System for Laboratory

and

Wildlife Mouse Tracking

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

Submitted by

Nathan Shen

MEng Field Advisor: Joe Skovira

MEng Outside Advisor: Michael Sheehan

Degree Date: January 2018

Abstract

Master of Engineering Program

School of Electrical and Computer Engineering

Cornell University

Design Project Report

Project Title: System for Laboratory and Wildlife Mouse Tracking

Author: Nathan Shen

Abstract: A major challenge for wildlife radio tracking is in obtaining high-accuracy position data of multiple individuals in a population. Systems currently exist that use multiple antennas to create an estimate of location based on the received strength of a signal from three or more receiver towers. However, these systems require bulky and expensive receiver modules, resulting in imprecise location data. Our goal is to create a small (350mg), energy efficient radio tag capable of communicating with the receiver network. For this project, we propose an Angle of Arrival (AOA) based automated radio telemetry system. The basic components of the direction finding (DF) system will use 2 dipole antennas to receive radio frequency (RF) packets from radio tags transmitting at a carrier frequency of ~150 Mhz. The other aspects of this DF system include a low noise amplifier, mixer, and local oscillator (LO) to boost the received signal and mix it with the LO, an RF demodulator to enable the estimation of differences in phase between the received signals, and ADC ICs; they are all typical components of this kind of system. Our system will use the CC1310 wireless-microcontroller (MCU) attached to Raspberry Pi's to collect the RF data and run the triangulation algorithm. We present a low cost, weight, and power system that can operate in short range (100-300m), cluttered environments with high spatial accuracy (~5m) triangulation results for approximately 50 transmitters.

Executive Summary:

The System for Laboratory and Wildlife Mouse Tracking is concerned with developing a system that can track multiple small organisms in simulated and natural habitats. There are many methods currently utilized by researchers today. However, they are either highly inefficient because they animals need to be manually tracked or the tags are too big for the animal.

The aim of this project is to create a low-cost system machine-based tracking system using a microcontroller and Raspberry Pi that can analyze groups of interacting animals. With the advent of low cost active RF and microcontroller (MCU) current consumption, in addition to flexible low-power modes, we can design our own direction finding system. This requires using a radio finding (RF) architecture that can operate in short range (100-300m), cluttered environments with high spatial accuracy (~5m) triangulation results for approximately 50 transmitters.

We have proposed an Angle-of-Arrival (AOA) RF solution for a low-cost system that is currently in its first stage of development. Accomplishments made during this project include creating a communication protocol between multiple receivers and transmitters while utilizing power saving techniques. This project is planned to be completed by December 2018. This document covers all the design choices and decision made during the development.

Table of Content:

2. Second Semester: Localization

2.1 Introduction

During the summer, a group of undergraduate students helped advance my M. Eng. project. While they were testing the system within the lab enclosure, they realized that the TABER wildlife tags have a radio frequency reception range as large as a few kilometers; for the mouse system, the reception distance must be limited to within a few feet. To solve this problem, they modified the antennas by building small loop antennas with radii less than one tenth of the emitted wavelength to reduce the reception distance between the tags and the base station. However, the small loop antenna design on the tag was proven to be noneffective.

At the same time, the TABER group decided to switch from the SI1060 to TI's CC1310. The Mouse Habitat also decided to switch after being persuaded by the TABER group and Julian Kapoor, a Post-Doctorate research of animal behavior. Because of this switch, we needed to resign the radio tags that I had been working with in the previous semester. This meant that I would no longer working on the original scope of the project outlined earlier. With the approval of my M. Eng. field advisor Joe Skovira and M. Eng. Outside Advisor Michael Sheehan, I joined the Localization team lead by Julian.

The localization team consists of a total of 5 people: 2 undergraduate ECE students (Mei Yang, Russell Silva), a ECE M.Eng. Student (Peidong Qi), the team lead (Julian Kapoor), and me. We were advised by Professor Joe Skovira and Edwin Kan. Mei was tasked with developing the testing interface for the system, Russell was tasked with the RF hardware design, Peidong was tasked with the CC1310 and Raspberry Pi communication interface, and I was tasked with the mobile-node (CC1310) to ground-node (CC1310) communication protocol.

2.2 System Design

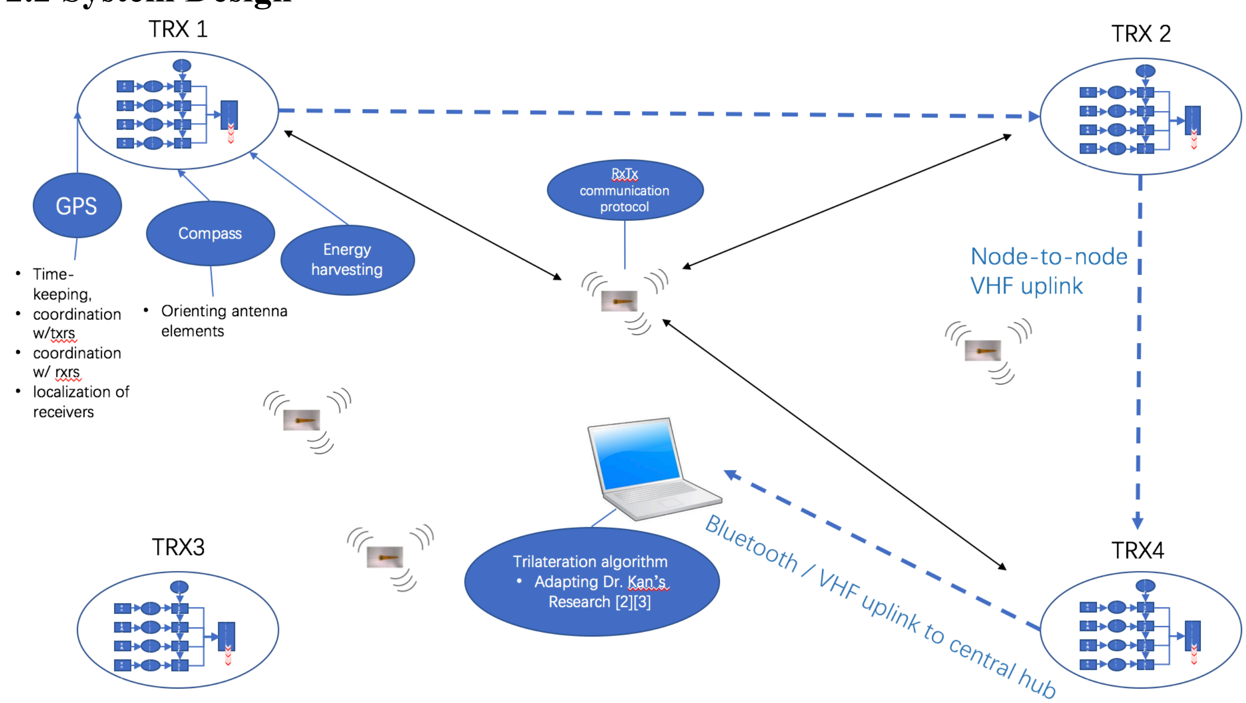

Figure 4: Julian Kapoor's proposed automated phase based telemetry receiver system [8]

A major challenge for wildlife radio tracking is in obtaining high-accuracy position data of multiple individuals in a population. There is currently automated tracking of multiple individuals from a network of receivers on stationary towers, but they suffer from several setbacks. First, most existing systems use multiple antennas to create an estimate of location based on the received strength of a signal from 3 or more receiver towers. This requires expensive receiver modules which results in imprecise location data. More recent work in automated telemetry has focused on the use of GPS technology to increase positon accuracy. Unfortunately, GPS technology is still far too large for many small organisms (such as mice) and is very expensive. Other efforts to create receiver networks have begun to develop the use of Time Difference of Arrival (TDOA) systems. Although these systems have great promise, they require more complicated transmitters and are also limited in the degree of precision they can obtain. Our proposed system uses an alternative to TDOA for radio direction finding. We use phase interferometry to estimate the Angle of Arrival (AOA) of radio signals. Unlike TDOA systems, the accuracy of AOA systems scales strongly with the spatial scale of the receiver network.

The basic components of this AOA system are shown in the Figure 5 below. The direction finding (DF) aspect of the receivers that we are hoping to develop will use 2-4 dipole antennas to receive RF packets from radio tags transmitting at multiple carrier frequencies in the Sub-1Ghz spectrum. The use of low frequencies for transmissions means that estimating the phase of signals may be very difficult with relatively closely-spaced antennas (<< 1 wavelength). We will employ techniques found in [2][3] to solve this problem. Other aspects of this DF system include a low noise amplifier (LNA), mixer, and local oscillator (LO) to boost the received signal and mix it with the LO, an RF demodulator to enable the estimation for difference in phase between the received signals, and ADCs.

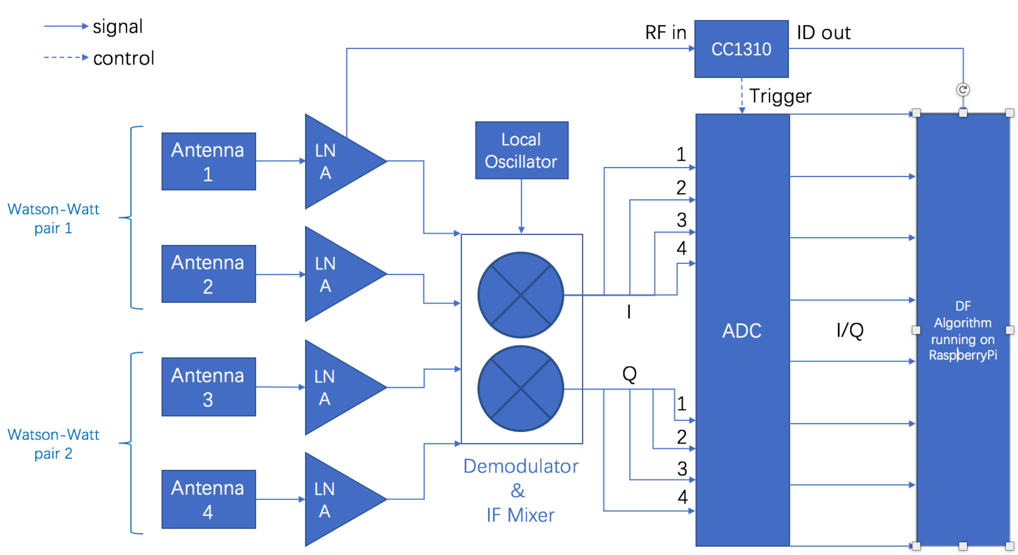

Figure 5: Initial Angle of Arrival (AOA) System Architecture

Because the tags must be extremely small, we will have to consider the possibility of energy-harvesting solutions like those developed by TABER [6] to extend battery life. Also, because transmitting data will require that the transceiver IC be in active mode, it will be important that the tags transmit only when the receiving transceiver is within range (meaning the tag must be able to listen for a targeted wake-up command from it).

Requirements and constraints:
1. Short range (100-300 m between receivers)
2. Extremely simple transmitter design (lightweight, low power)
3. System can operate in cluttered environments (multipath interference)
4. System can operate with ~50 Txers
5. High spatial accuracy (~5 m) triangulation results
6. Low cost receivers (COTS components)
7. Low power consumption of receivers

2.3.1 Radio Finding System Design

One of the big challenges with a new project is understanding and designing a new system and figuring out the constraints. We began our approach with the help of Dr. Kan's existing indoor localization [2][3]. For example, many terms and concepts we will need to understand well to move forward are triangulation vs. trilateration, phase cycle integer ambiguity, coherent detection, digital beamforming, heuristic optimized sparse multi-frequency ranging and why it can help resolve phase cycle integer ambiguity. After much discussion and debate, we decided to proceed with the following architecture for our radio finding system:

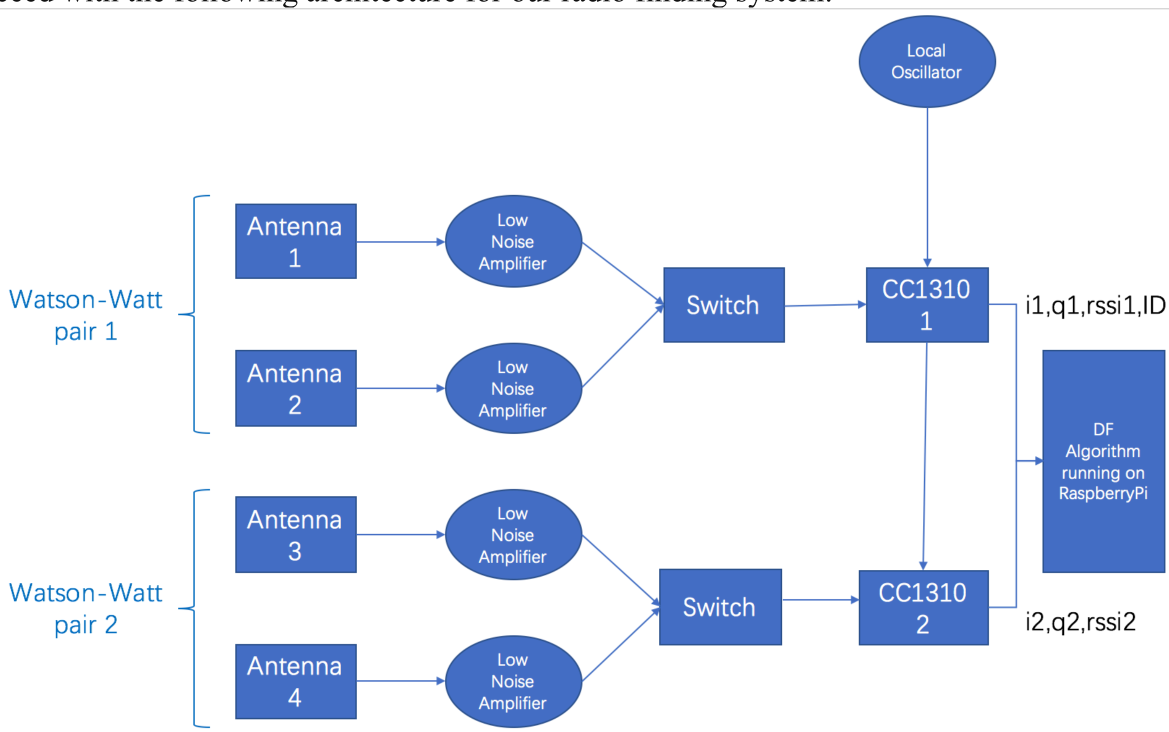

Figure 6: Proposed RF system architecture

We employed techniques found in [2][3] to come up with our system. Because we can extract I and Q data from the CC1310, it simplifies our design by not needing to include a Low-Noise Amplifier, ADC, Demodulator, or IF Mixer. We are taking an RF switch-based approach to receiving phase-difference information on two antennas with one CC1310. By using this approach, we can split the signal into two in-phase signals, feed them into the CC1310, and then create code to read the I and Q data into two buffers (one for each channel), calculate phase differences, and compare against the ideal of zero-degree phase offset.

2.4.3 Mobile-node to ground-node Protocol

As mentioned earlier, because the tags are solar powered, we will have to account for energy consumption. While in active mode, MCU's such as the CC1310 that we are using, consume a lot of power. Therefore, we need to take advantage of sleep mode but we need to also make sure that we do not miss a tag by oversleeping.

Another concern is transmitting and receiving signals so that multiple tags do not interfere with each other. To solve this problem, we developed a similar protocol to time-division multiplexing (TDM) which is a method of transmitting and receiving independent signals by means of synchronized switches at each end of the transmission line so that each signal appears on the line only a fraction of time in an alternating pattern.

The protocol is as follows:
Mobile nodes should sleep just under 5 s (ensuring they will hear a ground node transmission at least once if it is in range), then wake long enough to receive a single countdown signal from a ground node. Once they have received a countdown signal, and the checksum demonstrates a good link, update global time (it will have drifted over the last 5 min), then listen for rest of commands. Once commands received use global time, received command, and (assuming the command includes a simple transmit instruction) pre-programmed transmission time delay to send ID during the ground node's ~5 min RX period.

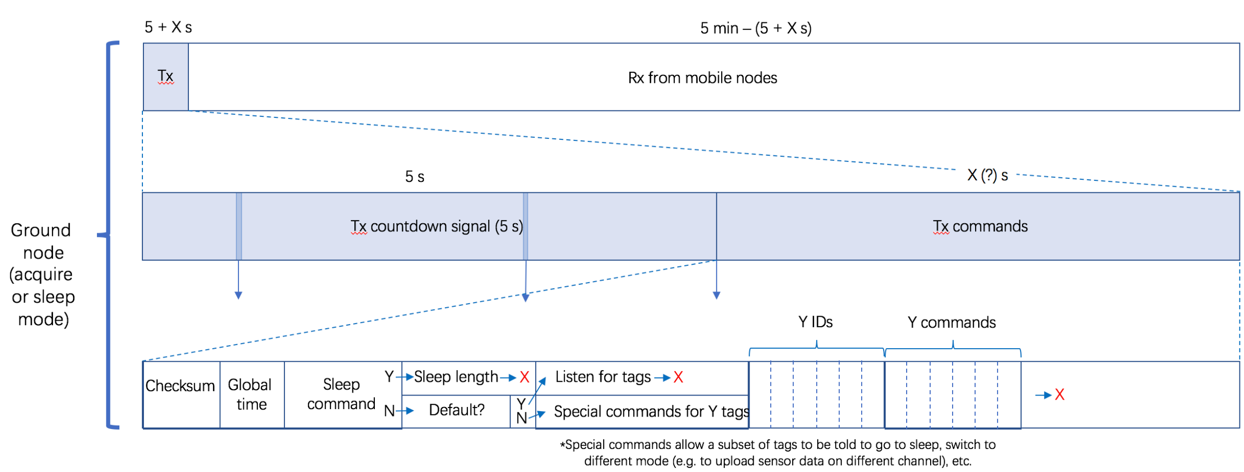

Figure 8: Mobile-Node to Ground-Node Protocol

2.5 Implementation

The following code is adapted from CodeComposerStudio's Resource Explorer [4] to fit the design of our system. The codes were used with minor parameter changes to investigate the capabilities of the devices and are included here to emphasize what sample elements were used for this initial testing. The following text is provided from TI's documentation and README files [4].

2.5.1 rfWakeOnRadio

This example uses the Wake-on-Radio functionality of the CC1310 to significantly lower the power consumption of an RF link. It shows how to use the RF Driver to schedule automatic wake-ups in the future and do a Carrier Sense as quickly as possible using RSSI and Preamble Quality (PQT).

Below is a typical radio physical layer packet format:

```
| Preamble  | Sync Word | Length Byte | Payload |   CRC   |
-----------------------------------------------------------------
|  4 byte   |  4 byte   |   1 byte    | X bytes | 2 bytes |
```

The preamble is usually set to a repeating 10101010 pattern, as the beginning of the packet is used for several purposes in a modern radio. This usually involves settling the Automatic Gain Control, estimating frequency error etc. In addition to this, it can also be used for detecting the presence of a signal.

If we use the preamble to detect the presence of a signal, then the receiver must wake up often enough to not miss the preamble. This means that the length of the preamble directly affects how often the receiver must wake up. At 50kbit/s 2-GFSK a 4-byte preamble is only 650 us long. This means that to not miss a packet, the receiver would have to wake up more than 1500 times per second. This is generally not a feasible solution, and does not save a lot of power. If we instead configure the transmitter to send a 100ms long preamble, this means that the receiver only must wake up 10 times per second to be guaranteed to receive the packet. This increases the latency in the system, but significantly reduces the average power consumption. In this Wake-on-Radio example, the default setting is to send a 500ms preamble and so wake up approximately two times per second to check for it.

There are generally two ways to check for the presence of a signal on the air with a receiver. One is to check the Received Signal Strength Indicator (RSSI) which simply indicates the energy received. The other is to check for the presence of a valid preamble and check the Preamble Quality (PQT). RSSI is usually quicker to check, but also gives less information. How long it takes to get a valid RSSI read to compare against a given threshold depends mainly on the configured receiver bandwidth. The information you get from an RSSI reading is only that there is a signal present, it gives no qualitative information. PQT takes a bit longer to check than RSSI. The main reason being that the receiver must receive a certain number of symbols before it can look at the received data and check that it does indeed look like a valid preamble. How long this takes mainly depends on the symbol rate. It is also possible to check both RSSI and PQT. In that case, one would normally first check RSSI, preferably at the sensitivity level, and then if the RSSI is above it, check for PQT.

To run the code:

- Run the example on one of the boards above, this will be the RX board. Board_LED0 will blink on this board for every wakeup. By default, the example is set up to wake up two times per second, so every 500ms.
- Start the rfWakeOnRadioTx companion example on another board (TX board) and press Board_BUTTON0 on that board to send a packet.
- Board_LED1 on the RX board should now toggle for every button press.
- The wakeup interval is set using the WOR_WAKEUPS_PER_SECOND define at the top of the rfWakeOnRadioRx.c file. This needs to be the same in both the RX and TX part of the Wake-on-Radio example.

2.5.2 rfListenBeforeTalk

This code illustrates how to implement a simple listen before talk(LBT) algorithm using command chaining.

When sending a packet, the radio first enters RX mode using CMD_PROP_CS. If the channel is IDLE (the RSSI is below RSSI_THRESHOLD) for IDLE_TIME_US, the radio enters TX and transmits a packet. If the channel is BUSY (RSSI above RSSI_THRESHOLD), the radio enters RX again to check the channel once more. This is repeated max CS_RETRIES_WHEN_BUSY number of times. The command chain will either finish with a packet being sent (if the channel is IDLE), or after checking the channel CS_RETRIES_WHEN_BUSY times.

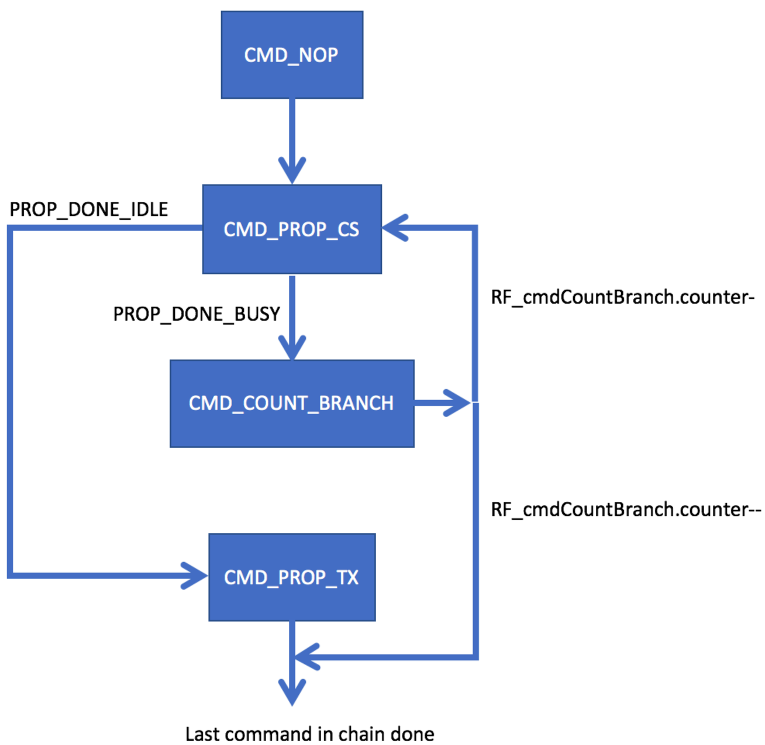

Figure 9: Control Flow of rfListenBeforeTalk (adapted from [4])

2.6 CC1310 Launchpad

To aide our development, we were given 2 CC1310 Launchpads. This gives us access to the integrated development environment (IDE) for development and rapid prototyping. A benefit of this launchpad is the availability of Sub-1GHz radio for wireless applications and an integrated PCB trace antenna.

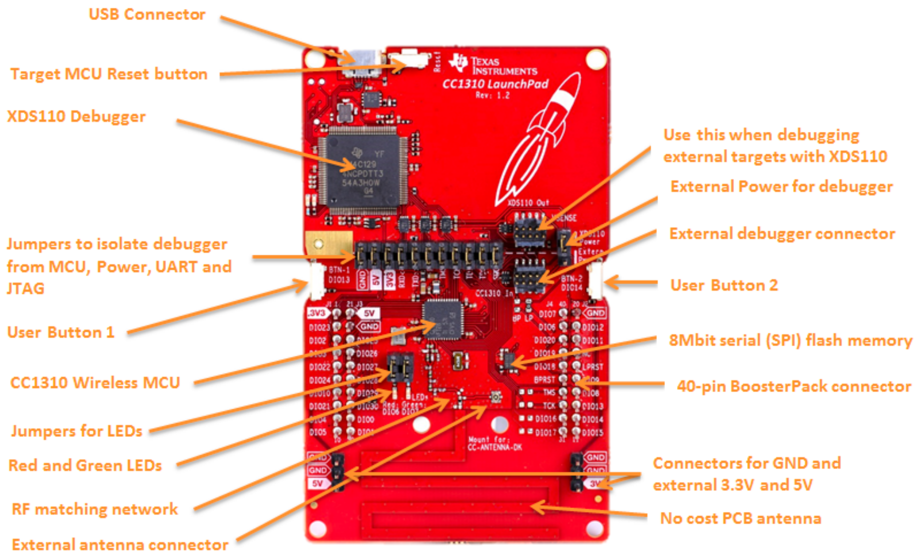

Figure 9:CC1310 Hardware Description [5]

3. Conclusion

My M.Eng. project can be divided into two parts. I first began with the goal of adapting the existing TABER system [6] for the requirements for a laboratory based mouse habitat. I made progress towards this goal and by the end of the first semester. Achievements including porting software from the Raspberry Pi 2B to the Raspberry Pi3 and having 2 client Raspberry Pi sending tag data over to a single server Raspberry Pi. During the summer, a couple of undergraduates advanced my project but ran into a problem with reception distance; the base stations were recording tag data from too large of a reception range. In parallel to the development during the summer, the TABER group decided to switch from the SI1060 to the CC1310.

The second part of my M.Eng. project started when I came back for the second semester. I transitioned onto the Localization team lead by Julian Kapoor. The reason for this transition is due to the lack of future support of the system by TABER as well as the difficulties of our previous system that was discovered during the summer. This team's goal is to create a telemetry system that can obtain high-accuracy position data of multiple individuals in a population. I was tasked with the mobile-node to ground-node communication protocol. Achievements include adapting the baseline rfWakeOnRadio and rfListenBeforeTalk code for our system as well as working with the team to draft up preliminary system design for our radio finding hardware.

4. Future Work

The localization team expects this project to be completed in one to two years and has laid out four milestones. For the first milestone, we want to be able to calculate an Angle of Arrival (AOA) from a received signal. The second milestone involves beamforming to calculate a direction from the signal. Milestone 3 is where we calculate the range of the signal. Lastly, milestone 4, consists of completing any further refinements to our system. This project is still in stage one of development that is scheduled to be completed by the end of Spring 2018.

5. References

[1] Weissbrod, Aharon et al. "Automated Long-Term Tracking And Social Behavioural Phenotyping Of Animal Colonies Within A Semi-Natural Environment". *Nature Communications* 4 (2013): n. pag. Web. 18 May 2017.

[2] Y. Ma, X. Hui and E. C. Kan, “3D real-time indoor localization via nonlinear backscatter in passive devices with centimeter precision,” ACM MobiCom, New York City, NY, Oct. 2016.

[3] Y. Ma and E. C. Kan, “Passive ranging by low-directivity antennas with quality estimate”, IEEE MTT 2015 International Microwave Symp. (IMS), Pheonix, AZ, May 18 – 22, 2015.

[4] CC13x0 Proprietary RF User’s Guide:
http://dev.ti.com/tirex/content/simplelink_cc13x0_sdk_1_30_00_06/docs/proprietary-rf/html/cc13x0/index.html

[5] CC1310 Description and Features
http://www.ti.com/tool/LAUNCHXL-CC1310

[6] Taber Work:
https://courses.cit.cornell.edu/ece6930/ECE6930_Spring16_Final_MEng_Reports/Bird_Tag_Team/Bird_Tags.pdf

[7] RPi TCP/IP Communication Tutorial
http://www.python-exemplary.com/index_en.php?inhalt_links=navigation_en.inc.php&inhalt_mitte=raspi/en/communication.inc.php

[8] Localization Github
https://github.com/jakapoor/AMRUPT