Transmitter Localization with a Two-Receiver Port PLUTO+ Software Defined Radio

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The PLUTO+ Software-Defined Radio (SDR) is an upgrade from the original Analog Devices ADALM-PLUTO SDR. It has two receiver and two transmitter ports, enabling MIMO capabilities. The PLUTO+ SDR is not standardized, as it is an off-brand product, so custom firmware is required for this to work. It is backward compatible with the original ADALM-PLUTO's firmware (AD9363), but the custom firmware (hacked AD9361) is required to unlock MIMO support and a higher frequency limit. Since the custom firmware is not recognized by software like MATLAB as a typical AD9363 chip from an ADALM-PLUTO (it instead sees a custom AD9361), creating a custom Analog Devices SDR in software like MATLAB is required. ***Detailed instructions on how to set up the PLUTO+ with custom firmware in MATLAB using the Analog Devices RF Transceiver Toolbox are included in the README of THIS GitHub repo in the "Installation & Setup Guide" section.***

I. INTRODUCTION

Wireless localization has become a very important part of modern wireless systems, including applications for networking, asset tracking, indoor navigation, defense, and even search and rescue missions. This project aims to replicate the principles of the "SpotFi" research paper [1], which uses Channel State Information (CSI) from typical WiFi hardware found in the average American home, to estimate the Angle of Arrival (AoA) and Time of Flight (ToF) of a signal. With those two metrics, software can be used to plot on a 2D grid where the transmitter is with respect to a network of receivers. While the original SpotFi implementation used 3 separate devices to act as receivers, this project explores the feasibility of achieving similar localization results using a low-cost MIMO-capable SDR. The SpotFi paper used 3 commercial Network Interface Cards (NICs) for localization. However, this project only uses a single SDR with 2 receivers to attempt to estimate the location of a device.

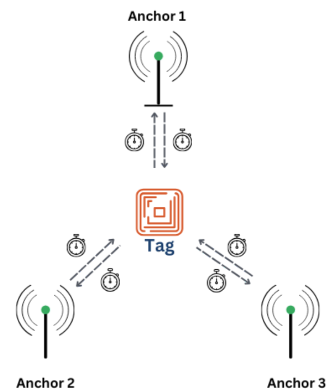

Figure 1: Localization with 3 Network Cards

By using the two receive antennas on a single PLUTO+ SDR, this project implements a complete software-level localization pipeline, accomplishes high-accuracy AoA estimation, and lays the framework for ToF estimation. This involves configuring a secondary ADALM-PLUTO as a constant OFDM transmitter and developing a MATLAB-based receiver engine to process raw I/Q samples for direction finding.

I successfully implemented accurate AoA estimation in a cluttered indoor environment using a 1.56 GHz carrier frequency on a single PLUTO+ as a receiver, and a constant 1.56 GHz OFDM signal from an ADALM-PLUTO across the room. I verified that One-Way Ranging with a typical ToF algorithm was impossible on unsynchronized SDR hardware due to Sampling Time Offset (STO) and possibly Sampling Frequency Offset (SFO). Two-Way Ranging (TWR) would be the fix to properly estimate ToF in future development on this project.

II. BACKGROUND & RELATED WORK

The foundation of this project is the SpotFi system, where everyday WiFi hardware was used to set up a localization system with AoA and ToF. I performed localization by using the concept of using subcarrier phase shifts in OFDM signals to estimate both AoA and ToF jointly, just like SpotFi did. SpotFi constructs a smoothed CSI matrix to apply the MUSIC (Multiple Signal Classification) algorithm, virtually expanding the number of antennas.

This project estimates the location of a transmitter using only the distorted signals received by two antennas in an indoor area with lots of multipath signals. Wireless signals bounce off walls and objects in the room, creating multiple signal paths that arrive at the receiver with different delays and phase shifts.

To resolve the direct path from these reflections, the system must separate the signal components in two domains:

1. Spatial Domain (AoA): Using the phase difference between the two receiving antennas to determine the angle of the incoming signal.

2. Frequency Domain (ToF): Using the phase shifts across subcarriers of an Orthogonal Frequency Division Multiplexing (OFDM) signal to estimate the propagation distance.

This problem is theoretically possible to solve due to the PLUTO+ being a single device with two receive ports. This allows for a one-time calibration of the two receive ports in software, as minimal clock offsets will cause an incorrect value for AoA.

While SpotFi utilized three antennas, other recent works, such as "A Hybrid AOA and TDOA-Based Localization Method Using Only Two Stations" [3], have explored methods using only two stations, but that requires very strict time synchronization, which a cheap SDR like the PLUTO+ lacks.

III. DESIGN - SIMULATION

This project was divided into two distinct parts: MATLAB-based simulations for AoA and ToF localization with a simulated PLUTO+ (using 2 receive antennas) to validate the theoretical algorithms and performance, and a hardware experiment using the PLUTO+ SDR and an ADALM-PLUTO SDR for a constant OFDM transmitter.

III.A. SIMULATION - AoA ESTIMATION

For a Uniform Linear Array (ULA) with antenna spacing d, a signal arriving at an angle θ travels an additional distance of $dsin(\theta)$ to reach the second antenna. This creates a phase shift ϕ:

$$\phi = - 2\pi\frac{d}{\lambda}sin(\theta)$$

By measuring the phase difference between the two (clock-synced and calibrated) receiver ports across all subcarriers, software can estimate θ. I used a spacing of $d = \lambda/2$ (about 9.6 cm at 1.56 GHz) with a simulated ULA to prevent spatial aliasing. Below are simulated results using the MUSIC algorithm for various signal-to-noise ratios (SNRs):

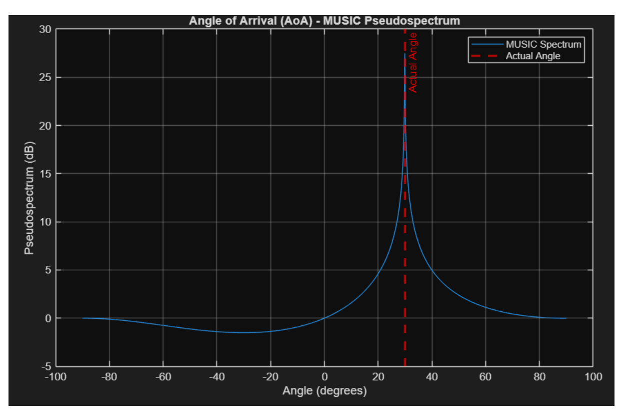

Figure 2: MUSIC Pseudospectrum (SNR = 10dB)

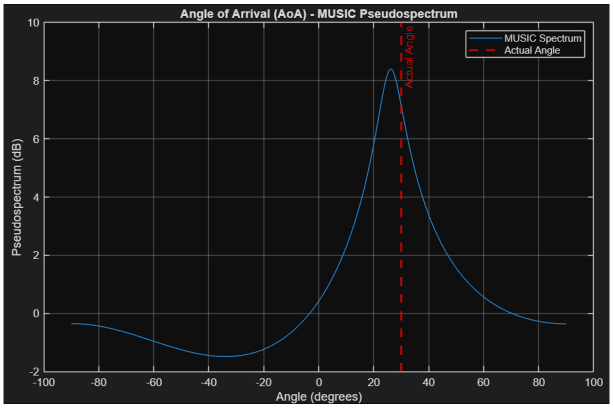

Figure 3: MUSIC Pseudospectrum (SNR = -10dB)

III.B. SIMULATION - ToF ESTIMATION

ToF shows up as a phase rotation across the subcarriers of the OFDM signal transmitted. This rotation in frequency with a time delay (τ) causes the following phase shift ϕ_k at index k:

$$\phi_k = -2\pi f k \tau$$

By measuring the slope of the phase across the subcarriers, the propagation distance can be estimated. Below are two simulated plots from an experiment where ToF was estimated from the received simulated OFDM signals. The MUSIC algorithm was used again to estimate the ground truth path:

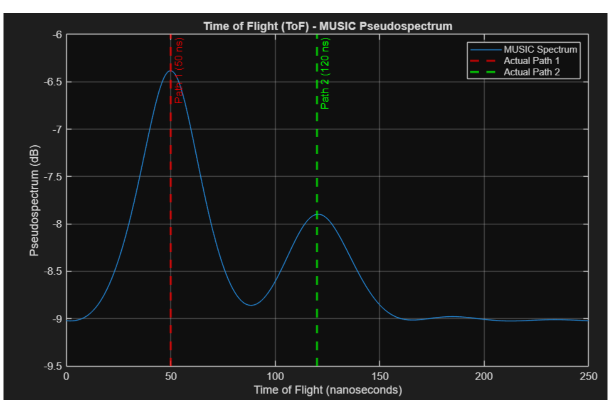

Figure 4: MUSIC Pseudospectrum (SNR = 0dB)

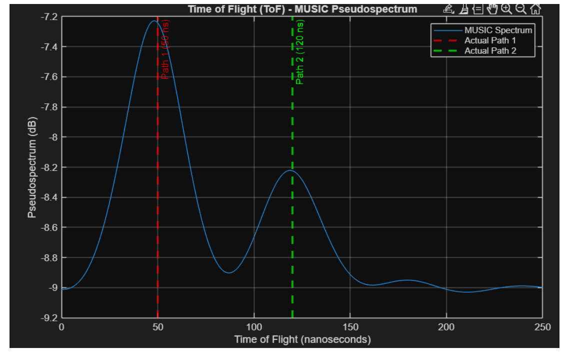

Figure 5: MUSIC Pseudospectrum (SNR = -20dB)

IV. IMPLEMENTATION - HARDWARE

First, an OFDM packet binary was generated using MATLAB, and sent to a GNURadio file for the standard ADALM-PLUTO to continuously send this signal as a transmitter. This file contained an OFDM packet structure generated in MATLAB with 64 subcarriers with a Cyclic Prefix (CP) of 16 samples:

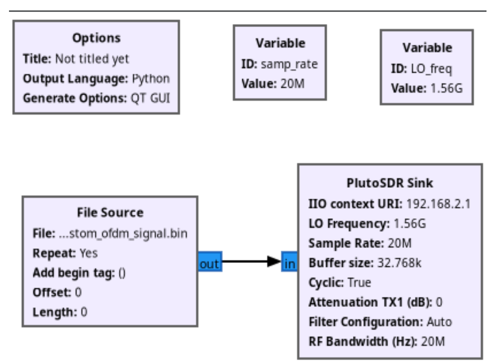

Figure 6: GNURadio Transmit Pipeline

The receiver pipeline then configured a PLUTO+ with custom firmware to operate with MATLAB. Only AoA was successfully implemented for localization, as ToF implementation was not functional (explained further in section V - evaluation). The receiver pipeline accomplished the following tasks in real-time:

1.) Packet Detection: First, a cross-correlation is performed against the known time-domain preamble to identify the start of a packet.

The binary file was generated with a set RNG seed. The receiver pipeline also used this seed to know the expected preamble.

2.) CSI Extraction: An FFT is performed on the synchronized packet. The received symbols are divided by the known symbols (with this fixed RNG seed) to obtain the raw CSI matrix H of size 64 by 2.

3.) Estimation Algorithm: While MUSIC was used in initial testing, the AoA algorithm was very jittery and wouldn't lock onto a single angle for very long (results seemed almost random). Much better results were found by using the Bartlett Beamformer algorithm for this two-antenna setup.

4.) Weighted Phase Averaging: To estimate the AoA, the measured phase difference between Antenna 1 and Antenna 2 was calculated in MATLAB. To combat multipath fading (where the room this was tested in was small and cluttered, making it very prone to multipath fading), a weighted average was used, where the phase of each subcarrier is weighted by its signal magnitude squared. This allowed my algorithm to try "ignoring" multipath despite it still being present. Results were mixed, but it definitely helped more than it hurt.

It is worth noting that a one-time calibration was necessary before running the experiment, as the difference in phase between the two antennas did not have the "zero" point that I wanted. I made a quick calibration script to store a phase offset for where I wanted 0 degrees to be (it measured an offset of about 75 degrees in my testing).

V. EVALUATION

V.A. SIMULATION

Looking at the plots for AoA estimation in a simulated environment, two blade antennas spaced apart at a half wavelength of 1.56 GHz was simulated as a single phased array antenna to generate a MUSIC pseudospectrum that was perfectly accurate at around SNR = 10 dB, slightly off from the ground truth angle at SNR = -10 dB, and was incapable of generating a MUSIC pseudospectrum below -15 dB.

Looking at the plots for ToF estimation in a simulated environment, two blade antennas spaced apart at a half wavelength of 1.56 GHz was simulated as a single phased array antenna to generate a MUSIC pseudospectrum that had 2 distinct peaks with accurate path estimations at SNR = 0 dB, and was slightly off from the ground truth paths at SNR = -20 dB, and was incapable of generating a MUSIC pseudospectrum below -25 dB.

V.B. HARDWARE EXPERIMENT

Initial tests at 2.4 GHz failed due to the noisy environment with Wi-Fi and other protocols using that band. To find the best place frequency for this experiment, a wideband noise floor sweep was performed, and 1.56 GHz was selected as a quiet band to perform this experiment.

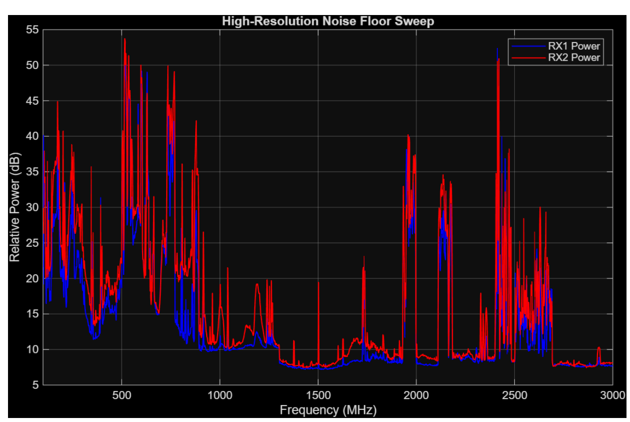

Figure 7: Wideband Noise Floor Sweep

AoA Performance: Linked HERE is a video of the experiment running on a PLUTO+, with MATLAB outputting the Bartlett Beamformer pseudospectrum to a plot. The system generated a clear heatmap peak at the angle of the transmitter, corresponding to the physical location of the transmitter after calibration (~2 meters away). The system successfully tracked the transmitter as it moved around the room.

ToF Failure Analysis: While AoA was successful, absolute ToF estimation failed. The hardware experiment revealed that unsynchronized clocks between the distinct TX and RX SDRs introduced a random Sampling Time Offset (STO). This caused the "Time" axis of the heatmap to jitter randomly by orders of magnitude (microseconds), making one-way ranging impossible without either a shared clock or a Two-Way Ranging protocol.

VI. CONCLUSION & NEXT STEPS

While the AoA estimation worked quite well with a little bit of noise, that little bit of noise may have been responsible for the ToF estimation algorithms failing in MATLAB.

ToF estimation worked with SpotFi because it used three receivers to differentiate Linear Phase Errors (STO) from Non-Linear Phase Errors (actual multipath). For a PLUTO+ to approximate ToF with only two antennas, the only way to accomplish this would be to properly implement Two-Way Ranging (TWR). The constant OFDM transmitter would need to be more than a “dummy” transmitter, and would need logic for two-way ranging to perform STO correction (along with SFO correction). While performing Pilot-Based SFO Estimation purely in software would theoretically fix frequency offset (SFO), it cannot fix the sampling time offset (STO) without a two-way handshake. This solidifies why TWR is the only path forward.

VII. ACKNOWLEDGEMENT

I would like to acknowledge Sean Trimper for his work in ECSE-6660 (IoT) at RPI in the previous semester, as his project with RSSI-based localization kick-started my interest in localization techniques.

Additionally, this project was for the course ECSE-6560 Modern Communication Systems (MCS) at RPI, which provided valuable insight into various localization techniques.

Google Gemini was used to check grammar for this report.

VIII. REFERENCES

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