

A Tutorial on Integrated Sensing and Communications: From Wireless Sensing to Network Intelligence

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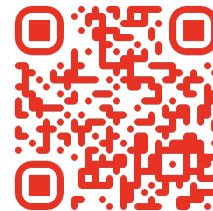
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Research Group Website: <http://mentis.info>

IEEE NETSOFT “Autonomous and Reliable Softwarized Networks in the
Age of Distributed Intelligence” – Berlin, Germany – June 29, 2026

The speaker

Dr. Francesca Meneghello



- Principal Research Scientist at the Institute for Intelligent Networked Systems, Northeastern University, USA
- PhD in Telecommunications Engineering 2022 from the Department of Information Engineering, University of Padova, Italy
- Fulbright-Schuman Scholar, Northeastern University, USA 2023



Northeastern University
**Institute for Intelligent
Networked Systems**



MENTIS research lab

- Prof. Francesco Restuccia
- Research Group
 - 12 PhD students, 1 Research Scientist
 - Mainly funded by NSF and DoW



- Research Focus
 - Cyber-physical AI-driven systems
 - **networking**, **learning**
 - ... and their **hardware** interfaces

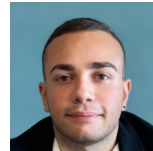
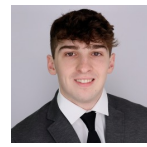
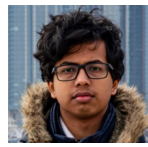
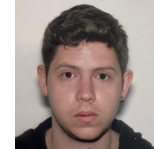


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 - ISAC algorithms
- 4. Will sensing be integrated in wireless networks?**
 - Challenges and research directions

1

Why ISAC?

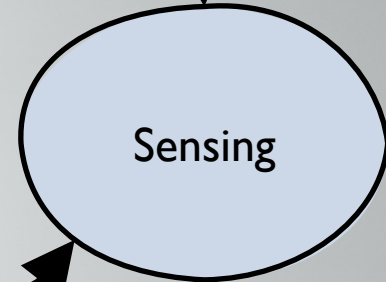
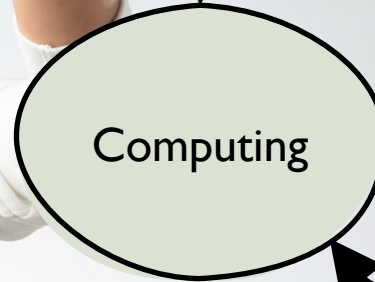
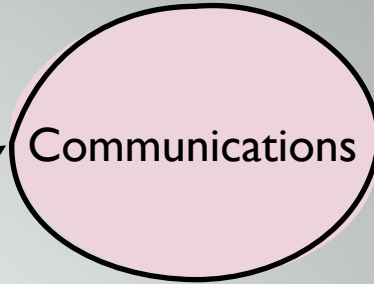
- Motivations



Physical
world



Digital
world



Virtual
reality

Telemedicine

Augmented
reality

Digital twin

Metaverse

Indoor
monitoring

Telepresence



**New paradigm for Autonomous
and Reliable Softwarized Networks**

**New applications in the Age
of Distributed Intelligence**

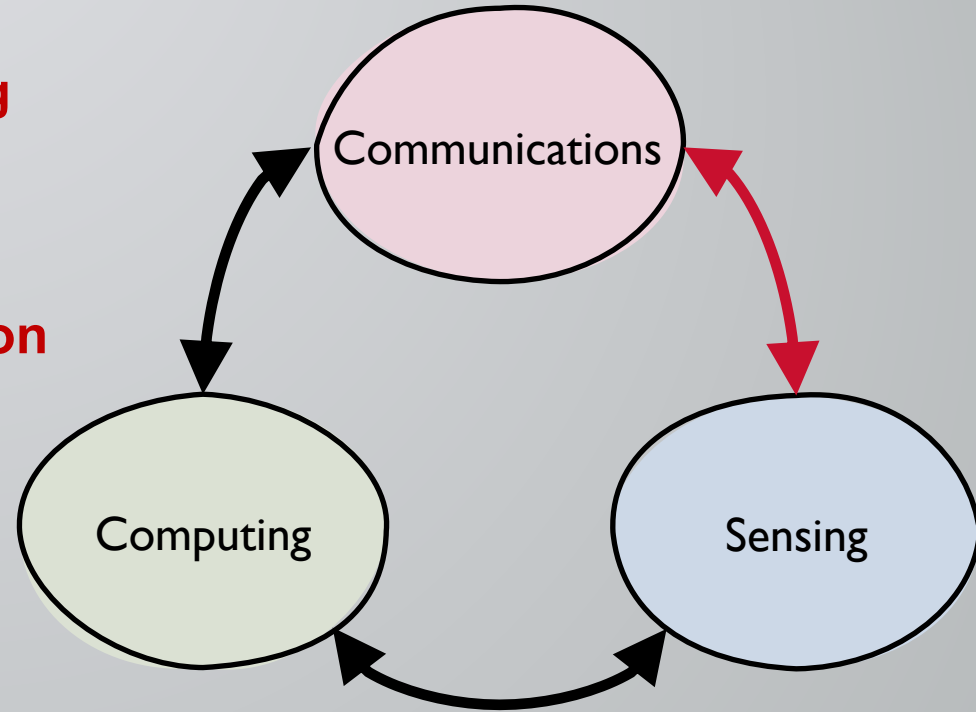
Integrated Sensing and Communications (ISAC)

1. Communication-assisted sensing

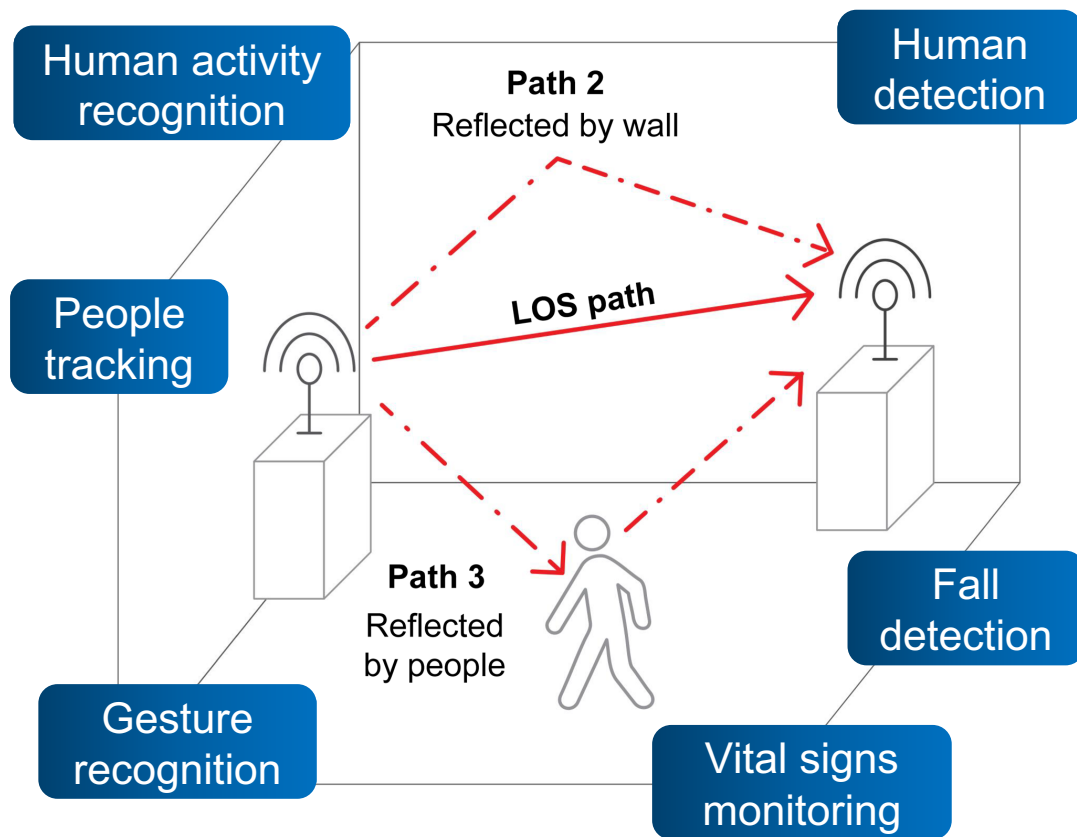
- ✓ Radio-waves for sensing

2. Sensing-assisted communication

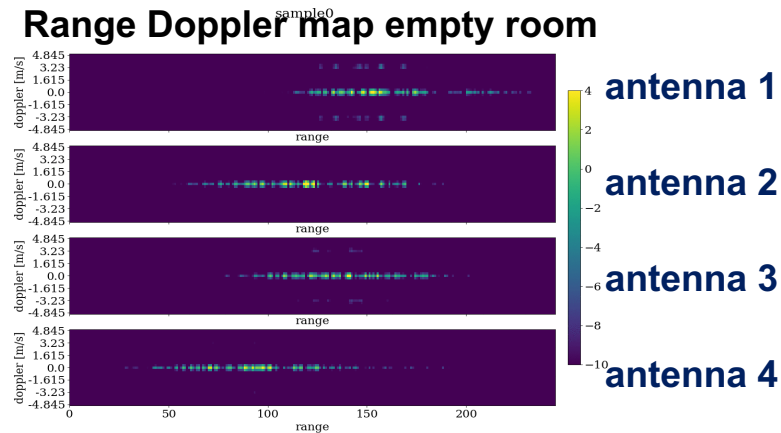
- ✓ Services context adaptation



Communication-assisted sensing



Range Doppler map empty room



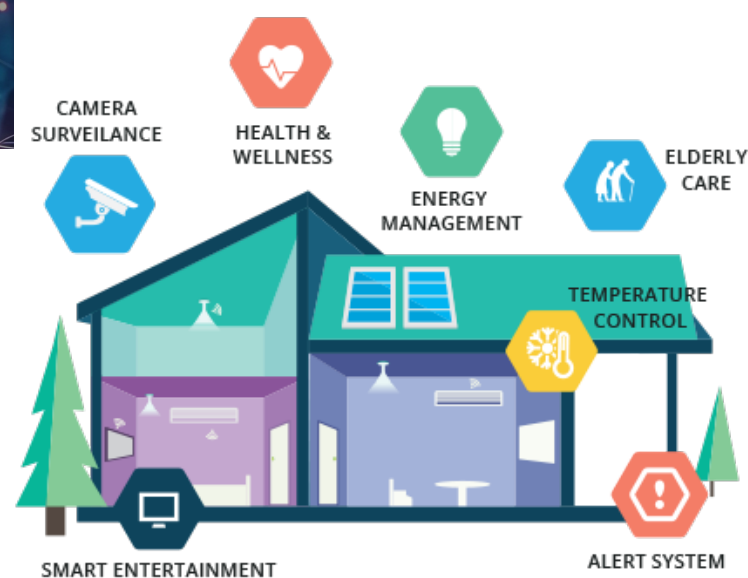
Range Doppler map walking person



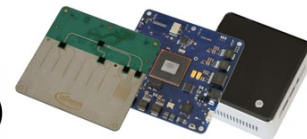
Communication-assisted sensing

Advantages over other sensing technologies

- **privacy preserving**: no images of subjects/scenes are captured
- **robust**: works also in the presence of dust and smoke, and in low light conditions
- **low-cost**: deploying specific hardware is not required, wireless communication devices can be used
- **communication-centric**: additional services on top of an existing one
- **user friendly**: users are not required to wear any device for health monitoring



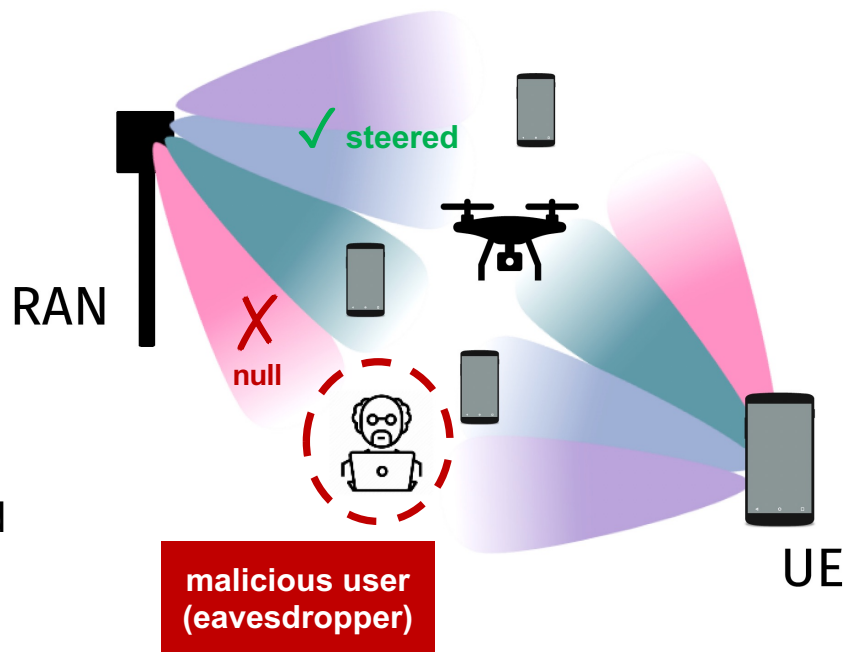
- Ad-hoc devices (RADARs)
 - + precision, customization
 - cost
- Commercial devices (Wi-Fi)
 - + availability, dual-functioning
 - resolution



Sensing-assisted communication

Sensing info about the propagation environment is fed back to optimize the communication link:

- **predictive beamforming**: less beam training → steer/track beams from position and velocity
- **reduce pilot and CSI feedback overhead**: higher spectral/energy efficiency
- **proactive handover and mobility**: predict link loss and switch before failure, no beam sweeping
- **physical-layer security**: place radiation nulls toward detected malicious users
- **smarter resource allocation**: schedule power, users and random-access from the sensed scene



Who cares about ISAC?

IEEE ISAC 2026

Lisbon, Portugal

15 - 18 November 2026

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The aim of this Emerging Technology Initiative is to explore and support a wide variety of research directions and standardization opportunities related to **Integrated Sensing and Communication (ISAC)**. ISAC refers to the design paradigm and corresponding enabling technologies that combine sensing and communication systems to utilize resources efficiently and even to pursue mutual benefits.

ISAC can acquire two main advantages over dedicated sensing and communication functionalities:

1) **Integration Gain** to efficiently utilize congested resources, and even more interesting, 2) **Coordination Gain** to balance dual-functional performance or/and perform mutual assistance. Benefiting from these two advantages, ISAC has been recently proposed for numerous emerging applications, including but

are not limited to, vehicular network, environmental monitoring, remote sensing, IoT, smart city as well as indoor services such as human activity and gesture recognition. More importantly, ISAC has been recently identified as an enabling technology for B5G/6G, and the next-generation Wi-Fi system.

Wi-Fi sensing through the IEEE 802.11bf amendment

About Us

Standards

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MAC

IEEE 802.11bf-2025

IEEE Standard for Information Technology -- Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks -- Specific Requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications - Amendment 4: Enhancements for Wireless LAN Sensing

O-RAN alliance and ISAC workshop – June 4, 2026



O-RAN ALLIANCE nGRG and ISAC Workshop



4 June • 8:30am-7:30pm PDT

ONLINE

from Seattle, USA

ISAC Workshop

The ISAC workshop, organized by O-RAN ALLIANCE's Industry Engagement Focus Group (IEFG), dives deep into various aspects of Integrated Sensing and Communications (ISAC) – standards, architecture, implementation, role of open interfaces, and path to 6G native sensing. Discussions will span from current state of ISAC implementations, performance, and validating testing to path to commercialization. We will examine how RAN sensing can leverage E3 (Edge-Enhanced Exposure) interface and dApps to support ISAC use cases such as drone swarm sensing and detection.

O-RAN IEFG is co-chaired by: AT&T - Pavan Gupta, NEC - Marko Babovic, Radisys - Ganesh Shenbagaraman.

Agenda

Pacific Daylight Time zone (PDT)

12:45 - 1:05 pm | ISAC Keynote - Making ISAC Real in Open RAN: The Path to 6G Native Sensing

AT&T - Brian Daly

▶ Watch video

🔊 Listen to podcast

1:05 - 1:25 pm | ISAC in Open RAN: System Design and Path to Realization

AT&T - Dr. Salam Akoum

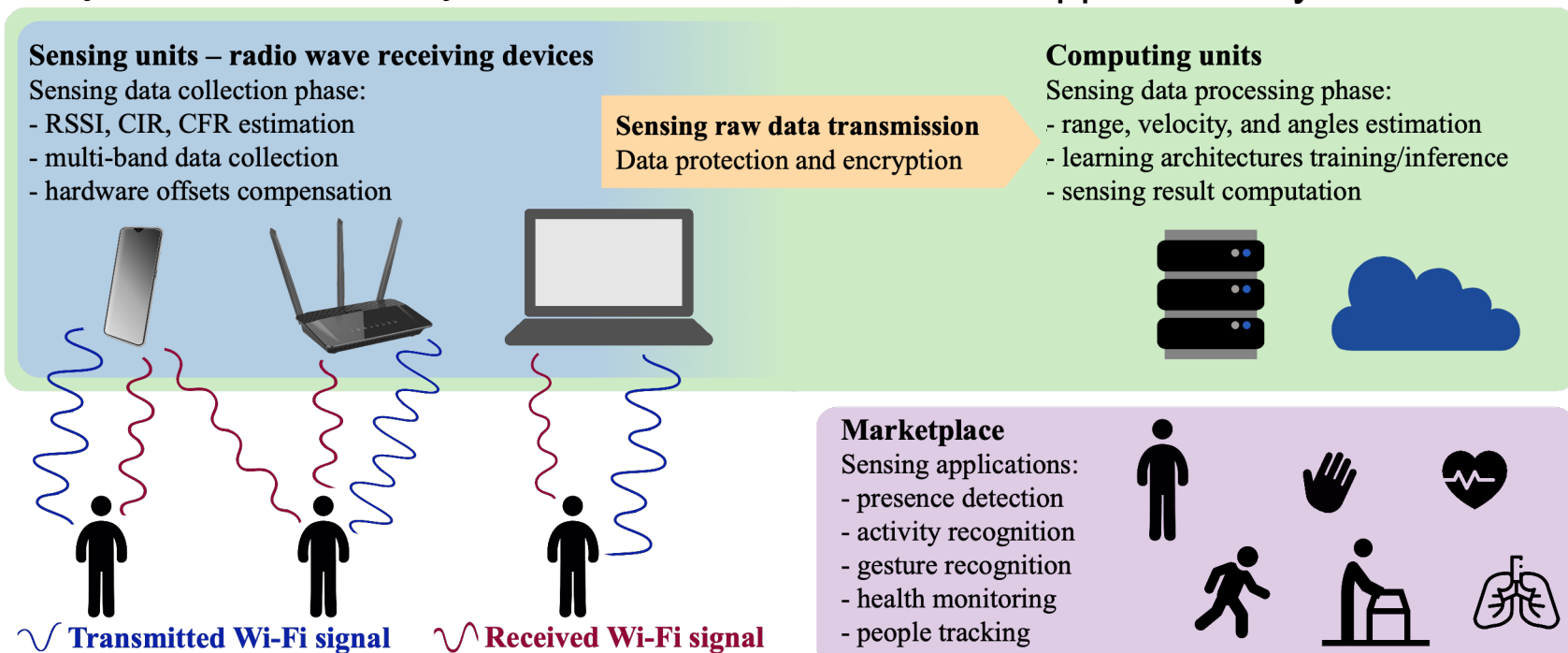
▶ Watch video

🔊 Listen to podcast

Wireless ISAC – research directions

1. Sensing primitives

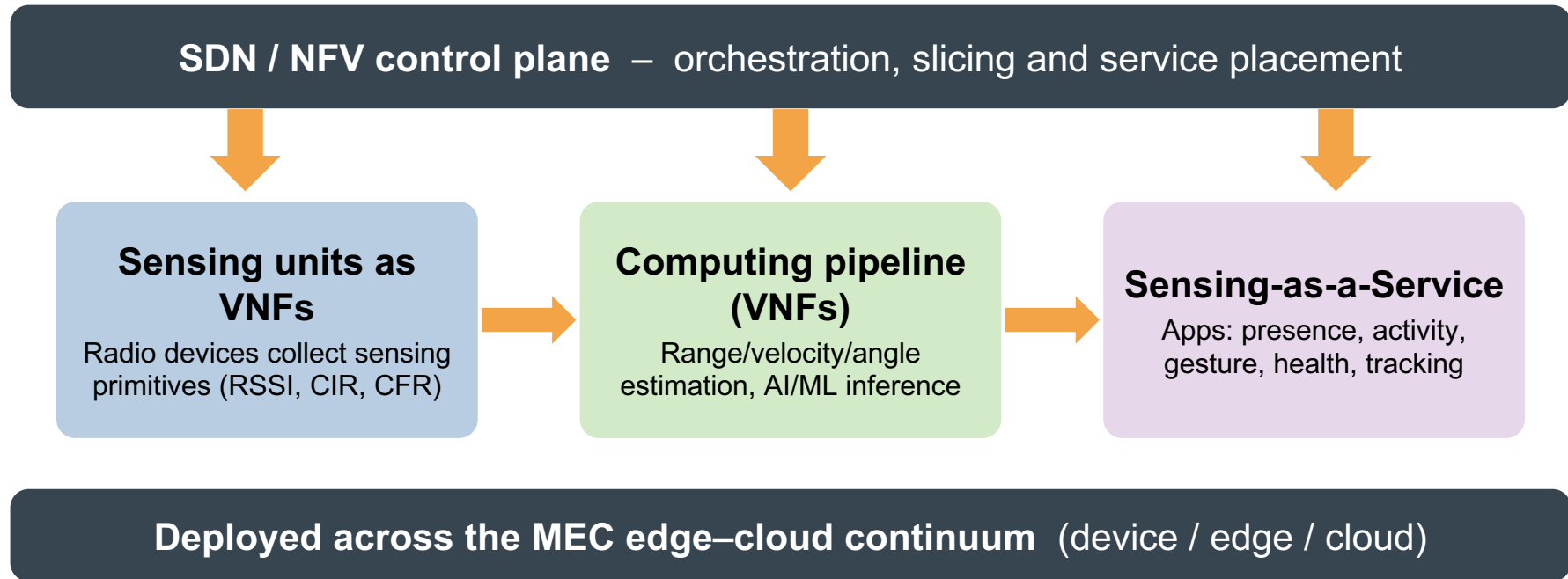
- Physical and MAC layers



2. Sensing algorithms

- Application layer

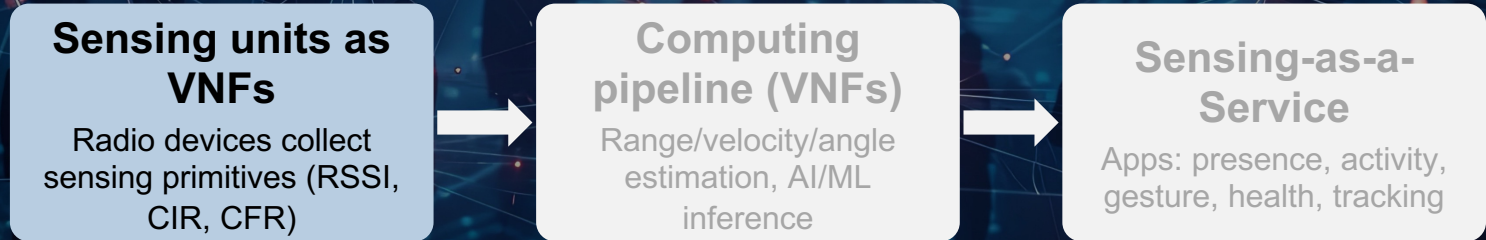
ISAC pipeline as a softwarized service function chain



2

What information can we use for sensing?

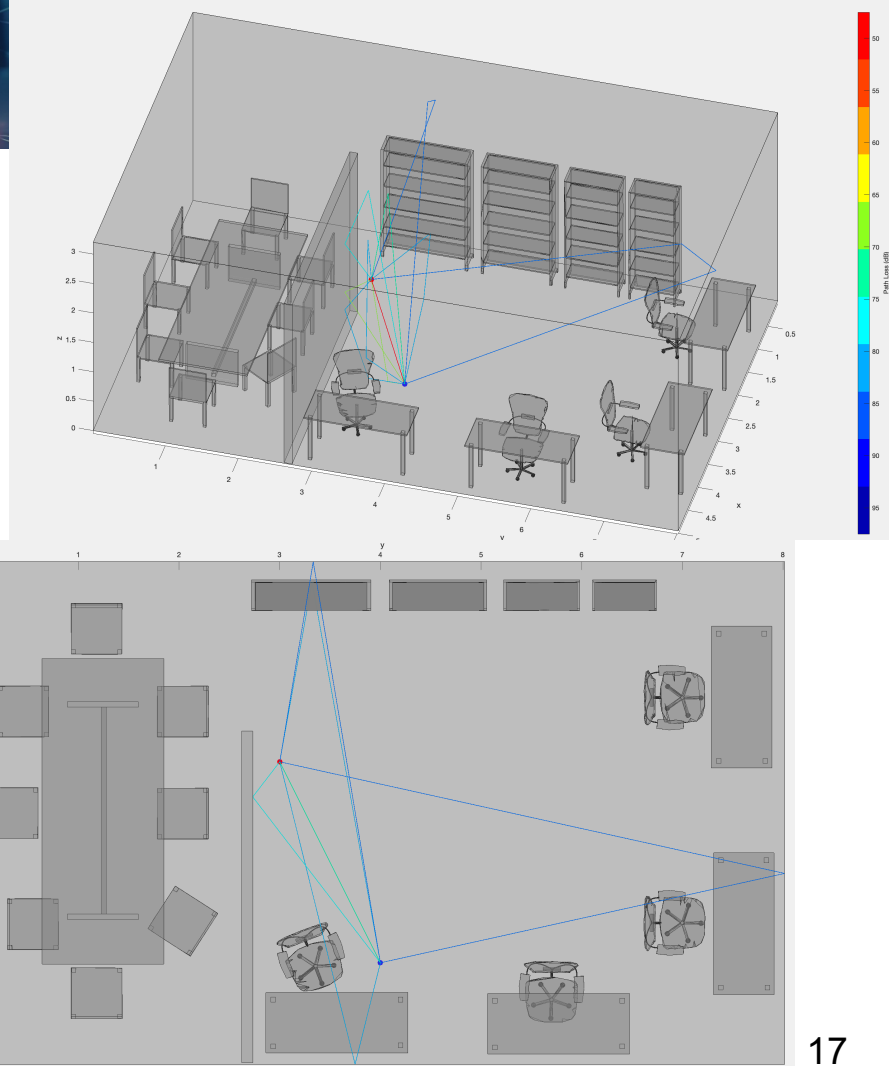
- Sensing primitives



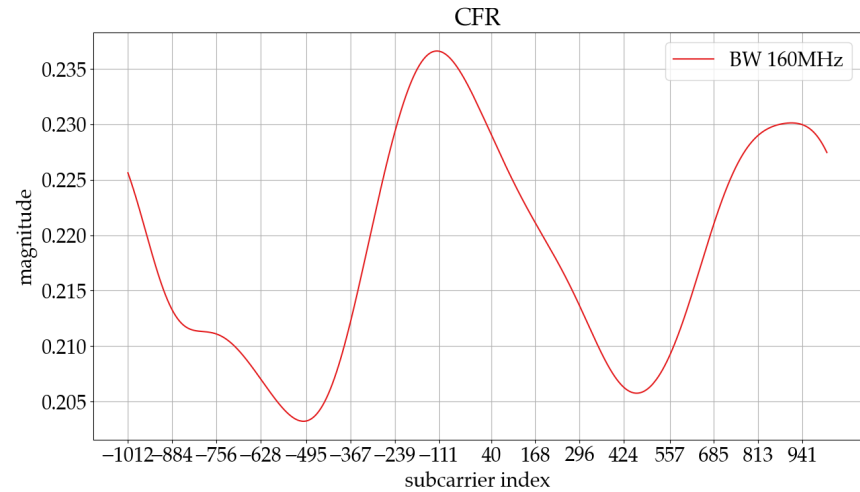
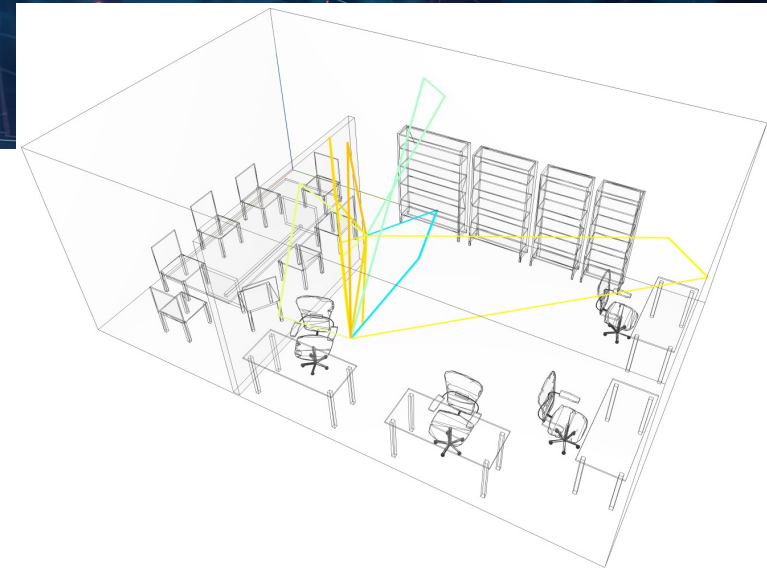
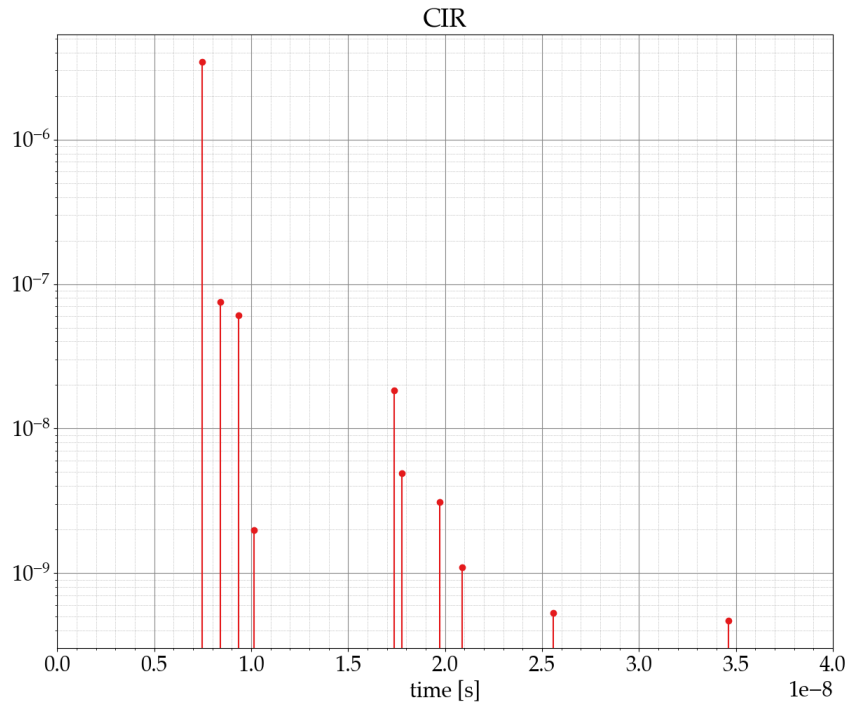
Sensing primitives

Channel state information (CSI)

- continuously estimated: **channel estimation** as a proxy for sensing
- necessary information for the correct functioning of wireless networks
- used for properly decoding and precoding data
- describes the way radio waves propagate from TX to RX through multiple-paths
- affected by obstacles in the propagation environment, i.e., it reveals their presence
- Time domain:**
channel impulse response (CIR)
- Frequency domain:**
channel frequency response (CFR)



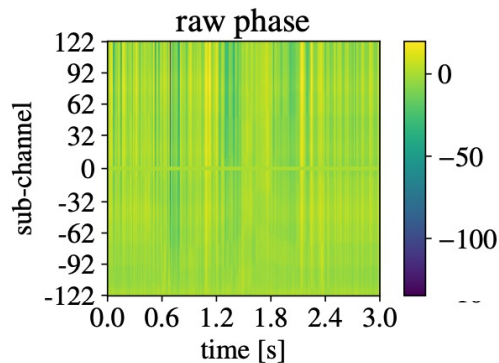
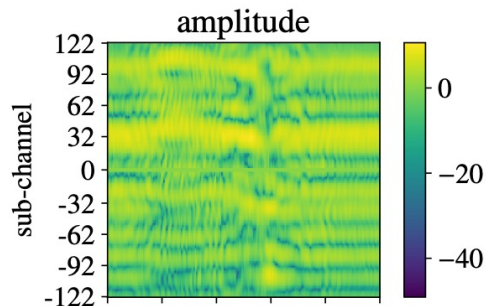
Wireless sensing



Diversity for improving sensing performance

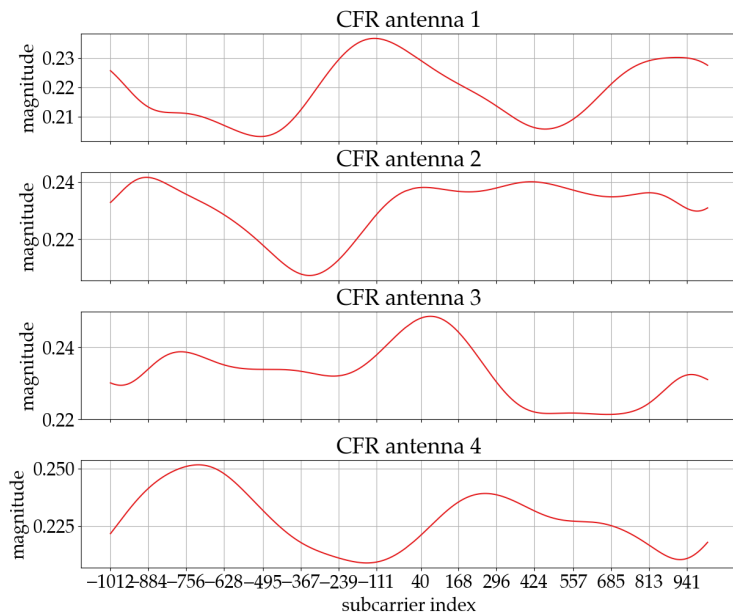
- **Frequency diversity**

- OFDM or OFDMA
- Data from multiple transmission bands in the sub-7GHz band or mmWave



- **Spatial diversity**

- MIMO (multiple-input multiple-output)
- Cooperative sensing



The CFR – MIMO OFDM

- Describes the **multi-path propagation**
 - P copies of the TX signal are collected at the receiver

$$H_{k,m_t,m_r}(n) = A_{k,m_t,m_r}(n)e^{j\theta_{k,m_t,m_r}(n)}$$
$$= \sum_{p=0}^{P-1} \underbrace{A_{p,m_t,m_r}(n)}_{\text{attenuation}} e^{-j2\pi \underbrace{(f_c + k/T)}_{\text{OFDM sub-channel frequency}} \underbrace{\tau_{p,m_t,m_r}(n)}_{\text{propagation delay}}}$$

OFDM sub-channel index
 $k \in \mathcal{K}$ OFDM sub-channel
 $\mathcal{K} = \{0, \dots, K-1\}$

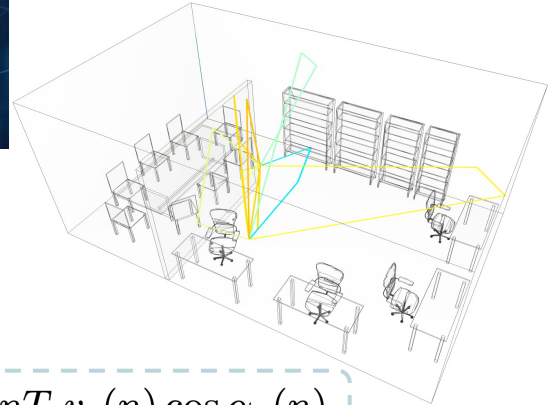
Tx antenna index

Rx antenna index

time index

copies of the TX signal collected at the receiver

Propagation delay



$$H_{k,m_t,m_r}(n) = \sum_{p=0}^{P-1} A_{p,m_t,m_r}(n) e^{-j2\pi(f_c + k/T) \tau_{p,m_t,m_r}(n)}$$

Doppler effect $\Delta_p^D(n) = -nT_c v_p(n) \cos \alpha_p(n)$

$$\tau_{p,m_t,m_r}(n) = \frac{1}{c} \left[\ell_p(n) + \Delta_p^D(n) + \Delta_{p,m_t}^{\text{tx}}(n) + \Delta_{p,m_r}^{\text{rx}}(n) \right]$$

path length

angle of departure (AoD)

$$\Delta_{p,m_t}^{\text{tx}}(n) = m_t \sin(\theta_{\text{tx},p}(n)) d_{\text{tx}}$$

angle of arrival (AoA)

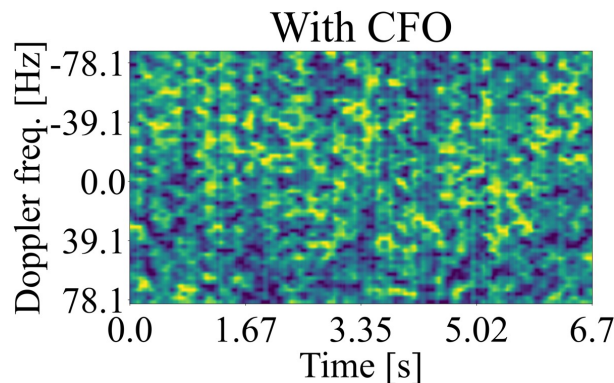
$$\Delta_{p,m_r}^{\text{rx}}(n) = m_r \sin(\theta_{\text{rx},p}(n)) d_{\text{rx}}$$

Challenge in extracting sensing primitives

- The CFR from commercial devices is affected by **hardware artifacts** that
 - introduce an **unwanted phase offset**

$$\bar{H}_k(n) = H_k(n)e^{j\theta_{\text{offs},k}}$$

$$\theta_{\text{offs},k} = -2\pi(f_c + k/T)\tau_{\text{TO}} + 2\pi f_{\text{CFO}}nT_c$$



- **hide the Doppler shift** preventing its direct computation
- require **software compensation (phase sanitization)**

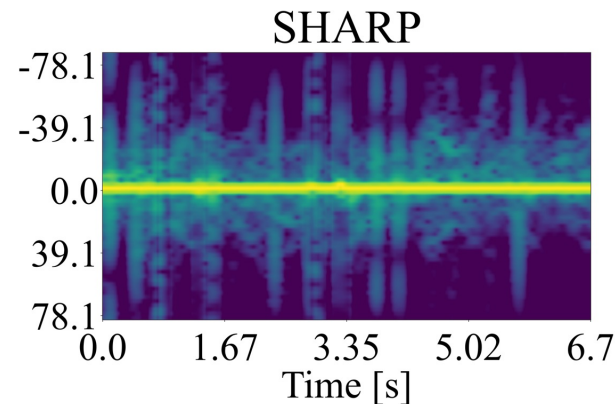
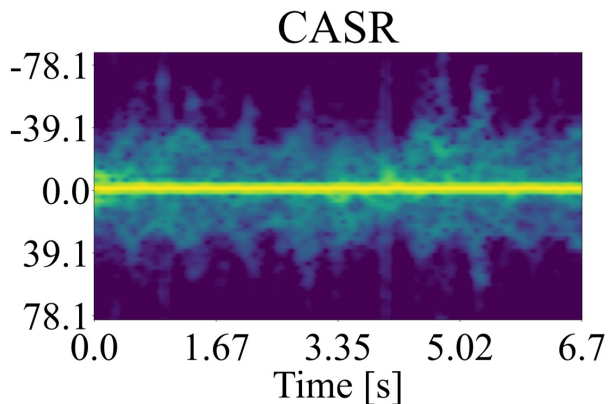
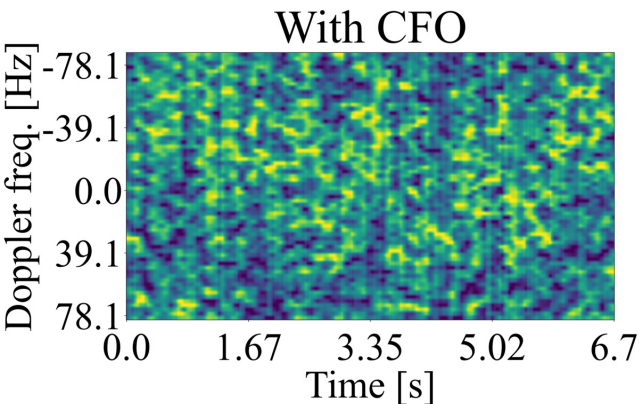
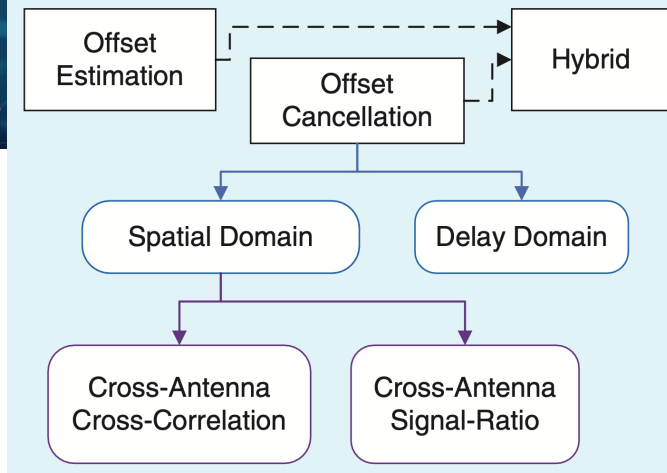
CFR offset compensation in software

- **Spatial domain cancellation**

- use one antenna as reference (CASR)

- **Delay domain cancellation**

- use one multi-path component as reference (SHARP)



Delay domain cancellation

- **Intuition:** Each multi-path component in the CFR is affected by the same phase offset

$$\bar{H}_k(n) = H_k(n)e^{j\theta_{\text{offs},k}}$$

- **Steps:** (applied to each antenna separately)

1. separate the contribution of the different components
2. use one of them as a reference to remove the phase offset

$$\mathbf{h} = [\bar{H}_{-K/2}, \dots, \bar{H}_0, \dots, \bar{H}_{K/2-1}]^T$$

ℓ_1 regularization

$$\mathbf{P1} : \mathbf{r} = \underset{\tilde{\mathbf{r}}}{\text{argmin}} \quad \|\mathbf{h} - \mathbf{T}\tilde{\mathbf{r}}\|_2^2 + \lambda \|\tilde{\mathbf{r}}\|_1$$

each non-zero entry in $\mathbf{r}$
reveals the presence of a path

$$\mathbf{r} = e^{j(\theta_{\text{CFO}} + \theta_{\text{PPO}} + \theta_{\text{PA}})} \begin{bmatrix} A_0 e^{-j2\pi f_c \tau_0} \\ \vdots \\ A_{P'-1} e^{-j2\pi f_c \tau_{P'-1}} \end{bmatrix}$$

matrix describing the contribution of
candidate multi-path components

$$\mathbf{T}_k = e^{-j2\pi k(\tau_{\text{SFO}} + \tau_{\text{PDD}})/T} \begin{bmatrix} e^{-j2\pi k\tau_0/T} & \dots & e^{-j2\pi k\tau_{P'-1}/T} \end{bmatrix}$$

Sanitized phase

GitHub repository with
code, dataset and paper



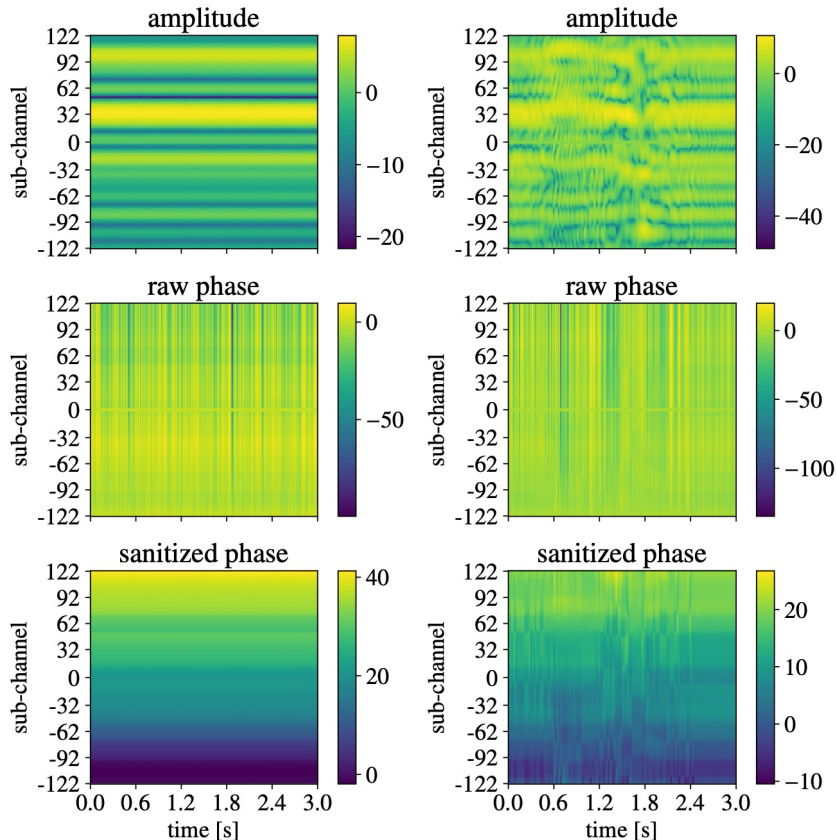
$$\bar{H}_k(n) = H_k(n)e^{j\theta_{\text{offs},k}}$$

- **P1** is a compressive sensing reconstruction problem
 - solved through quadratic optimization
- Select the **strongest path as a reference** to remove the offset

$$\hat{H}_k = \hat{A}_k(n)e^{j\hat{\phi}_k(n)}$$

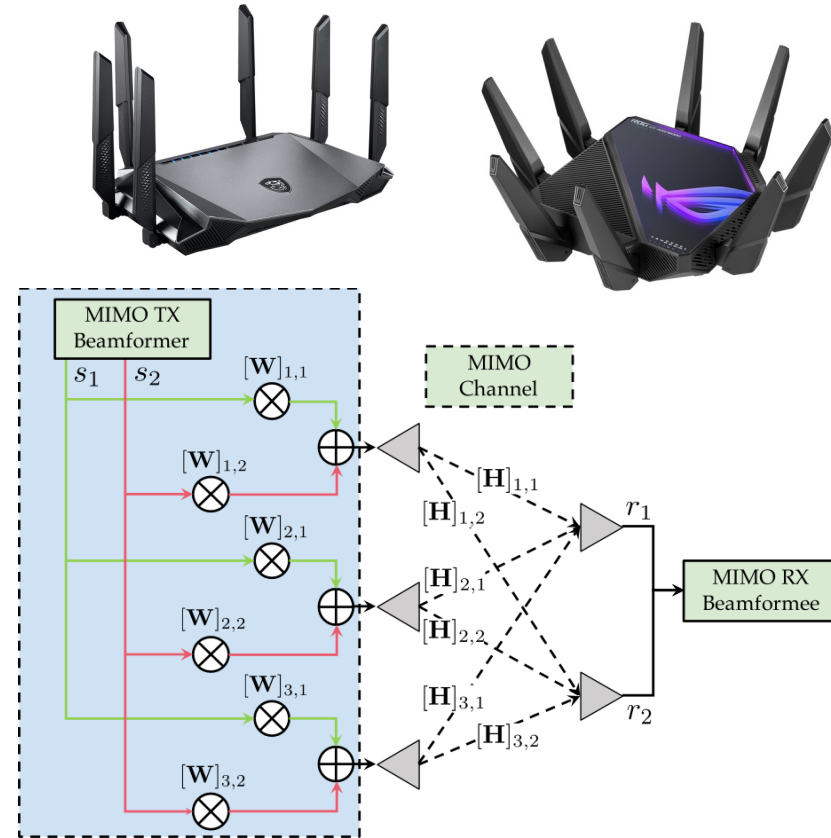
$$= A_{p^*} \sum_{p'=0}^{P'-1} A_{p'} e^{-j2\pi(f_c+k/T)\hat{\tau}_{p'}}$$

$$\simeq A_{p^*} e^{j2\pi(f_c+k/T)\tau_{p^*}} H_k$$

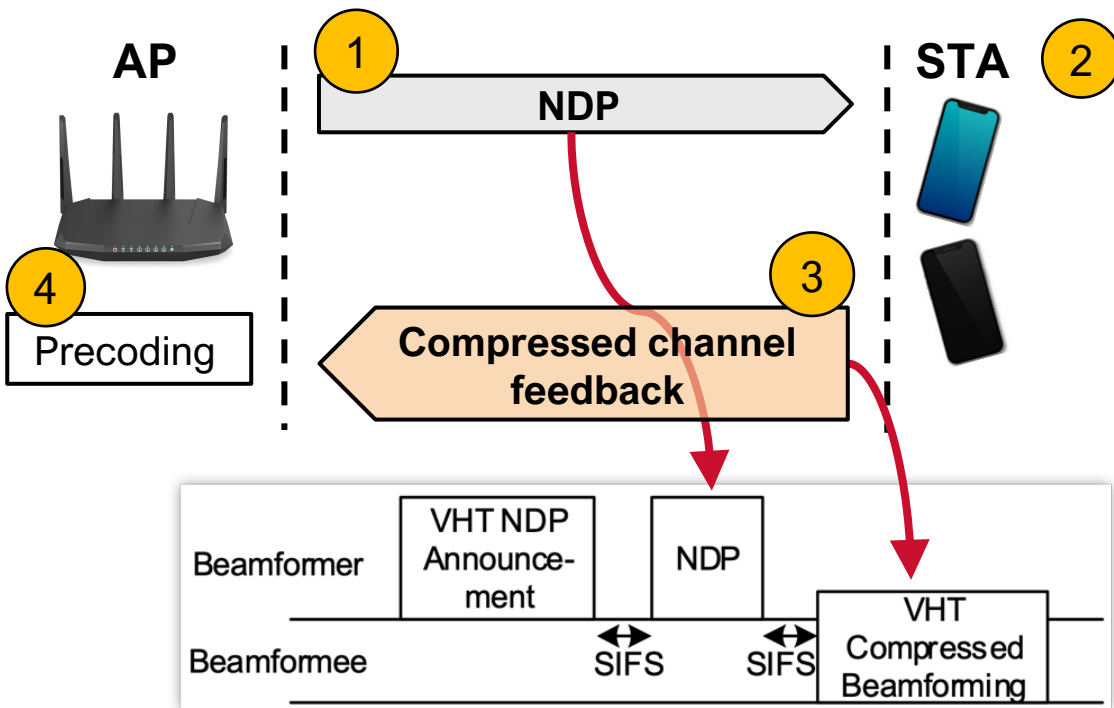


Sensing through MIMO systems – preliminaries

- MIMO provides several advantages
 - improve robustness to fading → **DIVERSITY**
 - increase data rate → **MULTIPLEXING**
 - increase SNR → **BEAMFORMING**
- Simultaneously transmit **multiple data** (or spatial) **streams** over **independent fading channels**
- Requires to perform **channel sounding** to combine the streams at the different TX antennas through **precoding weights**
→ **good for sensing!**



Beamforming feedback



For each subcarrier k

1. Estimate $\mathbf{H}_k$
2. Compress $\mathbf{H}_k$
 - a. SVD $\mathbf{H}_k^T = \mathbf{U}_k \mathbf{S}_k \mathbf{Z}_k^\dagger$
 - b. Beamforming feedback $\mathbf{V}_k$: first N_{SS} (no. spatial streams) columns of $\mathbf{Z}_k$
 - c. Beamforming feedback angles $\phi_{k,\ell,i}$ $\psi_{k,\ell,i}$ through Givens rotations
 - d. $\phi_{k,\ell,i}$ $\psi_{k,\ell,i}$ quantization
3. Feed back the angles to the TX

52 0.032155 BeijingX_76:65:3e ... 1a:e0:65:4e:ea:ca ... 802.11 61 VHT/HE NDP Announcement, Sounding Dialog Token=114, Flags=.....C
 53 0.033717 1a:e0:65:4e:ea:ca BeijingX_76:65:3e 802.11 1011 Action No Ack, SN=28, FN=0, Flags=.....C

Beamforming feedback for sensing

- The beamforming feedback angles $\phi_{k,\ell,i}$ $\psi_{k,\ell,i}$
 1. are derived from the beamforming feedback matrix $\mathbf{V}_k$
 - **can be used as a proxy of the MIMO CFR $\mathbf{H}_k$**
 2. are obtained from the NDP that is not beamformed
 - are not affected by inter-stream, inter-user interference (ISI / IUI)
 3. are transmitted in **clear text**
 - can be captured by any Wi-Fi-enabled device

Beamforming feedback angles

Wireshark · Packet 59 · 1696598795

```
> Frame 59: 1011 bytes on wire (8088 bits), 1011 bytes captured (8088 bits)
> Radiotap Header v0, Length 36
> 802.11 radio information
> IEEE 802.11 Action No Ack, Flags: .....C
> IEEE 802.11 Wireless Management
  > Fixed parameters
    > Category code: HE (30)
      > HE Action: HE Compressed Beamforming And CQI (0)
        > Total length: 947
          > HE MIMO Control: 0xcd2008099
          > Average Signal to Noise Ratio
            > Feedback Matrices
              SCIDX: -500, phi11:3, phi12:0, phi13:0, psi21:0, psi31:6, psi41:2, phi22:1, phi32:2, psi32:14, psi42:10
              SCIDX: -496, phi11:3, phi12:0, phi13:0, psi21:0, psi31:6, psi41:2, phi22:1, phi32:2, psi32:14, psi42:10
              SCIDX: -492, phi11:3, phi12:0, phi13:0, psi21:0, psi31:6, psi41:2, phi22:1, phi32:2, psi32:14, psi42:10
              SCIDX: -488, phi11:3, phi12:0, phi13:0, psi21:0, psi31:6, psi41:2, phi22:1, phi32:2, psi32:14, psi42:10
              SCIDX: -484, phi11:3, phi12:0, phi13:0, psi21:0, psi31:6, psi41:2, phi22:0, phi32:2, psi32:14, psi42:10
              SCIDX: -480, phi11:3, phi12:0, phi13:1, psi21:0, psi31:6, psi41:2, phi22:0, phi32:2, psi32:13, psi42:10
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              SCIDX: -468, phi11:3, phi12:0, phi13:1, psi21:0, psi31:6, psi41:2, phi22:0, phi32:2, psi32:13, psi42:10
              SCIDX: -464, phi11:3, phi12:0, phi13:1, psi21:0, psi31:6, psi41:2, phi22:0, phi32:2, psi32:13, psi42:10
              SCIDX: -460, phi11:3, phi12:0, phi13:1, psi21:0, psi31:6, psi41:2, phi22:0, phi32:2, psi32:13, psi42:10
              SCIDX: -456, phi11:0, phi12:1, phi13:1, psi21:0, psi31:6, psi41:2, phi22:0, phi32:2, psi32:13, psi42:10
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              SCIDX: -448, phi11:3, phi12:0, phi13:1, psi21:0, psi31:6, psi41:2, phi22:0, phi32:2, psi32:13, psi42:10
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              SCIDX: -424, phi11:0, phi12:1, phi13:1, psi21:0, psi31:6, psi41:2, phi22:3, phi32:1, psi32:13, psi42:10
              SCIDX: -420, phi11:0, phi12:1, phi13:1, psi21:0, psi31:6, psi41:2, phi22:3, phi32:1, psi32:13, psi42:10
              SCIDX: -416, phi11:0, phi12:1, phi13:1, psi21:0, psi31:6, psi41:2, phi22:3, phi32:1, psi32:13, psi42:10
              SCIDX: -412, phi11:0, phi12:1, phi13:1, psi21:0, psi31:6, psi41:2, phi22:3, phi32:1, psi32:13, psi42:10
              SCIDX: -408, phi11:0, phi12:1, phi13:1, psi21:0, psi31:6, psi41:2, phi22:3, phi32:1, psi32:13, psi42:10
```

```
0000 00 00 24 00 6f 08 00 40 f4 bb a5 36 00 00 00 00 ..$ o: @ ...6...
0010 12 0c 78 14 40 01 dd a6 00 d2 00 10 18 03 04 00 ...x @ .....
0020 02 00 00 00 e0 00 00 00 9c 9d 7e 76 65 3e 1a e0 .....~ve>
```

☒ Show packet bytes

Help

Table 9-526b—HE Compressed Beamforming/CQI frame Action field format

Order	Information
1	Category
2	HE Action
3	HE MIMO Control (see 9.4.1.64)
4	HE Compressed Beamforming Report (see 9.4.1.65)
5	HE MU Exclusive Beamforming Report (see 9.4.1.66)
6	HE CQI Report (see 9.4.1.67)

Table 9-91b—HE Compressed Beamforming Report information

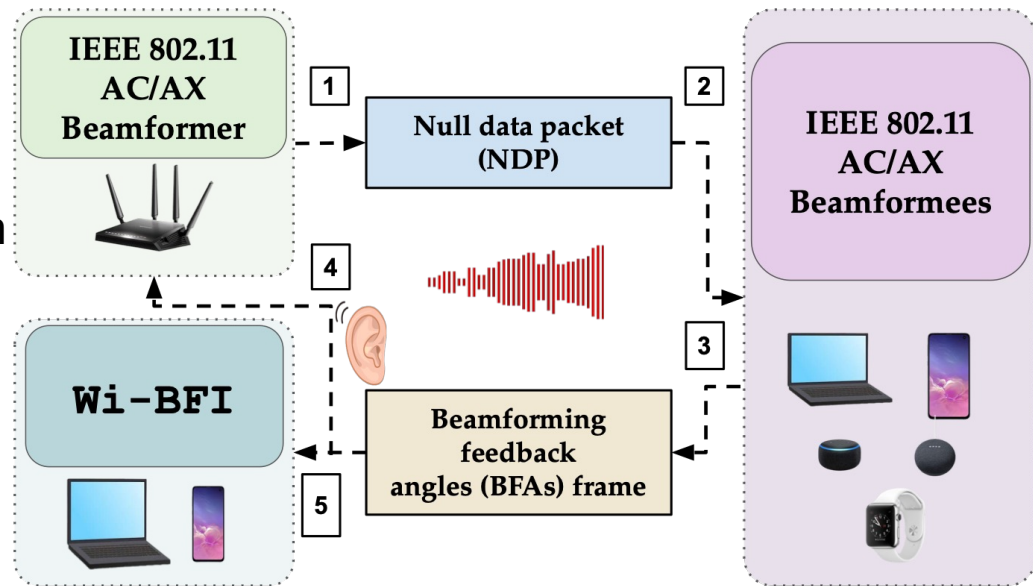
Field	Size (bits)	Meaning
Average SNR of Space-Time Stream 1	8	Signal-to-noise ratio at the beamformee for space-time stream 1 averaged over all data subcarriers. See Table 9-77.
...		...
Average SNR of Space-Time Stream Nc	8	Signal-to-noise ratio at the beamformee for space-time stream Nc averaged over all data subcarriers. See Table 9-77.
Compressed beamforming feedback matrix V for subcarrier $k = scidx(0)$	$N_a \times (b_\phi + b_\psi)/2$	Compressed beamforming feedback matrix defined in Table 9-71.
Compressed beamforming feedback matrix V for subcarrier $k = scidx(1)$	$N_a \times (b_\phi + b_\psi)/2$	Compressed beamforming feedback matrix defined in Table 9-71.
Compressed beamforming feedback matrix V for subcarrier $k = scidx(2)$	$N_a \times (b_\phi + b_\psi)/2$	Compressed beamforming feedback matrix defined in Table 9-71.
...		...
Compressed beamforming feedback matrix V for subcarrier $k = scidx(N_s - 1)$	$N_a \times (b_\phi + b_\psi)/2$	Compressed beamforming feedback matrix defined in Table 9-71.

53 0.033717 1a:e0:65:4e:ea:ca BeijingX_76:65:3e 802.11 1011 Action No Ack, SN=28, FN=0, Flags=.....C

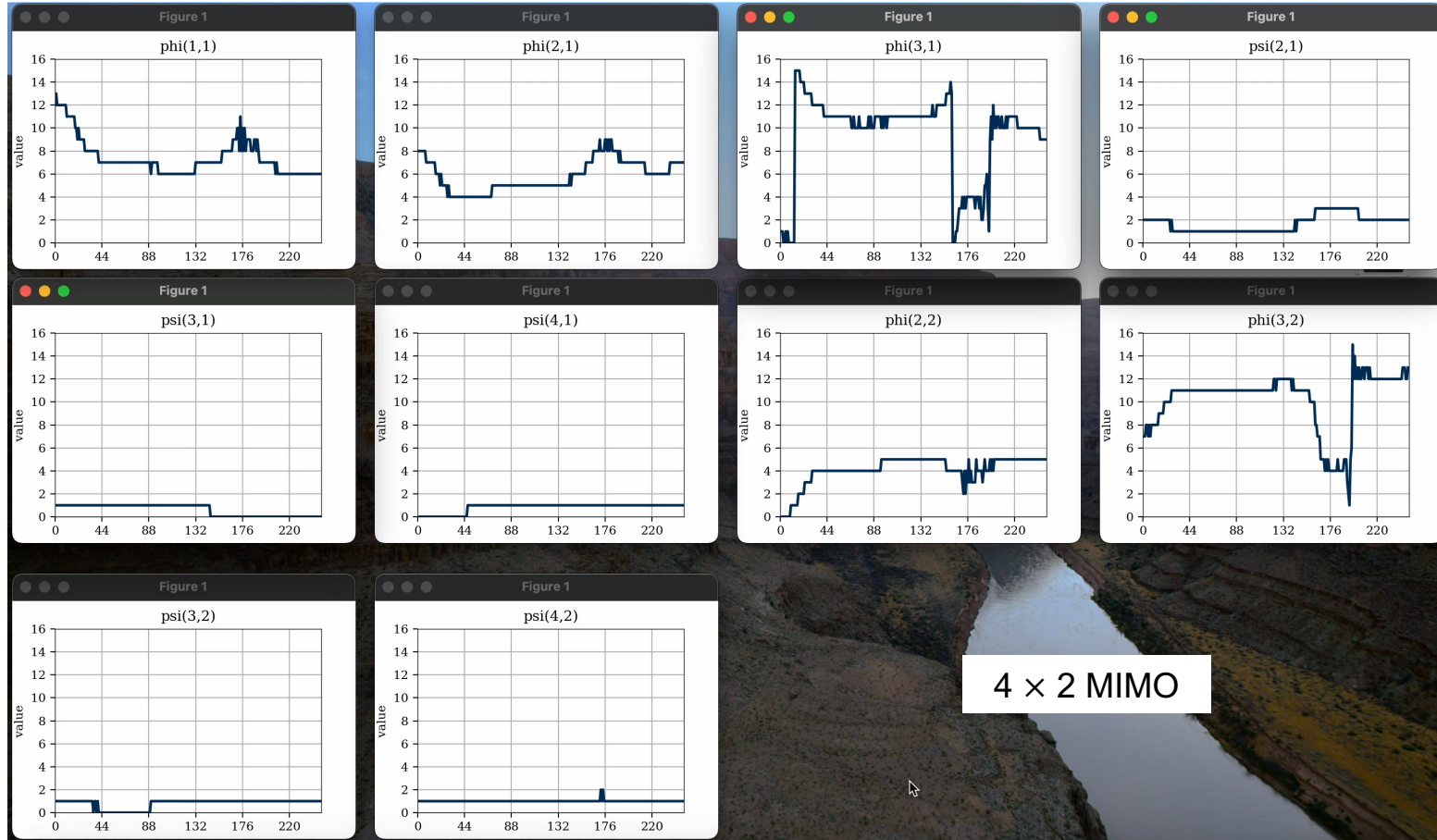
The Wi-BFI tool

```
52 0.032155 BeijingX_76:65:3e ... 1a:e0:65:4e:ea:ca ... 802.11 61 VHT/HE NDP Announcement, Sounding Dialog Token=114, Flags=.....C
53 0.033717 1a:e0:65:4e:ea:ca BeijingX_76:65:3e 802.11 1011 Action No Ack, SN=28, FN=0, Flags=.....C
```

1. **Capture** the beamforming feedback packet
2. **Decode** the **Wi-Fi BFAs** based on the network configuration
3. **Reconstruct** the beamforming feedback matrix



Captured beamforming feedback angles



How to get the CSI for sensing?

- The CSI is only available for communication on commercial devices



CSI will be available also for sensing **by standard** in new releases/amendments (e.g., **IEEE 802.11bf**)

Custom firmware/software to expose sensing primitives (e.g., Atheros CSI, Intel CSI extractors, NEXMON-CSI , AX-CSI, PicoScenese for 802.11)

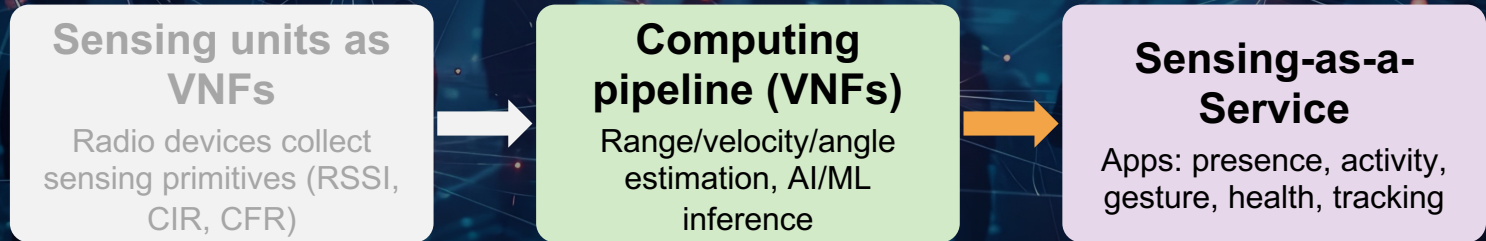
nexmon **AX-CSI**

Custom software to obtain and use **the MIMO beamforming feedback** as a proxy for the CFR

3

How can we develop sensing applications?

- ISAC algorithms – application layer



Model-based sensing algorithms

1. Use signal processing based on the wireless propagation models
2. Use the signal diversity in the different domains to obtain sensing parameters

Diversity domain	Spectrum computed along	Derived sensing parameter
Frequency	OFDM/OFDMA subchannels	Range of the target (ToA)
Space	Antenna array	Angular position (AoA, AoD)
Time	Subsequent time instants	Velocity (Doppler effect)

Multi-path parameters

ToA and AoA can be obtained through
inverse Fourier transformations

$$\Delta_f = 1/T$$

$$d_{rx} = d_{tx} = \lambda/2 = c/(2f_c)$$

ToA: IFFT over sub-channels k

$$\mathbf{H} = \sum_{p=0}^{P-1} A_p \phi(\theta_{rx,p}) \psi(\tau_p)^T$$

amplitude
attenuation

AoA: IFFT over the
receiver antennas m_r

$$[\phi(\theta_{rx,p})]_n = e^{-j\pi m_r \sin(\theta_{rx,p})}$$

$$\phi(\theta_{rx,p}) = [[\phi(\theta_{rx,p})]_0, \dots, [\phi(\theta_{rx,p})]_{M_r-1}]$$

$$[\psi(\tau_p)]_k = e^{-j2\pi k \Delta_f \tau_p}$$

$$\psi(\tau_p) = [[\psi(\tau_p)]_0, \dots, [\psi(\tau_p)]_{K-1}]$$

Nominal resolutions:

$$\Delta\tau_p = 1/B$$

bandwidth

$$\Delta\theta_{rx,p} = 360/(\pi M_r)$$

no. antennas

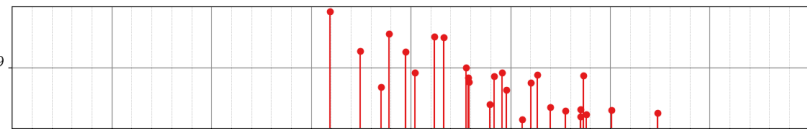
Similarly. **AoD:** IFFT over
the transmitter antennas m_t

Note: we consider baseband processing
here and remove the time index

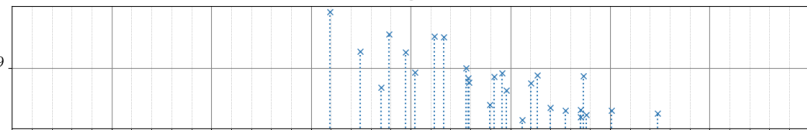
CIR from CFR through IFFT

CIR from collected data

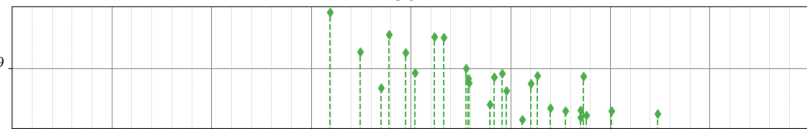
BW 20MHz



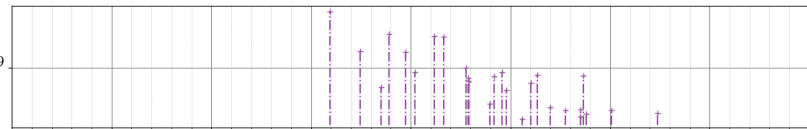
BW 40MHz



BW 80MHz



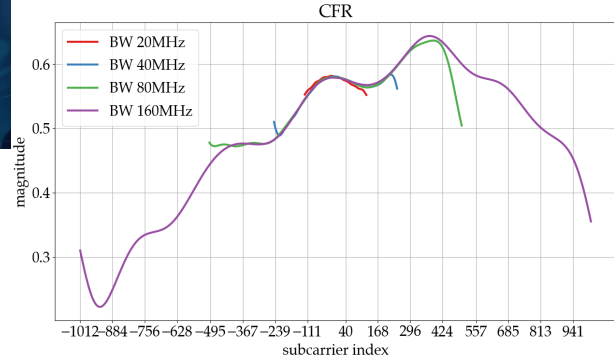
BW 160MHz



time [s]

1e-8

use **super-resolution approaches** to jointly estimate the parameters and go beyond the nominal resolution

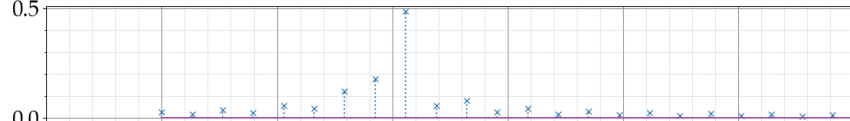


CIR from IFFT

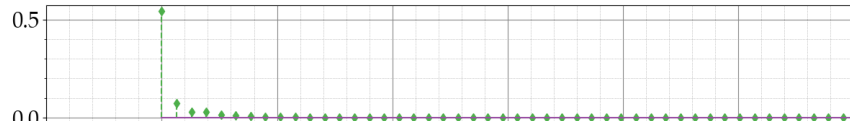
BW 20MHz



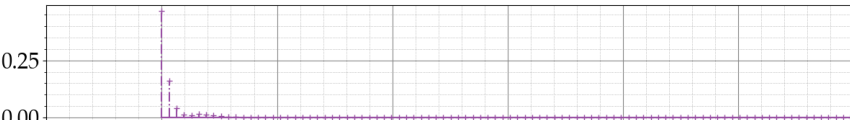
BW 40MHz



BW 80MHz



BW 160MHz



time [s]

1e-7

$$\Delta\tau_p = 1/B$$

50 ns

25 ns

12.5 ns

6.25 ns

37

Multi-path parameter estimation

- Can be formulated as a **sparse recovery problem**
 - obtain a sparse vector (channel impulse response **CIR $\mathbf{h}$**)
 - leveraging the multi-path propagation info in the **CFR $\mathbf{H}$**

The diagram illustrates the sparse recovery problem formulation. A yellow box contains the mathematical expression:

$$\mathbf{h} = \underset{\tilde{\mathbf{h}}}{\operatorname{argmin}} \|\mathbf{H} - \mathbf{T}\tilde{\mathbf{h}}\|_2^2,$$

subject to $\|\tilde{\mathbf{h}}\|_0 < m$

Annotations with red arrows:

- A red arrow points from the $\mathbf{h}$ in the equation to the text:
 - P' -dimensional vector
 - P' is the no. **candidate multi-path components** with a specific ToA/AoA
 - only the $P < P'$ components associated with objects in the environment are $\neq 0$
- A red arrow points from the m in the equation to the text: **no. non-zero components of the sparse vector $\tilde{\mathbf{h}}$ (user-defined) **sarsity constraint****
- A red arrow points from the $\mathbf{T}$ in the equation to the text: **matrix describing how the P' candidate paths combine at each sub-channels and receiving antennas to create $\mathbf{H}$**

Algorithms for multi-path parameter estimation



code of the
implementation
available

Compressive sensing-based methods (greedy algorithms)

- **OMP**: iteratively adds new components to $\mathbf{h}$ whose value is optimized based on the minimization of the cost function
- **IHT**: finds an $\mathbf{h}$ that minimizes the cost function and prune it based on thresholding strategies that maintain only the most significant elements

Ad-hoc approaches

- **SpotFi**: is based on eigendecomposition of the CFR
- **mD-Track**: first iteratively estimate and remove the strongest path from the signal; hence, a refinement phase is performed
- **UbiLocate**: similar idea of mD-Track, the refinement is performed though a Nelder-Mead search

Path resolvability and time comparison

Grid granularity (for matrix **T**)

- ToA 0.5 ns. - AoA 0.5 deg.

Max errors for resolvability

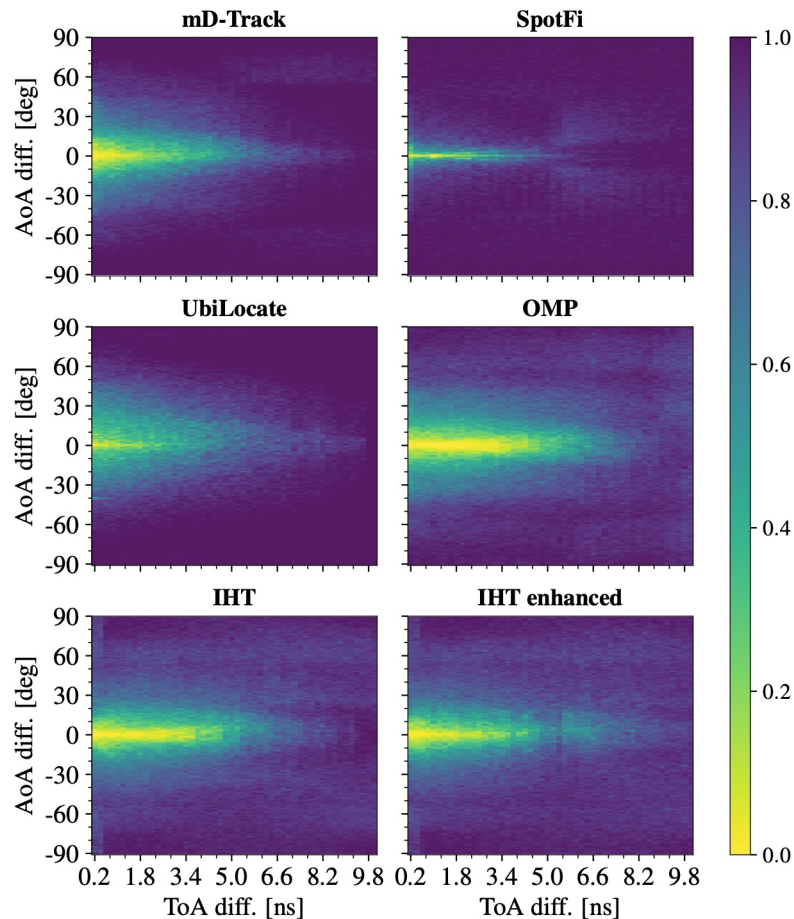
- ToA 5 ns - AoA 40 deg.

Nominal resolution

$$\Delta\tau_p = 1/B = 12.5 \text{ ns}$$

$$\Delta\theta_{\text{rx},p} = 360/(\pi N) \simeq 28.7 \text{ deg.}$$

method	time [$\times 10^{-2}$ s]
mD-Track	1.2
SpotFi	72.9
UbiLocate	2.3
IHT	113.8
IHT enhanced	140.3
OMP	235.9

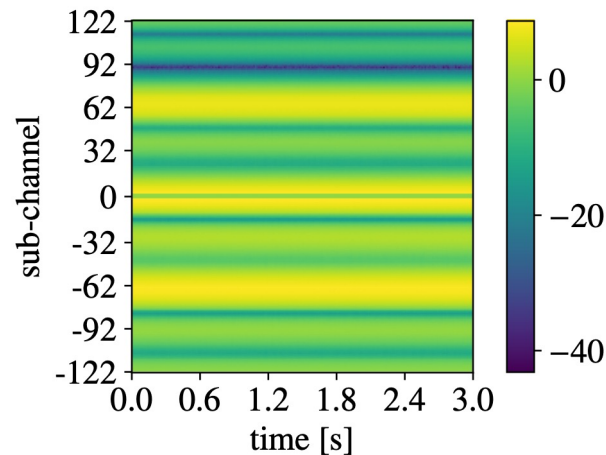
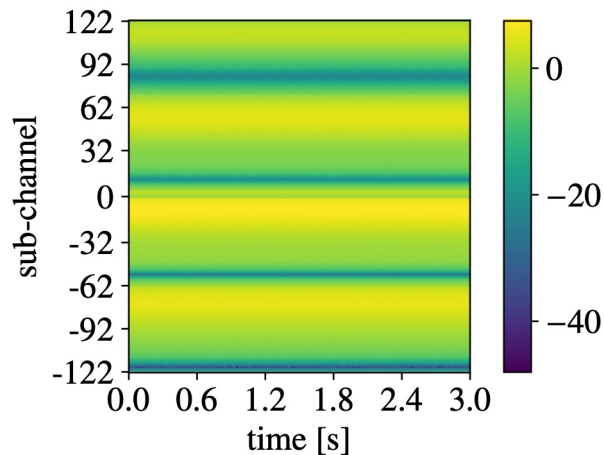


Doppler extraction from CFR

Diversity domain	Spectrum computed along	Derived sensing parameter
Frequency	OFDM/OFDMA subchannels	Range of the target (ToA)
Space	Antenna array	Angular position (AoA, AoD)
Time	Subsequent time instants	Velocity (Doppler effect)

Doppler extraction – motivation

- The CFR
 - also accounts for the reflections from static objects
 - is **environment-specific** → **not desirable for sensing**



CFR **amplitude** (dB scale) collected in the same empty room in two different days

Doppler extraction from CFR

$$H_{k,m_t,m_r}(n) = \sum_{p=0}^{P-1} A_p(n) e^{-j2\pi(f_c + k/T) \tau_{p,m_t,m_r}(n)}$$

- **Main idea.** Extracting the **micro-Doppler** traces from the CFR
 - allows removing static objects contributions

$$\text{Doppler effect } \Delta_p^D(n) = -nT_c v_p(n) \cos \alpha_p(n)$$

$$\tau_{p,m_t,m_r}(n) = \frac{\ell_p(n) + \Delta_p^D(n) + \Delta_{p,m_t}^{\text{tx}}(n) + \Delta_{p,m_r}^{\text{rx}}(n)}{c}$$

micro-Doppler computation

Diversity domain	Spectrum computed along	Derived sensing parameter
Time	Subsequent time instants	Velocity (Doppler effect)



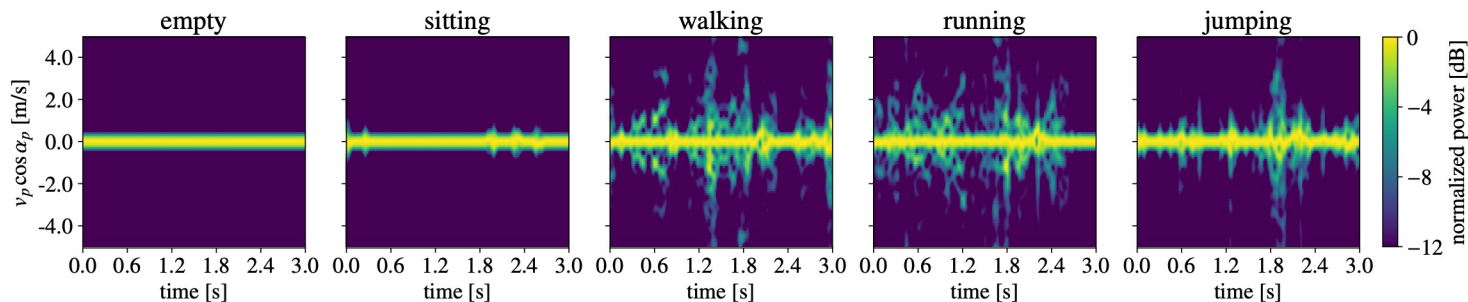
code of the
implementation
available

$$\mathbf{D}_i = [d_i(-N_D/2), \dots, d_i(N_D/2 - 1)]^T$$

- by computing the **Fourier transform** along the time dimension

$$\mathbf{H}_i = \begin{bmatrix} \hat{H}_{-K/2}(iN) & \dots & \hat{H}_{-K/2}((i+1)N - 1) \\ \vdots & & \\ \hat{H}_{K/2-1}(iN) & \dots & \hat{H}_{K/2-1}((i+1)N - 1) \end{bmatrix}$$

$$d_i(u) = \sum_{k=-K/2}^{K/2-1} |\mathcal{F}\{\mathbf{H}_i\}(k, u)|^2$$



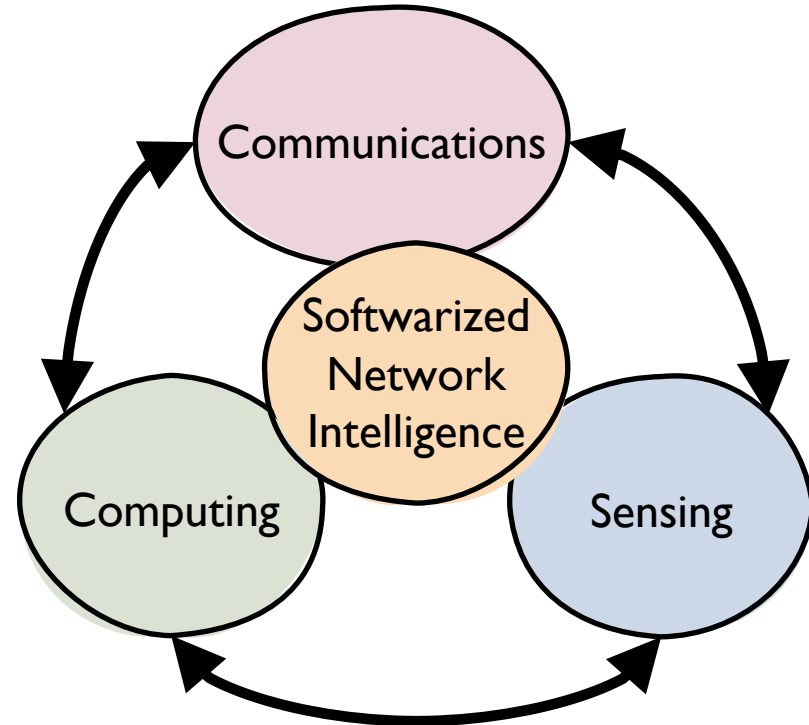
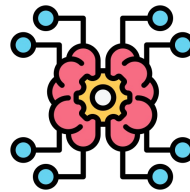
Model-based algorithms are not enough for ISAC

Challenges

- Radio signal propagation (multi-path) can be highly complex
- High amount of data to be processed
- Algorithms should be **plug-and-play**
- **Computational complexity should be adjusted based on the device**

Strategies

- **Pervasive AI-ML**



3a

Communication-assisted sensing applications

- Wireless sensing
- AI/ML-based solutions – some examples



AI/ML-based wireless sensing – examples

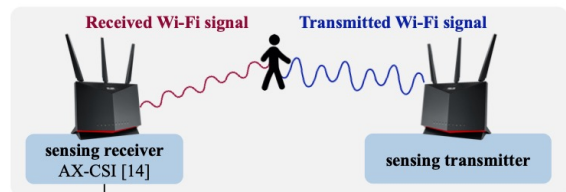
Comms

Sensing

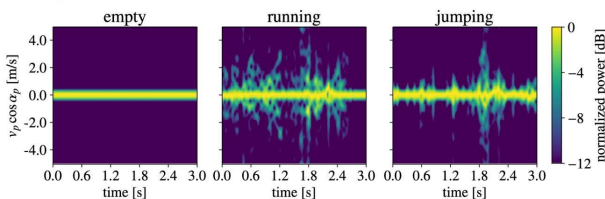
Channel freq. response 802.11ac/ax (sub-7 GHz)

- CFR extracted through custom tools

nexmon **AX-CSI**



802.11ax CFR data



F. Meneghello, D. Garlisi, N. Dal Fabbro, I. Tinnirello and M. Rossi, "SHARP: Environment and Person Independent Activity Recognition with Commodity IEEE 802.11 Access Points", in *IEEE Transactions on Mobile Computing* 2022

- Detect and classify human activities in indoor spaces based on Doppler effect

- **Robust to changing the environment, person and day**

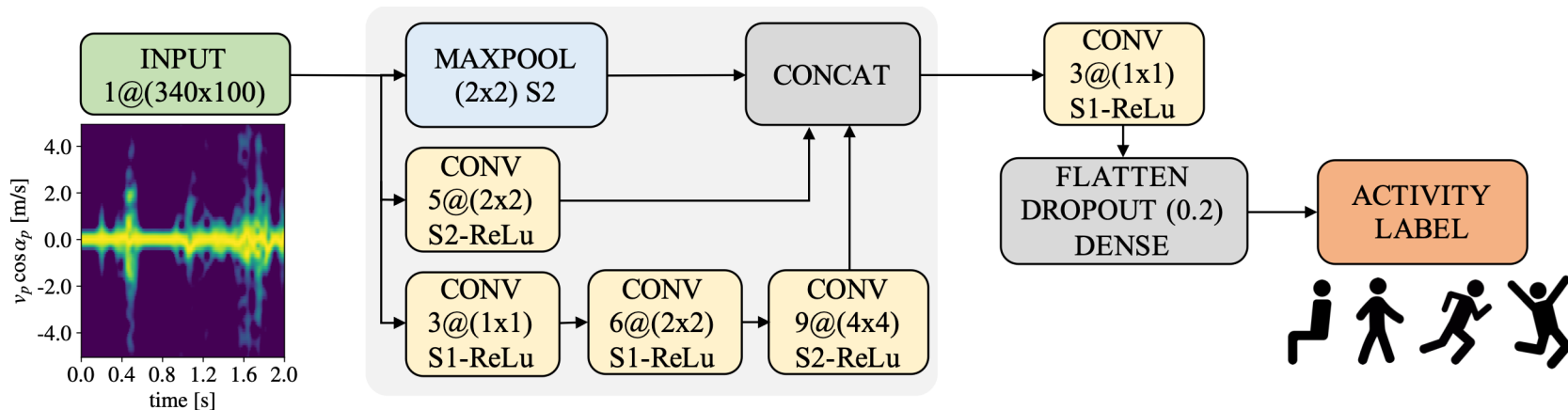
- Two steps

1. the learning-based algorithm is **independently applied** to the Doppler traces extracted from the CFR of each of the **receiving antennas** to obtain activity estimates
2. the predictions are combined through a **decision fusion** method

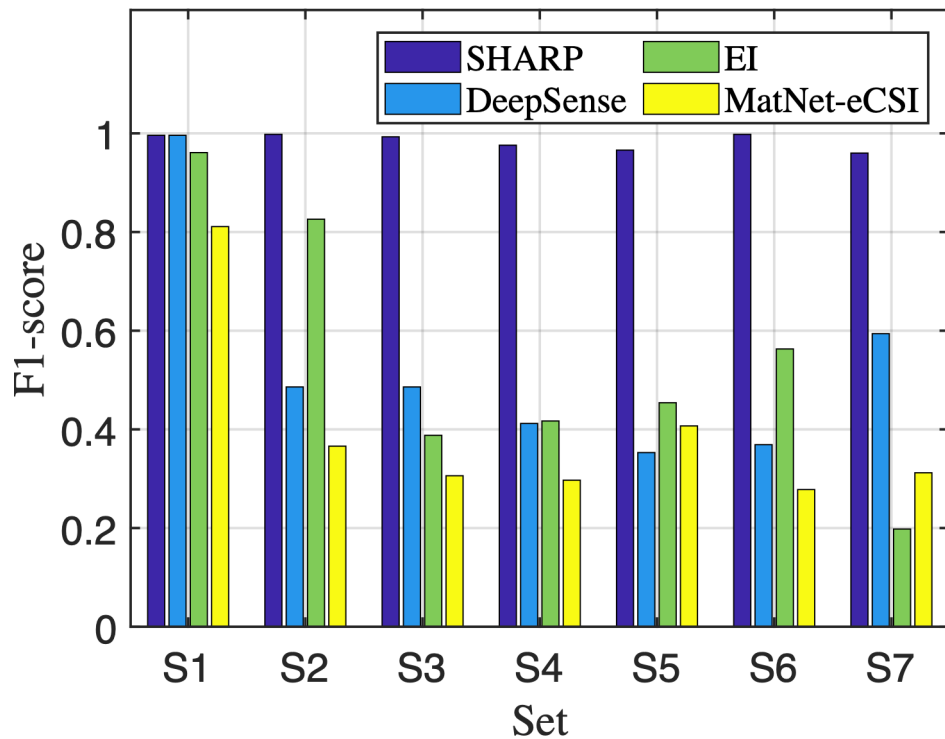


AX-CSI

nexmon



Experimental results



set	monitor position, M_j	person, P_i	direct path	type
S1	M1	P1	yes	train-test
S2	M1	P1	yes	test
S3	M1	P2	yes	test
S4	M2	P1	no	test
S5	M2	P2	no	test
S6	M3	P1	yes	test
S7	M4	P3	yes	test

AI/ML-based wireless sensing – examples

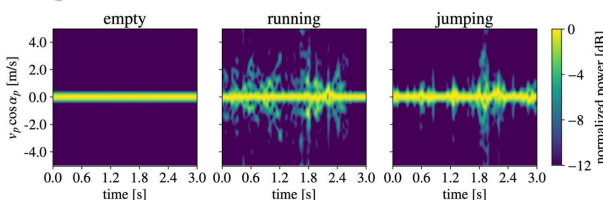
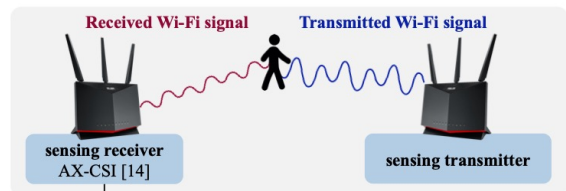
Comms

Sensing

Channel freq. response 802.11ac/ax (sub-7 GHz)

- CFR extracted through custom tools

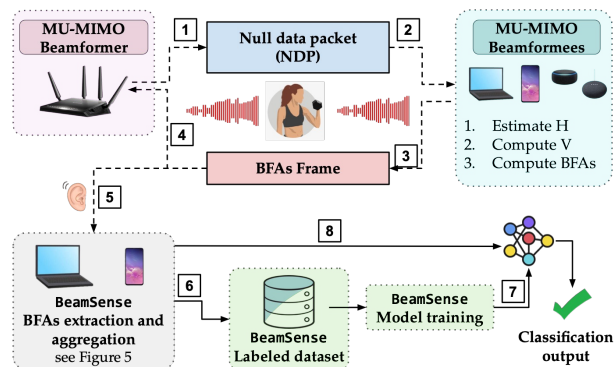
nexmon AX-CSI



F. Meneghello, D. Garlisi, N. Dal Fabbro, I. Tinnirello and M. Rossi, "SHARP: Environment and Person Independent Activity Recognition with Commodity IEEE 802.11 Access Points", in *IEEE Transactions on Mobile Computing* 2022

Beamforming feedback 802.11ac/ax (sub-7 GHz)

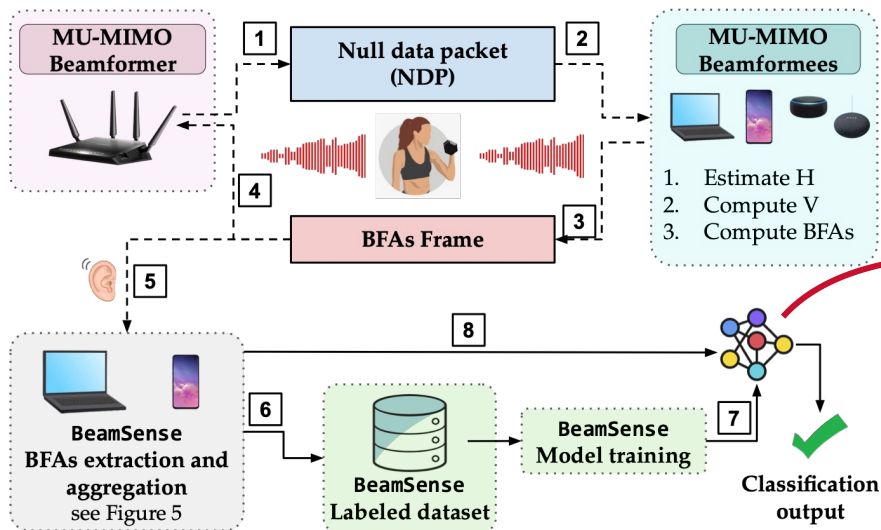
- BF transmitted in clear text during MIMO setup



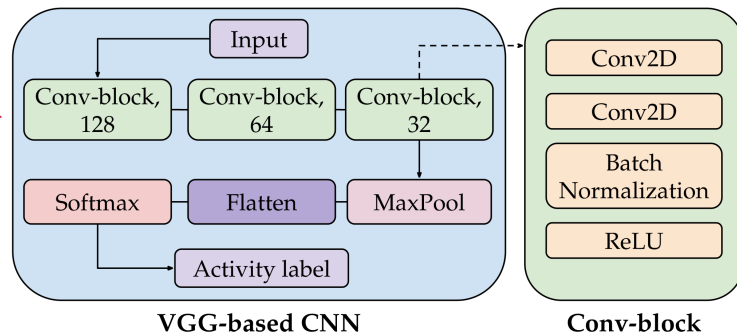
K. H. Haque, F. Meneghello, and F. Restuccia, "Wi-BFI: Extracting the IEEE 802.11 Beamforming Feedback Information from Commercial Wi-Fi Devices", in *Proc. of ACM WiTECH 2023*

BFA-Sense and BeamSense

- Human activity recognition through 802.11ac/ax beamforming feedback angles extracted through **Wi-BFI**
- BeamSense** uses few-shot learning to enforce generalization over different scenarios

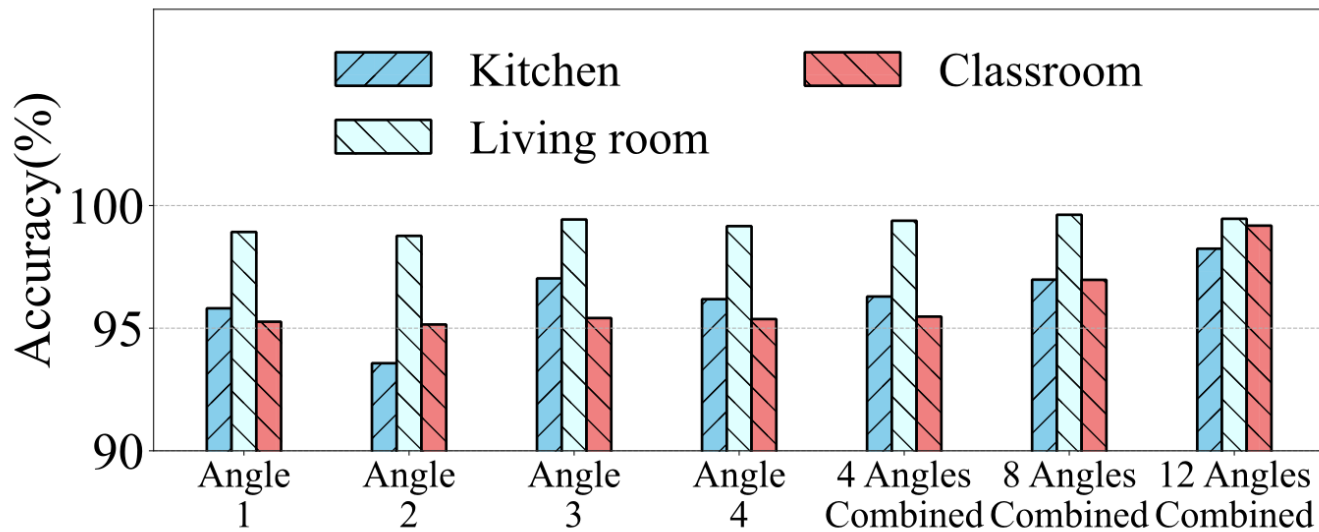


raw beamforming feedback angles as input





Experimental results



AI/ML-based wireless sensing – examples

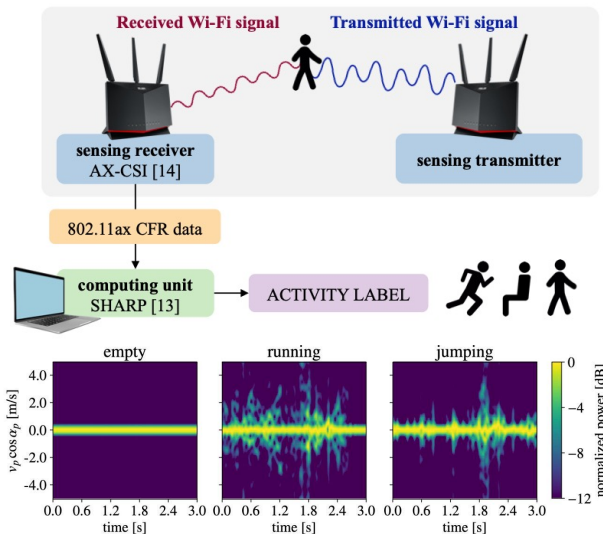
Comms

Sensing

Channel freq. response 802.11ac/ax (sub-7 GHz)

- CFR extracted through custom tools

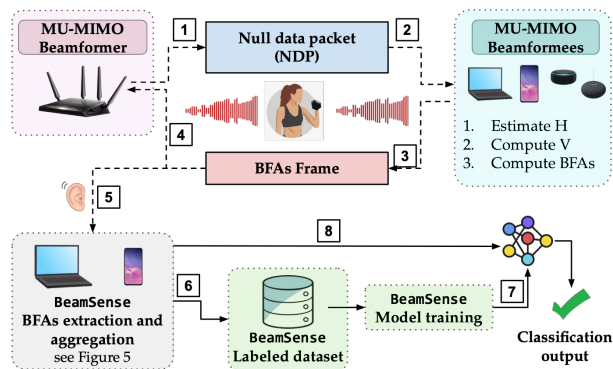
nexmon AX-CSI



F. Meneghello, D. Garlisi, N. Dal Fabbro, I. Tinnirello and M. Rossi, "SHARP: Environment and Person Independent Activity Recognition with Commodity IEEE 802.11 Access Points", in *IEEE Transactions on Mobile Computing* 2022

Beamforming feedback 802.11ac/ax (sub-7 GHz)

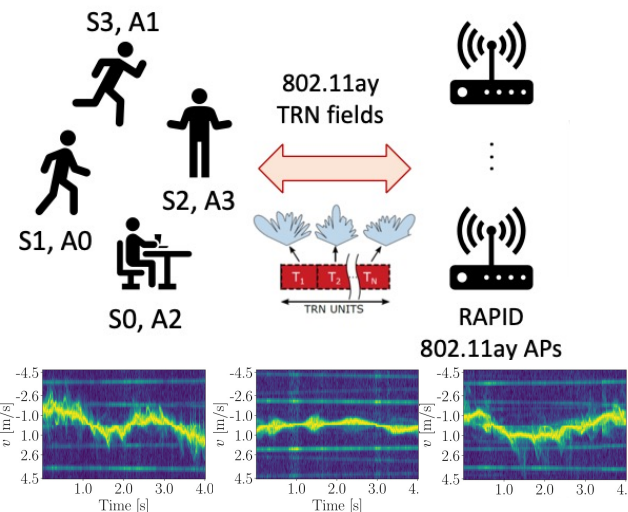
- BF transmitted in clear text during MIMO setup



K. H. Haque, F. Meneghello, and F. Restuccia, "Wi-BFI: Extracting the IEEE 802.11 Beamforming Feedback Information from Commercial Wi-Fi Devices", in *Proc. of ACM WiTECH 2023*

Channel impulse response 802.11ay (mmWave)

- CIR from the beam training and tracking fields



J. Pegoraro, O. J. Lacruz, F. Meneghello, E. Bashirov, J. Widmer and M. Rossi, "RAPID: Retrofitting IEEE 802.11ay Access Points for Indoor Human Detection and Sensing", in *IEEE Transactions on Mobile Computing* 2023

RAPID – 802.11ay (mmWave)

Sensing primitive:
Doppler signatures
from the beam training
and tracking fields

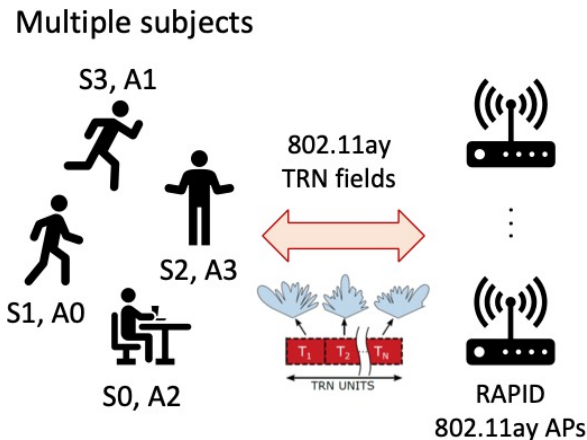
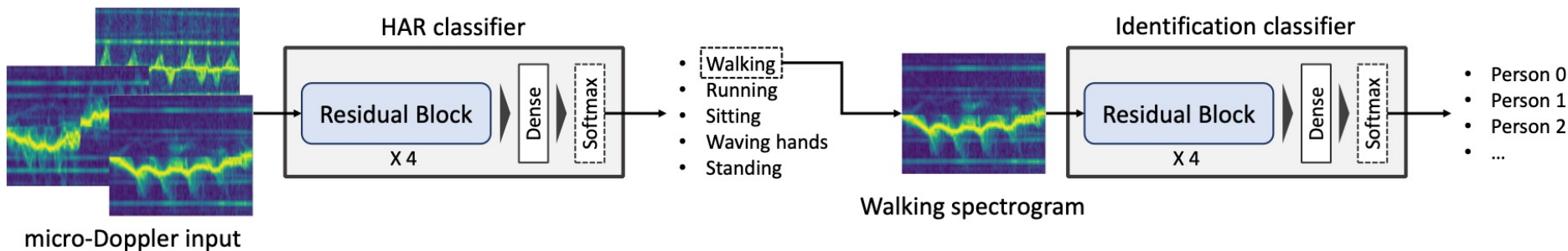


TABLE II
CONFUSION MATRIX AND F1-SCORES FOR THE BASELINE CASE

True [%]	Predictions [%]				
	Walking	Running	S. down	Waving	Still
Walking	97.7 61.4	0 18.3	2.3 0	0 0	0 20.3
Running	0 0.6	100 87.1	0 0	0 0	0 12.3
S. down	0 0	0 0	95.9 100	0 0	4.1 0
Waving	0 0	0 0	0 0.1	100 85.9	0 14.0
Still	0 0	0 0	0 0	0 0	100 100
F1-score [%]	98.8 75.8	100 91.2	96.3 99.9	100 92.4	98.4 85.4

Grey/white rows refer to RAPID and sub-6 GHz, respectively.



3b

Sensing-assisted communications applications

- Context adaptation
- AI/ML-based solutions – some examples



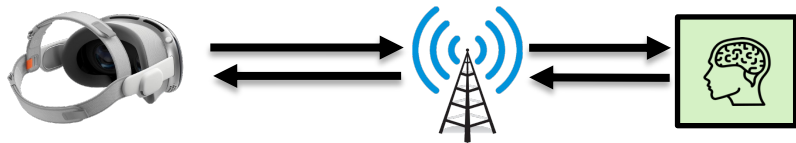
AI/ML-based context adaptation – examples

Comms

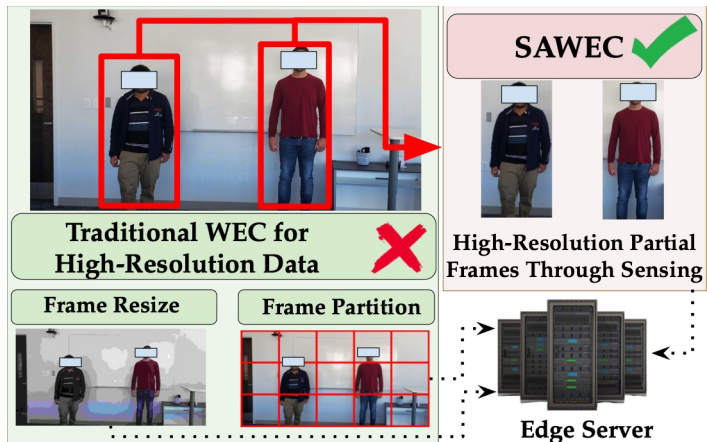
Sensing

Sensing-assisted edge computing

- Goal: reducing uplink data overhead



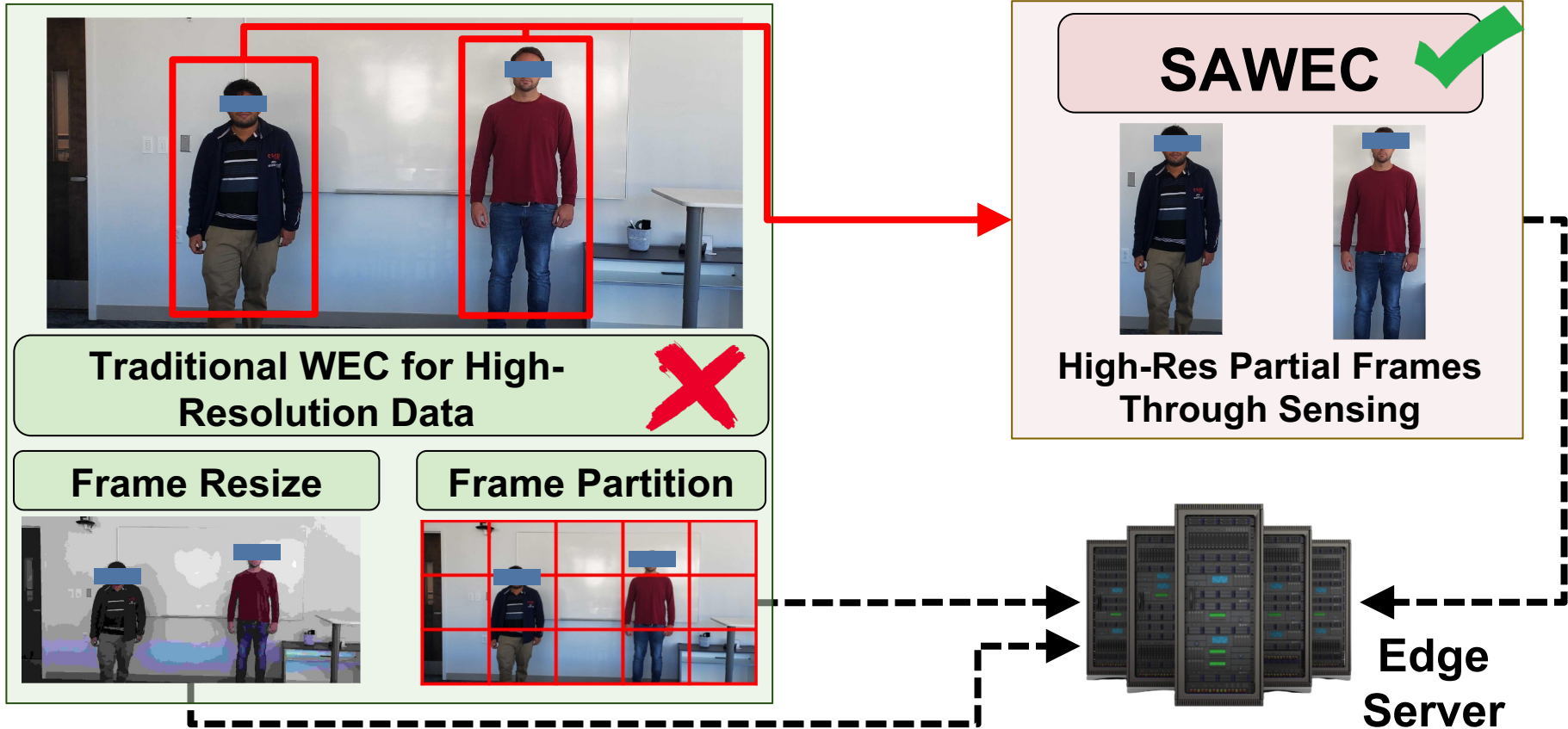
120 Hz @ 8K → 40 Gbps → Wi-Fi supports 1.2 Gbps



K. F. Haque, F. Meneghello, F. Restuccia, "Integrated sensing and communication for efficient edge computing", in *Proc. of IEEE WiMob, 2024*

K. F. Haque, F. Meneghello, M. E. Karim, F. Restuccia, "SAWEC: Sensing-assisted wireless edge computing." in *arXiv preprint arXiv:2402.10021, 2024*

Sensing-assisted wireless edge computing



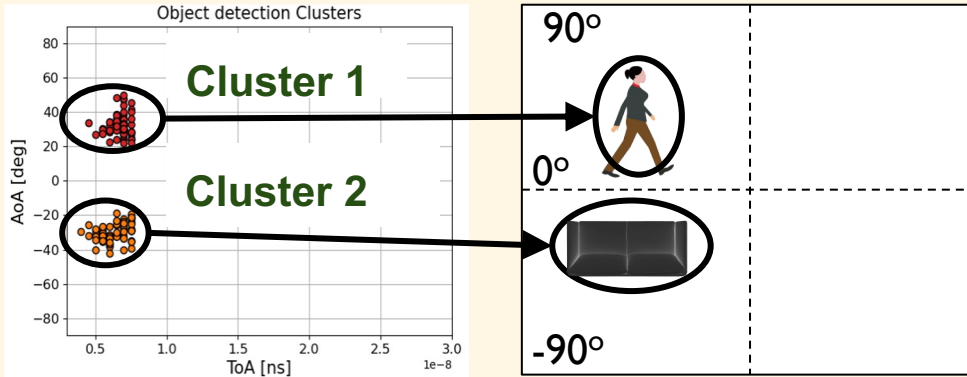
Detection of the region of interest (ROI)

Comms

Sensing

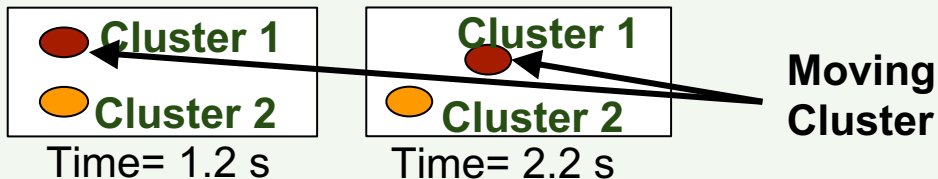
1

Localization based on AoA and ToA



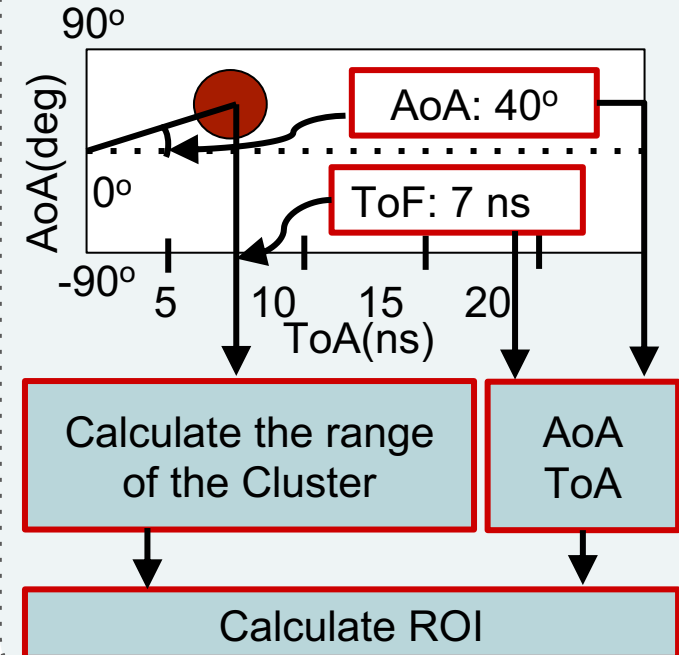
2

Track Environmental Change Through Moving Cluster



3

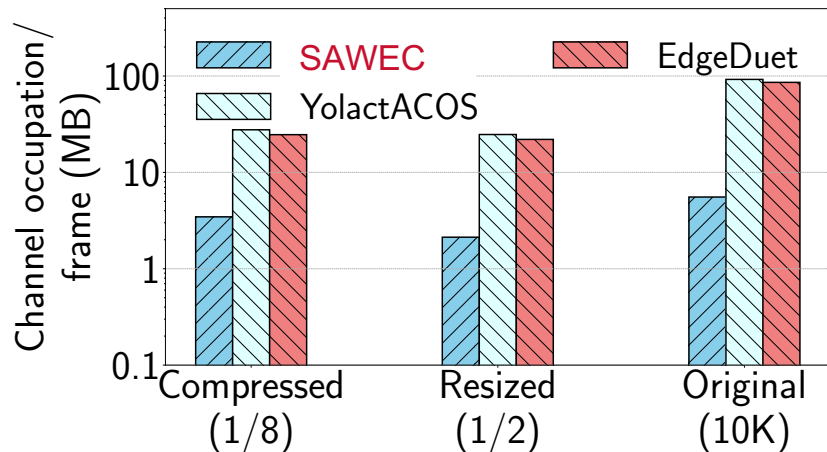
Find ROI based on AoA, ToA and Cluster Radius



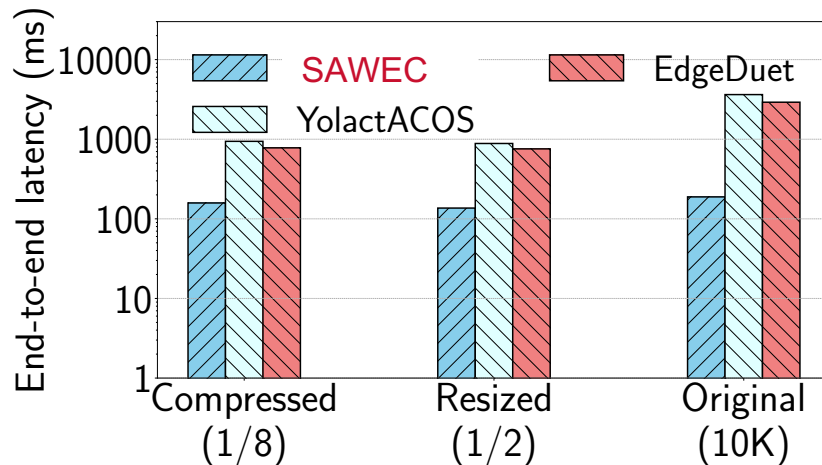
Comparative analysis of ISAC-EC

Analysis with original (10K), and tolerable compressed (1/8) and resized images (1/2)

Channel Occupation



End-to-end Latency

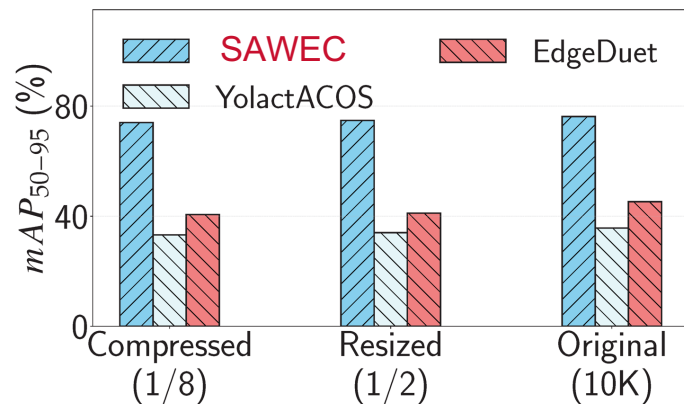


- The size of a 10K frame is **138.88 MB**
- **SAWEC**, YolactACOS, and EdgeDuet require **5.5 MB**, 92.2 MB and 85.9 MB per frame respectively

- **Latency reduced by 94% on an average**

Comparative analysis of SAWEC

mAP_{50-95} of Instance Segmentation



- models retain similar performance with compression and resize ratio of 1/8 and 1/2 respectively

SAWEC with 10K ROI



SAWEC with Compressed (1/16) ROI



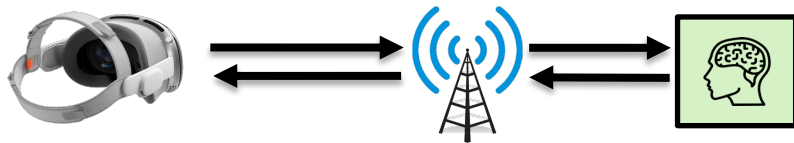
AI/ML-based context adaptation – examples

Comms

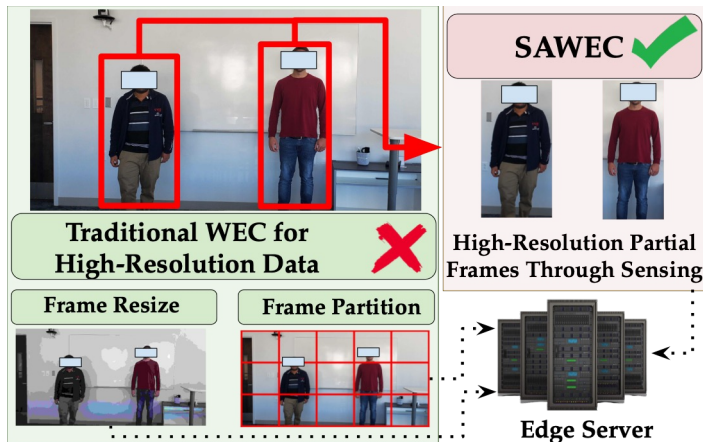
Sensing

Sensing-assisted edge computing

- Goal: reducing uplink data overhead



120 Hz @ 8K → 40 Gbps → Wi-Fi supports 1.2 Gbps

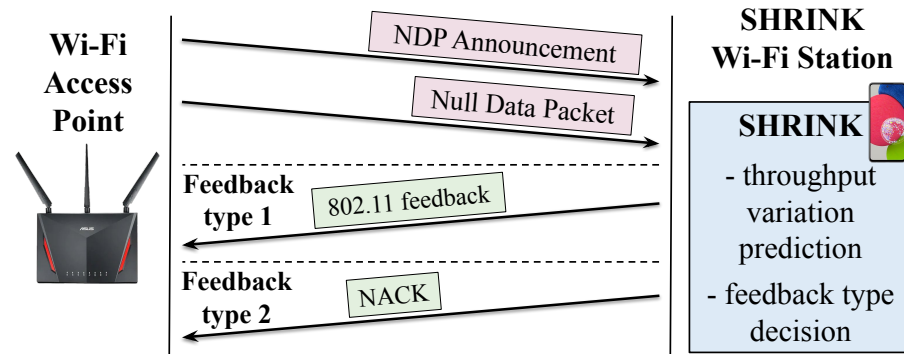
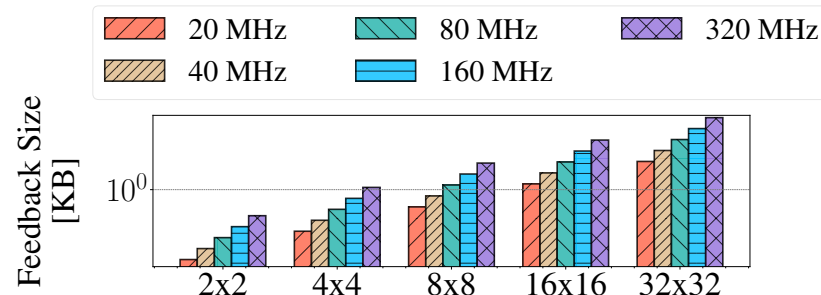


K. F. Haque, F. Meneghello, F. Restuccia, "Integrated sensing and communication for efficient edge computing", in *Proc. of IEEE WiMob, 2024*

K. F. Haque, F. Meneghello, M. E. Karim, F. Restuccia, "SAWEC: Sensing-assisted wireless edge computing." in *arXiv preprint arXiv:2402.10021, 2024*

Sensing-assisted channel sounding

- Goal: reducing MIMO sounding overhead



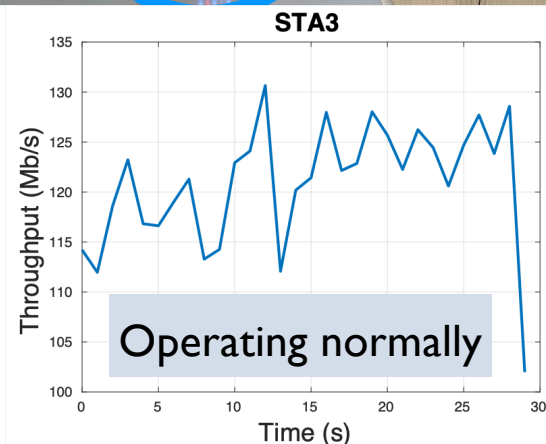
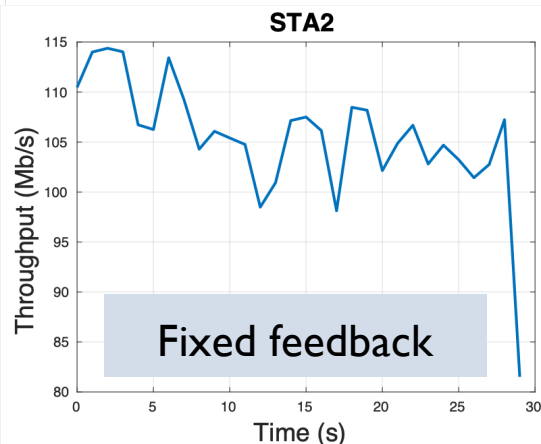
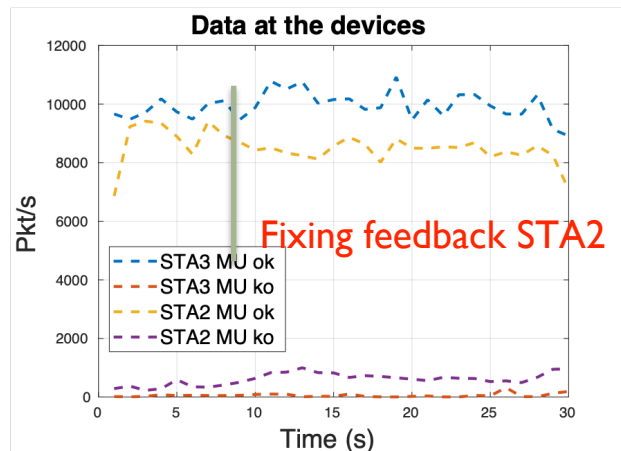
K M Rumman, F. Meneghello, K. F. Haque, F. Gringoli, F. Restuccia, "SHRINK: Reducing MIMO Feedback Overhead in Wi-Fi with Dynamic Data-Driven Channel Sounding", in *Proc. of ACM MobiHoc 2025*

Preliminary results

Comms

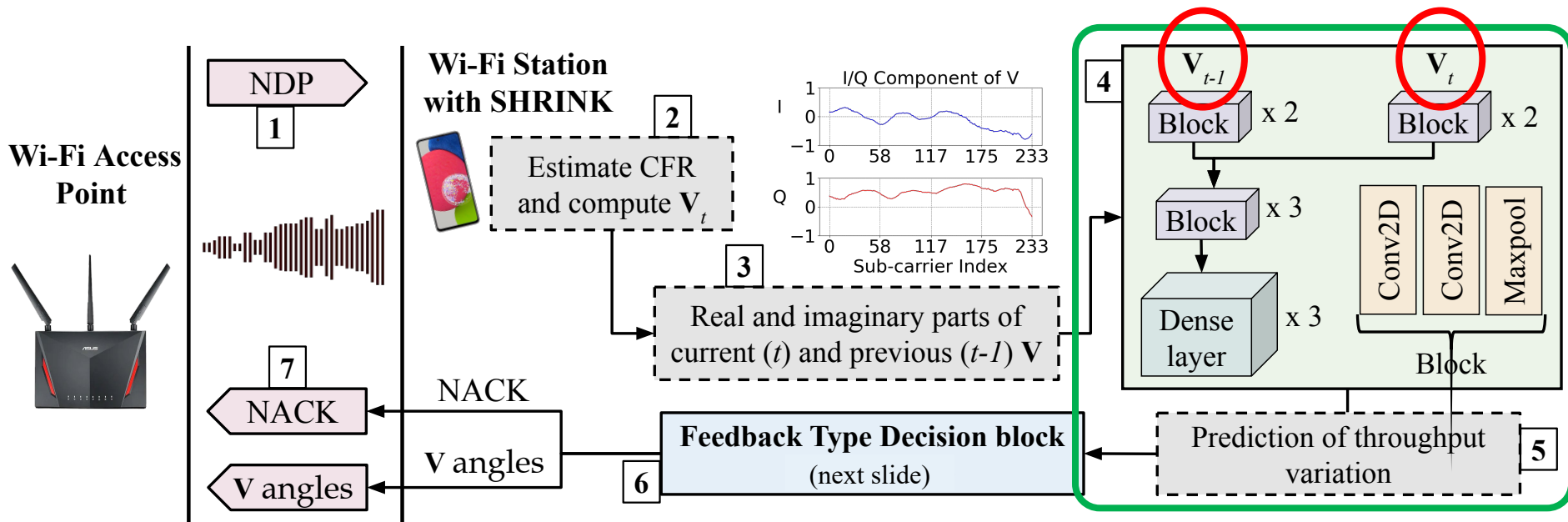
Sensing

- 4 antennas AP and two single-antenna stations
- Throughput still high for more than 20 s
~2,000 useless feedback transmissions:
(sounding every 10 ms)



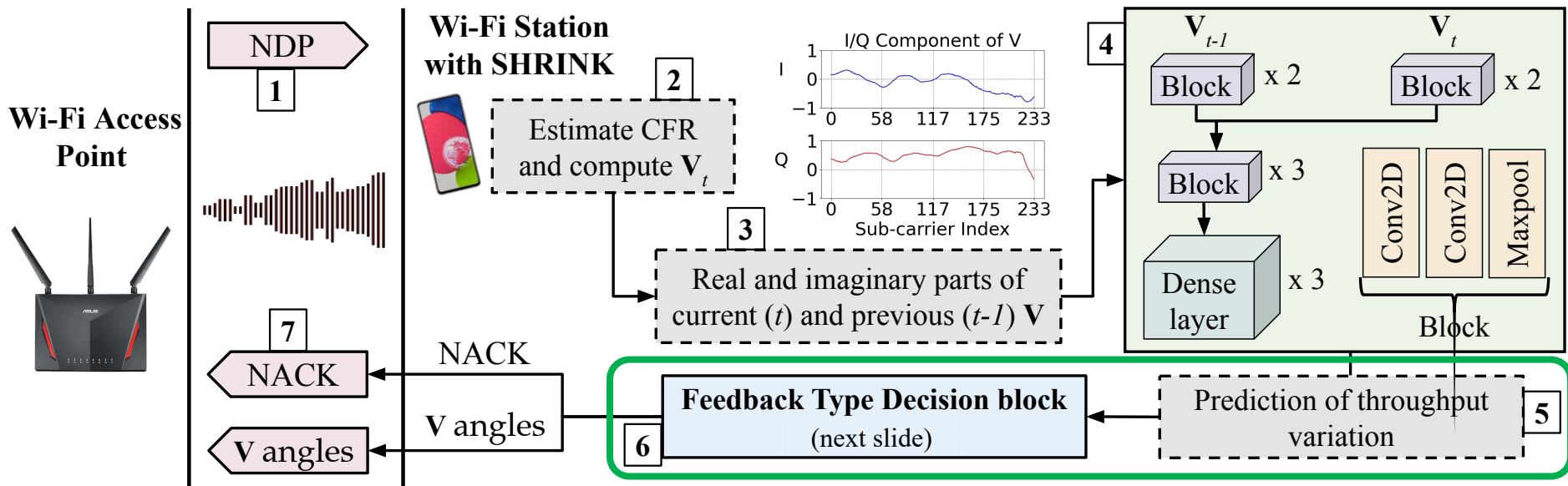
Dynamic Data-Driven Channel Sounding

SHRINK adapts to the channel dynamics performing a context-aware compression



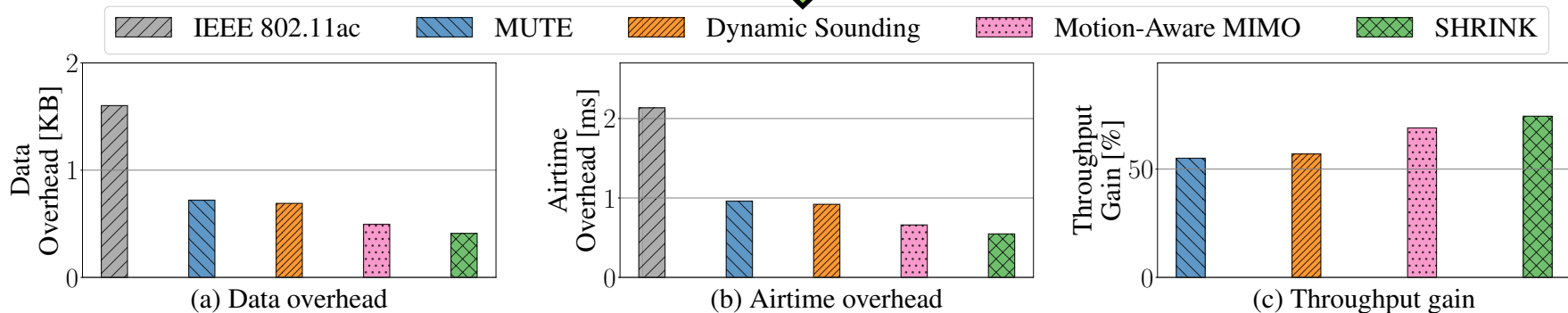
Dynamic Data-Driven Channel Sounding

SHRINK adapts to the channel dynamics performing a context-aware compression

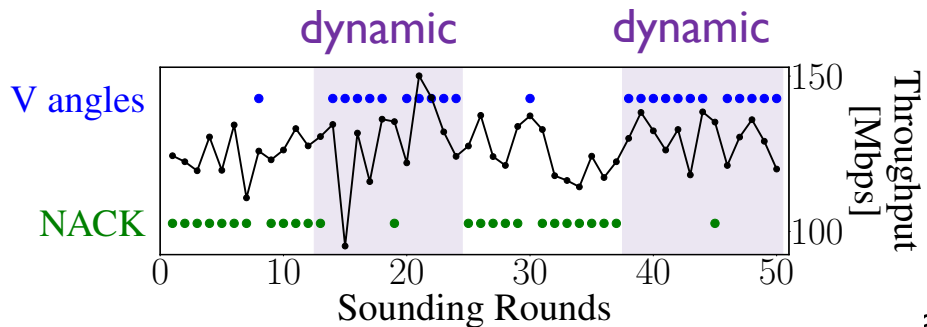


SHRINK

- SHRINK reduces overhead and increase throughput through context-adaptation



- Technical challenge addressed through throughput variation prediction



4

Will sensing be integrated in wireless networks?

- Challenges and research directions

Sensing units as VNFs

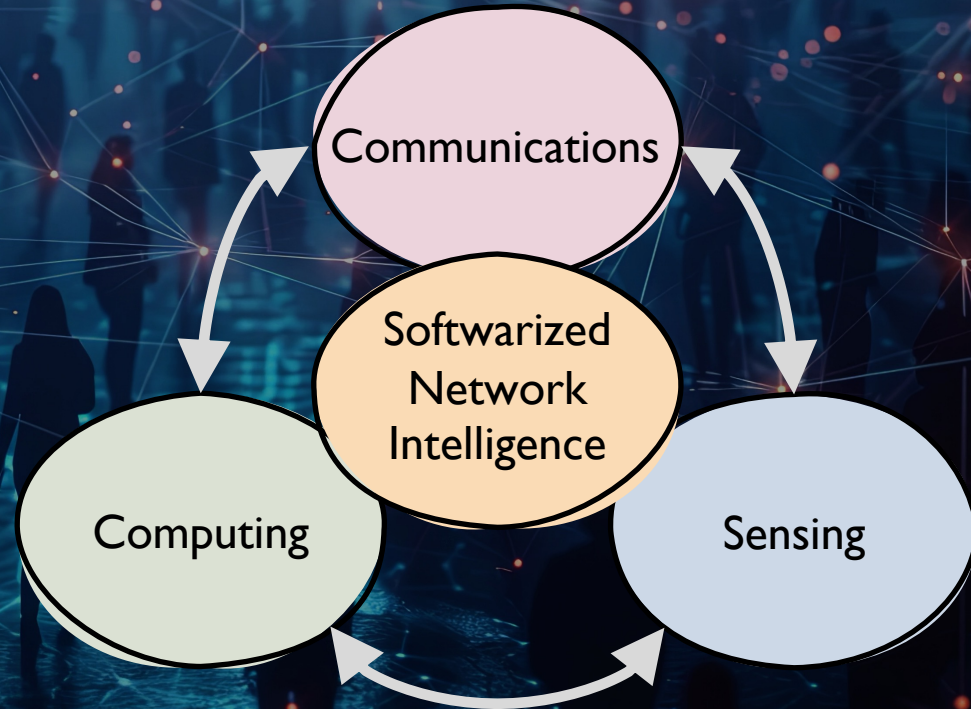
Radio devices collect sensing primitives (RSSI, CIR, CFR)

Computing pipeline (VNFs)

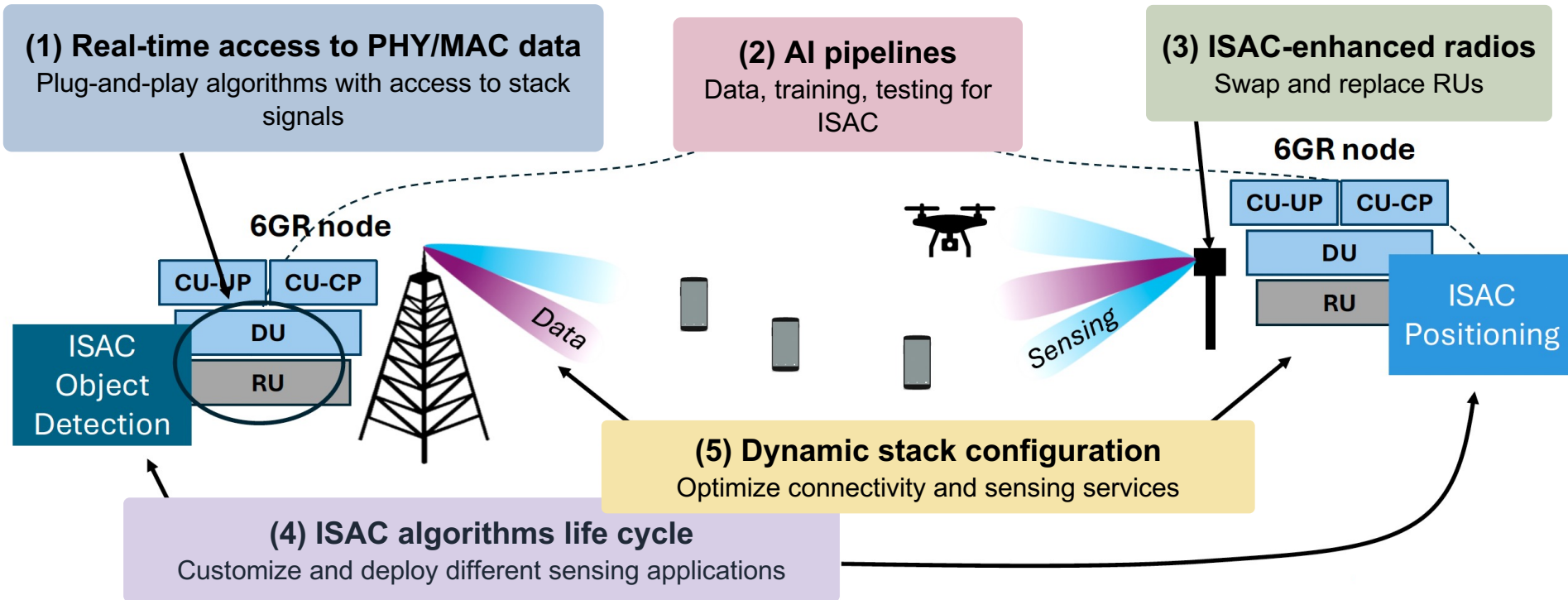
Range/velocity/angle estimation, AI/ML inference

Sensing-as-a-Service

Apps: presence, activity, gesture, health, tracking



System challenges toward ISAC in O-RAN



Sensing as a service in the O-RAN stack

O-RAN will expose sensing as a **softwarized service across three control loops**

tighter timescale
closer to the radio

Non-RT RIC: rApps

SMO · > 1 s

Sensing model life-cycle and orchestration

training, model catalog, retraining policy, slice and placement

Near-RT RIC: xApps

10 ms – 1 s

Sensing inference and multi-node fusion

activity / presence classification, cooperative sensing across cells

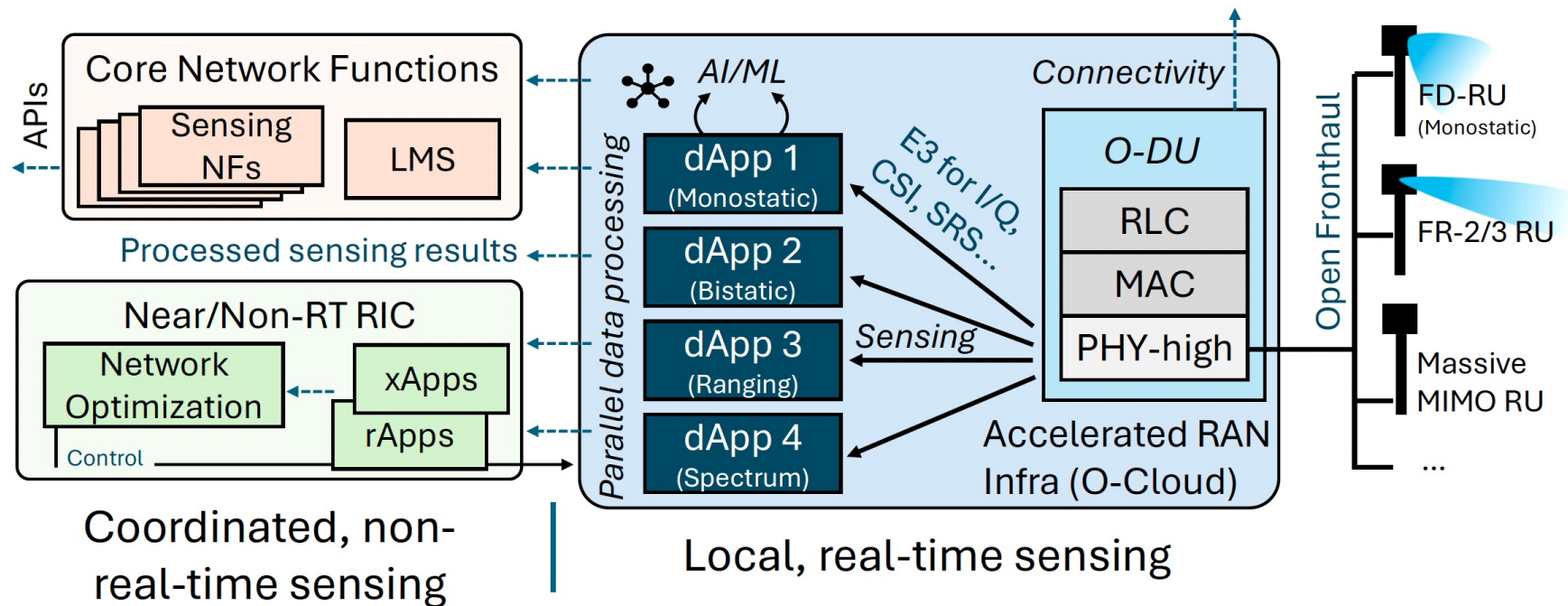
RAN node: dApps

real-time · < 10 ms

Sensing-primitive extraction at the radio

I/Q, CSI, SRS via E3 interface (Doppler / range / angle)

O-RAN dApps for ISAC



S. D'Oro, M. Polese, L. Bonati, H. Cheng, T. Melodia, "dApps: Distributed Applications for Real-Time Inference and Control in O-RAN," in **IEEE Communications Magazine**, 2022
A. Lacava, L. Bonati, N. Mohamadi, R. Gangula, F. Kaltenberger, P. Johari, S. D'Oro, F. Cuomo, M. Polese, T. Melodia, "dApps: Enabling real-time AI-based Open RAN control," in **Computer Networks**, 2025

S. D'Oro, Northeastern University, "ISAC in Open RAN with dApps", <https://www.o-ran.org/event/o-ran-alliance-6g-and-isac-workshop>

Technical challenges

- How to design sensing algorithms that are **robust to undesired hardware imperfections** (e.g., CFR offsets)?
 - Real-time is crucial → dApps
- How to keep the algorithms updated through **periodic retraining**?
 - Out-of-distribution detection and adaptation strategies → rApps
- How reach a **tradeoff** between the communication performance and the accuracy of the sensing algorithms?
 - rApps

Comm–sensing tradeoff

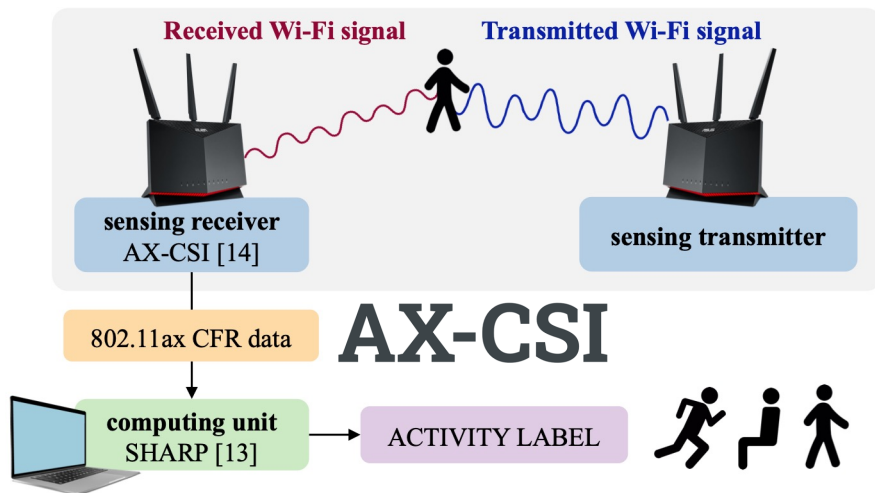
code of the
implementation
available



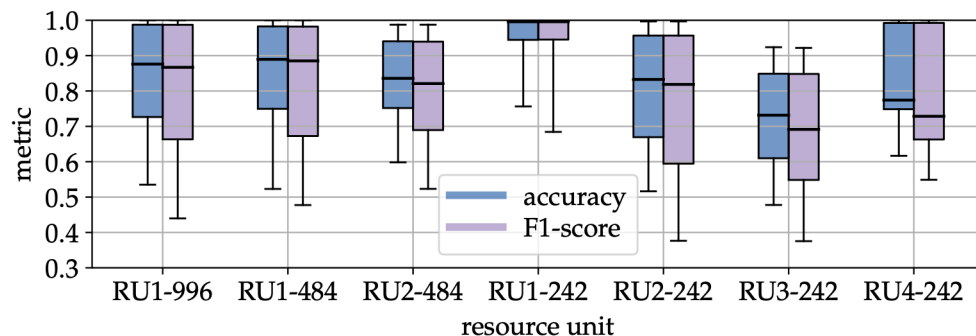
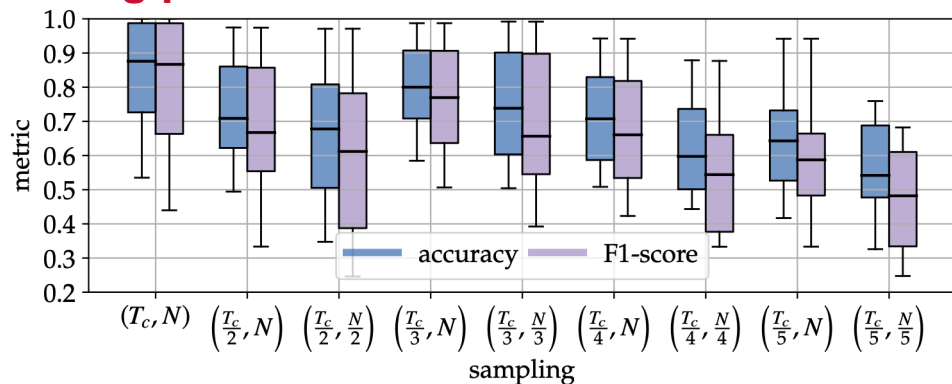
Comms

Sensing

Impact of communication parameters on sensing performance



- The **sensing performance decreases when decreasing the number of samples** (reducing $T_c \times N$, i.e., time window)
- The position of the RU for sensing impact more than the bandwidth



F. Meneghello, C. Cheng, C. Cordeiro and F. Restuccia, "Toward Integrated Sensing and Communications in IEEE 802.11 bf Wi-Fi Networks", in **IEEE Communications Magazine** 2023

Comm–sensing tradeoff

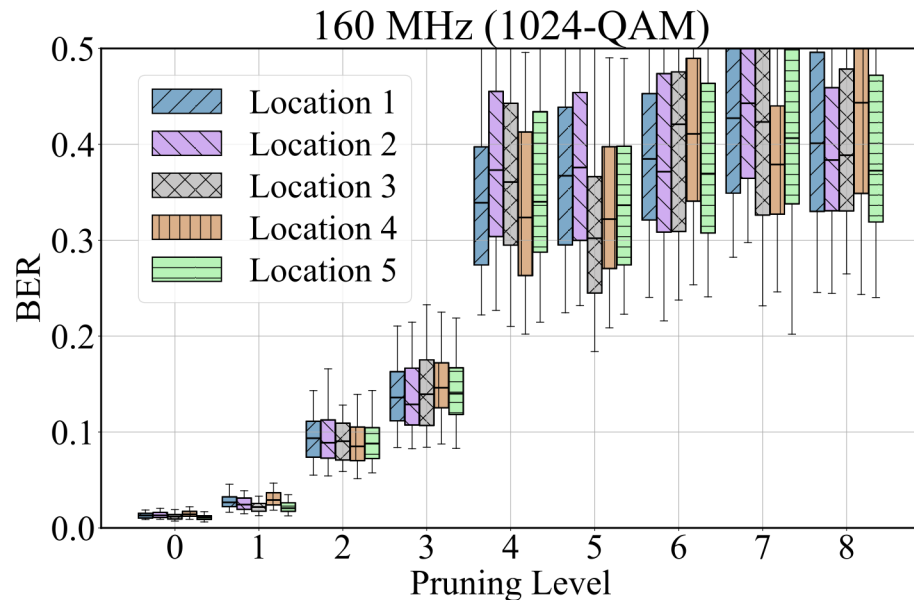
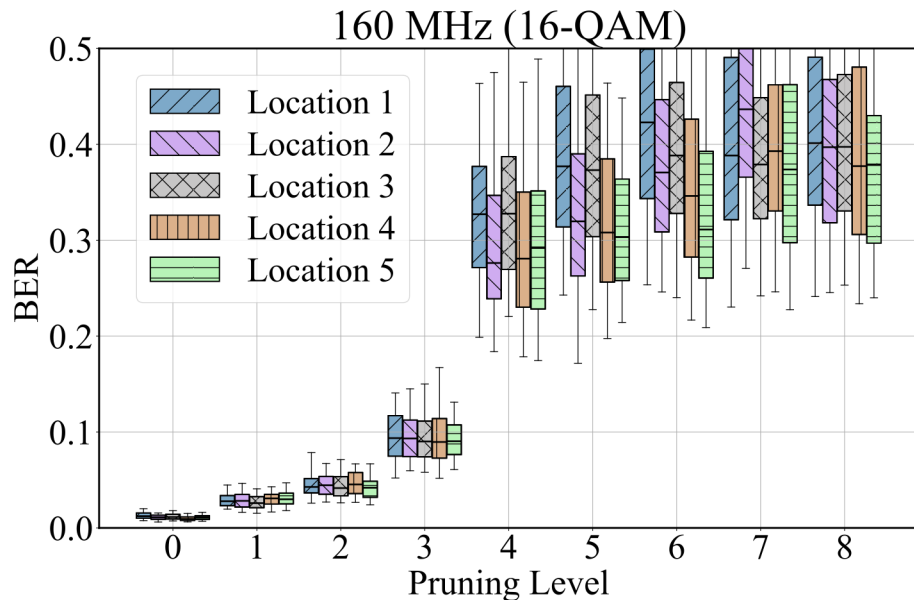
Comms

Sensing

Impact of sensing accuracy on communication performance

4×4 MIMO

- BER removing an increasing number of multi-path components (ordered) from the CFR



- Increasing the number of removed components (x-axis), the BER increases reaches a plateau

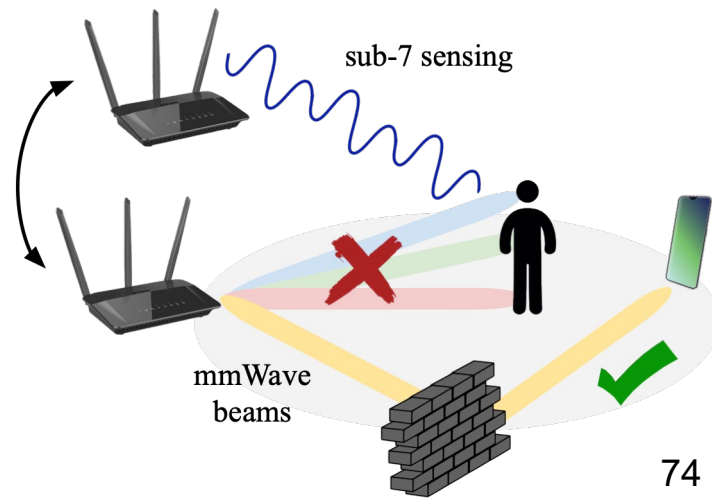
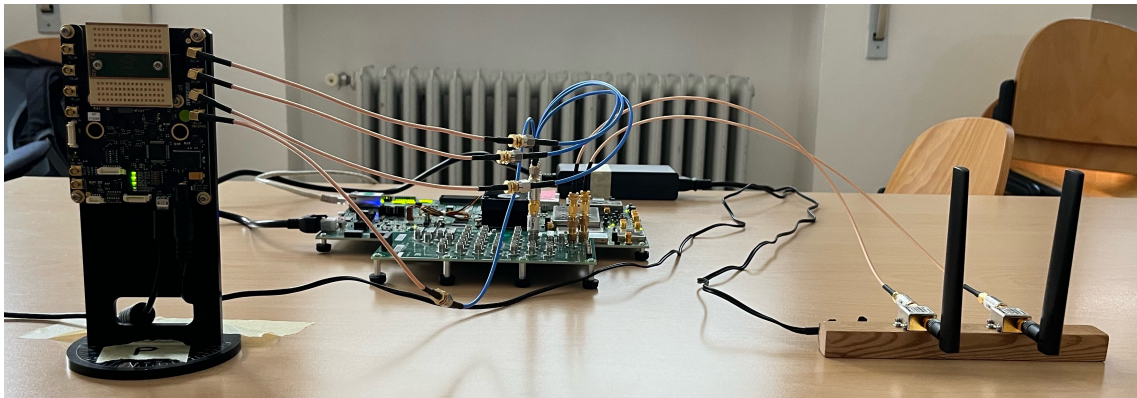
Comm–sensing tradeoff

Comms

Sensing

Multi-band cooperative sensing

- Improve diversity: boost sensing accuracy **combining different bands**
- **Allocate resources opportunistically** to communications or sensing services



Concluding remarks

1. Why integrated sensing and communications (ISAC)?

- Re-use already deployed infrastructures

2. What information can we use for sensing?

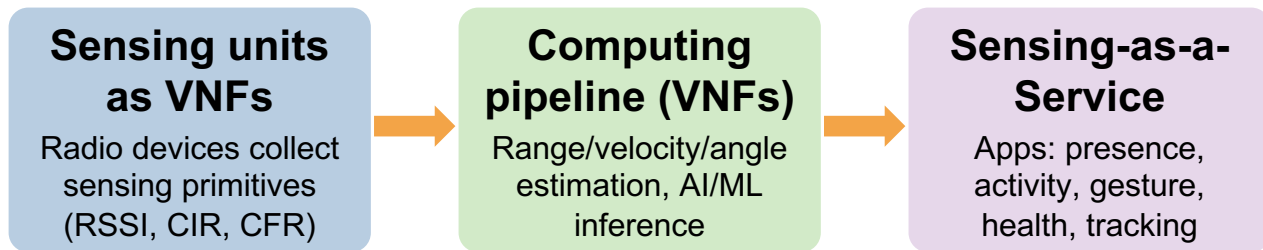
- CFR, CSI, beamforming information

3. How can we develop sensing applications?

- Virtualized network functions, AI/ML

4. Will sensing be integrated in wireless networks?

- Research and development in progress





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Institute for Intelligent
Networked Systems



MENTIS
LABORATORY

Thank you!

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