I. 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, or other biological attributes to most species. 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 Antenna 1 and Antenna 2 that is ambiguous between Quadrants 1&2 and Quadrants 3&4. An angle of arrival will be computed between Antenna 1 and Antenna 3 that is ambiguous between Quadrants 2&3 and Quadrants 1&4. The angle of arrival will be determined to be in the quadrant that contains both AOAs.

II. Introduction

The localization of small animals in the field of ecology is imperative to determining the flight patterns, social interactions, or other biological attributes to most species. Many attempts[1,2,3] have been made to determine the positioning of animals temporally and spatially in the past, but have been either inaccurate (errors over five meters) or have required constant manual human intervention. 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.

III. Review of Literature

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. 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. This flaw in time difference of arrival can be mitigated by subsample interpolation at signal correlation peaks

[1]. Another bottleneck with TDOA is sampling rate as our timing difference measurements are only as accurate as our our maximum sampling rate.

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.

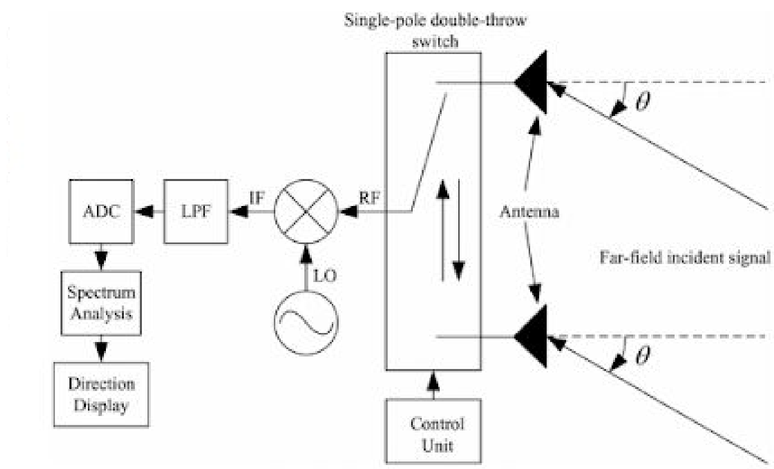

Fig. 1. Block diagram for direction finding of time-modulated array with harmonic characteristic analysis

In coherent receivers running on a single clock signal, synchronization errors from clock skew and other delays can be corrected by incorporating a signal generator input to each channel [8]. In addition, clock drifts and bulk delays can be mitigated by implementing cross correlation with virtual sources on a software level [9].

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.

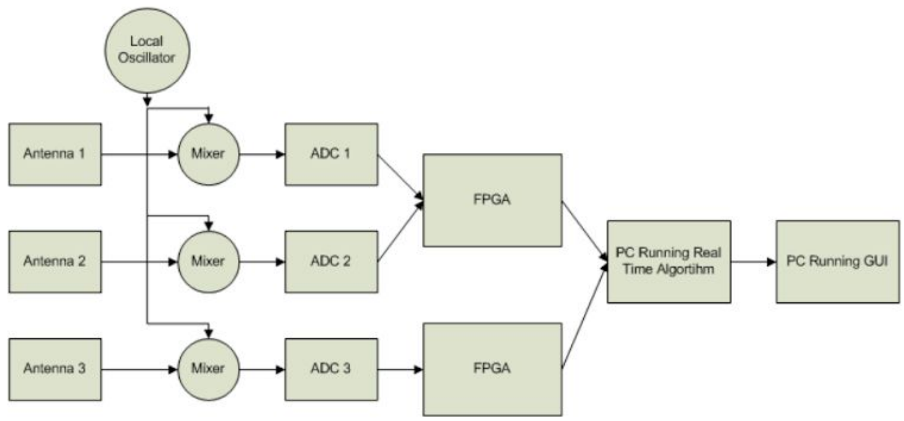

Figure 2: Block diagram for Phase Interferometry in Guerin, Jackson, and Kelly [4]

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 causes a constructive and destructive interference of the signal, as well as phase induced error in Figure 3.

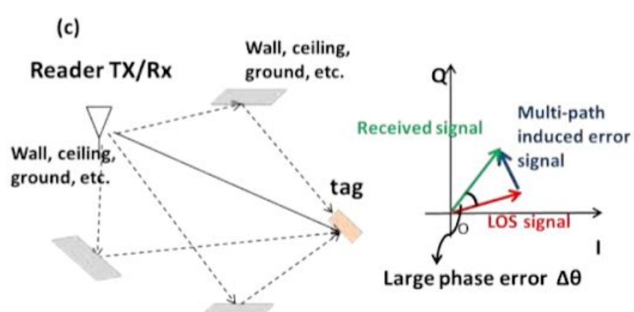

Figure 3: Dense indoor multi-path induced phase error [6]

In order to combat multipath interference, a phase error threshold is used. An algorithm is implemented which uses heuristic multi-frequency continuous wave (HMFCW), where the frequency is dynamically adjusted to identify an optimal frequency based on the phase error threshold. The optimal frequency allows an undistorted line of sight path. HMFCW ranging correctly pins down a phase cycle integer by transmitting a sequence of frequencies determined by a genetic algorithm to maximize an error tolerance equal to the percent bandwidth of the signal. 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 this system to ours 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 an ultra wide bandwidth transmission 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, the extensive digital signal processing (DSP) used to achieve these error thresholds will likely be too computationally expensive for portable embedded devices such as the Raspberry Pi, and will result in more power hungry measurement analysis (~3.7 Watts). We choose the less DSP heavy phase interferometry approach for its potential for high accuracy with low frequency transmissions in cluttered environments, which can be further improved upon by the multi-frequency techniques in [6]. Furthermore, 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.

IV. Design Requirements

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

1. The receiver system is low-power and can track up to 50 lightweight and low-power radio tags
2. System architecture is resilient in cluttered environment (unsusceptible to multipath interference, electromagnetic interference, and other environmental conditions)
3. 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
4. Forward compatibility: Must be compatible with and adaptable to a multi-frequency-phase-integer-disambiguation approach for future versions.
5. 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-mode to mobile-node communication protocol will be governed by how accurate our receivers are when taking angles of arrival measurements. If angle of arrivals from a at least three 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 and the same set of receivers can be used for all tags. 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 a false 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 because this is a minimum requirement to monitor the social interactions and movements of small mammal species and is already much more accurate than existing systems mentioned in the literature section. 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 based on [6] that trilaterates positions of mobile nodes if a 5-meter accuracy level has not been achieved by previous efforts (Phase 3). Figure 4 illustrates error minimization with relation to AOA calculations:

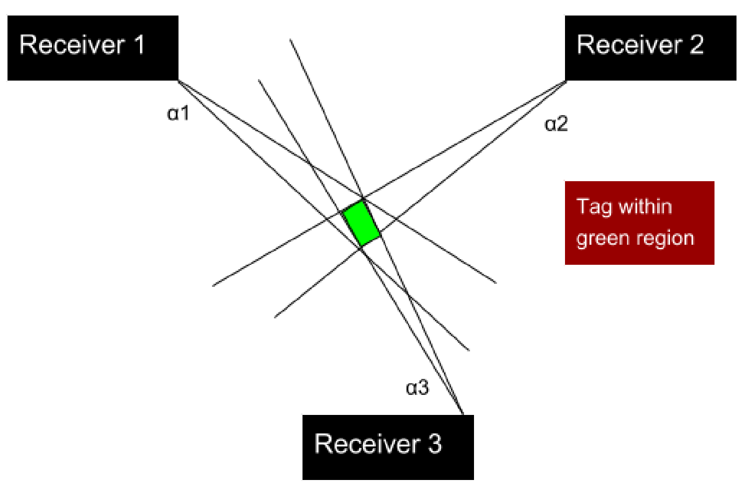

Figure 3: Error in triangulated area

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 5) 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. CDMA, after digitizing data, spreads it out over the entire available bandwidth. All of the users transmit in the same wide-band chunk of spectrum. Each user's signal is spread over the entire bandwidth by a unique spreading code. At the receiver, that same unique code is used to recover the signal. CDMA is a form of spread spectrum, which simply means that data is sent in small pieces over a number of the discrete frequencies available for use at any time in the specified range. However it is unclear if CDMA is compatible with making phase-based AOA measurements. CDMA codes are mutually orthogonal to each other, so it is possible to distinguish multiple bit streams from multiple tags at the same time. However, these codes may not be able to differentiate phases.

V. 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 6. Note that this now includes 4 antennas to complete Watson-Watt Angle of Arrival (AoA) measurements. Watson-Watt allows us to in the future implement a Phase Difference Angle of Arrival (PDOA) architecture. Also note the dedicated clock board with highly stable (0.1 ppm) TCXO. This board must also have the power to drive multiple SDRs.

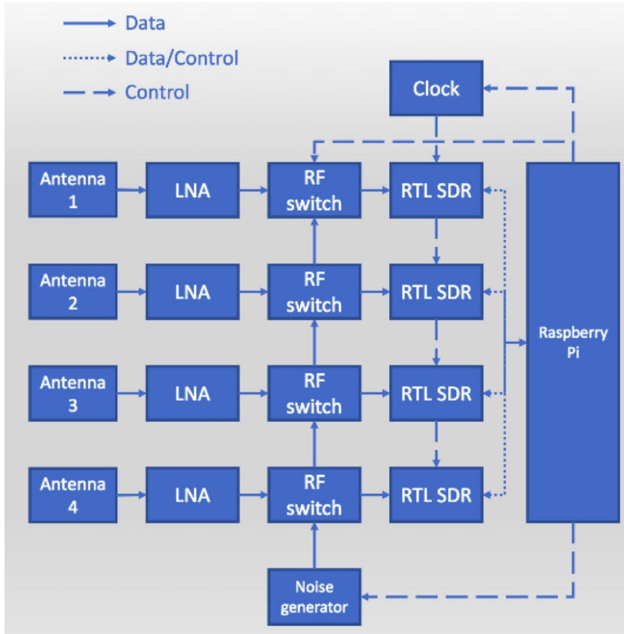

Figure 4: Receiver Architecture 12]

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 SDR chip itself. Note that we are using the RTL2832U.

B. RF Swtitch

The RF switch and amplifier are included in the “Antenna Switch Card” sold by coherent-receiver which includes a switch and an LNA. Controlled by I2C, this card has an LNA with 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. This is essential in order to get accurate readings from the radios by minimizing interference from the other antennas when reading the values on the Pi.

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 and Datalogging

Figure 5: 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 also has software support for the RTL2832U as it runs Linux which is essential for datalogging. Initial testing however is completed on an Ubuntu 16.04 VM as it more portable and easier to install. Installation of software is as follows:

1. RTL-SDR software is installed on the machine as per [17]
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]

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