Institute for the Wireless Internet of Things at Northeastern University

MENTIS LABORATORY

Beamsense: Rethinking Wireless Sensing with MU-MIMO Wi-Fi Beamforming Feedback

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AR/VR: Shaping the Future of Interactions

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Global market value is predicted to reach 1066 Billion by 2034 [1]

We are very far from truly seamless and immersive AR/VR experiences

1. Precedence Research. "Spatial Computing Market Size, Share, Trends, Analysis Report, 2025-2034." Accessed October 21, 2025. https://www.precedenceresearch.com/spatial-computing-market

What is the Current Bottleneck?

Semantic segmentation

Object recognition

Compute-intensive AI/ML tasks

120 Hz frame rate and 8K resolution are needed! [1]

1. M Gallagher, ER Ferrè, "Cybersickness: a multisensory integration perspective", Multisensory Research, 2018. Ars Technica, "Virtual Perfection: Why 8K resolution per eye isn't enough for perfect VR", 2013.

State of Current Wireless AR/VR Headsets

Meta Quest 3

1.5-2 hours

Weight

515 grams

Refresh rate

Up to 90 Hz

Controllers

Apple Vision Pro

Up to 2 hours

Weight

650 grams plus

353 grams battery

Refresh rate

Up to 90 Hz

External battery

Wireless Edge Computing and Sensing

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Offload intensive compute task to edge server

Wireless sensing for surrounding awareness

Light-weight & device free AR/VR experience

Introduction on Wireless Sensing

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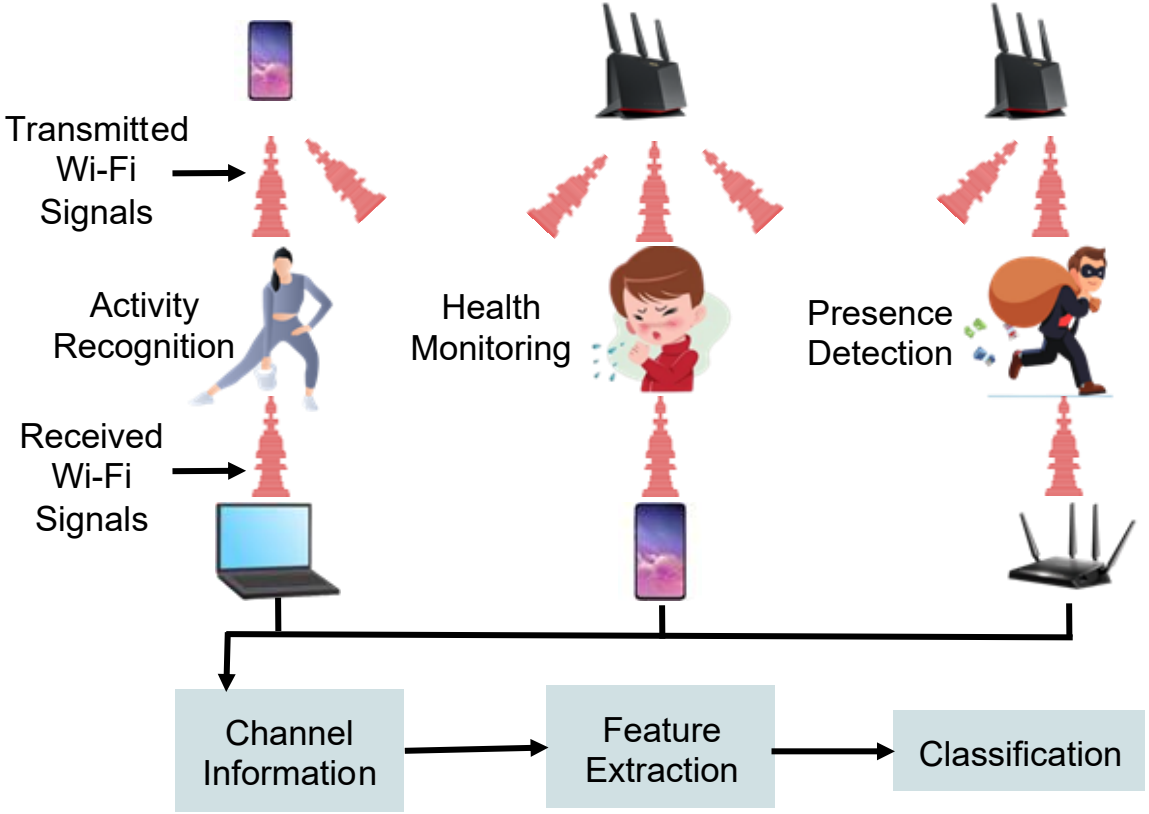
- Perceived by the changes in the received signal
- Main approaches [1] are based on:
  - Received Signal Strength
  - Passive Wi-Fi Radar
  - **Channel Frequency Response (CFR)**



1. Khandaker Foysal Haque, Milin Zhang, Francesca Meneghello, and Francesco Restuccia. "Beamsense: Rethinking wireless sensing with mu-mimo wi-fi beamforming feedback." Computer Networks 258 (2025): 111020.

Prior Work and Existing Challenges

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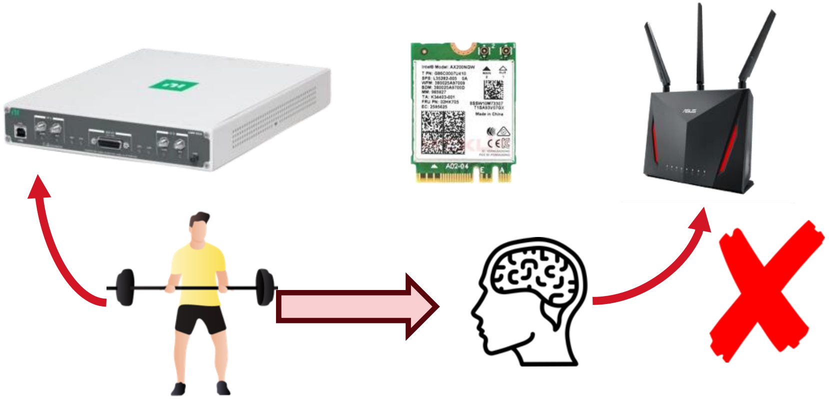
- Need Firmware Modifications
- Need Dedicated CSI Tools
- Limited Hardware
- Can't Generalize Domains

nexmon

PicoScenes

802.11n CSI Tool

AX-CSI



- Bahadori, N., Ashdown, J. and Restuccia, F., 2022, June. ReWiS: Reliable Wi-Fi sensing through few-shot multi-antenna multi-receiver CSI learning. In 2022 IEEE WoWMoM (pp. 50-59).
- 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,” IEEE TMC, 2022.
- R. Xiao, J. Liu, J. Han, and K. Ren, “OneFi: One-Shot Recognition for Unseen Gesture via COTS WiFi,” in Proceedings of the ACM Conference on Embedded Networked Sensor Systems (SenSys), pp. 206–219, 2021
- Yin, G., Zhang, J., Shen, G. and Chen, Y., 2022. FewSense, towards a scalable and cross-domain Wi-Fi sensing system using few-shot learning. IEEE TMC, 23(1), pp.453-468.
- Ma, Y., Zhou, G., Wang, S., Zhao, H. and Jung, W., 2018. SignFi: Sign language recognition using WiFi. Proceedings of the ACM IMWUT, 2(1), pp.1-21.

BeamSense: Overview and Novelties

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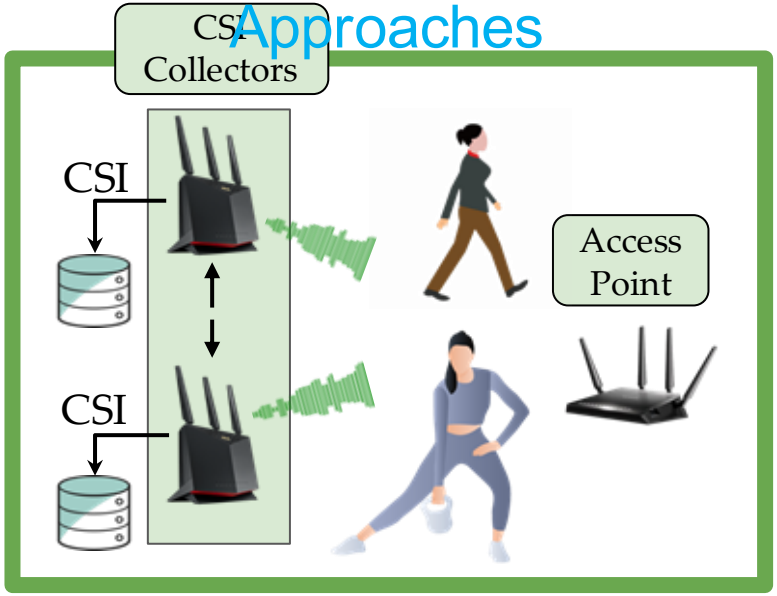
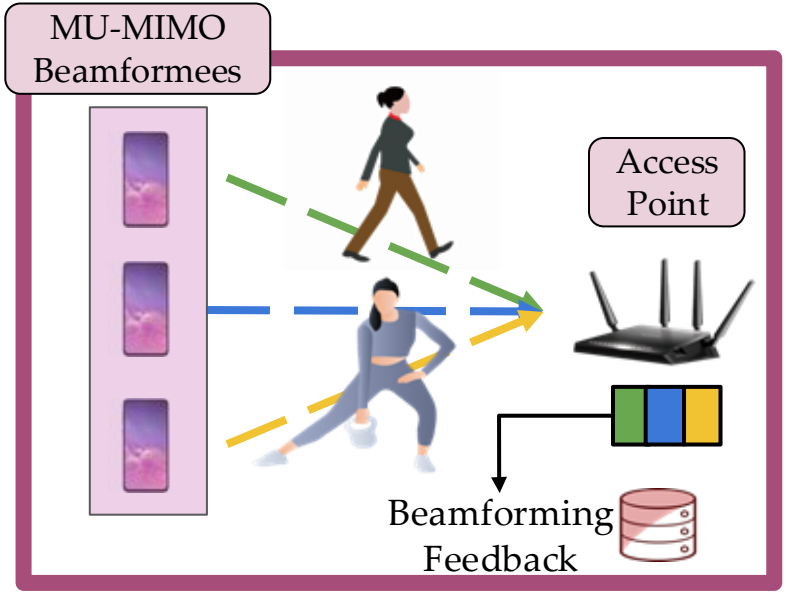
Existing CFR based Approaches



Requires specialized equipment
Requires Direct Access to Devices
Introduces additional overhead

BeamSense- based on BFI



No specialized equipment
No Direct Access Required
No additional overhead

From CFR to BFI

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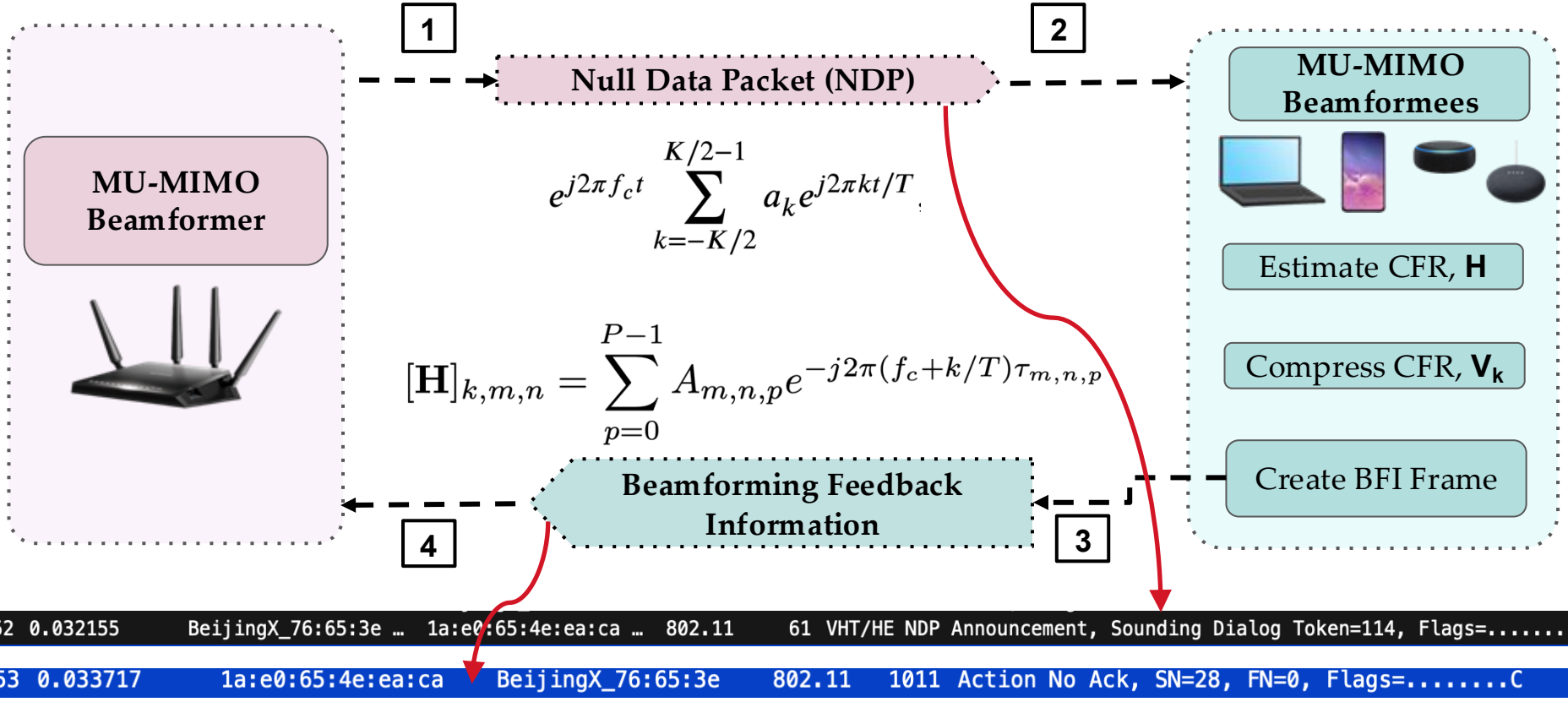



```
52  0.032155    BeijingX_76:65:3e …  1a:e0:65:4e:ea:ca …  802.11    61 VHT/HE NDP Announcement, Sounding Dialog Token=114, Flags=........C
53  0.033717    1a:e0:65:4e:ea:ca    BeijingX_76:65:3e    802.11  1011 Action No Ack, SN=28, FN=0, Flags=........C
```

Beamforming feedback matrices

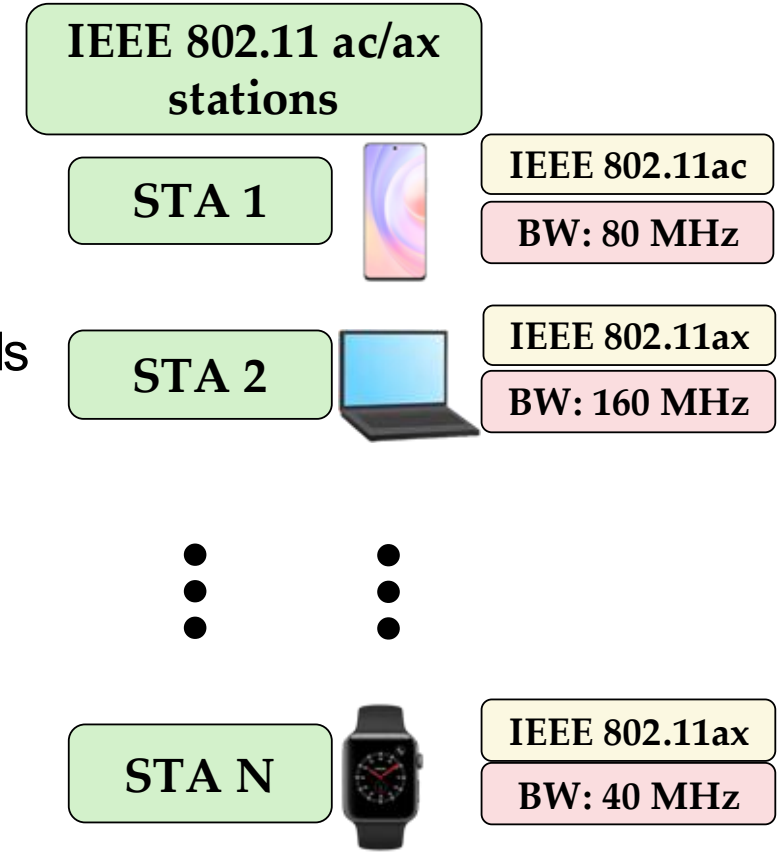

```
  29… 4.7133… Netgear_63… Netgear_24… 802…  1… Action No Ack, SN=33, FN=7, Flags=........C

› Frame 29814: 1095 bytes on wire (8760 bits), 1095 bytes captured (8760 bits) on interface wlp58s0mon, id 0
› Radiotap Header v0, Length 64
› 802.11 radio information
› IEEE 802.11 Action No Ack, Flags: ........C
⌄ IEEE 802.11 Wireless Management
  ⌄ Fixed parameters
      Category code: VHT (21)
      VHT Action: VHT Compressed Beamforming (0)
    › VHT MIMO Control: 0x548c90, Nc Index: 1 Column, Nr Index: 3 Rows, Channel Width: 80 MHz, Grouping (Ng): 1
    ⌄ VHT Compressed Beamforming Report [truncated]: 5ee5855a5dd2695e4fbd575a49a1375e437f0f664355e16d472fbf6d4f0
      › Average Signal to Noise Ratio
      ⌄ Feedback Matrices
          SCIDX: -122, ϕ11:485, ϕ21:322, ψ21:86, ψ31:46
          SCIDX: -121, ϕ11:466, ϕ21:308, ψ21:87, ψ31:39
          SCIDX: -120, ϕ11:445, ϕ21:299, ψ21:86, ψ31:36
          SCIDX: -119, ϕ11:417, ϕ21:283, ψ21:87, ψ31:33
          SCIDX: -118, ϕ11:383, ϕ21:263, ψ21:89, ψ31:33
          SCIDX: -117, ϕ11:341, ϕ21:240, ψ21:91, ψ31:35
          SCIDX: -116, ϕ11:303, ϕ21:223, ψ21:91, ψ31:39
          SCIDX: -115, ϕ11:271, ϕ21:215, ψ21:86, ψ31:40

0050  3c 37 86 24 52 63 17 02  15 00 90 8c 54 5e e5 85   <7·$Rc·· ····T^··
0060  5a 5d d2 69 5e 4f bd 57  5a 49 a1 37 5e 43 7f 0f   Z]·i^O·W ZI·7^C··
0070  66 43 55 e1 6d 47 2f bf  6d 4f 0f af 59 51 f7 aa   fCU·mG/· mO··YQ··
0080  39 4f e2 a6 1d 4d d0 a6  fd 4c bf a8 e1 48 ad ae   9O···M·· ·L···H··
0090  c5 3a 9d b0 ad 2a 8b a0  95 26 81 9c 79 24 6f 88   ·:···*·· ·&··y$o·
00a0  61 1c 32 08 51 10 c6 11  4c 16 94 53 67 30 81 19   a·2·Q··· L··Sg0··
00b0  83 32 70 ef aa 3a 5e d1  e2 42 44 b5 16 45 24 8f   ·2p··:^· ·BD··E$·
00c0  3a 45 06 65 4a 43 e3 46  5a 3f c4 26 62 3b b8 0c   :E·eJC·F Z?·&b;··
00d0  6a 3d b7 fa 7d 41 bc ec  95 43 ba e4 b5 47 e9 e4   j=··}A·· ·C···G··
00e0  d1 49 40 eb b9 4b 59 ef  89 49 66 f1 69 45 6d f3   ·I@··KY· ·If·iEm·
```

Transmitted unencrypted

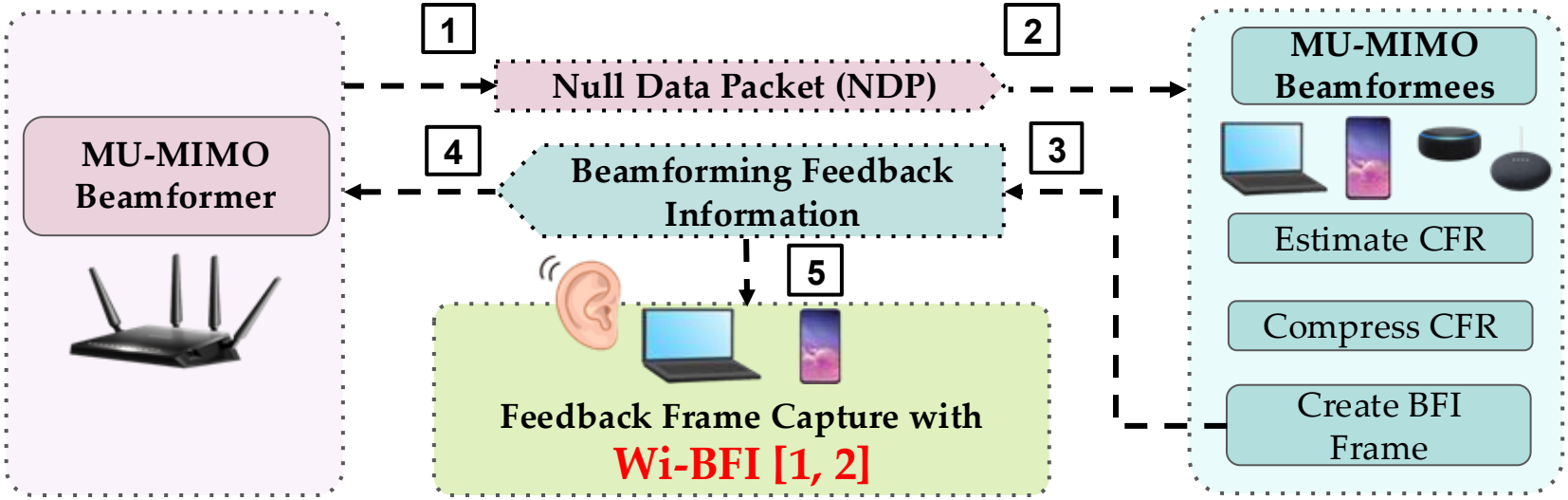
Packet Bytes

Operation of BeamSense

- Woks with any device supporting MIMO
- Support across multiple standard
- Works with multiple bands simultaneously
- No direct access to the network needed
- Can be collected with a single capture



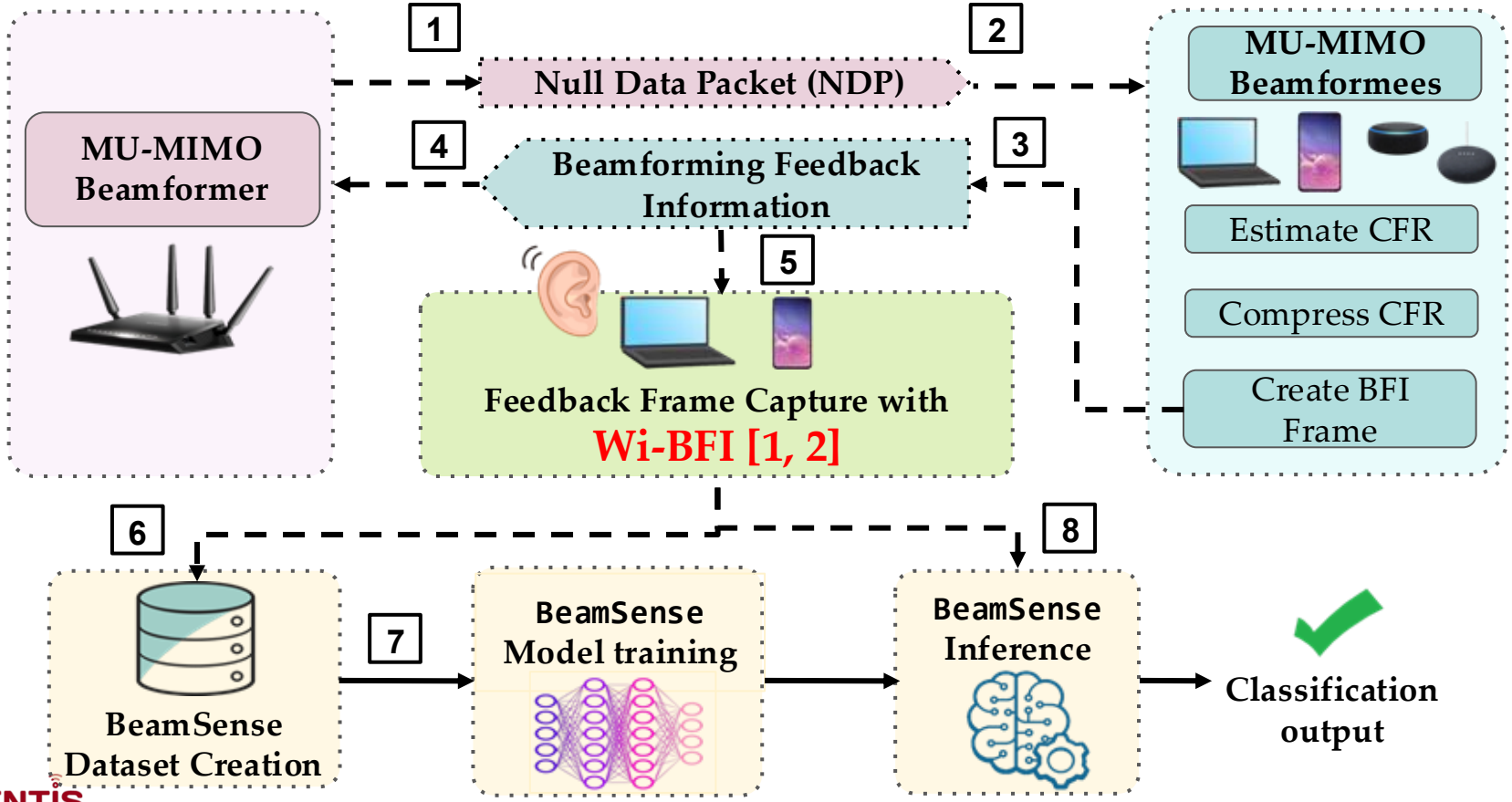
Capture BFI with Wi-BFI Tool



1. Wi-BFI captures the beamforming feedback packet
2. Decode the Wi-Fi BFAs based on the network configuration
3. Supports both online and offline extraction for IEEE 802.11ac and 802.11ax

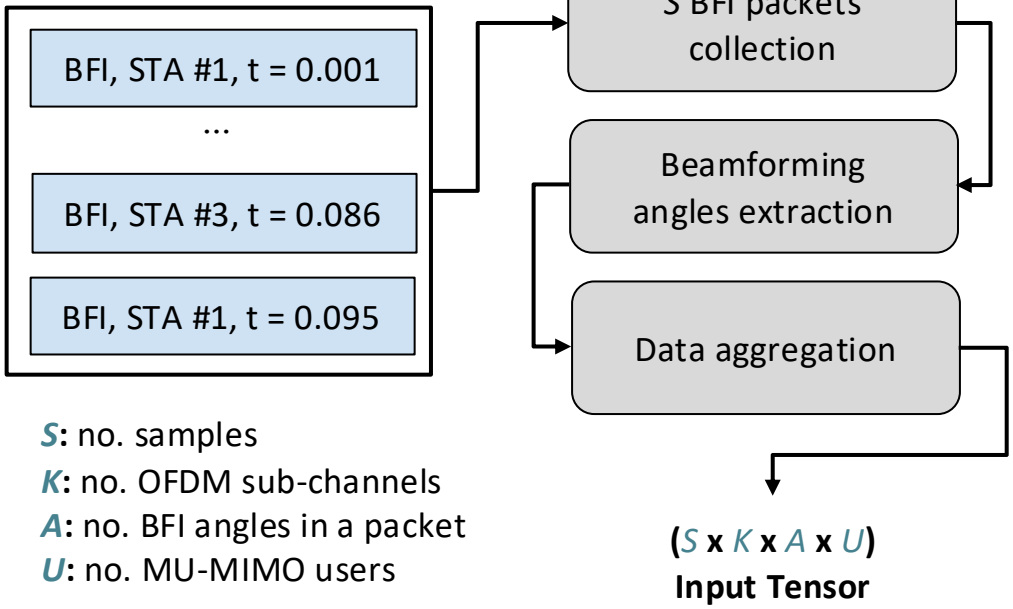
1. Khandaker Foysal Haque, Francesca Meneghello, and Francesco Restuccia. "Wi-BFI: Extracting the IEEE 802.11 beamforming feedback information from commercial Wi-Fi devices." In Proceedings of the 17th ACM Workshop on Wireless Network Testbeds, Experimental evaluation & Characterization, pp. 104-111. 2023.

BeamSense Walkthrough



Data Preprocessing

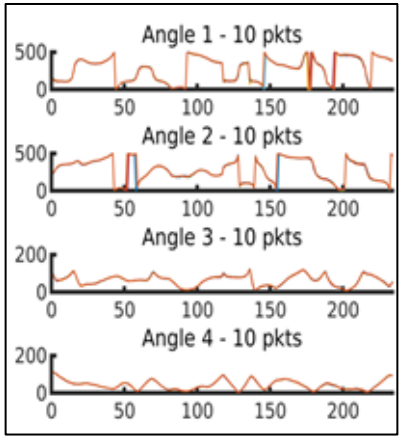
BFI packets in a window



S: no. samples
K: no. OFDM sub-channels
A: no. BFI angles in a packet
U: no. MU-MIMO users

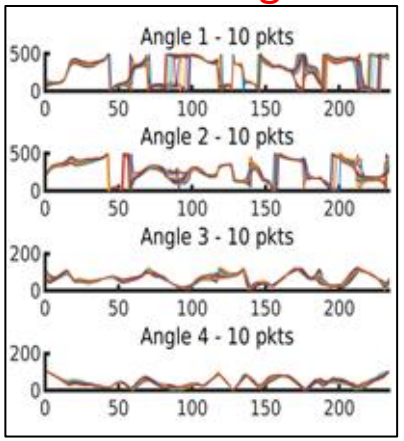
Each sample captures the variations of Angle 1 over subcarriers (234) and time (0.1s)

Browsing phone



Sub-channels

Walking



Sub-channels

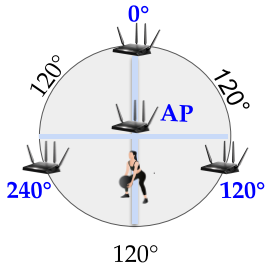
Data Collection Campaign

- Data collection campaign is done with 3 different persons, with 20 activities each in 3 different environment
- Data has been collected with 3 different orientations at different times of day
- Video Streams has been recorded as ground truth

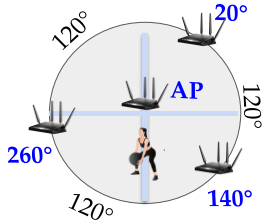
Kitchen ⟹ Subject 1 ⟹ side bend

Classroom ⟹ Subject 2 ⟹ reading book

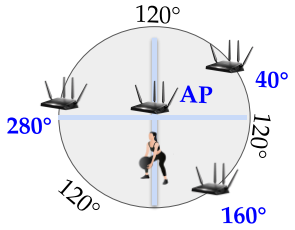
Living room ⟹ Subject 3 ⟹ boxing



Orientation 1



Orientation 2



Orientation 3

Experimental Testbeds

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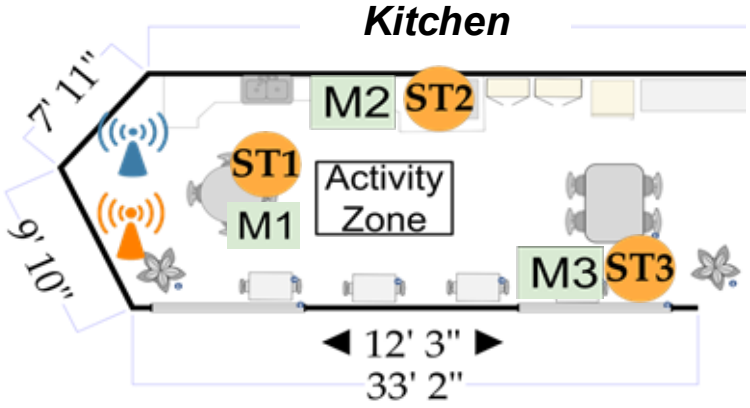
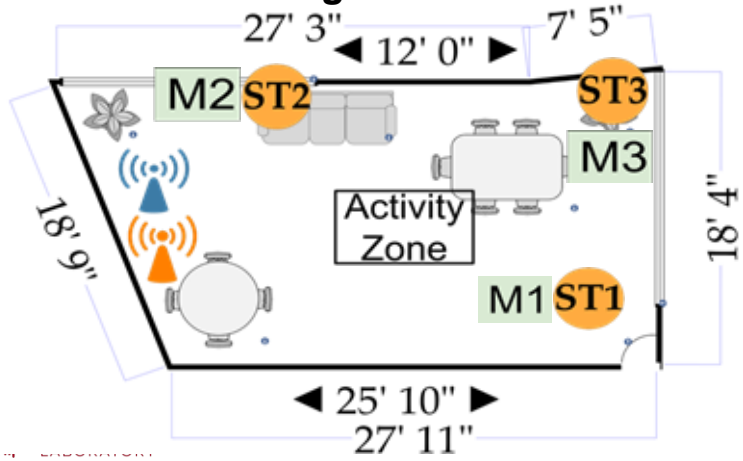
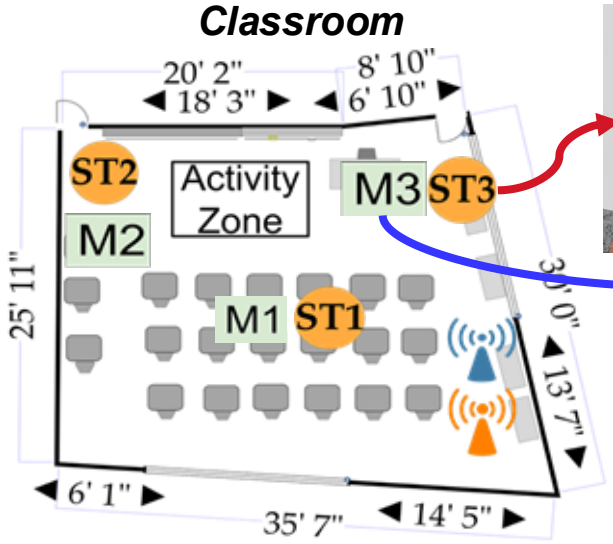






Access Point

CSI Access Point

ST1 Station

M1 CSI Monitor

BeamSense STA:
Netgear X4S AC2600

CSI Monitor:
ASUS AC86U

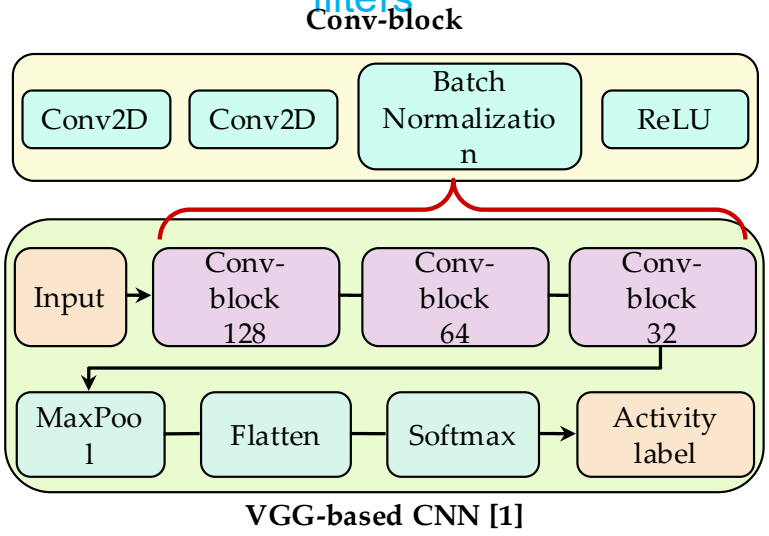
Standard: IEEE 802.11ac

MU-MIMO Config: 3 X 3

Channel BW: 80 MHz

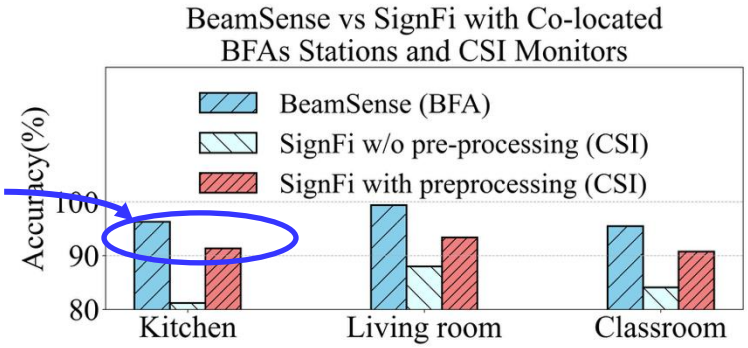
Performance with CNN Baseline

The baseline CNN consists of three conv-blocks with 128, 64 and 32 filters

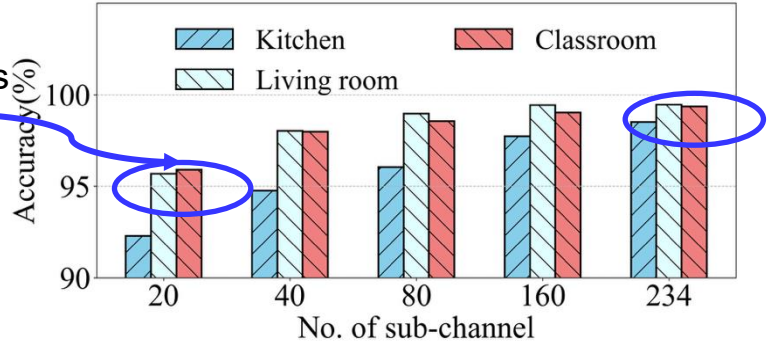


VGG-based CNN [1]

BeamSense improves the performance by 11%, compared to SOTA



The accuracy decreases by only 4.52% switching from 234 to 20 sub-channels



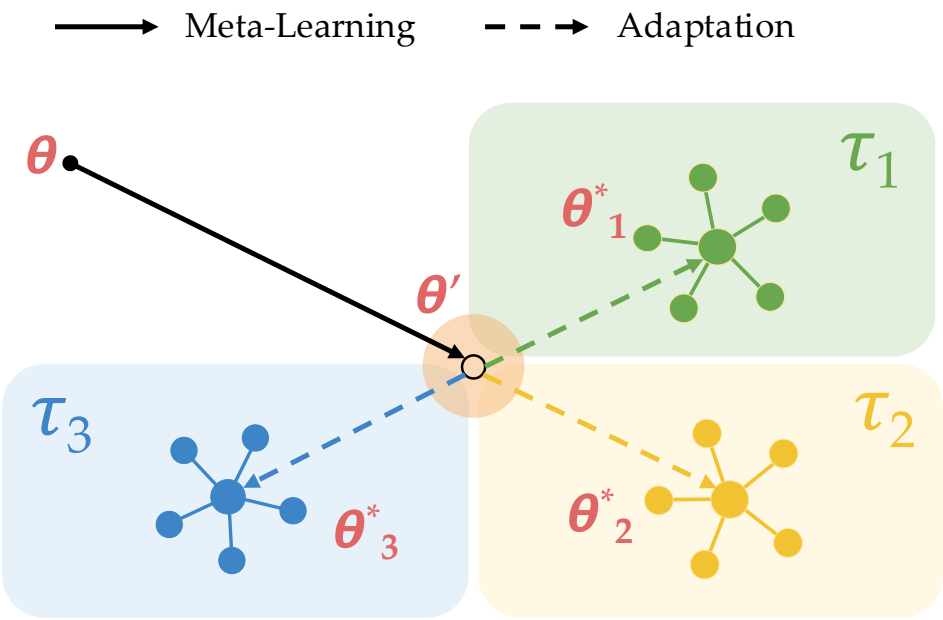
⚠ CNN cannot generalize to new domains

1. Simonyan, Karen, and Andrew Zisserman. "Very deep convolutional networks for large-scale image recognition." arXiv preprint arXiv:1409.1556 (2014).

Meta-Learning through Few-shots

- Find common features among different tasks
- Meta-learning is the warm-up phase before learning
- Fine-tuning on a specific task is faster with meta-learned weights

$$\theta' = \theta - \beta \frac{1}{n} \sum_{\tau=1}^{n} \left(\frac{1}{m} \sum_{i=1}^{m} \nabla_{\theta} L_{\tau} \left[f\left(x_i, y_i | \theta\right) \right] \right)$$
$$= \theta - \beta \frac{1}{n} \sum_{\tau=1}^{n} \left(\theta - \tilde{\theta} \right),$$



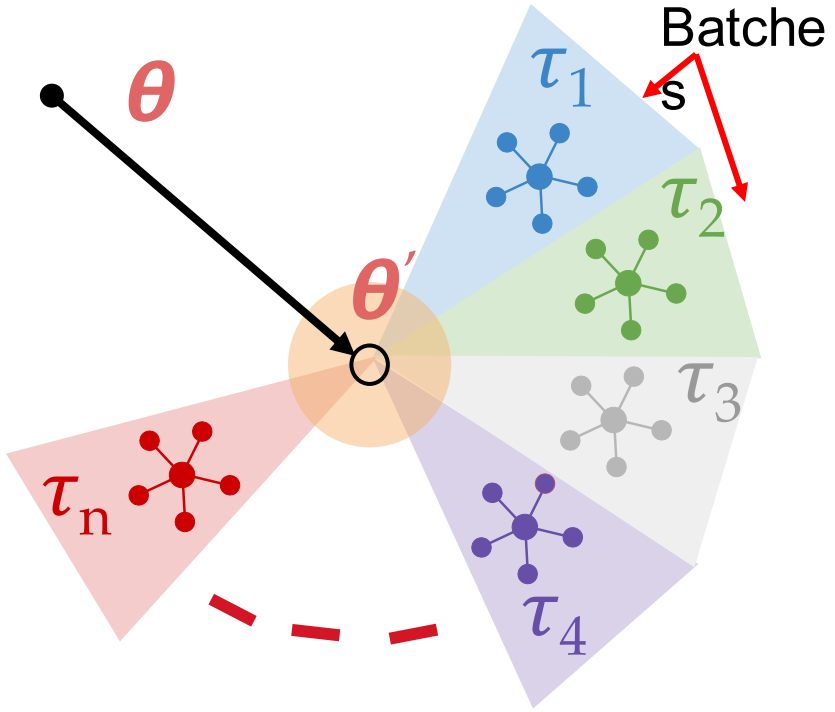
A. Nichol, J. Achiam, and J. Schulman, "On first-order meta-learning algorithms," arXiv preprint arXiv:1803.02999, 2018

FAMReS: Fast and Adaptive Micro Reptile Sensing

- **Due to infinite number of tasks** Reptile can't be directly adopted
- We consider each batch of training data as a new task in meta-learning

Algorithm 2: The FAMReS Algorithm

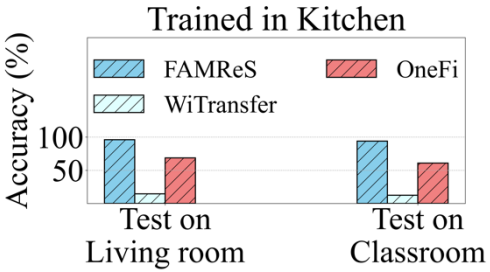
Require: step size β, micro dataset $\mathbb{D}$;
Initialize: a set of parameters θ;
for *iteration* $= 1, 2, \ldots$ **do**
  sample k points of data from $\mathbb{D}$; /*stage i*/
  compute $\tilde{\theta}$ using the SGD formulation;
  update the parameters: $\theta \leftarrow \theta + \beta\left(\tilde{\theta} - \theta\right)$;
for *epoch* $= 1, 2, \ldots$ **do**
  update θ running SGD on $\mathbb{D}$; /*stage ii*/

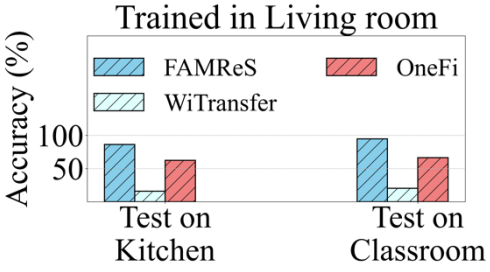


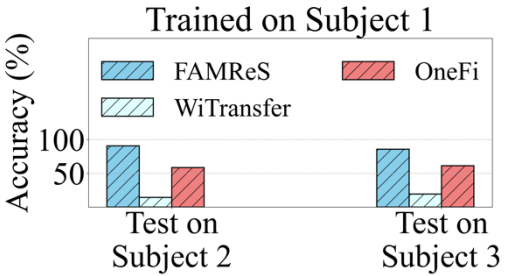
we only use a small portion of data in meta-learning and micro-learning for domain adaptation

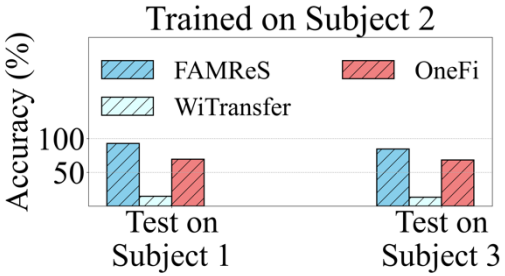
Performance of Domain Adaptation

FAMReS improves cross-environment and cross-subject accuracy by up to 35%

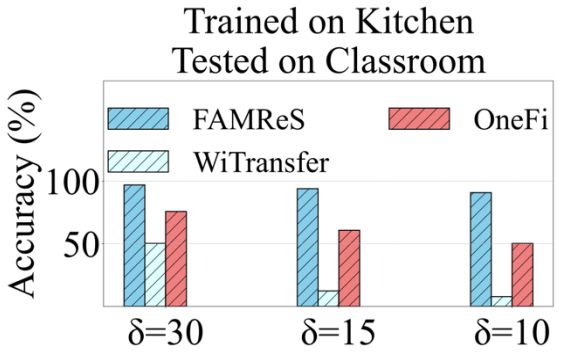




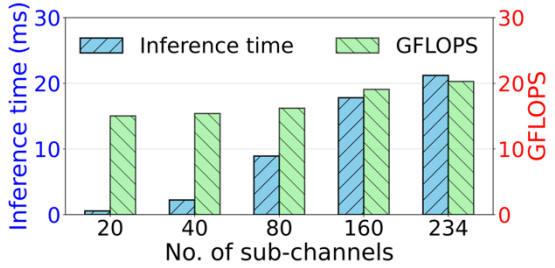




From 30s to10s of data from new Env , FAMReS accuracy drop by only 5.3



20 GFLOPs of computation with 20 ms of inference time



Key Findings

Beamsense: Rethinking Wireless Sensing with MU-MIMO Wi-Fi Beamforming Feedback

- ✓ No hardware specific firmware, or firmware modification needed
- ✓ Data Extraction can be performed with any Wi-Fi compliant device
- ✓ No dedicated extraction tool needed with tight synchronization
- ✓ Can generalize to new environments, subjects or orientations

Future Work

- Sensing without no additional data at all from new environment
- Sensing with larger band to have more sensing granularity

Thank You