AMRUPT PROJECT PROPOSAL:

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Contents

Executive Summary 4

Statement of Problem 4

Objectives 5

Technical Approach 7
- Receiver Architecture 7
- Antennas 9
- RF Switch 9
- CC1310 I/Q Extraction 9
- CC1310 to Raspberry Pi UART Connection and Datalogging 10
- Phase Disambiguation and Angle of Arrival Calculation 11
- RF Wave Reconstruction and Matlab Simulation 13
- Raspberry Pi 3 Network with Central Hub 14
- Separate Demodulator/ADC (Plan B Solution 14

Project Management 17

Conclusion 18

References 18

Appendix A: Relevant Links and Tutorials 18

I. Executive Summary

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 basestations. These tags will transmit sub 1-GHz UHF frequencies.

RF signals phase information is calculated on the CC1310. This requires multiple receive antennas connected to an RF switch which is attached to the CC1310 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. Statement of Problem

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 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. Design Objectives

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

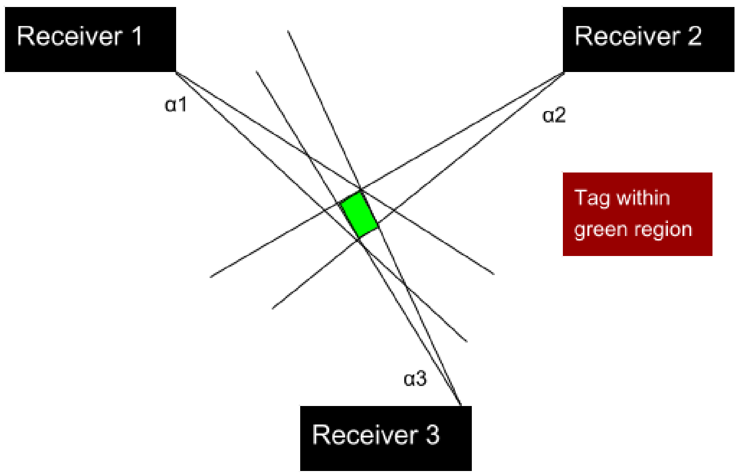
(1) The receiver system is low-power and can track up to 50 lightweight and low-power radio tags
(2) System architecture is resilient in cluttered environment (unsusceptible to multipath interference, electromagnetic interference, and other environmental conditions)
(3) System is able to achieve two dimensional high spatial accuracy (error for triangulation results is limited within 5 meters) with a 100-300m distance between receivers
(4) 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 specifies that the 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 node communication protocol will be governed by how accurate our receivers are when taking angle of arrival measurements. If angle of arrivals from a couple of basestations 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. The multipath interference could result a false transmit signal which would give us wrong information about the location of the tags. We have proposed a low frequency phase interferometry system to mitigate multipath interference. Additionally, our system will have the option of being further designed to overcome this interference by frequency hopping with to obtain minimum variation results.

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. We propose a triangulation algorithm for phase 1 of the project in order to acquire this accuracy: The diagram below is used to better understand how the scope of this error minimization with relation to AOA calculations.

Figure 1: 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 1) 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.

Last, but not least we have devised a system that is composed of cost-effective, off-the-shelf components. This is done to make this setup more reproducible in future works and more accessible to ecological hobbyists/researchers.

IV. Technical Approach

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. This is not to undermine the importance of mobile to ground node communication, which will be essential towards implementing a working receiver system that can accurately collect information from active radio tags.

IV. i. Receiver Architecture

We first propose a receiver architecture that consists of an embedded device to simplify wireless communication and improve the cost effectiveness of this project.

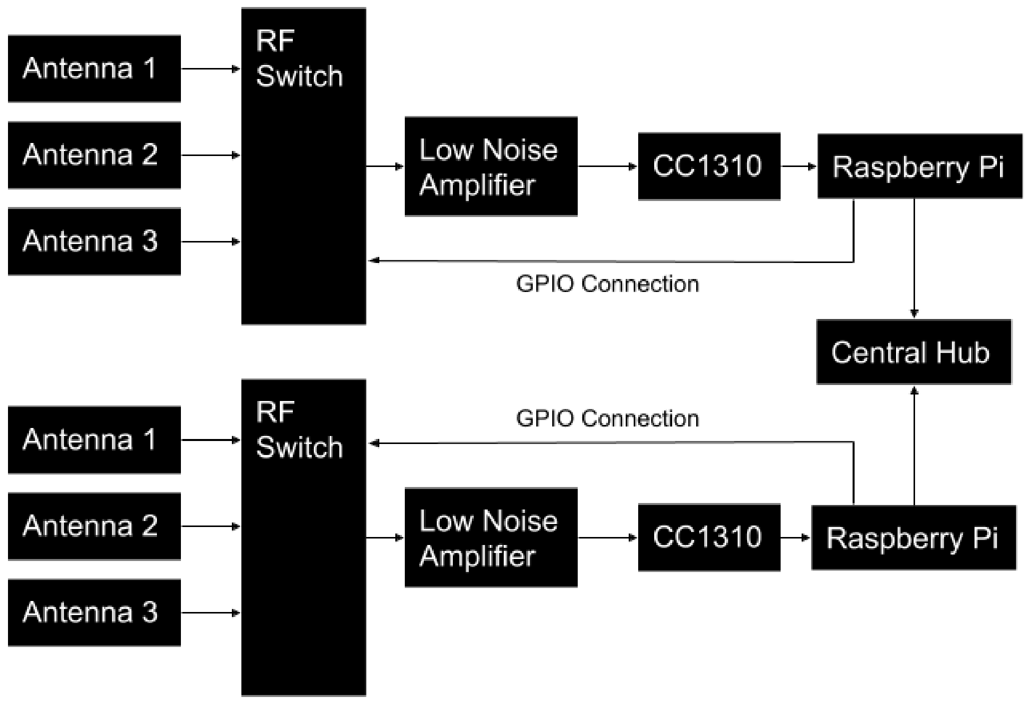
The ideal embedded device would include the following:

1. A sub 1-GHz device for 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.
2. A very high sample frequency during the analog to digital conversion of RF signals. This is essential for determining accurate phase differences from radio waves moving at the speed of light.
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 CC1310 was chosen. The CC1310's specifications are collated within the datasheet: http://www.ti.com/lit/ds/symlink/cc1310.pdf

- Suitable sampling rate and clock frequency: 200KHz ADC sample rate and runs on a 24MHz clock.
- 30 GPIO Pins with I2C and UART capability
- 128 Kb flash and 20 Kb ram

With the CC1310 in place, we refer to a simplified representation of our receiver system:



We choose to use three antennas to delimit phase ambiguity to expand the phase interferometry system's capabilities from determining AOAs from $-\pi < \theta < \pi$ to $-\pi n < \theta < \pi n$ where $n > 0$. The RF Switch was placed very early in the design to completely eliminate delay from multiple channels. With this system, only offsets from the antenna geometry or the wire lengths/connectors from each antenna to the switch could contribute to phase difference errors between each antenna, eliminating the need for Equalization with LFMs. A low noise amplifier is proposed to increase the power of the incoming signal, even though we may find it unnecessary after preliminary testing. Low noise amplification takes place after the RF Switching stage to decrease the length variability of different antenna channels. The CC1310's primary responsibility will consist of the analog to digital conversion of the signal, and an extraction of in-phase and quadrature values which will be sent to the Raspberry Pi over a UART connection. The RF signal from each antenna will be reconstructed using embedded programming on the Raspberry Pi. From this reconstruction, the phase differences for each antenna will be calculated along with phase disambiguation (from comparing the phase difference from antennas 1 and 2 to the phase difference of antennas 2 and 3). Subsequently at this stage, the angle of arrival will be calculated, timestamped, and sent wirelessly (over a unique frequency to avoid interference with the whole system) to a central hub which will triangulate the source of the signal.

IV. ii. Antennas

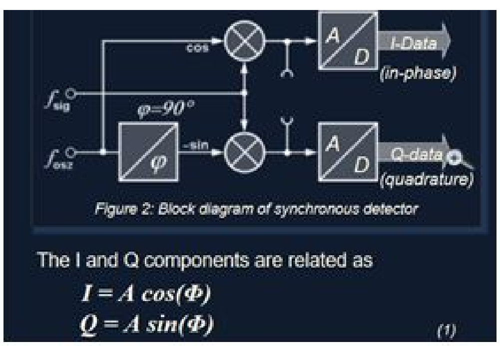
We seek an antenna that is in our target frequency range (the UHF band) and also has an SMA connection for ease of interfacing with other components in our system. To accomplish this, an antenna such as the ANT700 is compact high gain antenna and operates in the expected frequency range.

IV. iii. RF Switch

An RF switch board will be created for this project. Leveraging a high isolation and low insertion loss RF switch such as the ADG918 we can switch between two antennas mounted on a PCB. The ADG918 will operate in the UHF range making it a practical candidate for the project. The ADG918 will be controlled by the Raspberry Pi. By sending GPIO signals the Pi can toggle the ADG918 between two different antenna values. This setup would require the use of multiple GPIO ports and multiple chained switches to accomplish our goal of having 3 antennas. Another factor in this design is the SMA connection from the antenna to the PCB. Many mounts and cables are available for these connections allowing us to connect the antenna to the RF switch to the CC1310 by using commercially available adapters.

IV. iv. CC1310 I/Q Extraction

Since an RF wave can be essentially modeled as a sinusoidal function, the instantaneous phase, or the wave's offset from its from its origin (universally recognized as f(x) = 0, f'(x) > 0) can be more effectively determined by using the signal's real (I: In-phase) and imaginary (Q: Quadrature) components (Guerin, Jackson, Kelly 2012).



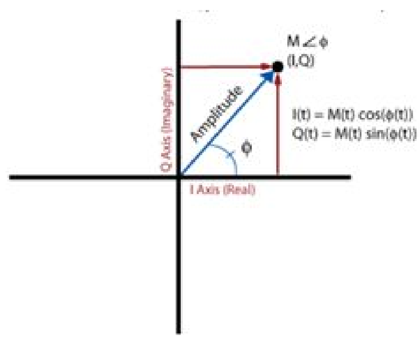


Table 1. Format of IQ Samples Stored in RAM

Byte	Bit Definition							
0	I_7	I_6	I_5	I_4	I_3	I_2	I_1	I_0
1	Q_3	Q_2	Q_1	Q_0	I_{11}	I_{10}	I_9	I_8
2	Q_{11}	Q_{10}	Q_9	Q_8	Q_7	Q_6	Q_5	Q_4

Figure 3: A radio frequency signal can be decomposed into a real and imaginary value top-right. The in phase and quadrature information can be obtained from the top-left setup. I/Q Samples are stored in RAM using 3 byte data packages (bottom).

If the I/Q data of an RF signal is received from two antennas in real time, the phase difference between these two signals can be determined by the following calculations:

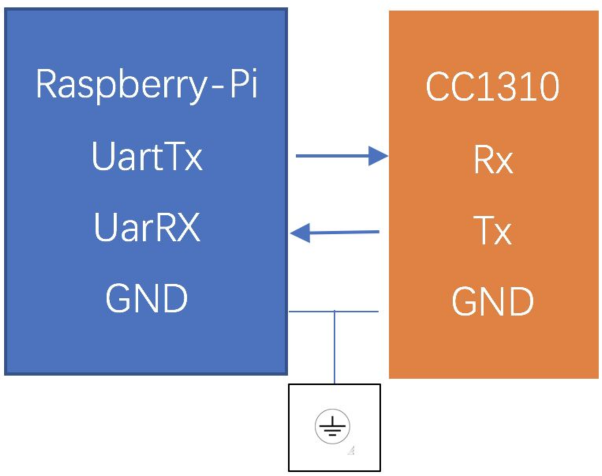
Phase angle between Signal 1 (ph2) =atan(Q/I)

Phase angle between Signal 2 (ph1) =atan(Q/I)

Phase difference = ph1-ph2

An I/Q document detailing the steps to accessing the I/Q data collected by the CC1310 can be found in Appendix A.

IV. v. CC1310 to Raspberry Pi UART Connection and Datalogging

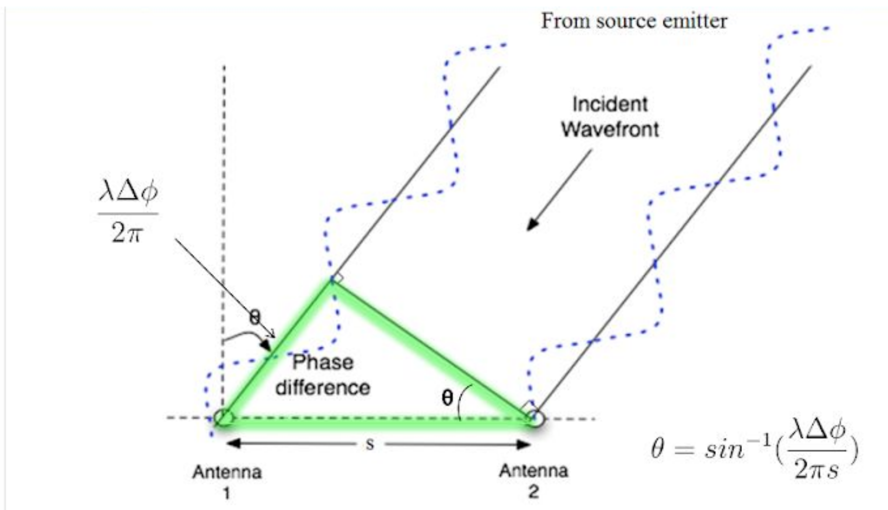


The data transfer from CC1310 to Raspberry Pi can be done through different ways. There are three major ways: Uart, SPI and I2C. SPI has the fastest data transfer rate. Uart is easiest to set up. Without knowing the maximum data transfer rate, we choose to use Uart for test purposes. We will modify our plan according to the maximum data transfer rate. For the phase 1, we will use Uart to communicate. The setup for the uart is shown in the above figure. To active Uart, we need to use three ports on both Raspberry-pi and CC1310. Both Raspberry-pi and CC1310 have those ports setuped. We need to connect both GND together to the ground. Connect Tx to Rx and Rx to Tx. The Tx stands for transmit, the Rx stands for read. For communication, Tx connects to Rx will allow the data transfer from one device to another device. Our goal for phase is transfer data from CC1310 to Raspberry-Pi.

Once we get the data from the CC1310, we will run a program on Raspberry-pi to log those data. The program to create a tag label and time label for each signal received.Then put the signal in a file. It will be convenience for user and system to track tags.Once the file is required, the Raspberry-pi will call the file.

IV. vi. Phase Disambiguation and Angle of Arrival Calculation

The phase difference between two antennas models the extra distance that a radio wave has to travel to reach one antenna over the other (Guerin, Jackson, Kelly 2012). The geometry that demonstrates this phenomenon is displayed in Figure 5, where an angle of arrival is dependent on a signal's wavelength, the separation between two antennas, and the phase difference. Using these fundamental notions of phase interferometry, the angle of arrival will be calculated at this stage using the phase differences obtained from the CC1310.



There are two types of phase disambiguation that will be covered in this section. One type of phase disambiguation results from mobile nodes that are flipped above and below the receiver's 0 degree horizontal axis reference. This will be defined as quadrant ambiguity. The second type of phase disambiguation results from antennas separated greater than $\lambda/2$ in which a phase difference is outside the $-\pi < \theta < \pi$ range. This will be defined as distance ambiguity. Distance ambiguity is not to be confused with the phase integer ambiguation that occurs when calculating differential distances from mobile to ground node as discussed in (Ma, Hui, Kan 2016).

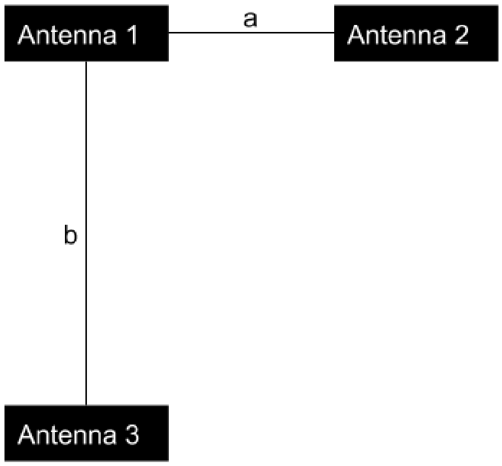


Figure 6

We propose to solve quadrant ambiguity by adding a third antenna that is placed at a right angle from the line formed by antenna 1 and antenna 2 (Figure 6). 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.

Since we are using sub-1GHz frequencies, placing the antennas at distances less than $\lambda/2$ is a feasible solution. For example, a 300 MHz signal will have a wavelength of 1 meter. So placing antennas around 0.4m < d < 0.5m from each other would not have a detrimental effect on signal gain, especially if PCB antennas are used. Frequency hopping at frequencies lower than 300 MHz will also be supported.

If the above solution is found to be infeasible, and one of the antennas is placed greater than $\lambda/2$, distance ambiguity can be solved by making distance b > distance a (Figure 6) to a suitable offset determined the signal wavelength.

This approach relies heavily on (Jackson, Guerin, Kelly 2012):

The number of phase ambiguities n is dependent on the following formula where s is the distance between two antennas and lambda is the wavelength of the signal. Theta resembles the maximum angle arrival of the system which in our case is pi.

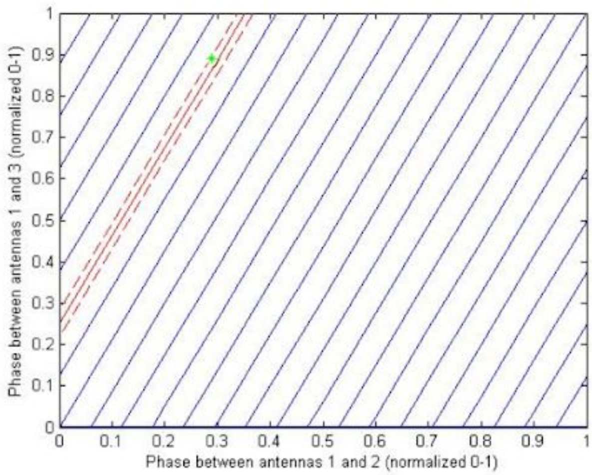
$$n = \frac{s}{\lambda} sin\theta_{max},$$

We can formulate this equation for both pairs of antennas by replacing n by the normalizing phase difference from 0 to 1 (division by 2π) added to the number of possible phase difference in each antenna pair.

$$\Delta\phi'_{12} + i_{12} = \frac{s}{\lambda} sin\theta_{AoA}$$
$$\Delta\phi'_{13} + i_{13} = \frac{s}{\lambda} sin\theta_{AoA}.$$

Finally we combine both equations to form a set of lines which correlates a disambiguated phase difference for each pair of antennas to a maximum likelihood by determining the number of full phases for a phase offset.

$$\Delta\phi'_{13} = \frac{s_{13}}{s_{12}}\Delta\phi'_{12} + \frac{s_{13}}{s_{12}} i_{12} - i_{13}.$$



We do not believe that the 90 degree offset from quadrant disambiguation will affect the geometry of this solution.

After the phase disambiguation process, error from antenna wire lengths mentioned in section IV. i. will be corrected by connecting an additional GPIO pin on the Raspberry Pi 3 to an overpowered radio transmitter equidistant to the three known locations of each antenna. From this setup, each reconstructed wave should have no phase offset from each other. If there is a phase offset at antenna 2 or antenna 3 in relation to antenna 1, that amount will be subtracted from phases collected at antenna 2 or antenna 3 respectively for future AOA calculations. This process will be repeated at a suitable rate determined through testing.

IV. vii. RF Wave Reconstruction and Matlab Simulation

Upcoming

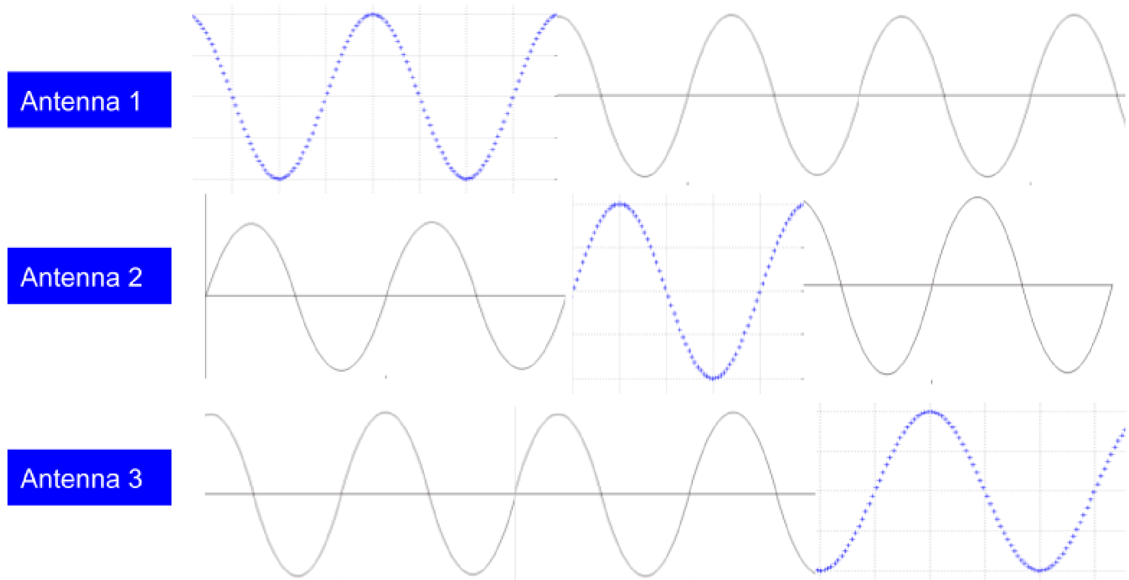


Figure 8: Blue regions represent areas that are being currently reconstructed by I/Q samples. Grey regions represent areas that continue the reconstructed signal and can be used for comparing phases to other antennas, but are not composed of collected data.

IV. viii. Raspberry Pi 3 Network with Central Hub

We will connect the Raspberry Pi 3 basestations wirelessly at a frequency outside the bandwidth of the rest of our system to prevent constructive or destructive interference. The Raspberry Pi 3 will send timestamped and identified angle of arrival measurements to a central hub/laptop at a sample rate based on the maximum speed of the animal that is being tracked. The central hub will then triangulate the position of a radio tag (based on the AOA identifications) in two dimensional space. A GUI on the central hub has been proposed to monitor the positions of different mobile nodes; however, this will likely be outside the scope of this semester's work.

IV. ix. Separate Demodulator/ADC (Plan B Solution)

Unfortunately, we have hit many roadblocks with the CC1310's I/Q extraction in the past. A report has been used as our most significant reference for debugging (Appendix A: I/Q Extraction Document Link). We found this source of information to be incomplete with the following statement, "The processing of the I/Q samples should be done outside the callback. It is not the scope of this application report to show how this can be done." The device's manufacturer, Texas Instruments, has been unresponsive to our questions regarding this issue.

If the problem persists we propose using a I/Q demodulator (with IF mixing) and an ADC that will replace the CC1310 in our block diagram. We have done extensive research on our options, and the following I/Q demodulator is very promising:

EV9700 Evaluation Kit:

http://www.cmlmicro.com/products/EV9700_Evaluation_Kit/

CMX970:

http://www.cmlmicro.com/products/CMX970_IF_RF_Quadrature_Demodulator/

The CMX970 is an ideal demodulator for its low power consumption and its integrated intermediate frequency mixing. Its in-phase and quadrature analog output signals are nicely displayed in the component's datasheet (Figure 9).

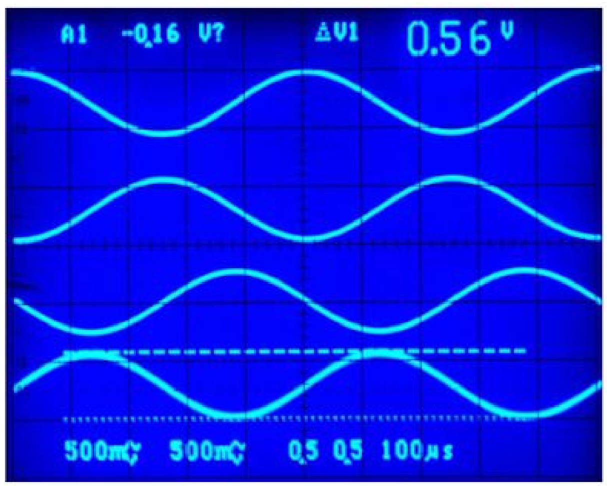


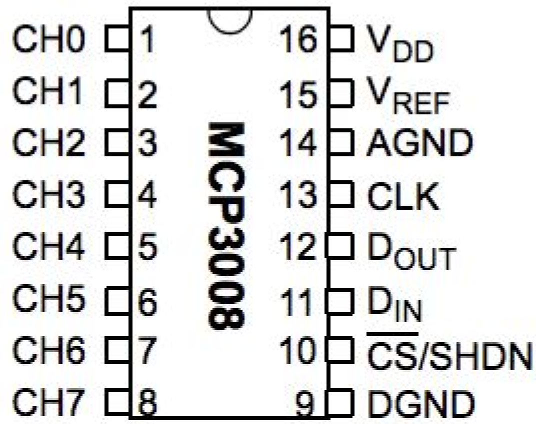
Figure 9 I/Q Output Signals

The signals, from bottom to top, are RXQ-, RXQ+, RXI-, RXI+

Since, we are still using our RF switch and reconstruction method, local oscillator synchronization will not be necessary. However, if we decide to change to a multiple channel architecture, each CMX970 has an input to an external local oscillator (each output can be connected to the same local oscillator).

After the demodulation/intermediate frequency mixing stage, we propose to use a multichannel ADC with a normal sampling rate such as the MCP3008 which has a maximum sampling rate of 200 ksps, more than enough for sampling sinusoidal functions in the KHz range (the frequency of the demodulated signal is much lower than the signal received at the antenna stage). From the ADC, the digitally sampled in phase and quadrature signals will be connected to two different GPIO pins on the Raspberry Pi. A tutorial on this can be found in Appendix A:

Since the Raspberry Pi 3 does not have a built in analog-to-digital converter, we we will use the following external analog-to-digital converter. We will use SPI to communicate from the external ADC to the Raspberry pi. The ADC's pinout diagram is shown below:

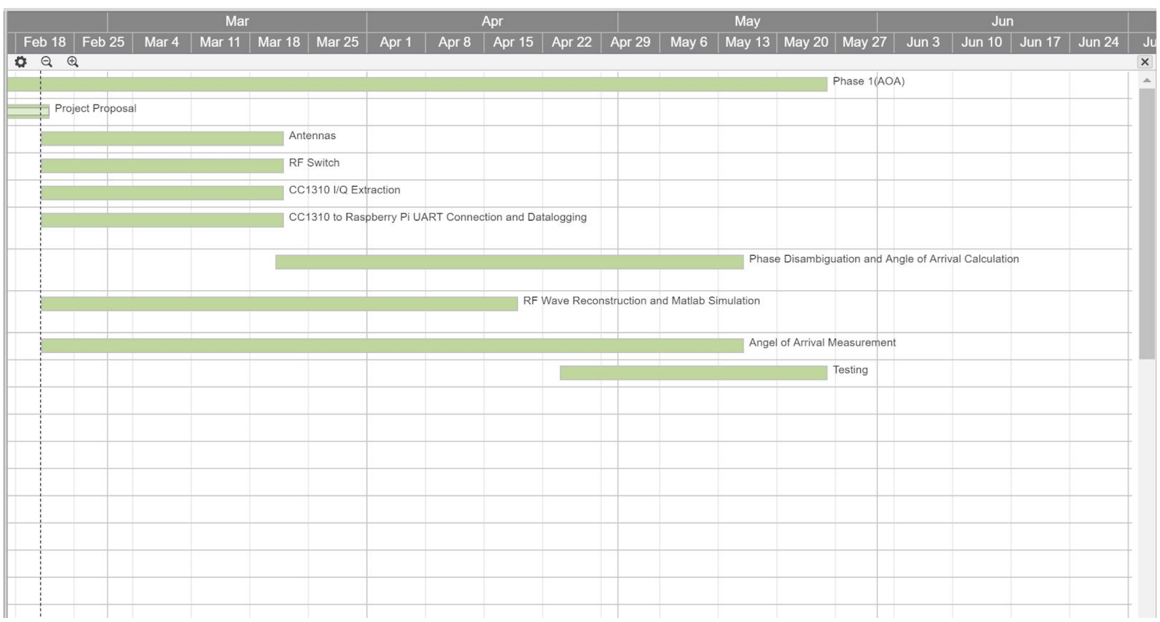


The manufacturer of the CMX970 has already been contacted, and have already expressed interest in our project/providing us with EV9700 evaluation kits for the demodulator. A PE0003 can be used to more easily manipulate the demodulator for a better signal to noise ratio through a GUI.

Project Management

Below is the proposed schedule for this semester's allocated work. Please note this is subject to change:

Task Name	Start Date	End Date	Duration	% Complete	Status	Assigned To
Phase 1(AOA)	**18-01-24**	**18-05-25**	**88d**	**8%**	**In Progress**	
Project Proposal	18-01-24	18-02-21	21d	100%	Completed	Russell Silva, Mei Yang, Justin Cray, Peidong Qi
Antennas	18-02-21	18-03-21	21d	0%	In Progress	Justin Cray
RF Switch	18-02-21	18-03-21	21d	0%	In Progress	Justin Cray
CC1310 I/Q Extraction	18-02-21	18-03-21	21d	0%	In Progress	Russell Silva
CC1310 to Raspberry Pi UART Connection and Datalogging	18-02-21	18-03-21	21d	0%	In Progress	peidong qi
Phase Disambiguation and Angle of Arrival Calculation	18-03-21	18-05-15	40d	0%	Not Started	Russell Silva, Mei Yang, Justin Cray
RF Wave Reconstruction and Matlab Simulation	18-02-21	18-04-18	41d	0%	In Progress	Mei Yang
Angel of Arrival Measurement	18-02-21	18-05-15	60d		In Progress	
Testing	18-04-24	18-05-25	24d		Not Started	
Separate Demodulator/ADC (Plan B Solution)						Russell Silva, Mei Yang, Justin Cray, Peidong Qi



Conclusion

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 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. In order to accomplish this, a low weight radio tag is being developed to transmit signals to radio basestations. These tags will transmit sub 1-GHz UHF frequencies.

References

1. Guerin, Daniel, et al. “Passive Direction Finding.” 10 Oct. 2012.

2. Ma, Yunfei, et al. “3D Real-Time Indoor Localization via Broadband Nonlinear Backscatter in Passive Devices with Centimeter Precision.” Oct. 2016,

Appendix A: Relevant Links and Tutorials

External antenna module for the CC1310:

http://www.ti.com/tool/CC-ANTENNA-DK2

RF Switch:

https://e2e.ti.com/support/wireless_connectivity/proprietary_sub_1_ghz_simpliciti/f/156/t/554880

https://e2e.ti.com/support/wireless_connectivity/proprietary_sub_1_ghz_simpliciti/f/156/p/532331/1938371

CC1310 Other:

http://www.ti.com/lit/ds/symlink/cc1310.pdf : Datasheet

http://www.ti.com/lit/an/swra571/swra571.pdf : I/Q Extraction Document

http://www.ti.com/lit/an/swra523b/swra523b.pdf : Antenna Diversity with RF Switch

http://www.ti.com/lit/an/swra495f/swra495f.pdf: CC1310 Crystal Oscillator

In Phase and Quadrature Helpful Tutorials:

http://www.ni.com/tutorial/4805/en/

http://whiteboard.ping.se/SDR/IQ

UART Setup on the Raspberry Pi:

https://www.raspberrypi.org/documentation/configuration/uart.md

Comparison of UART, SPI, and I2C:

http://www.rfwireless-world.com/Terminology/UART-vs-SPI-vs-I2C.html

Analog to Digital Conversion (Plan B):

MCP3008: https://www.adafruit.com/product/856

ADC Connection to Raspberry Pi 3:
https://learn.adafruit.com/reading-a-analog-in-and-controlling-audio-volume-with-the-raspberry-pi/overview

MCP3008(external ADC) datasheet:

https://cdn-shop.adafruit.com/datasheets/MCP3008.pdf