Animal Movement Research Using Phase-based Trilateration

A Design Project Report

Presented to the School of Electrical and Computer Engineering of Cornell University

in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering, Electrical and Computer Engineering

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Degree Date: May 2018

Abstract

Master of Electrical Engineering Program
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Project Title: Animal Movement Research Using Phase-based Trilateration

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In order to accomplish the localization of small animals, we plan to develop a cost effective and automated system to track animal movements within the accuracy of five meters while taking into account expected causes of error. Our proposed system consists of a receiver architecture that is built specifically for phase interferometry direction finding to facilitate accurate measurements from radio tags on tracked individuals. In order to accomplish this, a low weight radio tag is being developed to transmit signals to radio base stations. These tags transmit sub 1-GHz UHF frequencies. Early testing shows we are able to obtain angle of arrival measurements with limited accuracy. In the future we will be able to use the calculated angle of arrival for spacalization and increase the accuracy of switching via RF switching with a noise source.

Executive Summary

Animal Movement Research Using Phase-based Trilateration (AMRUPT) is a technology being designed for the localization of small animals in the field of ecology. This is used for the study of flight patterns, social interactions, and other biological attributes. Finescale wildlife tracking is essential to study the social interactions and group behavior of animals. Having the ability to locate individual animals would allow us to see when animals interact and how they behave. The system utilizes Phase Interferometry for use in estimating the Angle of Arrival (AOA) of radio signals. These systems are substantially more accurate than other common methods, although performance scales strongly with the spatial scale of the receiver network. Because many researchers are interested in small-scale movements of animals within populations, such a system may be extremely useful. To accomplish this, a low weight radio tag is being developed to transmit signals to radio base stations. These tags will transmit sub 1-GHz UHF frequencies. The phase information of these RF signals will be calculated on the RTL SDR. This requires multiple receive antennas connected to an RF switch which is attached to the RTL SDR which communicates the I & Q values of the received to a Raspberry Pi for angle of arrival calculation. A three antenna system is used for angle of arrival. An angle of arrival will be computed between different antennas which will allow us to triangulate the signal location.

Introduction

The localization of small animals in the field of ecology is imperative in order to determine the flight patterns, social interactions, or other biological attributes of animals. Many attempts have been made to determine the positions of animals temporally and spatially in the past, but have been either inaccurate (errors over five meters) or have required constant manual human intervention [1,2,3]. Since direction finding requires wireless telecommunication, measurements have been thwarted by multipath interference from vegetation, electromagnetic interference, or other environmental conditions. Our objective is to develop a cost effective and automated system to track animal movements within the range of five meters while taking into account expected causes of error. Our proposed system consists of a receiver architecture that is built specifically for phase interferometry direction finding to facilitate accurate measurements from radio tags on tracked individuals.

Literature Review

Many different techniques have been explored to achieve localization. Transmitted signals at antenna array elements can be quantized at receivers to provide phase difference information such as in phase interferometry [4,6]. Phase based measurements can be skewed by multipath effects in the environment by constructive and destructive interference for line of sight signals [6]. Received signal strength can be also be used for localization through several different algorithms however these metrics have been found to be unreliable [5] and thus do not have high accuracy. Another common approach is Time Difference of Arrival (TDoA) [1], where the position of a transmitter is determined cooperatively by a group of receiver stations from the differences in the time at which a short-lived transmission reaches. TDoA systems are not as susceptible to multipath effects; however, obtaining precise positioning from close proximity transmitters in TDoA is difficult because nanosecond synchronization is required to compare lightspeed propagated signals. Subsample interpolation improves the resolution of the arrival time estimate to an accuracy that is better than a specified sampling period by interpolating between the samples of a correlation peak [1 - p. 40]. Another bottleneck with TDoA is sampling rate as our timing difference measurements are only as accurate as our maximum sampling rate. Finally, TDoA systems suffer from the requirement that signals are extremely broadband, which could make RF transmissions more susceptible to interference from multiple narrow-band signals in the broadband transmission's range. However, a simple transmitter in TDoA could be constructed to transmit on a narrower frequency range [1].

Although lightspeed propagation substantially helps with obtaining real time results, it adversely affects the collection of synchronized data at antenna array elements in the radio frequency direction finding systems mentioned. More intensive hardware synchronization can be avoided by using a time-modulated array to switch between antennas in a direction finding system [7], shown in Figure 1. However, these systems perform poorly in direction finding of multiple coherent sources. Because these systems have trouble to identify coherent signals. These system will detected the last arrivaled signal. The result will completely wrong if this signal is generated by multipath. Our produce will applied to complicada environment. The multipath issue will be huge concern.

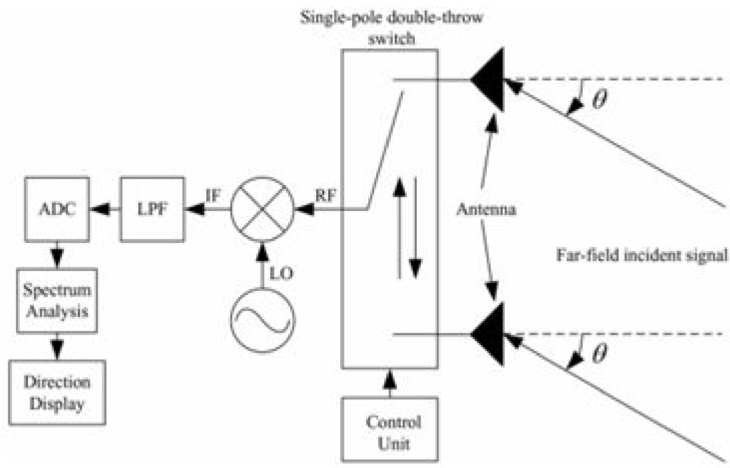

Fig. 1. Block diagram for direction finding of time-modulated array with harmonic characteristic analysis [7]

A phase interferometry system with real time operation on multiple receivers driven by a common local oscillator was able to identify an angle of arrival within degrees for all emitter distances from 1 km to 100 km [1]. Because this system was driven by a common local oscillator, the resulting intermediate frequency at each receiver could be compared without phase-offset synchronization. The error .5± 2 threshold from this system is less than the degree angle of arrival threshold error determined ± 5 in the time-modulated approach [21]. Although, this error rate is promising, this receiver system was designed to receive line of sight airborne signals. This does not account for the adverse effects of a ground environment, which will add additional factors to AoA error such as multipath interference.

The phase interferometry system in [4] was primarily developed to handle UHF frequencies for airborne sources. Because the frequency of this system was relatively high for phase interferometry, antennas were spaced at distances larger than half the wavelength of transmitted signals. Thus, the system was optimized to handle phase ambiguity, which is explored more in the technical section of this proposal. Testing protocols and optimization were handled in Matlab and C, modeling the effects of antenna spacings on AOA accuracy under worst-case conditions. In the hardware setup, three antennas were used to resolve phase ambiguities and determine the azimuthal AOA in a synchronized three channel system with RF mixers driven by a common local oscillator. The design of this system provides a basis for a three antenna architecture as discussed in the technical section of this proposal. The block diagram of this system is shown in Figure 2.

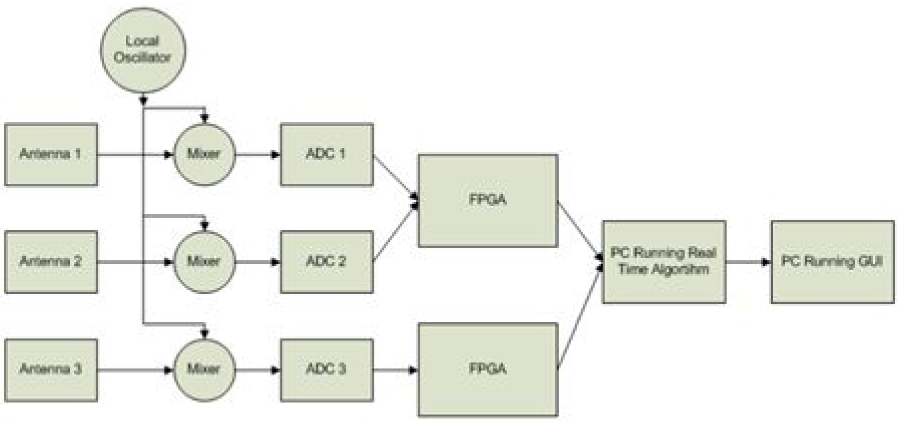

Figure 2: Block diagram for Phase Interferometry in Guerin, Jackson, and Kelly [4]

To ameliorate the problem of multipath interference that plagues AOA-based direction finding approaches Ma , Hui and Kan [6] proposes a 3D indoor passive tag localization method with an accuracy of a few centimeters in a multi-frequency identification system. The paper leverages nonlinear elements in passive devices to generate second or higher-order harmonics which are used for location detection. This paper introduces a novel approach in mitigating multipath interference, defined as the occurrence when radio waves reach a receiver via two or more paths. This effect causes constructive and destructive interference of the signal, which in turn introduces a phase error (illustrated in Figure 3).

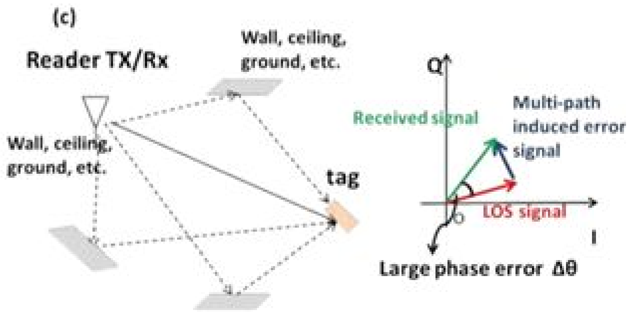

Figure 3: Dense indoor multi-path induced phase error [6]

In order to combat multipath interference, a phase error threshold defined by the bandwidth of operation and the number of frequencies used for ranging is used. An algorithm is implemented which uses heuristic multi-frequency continuous wave (HMFCW) ranging algorithm, where the frequency is dynamically adjusted to identify an optimal combination of frequencies based on the phase error threshold. HMFCW ranging can correctly identify the phase cycle integer with 100% reliability as long as the phase error falls within $\pm 90^{\circ} \times$BW% (percentage bandwidth). An optimal frequency combination is more likely to yield a correct phase cycle integer (when the measured phase is θ, the actual phase can be $\theta + 2n\pi$) to determine a correct line of sight path. Ultimately, 3D positions are localized using differential distances modeled with optimized hyperboloid functions. The larger the bandwidth of the multi-frequency transmission, the more robust the system will be to multi-path induced phase error. The forward compatibility of our system to this one is discussed in the design objectives section of this proposal.

In order to improve the cost effectiveness of direction finding, [1] has used low-cost RTL SDRs to extract in-phase and quadrature samples from incoming radio signals for TDOA and AoA calculations respectively. Direction finding implementations using RTL SDRs are promising alternatives to more expensive options by achieving up to 3.5m accuracy in TDOA [1] and by having an extensive hobbyist base with multiple Github repositories such as this one [10], demoed here. The advantages of having this repository available to us is that it will provide us with a point of reference when implementing our code and hardware. This specific repository was a precursor to the RTL SDR system developed by Sam Whiting in [11].

The TDoA approaches discussed above have been promising, as ultra-wide bandwidth transmissions would be less susceptible to signal refractions from a cluttered environment. The TDoA approach implemented with RTL SDRs in [1] does have error thresholds within 5 meters; however, this TDoA system may be limited by transmitter complexity.

In phase interferometry, triangulation error can be scaled lower with an increased number of receivers per unit area with angle of arrival calculations. This option will be effective with low cost and on site programmable receiver units such as the RTL SDR. Also, phase interferometry's potential for high accuracy with low frequency transmissions in cluttered environments can be further improved upon by the multi-frequency techniques in [6].

We chose a phase interferometry approach initially before coming across [1], and this project may switch into a TDoA approach in the future if we determine a TDoA system like [1] is computationally less expensive, more accurate, and can be altered to have more narrowband transmitters. Alternatively, a hybrid TDoA and phase based system may also be implemented in the future based on previous works on hybrid TDoA and Frequency Delay of Arrival (FDoA) systems such as in [28].

Design Requirements

In order to accomplish the goals listed in the problem statement, we have proposed the following objectives in the design:

- The receiver system is low-power and can track up to 50 lightweight and low-power radio tags
- System architecture is resilient in cluttered environment (unsusceptible to multipath interference, electromagnetic interference, and other environmental conditions)
- System is able to achieve two dimensional high spatial accuracy (error for triangulation results is limited within 5 meters) with a 100-300m distance between receivers
- Forward compatibility: Must be compatible with and adaptable to a multi-frequency-phase-integer-disambiguation approach for future versions.
- System is cost-efficient (almost all components are commercially off-the-shelf)

The first objective is to successfully track the locations of 50 individuals in the testing environment. We need to design the tags as lightweight as possible since the individuals are small in size and heavy tags may affect the individuals' biological activities. To allow for the least possible human intervention during the tracking process, both the receivers and tags need to operate with minimal power consumption to increase automatic tracking period. In addition, both the transceivers (ground nodes) and tags (mobile nodes) follow a communication protocol in which the mobile nodes will go to sleep when they are not communicating with the ground nodes to reduce power consumption.

The communication protocol is an intended route for development, but has not yet been designed. It specifies that mobile nodes wake up every 5 minutes to prepare for data transmission to the ground nodes. The mobile node will receive a 5-second countdown signal once it wakes up. As soon as the mobile node is verified to be within the receiver's range and has good link, it will be synchronized to global time before it is given a scheduled transmission time by the receiver or sent back to sleep again. If the mobile node is not within range of any receiver, it will go to sleep and wake up every 5 minutes to check whether it's within range again. The complexity of the ground to mobile node communication protocol will be governed by how accurate our receivers are when taking angle of arrival measurements. If angles of arrivals from base stations intersect to a triangulation area of no more than 5 meter error (discussed further) over the specified tracking area, then tags will not have to be linked to different receivers depending on location. The communication protocol will also be used for a multi-frequency system, which is a possibility in the future of this project.

Furthermore, the system must be able to obtain accurate results in a cluttered environment. We agreed that a real environment would have substantial multiple interference as there will be trees and rocks that can reflect a wireless signal. Multipath interference could result in an inaccurate transmit signal which would give us wrong information about the location of the tags. The effects of multipath are more amply discussed in the literature review section.

We agreed to set the tracking accuracy of our system to 5 meters. We propose a triangulation algorithm for Phase 1 of the project in order to acquire this accuracy: Phase 1 will be the development of the necessary base station algorithms and hardware setup to achieve an accurate angle of arrival measurement. In a future semester, we plan to modify our system to better overcome the effects of multipath interference by frequency hopping to obtain minimum variation results (Phase 2). If necessary, we plan to implement a multi-frequency phase integer disambiguation system that trilaterates positions of mobile nodes if a 5-meter accuracy level has not been achieved by previous efforts (Phase 3).

The diagram below is used to better understand error minimization with relation to AOA calculations.

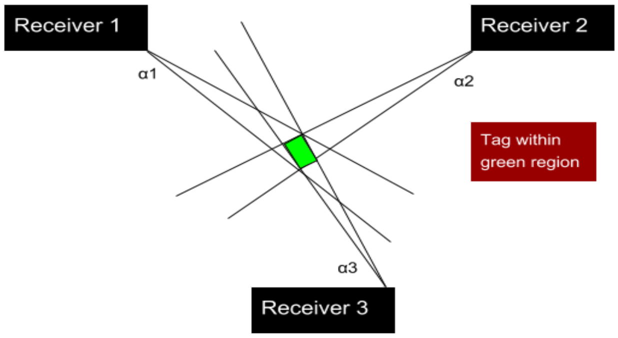

Figure 4: Error in triangulated area

In order to accomplish at least a 5 meter accuracy, a line of more than five meters cannot be drawn within the triangulated area of error . This area of error will be determined by α1, α2, and α3 (Figure 4) which resemble the angle of arrival error from receiver 1, 2, and 3 respectively. α1, α2, and α3 will be determined by phase difference errors from a transmitting RF signal to multiple antennas. Sources of AOA error are further discussed in the technical section of this proposal, and simulations have been planned to find algorithms that can make additional steps in minimizing this error.

To address forward compatibility, we must have a system in mind to distinguish tags. Code-division multiple access (CDMA) is a very popular method for doing this due to the coding infrastructure. We plan to use a less complex Time Division Multiple Access (TDMA) approach instead. After synchronizing samples and computing raw AoAs in our system, error thresholds as described in [6] can be computed for multiple sets of frequencies. Then, phase and consequently AoA measurements can be computed heuristically by HMFCW which is able to compute a correct cycle integer with 100% reliability when multi-path induced phase error is within $\pm 90^\circ \times$ BW%, and thus can resolve our multi-path interference issues.

Design Implementation

The entirety of the proposed direction finding system consists of radio transmitters and receivers. This section will focus primarily on receiver design as the lightweight radio tags are being developed by another party. In order to achieve our design objectives, the receiver architecture will require the most development.

A. Receiver Architecture

We first propose a receiver architecture that consists of an RTL SDR to simplify wireless communication and improve the cost effectiveness of this project. The receiver architecture is outlined in Figure 5 . Note that this includes 4 antennas to complete Watson-Watt Angle of Arrival (AoA) measurements for future implementation. See the Future Work section for more details on Watson-Watt. Also note the dedicated clock board with highly stable (0.1 ppm) TCXO. The dedicated clock card allows us to achieve coherent detection as the different radios can be synchronized. This board must also have the power to drive multiple SDRs.

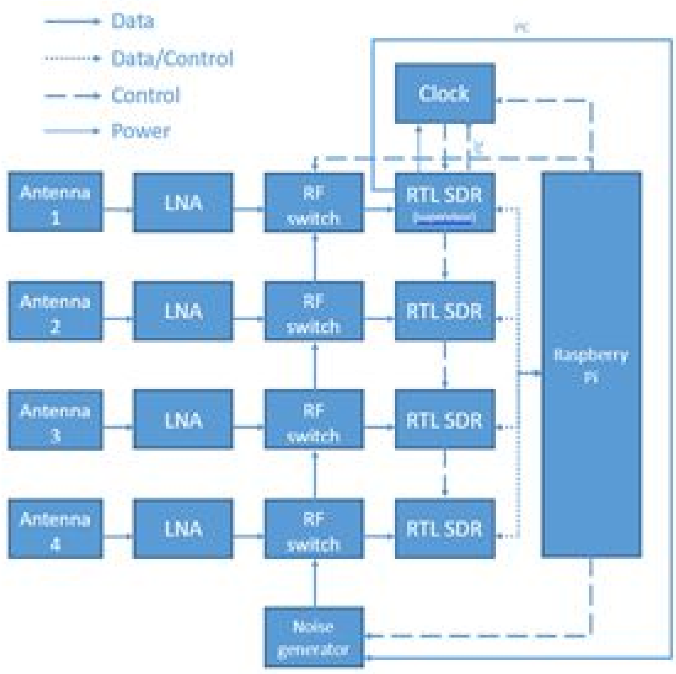

Figure 5: Receiver Architecture [12]

The ideal embedded device would include the following:

1. A sub 1-GHz device for VHF or UHF frequencies transmitted from radio tags. We choose a lower frequency band (relative to most RF applications) to mitigate multipath interference and better determine the phase difference of signals [14]. Previous systems have used ~200 MHz [12] as the operating frequency of transmitters because of the impact of large trees on multipath interference.
2. A very high sample frequency during the analog to digital conversion of RF signals. This is essential for mitigating adverse effect from noise when determining accurate phase differences from radio waves moving at the speed of light [15]. However, a sampling frequency above twice the radio frequency (constant in a non-frequency modulated signals) is not needed. Sampling rates are further discussed in section IV. Vii. "RF Wave Reconstruction and Matlab Simulation".
3. Ample UART/I2C/SPI/GPIO connections for data logging and transfer
4. Contains every component necessary for receiving an RF signal from an external antenna – ADC, local oscillator, etc.
5. Extremely high RF sensitivity and blocking performance

6. Programmable and highly used by the public – helpful for finding more tutorials and readily available information on the device
7. Low power and low cost

From this list of specifications, the RTL SDR was chosen. The RTL SDR specifications are outlined in [28]. To address the above, the following specifications are highlighted. The maximum sample rate that does not drop samples is 2.4 MS/s. The RTL SDR uses USB to interface directly with the Raspberry Pi. The frequency range depends on the dongles used on the RTL-SDR chip itself. Note that we are using the RTL2832U.

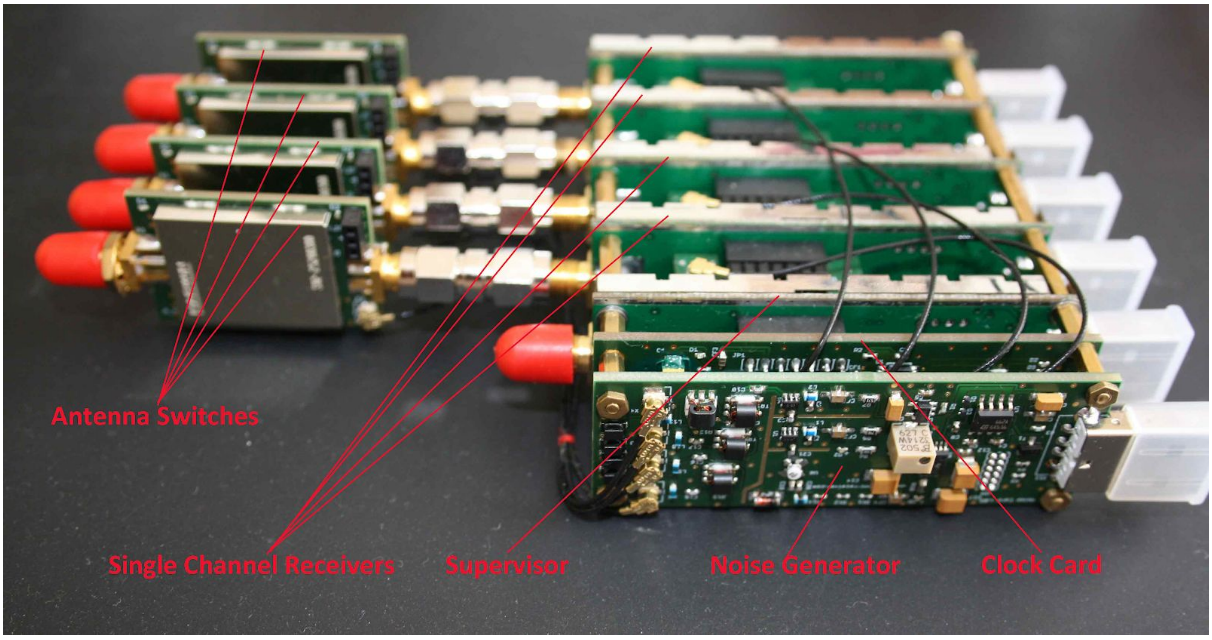

Figure 6: Hardware for Receiver Architecture [12]

B. Channel Synchronization: RF Switch and LNA

The RF switch and amplifier are included in the "Antenna Switch Card" sold by coherent-receiver which includes a switch and a low noise amplifier (LNA). Controlled by I2C, this card's LNA has a gain from 15-23 dB and a noise figure from .7-.8 dB. The MOSFET switch has unspecified insertion loss but since it is included in the hardware setup it should be compatible with the rest of the design. The RF switch is used to switch between the received signal and the noise source, an additional hardware component we have been unable to acquire and have used a function generator in the interim to generate noise. This is essential in order to get accurate readings from the radios by allowing us to get more accurate phase readings by eliminating delays internal in the hardware. Some delay in the received signal will be to intrinsic characteristics of the hardware setup. This can be ameliorated by measuring the delay caused by the hardware. By switching all channels at the same time to a noise source, we can measure the delay caused by the hardware and use that to remove that delay when finding phase differences.

C. Antenna

An antenna that is in our target frequency range (the VHF/UHF band) is selected that also has an SMA connection for ease of interfacing with other components in our system, primarily the RTL-SDR and corresponding SMA adapters. To accomplish this we are using the ANT500 as it is a compact and high gain antenna and operates in the expected frequency range.

Note that the ANT500 is a monopole antenna which is used largely due to its simplicity in the architecture. While other antenna architectures such as a loop antenna and a dipole antenna are considered, a monopole antenna is chosen due to the fact that it’s nearly an isotropic radiator and is used in previous experiments [1]. A sector antenna may be considered however if the observation area for an application of this technology is more readily defined.

D. RTL-SDR to Raspberry Pi Connection

Figure 7: RTL SDR connect to Raspberry Pi [16]

The Raspberry Pi is chosen as our computer system as it has USB support, is low power, lightweight and is small. The Raspberry Pi acts as both a signal processing computer and a datalogger. The Raspberry Pi also has software support for the RTL2832U as it runs Linux which is essential for datalogging. In order to validate the software setup, initial work is completed on an Ubuntu 16.04 VM as it more portable between team member's computers and easier to install for our initial software installation and testing. Once we have fully determined which software and code will be used, we can make a more targeted effort to install the software on a Raspberry Pi compatible software setup.

RTL-SDR is installed on the Pi in order to interface with the RTL-SDR. Ettus Research's DOA code is used [18]. This is code written with GNU Radio, an IDE designed to interface with radio equipment. This has implemented many functionalities key for our system including the MUltiple SIgnal Classification (MUSIC) algorithm, a well-known high resolution eigen structure method, extensively used to estimate the number of signals[24] and their angles of arrival. Ettus' code depends on a package on Armadillo[27], a linear algebra library, as well as a few other packages. Brief installation instructions are outlined below while more detailed ones exist in a separate document.

Installation of software is as follows:

1. RTL-SDR software is installed on the machine as per [17] in order to be used to read data from the RTL-SDR
2. Install Armadillo as per [19]'s "Easiest version for Ubuntu users."
3. Install GNU Radio as per [20]
4. Ettus Research's DOA system is installed as per [18]

E. Coherent Detection- Software

A protocol has been developed to synchronize multiple channels in a coherent radio receiver platform using SDRs. The flowchart below defines a sequence of DSP functions that need to be implemented to correct time and frequency offsets from RTL SDR measurements. This protocol can be adapted to a platform with four different SDR receivers, but has been truncated to 2 input SDR blocks for the means of simplicity. The system flowchart is shown below. We implement some changes base on Ettus project. Since Ettus project used the TCP to wirelessly transfer the received signal to mobile device to do direction finding computation, they need TCP block to achieve it. For our project, the RTL-SDR source will directly connected to our host. So we modelfied the TCP block.

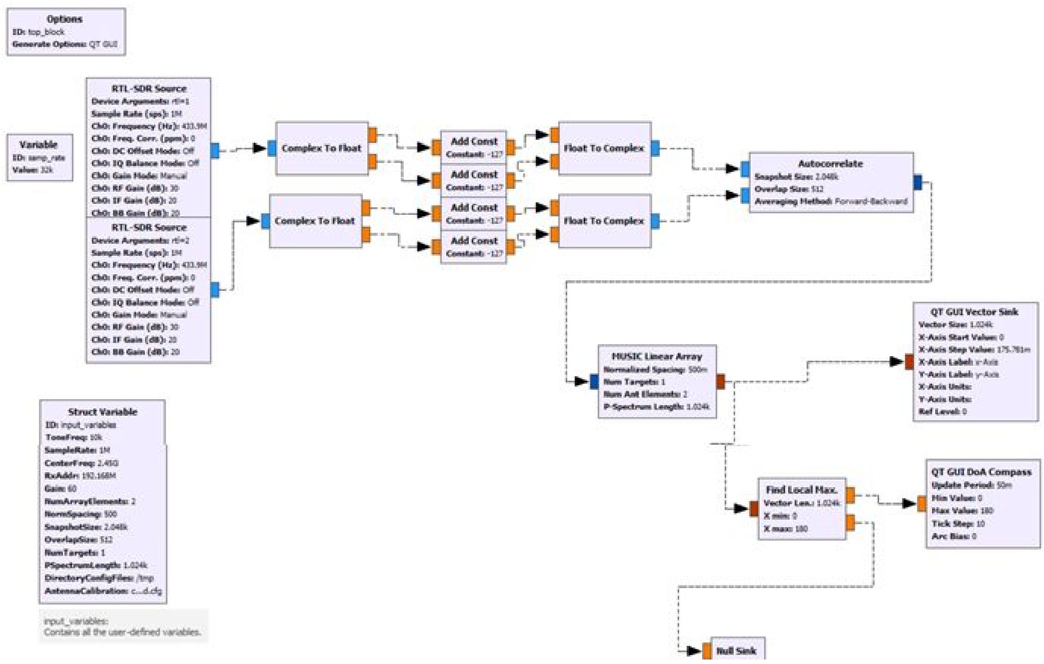

Figure 8: GNU Radio Digital Signal Processing Flowchart

The two RTL-SDR sources output signals harvested from antennas connected to the RTL-SDR cards. Even though SDRs in our system will share a common clock, signal sampling of these receivers is not expected to start at the same time, causing large bulk delays. To compensate for bulk delay, each of our SDRs will be coupled with an RF Switch connected to a common constant offset. The noise source will be used in cross correlating samples between signal channels in the Autocorrelate block of the above flowchart. MUSIC deals with the decomposition of correlation matrix into two orthogonal matrices, signal-subspace and noise-subspace. Estimation of direction is performed from one of these subspaces, assuming that noise in each channel is highly uncorrelated. This makes the correlation matrix diagonal[24]. The MUSIC Block computes the delay of one signal over another by taking a Fast Fourier transform of both signals, convoluting both signals in the frequency domain, and then taking the inverse Fast Fourier transform of the convolution to find the maximum argument (time value) of the output signal's amplitude in the time domain. The reason for the performing the final step is that the peak of the convolution will correspond to the delay between the two signals.

Test Results

The above architecture is the result of numerous design iterations. First, the transition to the RTL-SDRs was a vital design change. Transitioning to these low-cost SDRs on the receiver side allowed to have more robust functionality and leverage more sophisticated tools such as GNU radio. Switching to the RTL-SDR has also given us the ability to leverage Ettus Research's angle of arrival software mentioned above as well as other industry standard tools such as GQRX. The RTL-SDR also allows us to easily interface with it via USB, making it simple for the Raspberry Pi. By contrast the CC1310 while smaller and able to transmit lacks the ability to interface with GNU Radio making it substantially more challenging to implement basic functionality such as a cross correlation and angle of arrival calculations. To resolve synchronization issues, we leveraged the addition of a clock card which outputs a clock signal. We found that this clock card is able to provide the same clock signal to all RTL-SDRs with only a few nanoseconds of delay between the different cards.

For this project, we have tried to run ettus's project. We have tried several different platform to run GRC. So far, we have tried Raspbian, Ubuntu MATE, Ubuntu Core, Windows. Unfortunately, we have run different problems with those operating systems. For Raspbian, we have problem about the miss library which the Ubuntu have. After we checked Ettus's configuration, we found out the Ettus run their project on Ubuntu operating system. Then we switched to ubuntu system. At beginning, we installed UbuntuMATE on Raspberry Pi3. Then we installed everything we needed to run Ettus's project. However, we have another problem that we can't import error for the Ubuntu operating system. So we decided to switched to Ubuntu Core. After we installed everything, we found out that Ubuntu Core didn't support GUI interface. And the GRC need GUI interface to run. We have tried a lot of solutions to install GUI interface on Ubuntu Core. However, none of those solutions works. Then we installed Ubuntu on the PC, the import error has fixed. But the PC didn't recognize the SDR cards since itis the virtual system. Then we use VM to be our final choice. we has successfully run the GRC on VM.

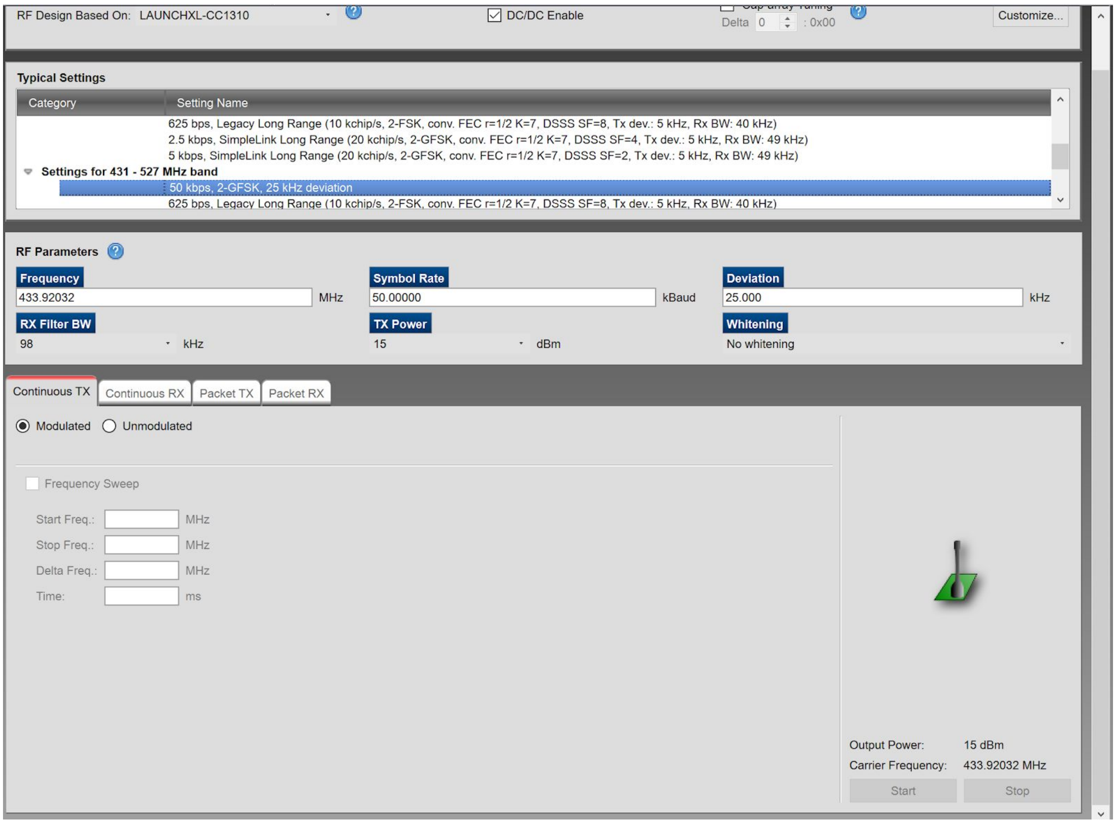

Figure 9: SmartRF radio settings for CC1310

In order to test our prototype, we used CC1310 as transmitter. The figure 9 shows how we set up CC1310 in SmartRF radio. We setup the frequency of CC1310 to be 433MHz. The SmartRF Radio for CC1310 only support 866MHz mode and 433MHz mode. Since the 866MHz is too high for our RTL-SDR card, we used 433MHz. We also setup the SDR cards as receive end to able to receive 433MHz frequency. In order to make SDR card work, the receive frequency must match the transmit frequency.

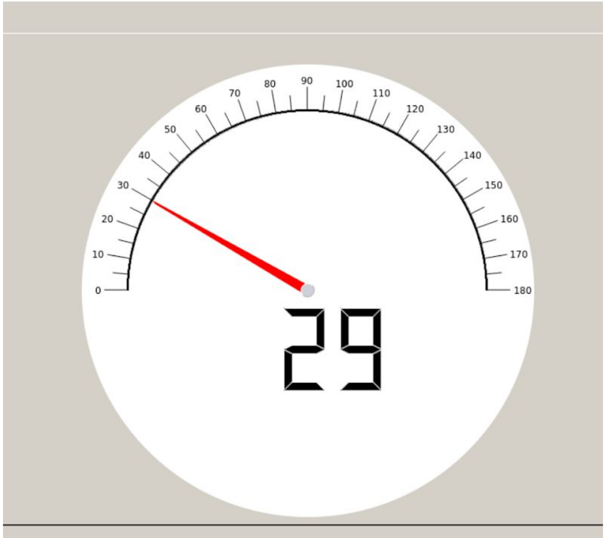

Figure 10: AOA Results on GRC

Conclusions

We have been able to integrate many different components including RTL-SDRs, Ettus Research's gr-doa system and GNU Radio. We have built a prototype with two RTL-SDR cards as receivers and CC1310 as transmitter. During our test, we activated CC1310 to send out 433MHz frequency signal. Then we run Ettus's project on GRC, we can get some results to indicate the AOA. But the results are not constant and accurate. One cause of this may be the lack of switching between noise and the signal as this was not implemented yet. Another cause of this may be the PCB antenna as this is not expected to get more than a few meters of transmitted distance [29]. For the future work, we will switch to better signal generator to finish our test. The test strategy will be test the prototype from ideal and small environment to complicate and large environment.

Future Work

In order to start testing the prototype, We will set the tag 20 meters away from the base station. The first test performed will be set in an small open area with no large natural vegetation to eliminate the multipath interference effect. The verification experiments will be performed in such a way that when we move the tag, the prototype we have developed will calculate the updated AOAs along the way. As a comparison, we also will measure the expected angle by protractor. The appropriate errors and standard deviations for these data trials will be computed. The next experiment will be to test the multipath interference. Some large blocking items such as large desks or chairs will be put in the same testing environment to see how our system handles the multipath interference. Again, many trials of measured and expected AOAs will be tested and compared in the block-free and with-block environments. After those two test suites are finished, we are going to improve the detection range from 20 meter to 50 meter so the tags are now more far apart. We will start with the block-free environment, collecting data for both the measured and expected AOAs, and then move to the with-block environment. In addition, we plan to test 100 meter, 200 meter, 300 meter, 500 meter, 1000 meter separation to check the limit of our prototype. In addition, these changes in distance also partially simulate the movement of an animal although the animal may move really fast in the environment while our test manually set the distance between the tag and base station at a much slower rate. Therefore, our test cases are taken under really good SNR conditions. For each test case, we will measure the angle several times to make sure we test our prototype properly. For the phase one, we are not able to solve the multi-path issue due to our direction finding algorithm.

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