Northeastern University
Institute for Intelligent Networked Systems

MENTIS LABORATORY

Improving MIMO Channel Acquisition through Multi-Band Fusion and Uncertainty-Aware Subcarrier Feedback

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Dipartimento di Ingegneria dell'Informazione

- Fulbright-Schuman Scholar, Northeastern University, USA (2023)

MENTIS Laboratory

- **Research Group**
  - 11 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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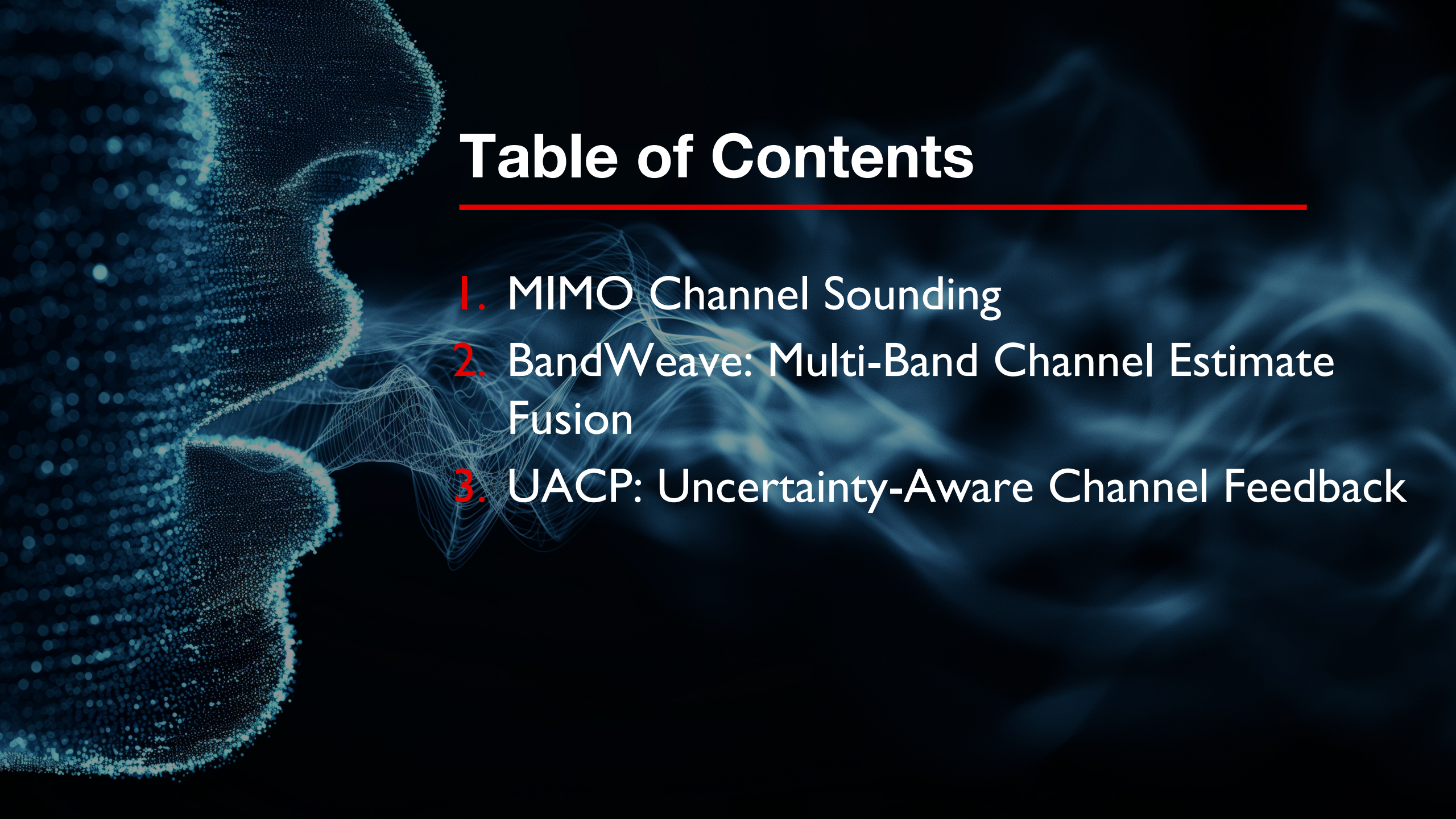

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2. BandWeave: Multi-Band Channel Estimate Fusion
3. UACP: Uncertainty-Aware Channel Feedback

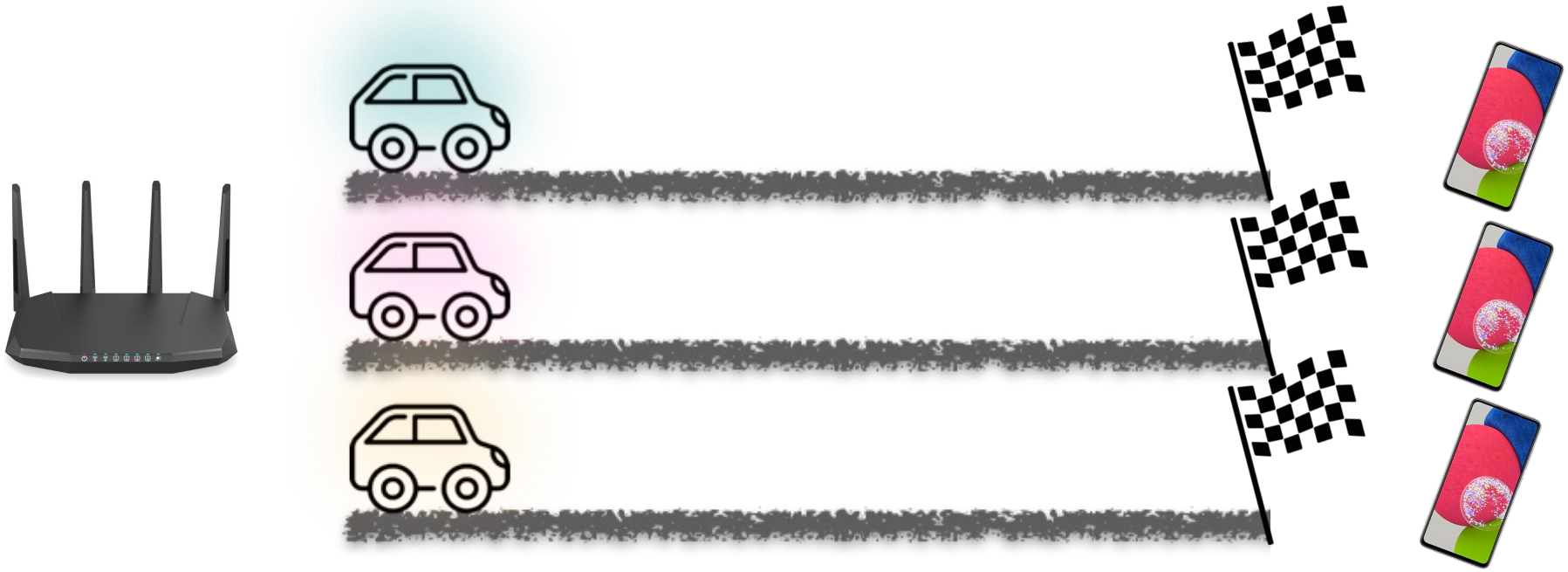
MIMO Channel Sounding



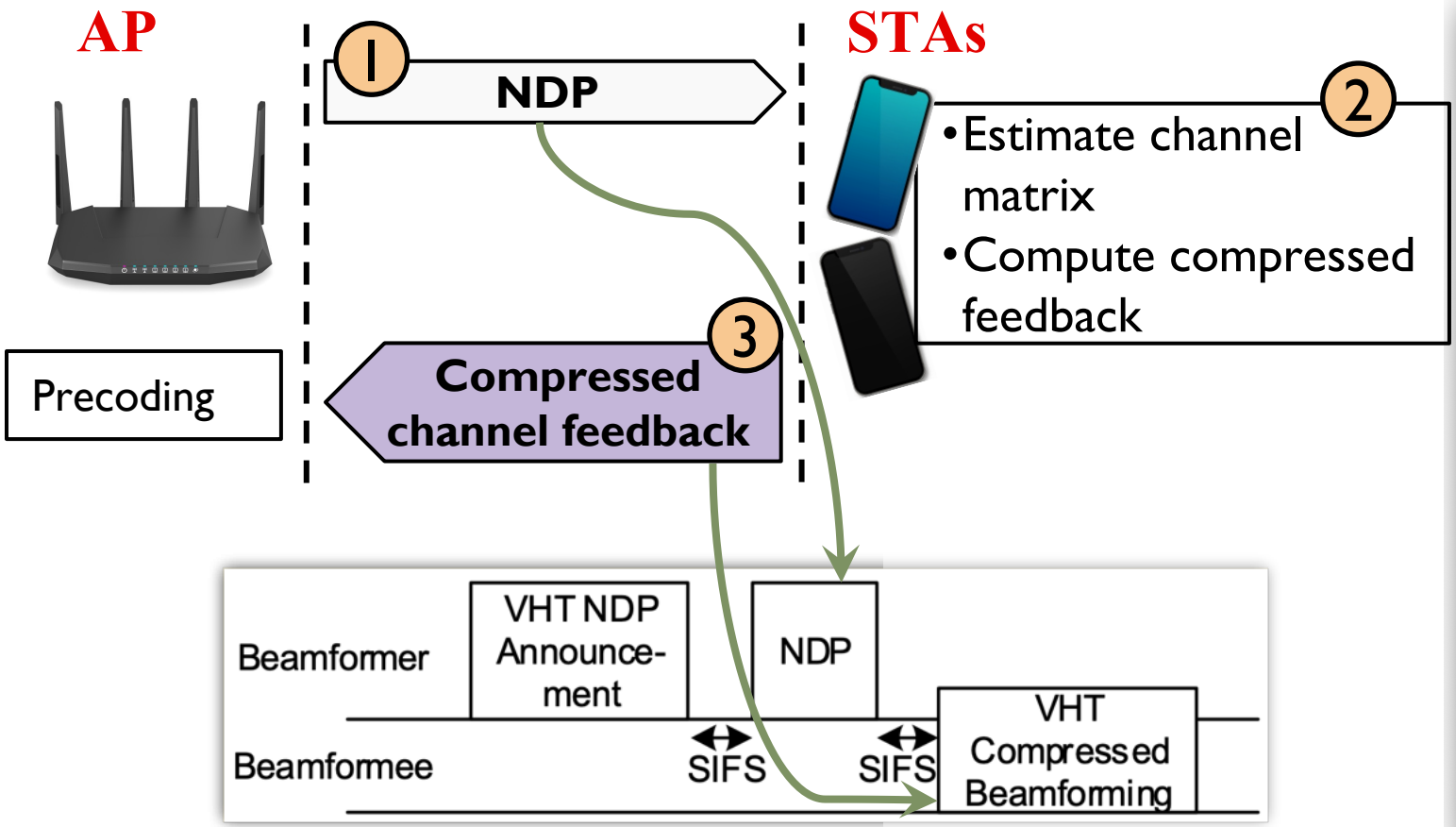
SISO Transmission

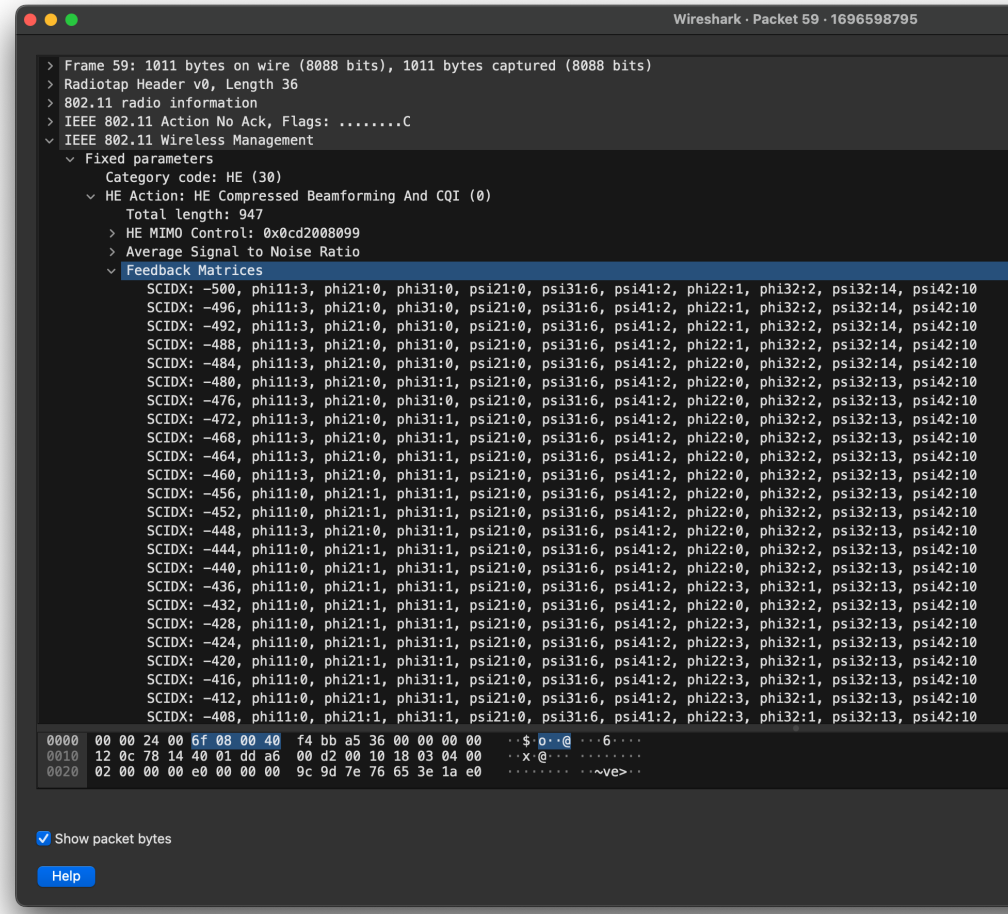


MIMO for Next-generation Wi-Fi



MIMO Channel Sounding: the Key Enabler for MIMO





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

BandWeave

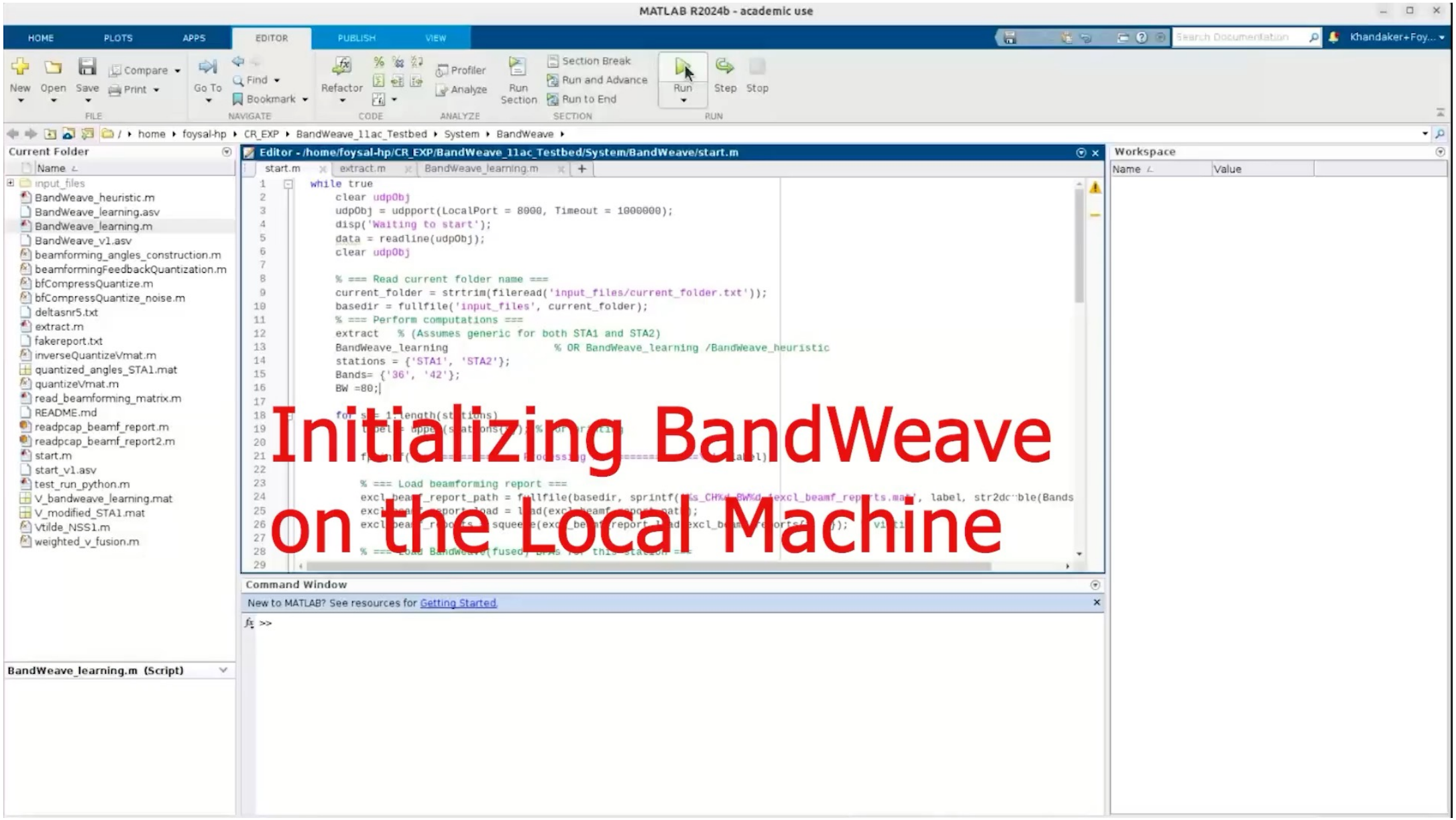
K. F. Haque, F. Meneghello, J. Ashdown and F. Restuccia

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

in Proceedings IEEE INFOCOM 2026

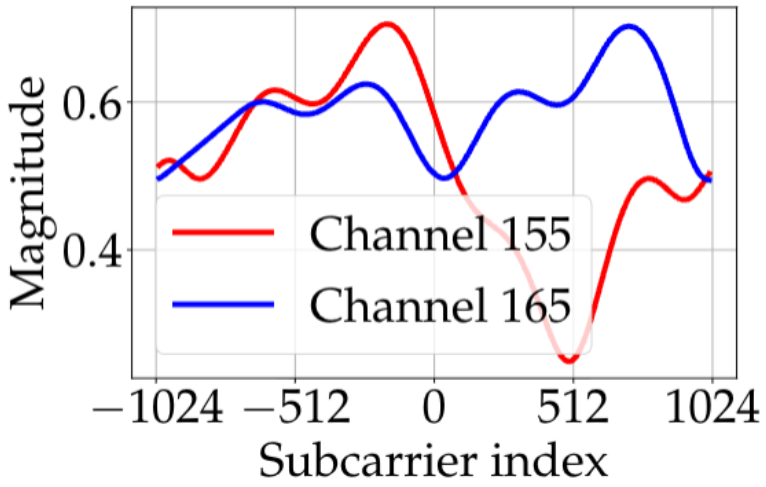
Best Paper Award

BandWeave Effect

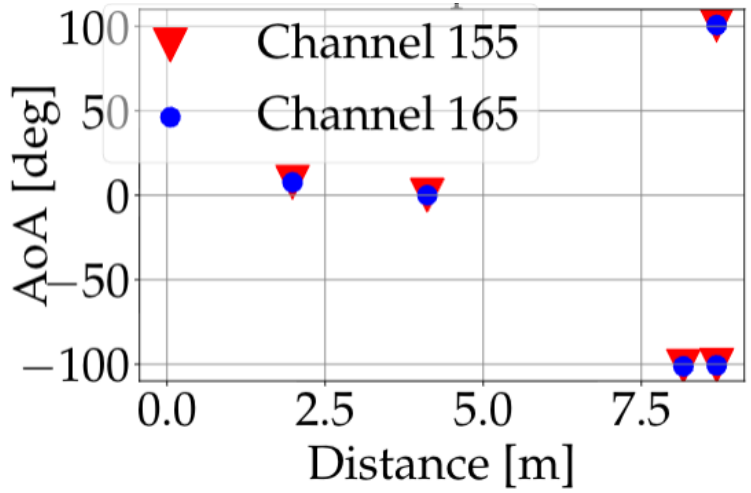


Main Intuition

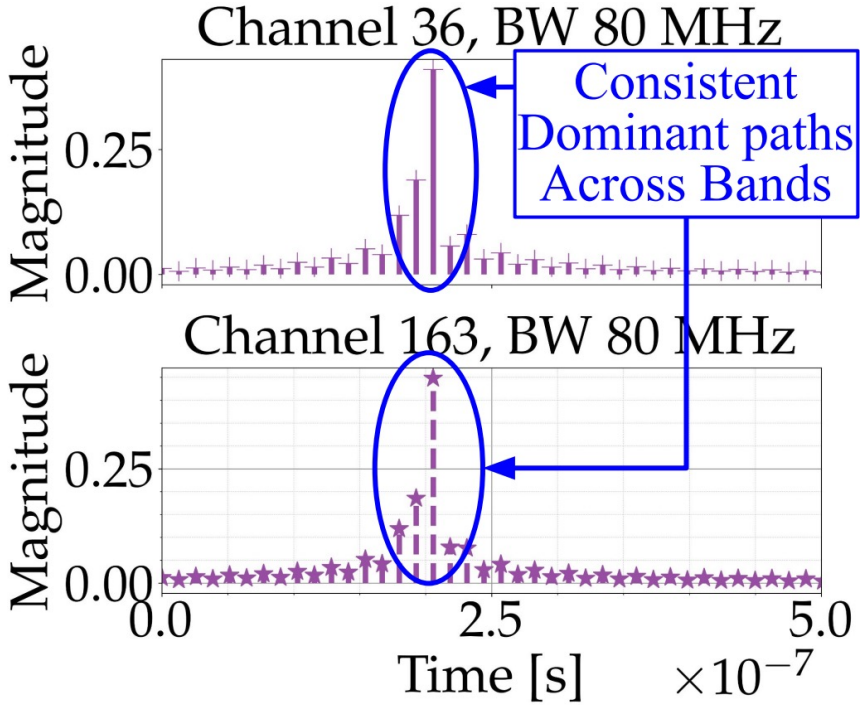
CFR is band-specific



Multipath components are band-independent



CIRs from different center frequencies exhibit consistent dominant multipath components



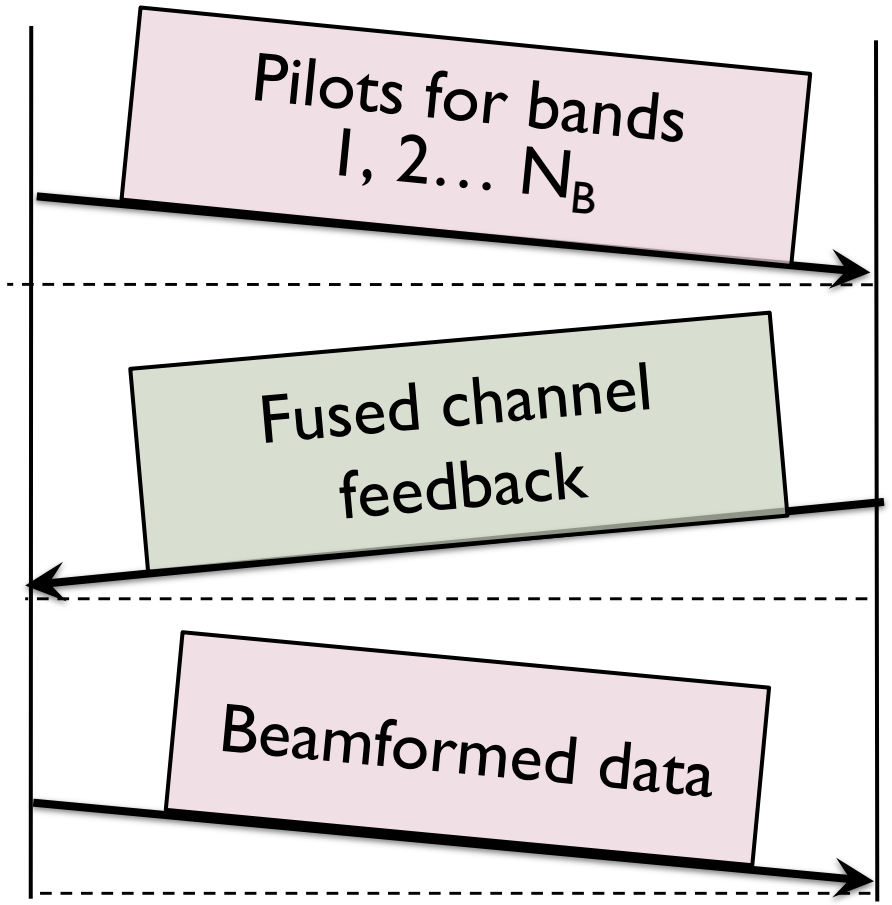
Different bands provide complementary views of the same physical phenomenon

Enhanced Channel Estimation with Band Fusion

BandWeave Beamformer



Compute the precoding matrix for multiplexing



BandWeave Beamformee



-Estimate channel response for bands 1 to N_B

- Fuse responses in the time domain

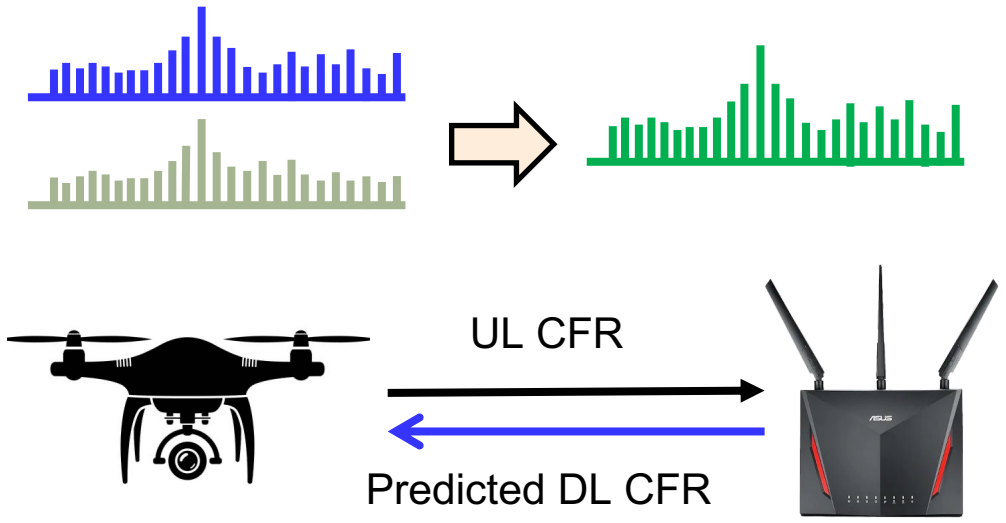
BandWeave ➔ Enhanced channel estimation ➔ Improved communications

Prior Work

Spectrum Splicing [1, 2]

Cross-Band CFR Estimation [3, 4]

Cross-Link CFR Estimation [5]

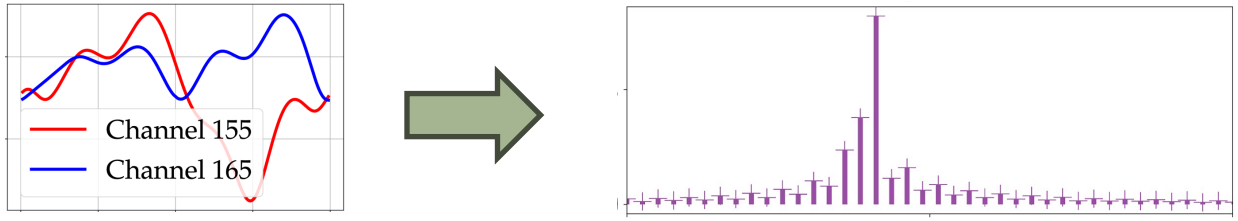


Prior work focuses only on sensing or CFR prediction and does not improve estimation fidelity

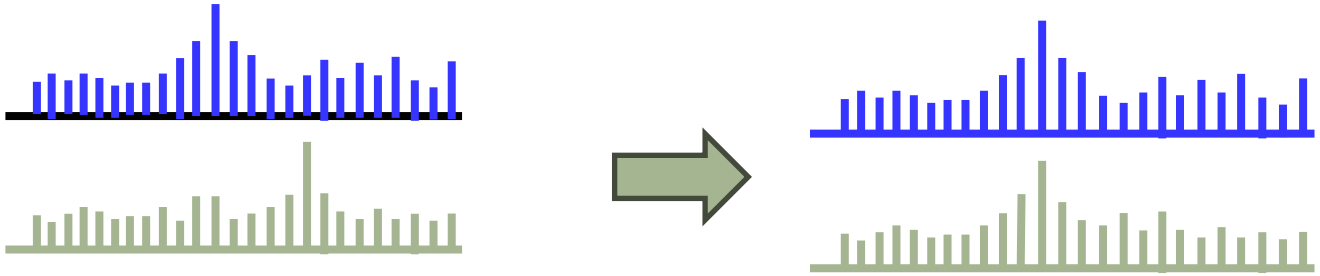
[1] X. Li, H. Wang, Z. Chen, Z. Jiang, and J. Luo, "UWB-Fi: Pushing Wi-Fi Towards Ultra-Wideband for Fine-Granularity Sensing," in Proc. of MobiSys, 2024.
[2] J. Pegoraro, J. O. Lacruz, M. Rossi, and J. Widmer, "HiSAC: High-Resolution Sensing with Multiband Communication Signals," in Proc. of ACM SenSys, 2024.
[3] A. Banerjee, X. Zhao, V. Chhabra, K. Srinivasan, and S. Parthasarathy, "HORCRUX: Accurate Cross Band Channel Prediction," in Proc. of MobiCom, 2024.
[4] 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.
[5] K. W. Cho, M. Cominelli, F. Gringoli, J. Widmer, and K. Jamieson, "Scalable Multi-modal Learning for Cross-link Channel Prediction in Massive IoT Networks," in Proc. of ACM MobiHoc, 2023.

Signal Processing-based Fusion

Step 1 & 2: Extract CIR and normalize



Step 3: Delay and phase alignment



Step 4 & 5: Component-wise fusion and CFR reconstruction

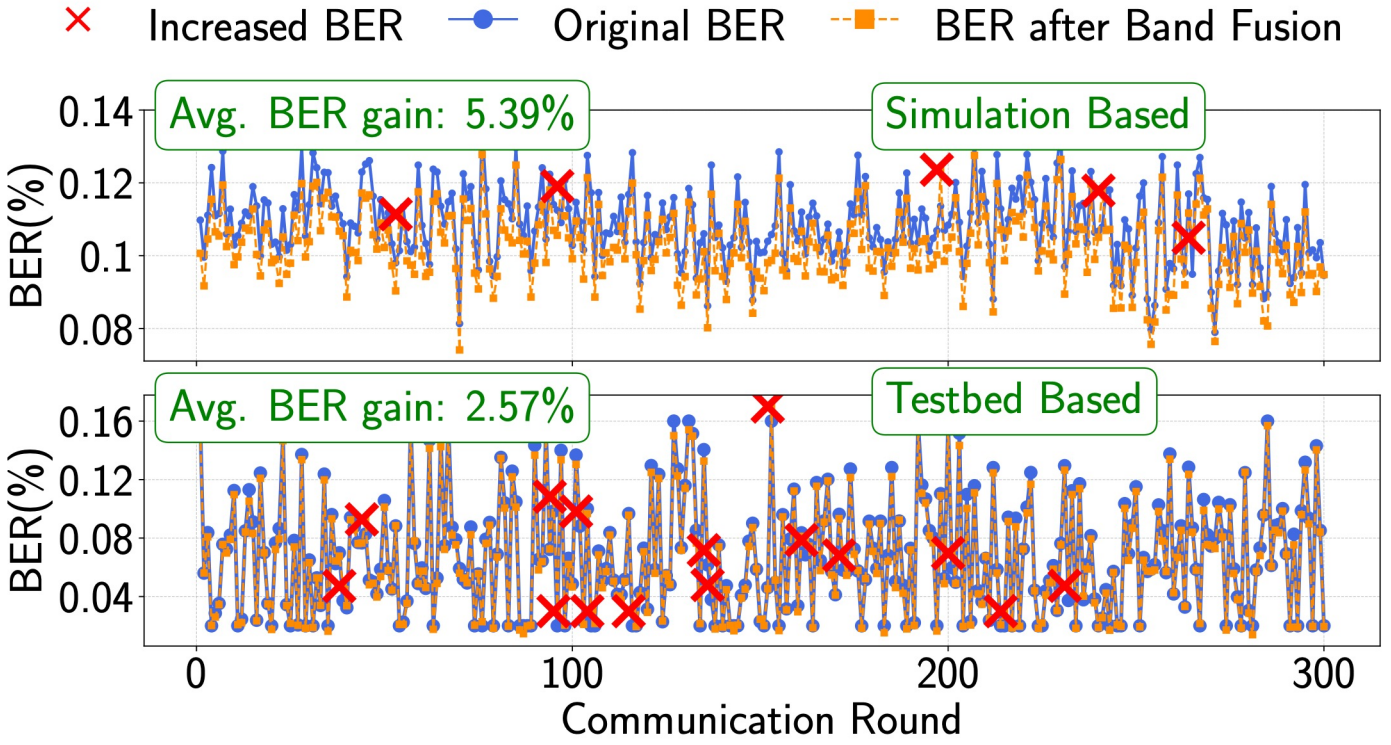


Algorithm 1: Signal Processing-based Multi-Band CFR Fusion

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

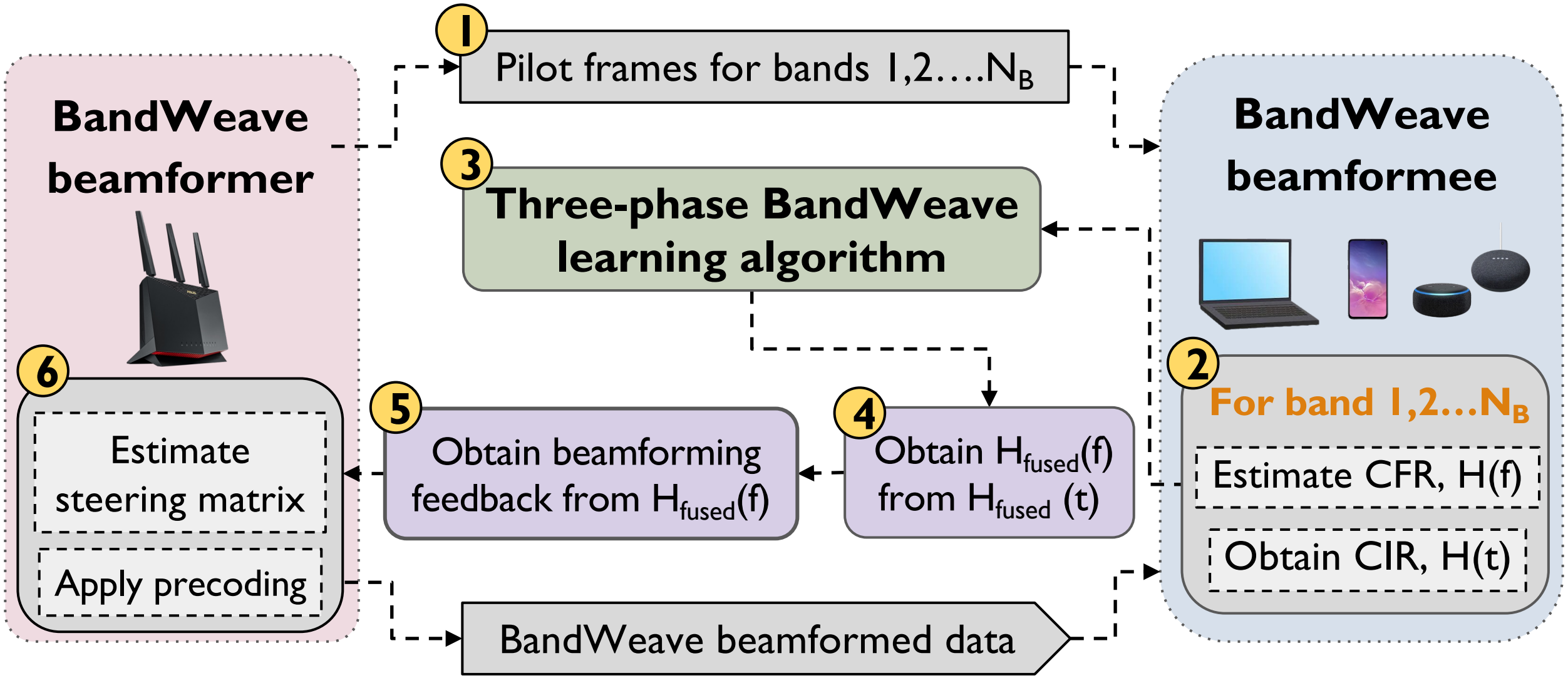
Performance of Signal Processing-based Fusion

- Simulation: one access point (AP) and one station (STA)
- CFRs from channels 36 and 163 are fused
- The fused band is used to beamform in channel 36
- Testbed (57 and 58 GHz): rounds where fusion increases BER are frequent



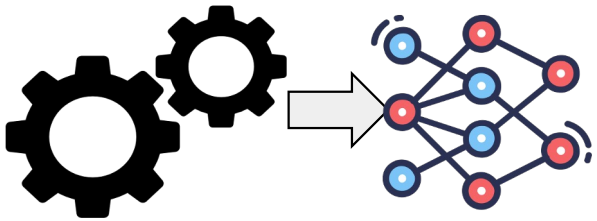
Signal strength-based heuristic fusion is not very robust
→ we develop a domain-adaptive learning-based approach

BandWeave Walkthrough

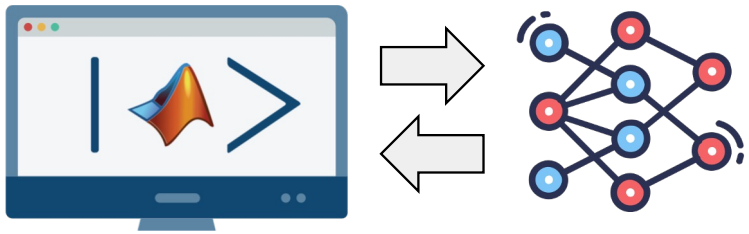


Learning Algorithm

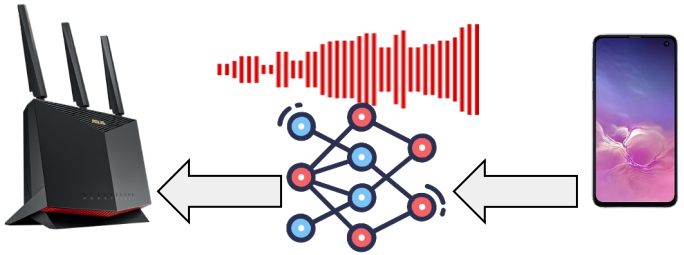
Phase 1
Supervised pre-training



Phase 2
Simulation-in-the-loop fine-tuning

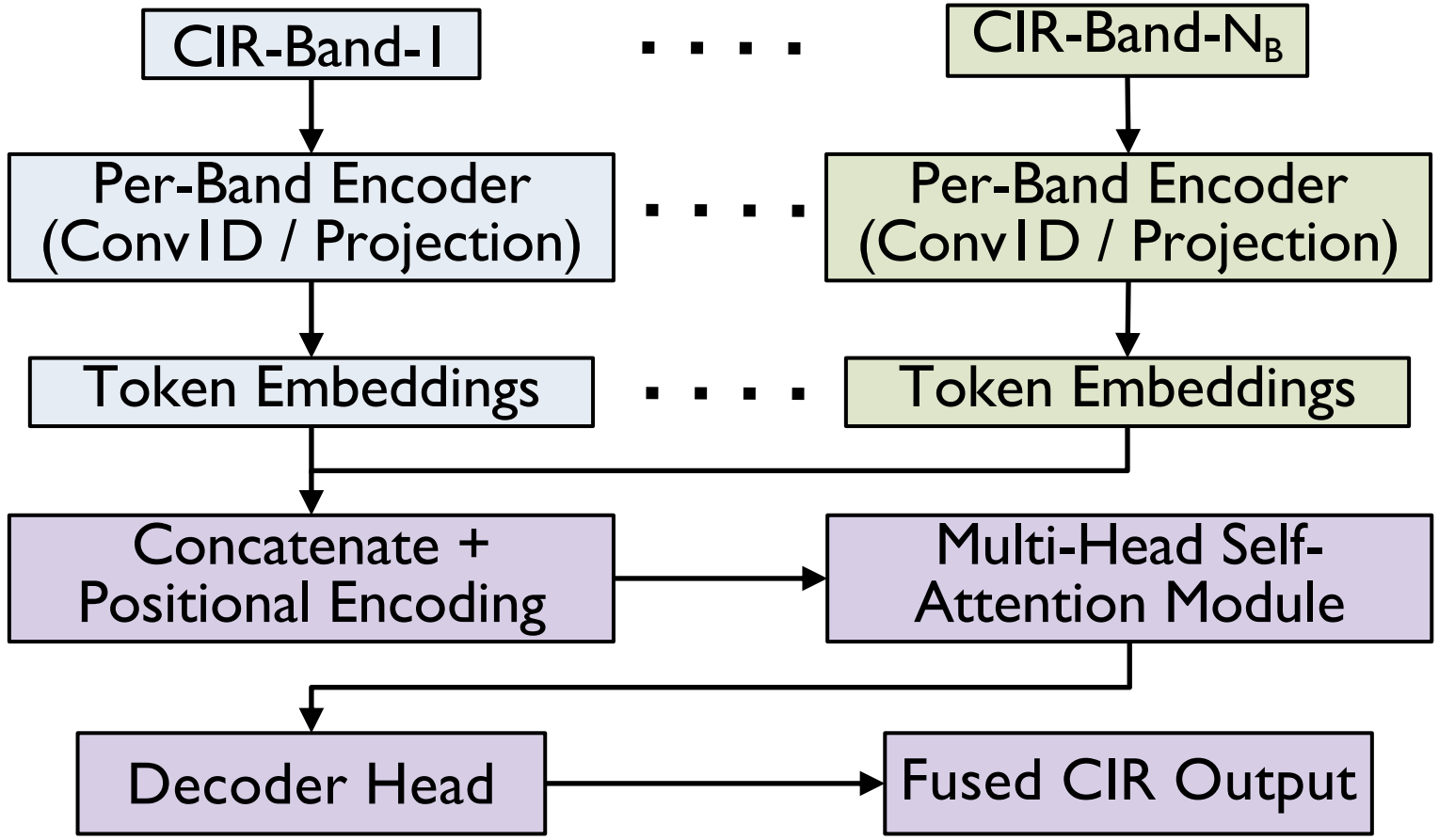


Phase 3
Online feedback-aware adaptation



Phase 1: Supervised Pre-training

- CIRs are projected into embeddings via an encoder
- Embeddings are concatenated and processed by multi-head self-attention module
- Signal Processing-based CFR Fusion as pseudo-ground truth with the loss:



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

Phases 2 and 3: Fine-tuning and Online Adaptation

Phase 2: Fine-tuning through simulation in the loop

- Fused CIR is evaluated in a full-stack simulator to obtain BER
- Parameters tuned using robust derivative-free optimization

$$\mathcal{L}_{\text{sim}}(\theta) = \left\| \mathcal{B}\left(\widehat{\mathbf{C}}_{\text{fused}}\right) \right\|_2^2$$

Phase 3: Online feedback-aware adaptation

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

Step 2: Otherwise, fine-tune using Signal Processing-based CFR Fusion 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: $\widehat{\mathbf{C}}_i = f_\theta(\{\mathbf{C}_i^{(k)}\})$
  Measure throughput $T_{\text{model}}^{(i)}$
  if $T_{\text{model}}^{(i)} \geq T_{\text{base}}^{(i)} + \delta$ **then**
    $\tilde{\theta} = \theta + \mathcal{N}(0, \sigma^2 \mathbf{I})$
    if $T_{\text{perturbed}} > T_{\text{model}}^{(i)}$ **then**
      $\theta \leftarrow \tilde{\theta}$
  else
    Generate teacher $\widehat{\mathbf{C}}_{\text{teacher}}$ via Algorithm 1
    Minimize $\mathcal{L}_{\text{MSE}}(\theta)$ defined in Equation 8

Experimental Setup

- Evaluated on IEEE 802.11ac MU-MIMO (80 MHz bandwidth) and mmWave SU-MIMO testbeds (1 GHz bandwidth)
- Tested across LoS, NLoS, and dynamic scenarios in three environments
- **Baselines**:
  - UWB-FI [1]
  - HiSAC [2]

IEEE 802.11ac MU-MIMO Experiments

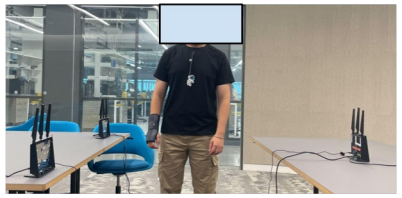
LoS in Anechoic Chamber



NLoS in Classroom

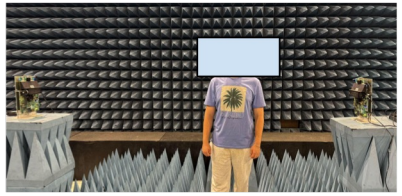


Movement in Conference Room



mmWave SU-MIMO Experiments

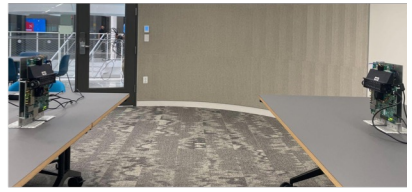
Movement in Anechoic Chamber



NLoS in Classroom



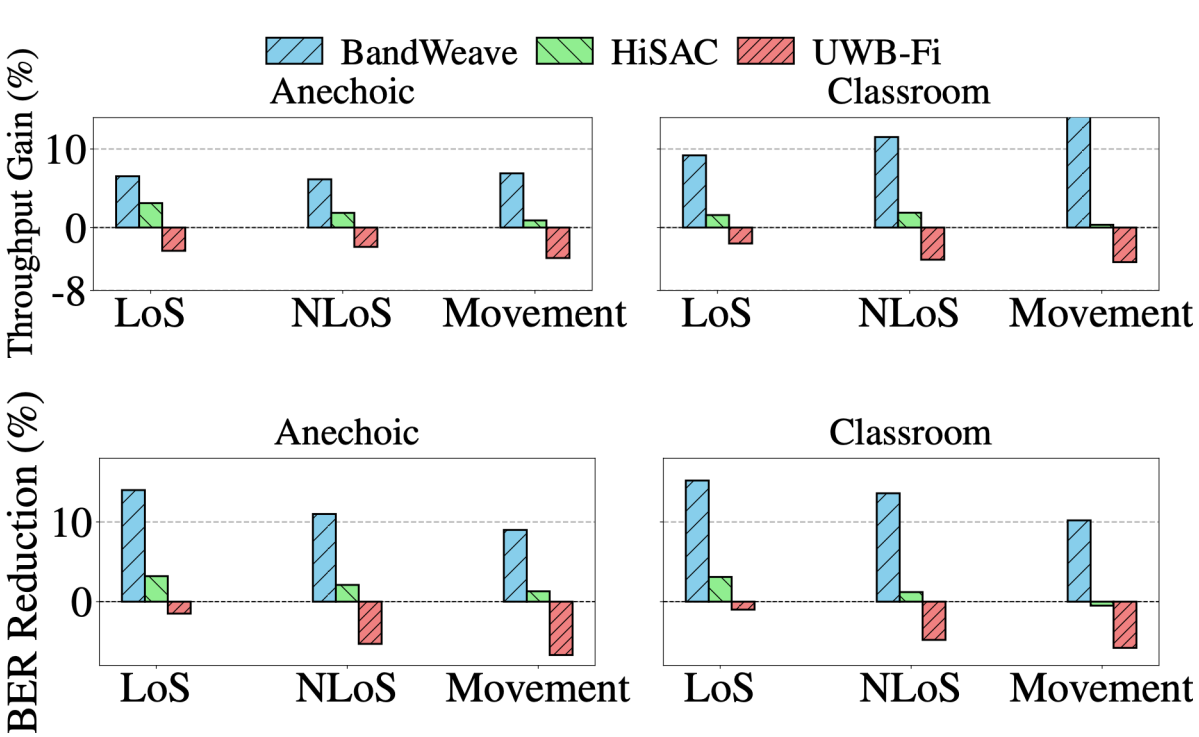
LoS in Conference Room



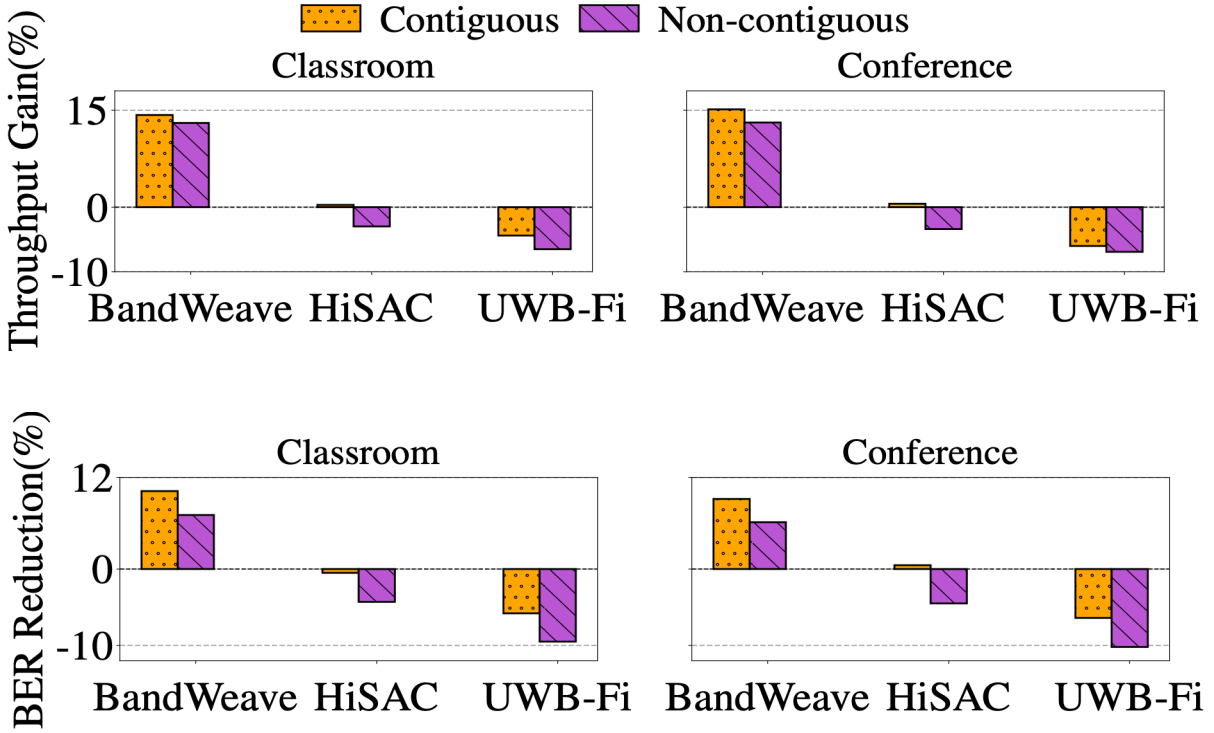
[1] X. Li, H. Wang, Z. Chen, Z. Jiang, and J. Luo, "UWB-Fi: Pushing Wi-Fi Towards Ultra-Wideband for Fine-Granularity Sensing," in Proc. of MobiSys, 2024.
[2] J. Pegoraro, J. O. Lacruz, M. Rossi, and J. Widmer, "HiSAC: High-Resolution Sensing with Multiband Communication Signals," in Proc. of ACM SenSys, 2024.

Throughput Gain / BER Reduction

Performance with varying conditions



Performance with non-contiguous bands

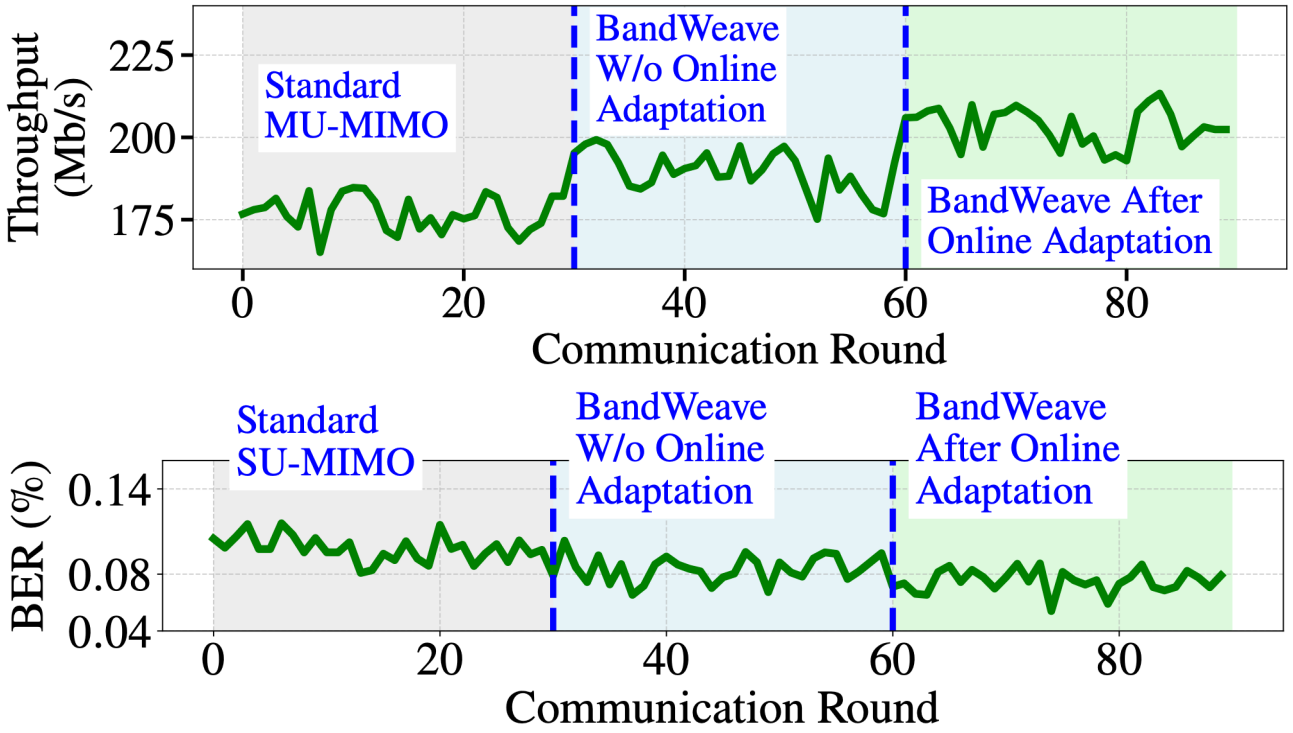


Contiguous bands (Wi-Fi channels 42 and 58, mmWave 57 and 58 GHz): BandWeave achieves up to 7.5× throughput gain and 4.9× BER reduction over SOTA (HiSAC)

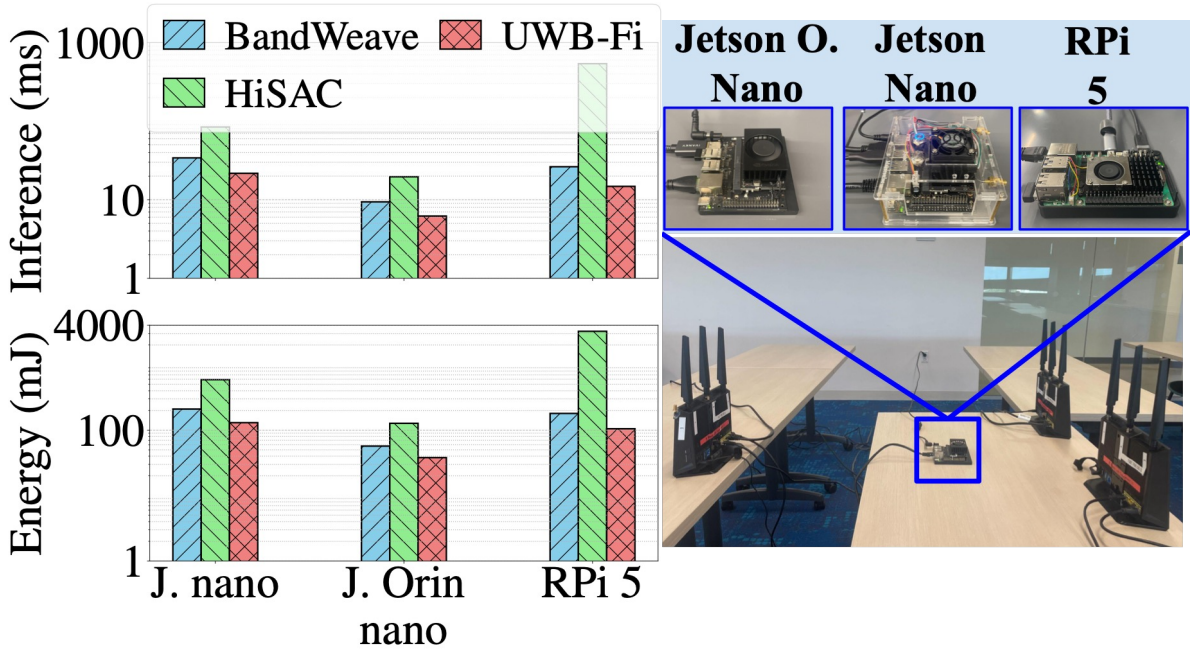
Non-contiguous bands (Wi-Fi channels 42 and 155, mmWave 57 and 59 GHz): BandWeave achieves up to 13.1% throughput gain and 7.1% BER reduction

Adaptation and Energy Consumption

Impact of online adaptation



Inference-time and energy consumption



- Online adaptation adds ~7.3% throughput on top of the offline model, reaching 15% total gain
- BandWeave achieves up to 20× lower latency and 18× lower energy than SOTA (HiSAC)

UACP

M. Abdi, A. Elyasi, N. D. Bastian, F. Meneghello and F. Restuccia

UACP: Uncertainty-Aware Channel Prediction in MIMO Networks

in Proceedings of ACM MobiHoc 2026

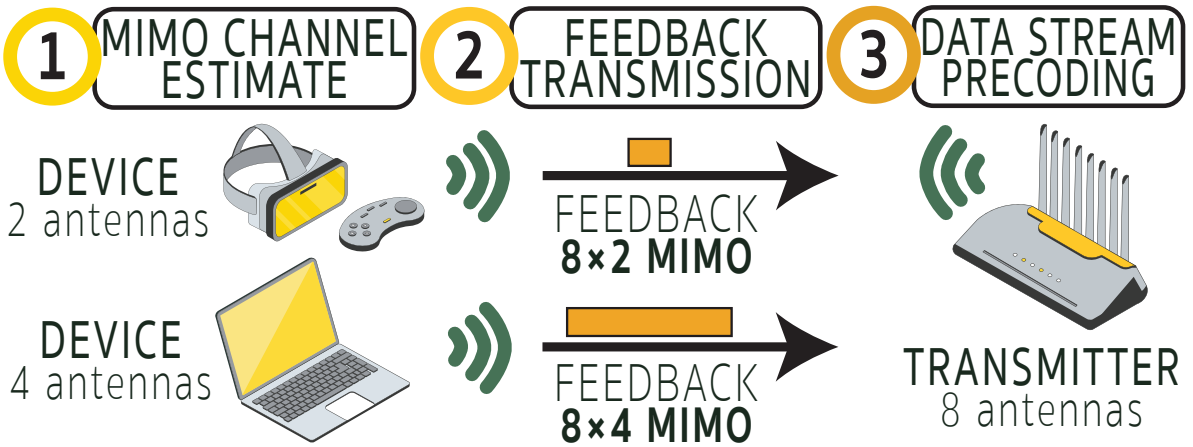
The MIMO Bottleneck

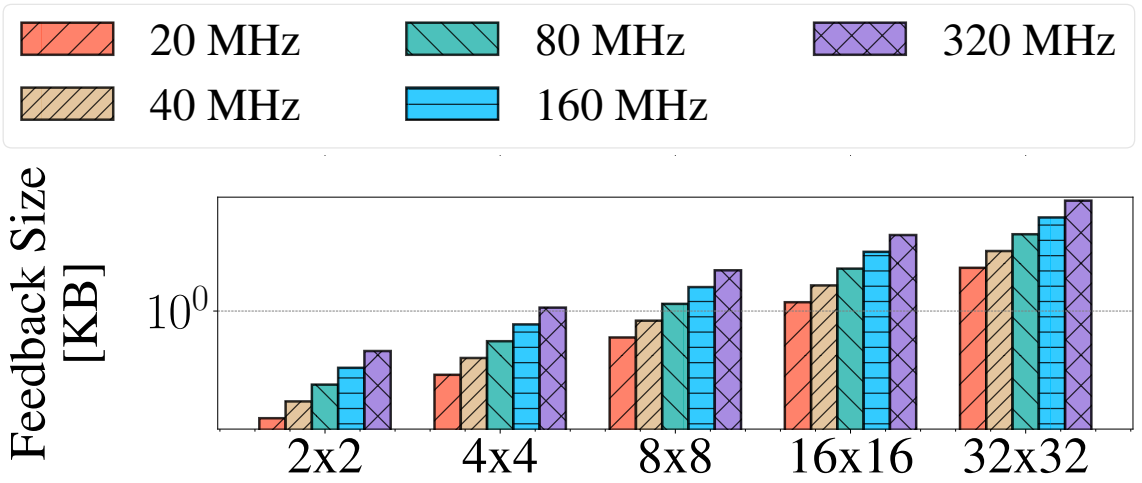
- MIMO capacity increases with antennas

- MIMO requires frequent channel sounding
  - channel estimated at the user and
  - fed back to the access point

- Feedback size increases with antennas

Feedback reduction strategies are required



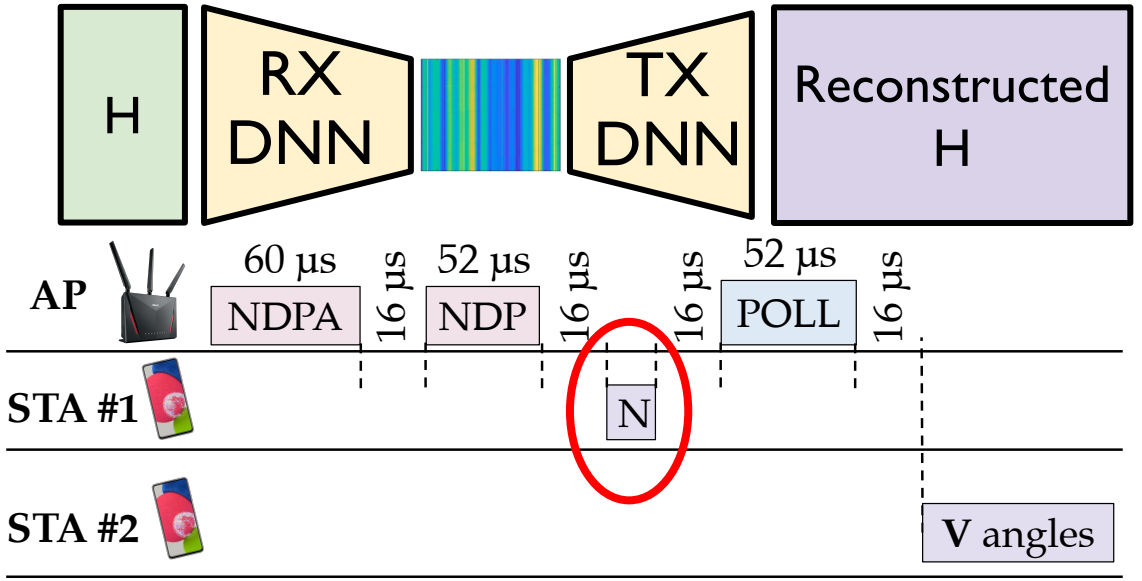


Prior Work

Channel feedback compression [1, 2]

Sounding period sparsification [3]

Selective Subcarrier Reporting [4, 5]



Prior work relies on deterministic/fixed channel statistics while channel models are inherently imperfect

[1] N. Bahadori, Y. Matsubara, M. Levorato, and F. Restuccia, "SplitBeam: Effective and Efficient Beamforming in Wi-Fi Networks Through Split Computing," In Proc. of IEEE ICDCS, 2023.

[2] P. K. Sangdeh, H. Pirayesh, A. Mobiny, and H. Zeng, "LB-SciFi: Online Learning-Based Channel Feedback for MU-MIMO in Wireless LANs," In Proc. of IEEE ICNP, 2020.

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

[4] B. Zhou, X. Yang, J. Wang, S. Ma, F. Gao, and G. Yang, "A Low-Overhead Incorporation-Extrapolation based Few-Shot CSI Feedback Framework for Massive MIMO Systems," in IEEE Transactions on Wireless Communications, 2024.

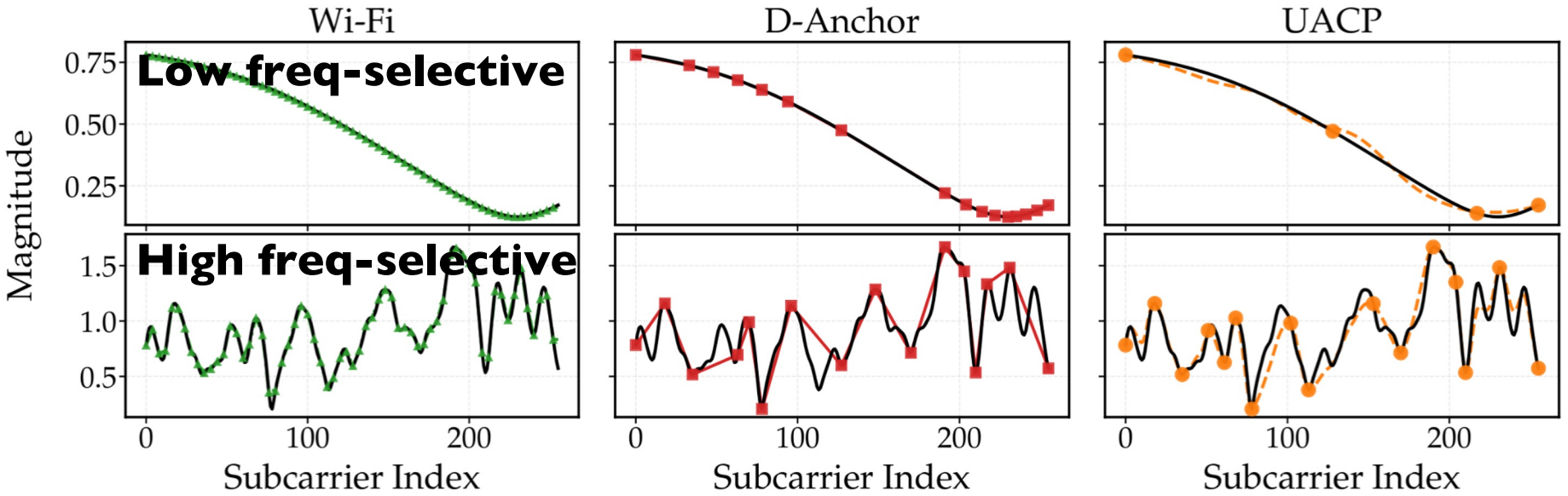
[5] E. Endovitskiy, V. Loginov, M. Dekanoidze, A. Tretiakov, and E. Khorov "Dynamic Anchor Subcarriers Selection for 802.11 CSI Compression with Optimal Piecewise Linear Interpolation," IEEE Wireless Communications Letters, 2026.

Selective Subcarrier Reporting & Prediction

IEEE 802.11 (Wi-Fi): The receiver performs subcarrier grouping, i.e., uniformly samples the subcarrier indices. The transmitter predicts the CSI on the unreported subcarriers through interpolation

D-Anchor: The receiver first estimates the full CSI and then selects the subcarriers to be fed back to minimize the expected CSI interpolation error at the transmitter [1]

UACP: The receiver **estimates the CSI on a subset** of subcarriers requested by the transmitter. The transmitter uses an **evidential regressor** that captures the underlying statistics of signal propagation and enables more accurate CSI reconstruction even with higher levels of compression than existing approaches



Total: 256 subcarriers
Wi-Fi: 64 subcarriers
D-Anchor: 16 subcarriers
UACP: 4 subcarriers (16 if frequency-selective)

[1] E. Endovitskiy, V. Loginov, M. Dekanoidze, A. Tretiakov, and E. Khorov "Dynamic Anchor Subcarriers Selection for 802.11 CSI Compression with Optimal Piecewise Linear Interpolation," IEEE Wireless Communications Letters, 2026.

UACP Walkthrough



Transmitter

Receiver



Value
Zero

1 Sounding packet (pilots) + Feedback subcarrier set $\mathcal{S}_u$

2 Estimate CFR $\widetilde{\mathbf{H}}_u$ for subcarriers in $\mathcal{S}_u$

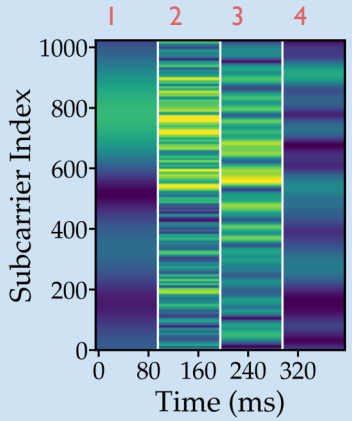
3 Sparse channel feedback

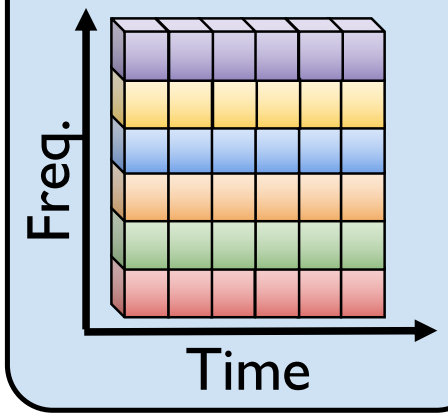
4 Predict full CFR $\widehat{\mathbf{H}}_u$
Quantify uncertainty Θ_u
Decide subset $\mathcal{S}_{u+1}$

5 Precoded data packets

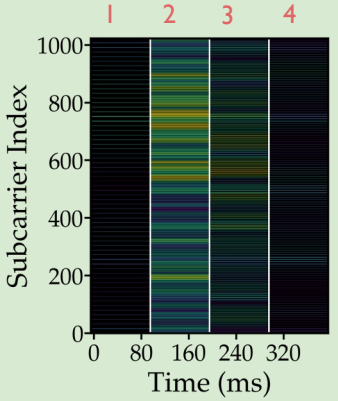
6 Postcoding

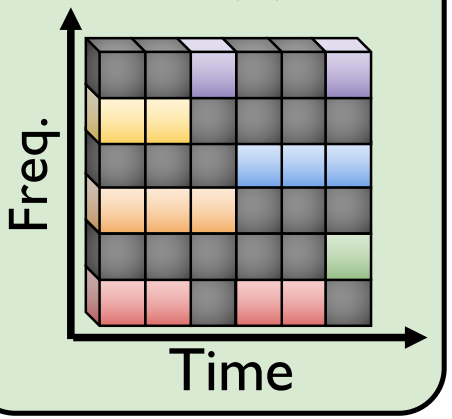
Predicted CSI





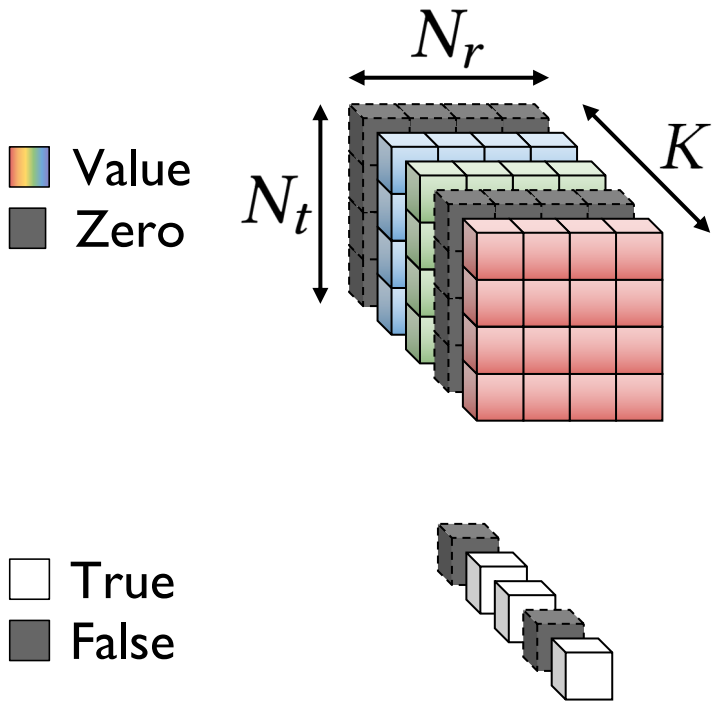
Sparse CSI





Evidential Channel Prediction

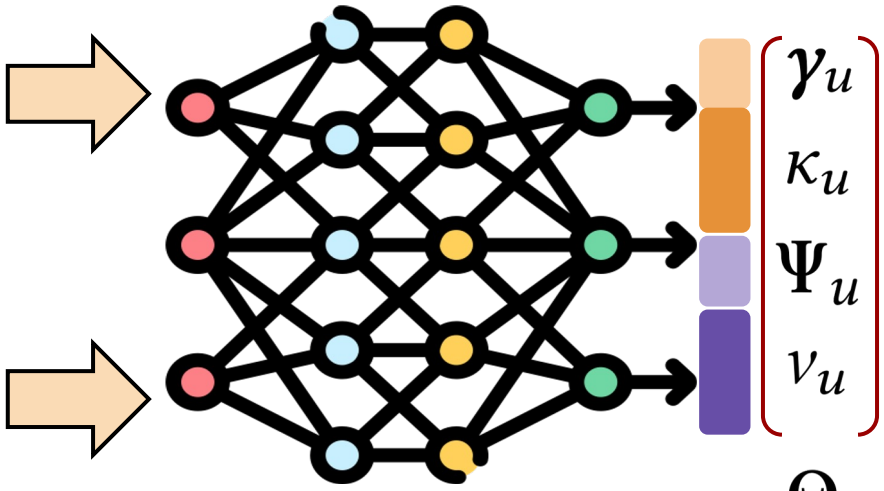
Sparse CFR $\mathbf{Z}_u$



Mask $\mathbf{M}_u$

Evidential Model

$f_{\boldsymbol{\varphi}}(\cdot,\cdot)$



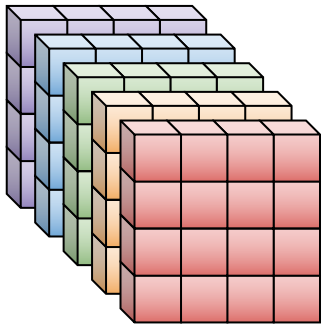
γ_u
κ_u
$\boldsymbol{\Psi}_u$
ν_u

$\boldsymbol{\Theta}_u \ \forall r, t$

Full CFR $\widehat{\mathbf{H}}_u$

+

Uncertainty covariances $\boldsymbol{\Sigma}_u^{\text{ale}}$ $\boldsymbol{\Sigma}_u^{\text{epi}}$



Subcarrier selection matrix

Uncertainty

$$\mathcal{U}_u(\bar{\mathcal{S}}) = \frac{1}{|\bar{\mathcal{S}}|} \sum_{k \in \bar{\mathcal{S}}} \mathcal{U}_u[k]$$

$$\mathcal{U}_u[k] \triangleq \frac{1}{N_r N_t} \sum_{(r,t) \in \mathcal{P}} \operatorname{tr}\left(\mathbf{P}_k \boldsymbol{\Sigma}_{u,r,t} \mathbf{P}_k^\top\right)$$

UACP Algorithm 1/2

Algorithm 1: UACP channel prediction, feedback adaptation

Input: Subcarrier set $\mathcal{S}_u$; sparse CFR observation $\mathbf{Z}_u$.
Output: Predicted full CFR $\widehat{\mathbf{H}}_u$; next subcarrier set $\mathcal{S}_{u+1}$.

Step 1: Evidential Regression (Section 3.2)
Execute the evidential model $\mathbf{\Theta}_u \leftarrow f_{\boldsymbol{\varphi}}(\mathbf{Z}_u, \mathbf{M}_u)$
Obtain the predicted full CFR $\widehat{\mathbf{H}}_u$ using Equation (6)
Obtain the aleatoric and epistemic uncertainty covariance according to Equations (7)-(8)
Step 2: Evaluate Feedback Relevance (Section 3.3.1)
Compute the epistemic uncertainty score $\mathcal{U}_u^{\text{epi}}(\bar{\mathcal{S}}_u)$
if $\mathcal{U}_u^{\text{epi}}(\bar{\mathcal{S}}_u) > \mathcal{U}_{\max}^{\text{epi}}$ **then**
    Request all subcarriers for the next round $\mathcal{S}_{u+1} \leftarrow \mathcal{K}$
    Trigger model adaptation
    return $\widehat{\mathbf{H}}_u, \mathcal{S}_{u+1}$

High epistemic uncertainty → the model is not longer good to describe the data

UACP Algorithm 2/2

Step 2-a: Subcarrier Rate Selection Only (Section 3.3.2)

`// Uniform Subsampling`

Compute the aleatoric uncertainty score $\mathcal{U}_u^{\text{ale}}(\bar{\mathcal{S}}_u)$

if $\mathcal{U}_u^{\text{ale}}(\bar{\mathcal{S}}_u) < \mathcal{U}_{\text{opt}}^{\text{ale}} - \Delta$ **then**

  Decrement rate

else if $\mathcal{U}_u^{\text{ale}}(\bar{\mathcal{S}}_u) > \mathcal{U}_{\text{opt}}^{\text{ale}} + \Delta$ **then**

  Increment rate

Step 2-b: Full Subcarrier Set Selection (Section 3.3.3)

`// Non-uniform Subsampling`

Select the next subcarrier set $\mathcal{S}_{u+1}$ using Equation (14)

return $\widehat{\mathbf{H}}_u, \mathcal{S}_{u+1}$

Low aleatoric uncertainty → the model is able to predict well with less samples

High aleatoric uncertainty → the model requires more data to predict well

Experimental Setup

Simulations using **Nvidia Sionna**

2 transmitter antennas, **2** receiver antennas, **1024** subcarrier frequencies

Training:

- 100,000 independently-generated CFRs
- Delay spread drawn uniformly from [10, 100] ns

Testing:

- 60,000 sequences of 64 temporally-correlated CFRs
- Fixed delay spread in the evaluation regimes

Evaluation Regimes:

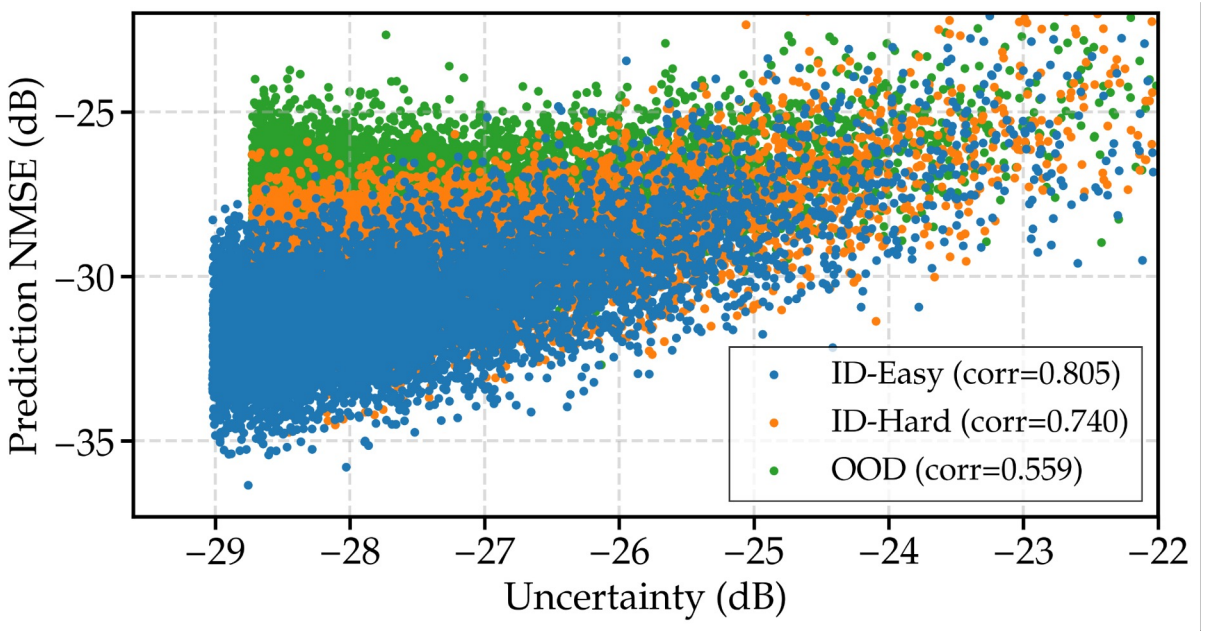
- **ID-Easy**: 20 ns delay spread
- **ID-Hard**: 80 ns delay spread
- **OOD**: 120 ns delay spread

Baselines:

- Full feedback (**Oracle**)
- Fixed sparse feedback and interpolation (**Wi-Fi**)
- Dynamic anchor feedback and interpolation (**D-Anchor**) [1]

[1] E. Endovitskiy, V. Loginov, M. Dekanoidze, A. Tretiakov, and E. Khorov "Dynamic Anchor Subcarriers Selection for 802.11 CSI Compression with Optimal Piecewise Linear Interpolation," IEEE Wireless Communications Letters, 2026.

Uncertainty vs System Performance

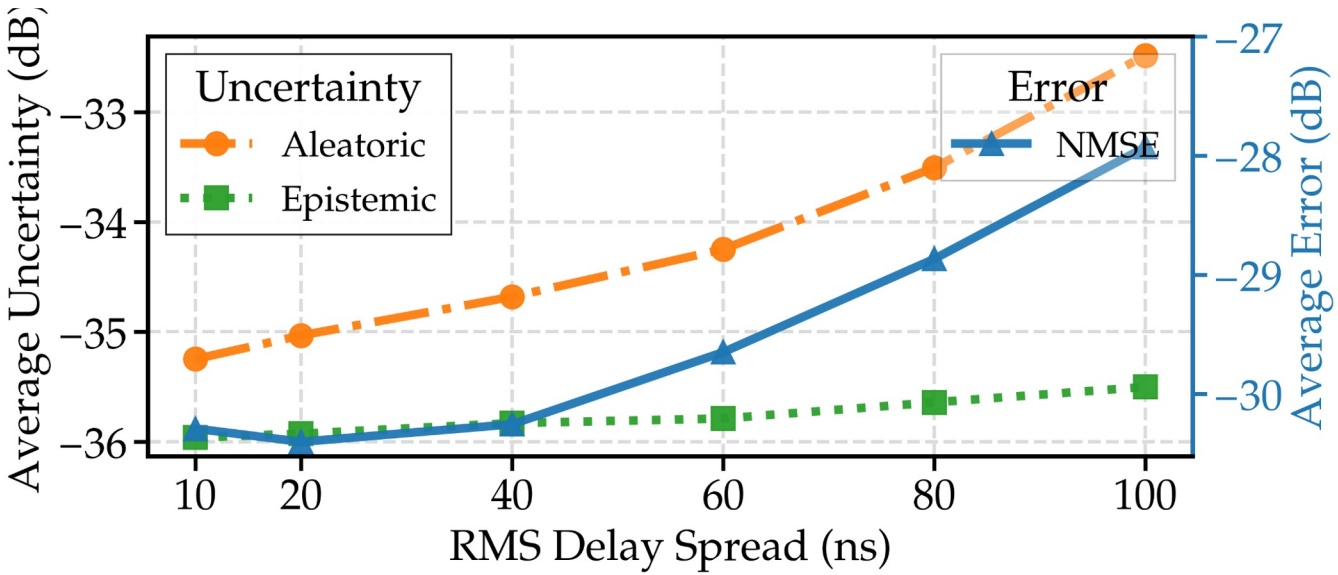


- **Uncertainty-error correlation** is 0.805 in ID-easy regime, 0.740 in ID-hard regime, 0.559 under OOD conditions
- Prediction NMSE consistently grows with the uncertainty score:

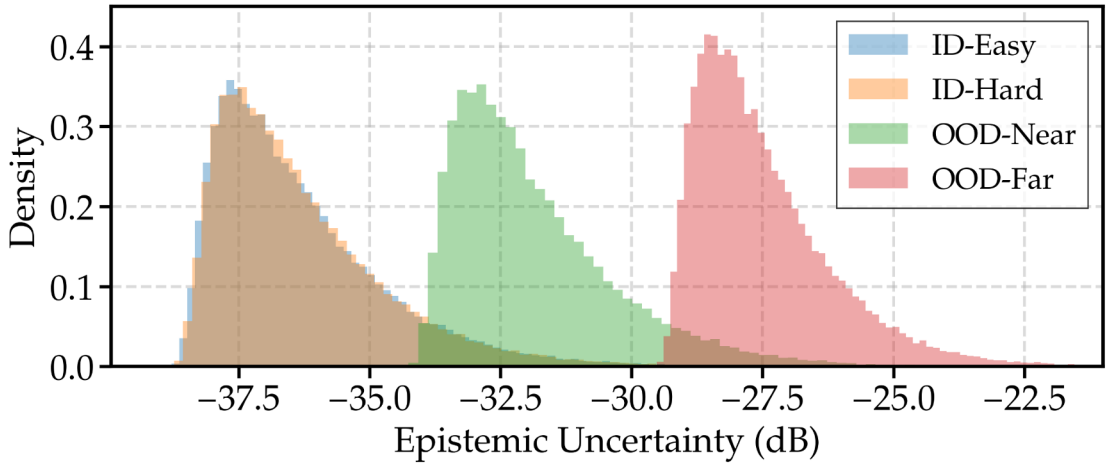
higher uncertainty ⟺ **worse reconstruction quality**

Aleatoric and Epistemic Behavior

ID with Delay Spread Sweep



ID vs OOD Histogram



ID case: the aleatoric uncertainty grows with the average error → uncertainty is a good proxy for error; epistemic component remains stable → uncertainty in ID is not related to model misspecification but only to the data

OOD case: epistemic uncertainty is high → the previously learned channel structure is no longer valid → the evidential prediction cannot be reliably used for precoding

Wireless System Performance

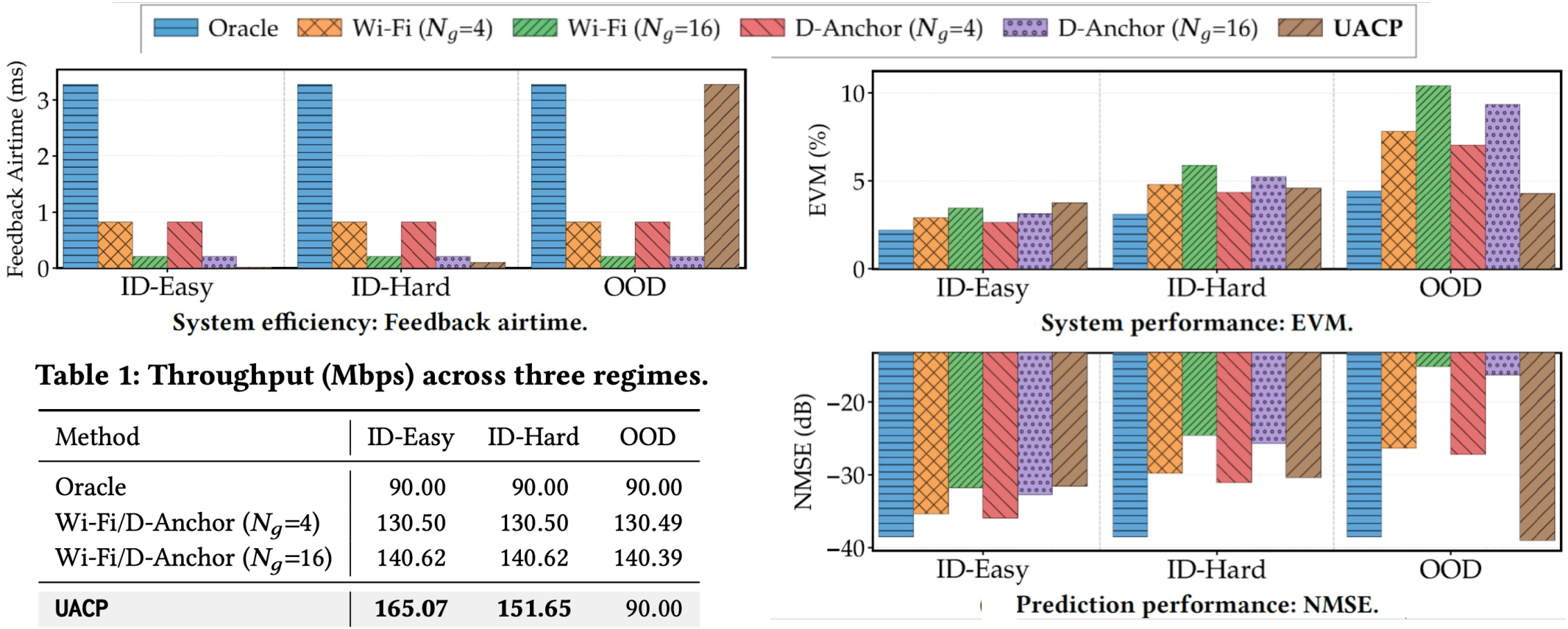


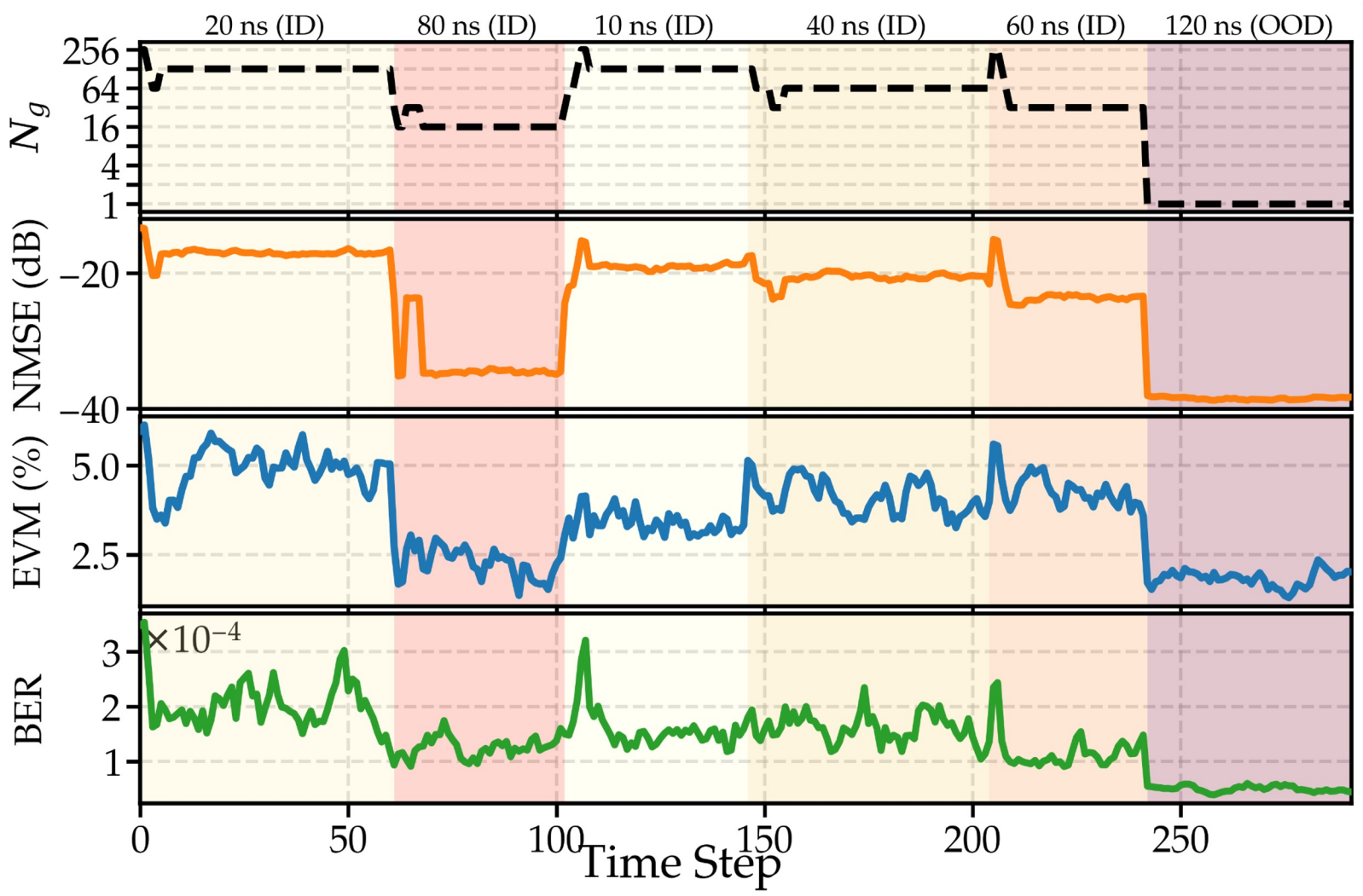
Table 1: Throughput (Mbps) across three regimes.

Method	ID-Easy	ID-Hard	OOD
Oracle	90.00	90.00	90.00
Wi-Fi/D-Anchor (N_g=4)	130.50	130.50	130.49
Wi-Fi/D-Anchor (N_g=16)	140.62	140.62	140.39
UACP	**165.07**	**151.65**	90.00

N_g is the subcarrier grouping factor

- **ID-easy**: 99.4% and 97.6% overhead reduction relative to oracle and Wi-Fi/D-Anchor with Ng=4 with negligible performance loss (EVM 3.75%)
- **ID-hard**: D-Anchor with Ng=4 is slightly better on BER/EVM but uses 8.2× more feedback airtime
- In the **OOD** case UACP sends all subcarriers (high overhead, low reconstruction NMSE)

Adaptation to Regime Variations



N_g is the subcarrier grouping factor (total 1024 subcarriers)

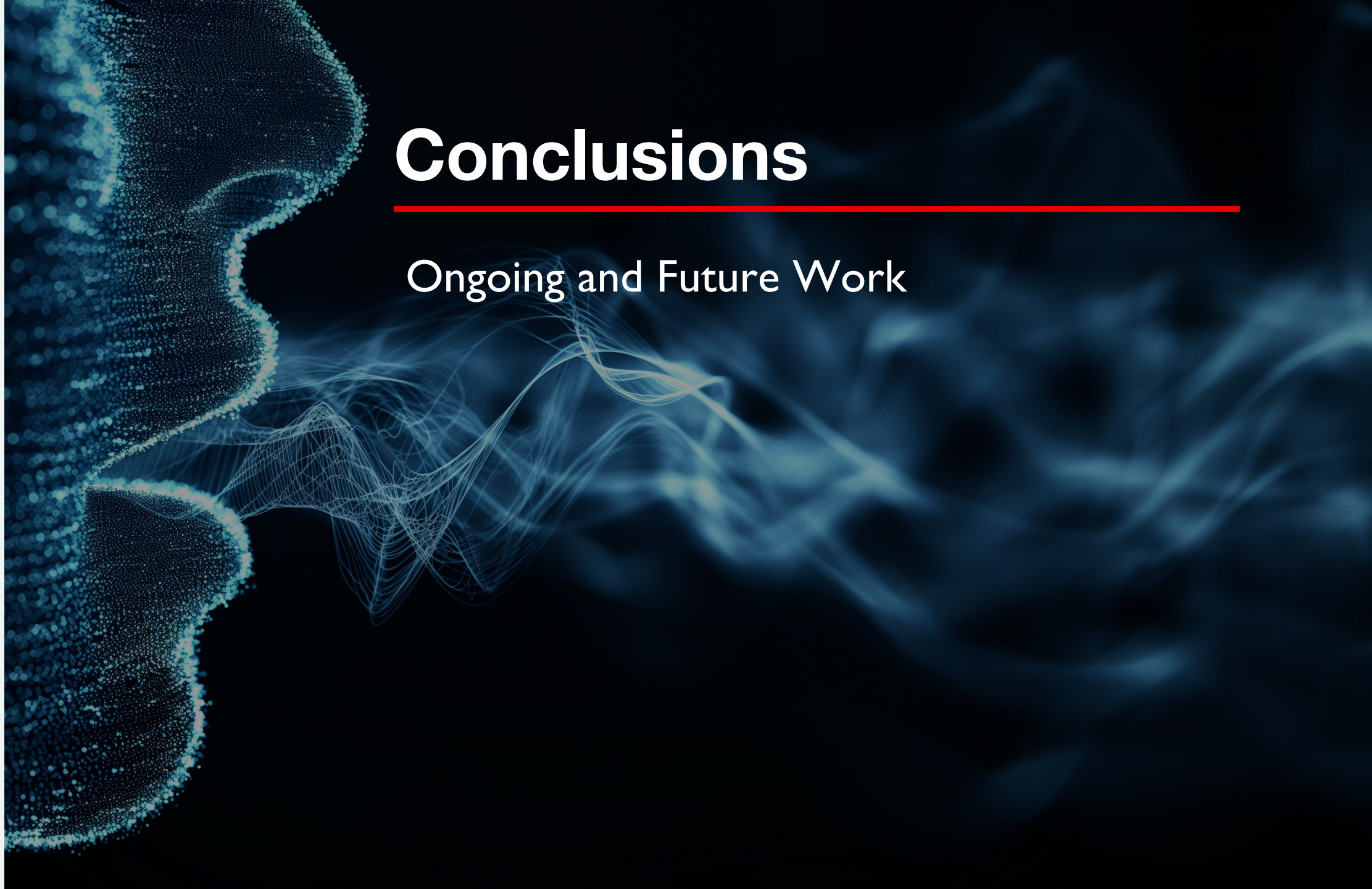
BER remains low when changing the operating regime

NMSE is lowest in the OOD phase, where UACP falls back to full feedback

4

Conclusions

Ongoing and Future Work



Improving MIMO Channel Acquisition

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

- Improves channel estimation available at the transmitter for better precoding through multi-band fusion

UACP: Uncertainty-Aware Channel Prediction in MIMO Networks

- Reduces feedback overhead in frequency through uncertainty-aware feedback subcarrier selection

SHRINK: Reducing MIMO Feedback Overhead in Wi-Fi with Dynamic Data-Driven Channel Sounding

- Reduces feedback overhead in time through throughput variation prediction

What's next?

- Cross-band channel prediction for channel estimate polymorphism
- Physically-grounded constant-size feedback

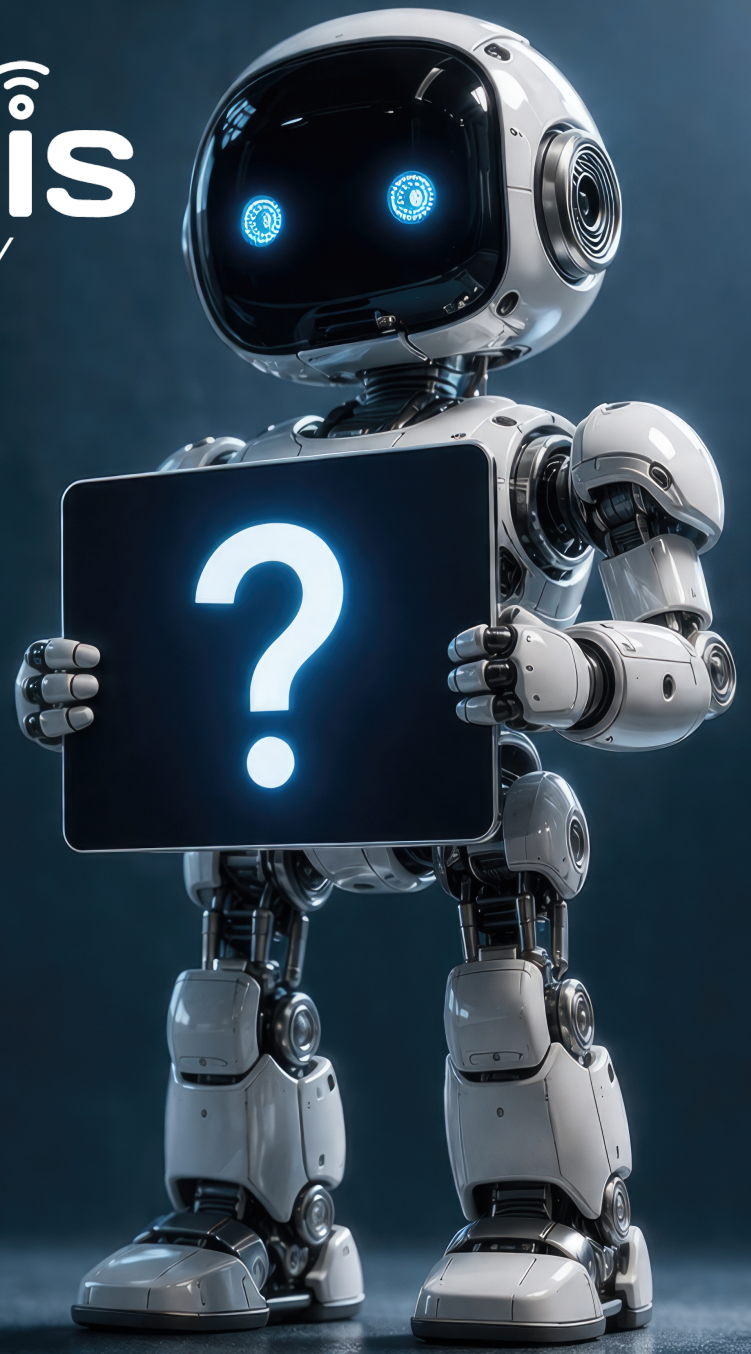
Final objective

Efficient and high-performance large-scale MIMO networks

Northeastern University
Institute for Intelligent Networked Systems

MENTIS LABORATORY

Thank you!



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