experimental evaluation of mmWave location accuracy
  – Extremely accurate AoA (~1 deg.) and ranging (~10 cm)
  – Under good conditions
    - Line-of-sight (LOS)
    - Angle not too extreme for FoV of antenna



First open tool for CSI and FTM extraction for 802.11ad mmWave devices (https://github.com/IMDEANetworksWNG/MultiLoc)

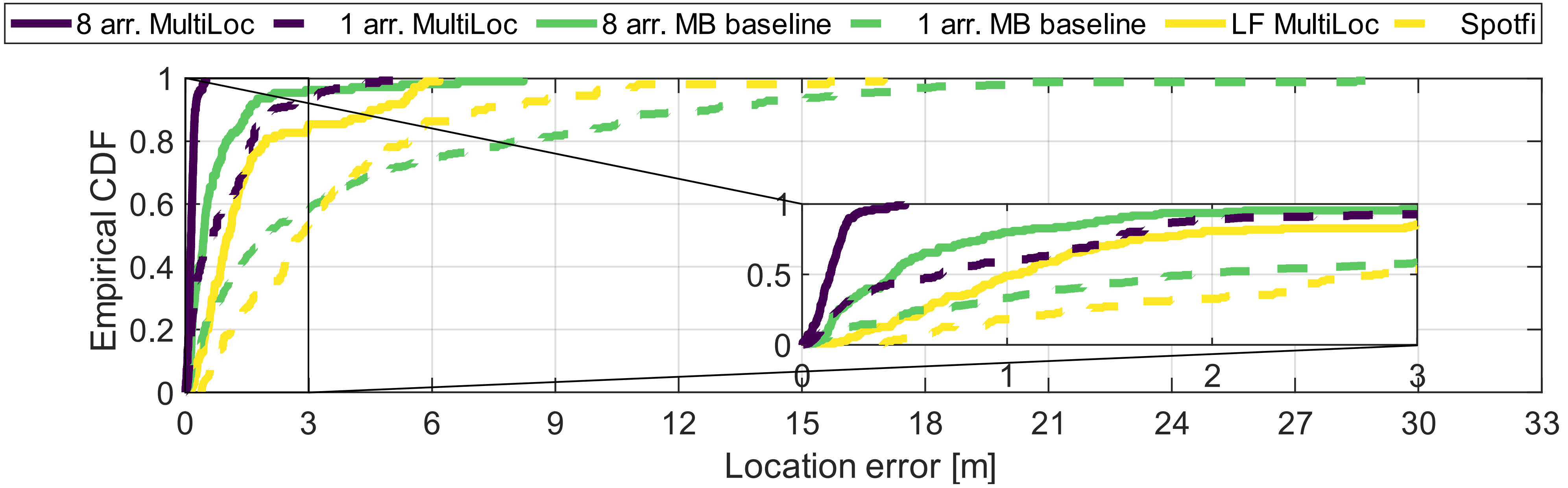
Mm-wave Localization

- BUT: very high error when an NLOS path is chosen for the localization
- Very difficult to distinguish an NLOS path from a LOS path
- Sub-6 GHz to the rescue
- Building a multi-band system
  - Not to merge information (mm-wave is much more accurate or useless), 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



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

Localization results. Indoor scenario



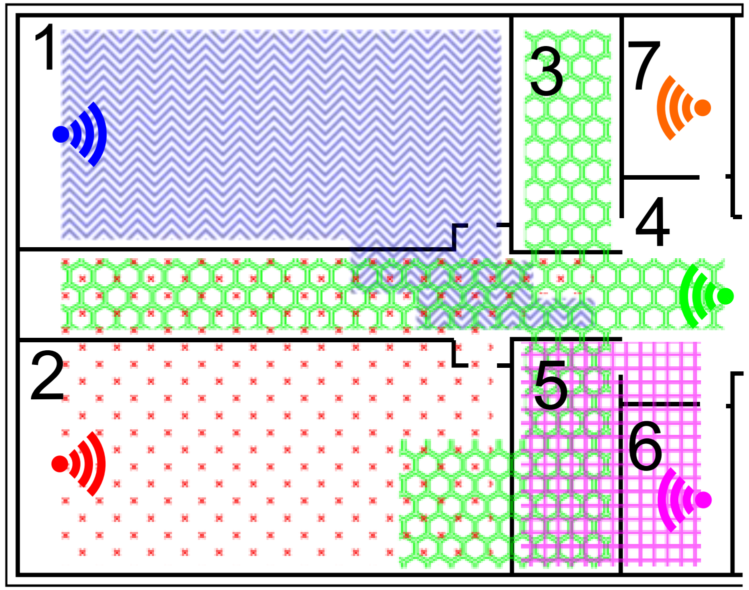
8 arrays:

- MultiLoc: **13cm** of median error and a maximum error of **50cm**
- MB baseline gets higher errors (45cm of median error)

1 array:

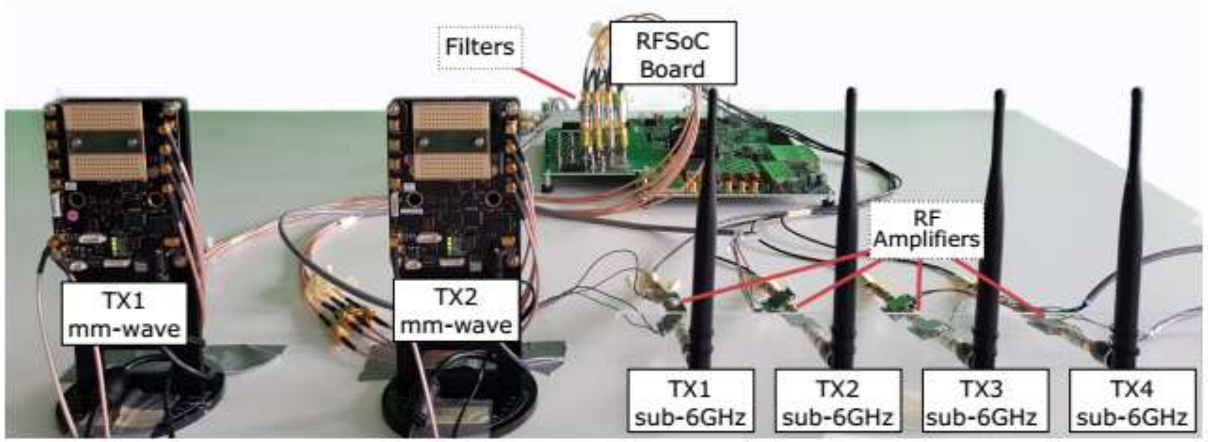
- MultiLoc: **60cm** of median error and a maximum one **of 5m**
- MB baseline gets 2m in median. Maximum error of more than 20m

Improvement by a factor of ~3-4



Platform for mmWave (and sub-6 GHz) Research

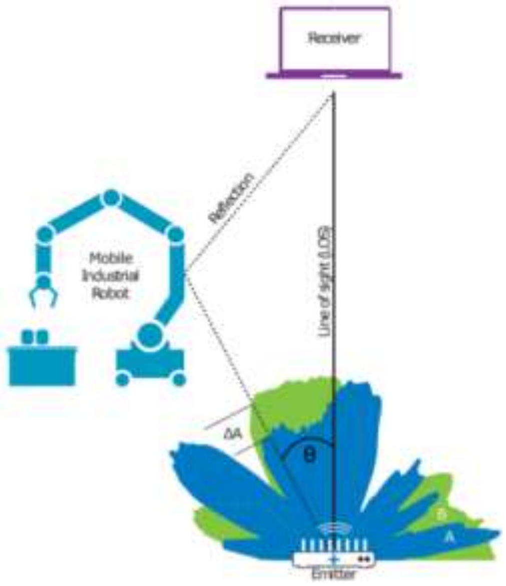
- COTS devices are very useful, but inherently limited
- Sensing research often requires lower-level access to the signal or channel state information
- Built open-source system based on Xilinx RFSoC board
  - Configurable data-paths for flexible bandwidth, MIMO-order
  - Memory-based design (to speed 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

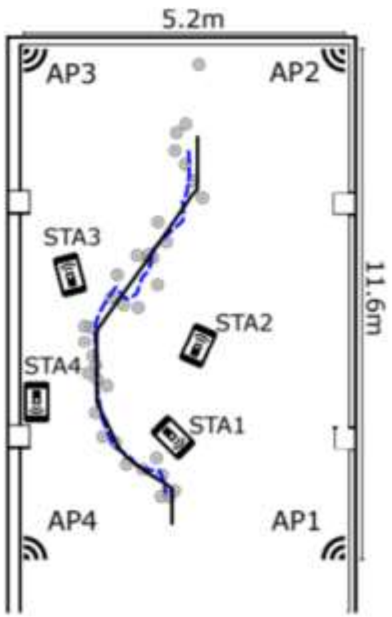


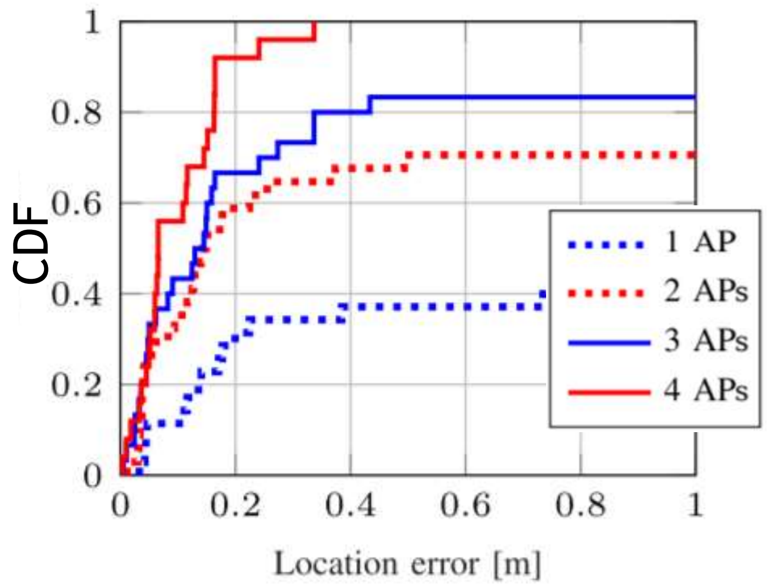
J. O. Lacruz et al., "A real-time experimentation platform for sub-6 GHz and millimeter-wave MIMO systems", *ACM MobiSys*, 2021

Passive Mm-Wave Localization

- mm-wave provides high accuracy due to the high bandwidth and large antenna arrays
  - Tracking changes of the channel impulse response over time allows classifying reflections into static and mobile
- Challenges:
  - Sparse multi-path environment
  - Specular (mirror-like) reflections
  - Weakness of the reflected paths
- Results:
  - Needs dense deployment
  - Decimeter-level accuracy

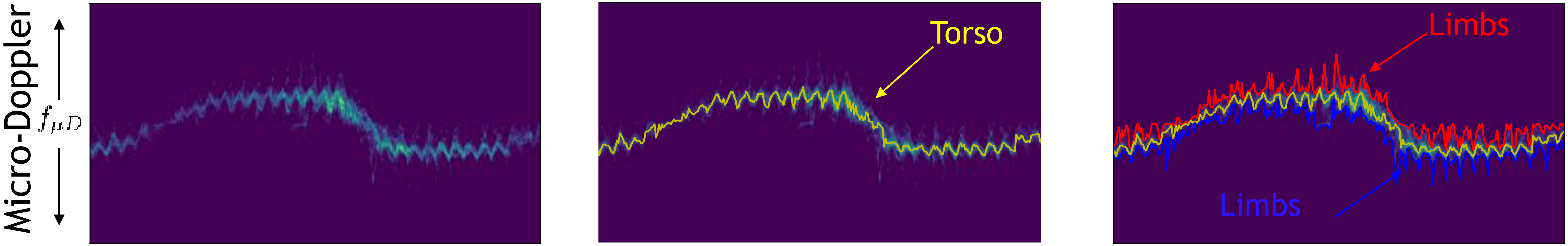






Beyond Passive Localization

- 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 signal, not straightforward 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

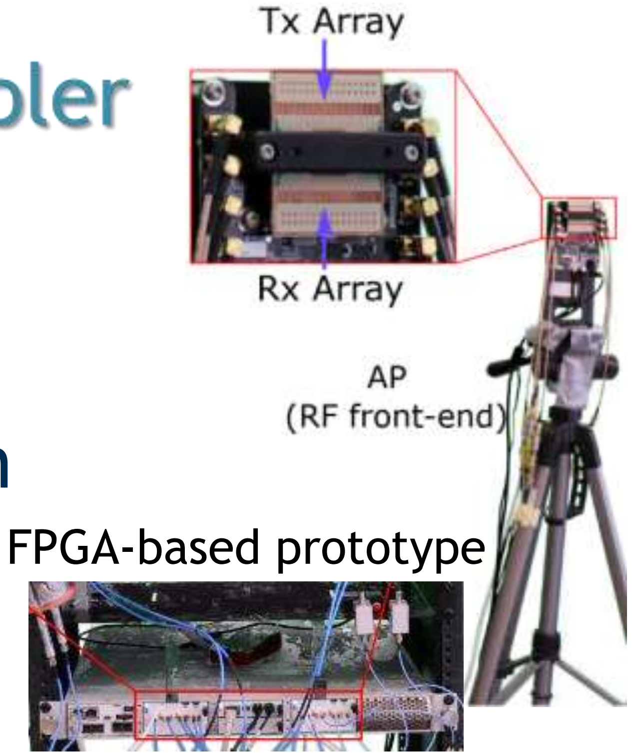
Wavelength

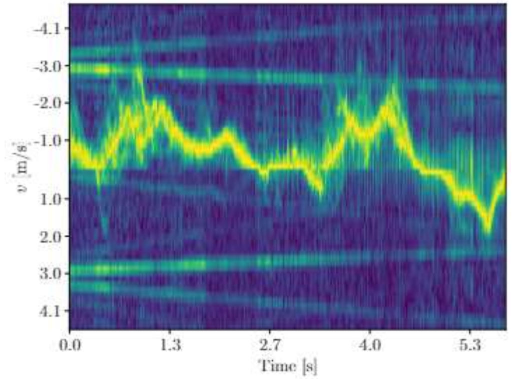
Vibration frequency

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

Mm-wave JCAS Micro-Doppler

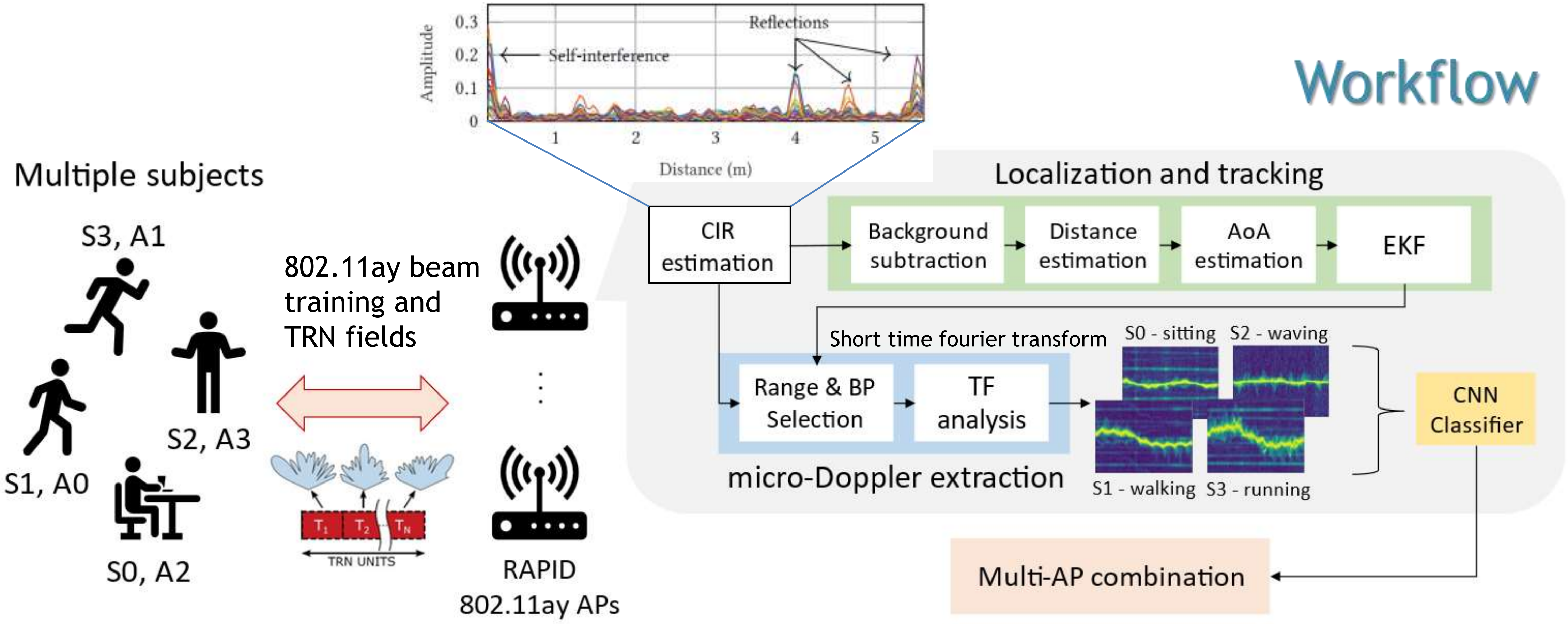
- Wide bandwidth (400 MHz - 2 GHz) required to track small movements
- Mono-static design: operate one MIMO RF chain as transmitter and one as receiver
  - Low self-interference due to directional mm-wave antenna arrays
- Passive localization for multi-person tracking using beam training information (SLS, SSB)
- Micro-doppler extraction using a sequence of data packets with training fields (TRN, CSI-RS)
- ML-based activity recognition and person identification





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

Workflow



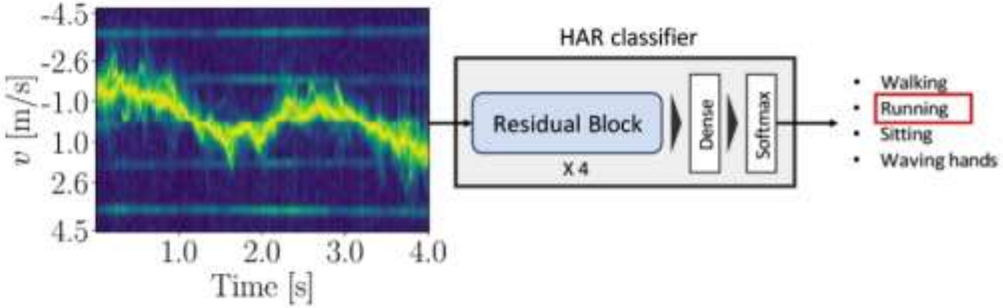
- Phase estimation from Channel Impulse Response changes
- Inter-arrival time determines maximum velocity, length of packet sequence determines velocity resolution
- Sparse estimation to deal with random packet inter-arrival times

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

Demo

Multi person/Multi AP

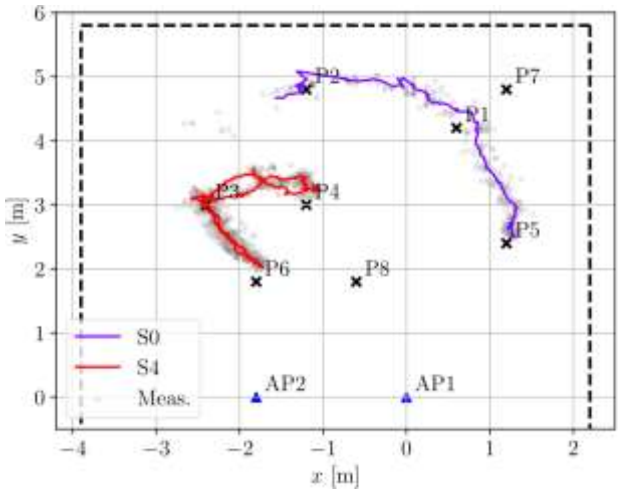
Activity classification

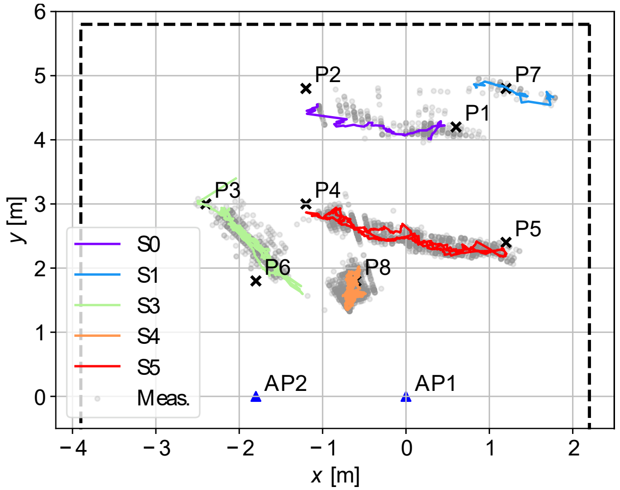


institute IMdea networks

Activity recognition and person identification

- 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**

Current Work: Multi-Static Micro-Doppler Extraction

- Previous design required simplified full-duplex operation, which may not be supported by communication hardware
- Sensing should make use of the many different available links in a wireless network to learn more about the environment
- Some of the challenges:
  - **Much** harder to see reflections at all (compared to monostatic design)
  - Reflections are highly angle dependent
  - Phase noise and CFO on the order of 100s of kHz and a Doppler of a few kHz!
  - No synchronization among transmitter and receiver; random timing offsets and sampling time offsets
    → Communication devices correct those as part of the channel but we can’t do that without loosing the sensing information
  - Merging information from multiple APs