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BandWeave: Enhanced Channel Estimation in MIMO Networks with Multi-Band Fusion

(Best Paper INFOCOM-2026)

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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

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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?

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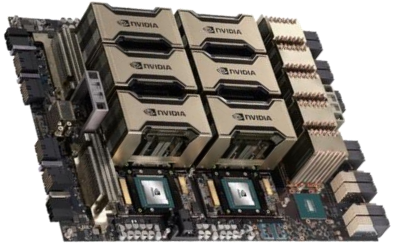
Object recognition
Semantic segmentation

Compute-intensive AI/ML tasks



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

Weight
515 grams

Meta Quest 3 (1.5-2 hours)

Weight
650 grams plus 353 grams battery

Apple Vision Pro (Up to 2 hours)

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.

Wireless Edge Computing For Next-Gen App

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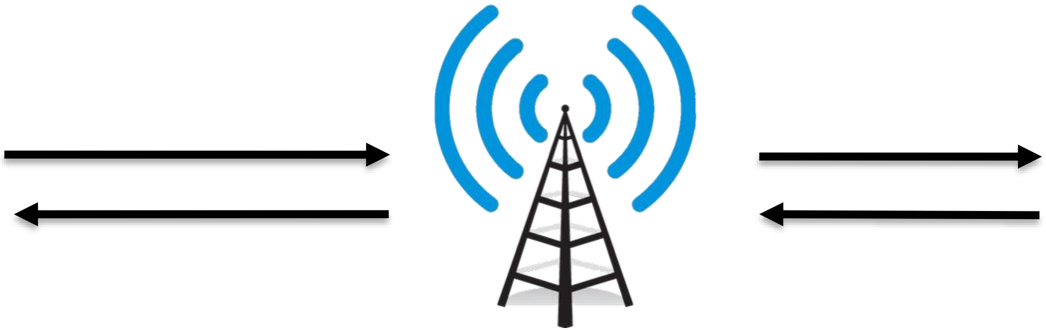
Offload compute intensive task to edge server



Edge Devices

Wireless Link

Edge Server

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

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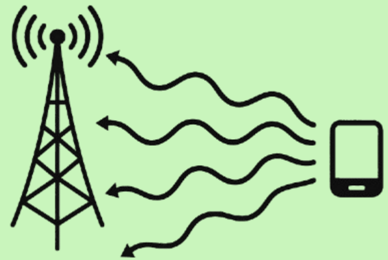
1. M Gallagher, ER Ferrè, "Cybersickness: a multisensory integration perspective", Multisensory Research, 2018. Ars Technica, "Virtual Perfection: Why 8K resolution per eye isn't enough for perfect VR", 2013.

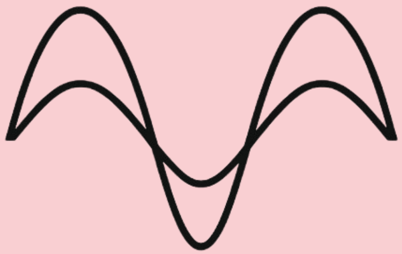
Channel-Estimation– the Key Enabler of MIMO

Accurate channel estimation enables spatial multiplexing and interference mitigation in MIMO systems

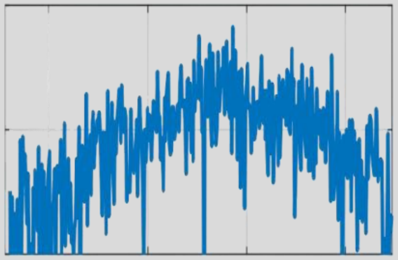
Multi-path superposition



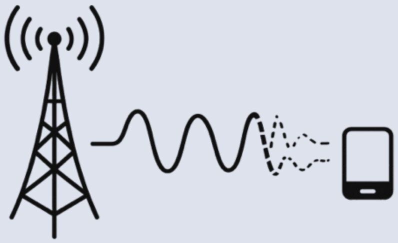
Destructive interference



Degraded Channel estimation

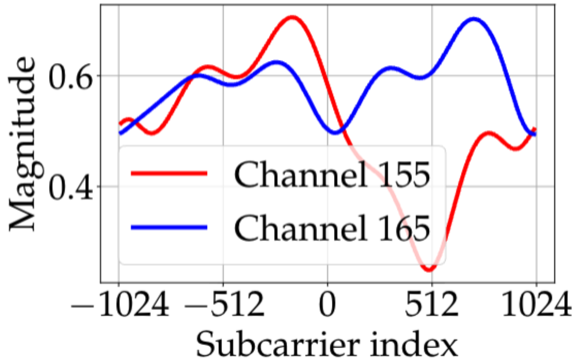


Hamper Communication

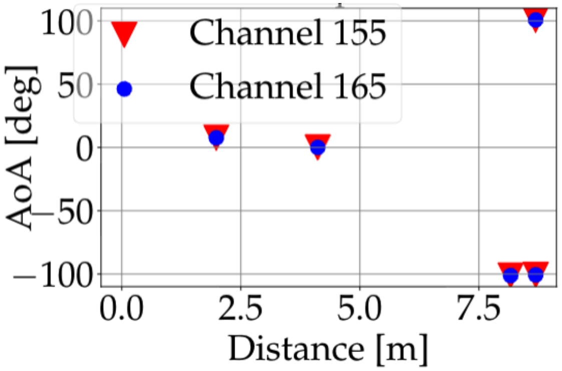


Analyzing CFR at Different Center Freq.

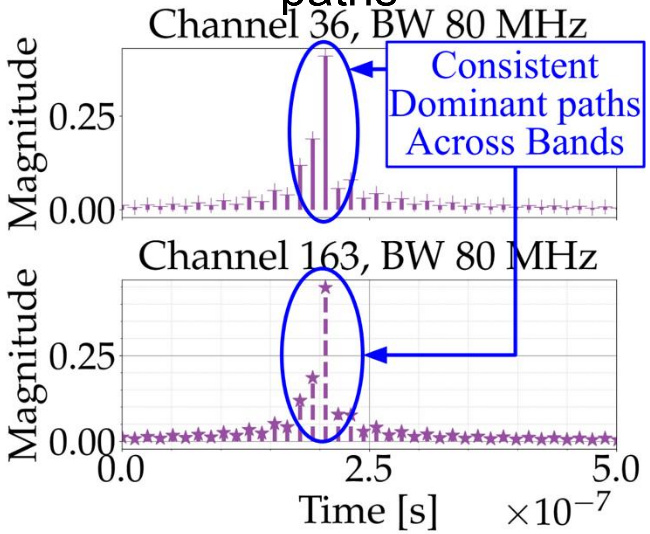
CFR is band-specific



Multipath components are band-independent



CIRs from different center frequencies exhibit consistent dominant multi-paths



Diff. bands provide complementary views of the same instances

BandWeave: Enhanced Ch. Est. with Band Fusion

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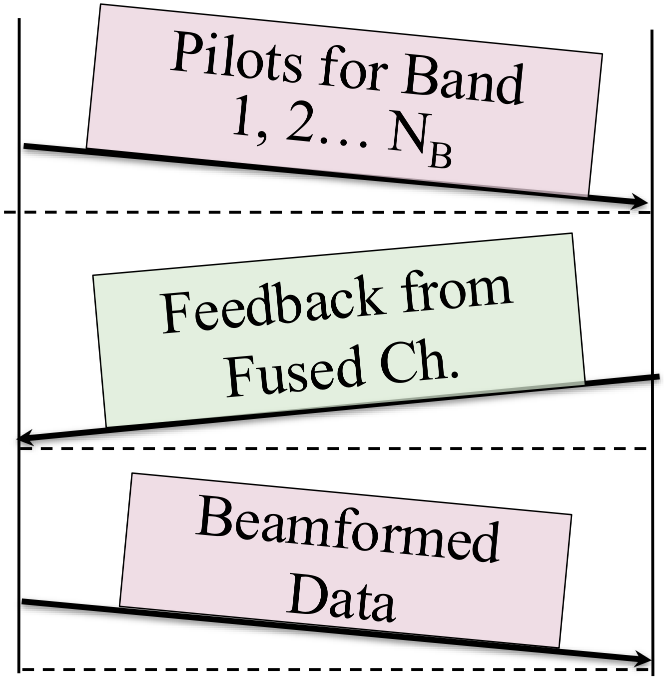
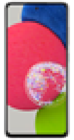
BandWeave Beamformer

- Estimate Precoding Matrix



BandWeave Beamformee



-Est. Ch. Response for Bands 1 to N_B

- Fuse Responses in Time Domain

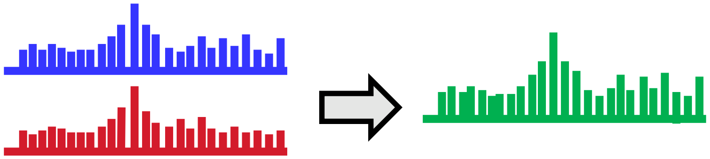
BandWeave → Enhanced Ch. Est. → Improved Comm.

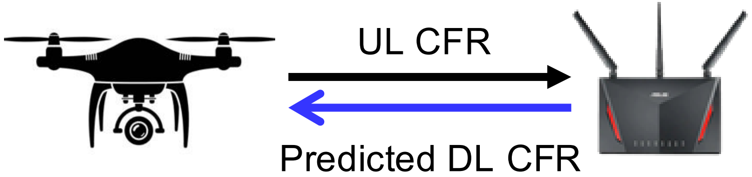
Prior Work and Existing Challenges

Spectrum Splicing

Cross Link CFR Estimation

Cross Band CFR Estimation





Prior work focuses only on sensing or CFR prediction and does not improve estimation fidelity

- A. Banerjee, X. Zhao, V. Chhabra, K. Srinivasan, and S. Parthasarathy, “HORCRUX: Accurate Cross Band Channel Prediction,” in Proceedings of the 30th Annual International Conference on Mobile Computing and Networking, pp. 1–15, 2024.
- M. S. Safari, V. Pourahmadi, and S. Sodagari, “Deep UL2DL: Data-driven Channel Knowledge Transfer from Uplink to Downlink,” IEEE Open Journal of Vehicular Technology, vol. 1, pp. 29–44, 2019.
- X. Li, H. Wang, Z. Chen, Z. Jiang, and J. Luo, “UWB-Fi: Pushing Wi-Fi Towards Ultra-Wideband for Fine-Granularity Sensing,” in Proceedings of the 22nd Annual International Conference on Mobile Systems, Appli-cations and Services, pp. 42–55, 2024
- J. Pegoraro, J. O. Lacruz, M. Rossi, and J. Widmer, “HiSAC: High-Resolution Sensing with Multiband Communication Signals,” in Proceedings of the 22nd ACM Conference on Embedded Networked Sensor Systems, pp. 549–563, 2024.

Summary of Key Contributions

- BandWeave is the first framework to coherently fuse CFRs to enhance channel estimation resolution
- We introduce a 3-phase learning framework to address frequency-dependent path loss and phase misalignments
- We extensively evaluate BandWeave with an IEEE 802.11ac MU-MIMO and a 60 GHz SU-MIMO testbed

Signal-Processing based CFR Fusion

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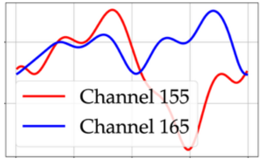
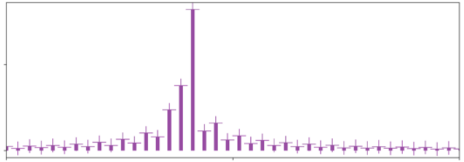
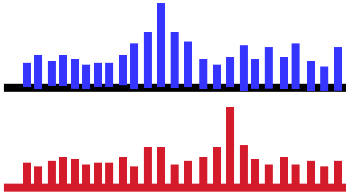
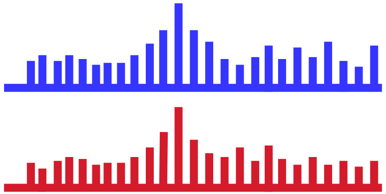
Step 1 & 2: Extract CIR and Normalize



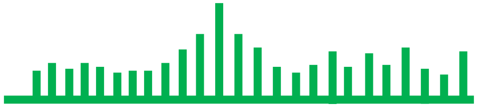


Step 3: Delay and Phase Alignment





Step 4 & 5: Comp.-wise Fusion & CFR Reconstruction

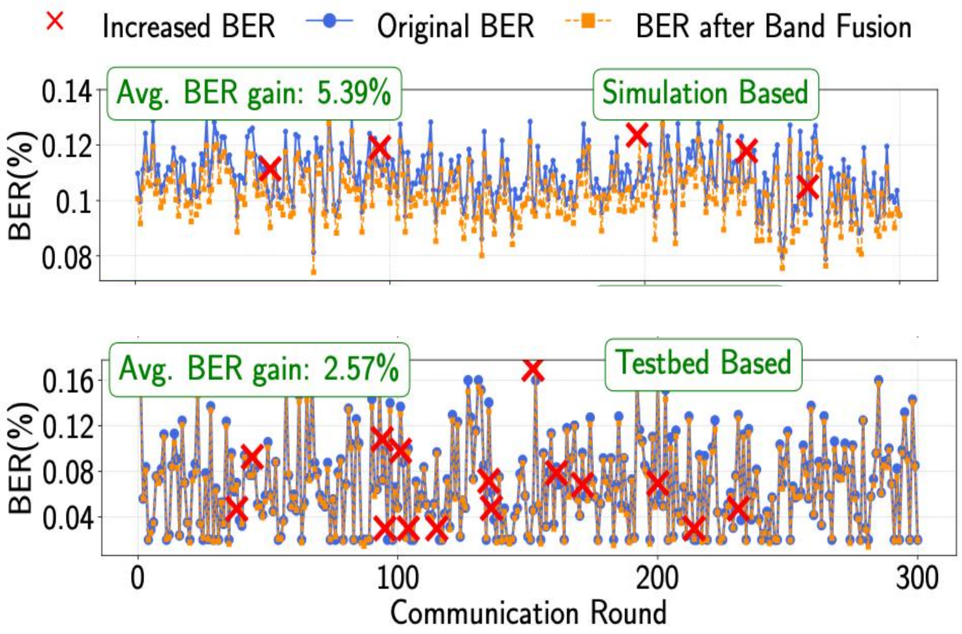


Algorithm 1: Signal Processing-based Multi-Band CFR Fusion

Input: $\{\mathrm{CFR}_i(f)\}_{i=1}^{N_B}$ (CFRs from N_B bands)
Output: Fused CFR, $\mathrm{CFR}_{\mathrm{fused}}(f)$
Step 1: CIR Extraction
for $i = 1$ to N_B **do**
  $\mathrm{CIR}_i(t) \leftarrow \mathrm{IFFT}(\mathrm{CFR}_i(t))$
Step 2: CIR Normalization
for $i = 1$ to n **do**
  $\mathrm{CIR}_i^{\mathrm{norm}}(t) \leftarrow \frac{\mathrm{CIR}_i(t)}{\|\mathrm{CIR}_i(t)\|}$
Step 3: Delay and Phase Alignment
Select reference CIR: $\mathrm{CIR}_{\mathrm{ref}}^{\mathrm{norm}}(t) \leftarrow \mathrm{CIR}_1^{\mathrm{norm}}(t)$
for $i = 2$ to N_B **do**
  Estimate delay offset using Equation 1
  Refine $\Delta\tau_i$ using parabolic interpolation
  Delay-align using $\mathrm{CIR}_i^{\mathrm{aligned}}(t) \leftarrow \mathrm{CIR}_i^{\mathrm{norm}}(t + \Delta\tau_i)$
  Estimate phase offset as
  $\phi_i(t) \leftarrow \angle\mathrm{CIR}_{\mathrm{ref}}^{\mathrm{norm}}(t) - \angle\mathrm{CIR}_i^{\mathrm{aligned}}(t)$
  Apply phase correction with Equation 2
Step 4: SNR-Based Component-wise Fusion
for all components t **do**
  for $i = 1$ to N_B **do**
    $P_i(t) \leftarrow |\mathrm{CIR}_i^{\mathrm{aligned}}(t)|^2$
  Normalize the weights as $w_i(t) \leftarrow \frac{P_i(t)}{\sum_{i=1}^{N_B} P_i(t)}$ $\forall i$
  Obtain the fused CIR using Equation 3
Step 5: CFR Reconstruction
$\mathrm{CFR}_{\mathrm{fused}}(f) \leftarrow \mathrm{FFT}(\mathrm{CIR}_{\mathrm{fused}}(t))$
Return: $\mathrm{CFR}_{\mathrm{fused}}(f)$

Performance of the Heuristic Algorithm

- One access point (AP) and one station (STA) is considered
- CFR from channel 36 and 163 are fused
- The fused band is used to beamform in channel 36



Signal-Strength-based heuristic fusion is not very robust

We focus on domain adaptive learning-based approach

BandWeave Walkthrough

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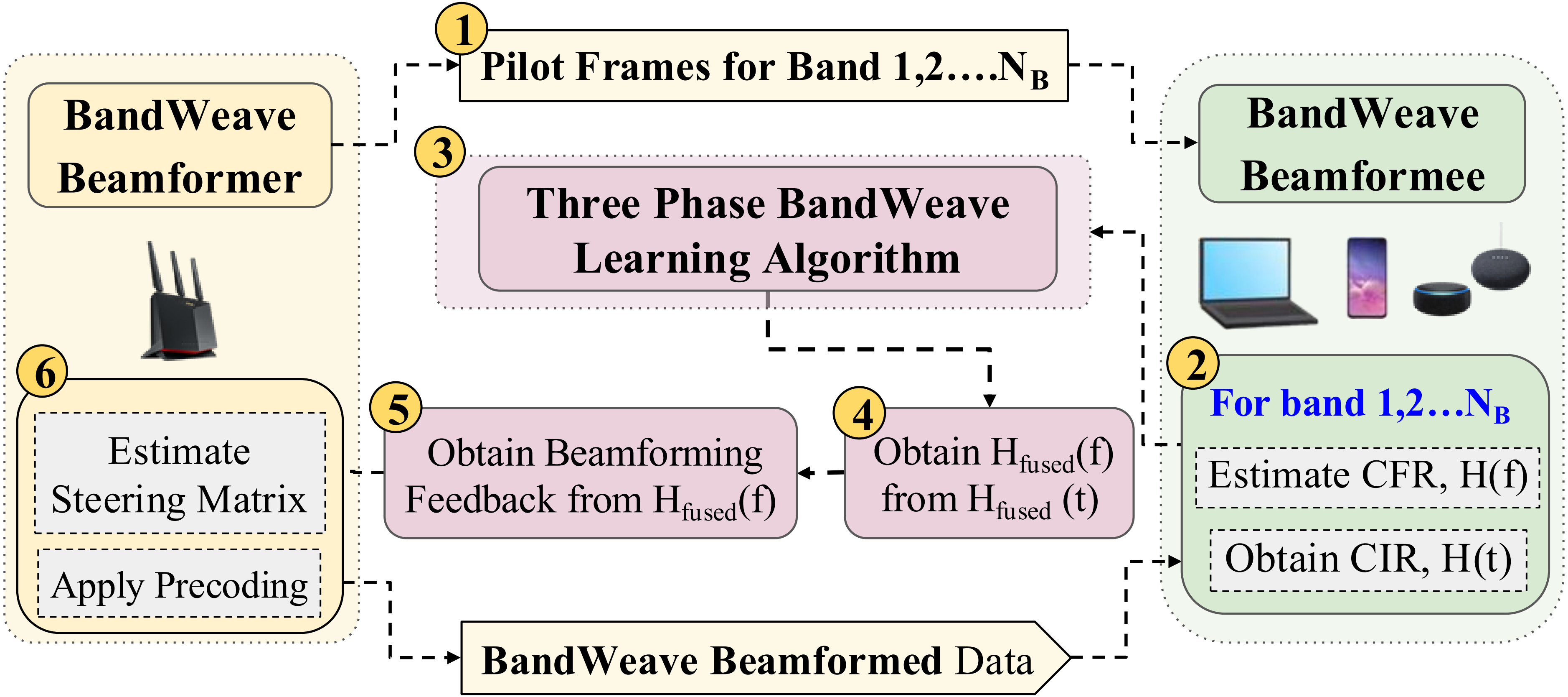


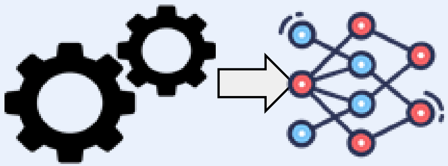
BandWeave Learning Algorithm

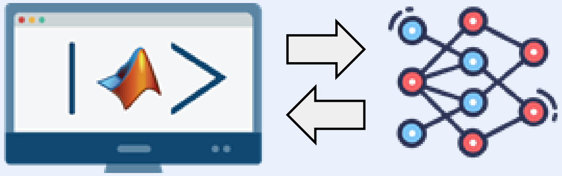
BandWeave Learning Algorithm

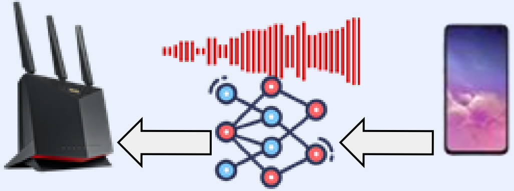
Phase 1
Supervised Pre-training

Phase 2
Simulation in the Loop Fine-tuning

Phase 3
Online Feedback Aware Adaptation







Phase-1: Supervised Pre-training

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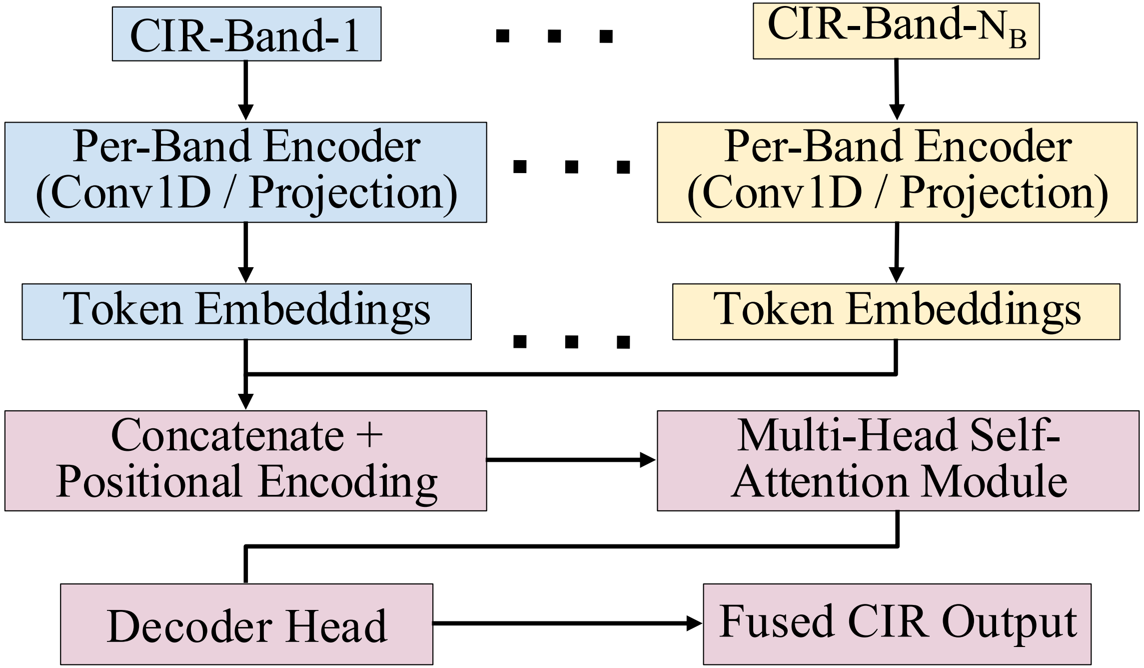
- CIRs are projected into embeddings via encoder
- Embeddings are concatenated and processed by multi-head self-attention module
- Algorithm 1 as pseudo-ground-truth with the loss as:



$$\mathcal{L}_{\mathrm{MSE}} = \frac{1}{T \cdot M \cdot N} \sum_{t,x,y} \left\| \widehat{\mathbf{C}}_{\mathrm{fused}}[t,x,y,:] - \mathbf{C}^*[t,x,y,:] \right\|_2^2$$

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Phase-2 and 3: Finetuning and Online Adaptation

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Phase 2: Finetuning through Simulation in the Loop

- Fused CIR is evaluated in a full-stack simulator to obtain BER
- Model parameters are fine-tuned to minimize BER $\mathcal{L}_{\text{sim}}(\theta) = \left\| \mathcal{B}\left(\widehat{\mathbf{C}}_{\text{fused}}\right) \right\|_2^2$

Phase 3: Online Feedback Aware Adaptati

Step 1: If performance is better than the baseline, apply gradient-free perturbations to refine the model

Step 2: Otherwise, fine-tune using Algorithm 1 as surrogate supervision

$$\mathcal{L}_{\text{MSE}}(\theta) = \left\| f_\theta\left(\left\{\mathbf{C}_i^{(k)}\right\}_{k=1}^{N_B}\right) - \widehat{\mathbf{C}}_{\text{teacher}} \right\|_2^2$$

Algorithm 2: Online Feedback-Aware Adaptation

Require: Model f_θ, deployment data $(\{\mathbf{C}_i^{(k)}\}_{k=1}^{N_B}, T_{\text{base}}^{(i)})_{i=1}^{D}$

```
Set threshold δ, noise scale σ
for each round i = 1 to D do
    Predict fused CIR: Ĉ_i = f_θ({C_i^(k)})
    Measure throughput T_model^(i)
    if T_model^(i) ≥ T_base^(i) + δ then
        θ̃ = θ + N(0, σ²I)
        if T_perturbed > T_model^(i) then
            θ ← θ̃
    else
        Generate teacher Ĉ_teacher via Algorithm 1
        Minimize L_MSE(θ) defined in Equation 8
```

BandWeave Experimental Setup

- Evaluated BandWeave on IEEE 802.11ac MU-MIMO and mmWave SU-MIMO testbeds
- Tested across LoS, NLoS, and dynamic scenarios in three environments

IEEE 802.11ac MU-MIMO Experiments

LoS in Anechoic Chamber

NLoS in Classroom

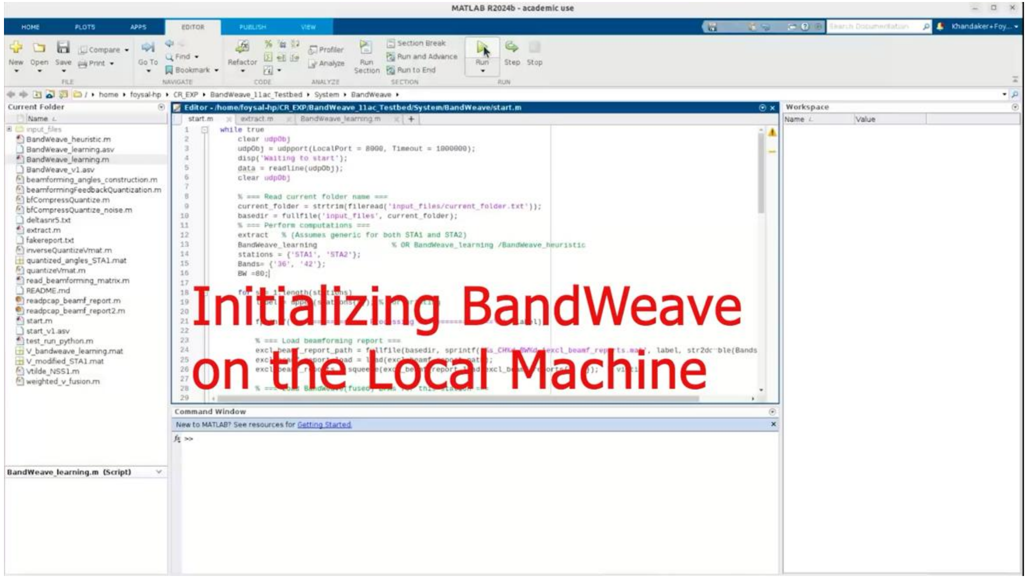
Movement in Conference Room

mmWave SU-MIMO Experiments

Movement in Anechoic Chamber

NLoS in Classroom

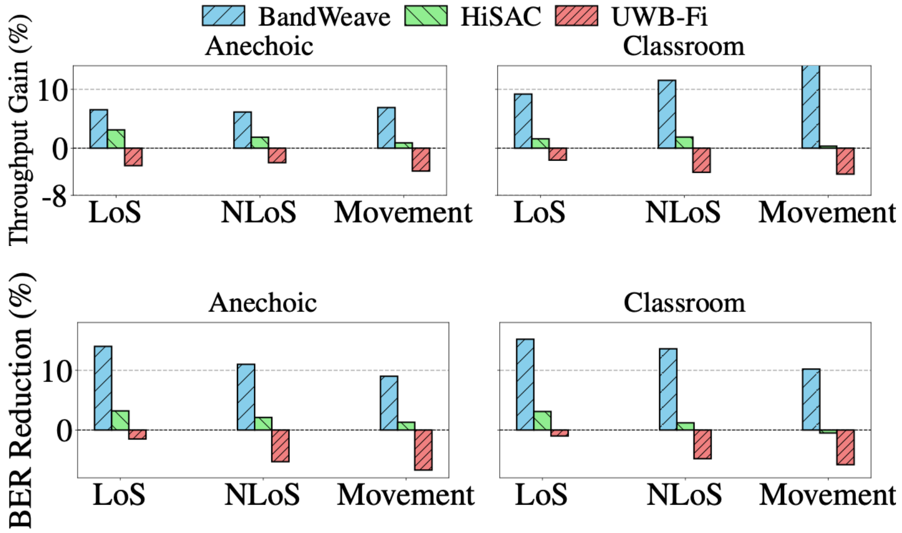
LoS in Conference Room



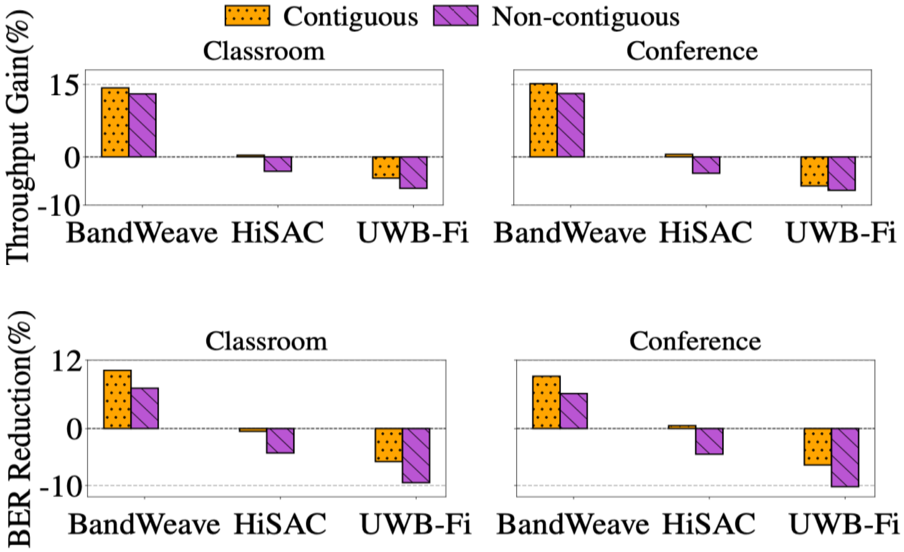
Performance Analysis of BandWeave (1)

- Achieves up to 7.5x throughput gain and 4.9x BER reduction over SOTA
- Robust in non-contiguous bands, achieving up to 12.6% throughput gain and 7.1% BER reduction

Performance with Varying Channel Condition



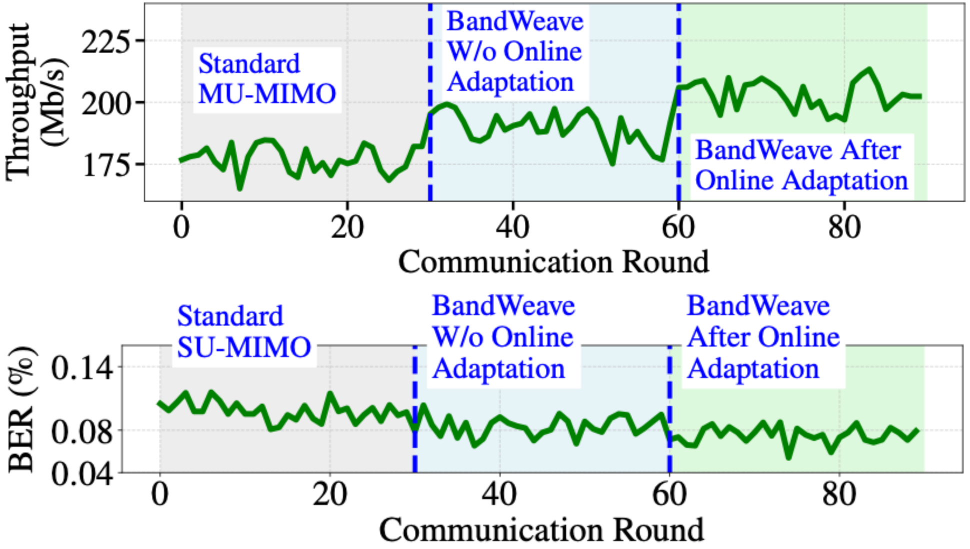
Performance with Non-Contiguous Band



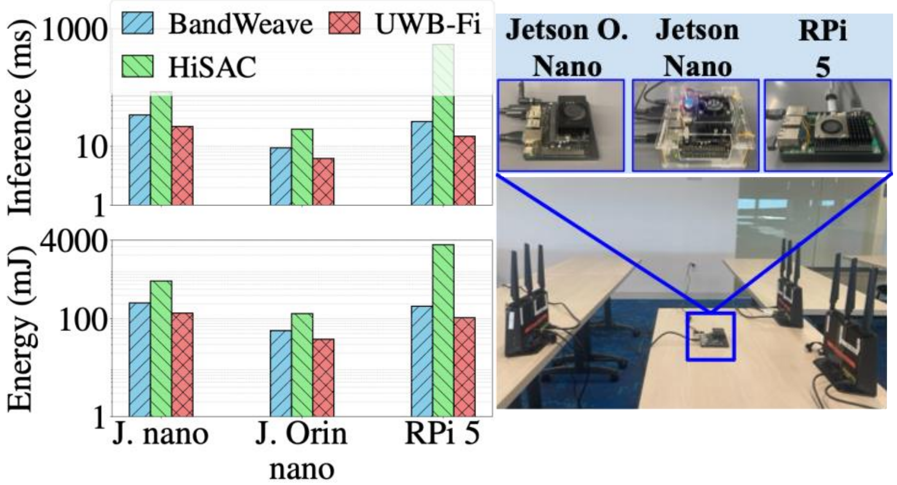
Performance Analysis of BandWeave (2)

- Online adaptation boosts performance by ~7 %, reaching up to 15% total throughput gain
- BandWeave achieves up to 20x lower latency and 18x lower energy than SOTA (HiSAC)

Impact of Online Adaptation



Inference-time and Energy Consumption Analysis



Possible Next Steps?

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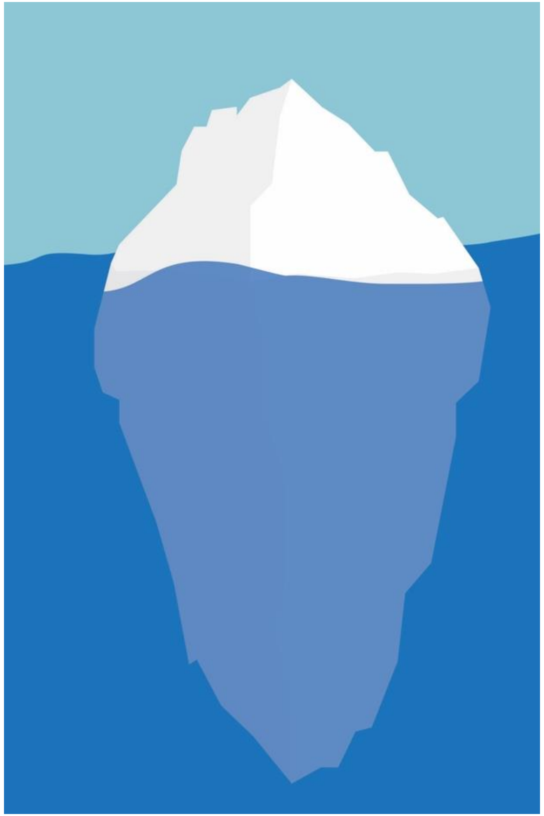

This work 💪

✅ Multi-Band Fusion within the Same Frequency Range (e.g., 5 GHz Wi-Fi bands)

Future Direction
s 🚀

⚠️ Fusion Across Different Frequency Ranges (e.g., 2.4 GHz ↔ 5 GHz ↔ mmWave)

⚠️ Generalizable channel representation

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BANDWEAVE: Enhanced Channel Estimation in MIMO Networks with Multi-Band Fusion

THANK YOU

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