Collaborative Research: SWIFT: AI-based Sensing for Improved Resiliency via Spectral Adaptation with Lifelong Learning

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VISION: Continual-Learning AI-Perception and Sensing of Spectrum

Multi-beams, Adaptive Nulls, Digital Systolic Arrays, Fast Algorithms, AI Theory, Deep Learning, System Integration, Testbeds in FR1-FR3 Band

Graduate Students: Gayani Rathnasekara (FIU, PhD), Umesha Kumarasiri (FIU, PhD), Sivakumar Sivasankar (FIU, PhD), Hansaka Aluvihare (ERAU, MS), Varun Magotra (UMBC, MS) and Franchesco Pessia (Northeastern, PhD)

Spectral Array Processors for Sensing and AI-Perception

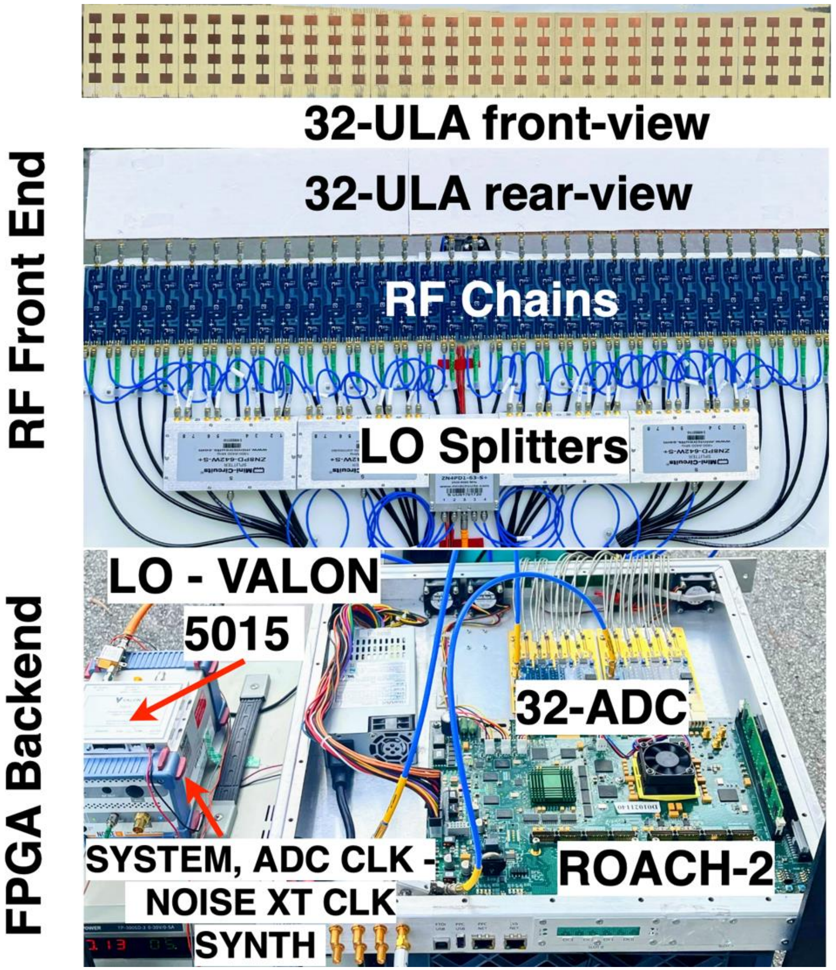
- **Sensing and AI-perception of spectrum**

- **Multi-beams and adaptive null-formation**
- **Modulation recognition (RadioML2018.a)**
- **Temporal channelization @100 kHz res over 32 beams**

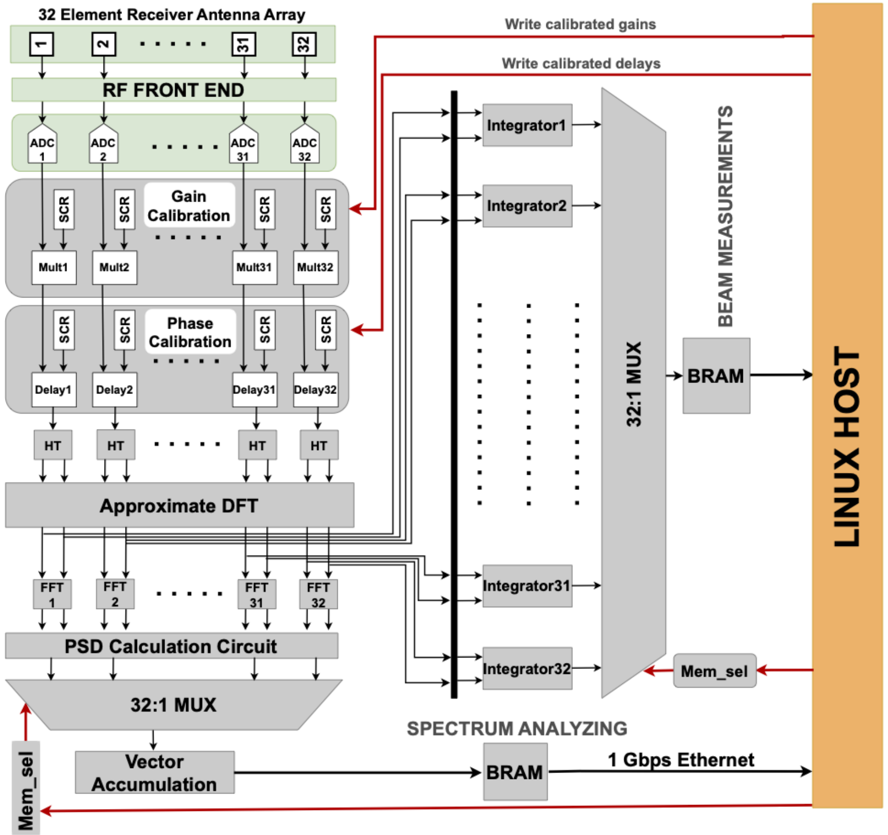
- **Phased array**
  - 32 elements, 5.7-5.8 GHz
  - 4-element sub-arrays

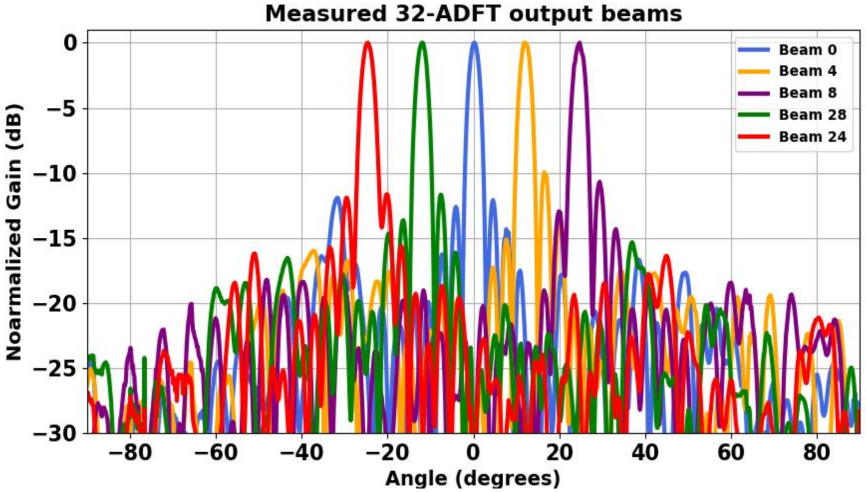
- **RF chains (designed by students)**
  - Filtering – Bandpass (4.7 - 6 GHz)
  - LO – 5.75 GHz spilt across 32 channels

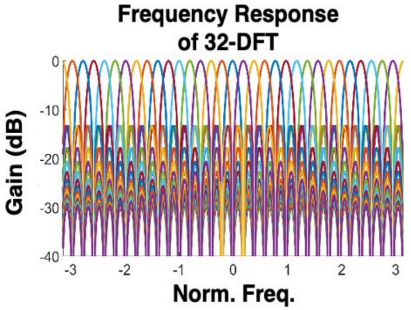
- **FPGA backend – ROACH-2**
  - 2 x ADC16x250-8 (8-bit precision)
  - Xilinx Virtex6 Sx475t
  - PPC Ethernet Interface at 1Gbps

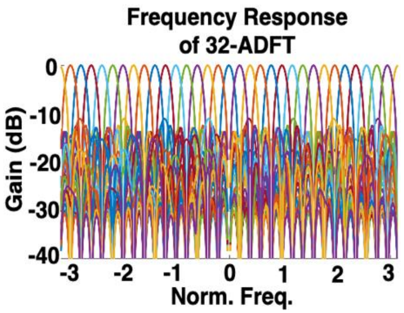


FPGA-Spectral AI-Perception in Space and Time

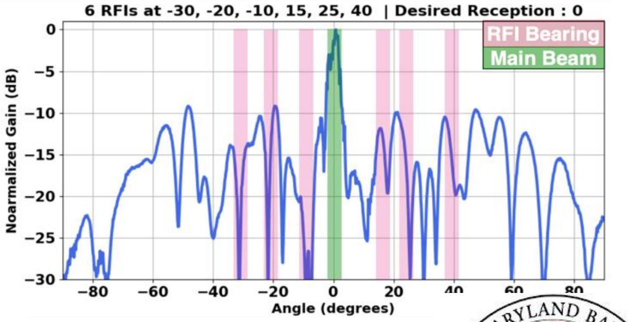






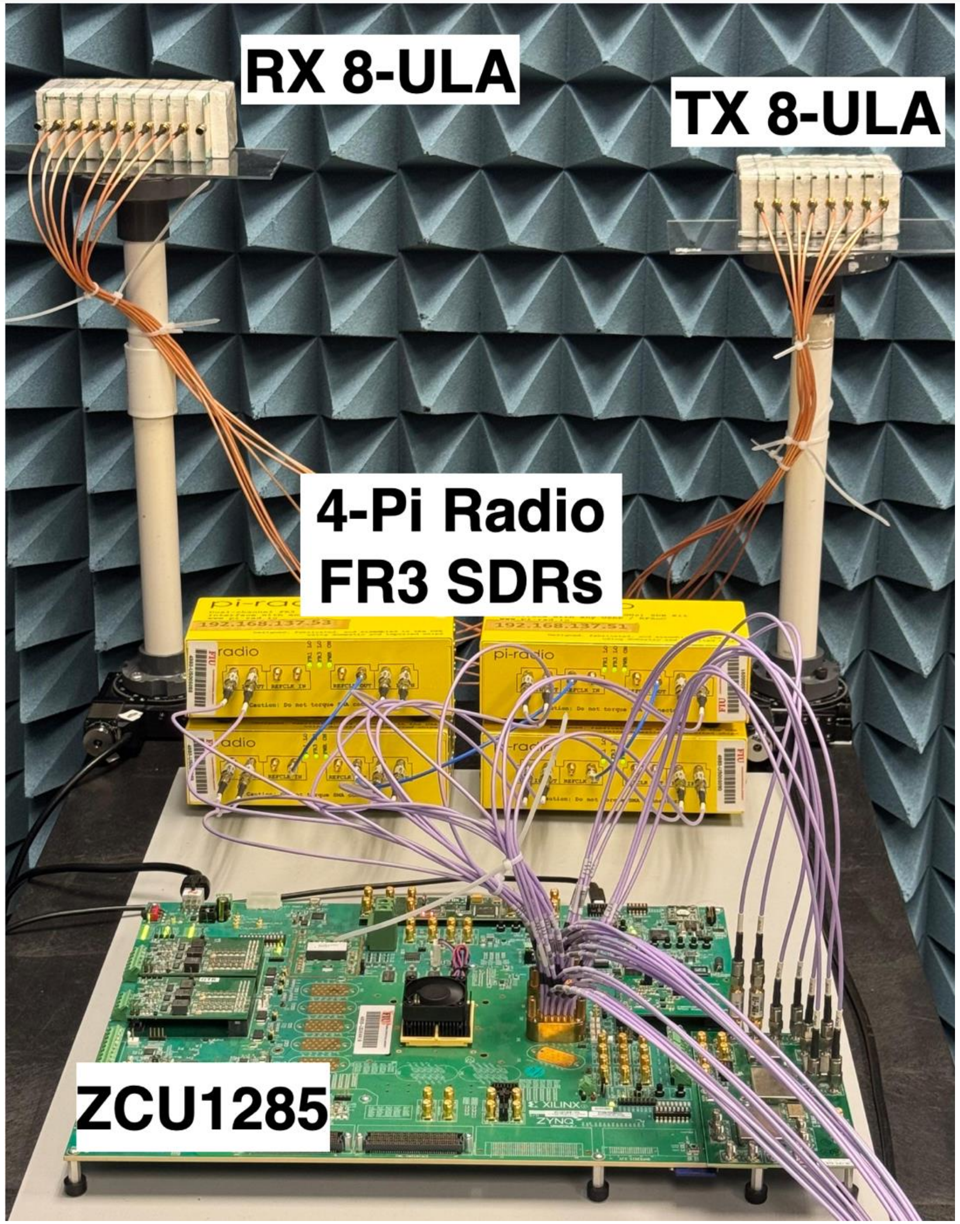


- Madanayake, A., Kumarasiri, U., Sivasankar, S., Lawrance, K., Gayanath, B., Silva, H., Mandal, S., and Cintra, R. J., "Real-time 5.7–5.8 GHz 32-beam approximate discrete Fourier transform spectrum sensor for RF perception on Xilinx Sx475T", *IEEE Transactions on Circuits and Systems I: Regular Papers*.
- Kumarasiri, U., Sivasankar, S., Weerasooriya, H., Silva, H., Edussooriya, C., Ariyarathna, V., Restuccia, F., & Madanayake, A, "RF anti-jamming via multi-level Howells-Applebaum null-forming: 32-channels, 5.8 GHz/100 MHz/beam on Xilinx Sx475T FPGA", *IEEE Journal of Radio Frequency Identification, 2025.*
- Kumarasiri, U., Sivasankar, S., Edussooriya, C., Ariyarathna, V., and Madanayake, A. "*A 32-Channel Fully-Digital Adaptive Applebaum Aperture at 5.8 GHz for Array RF Sensing". Proceedings of the 2024 IEEE International Conference on RFID Technology and Applications (RFID-TA)*



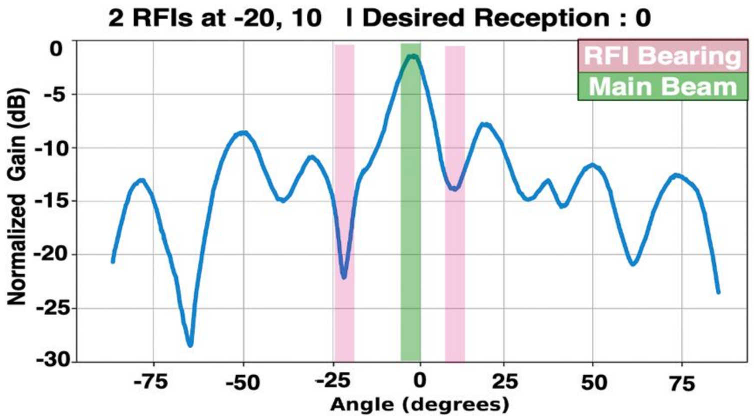
Source position & modulation	Results with beamforming		Results without beamforming
	Prediction from beam 0	Prediction from beam 11	
At 0° – 16PSK At 40° – 16QAM	16PSK – 4986 (99.7%)	16QAM – 4705 (94.1%)	16PSK – 0 (0%) 16QAM – 1 (0.02%)
At 0° – 8ASK At 40° – 16QAM	8ASK – 3418 (68.4%)	16QAM – 3980 (79.6%)	8ASK – 405 (8.1%) 16QAM – 4 (0.08%)
At 0° – BPSK At 40° – 16QAM	BPSK – 5000 (100%)	16QAM – 4375 (87.5%)	BPSK – 2657 (53.1%) 16QAM – 0 (0%)

FIU Ongoing Work – FR3 Spectral AI Perceptions



- **Phased Array**
  - 8-Vivaldi wideband elements (6-24 GHz)
  - 4-Pi Radio FR3 SDR Boxes

- **FPGA Backend**
  - AMD Xilinx ZCU-1285 RF-SoC
  - 1GHz of Instantaneous BW



FR3 Nulling at 10.7 GHz at the presence of 2 RFIs

Kumarasiri, U., Roshnan, B., Sivasankar, S., Zekios, C. L.,Madanayake, A., Edussooriya, C. U. S., Rangan, S., and Dhananjay, A., "*X-band adaptive Applebaum null-forming array processor on Xilinx Sx475T FPGA*", *Proceedings of the 19th ACM Workshop on Wireless Network Testbeds, Experimental evaluation & Characterization (WiNTECH 2025) [Accepted]*

A Low-complexity LSTM (S-LSTM) Network to Realize Multi-beam Beamformers: Dr. Sirani Perera, ERAU

Key papers:

H. Aluvihare, C. Shanahan, S. M. Perera, S. Sivasankar, U. Kumarasiri, A. Madanayake, and X. Li, **A Low-Complexity LSTM Network to Realize Multibeam Beamforming**, the proceedings of 2024 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE), (2024).

H Aluvihare, S. Sivasankar, X. Li, A. Madanayake, and S. M. Perera, ***A Low-complexity Structured Neural Network Approach to Intelligently Realize Wideband Multi-Beam Beamformers***, in *IEEE Journal of Radio Frequency Identification*, doi: 10.1109/JRFID.2025.3602901

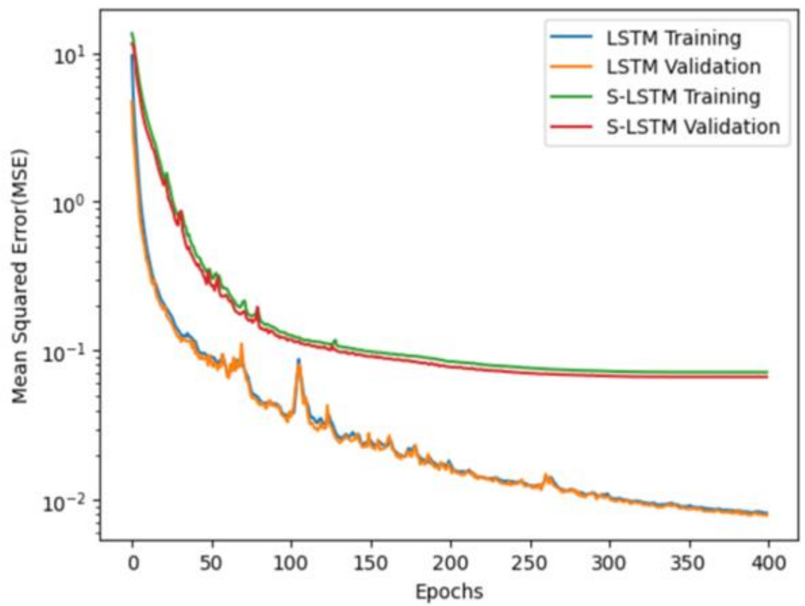


Fig. 4: Training and Validation MSE comparison between LSTM and S-LSTM models over 400 epochs. The LSTM model (blue and orange) demonstrates a higher initial MSE, while S-LSTM (green and red) indicates efficient convergence with fewer variations, particularly in the early epochs.

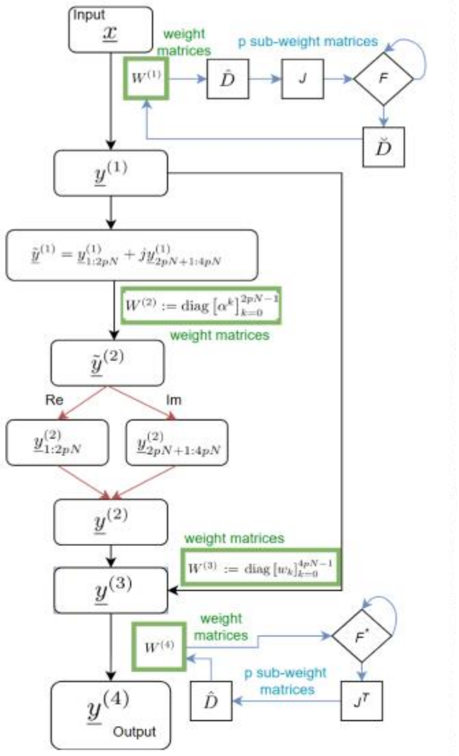
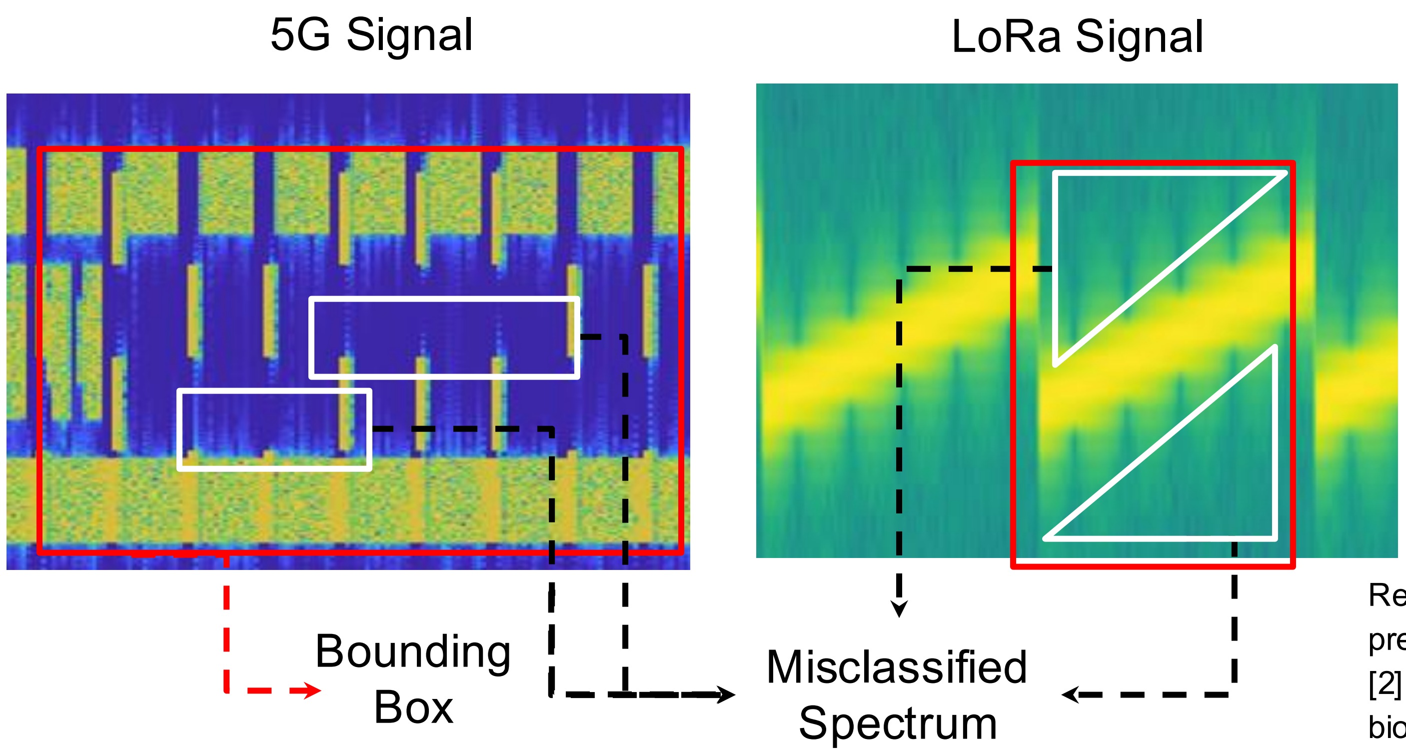
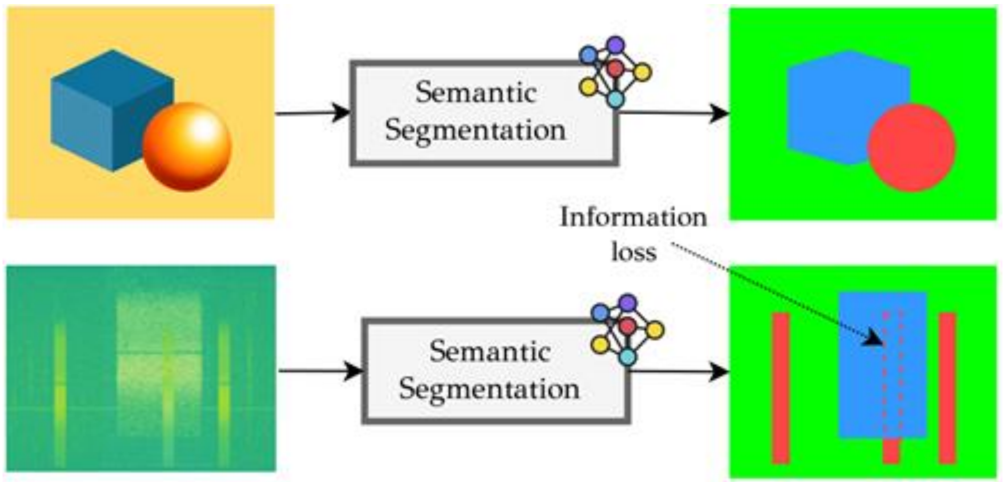


Fig. 3. The forward propagation of the StNN architec x, output $y^{(4)}$, the weight matrices $W^{(1)}, W^{(2)}, W^{(3)}$, weight matrices $\check{D}_i, J, \hat{D}_i$ complemented by the recursion F_i^* as shown in equations (11) and (12).

AI/ML for Spectrum Access: Spectrum Segmentation: Dr. Francesco Restuccia, Northeastern University



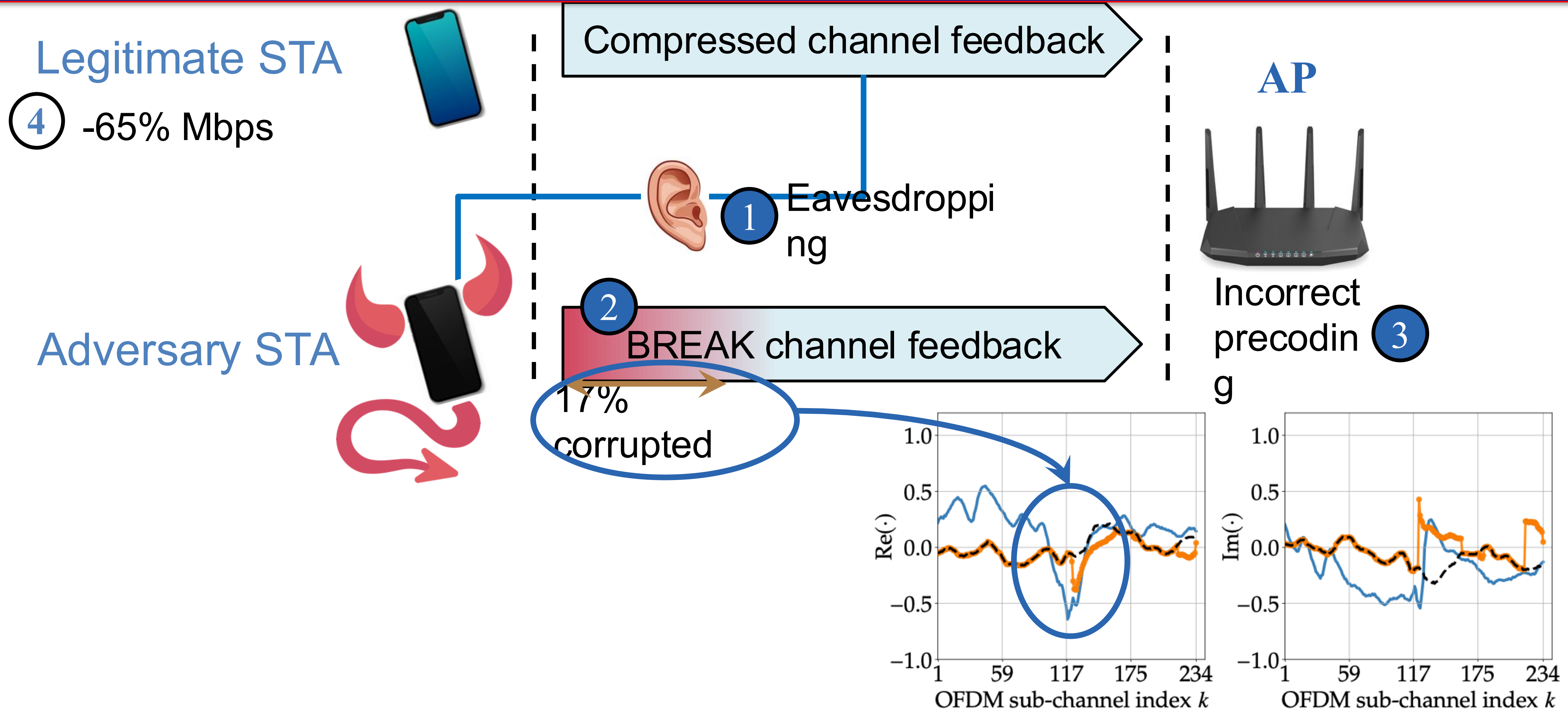


Object detection cannot achieve fine-grained granularity for spectrum sensing

Ref: [1] J. Redmon and A. Farhadi, “Yolov3: An incremental improvement,” arXiv preprint arXiv:1804.02767, 2018.3

[2] O. Ronneberger, P. Fischer, and T. Brox, “U-net: Convolutional networks for biomedical image segmentation,” in Medical Image Computing and Computer-Assisted Intervention–MICCAI 2015: 18th International Conference, Munich, Germany, October 5-9, 2015, Proceedings, Part III 18, pp. 234–241, Springer, 2015.

The BREAK Attack to MU-MIMO



Ref: F. Meneghello, F. Gringoli, M. Cominelli, M. Rossi and F. Restuccia, “How to BREAK MU-MIMO Precoding in IEEE 802.11 Wi-Fi Networks”, **IEEE INFOCOM 2025 Best Paper Award**

Explainable AI: Enhancing Interpretability in AI-Driven Spectrum Sensing: Dr. Houbing Song, UBMC

Explainability Challenges in Deep Learning Models

- **"Black Box" Models:** Deep neural networks often **lack transparency**
- **Trust & Validation Issues:** In critical applications (military, safety), a decision must be explainable.
  - The inability to understand DL decisions **undermines trust and acceptance**. Operators need insight to validate that the AI isn't focusing on wrong cues (e.g., noise artifacts).
- **No Continuous Learning:** Standard trained models are static; trying to update them with new data typically causes **catastrophic forgetting**.
- **Need for Interpretable, Adaptive AI:** The goal is AI that explains why it chose a classification and can learn lifelong, improving with new signals without forgetting the old.

• Proposed Solution

Introduce a **Zero-Bias Neural Network (ZBNN)** that replaces the penultimate layer with a cosine similarity-based "zero-bias" dense layer to enhance transparency.

- **Dataset & Setup:** Evaluate on **RadioML 2016.10A** dataset (11 modulations, analog & digital signals across various SNRs) using identical training setups for ZBNN and a baseline CNN.
- **Key Result:** ZBNN achieves accuracy on par with a conventional CNN (~63% vs ~65%), demonstrating explainability **without sacrificing performance**. It shows promise as a building block for **XAI** in spectrum sensing.

Ref: V. Magotra, S. M. Perera, A. Madanayake and H. H. Song, "Explainable AI for Spectrum Sensing," *2025 34th International Conference on Computer Communication and Networks (ICCCN)*, Tokyo, Japan, 2025, pp. 1-6, doi: 10.1109/ICCCN65249.2025.11133914.