RADIO FREQUENCY INTERFERENCE DETECTOR

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Abstract

In this report, we detail our steps of building our Radio Frequency Interference (RFI) Detector throughout this semester. To do this, we used knowledge of bandpass filter design along with a microcontroller to produce a handheld product that tells the user if a cell phone is on in the immediate area. We begin with our project's objective and block diagram. The design process and decisions we made during testing that impacted our verifications follows this. Lastly, we end with addressing the cost, our conclusions about the device, and then our ideas for future work.

Contents

1 Introduction

1.1 Objective

The idea for our project was given as a pitch by researchers from the Arecibo Observatory in Puerto Rico at the beginning of the semester. The observatory uses antennas to measure radio frequency (RF) energy so that they can gain knowledge about space and the atmosphere. The collection of this data is very sensitive to outside interference, one example being cell phones, which transmit energy with output powers between 0 and 30 dBm [1]. Knowing this, the observatory asks its visitors to turn off or put their cell phones on airplane mode due to the interference they can cause. Not every visitor complies with this wish, so we set out to build a device to help the employees deal with this problem. Our device is a Radio Frequency Interference (RFI) Detector. With this device the employees of the observatory can ask the visitors to turn off their cell phones, then using our device, check to see if everyone complied with their policy.

Our original design was close to our final product. There were no major overhauls that we had to perform. We did add a number of components to increase the stability and safety of our circuit, including a fuse, diode and a thermistor. An extra voltage regulator was decided on later as we needed a better reference than the internal one supplied by our microchip.

1.2 Review of High Level Requirements

1. Device must be able to properly sense an RF signal with transmit power above for frequencies 704-849 MHz and 1710-1915 MHz.

2. Device correctly detects presence of these interfering signals from up to 1 meter away and displays the results of the detection.

3. The device should be hand-held for use by on-site personnel.

2 Design

2.1 Block Diagram

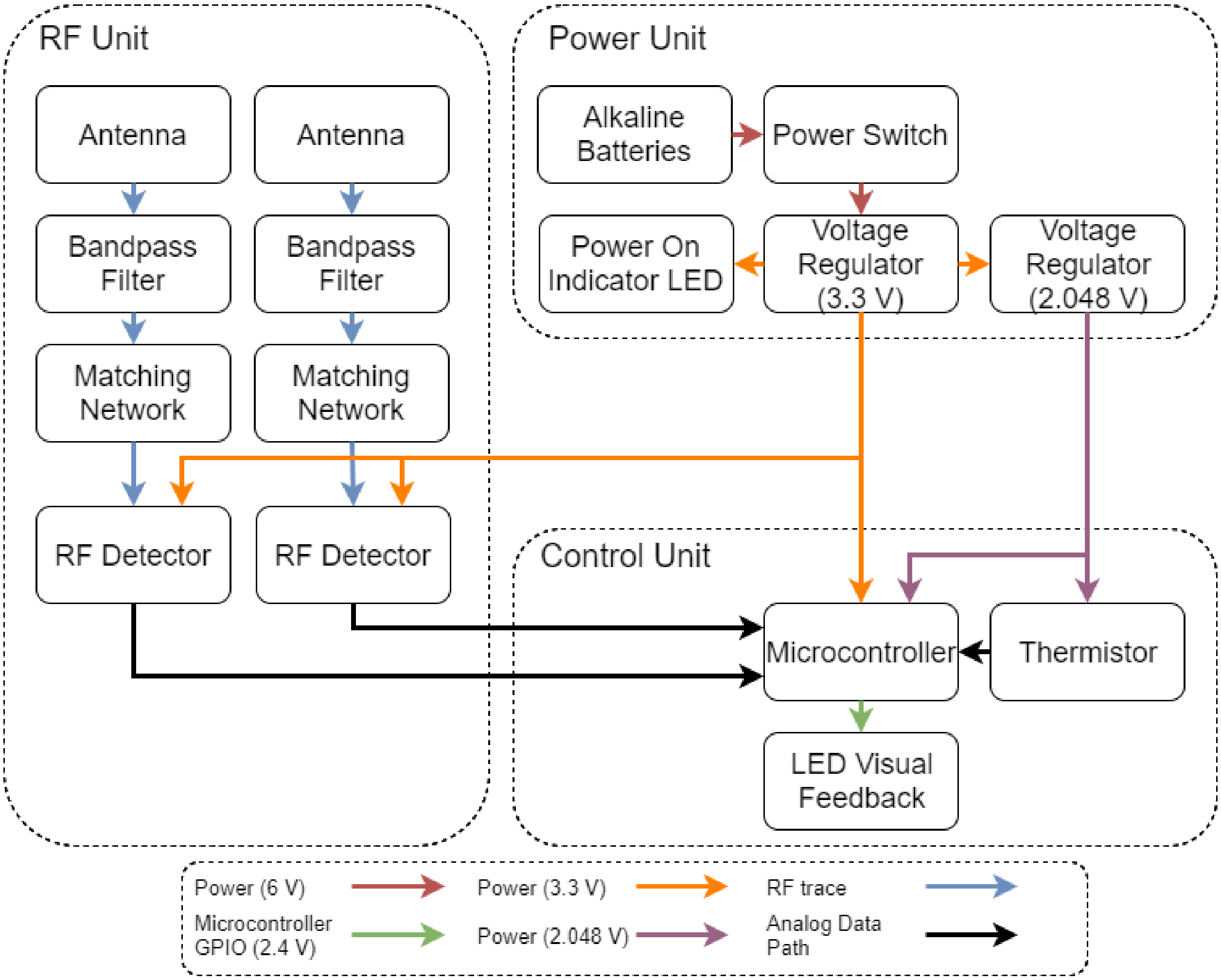


Figure 1: Block diagram for RFI detector

Power Unit: The supply voltage from our batteries is 6 V. This is then stepped down twice using two voltage regulators. This first steps the voltage down to 3.3 V to be used to power the ATmega328P chip and the RF detectors. The second steps it down further to 2.048 V to be used as a reference voltage for the ADC inputs from the RF detectors. It also includes a yellow LED to indicate that the device is on.

Control Unit: The ATmega328P chip is programmed using the Arduino IDE to allow it to interpret the data that it is receiving from the RF detectors and the thermistor. The thermistor allows us to check if the device is overheating and turns on an orange LED to tell the user to turn the device off. The other two LEDs (green and red) indicate whether a cell phone is active in the area or not.

Radio Frequency Unit: Two antennas receive the surrounding RF energy. The signals received are passed through bandpass filters designed to only allow cellular frequencies used in Puerto Rico. After this stage, the power of the signals are measured by RF detectors. From there those signals are sent to the control unit for interpretation.

2.2 Power Unit

2.2.1 Alkaline Batteries

We used a four-cell battery pack to power our device. With these batteries we were able to get a voltage draw of 6V. We chose to use alkaline batteries for a variety of reasons. The first being that they provided a stable input voltage for a long time: each battery contains 2800 mAh [2] for use by the circuit. Using the battery pack that we did gives the user the chance to replace dead batteries easily and ensure a longer lifespan of the device as a whole. The reason we chose to begin with 6 V is that our first voltage regulator required at least 5.3 V input based on our reading of the datasheet. This means that the starting voltage had to be greater than this even after passing through a diode to prevent charging of the batteries. Choosing alkaline batteries limited our options to multiples of 1.5 V, so we chose the closest one greater than 5.3 V.

2.2.2 Switch

The switch controls when power can flow from our batteries to the rest of our circuit.

2.2.3 Voltage Regulators

Our design had two voltage regulators. This first was a 3.3V linear voltage regulator (LD1117SOT-223). This regulator was used to power the ATmega328P chip in the control unit and the two RF detectors in the RF unit. We chose the LD1117 over other options because it had a wider range of input voltages that could still be stepped down to a constant value [3].

Figure 2 shows the circuit design of the LD1117 voltage regulator. When we compare this with Fig 22 in Appendix A, we changed the input coupling capacitor in our design to a higher value. This change helps hold our input value constant without affecting the actual operation.

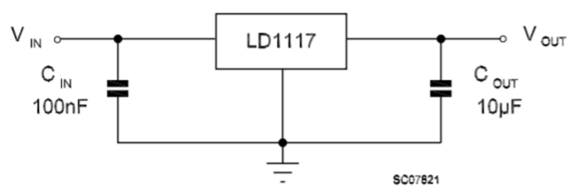


Figure 2: 3.3 V Voltage Regulator Circuit from Datasheet

The second voltage regulator was a 2.048 V reference voltage regulator (ADR3420). This chip had low power consumption and held a useful output. By choosing such a specific number, we were able to get fidelity of 2 mV per each number in our ADCs, which assign the voltage a number between 0 and 1023.

Figure 3 shows the circuit diagram for the ADR3420 voltage regulator. This was a general diagram from the datasheet [4]; ours specifically holds a different output voltage.

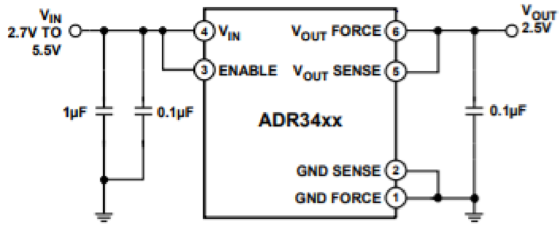


Figure 3: 2.048 V Voltage Regulator Circuit from Datasheet

2.2.4 Power Indicator LED

This LED is connected directly to the power source. It should always see power as long as the switch is on, so if the LED is off, it is a good indicator to the user that the batteries may be dead.

2.3 Control Unit

2.3.1 Microcontroller

We chose to use the ATmega328P microchip as our microcontroller in the control circuit. The benefits of this chip that we were able to take advantage of included multiple 10-bit analog-to-digital converters (ADCs), multiple I/O pins that we could control the output of, the ability to set our own reference voltage and the synergy with the Arduino development environment [5]. This last one was especially important, as it allowed us to upload the code onto the chip using an Arduino Uno development board and then transfer the chip into our circuit. It also gave us the resources of the vast Arduino library of functions and support. During testing we had to constantly modify code to get all systems working, so being able to remove the chip from our circuit was vital. This was the biggest advantage over the other microcontroller we looked at: the LPC2131. While it also contained 10-bit ADCs and ran at a slightly higher clock rate, it could not be mounted onto a socket to be removed for programming.

The code used in the device was pretty straight-forward. Using a single loop statement we were able to read in data from the ADCs, run checks on the data and make decisions of which LED to light up, then repeat. We take multiple samples from the ADC consecutively, then average these values together to avoid random noise triggering the DETECT state. The method of assigning a voltage a digital number is given in Equation 1.

$$\frac{V_{in}}{2.048} = \frac{NumberAssigned}{1023} \tag{1}$$

Over the course of the loop, we transfer this average to two different pass state variables so that we are holding three sets of averages at any given point in time. When all three of these values are higher than the threshold set by us, the red LED is activated, the green LED is deactivated and we enter our count loop. The code is located in Appendix D for a more detailed look at how this operates. The count checks again to see if there is RF detected. If there is, the counter is reset to keep the red LED on. If there is nothing detected at that point in time, then the timer is incremented. In this way, we give the user enough time to confirm that they are in the presence of an RF-emitting device and there are no questions about false positives. The ADC connected to the thermistor sub-circuit operates similarly, where data is taken in and

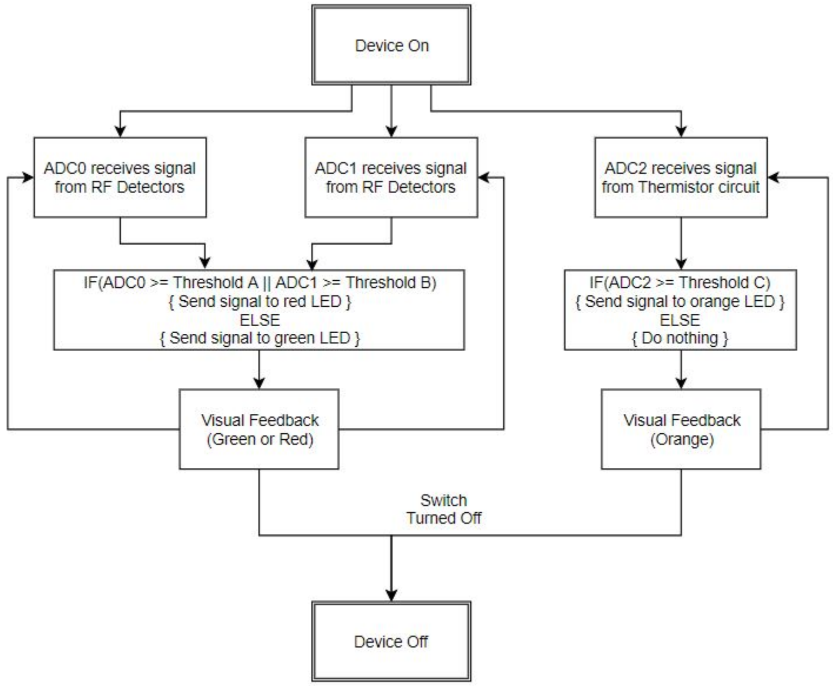


Figure 4: Logic Diagram used by Microcontroller

compared to a threshold once every second. We slowed this process down as it is not as time sensitive and it eases strain on the amount of processing time required per loop. Fig. 4 shows a good overview of the logic.

2.3.2 Thermistor

The thermistor sub-circuit was added to our design as a safety feature. The thermistor acts as a temperature dependent resistor. Using this component, we can monitor the internal temperature of our device by reading the change in resistance of the thermistor. The circuit is shown in Fig. 5. Using a potential divider circuit we can feed data into the microcontroller using the third ADC in our design. The variable V_{out} shown is our value of interest. At room temperature, the thermistor is a 1 kΩ resistor. As the temperature rises, the resistance rises as well. Fig. 6 shows the curve given by the products datasheet. Through research we found that the internal safe temperature limit is about 85 degrees Celsius [6]. Using this number and Fig. 6 we selected 81 degrees to be our cutoff, as it resulted in a close approximation of 1.5 kΩ. Using the equation shown in Fig. 5 we can solve for the value of V_{out} where it become dangerous for our circuit, shown in Equation 2.

$$2.048\left(\frac{1.504}{1.504+1}\right) = 1.23V = V_{out} \tag{2}$$

With this in mind, we can convert to a digital number using Equation 1 to find the threshold we use in the code. We then run the loop shown in Fig. 4 about once every second to check the temperature around the thermistor and alert the user if there is any problem.

2.3.3 Visual Feedback LEDs

We have three visual LEDs. The first is a green LED indicating that the device does not detect a cell phone signal in the area. The second is an orange LED which indicates that the thermistor is seeing an unsafe

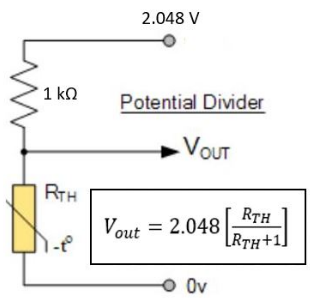


Figure 5: Thermistor Sub-Circuit Schematic

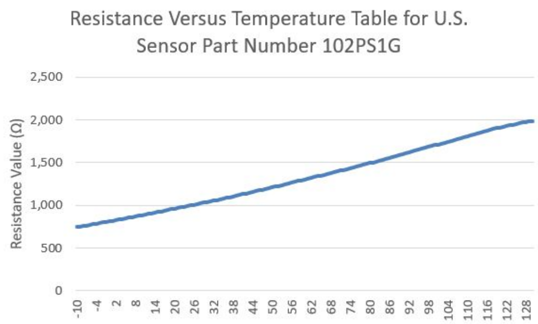


Figure 6: Thermistor Resistance Values

temperature value and the user needs to turn the device off. The third is a red LED indicating that the device detects a cell phone signal in the area. We chose them as they all light up with a 2 V operating voltage, which is below the I/O pins reported output.

2.4 RF Unit

The frequency bands used in Puerto Rico are given in Table 1 [7]. We condensed these down into two larger bands, which we designed the RF detection around. Table 2 shows the two frequency bands we used in our design. For the remainder of this report, the 704-849 MHz band will be called the "lower band", and the 1710-1915 MHz band will be called the "upper band". Figures 24 and 25 in Appendix A show the RF circuit schematic and printed circuit board (PCB) layout.

Technology	**Frequency (MHz)**
LTE B17	704-716
LTE B13	777-787
UMTS B5 850	824-849
GSM 850	824.2-848.8
LTE B4	1710-1755
UMTS B4 (1700/2100 AWS 1)	1710-1755
UMTS B2 (1900 PCS)	1850-1910
GSM 1900 (PCS)	1850.2-1909.8
LTE B25	1850-1915

Table 1: Frequency Bands of Cellular Phones in Puerto Rico

Band	Frequency (MHz)
Lower	704-849
Upper	1710-1915

Table 2: Frequency Bands of Receive Paths

2.4.1 Antennas

The antennas serve to pick up radiated energy that exists around the device. We chose to use two cellular whip antennas that provide 40-50% efficiency [8] for the frequencies we want to detect. The antennas are advertised to be matched to 50 ohms, which is the reference impedance of our circuit. These antennas are mounted by SMA, which lends itself to being easily mountable to the edge of the RF PCB. Purchasing antennas allowed us to focus on the design of other components, as well as being assured we would get good performance out of a critical portion of the RF unit.

Alternatively, we could have designed the antennas ourselves. We looked into microstrip patch antennas and microstrip line antennas. Patch antennas are easy to design and simulate, however they would have been large and would not have had the bandwidth we required. Microstrip line antennas can be quite complex to design, so we ultimately decided to use pre-built antennas.

2.4.2 Bandpass Filters

At the beginning of the project, we decided to build the two bandpass filters using lumped elements. These filters consist of inductors and capacitors with values that allow the frequencies of interest to pass through, while unwanted frequencies are heavily attenuated. Lumped element filters are small, cheap to produce, and allow tunability by swapping out parts after the filter is constructed. The first bandpass filter is designed for 704-849 MHz, and the second filter is designed for 1710-1915 MHz.

We also considered microstrip coupled-line filters. These are bandpass filters made entirely of PCB traces in microstrip form, which means there is always a ground plane underneath the copper trace. These filters can be quite large and difficult to maneuver on a PCB. However, they are less susceptible to manufacturing issues as they can be very accurately modeled in Momentum, an electromagnetic simulation tool in Keysight's Advanced Design System (ADS).

During the design and testing process, we encountered several issues with the bandpass filters. The first version of the lumped filters were 2nd order maximally flat filters and did not account for parasitics of the components. Neither filter exhibited a filter shape, and the amount of loss rendered them useless. After redesigning the filters as 3rd order filters while modeling the parasitics of each component, we found that the lower band filter performed much better, although it was 200 MHz off of the desired center frequency. Through trial and error, we were able to swap out some components until the lower band filter captured the entire lower band. The upper band filter still did not work, so we decided to switch to a microstrip filter.

A lumped element bandpass filter can be designed using a lowpass filter prototype. The lower band filter is a third order maximally flat filter, which has the general circuit form shown in Figure 7. Component values are determined by lowpass to bandpass transformation equations [9]

$$L_{shunt} = \frac{1}{g_n}\frac{\Delta R_s}{\omega_0}$$

$$C_{shunt} = g_n \frac{1}{\omega_0 \Delta R_s}$$
$$L_{series} = g_n \frac{R_s}{\omega_0 \Delta}$$
$$C_{series} = \frac{1}{g_n} \frac{\Delta}{\omega_0 R_s}$$

where $\omega_0 = 2\pi\sqrt{f_2 f_1}$, the center frequency of the filter. Δ is the fractional bandwidth of the filter given by $\frac{f_2 - f_1}{f_0} = \frac{849-704}{\sqrt{(849)(704)}} = 0.1876$. R_s is the reference impedance of the system, which is 50 ohms. The values of g_n are based on lowpass filter prototype values shown in Table 3 [10]. For our filter, the results of the calculations are shown in Table 4.

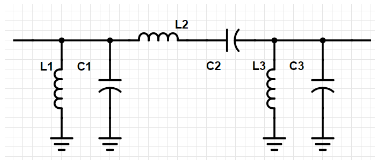


Figure 7: 3rd order bandpass filter form

g_1	g_2	g_3	g_4
1.0000	2.0000	1.0000	1.0000

Table 3: Lowpass filter prototype values for 3rd order filter

	L_1	C_1	L_2	C_2	L_3	C_3
Value	1.93 nH	21.95 pF	109.74 nH	0.39 pF	1.93 nH	21.95 pF

Table 4: Coupled line impedance calculations

We learned after the first PCB fabrication that it is necessary to model parasitics for components. Inductors have parallel parasitic capacitances and series resistance. Capacitors have series parasitic inductance and resistance. Data sheets for inductors provide the self-resonant frequency as well as maximum loss. Capacitor data sheets provide the self-resonant frequency as well as equivalent series resistance. These values allow us to model the parasitics of each component. After doing so, we tuned our inductor and capacitor values until we achieved the desired filter simulation. We also made sure our component values were actually purchasable. Figure 8 shows the ADS circuit schematic where the parasitics are modeled. The boxed in components represent parasitics, while the other components are the actual parts used on the board. Figure 9 shows the ADS simulation, where we see there is less than 3 dB of loss within the passband, and our 30 dB shape factor is

$$SF = \frac{30\,dB\,bandwidth}{3\,dB\,bandwidth} = \frac{1063-531}{849-704} = 3.67.$$

To design a microstrip coupled line filter, we first start with a lowpass filter prototype. The element values for a third order filter are shown in Table 3. We use these values to calculate the even and odd mode impedances of the coupled lines. We first calculate the normalized impedance of each section [10].

$$Z_0 J_1 = \sqrt{\frac{\pi\Delta}{2g_1}}$$

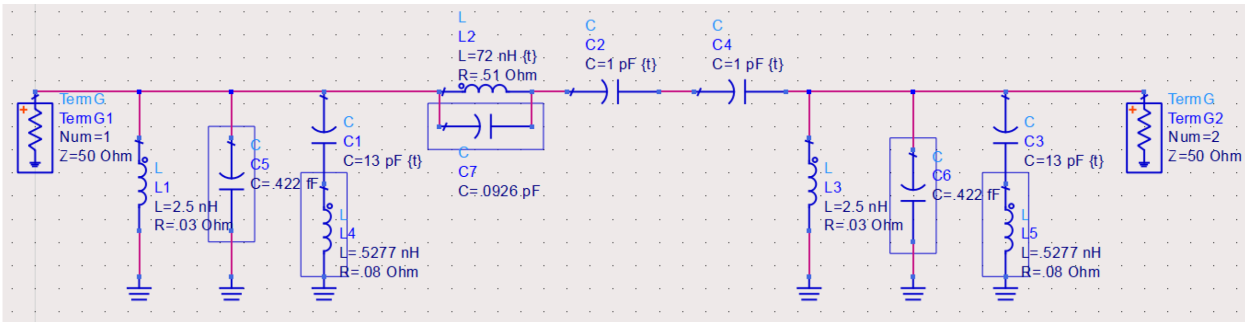


Figure 8: Lower band filter with modeled parasitics

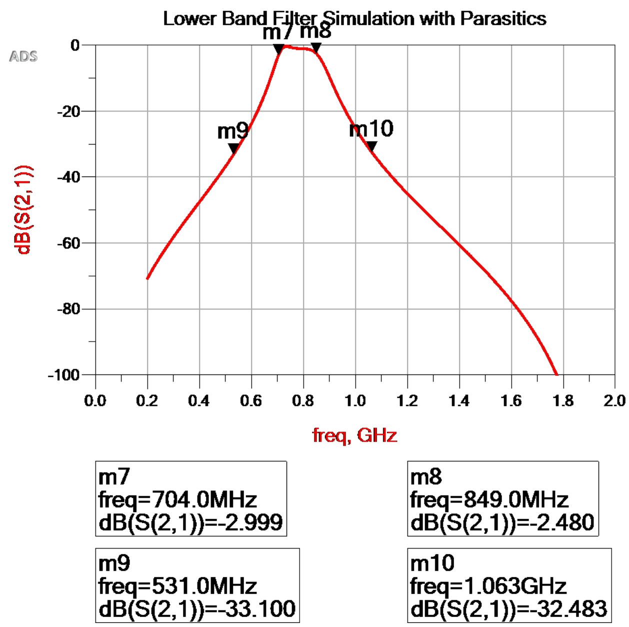


Figure 9: Lower band filter simulation

$$Z_0 J_n = \frac{\pi\Delta}{2\sqrt{g_{n-1}g_n}} \text{ for } n = 2, 3, ..., N$$
$$Z_0 J_{N+1} = \sqrt{\frac{\pi\Delta}{2g_N g_{N+1}}}$$

Where Δ is again the fractional bandwidth of our filter. Then we use these values to calculate the even and odd mode impedances for each section.

$$Z_{0even} = Z_0[1 + JZ_0 + (JZ_0)^2]$$
$$Z_{0odd} = Z_0[1 - JZ_0 + (JZ_0)^2]$$

As an example, we will show the calculations for the first section where $n = 1$, $N = 3$, and $Z_0 = 50$.

$$\Delta = \frac{1915MHz - 1710MHz}{\sqrt{(1915MHz)(1710MHz)}} \approx 0.12$$
$$Z_0 J_1 = \sqrt{\frac{\pi 0.12}{2(1.0000)}} = 0.434$$

$$Z_{0even} = 50[1 + 0.434 + (0.434)^2] = 81.13\Omega$$
$$Z_{0odd} = 50[1 - 0.434 + (0.434)^2] = 37.72\Omega$$

The full result of the calculations are shown in Table 5. Using the LineCalc tool in ADS, we determined the dimensions for our coupled lines for our substrate. We plugged in our even and odd impedances, imported our substrate parameters, and set the frequency to design around. LineCalc gave us the width, length, and spacing for the coupled line section. Once we had these, we increased the spacings so the lines could be manufacturable by PCBway. Then we placed bends in the filter to save space on the PCB. We tuned the widths and lengths until we achieved a satisfactory simulation. Figure 10 shows the final ADS schematic for our coupled line filter, and Figure 11 shows its layout on the PCB. Figure 12 shows a Momentum simulation of the filter, where we see we have less than 4 dB of insertion loss and a 30 dB shape factor of 3.46.

n	$Z_0 J_n$	$Z_{0even}(\Omega)$	$Z_{0odd}(\Omega)$
1	0.434	81.1328	37.7167
2	0.133	57.5526	44.2239
3	0.133	57.5526	44.2239
4	0.434	81.1328	37.7167

Table 5: Coupled line impedance calculations

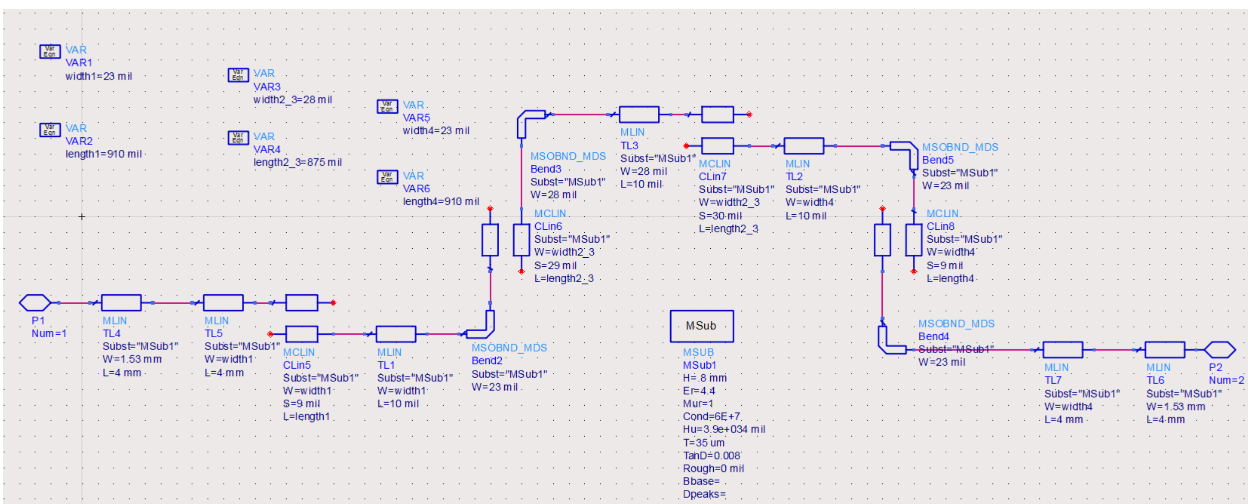


Figure 10: Upper band microstrip coupled line bandpass filter schematic

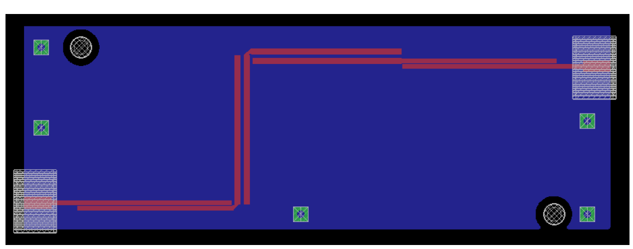


Figure 11: PCB layout for microstrip filter

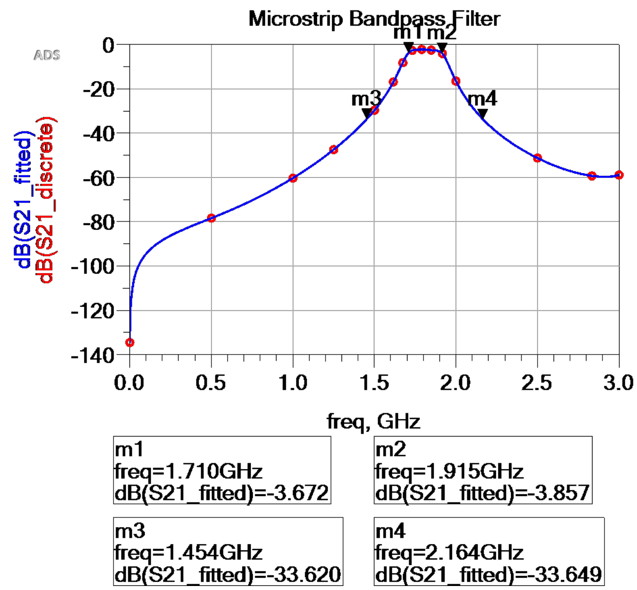


Figure 12: Momentum simulation of upper band filter

2.4.3 Matching Networks

Proper impedance matching is necessary for maximum power transfer within sections of the RF unit. Since the reference impedance of our system is 50 ohms, we desire the input impedance of each RF detector to be transformed to 50 ohms. The RF input pin of the LT5534 has a different input impedance for each frequency band. At 800 MHz (lower band), the input impedance is $Z_{lower} = 96.8 - j278\Omega$. At 1800 MHz (upper band), the impedance is $Z_{upper} = 25.4 - j125\Omega$.

The simplest matching network is a two element "L network", which is comprised of one series component and one shunt component. Usually these components are inductors or capacitors, so the network is as lossless as possible [11]. In ADS, we used the Smith Chart tool to design the lossless matching networks. Table 6 gives the component values that were found.

Another method of matching is to use a resistive network. This gives more loss, however resistors are very broadband devices so we can get a wide band match. Resistors are also still accurate at high frequencies, unlike inductors and capacitors. For our design, we used the LT5534's suggested resistive and capacitive matching. Figures 13 and 14 show ADS schematics for the lossless and resistive matching networks for each frequency band.

	Ideal Series	Ideal Shunt	Actual Series	Actual Shunt
Lower Band	1.0 pF	26.28 nH	1.0 pF	25 nH
Upper Band	15.07 nH	38.24 nH	16 nH	37 nH

Table 6: Matching network component values

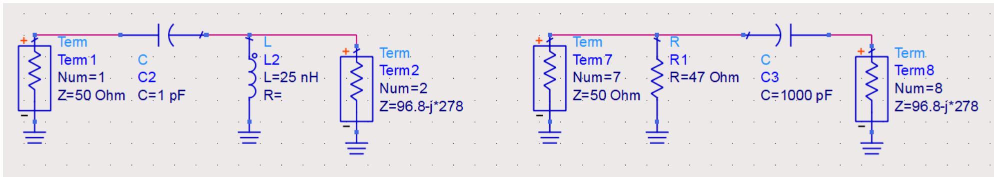


Figure 13: Two options for lower band matching

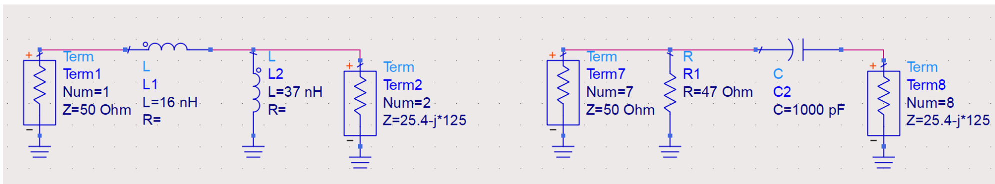


Figure 14: Two options for upper band matching

2.4.4 RF Detectors

The RF detectors are responsible for the power measurement of the signals received by the antennas. It is important that they detect the frequencies of interest and they must be sensitive enough to detect signals radiated from one meter away. Our first design used detectors that could only detect down to -20 dBm. We found this would not work due to the loss in our filters and the path loss of radiated energy in air. Our second design settled on Linear Technology's LT5534, which can detect down to -60 dBm [12]. For the supporting circuitry, capacitor and resistor values were taken from the recommended values on the data sheet.

3 Design Verification

3.1 Power Unit

3.1.1 Alkaline Batteries

With 4 batteries we expect a voltage output of 6V. To measure this we used a multimeter to get the voltage across the batteries. The first time we measured it we got 6.4V and then the next time we measured it we got 5.6V. This could be because of the different resistances of the multimeters used or the gradual drain of the batteries. We also measured 120 mA of current from the batteries while the device was active. This is much higher than our original expectation, but between this and the fluctuating voltage, everything still operated correctly.

3.1.2 Voltage Regulators

Our design incorporated two different voltage regulators. The first regulator (LD1117) was to output a steady voltage of 3.3V. Using a multimeter we were consistently able to measure a voltage of 3.298 V. The second voltage regulator (ADR3420) was to output a voltage of 2.048V. The multimeter showed an output voltage of 2.048 V each time we probed it.

3.1.3 Power Indicator LED

The yellow LED was connected to the output of the first voltage regulator. At an operating voltage of 2 V and an input voltage of 3.3 V, this leaves a value of 1.3 V at the output. This in turn is connected to a 130 Ω resistor, resulting in a current of 10 mA which was our original goal.

3.2 Control Unit

3.2.1 Microcontroller

As discussed earlier, our microcontroller contained all of the required features that we were looking for at the beginning of the semester. The ADCs were able to sample fast enough to allow our code to be accurate and give a proper response continuously. It also had no issues outputting 2.34 V to the LEDs when required, even with an input of 3.3 V, which was more than our research led us to believe. The initial data we had seen said that it would be lucky to give out 2.1 V, which was what we planned our current limiting resistors for. This only affected the current drawn from the microcontroller, but we saw nothing to suggest that this negatively impacted our design.

3.2.2 Visual Feedback LEDs

We had numerous opportunities to observe the green, red and orange LEDs while they were active and can confirm that they shine brightly enough to be visible from an arms length away and beyond. Our initial requirement was that the LEDs consume less than 15 mA of current while active. With the higher output voltage from the microcontroller, we calculated the current to be 34 mA, which is above our goal. This can be fixed however by swapping from 10 Ω resistors to 30 Ω resistors. We did not have time to make this correction before our demo and final product was complete, but it is a relatively easy fix in future iterations.

3.3 RF Unit

3.3.1 Antennas

The first requirement for our antennas is that they receive the frequencies we want to detect. Originally we decided to verify this by radiating a frequency using a signal generator and antenna so we could observe the received power on a spectrum analyzer using another antenna. We decided this setup was too complicated, so instead we used one of our RF detectors to test. We attached the antenna directly to the input of the RF detector and radiated signals from a signal generator at one meter away. We observed the output voltage of the detector and found that the antenna successfully receives 704-849 MHz and 1710-1915 MHz.

To test for a 50 ohm impedance match, we measured the return loss of the antennas on a network analyzer. First we calibrated the network analyzer, then took a one-port measurement of the antenna's return loss, S_{11}. We can determine the input impedance of the antenna using

$$Z_{in} = Z_0 \frac{1-S_{11}}{1+S_{11}}$$

where $Z_0 = 50$ ohms, the reference impedance of our system. Figure 15 shows the impedance versus frequency plot for the antennas, and we see by the markers that our antenna is not well matched to 50 ohms in our frequency bands of interest. Therefore, we have failed this requirement, however the antennas still work for our intended purpose.

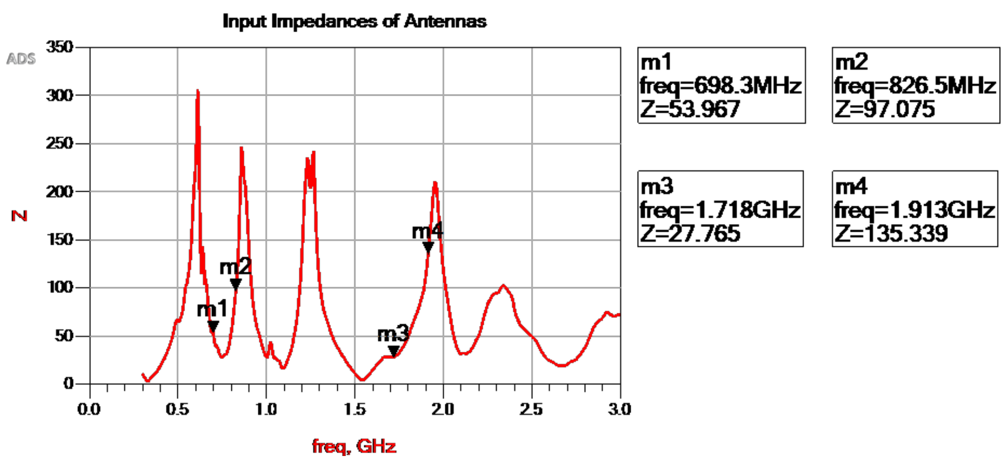


Figure 15: Input impedance of antenna

3.3.2 Bandpass Filters

To verify the performance of the filters, we attached SMA connectors to the edges of each filter board. Using a calibrated network analyzer, we measured the 2-port S parameters of the filters. Figure 16 shows the measured (blue) insertion loss of the lumped element lower band filter compared to the simulation (red). We see that the center frequency of the measured filter is about 200 MHz lower than desired. There is also a considerable amount of loss. To fix this, we iteratively decreased the series inductance from its original value of 72 nH. The final design settled on a 30 nH inductor. Figure 17 shows the insertion loss of this filter. We see that we have fully captured the frequency band of interest, yet it is much lossier than desired. Using the markers, we determined that the loss within this circuit is greater than 13 dB in the passband. This means the filter failed our first requirement, which called for less than 3 dB of passband loss. We also looked at the 30 dB shape factor, and found that it was 2.6. Our second requirement called for a 20 dB shape factor less than 7, and a 30 dB shape factor will always be larger than a 20 dB one, so this filter fulfills the second requirement.

Figure 16: Insertion loss of low band filter

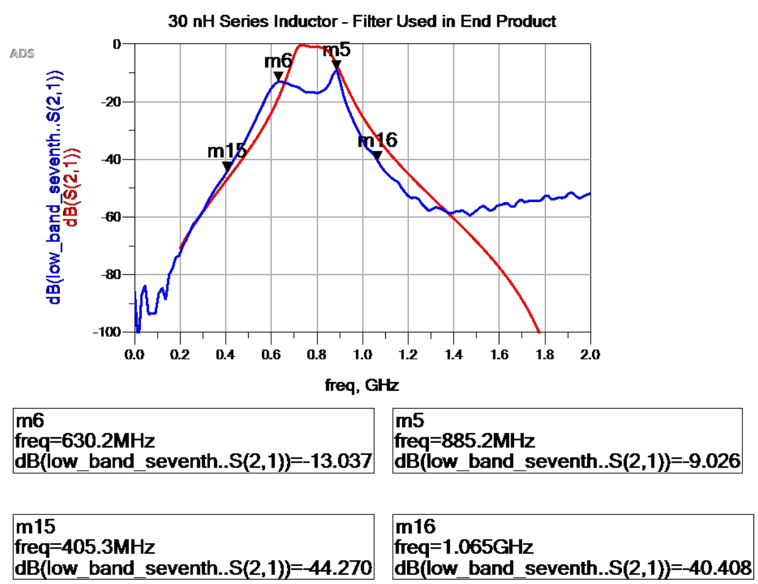


Figure 17: Insertion loss of low band filter used in final product

The passband loss of our upper band filter is shown in Figure 18. This time, our measurement (red) matches the ideal (blue) response very well. It is slightly lossier than desired, but it has a better filter shape. The passband loss is less thant 6 dB and the shape factor is found to be 4.38. Therefore the upper band filter passes both requirements.

3.3.3 Matching Networks

To verify less than 3dB of loss within the matching networks, we used a network analyzer to measure the insertion loss of each network. We calibrated a network analyzer and took a two-port S parameter measurement for each network. Figure 19a shows the simulated and measured values for the lower band

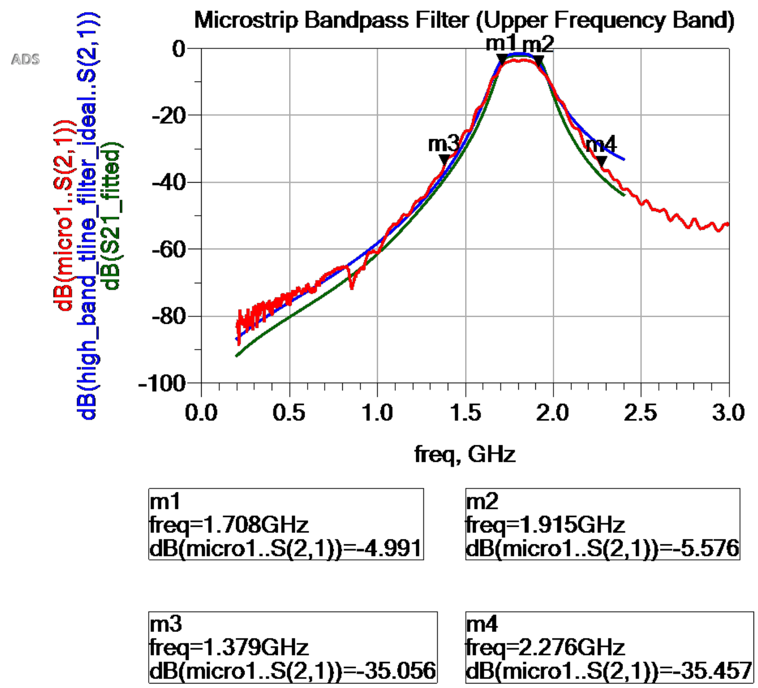
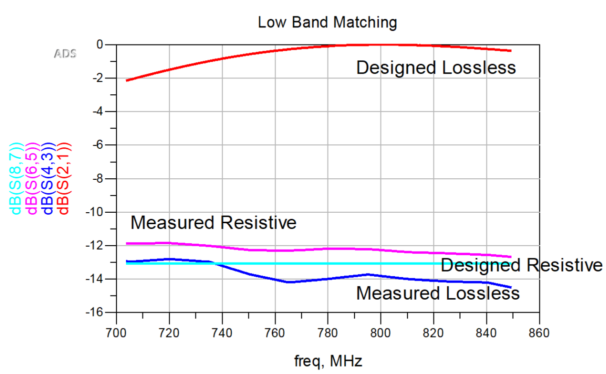
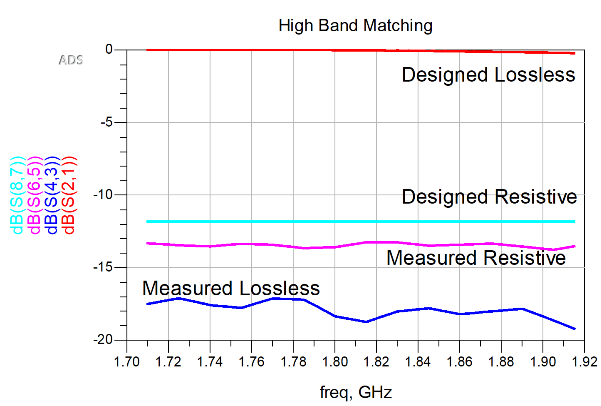


Figure 18: Insertion loss of low band filter used in final product

matching, and Figure 19b shows the same for the upper band. In both cases, we see that the "lossless" network performed poorly, so we used the resistive matching in both cases. Our requirement of less than 3 dB loss failed as there is at least 12 dB of loss in each network, however it does not hinder successful operation of our device.



(a) Insertion loss of lower band matching networks



(b) Insertion loss of upper band matching networks

3.3.4 RF Detectors

The RF detectors need to be able to detect the frequencies 704-849 MHz and 1710-1915 MHz, as well as detect input powers as low as -40 dBm. To test both of these, we attached a signal generator to the input of the RF detector using a coaxial cable. We swept over the frequencies of interest at a constant power and observed the output voltage of the detector. If the output voltage was higher than the detector's "no input" value, then we confirmed that detector properly detected the given frequency. We also decreased the input power down to -50 dBm at several frequencies to test the detector's sensitivity. We confirmed that the detectors properly sensed the frequencies of interest and detected powers down to -50 dBm.

4 Cost

4.1 Parts

The single unit production parts cost for this project is \$134.49. For 1000+ units, the parts cost is \$81.99. Table 7 in Appendix B shows the detailed parts list for our project.

4.2 Labor

The labor costs for this project are set at \$30/hr. Each member worked approximately 15 hours per week on this project over a total of fourteen weeks in the semester. This brings our labor costs to

$$\frac{\$30}{hr} \times \frac{15\, hrs/week}{partner} \times 14\, weeks \times 2.5 \times 3\, partners = \$47,250.$$

The total cost to produce a single unit is \$47,384.49.

5 Conclusion

5.1 Accomplishments

Our final prototype was successfully able to accurately detect active cell phones and relay that information quickly and succinctly. The power unit was able to provide all necessary power levels required by the rest of the circuit. The control unit has proved to be able to read and interpret our data without any flaws. The RF unit proved that it could use both a lumped component and a microstrip filter to correctly identify RF signals in the immediate vicinity. Together these units are embedded in a housing unit that gives the prototype the feel of a finished product. Figure 20 shows the final product as it is detecting interference, and Figure 21 shows the inside of the housing.

Figure 20: Final product

5.2 Uncertainties

Our tests did reveal one small flaw that might impact the reliability of our device. In the presence of crowded lab spaces and areas with strong Wi-Fi signals our device would be triggered almost immediately. It is incredibly sensitive in a quiet, isolated environment but that may not always be the case. Luckily the location we designed and built this device for should not have to deal with these problems, as they are a remote observatory with wired Ethernet that runs through the building.

5.3 Ethical considerations

Our device is a RF receiver that contains an antenna, so it is important not to radiate power that could be harmful to the cell phones we are trying to detect. To make sure this does not happen, we use passive components that should only allow receiving and no transmission. This allows our us to comply with Title 47 of the Code of Federal Regulations 15.5 General Conditions of Operations [13], which states that our device should not be an incidental radiator. We also hope to maintain the honesty and trustworthiness as specified by Imperative 1.3 of the ACM Code of Conduct [14]. The targeted nature of our device could be viewed

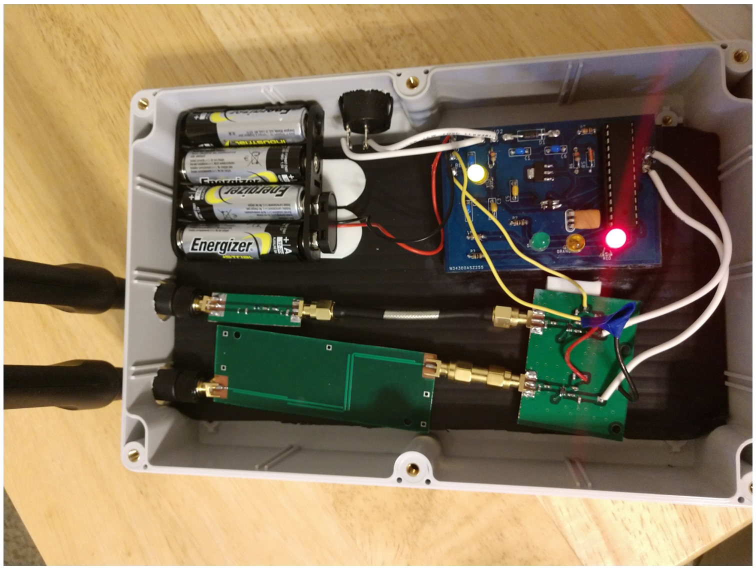


Figure 21: Interior of housing

as a invasion of privacy, as a cell phone in a pocket could be considered a personal item. However, it will be up to the personnel on site to inform visitors why they are using our device. They should explain what the device is looking for, explain why they need minimal radio interference and how it will harm their data if not complied. This presents a good time for researchers at Arecibo to uphold principle #5 of the IEEE Code of Conduct, which states we must aim "to improve the understanding of technology; its appropriate application, and potential consequences [15]. This will give the scientists at Arecibo the opportunity to teach visitors about how they collect their information and how harmful something as innocent as a cell phone can be.

5.4 Future work

Even with a working prototype, there is always room to improve upon the design. We would like to combine our filters, RF detectors, microcontroller and power circuitry onto a single board. Figures 23 and 25 in Appendix A show two separate PCBs for our project. Combining them would remove the cost of multiple board orders and allow for the device to be smaller. It would also eliminate the need for the expensive SMA connectors and cables between the different boards. We would also change the substrate of the board. Currently we are using FR4 because it is cheap, however its dielectric constant is not always stable across the same PCB. This introduces extra losses and changes the impedances of traces, even if they have the same widths. During testing, we found that the high band microstrip filter performed significantly better than the lumped element low band filter. We would like to switch the low band filter over to a microstrip one as well to achieve better accuracy in frequency detection. Finally, we could change some resistor values to reduce the current draw of the LEDs and extend the lifespan of the batteries.

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Appendix A Schematics and Layouts

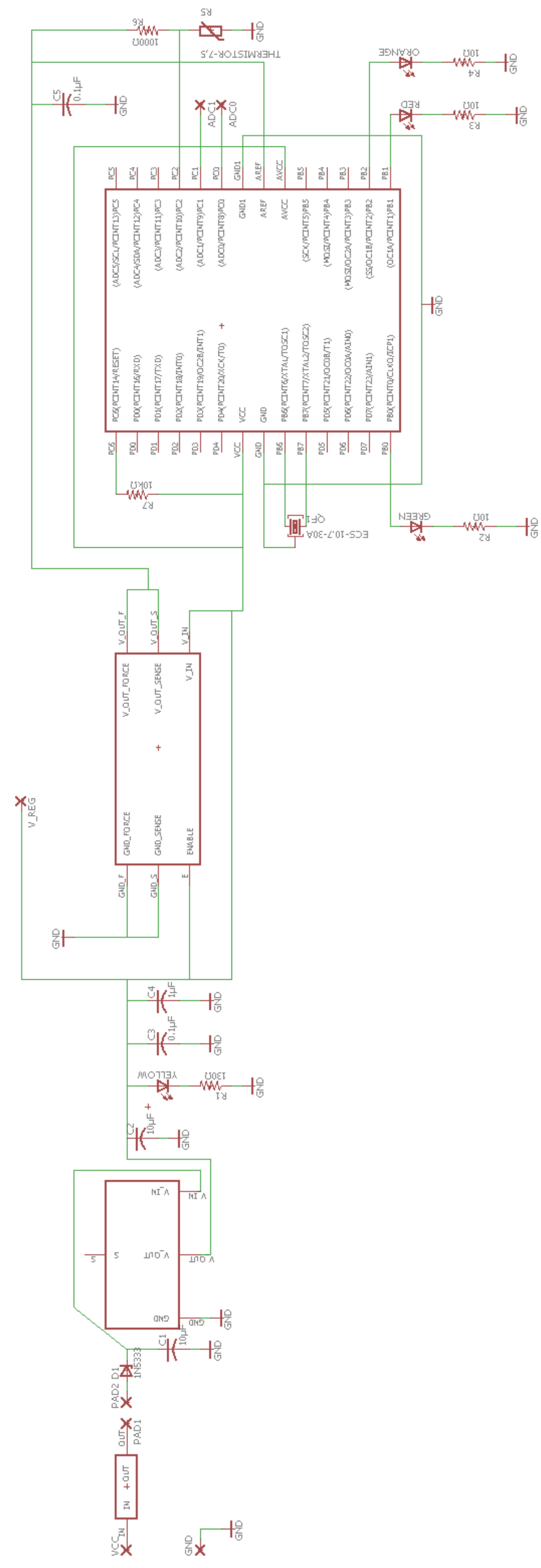

Figure 22: Schematic of the Power and Control Units

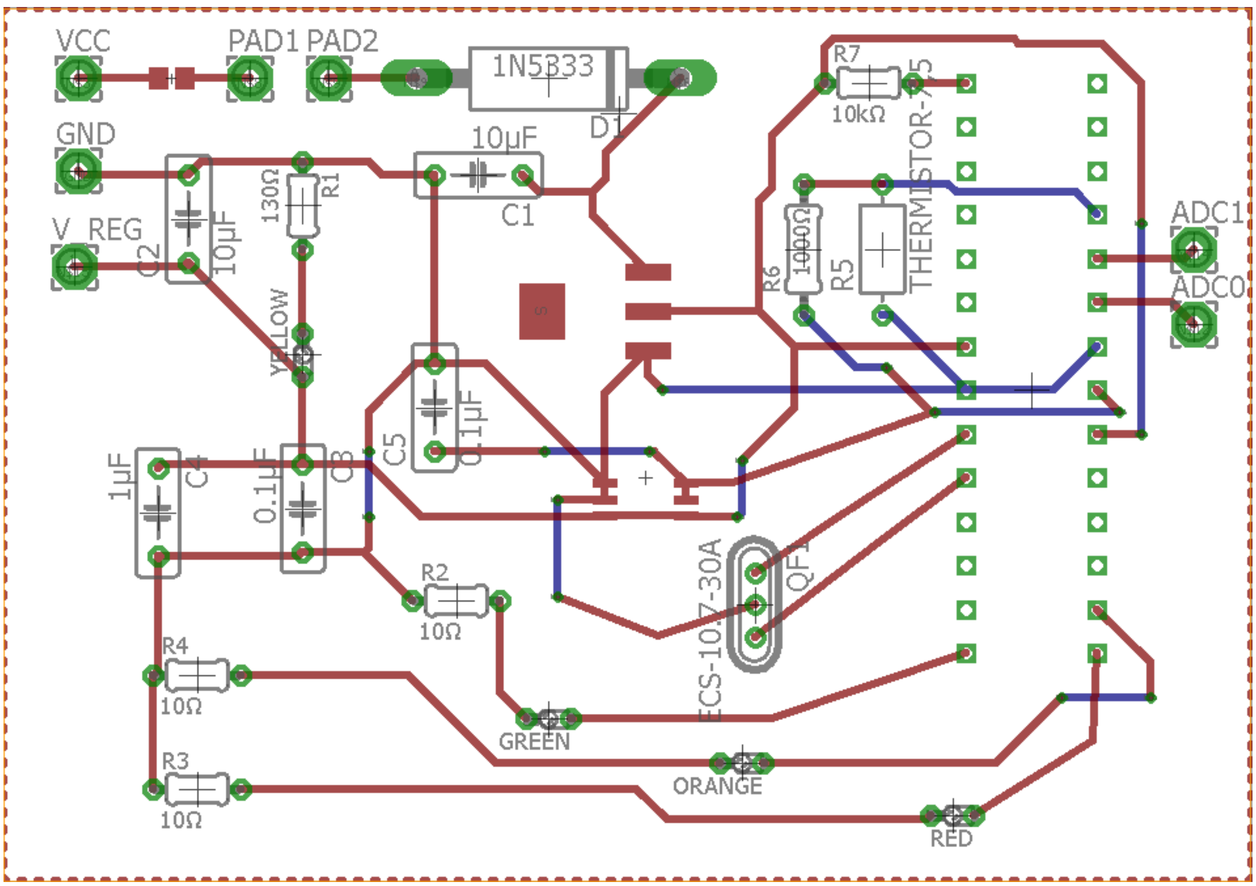

Figure 23: PCB Layout for Power and Control Units

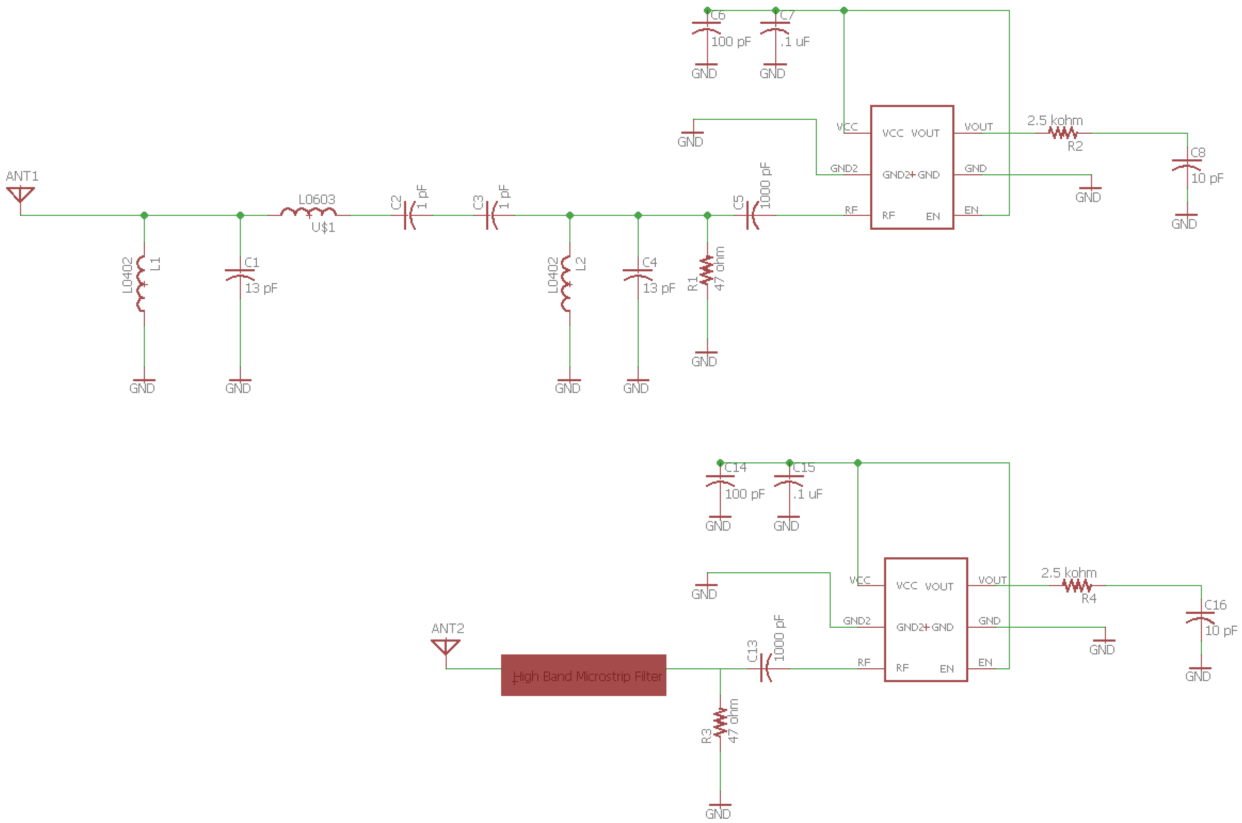

Figure 24: RF circuit schematic

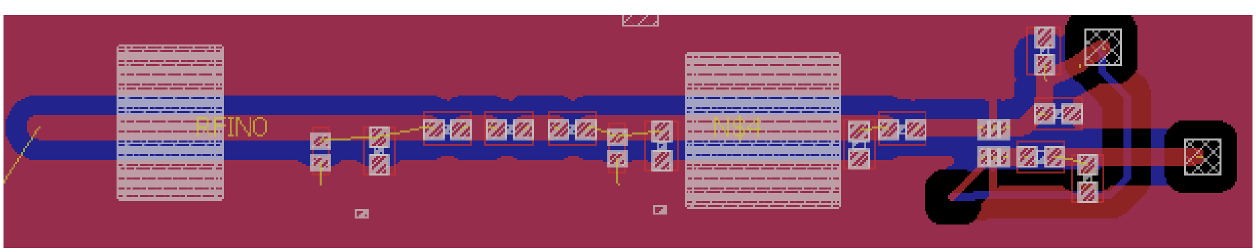

Figure 25: RF PCB for lower band

Appendix B Requirement and Verification Table

B.1 Power Unit

B.1.1 Alkaline Batteries

Requirements	Verification	Status
Batteries need to supply up to 50 mA to the system for a voltage range of 3.3 to 6 V.	(1) Hook battery up to a test circuit that simulates power usage (2) Use voltage meter and current meter to test the voltage output and the current output of the batteries.	Y
Batteries should be easily accessible so as to be replaceable.	(1) Open the housing where the battery is stored (2) Ensure battery can be replaced easily and safely.	Y

B.1.2 Voltage Regulator

Requirements	Verification	Status
Supply a constant 3.3 V ±5% for use by the RF detectors.	(1) Connect V_{in} to the battery source (2) Using a DC load, draw a constant 50 mA current. (3) Measure V_{out} using an oscilloscope, ensuring the output voltage stays within 5% of 3.3V	Y

B.1.3 Power Switch

Requirements	Verification	Status
The switch should be rigid enough to avoid accidental flipping.	(1) Lightly tap the switch to make sure it does not move to the on position. (2) Once on, tap it to make sure it doesn't turn back off.	Y

B.1.4 Power On Indicator LED

Requirements	Verification	Status
The LED must be visible when being held by the user	(1) Connect LED to test circuit composed of voltage source and protective resistor. (2) Hold it out at arm's length and ensure that the light is visible.	Y
The LED must consume less than 15 mA.	(1) Turn on LED on as it would be on during normal device operation. (2) Test current running through circuit to see that it is below the desired level of 15 mA.	Y

B.2 RF Unit

B.2.1 Antennas

Requirements	Verification	Status
Antenna 1 must receive 704-849 MHz and Antenna 2 must receive 1710-1915 MHz	(1) Attach a coaxial pigtail to the output of the antenna system. (2) Use a signal generator and antenna to radiate the desired frequencies. (3) Measure the output of the antenna on a spectrum analyzer. (4) Ensure the desired frequencies are received by the antenna.	Y
Each antenna and transformer system should have an impedance of 50 ohms $\pm 10\%$ at the junction to a 50 ohm feed line over their respective frequency bands.	(1) Attach a coaxial pigtail to the output of the antenna system. (2) Use a network analyzer to measure the impedance match. (3) Ensure each antenna is matched to 50 ohms $\pm 10\%$ at the center frequency of each band.	N

B.2.2 Bandpass Filters

Requirements	Verification	Status
Bandpass filter 1 must have a passband of 704-849 MHz. There must be less than 5 dB of loss within each passband.	(1) Attach coaxial pigtails on each end of the bandpass filter. (2) On a network analyzer, measure the insertion loss. (3) Ensure that the loss within each passband is less than 5 dB.	N
Bandpass filter 2 must have a passband of 1710-1915 MHz. There must be less than 5 dB of loss within each passband.	(1) Attach coaxial pigtails on each end of the bandpass filter. (2) On a network analyzer, measure the insertion loss. (3) Ensure that the loss within each passband is less than 5 dB.	Y
To ensure the correct filter shape, there should be greater than 20 dB of rejection in the stop band. We will define the shape factor to be the 20 dB bandwidth divided by the 5 dB bandwidth. The shape factor should be less than 5.	(1) Attach pigtails on each end of the filter. (2) Measure the insertion loss on a network analyzer. (3) Ensure that the shape factor is less than 5.	Y

B.2.3 Matching Network

Requirements	Verification	Status
Each matching network must match the RF_{in} port to 50 ohms $\pm 10\%$ for their respective frequency bands.	(1) Attach coaxial pigtail to the input of the matching network. (2) On a network analyzer, measure the impedance match. (3) Ensure that the measured impedance is 50 ohms $\pm 10\%$ at the center frequency of each band	N

B.2.4 RF Detector

Requirements	Verification	Status
The detector must be able to measure the power of frequencies 704-1915 MHz.	(1) Use a signal generator to input a signal to the RF detector. (2) Vary the power level of the signal. (3) Observe that the output voltage of the detector is changing in response to the change in input power.	Y
The detector must detect signals with input powers above -20 dBm.	(1) Use a signal generator to input a signal to the RF detector. (2) Lower the signal power to -20 dBm. (3) Ensure that the output voltage of the RF detector has risen above the voltage level when there is no RF input.	Y

B.3 Control Unit

B.3.1 Microcontroller

Requirements	Verification	Status
ADC must have 8-bit resolution and must have multiple channels in ADC to handle both RF detector outputs.	(1) Connect outputs of both RF detectors to ADC on microcontroller. (2) Apply input RF power to both detectors. (3) Sample both channels to ensure ADC accuracy.	Y
Must have at least two GPIO pins for controlling the detection LEDs and provide a minimum of 10 mA to each.	(1) Program microcontroller to enable and disable LEDs. (2) Connect LEDs and resistors to output pins and test the current to ensure both LEDs turn on.	Y

B.3.2 LED Visual Feedback

Requirements	**Verification**	**Status**
Must be visible while user is holding the device.	(1) Connect LEDs to test circuit composed of voltage source and protective resistor. (2) Hold it out at arm's length and ensure that the light is visible.	Y
Each LED must consume less than 15 mA.	(1) Connect LED to test circuit composed of voltage source and protective resistor. (2) Test current running through circuit to see that it is below the desired level	N

Appendix C Parts List

Part	Part Number (Digi-Key)	Quant.	Single Unit	1000 Units
10 ohm resistor 3	CF18JT10R0CT-ND	3	$0.30	$27.12
130 ohm resistor	CF18JT130RCT-ND	1	$0.10	$9.04
0.1uF capacitor	399-13734-1-ND	2	$1.02	$301.08
10uF capacitor	445-173370-1-ND	2	$1.16	$340.18
1uF capacitor	445-173583-1-ND	1	$0.32	$85.65
Fuse	490-8505-6-ND	1	$0.65	$255.64
Thermistor	615-1138-ND	1	$2.91	$1,245.00
1k ohm resistor	CF18JT1K00CT-ND	1	$0.10	$9.04
Chip socket	ED3050-5-ND	1	$0.33	$157.50
ATmega328P	ATmega328P-PU-ND	1	$2.18	$181.65
3.3V Linear Regulator	497-1242-1-ND	1	$0.51	$157.59
2.048V VREFF Series	ADR3420ARJZ-R2DKR-ND	1	$4.27	$314.43
Resonator	X908-ND	1	$0.60	$320.00
10k ohm resistor	CF18JT10K0CT-ND	1	$0.10	$9.04
Diode	C1Z200B CT-ND	1	$0.47	$103.00
Battery pack	BC4AAW-ND	1	$1.64	$1,029.40
Switch	EG4777-ND	1	$0.93	$593.60
Batteries	SY630T-ND	4	$4.20	$2,304.52
Power/Microcontroller PCB	PCBway	1	$5.00	$373
TG.10.0113 Whip Antenna	931-1163-ND	2	$20.42	$16,128.08
Inductor, 2.5 nH	490-15388-1-ND	2	$0.46	$186.30
Capacitor, 13 pF	712-1315-1-ND	2	$0.92	$270.96
Inductor, 30 nH	490-6882-1-ND	1	$0.19	$79.70
Capacitor, 1 pF	712-1323-1-ND	2	$0.54	$127.52
Resistor, 47 ohm	311-47GRCT-ND	2	$0.20	$4.14
Capacitor, 1000 pF	587-1069-1-ND	2	$0.70	$183.54
Capacitor, 100 pF	399-1061-1-ND	2	$0.20	$16.70
Capacitor, 0.1 uF	399-1096-1-ND	2	$0.20	$12.52
Resistor, 2.49 kOhm	311-2.49KHRCT-ND	2	$0.20	$5.36

Part	Part Number (Digi-Key)	Quant.	Single Unit	1000 Units
Capacitor, 10 pF	490-1403-1-ND	2	$0.20	$35.52
LT5534 RF Detector	LT5534ESC6#TRMPBFCT-ND	2	$21.12	$12,005.44
SMA Conn Edge Mnt	931-1175-ND	6	$19.32	$16,506.06
SMA Male to Male 3in cable	744-1446-ND	1	$13.30	$11,875
SMA male to male connector	ACX1240-ND	1	$6.23	$3,610.50
Housing		1	$18.50	$12,302.50
RF PCB	PCBway	1	$5.00	$828
Various LEDs	HLMP-XXXX	4	$1.64	$432.00
		Total:	$134.49	$81,994.32
		Unit Cost	$134.49	$81.99

Table 7: Total Parts List

Appendix D Code

```
// Names given to the ADC inputs to represent which set of data they are drawing from.
const int highPassFilter = A0;
const int lowPassFilter = A1;
const int thermistor = A2;


// Names given to represent LEDs and pin numbers. Here for testing
const int LED1 = 8;
const int LED2 = 9;
const int LED3 = 10;


// Storage variables to hold data from each analogRead command each loop
int hd0 = 0; // value read from high pass filter
int ld0 = 0; // value read from low pass filter


int hd1 = 0;
int ld1 = 0;


int hd2 = 0;
int ld2 = 0;


int hd3 = 0;
int ld3 = 0;


int hd4 = 0;
int ld4 = 0;


int hd5 = 0;
int ld5 = 0;


// Storage variables to hold the average of the reads for each loop
int highData = 0;
int lowData = 0;


int prev1High = 0;
int prev1Low = 0;
```

```
int prev2High = 0;
int prev2Low = 0;


int thermData = 0; // value read from thermistor circuit
int THRESHOLDH = 300; // High-band filter threshold
int THRESHOLDL = 175; // Low-band filter threshold


// counter variable to cause temp data to be sampled less frequently
int slowSample = 0;
// counter variable to allow a hold state
int detectSignal = 0;
// boolean to initiate detect loop to begin
boolean signalPresent = false;



voidsetup() {
    // These are the output pins that will control the LEDs.
    pinMode(LED1, OUTPUT);
    pinMode(LED2, OUTPUT);
    pinMode(LED3, OUTPUT);
    // Set the reference voltage that we will compare our data to
    analogReference(EXTERNAL);
    //Serial.begin(9600); // De-bugging tool
}

voidloop() {

    // This allows us to have three sets of averages compared per loop
    prev2High = prev1High;
    prev1High = highData;
    prev2Low = prev1Low;
    prev1Low = lowData;

    // read in values from ADCs
    hd0 = analogRead(highPassFilter);
    ld0 = analogRead(lowPassFilter);

    hd1 = analogRead(highPassFilter);
    ld1 = analogRead(lowPassFilter);

    hd2 = analogRead(highPassFilter);
    ld2 = analogRead(lowPassFilter);
```

```
hd3 = analogRead(highPassFilter);
ld3 = analogRead(lowPassFilter);

hd4 = analogRead(highPassFilter);
ld4 = analogRead(lowPassFilter);

hd5 = analogRead(highPassFilter);
ld5 = analogRead(lowPassFilter);

highData = (hd0 + hd1 + hd2 + hd3 + hd4 + hd5) / 6;
lowData = (ld0 + ld1 + ld2 + ld3 + ld4 + ld5) / 6;

//Serial.print(highData);
//Serial.print(" ");
//Serial.print(lowData);
//Serial.print("\\n"); // debugging code

// This is the trigger to the 'detect' state. If a signal is detected, LEDs change and we enter the countdown loop
if ((highData > THRESHOLDH && prev1High > THRESHOLDH && prev2High > THRESHOLDH) ||
(lowData > THRESHOLDL && prev1Low > THRESHOLDL && prev2Low > THRESHOLDL))
{
    signalPresent = true;
    digitalWrite(LED2, HIGH);
    digitalWrite(LED1, LOW);
}
// If triggered above, this statement begins. It is what resets the count timer
if (signalPresent)
{
    //this should hold the light on for 5 seconds after the last time it read a signal
    if (detectSignal < 3000)
    {
        if ((highData > THRESHOLDH && prev1High > THRESHOLDH && prev2High > THRESHOLDH) ||
        (lowData > THRESHOLDL && prev1Low > THRESHOLDL && prev2Low > THRESHOLDL))
            { detectSignal = 0; // reset the counter }
        else
            { detectSignal = detectSignal + 1; // increment the counter }
    }
    else
    {
        detectSignal = 0; // reset the counter for the next time the loop is triggered
        signalPresent = false; // break out of the detection branch and allow green LED to turn on
    }
```

```
    }
    else
    {
        digitalWrite(LED1, HIGH);
        digitalWrite(LED2, LOW);
    }
    // This is how we will read data from the thermistor circuit. Calculations have been
    // done to find the correct value that signals that the internal temp is too high.
    if (slowSample == 1000)
    {
        thermData = analogRead(thermistor);
        if (thermData > 615)
            digitalWrite(LED3, HIGH);
        else
            slowSample = 0;
    }
    else
        slowSample = slowSample + 1;
}
```