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Demonstration of FPGA-Accelerated ML-based Wideband Spectrum Awareness and Signal Characterization in Real-Time

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***Abstract*—This paper proposes a sophisticated spectrum awareness tool that introduces a novel approach at the intersection of spectrum sensing and signal characterization, leveraging an optimized 1-dimensional (1D) faster region-proposal convolutional neural network (FR-CNN). Our research addresses the evolving challenges in cluttered radio frequency environments, where multiple transmissions occur simultaneously. The FR-CNN model is tailored for 1D signal processing, incorporating machine learning for precise angle of arrival (AoA) estimation. Notably, our framework outperforms conventional methods in terms of efficiency and accuracy, extending to signal characterization through over-the-air testing with software-defined radios (SDR). Additionally, our approach demonstrates adaptability to wideband signals, enabling effective analysis and classification across a broad range of frequencies and waveforms. In a complementary study, we evaluate machine learning methods for AoA estimation in wireless communication systems. Despite a slightly higher error rate, the machine learning algorithm demonstrates robustness and stability in synthetic and over-the-air (OTA) test scenarios. The sensing results will be displayed in real-time in the frequency domain, indicating the signal's angle of arrival, center frequency, bandwidth, and modulation type.**

I. Introduction

Spectrum awareness is crucial for identifying and efficiently allocating available frequency bands in dynamic radio frequency (RF) environments. The challenge arises from the need for rapid and accurate detection of signals amid multiple transmissions at varying frequencies and bandwidths. Current sensing methods often rely on simple and fast energy-based detection, which exhibits limitations in terms of accuracy and characteristics of the active signals. To overcome these challenges, we propose to adapt faster region-proposal based convolutional neural network (FR-CNN) model to facilitate real-time detection and isolation of RF signals. The innovative approach focuses on simplifying signal processing complexity by directly handling 1-dimensional (1D) signals, avoiding unnecessary computational expenses associated with converting signals into 2D images. Our solution aims to enhance the performance of spectrum sensing in dynamic RF environments. Meanwhile, we introduce machine learning-based angle-of-arrival (AoA) estimation techniques, comparing a direct utilization of in-phase and quadrature (I/Q) samples with the covariance matrix of I/Q samples. The tailored FR-CNN model serves as a versatile tool for both AoA estimation and RF characterization, demonstrating efficiency and accuracy. This proposed approach is positioned to outperform existing methods, offering enhanced speed and precision of RF characteristics including center frequency, bandwidth, waveform and modulation type, and AoA. The potential applications of our methodology span wireless communication, radar systems, navigation, and beyond, where rapid and accurate spectrum sensing and AoA estimation are critical for optimal system performance.

II. ML-based AoA Estimation Framework

Our framework is influenced by a convolutional recurrent neural network (CRNN) used for AoA estimation in acoustic signals [1] and the RFDOA-Net architecture for unmanned aerial vehicle (UAV) direction finding [2]. Leveraging the success of the CRNN architecture, which combines long-short term memory (LSTM) and CNN layers for AoA estimation in acoustics, we experiment with the use of I/Q and covariance of I/Q as input modalities for our models. Inspired by RFDOA-Net's innovative approach to UAV direction finding using I/Q data, we explore similar input strategies for enhanced AoA estimation in our proposed framework. Additionally, benchmarking our framework on a self-created dataset with real signals from universal software radio peripheral (USRP), applying CNN architectures on the covariance matrix for AoA regression aligns with established methodologies for effective input representations. Synthesizing insights from these studies, the objective is to optimize our framework, positioning it at the forefront of AoA estimation advancements for enhanced accuracy in dynamic RF environments.

III. Optimized FR-CNN Framework

Our optimized FR-CNN [3] for 1D signal processing involves key considerations in feature extraction and region proposal, tailored to the unique characteristics of wireless signals. FR-CNN employs a fully convolutional network for feature extraction, balancing data reduction, feature complexity, and accuracy in 1D signal processing. We analyze different architectures and downsampling factors to optimize performance for wireless signals. The region proposal network (RPN) efficiently detects objects within the dataspace using anchor intervals. It comprises a three-layer convolutional network, including a 3×1 convolutional layer for feature extraction and separate 1×1 convolutions for classification and regression. The regression layer enables precise signal localization in frequency domain. Fine-tuning proposed regions, the region pooling and classification stages process windowed features through fully connected layers. The output includes classification ("foreground" or "background") and regression results. A threshold of 0.70 ensures confident predictions.

IV. Demo Equipment and Setup

To assess the performance using over-the-air (OTA) signal, we conduct tests using our RF testbed as shown in Fig 1. It comprises two USRP X310s, an Octoclock for synchronization, four antennas, and one Xilinx ZCU102 for ML acceleration. A third USRP is set up approximately 3 meters away from the RF testbed as a transmitter, allowing for comprehensive testing and evaluation of the system's sensing and characterization capabilities.

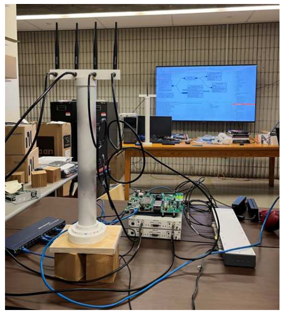

Fig. 1: Testbed

V. Simulation Results and Expected Outcome

To assess ML-based AoA, diverse models have been tested on a Matlab synthetic dataset, detailed in Table I. Utilizing the Adam optimizer with mean squared error (MSE) loss, ResNet with LSTM (ResNet) exhibited superior mean absolute error (MAE) and root mean squared error (RMSE) performance. Despite its longer inference time due to a larger layer count, ResNet has outperformed networks like ANN or CNN with covariance input. Therefore, ResNet is selected for the OTA test. Specifically, the ResNet was evaluated using data collected from a 4-antenna array. For a test case, a signal starting at 0° AoA was recorded, and the array was subsequently rotated to -30° (as rotating the transmitter to 30°). The MAE and RSME are 2.22° and 2.23°, respectively, at 0°; and 5.87° and 5.88°, respectively, at -30°.

TABLE I: ML-based AoA using Synthetic Dataset

Network	RMSE	MAE	Inference Time
CNN Cov	0.81°	0.54°	**0.0027s**
CNN	26.40°	22.92°	0.0040s
ResNet Cov	0.76°	0.58°	0.0078s
ResNet	**0.51°**	**0.36°**	0.0145s
ANN Cov	2.28°	1.36°	0.0040s
ANN	25.80°	22.28°	**0.0027s**

To assess performance of 1D FR-CNN, we conducted offline testing on a synthesized dataset, spanning -5dB to +20dB SNR, and metrics such as mean average precision (mAP), mean intersection over union (mIoU), probability of detection (Pd), and probability of false alarm (Pfa) are used. The assessment summarized in Table II revealed the superior performance of FR-CNN methods over energy-based sensing. A pivotal selection criterion for OTA testing was the Pfa metric. Despite comparable metrics, the optimized 1D FR-CNN with automatic modulation classification (AMC) displayed a significant Pfa improvement (10% drop to 0.149), making it a preferred choice. This model's adaptability was highlighted in mixed signal classification scenarios, proving effective in uncontrolled bands with multiple unknown signals.

TABLE II: Average Performance of Spectrum Sensing Methods using Synthesized Dataset

Algorithm	mAP	mIoU	Pd	Pfa
Energy Based	0.239	0.125	0.469	0.169
2D FRCNN	0.686	0.307	0.940	0.276
1D FRCNN	0.716	0.587	0.823	0.166
1D FRCNN w/AMC	0.638	0.413	0.594	0.149

Leveraging our preliminary work on ML-based AoA estimation and 1D FR-CNN, we propose to demonstrate a sophisticated wideband spectrum awareness tool by expanding the size of antenna array from 4 to 8, configuring FPGA on X310 for wideband reception, optimizing ML models using genetic algorithm [4], and accelerating ML on Xilinx ZCU 102. Specifically, this spectrum awareness tool can detect and blindly separate multiple active signals, simultaneously characterize signals in terms of AoA, center frequency, bandwidth, waveform and modulation types, and visualize the spectrum as shown in Fig. 2.

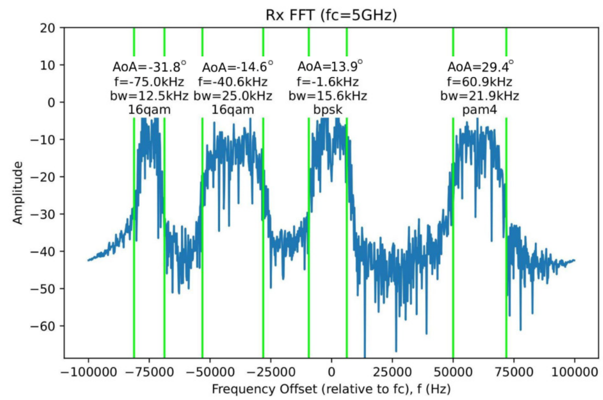

Fig. 2: Expected Demonstration Deliverables

VI. Conclusion

We propose to demonstrate a sophisticated spectrum awareness tool in cluttered RF environments. The integration of machine learning techniques for AoA estimation, coupled with the modified FR-CNN model for spectrum sensing and accelerated by FPGA, can demonstrate superior efficiency and accuracy, outperforming conventional methods.

Acknowledgements

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