ECE 445
Fall 2017

RFI Detector
Design Document

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1 Introduction

1.1 Objective

The Arecibo Observatory in Puerto Rico asks visitors to turn their cell phones off or place them in airplane mode, but they do not always obey. Our goal is to create a device that will be able to detect the presence of RF signals given off by cell phones. The frequencies of interest will be the cellular bands used in Puerto Rico. The device will then display using LEDs what it detects: either green for ‘No Transmission Present’ or red for ‘Cellular Transmission Present.’ This will allow the employees at Arecibo to manually check groups of visitors to ensure that the guests comply with their cell phone policies.

1.2 Background

The radio observatory in Arecibo, Puerto Rico uses antennas to measure radio frequency energy in order to gather scientific insight into space and the upper atmosphere. This research can be impacted by outside interference from external sources, one example being cellular phones. Phones typically transmit signals between 0 dBm and 30 dBm [1], which is enough power to significantly impact data collection. Many visitors of the observatory who carry cell phones are unknowingly transmitters of unwanted RF signals that can affect the measurements taken by the equipment on-site. Cell phones, when activated, frequently send these signals out unless they are turned off or the phone is placed in airplane mode. Even when asked, some people do not understand the harm they can do with their cellular devices and choose to not follow instructions.

1.3 High Level Requirements

1. Device must be able to properly sense an RF signal with transmit power above 0 dBm 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

Figure 1 shows the block diagram for the design of the RFI detector. The RF unit consists of two distinct receive paths, each with a unique bandpass filter that will pass the two frequency bands of interest. RF power meters will be used to measure the power, and the outputs from these will be measured with an ADC. This data will be processed by the microcontroller and the user will be alerted to the presence of interference should it exist. The system will be powered with alkaline batteries.

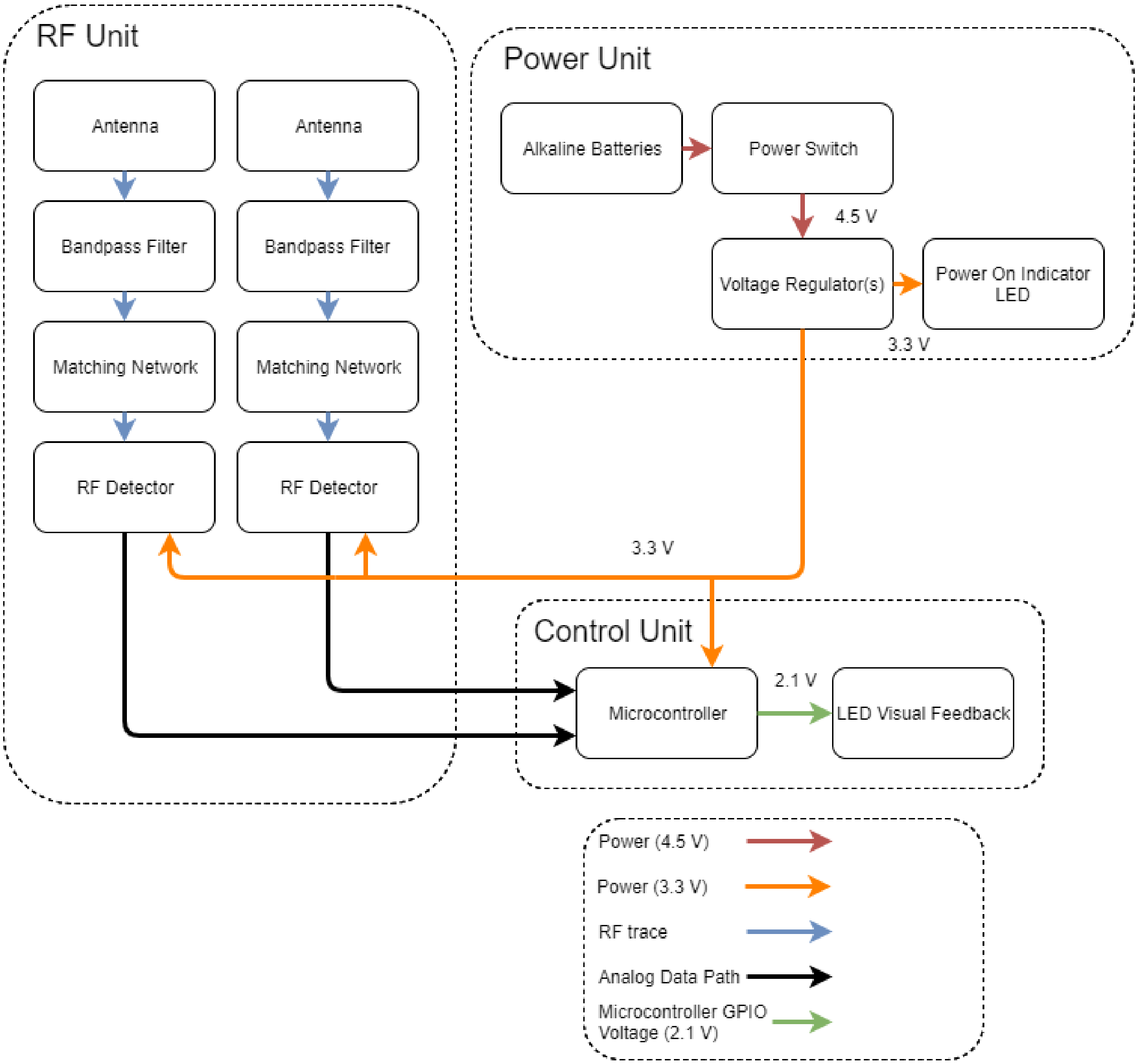

Figure 1: Block Diagram

2.1 Power Unit

The power unit will be in charge of feeding energy to the device for any period of time that it is needed.

2.1.1 Alkaline Batteries

We will use three 1.5V AA batteries in series as a base and use a voltage regulator to step this down. The microcontroller and RF detectors both operate around 3.3V, which is common enough for a voltage regulator that we can find a pre-made unit. The microcontroller, RF detectors, and LEDs collectively use approximately 50 mA of current, so using alkaline batteries will be adequate [2]. We will be using alkaline batteries over Li-ion batteries as they are safer and we do not require the levels of current draw that Li-ion batteries usually supply. The device will only be used in short bursts throughout the day. If the lifetime is around 10-20 hours, this will provide two to four months of use at ten minutes per day.

Requirements	**Verification**
Batteries need to supply up to 50 mA to the system for a voltage range of 3.3 to 4.5 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.
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.

2.1.2 Voltage Regulator

This component will ensure that a steady 3.3V is delivered to the LEDs, microcontroller and RF detectors from the 4.5V battery source.

Requirements	**Verification**
Supply a constant 3.3 V $\pm 5\%$ 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

2.1.3 Power Switch

This device does not need to run continuously. We will have a switch to power it on and begin detecting. Once groups have been scanned for RF interference, it can be switched off to keep batteries alive as long as possible.

Requirements	Verification
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.

2.1.4 Power On Indicator LED

This will be a small LED that will be in series with the power switch to indicate if the device is on or not. This is to ensure that users will not mistakenly leave it on for extended periods of time unnecessarily.

Requirements	Verification
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.
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.

2.2 RF Unit

The RF unit will be responsible for the reception, filtering, and power measurement of the desired RF signals. The device needs to detect signals from approximately one meter away, which is close enough to capture the high power transmission from cell phones, so amplification of these signals is not needed. The frequency bands of interest [3] are listed in Table 1. From these frequencies, we can choose two larger frequency bands which will capture all of the individual bands. Table 2 lists the frequencies of the two bands for which we will design the RF receive paths.

For ease of testing and to have a more modular design, we will have separate PCBs for the RF system and the control/power system.

2.2.1 Antennas

We will design two microstrip antennas to detect the radio frequency interference coming from cell phones. Each antenna will be responsible for the detection of one of the receive paths from Table 2. The antennas will likely not be matched to 50 ohms, so there will be an impedance transformer that will match the antenna impedance to a 50 ohm feed line. A good impedance match will provide better power transfer of the detected signals.

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

Requirements	Verification
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.
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.

2.2.2 Bandpass Filters

Two lumped element bandpass filters will be designed for detection of the two frequency bands listed in Table 2. They must be low loss so the received signals remain above the detection threshold of the RF detector. The filters must also have enough rejection to avoid detecting signals outside of the frequency bands of interest. Figure 2 shows the ADS simulation for an ideal band pass filter and one with realizable components.

Requirements	**Verification**
Bandpass filter 1 must have a passband of 704-849 MHz and 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.
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.

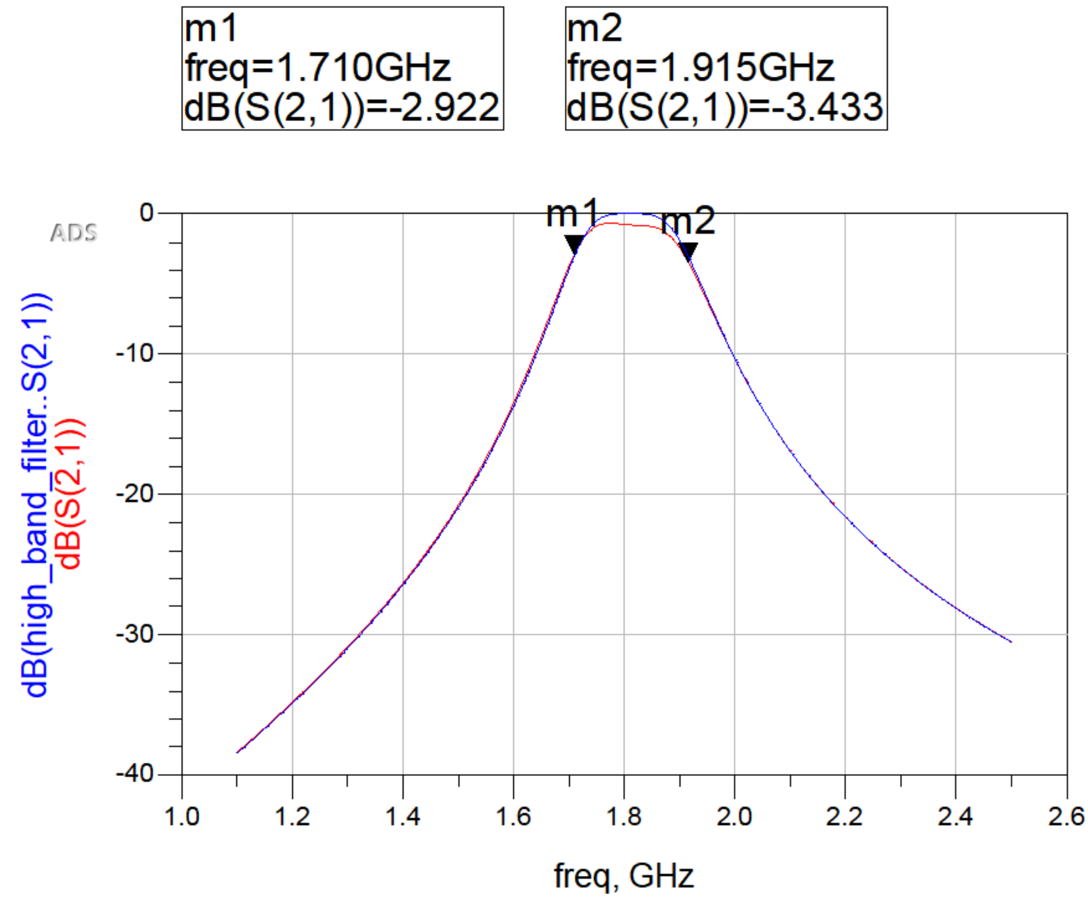

Figure 2: Insertion loss of ideal band pass filter (blue) and realizable bandpass filter (red).

2.2.3 Matching Network

Two lumped element matching networks will be implemented for optimal power transfer between the bandpass filters and the RF detectors. The RF detector will have different input impedances for each frequency bands, so each matching network will be designed differently. A good matching network will provide more accurate RF power detection.

Requirements	**Verification**
Each matching network must match the RF_{in} port to 50 ohms ±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 ±10% at the center frequency of each band

2.2.4 RF Detector

The RF detectors will measure the power of the received RF signals. The detectors will measure signals above a threshold of -20 dBm, which will effectively avoid detecting background downlink cell signals while also still detecting signals after they have experienced attenuation in the RF circuitry. Each detector will output a voltage relative to the power of the input signal, which can then be measured with an ADC to determine the received power. The RF Detector will be an LTC5505-2.

Requirements	**Verification**
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.
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.

2.3 Control Unit

The control unit is responsible for signal processing and alerting the user to the presence of RF signals. The integrated analog to digital converter in the microcontroller will convert the analog5 voltage from the RF detector to a digital scale. If RF interference is present, the microcontroller will turn on a red LED to alert the user. If no interference is detected, a green LED will turn on.

2.3.1 Microcontroller

The microcontroller we will use is the ATmega328. Through an integrated ADC, the microcontroller will measure the output voltage of each RF detector. The value obtained from the conversion will be used to determine if a threshold for received power has been met. The threshold will be determined through experimentation in the lab. If the threshold has been exceeded, the microcontroller will turn on an LED to indicate to this to the user.

The ADC sampling frequency will be set based on the burst time for the cellular technologies we will be detecting. In Figure 1, we show that we are specifically looking for three different cellular technologies: GSM, UMTS, and LTE. The transmission of each technology is made up of frames with smaller subframes and even smaller slots. We determine the sampling frequency based off of the smallest slot time. Table 3 lists the slot times of each technology, where LTE has the smallest slot time of 0.5 ms. For convenience, we will assume each slot is sent with constant transmit power, so we will set our sampling frequency to measure twice within each LTE slot. According to Nyquist sampling theorem, our sampling frequency should be

$$f_{sampling} = 2 * \frac{1}{0.5\,ms} = 4\,kHz,$$

which our microcontroller is more than capable of. Figure 3, shows the timing diagram of our RF connector. We see that the output voltage of the RF detector remains high during the period where the RF input receives a power. The pulse time shown is typical for a slot of a cellular signal, so our sampling rate will be able to handle the power measurements.

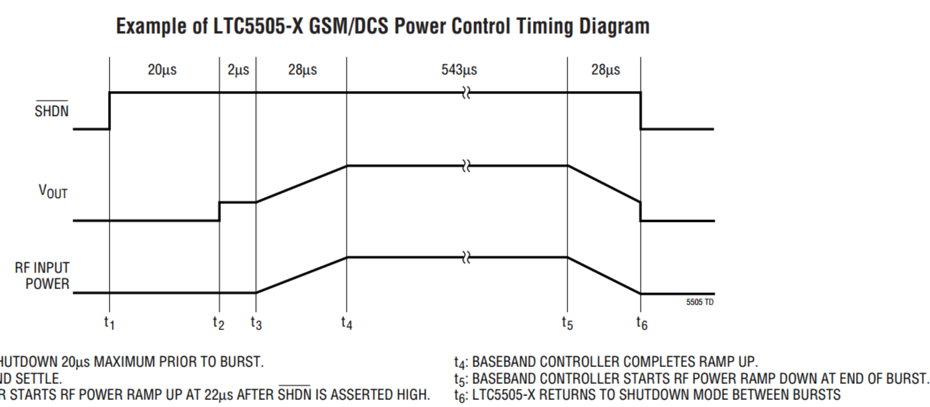

Figure 3: Timing Diagram of RF detector

	GSM	UMTS	LTE
Slot Time (ms)	0.577	0.666	0.500

Table 3: Slot times of cellular technologies

Requirements	**Verification**
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.
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.

2.3.2 LED Visual Feedback

We will have two different colored LEDs that act as the visual feedback for the user of our device. These will be controlled by the microcontroller.

Requirements	**Verification**
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.
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

2.4 Software

The microcontroller software is responsible for reading in the ADC data and comparing to the threshold we will determine through experimentation. The microcontroller will continuously read data from the ADC and determine whether either of the RF paths have received power above the threshold. If RF power is detected, we will turn on the appropriate LED indicator light. If we go a certain amount of time without RF power detected, we will then turn the indicator off. Figure 4 shows a basic flow chart for the software logic.

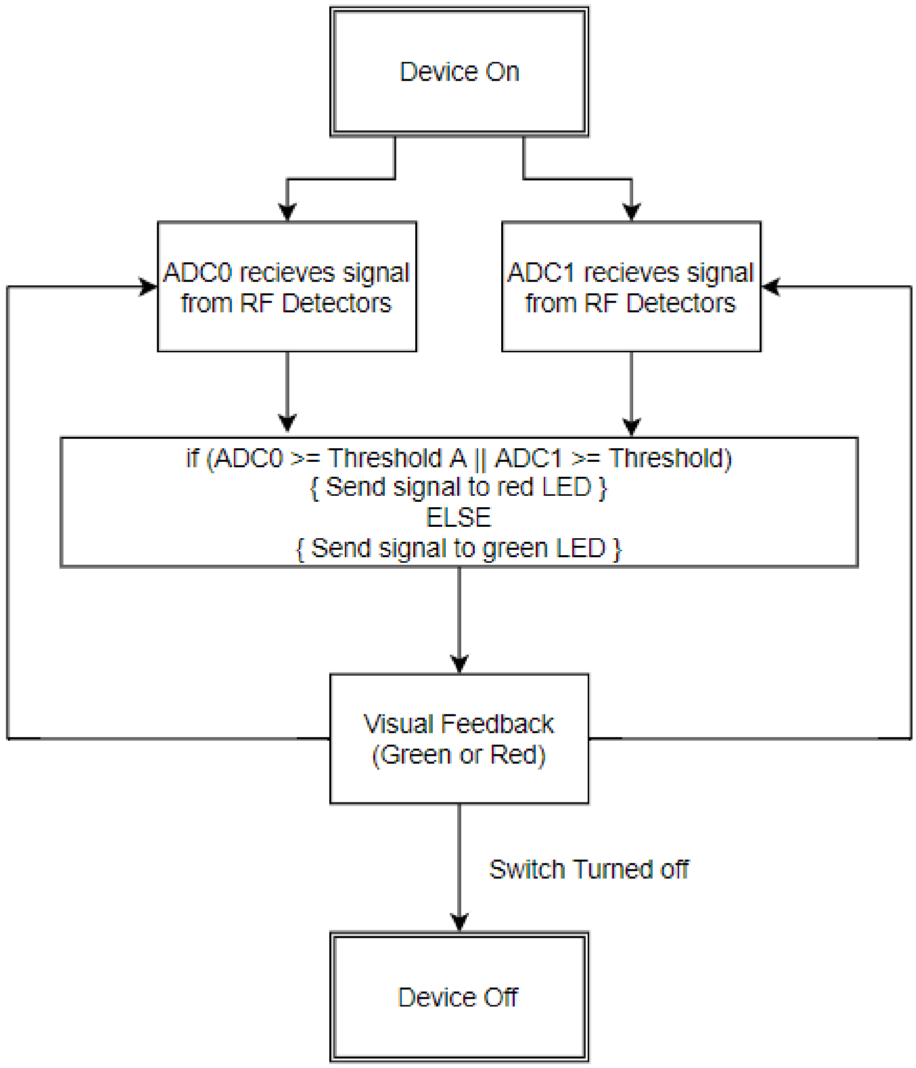

Figure 4: Logic diagram for software

2.5 Schematics

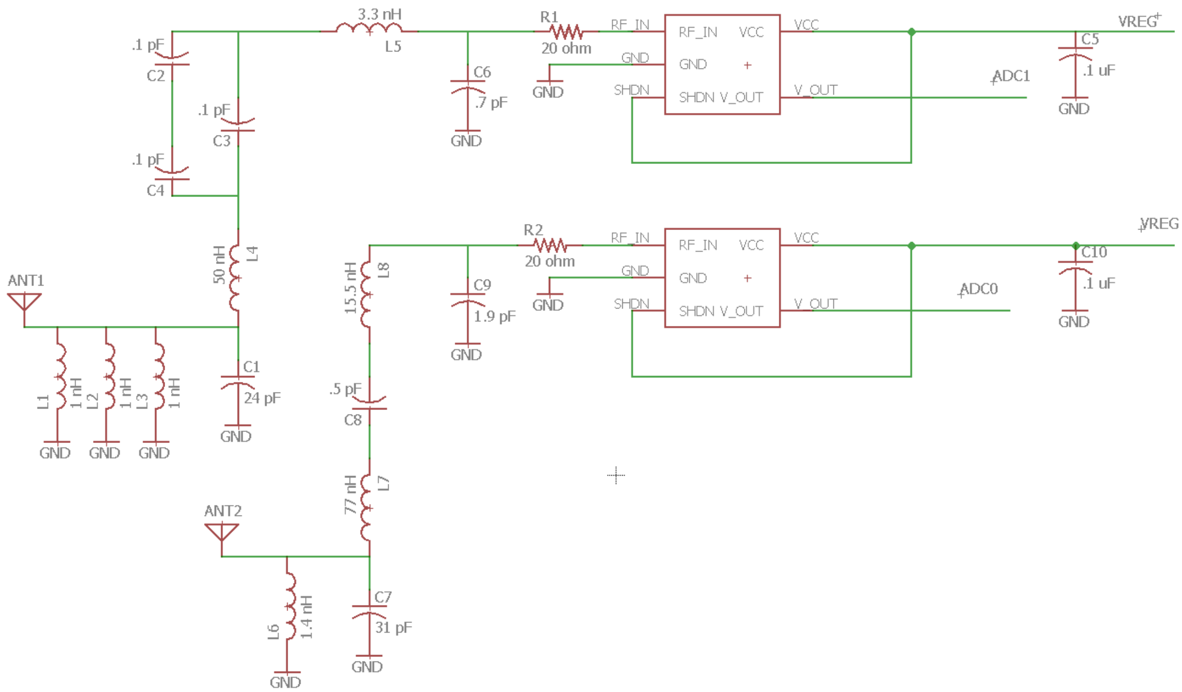

Figure 5: Schematic for RF Block

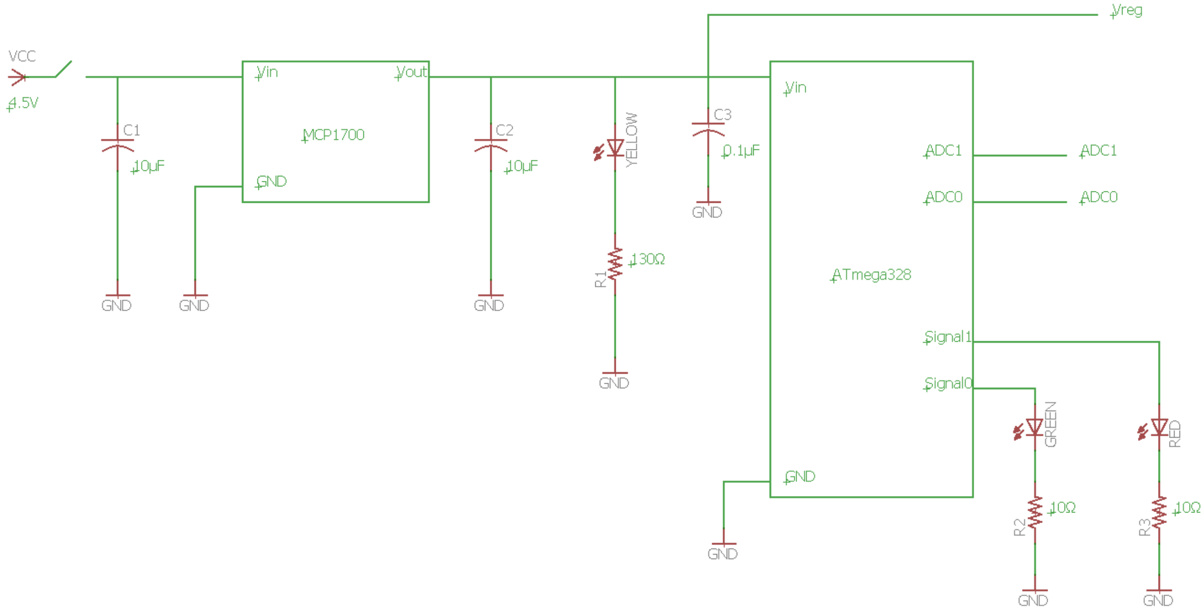

Figure 6: Schematic for Control and Power Block

3 Tolerance Analysis

In any RF system, one of the most important factors is the impedance match between subsections of the system. For optimal power transfer, the impedance of each section (such as the antenna, filters, and load) should be the same. The standard is 50 ohms. In our RF system, the impedance of the RF detector inputs pin is not 50 ohms. At 850 MHz (our low band), the impedance is 165 ohms. At 1850 MHz (high band), the impedance is 59 ohms. Therefore, we use two different matching networks for each receive path.

Both matching networks are lumped two-element impedance transformers. This is the simplest kind to make even though we have no control over the bandwidth, which is determined by the input and output impedances. However, after simulation, we see we meet the bandwidth requirements so a third element is not necessary. Each matching network consists of a series inductor followed by a shunt capacitor as shown in Figure 7.

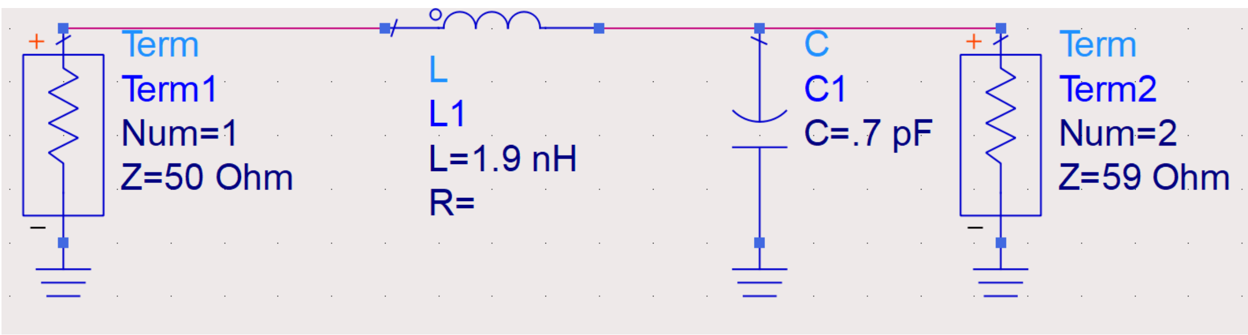

Figure 7: Example two element matching network

The transmitted power into a load can be calculated by first calculating the load reflection coefficient. The reflection coefficient is

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0}.$$

The power delivered to the load is

$$P_L = P_{in}(1 - |\Gamma_L|^2).$$

For the low band, if no matching is used, the power delivered to the load is 71.34% of the input power. For the high band, the delivered power is 99.32%. We can improve these numbers with matching networks. For a two element matching L-network, the magnitude of the input impedance when connected to a load is given by

$$Z_{in} = |(\frac{1}{Z_L} + \frac{1}{Z_{cap}})^{-1} + Z_{ind},$$

where the impedances of the inductor and capacitor are given by

$$Z_{ind} = j\omega L \text{ and } Z_{cap} = \frac{1}{j\omega C}.$$

Using a Smith Chart, the we determine the values for the low band matching network as L = 15.5 nH and C = 1.9 pF. For the high band, we use L = 1.9 nH and C = 0.7 pF. If we consider a tolerance of 5% for each part, we can determine if we will meet our requirement of an input impedance of 50 ±10%. Table 4 shows the results of the tolerance analysis, where we see we meet the requirement of $Z_{IN} = 50 \pm 5\%$ for each case.

	+/+	+/-	-/+	-/-
$\lvert Z_{IN_{low}} \rvert$	46.4	46.2	53.1	53.3
$\lvert \Gamma_{L_{low}} \rvert$	.0372	.04	.03	.03
$\frac{P_{L_{low}}}{P_{IN_{low}}}$	99.86 %	99.83 %	99.91 %	99.90 %
$\lvert Z_{IN_{high}} \rvert$	50.07	49	52.2	51.06
$\lvert \Gamma_{L_{high}} \rvert$	.0007	.01	.02	.01
$\frac{P_{L_{high}}}{P_{IN_{high}}}$	100 %	99.99 %	99.95 %	99.99 %

Table 4: Tolerance analysis for matching networks to RF Detectors where we analyze $C \pm 5\%/L \pm 5\%$

4 Costs

The labor costs for this project are set at \$30/hr. Three group members will approximately work 15 hours per week for fourteen total labor weeks in the semester. This brings our labor costs to

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

Part	**Cost**
ATmega328 Microcontroller	\$1.90
LTC5505-2 RF Power Detector	\$2.90 (x2)
Assorted LEDs	\$0.60
3-Cell AA Battery Holder	\$1.40
Power Switch	\$0.50
MCP1700 Voltage Regulator	\$1.50
Assorted resistors and capacitors for control/power units	\$1.00
3 AA Batteries	\$1.02
SMA cable	\$9.03 (x2)
SMA connectors	\$1.94 (x4)
Assorted inductors and capacitors for RF system	\$6.00
PCBs (PCBway)	\$8.00
Total	\$53.54

After building one unit, the total cost of this project is \$47,303.63.

5 Schedule

Week	**Tyler**	**Kyle**	**Jamie**
10/2	Design Document	Design Document	Design Document
10/9	Finalize bandpass filters and matching networks	Power system schematic	Design and simulate microstrip antennas and impedance transformers
10/16	Design and order version 1 RF PCB. Test RF detectors.	Test voltage regulator and mock power circuit	Finalize version 1 schematic of control/power PCB
10/23	Test version 1 RF PCB	Begin programming of microcontroller	Finalize and order version 1 control/power PCB
10/30	Test filter response and matching networks. Test inductors and capacitors for tolerance accuracy.	Test RF detector output and ADC sampling frequency	Test antennas impedance match, make adjustments if needed
11/6	Finalize and order version 2 RF PCB	Assemble power/control circuit and test performance	Finalize and order version 2 control/power PCB
11/13	Test RF system	Test RF and Control system cooperation. Prototype housing	Test antennas impedance match
11/20	Test device performance for various input powers with signal generator	Assemble device in housing	Test device performance with cell phone
11/27	Prepare for mock demo	Prepare mock presentation	Prepare presentation
12/4	Prepare demo and final report	Prepare demo and final report	Prepare final report
12/11	Finalize report	Finalize report	Finalize report

6 Ethics and Safety

6.1 Ethics

Our device is simply an RF receiver, however it does contain an antenna, so it is important not to radiate power that could be harmful to the devices we are trying to detect. To ensure this, we are using passive components that should only allow receiving and no transmission. Our device must comply with Title 47 of the Code of Federal Regulations §15.5 General Conditions of Operations [4], 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 [5]. As this device is looking for information about people's property that they may consider a private affair, it will be up to the personnel on-site to inform visitors what the device is doing. 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" [6]. For a minor inconvenience of turning off cell phones, visitors would be given the chance to learn about the harmful effects of interference and more about how the observatory receives their data.

6.2 Safety

According to the principle #1 of the IEEE Code of Ethics, we are responsible for making our device safe for the user [6]. Since the device is portable it will be kept near or on a person, therefore the device needs to operate safely and not cause physical harm to the user. To avoid potential injury, all current carrying circuit elements will be enclosed within the protective shell. This will protect the user and the device itself.

Since alkaline batteries have the potential to rupture and leak potassium hydroxide[7], the battery pack should be sealed and isolated. By isolating the batteries we can protect the circuit from corrosive leakage and give the user a chance to change and clean the area before installing new batteries.

In the construction of our device, we will be using soldering irons and lab equipment to test our circuit components. We have all taken the lab safety training so as to be properly informed on how to avoid inflicting pain on ourselves as well as damage to measuring instruments.

References

[1] Lnn S, Forssn U, Vecchia P, et al Output power levels from mobile phones in different geographical areas; implications for exposure assessment Occupational and Environmental Medicine 2004. [Accessed: 21-Sep-2017].

[2] “Battery Capacity.” Techlib.com, www.techlib.com/reference/batteries.html. [Accessed: 21-Sep-2017].

[3] “Puerto Rico Wireless Frequency Bands and Carriers.” FrequencyCheck, www.frequencycheck.com/countries/puerto-rico. [Accessed: 21-Sep-2017].

[4] “General Conditions of Operation.” Code of Federal Regulations. Title 47 Chapter I Part 15.5.

[5] Acm.org, ”ACM Code of Ethics and Professional Conduct”, 2016. [Online]. http://www.acm.org/about-acm/acm-code-of-ethics-and-professional-conduct. [Accessed: 5 Oct. 2017].

[6] IEEE.org. (2017). “IEEE Code of Ethics.” [Online] http://www.ieee.org/about/corporate/governance/p7-8.html [Accessed: 21 Sep. 2017].

[7] D. Berndt, D. Spahrbier, ”Batteries” in Ullmanns Encyclopedia of Industrial Chemistry 2005, Wiley-VCH, Weinheim. [Accessed 30 Sep. 2017].