CELLPHONE TRANSMISSION DETECTOR

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Abstract

This project serves as a stationary cellular transmission detector in the United States and Puerto Rico. It features LEDs that notify users when there is significant radio-frequency transmission generated by a cellular device. This project also features an LCD display that shows a real-time plot of the cellular signal strength in the area. Originally designed to work at a distance of one meter, this device works effectively at a distance of three meters.

Contents

1. Introduction

1.1 Objective

Radio astronomy and weather research often relies on the detection of weak signals that must be distinguished from surrounding radio-frequency (RF) background noise [1]. Though there are attempts to limit the bands used for such remote sensing research to those outside crowded domains, signals such as giant pulses from Crab-like pulsars and HI emissions from galaxies are found in bands dominated by communications and other interference [2]. In addition, the bands that can be used for observations are often limited by the attenuation effects of the Earth's atmosphere (allowing only frequency bands in the so-called radio window) and man-made radio frequency interference (RFI) [3].

Internal RFI sources mainly include cellular devices and microwave ovens. The RF signal generated or received via active cellular transmission during a phone call, SMS sending/reception, and LTE connection completely overpowers the signals of interest received by the observatories. In fact, an equivalent cellular transmission originating from the Moon would still serve as disrupting interference inhibiting astronomical research on Earth [4]. In Puerto Rico, the Arecibo Observatory encounters this exact form of interference as a result of tourism to the site.

Our goal in this project is two-fold. First, it is to mitigate the internal RFI contributions of active cellular transmission through a detection-and-prevention plan of action. We develop a cell phone transmission detector that notifies a user if there is significant power in a certain RF band of interest (corresponding to call, SMS, or data) nearby. This device is developed such that it is stationary and housed in a gate that every visitor to an RF observatory will walk through. The second goal of our project is to educate the public on RFI. We do this by developing a visual display that describes the ambient RF signals detected in the room. This public outreach factor will portray to viewers the various RF frequency bands of interest and their corresponding signal strength in real-time.

Additionally, different countries across the globe use different bands in the RF spectrum for CDMA, GSM, and LTE signals. Therefore, our solution is capable of detecting signals in a United States band (700-850 MHz) in order to show correct functionality directly using a cell phone, and a Puerto Rico band (1.5-1.9 GHz) for actual use at Arecibo.

1.2 High-Level Requirements

More specifically, our solution includes some form of an RF receiver, a power detector, a display, and a power supply. Furthermore, our solution should be capable of three distinct functions:

- The device must be able to detect two different frequency bands; the first band should center on CDMA, GSM, or LTE protocol bands of the United States, and the second band should center on a protocol band of typical cellular transmission in Puerto Rico.
- A display should show the relative strengths of the two active frequencies detected by the device.

- The device must notify the user or operator via a specific notification element when a signal of reasonable strength in one of the two notable frequency bands is detected.

A simple block diagram of this device is shown in Figure 1.

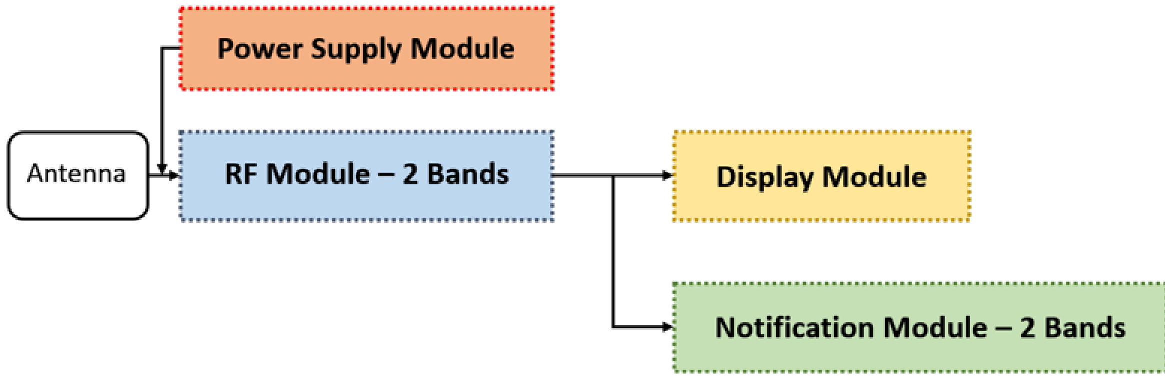

Figure 1: Simplified block diagram

2 Design

The high-level design of this device is composed of four main modules: a power supply module, a receiving module, a notification module, and a display module. The two receiving modules and two notification modules serve to distinguish between the two different frequency bands of interest. The power supply will provide necessary power to our entire system. The receiving modules will receive the same signal from an antenna, and then individually feed it to their own bandpass filter, amplifier, and half-wave rectifier. The antenna should provide a usable signal in the presence of active RF transmission at a distance of one meter. The notification module will determine if a non-trivial amount of power is present in relevant frequency bands and notify the user accordingly via an LED. Lastly, the display module will provide a real-time visual representation of the nearby RF signals. A robust block diagram including sub-components is shown in Figure 2.

There are a couple other ways to approach the design for this project. We could make use of software to perform the signal processing and achieve detection based off this. A software-defined-radio would be useful for this purpose. However, we maintain a strong hardware focus in this project.

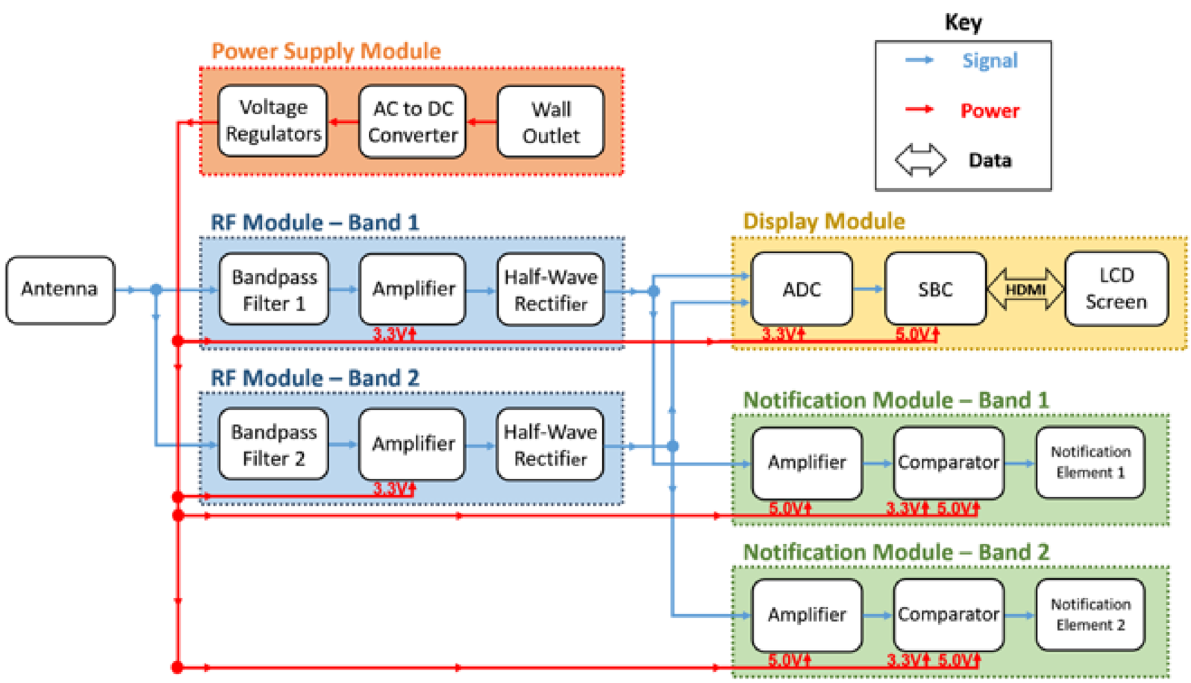

Figure 2: Detailed block diagram

2.1 Power Supply Module

Since our device is not required to move, it can be powered from a standard U.S. outlet (120 VAC, 60 Hz). The AC to DC conversion is achieved with a small AC-DC wall converter. The rest of our required voltages (bias/reference voltages for ICs, etc.) are achieved using voltage regulators.

We first determined the requirements of the other modules in order to calculate the necessary voltage and current requirements for the power supply. We then calculated the total power needs of the entire system and began to select components. Table 1 shows the various voltage and power needs of the other components in our design, which in turn dictates the total voltage and current specifications of our supply.

Table 1: Power and Voltage Characteristics of Device Components

Device	Current Needs (mA)	Voltage Needs (V)
Notif. Mod. Band 1 Amplifier	*.5*	*5*
Notif. Mod. Band 2 Amplifier	*.5*	*5*
Notif. Mod. Band 1 Comparator	*5*	*5*
Notif. Mod. Band 2 Comparator	*5*	*5*
RF Mod. Band 1 RF Amplifier	*50*	*3.3*
RF Mod. Band 2 RF Amplifier	*50*	*3.3*
Display Mod. ADC	*.5*	*3.3*
Display Mod. Single-Board Computer	*Up to 1500*	*5*

$$Power_{total} \leq 5 + 5 + .5 + .5 + 50 + 50 + .5 + 1500 = 1611.5\, mA \qquad \textbf{(1)}$$

Our total power consumption is given by Equation 1.

This current, although somewhat high, can also be achieved using standard AC-DC wall adapters. The single-board computer (SBC) draws the most power in our device. This is due to it running Python libraries live and powering the LCD screen.

The TMEZON AC-DC wall adapter is capable of maintaining a 12 VDC output with a maximum load of 2 A. The device is easily plugged into a standard DC jack. The 3.3 V and 5 V requirements of our design are achieved with the LM1117 voltage regulators from Texas Instruments. Both of these regulators regulate their respective voltages to within less than 50 mV with 12 V applied, with 1500 mA drawn. These devices imply that our design does not require a step-down (buck) converter. Note that although our total power is 1611.5 mA, the 3.3 V regulator must only need to withstand 100.5 mA. The 5 V regulator must withstand the remaining 1511 mA.

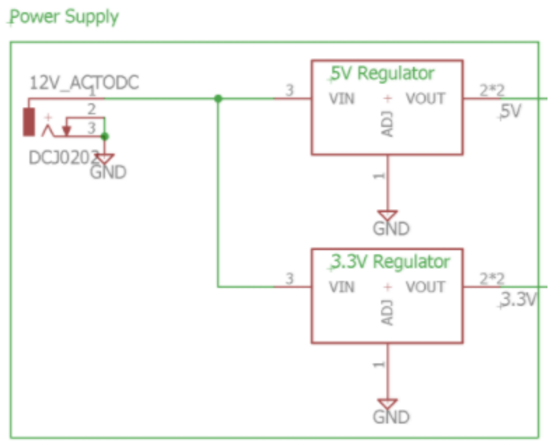

Figure 3: Power Supply schematic

2.2 RF Module

We choose a wideband antenna for our wide frequency range requirements (700-850 MHz and 1.5-1.9 GHz). We also must keep in mind that the antenna must have minimal attenuation. Given the intended form factor of both our PCB and final physical design, an antenna with an SMA connector is preferable.

Incoming signals are filtered with a passive bandpass filter using a capacitor and an inductor. An ideal bandpass filter attenuates all signals outside of a certain passband oriented around a center frequency as shown in Figure 4.

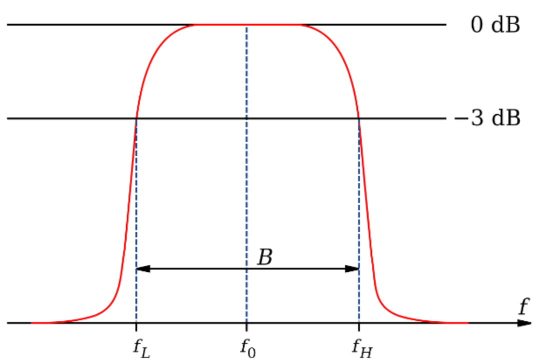

Figure 4: Ideal bandpass filter response with center frequency f_0

Using passive components ultimately makes our device cheaper and easier to produce. A circuit model of a simple bandpass filter is shown in Figure 5.

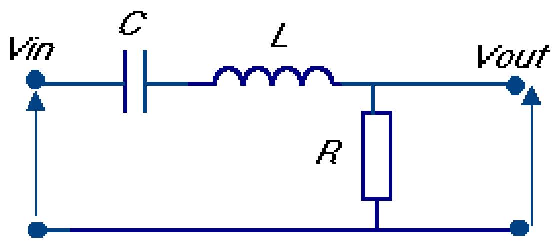

Figure 5: First-order bandpass filter circuit

Although capacitors and inductors can have issues at high frequencies (parasitics, self-resonance, etc.) our filter does not require a very narrow passband. Therefore, we can use Equation 2 the standard formula for a lumped bandpass filter.

$$f_c = \frac{1}{2\pi\sqrt{LC}} \Rightarrow LC = \left(\frac{1}{2\pi f_c}\right)^2 \tag{2}$$

An RF amplifier is used to boost the filtered signal to a level such that it can be translated into a DC signal via a half-wave rectifier. The rectifier circuit is a high frequency Schottky diode in conjunction with a smoothing capacitor as shown in Figure 6.

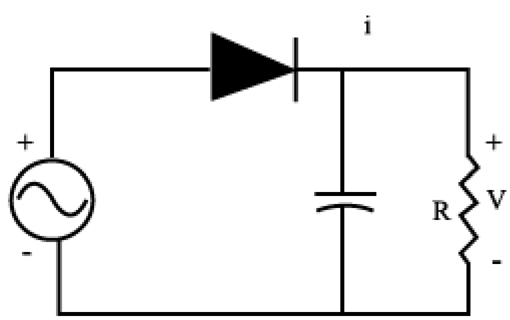

Figure 6: Half-wave rectifier circuit

Given these general requirements, I selected the wideband (698 – 2680 MHz) W5084K antenna from Pulse Electronics. Many antennas available reach frequencies as low as 715 MHz, but preliminary test results showed frequencies in the United States can reach as low as 710 MHz. Therefore, 698 MHz is a proper lower bound for our antenna's receiving capabilities. The upper bound of the antenna, 2.68 GHz, is enough to eliminate many high frequency signals. Given that our upper band of interest is in line with Puerto Rico cellular frequencies, we can ignore WiFi (2.4 GHz) signals as there is no WiFi available at the Arecibo Observatory. Therefore, 2.68 GHz is a sufficient upper bound.

Next, the bandpass filter was designed using Equation 2. When considering the lower band, this filter should pass all signals in our band of interest while attenuating neighboring signals (FM radio below our band, WiFi and Bluetooth above our band). Note that we cannot ignore WiFi when designing the lower band as this band will be tested in the United States with WiFi signals present. Due to these restrictions, the filter is designed with the intention of achieving 3 dB attenuation at 250 MHz (FM radio) and 1.5 GHz (WiFi and Bluetooth) for the lower bandpass filter and 0.5 dB attenuation at 800 MHz for the upper bandpass filter.

Bandpass filter transfer functions at higher (greater than 500 MHz) frequencies are significantly elongated on the right, higher frequency side. An intended filter center frequency of 720 MHz was chosen for the lower filter to compensate. A center frequency of 1.7 GHz was chosen for the upper filter as we do not care about an elongated right side. Using Equation 2, we first calculated the lower filter C and L values; we then arrived at Equations 3 and 4.

$$f_c = \frac{1}{2\pi\sqrt{LC}} \Rightarrow LC = \left(\frac{1}{2\pi f_c}\right)^2 \xrightarrow{f_c = 720\,MHz} C = 4.8\,pF,\, L = 10\,nH \tag{3}$$

$$f_c = \frac{1}{2\pi\sqrt{LC}} \Rightarrow LC = \left(\frac{1}{2\pi f_c}\right)^2 \xrightarrow{f_c = 1700\,MHz} C = 8.8\,pF,\, L = 1\,nH \tag{4}$$

The resulting circuit and corresponding values were simulated in Keysight ADS. The results of the lower bandpass filter and upper bandpass filter simulations are shown in Figure 7.

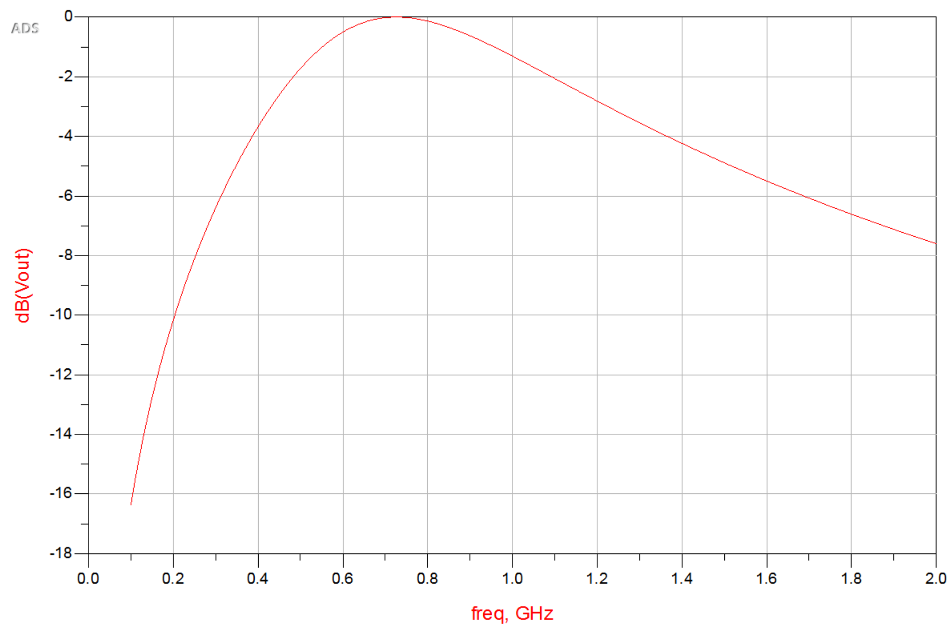

Figure 7: Lower bandpass filter simulation; the -3 dB values are located at 430 MHz and 1.22 GHz

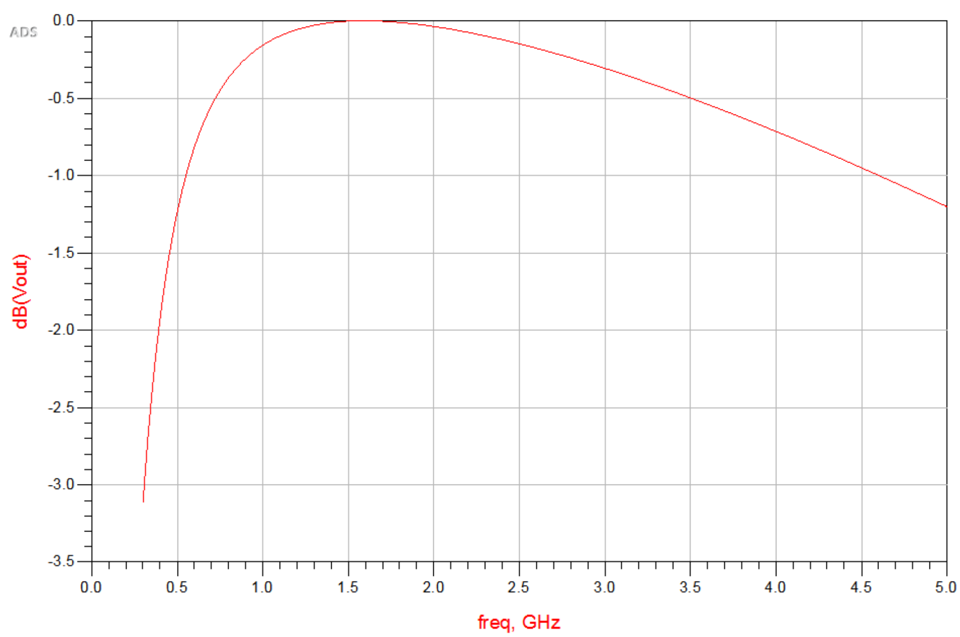

Figure 8: Upper bandpass filter simulation; the -0.5 dB values are located at 800 MHz and 3.5 GHz

As can be seen from the simulations, each of these filters properly attenuate unwanted signals.

Next, we need an amplifier that provides proper gain in our bands of interest. We selected the Qorvo TQP3M9008 for our circuit. The relative S-parameters, OIP3, and P1dB characteristics were verified to be compatible with our needs. It is a wideband RF amplifier with gains above +20 dB from 500 - 2100 MHz, thus we will not experience any issues with 3rd order distortion or power dropout. Additionally, it only requires a DC power source whereas some RF amplifiers require an AC bias. This makes it an excellent choice for our device. The amplifier's gain at different frequencies is shown in Figure 8.

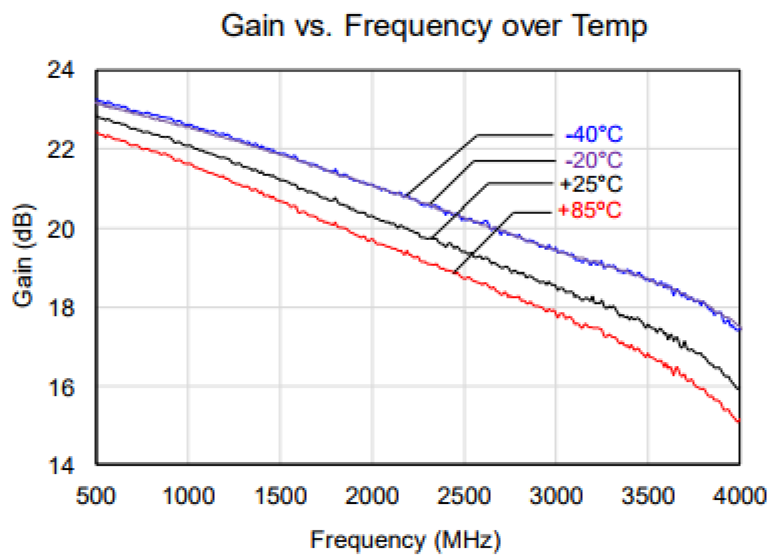

Figure 9: Qorvo RF amplifier gain versus frequency

The half-wave rectifier, as described earlier, is a BAT63 Schottky diode with a proper capacitor. This rectifies the incoming filtered signals, and makes them usable by our other design blocks. A schematic of our final RF module is illustrated in Figure 9.

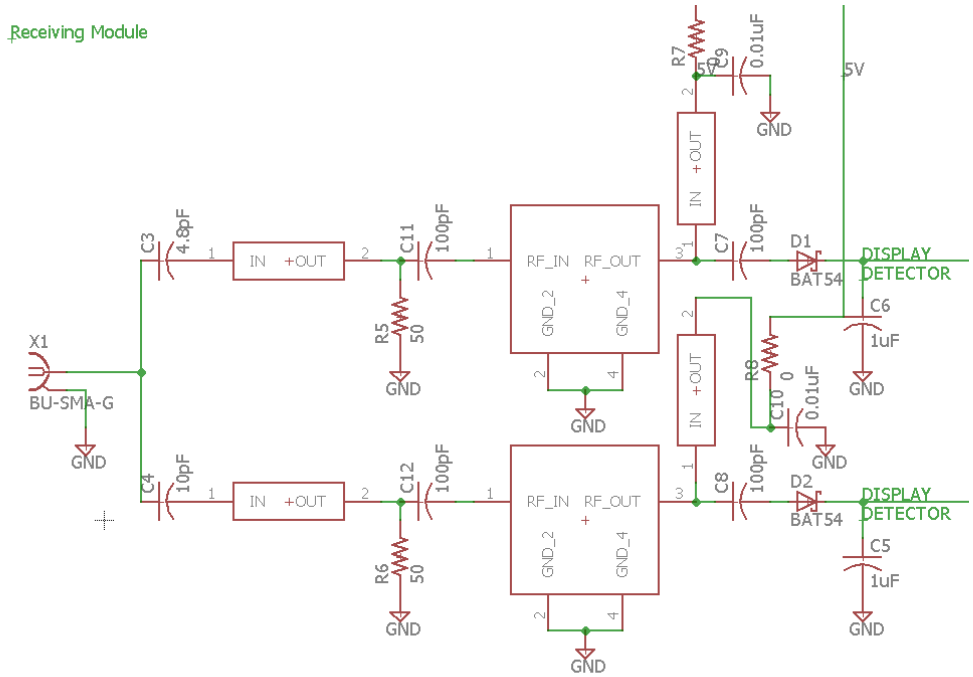

Figure 10: RF Module schematic

2.3 Notification Module

The objective for this module is to create a hardware solution for triggering a human-read notification element based on the rectified signal received from the RF module. This captures the most essential requirements of our project: a binary ON/OFF output that determines whether a nearby phone is transmitting or not. This operation must be done for both bands, and therefore the circuit design has identical branches. The basic order of operations for each branch is DC amplification, signal-reference comparison, and notification element (LED) triggering. Note that during operation, the LED is on when no transmission is detected, and it turns off when transmission is detected.

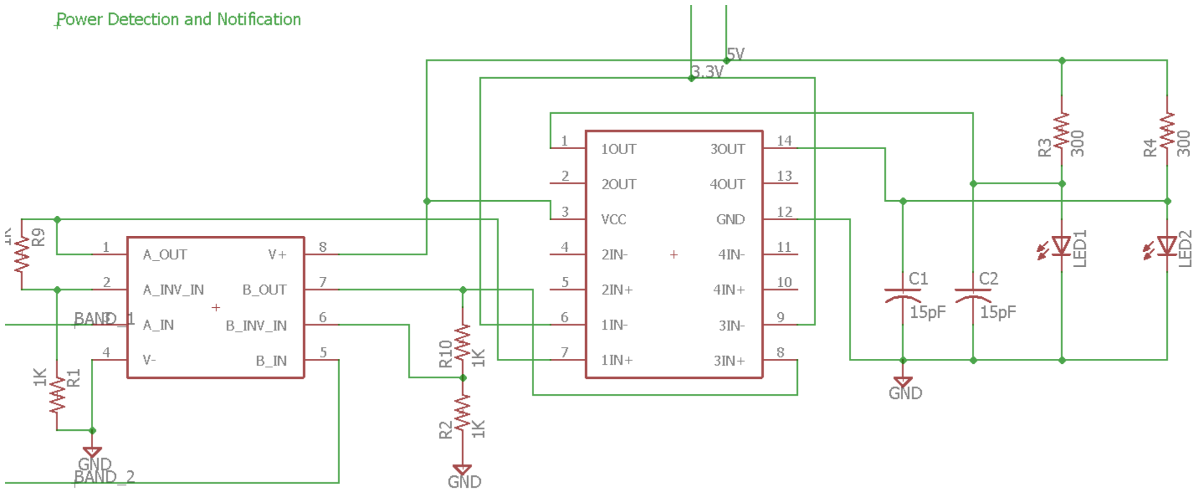

Figure 11: Notification Module schematic

The first block in this module is the DC Amplifier. The TI LMC6022IM is chosen since it operates with the available 5 V supply and uses a simple resistor biasing network to manipulate the large signal (DC) gain. The formula for calculating the gain (A_{CL}) of a non-inverting amplifier with a resistor network is shown in Figure 12.

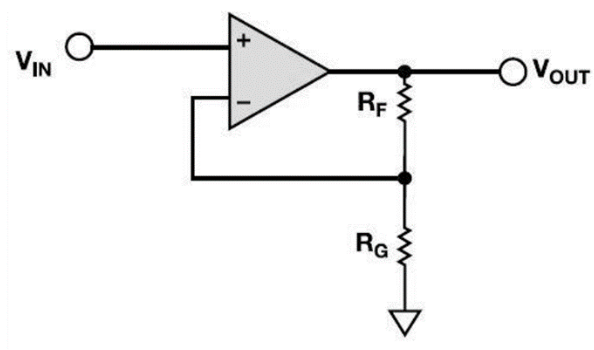

Figure 12: Non-inverting large-signal amplifier circuit

$$A_{CL} = 1 + \frac{R_f}{R_g} \tag{5}$$

The comparator following this amplifier must compare the active, rectified signal to a reference voltage. Since a requirement of the preceding RF Module is to output a DC signal of at least 50 mV during detection, this implies that the required gain from this DC amplifier is calculated as in Equation 6. Please note that the resistor values in the biasing network in the Figure 11 schematic are not accurate and are merely placeholders.

$$A_{CL} = \frac{3.3V}{50mV} = 6.67$$
$$\Rightarrow 1 + \frac{R_f}{R_g} = 6.67 \xrightarrow{R_f = 10{,}000\Omega} R_g = 1764\Omega \tag{6}$$

A comparator, the TI LM339 Quad Differential Comparator, was used to compare the signal strength (in voltage) to a threshold. This threshold came directly from the 3.3 V voltage regulator, and the chip uses a 5 V supply. The two branches each used a single comparator in the chip (comparators 1 and 3 as seen in Figure 11). Based on the input differential polarity, the comparator circuits output a high or low impedance and therefore will drain the current when not triggering the notification element. Please note that the way the circuit was wired results in a logical high when the signal is below the reference, and outputs a logical low when the signal strength is high and above the reference.

The primary purpose of the notification element block is to provide a universally recognizable binary output translated from the high or low signal received by the behavior of the comparator. For this purpose, we used a 2.7 V LED powered by the 5 V supply across a voltage divider circuit. When the comparator outputs a logical high, current is allowed to flow through the LED branch and the LED turns on. When the comparator outputs a logical low, the current is drawn through the low impedance comparator.

2.4 Display Module

Our display module's main goal is to visualize the signal strengths of the two bands of interest. Since this module receives pre-processed DC voltages from the RF module, visualizing these same voltages in real-time on an LCD screen is sufficient.

We use a Raspberry Pi 3 Model B to read voltages into its GPIO pins, and then subsequently display these voltage levels. This is done using the software package 'matplotlib', a Python plotting library. The pins on the Raspberry Pi are purely digital, so we use an analog-digital converter, the MCP3004, to sample the voltages.

The LCD screen (5" 800x480) is connected to the Raspberry Pi via the HDMI interface after adjusting some of the system configuration parameters. The analog-digital converter takes the two RF module outputs as separate channel inputs. In order to sample with the analog-digital converter and read data into the Raspberry Pi, the SPI (Serial Peripheral Interface) communication protocol must be used. To facilitate SPI communication, we enable the SPI bus on the Raspberry Pi and attach the analog-digital converter to the Raspberry Pi as shown in Figure 13:

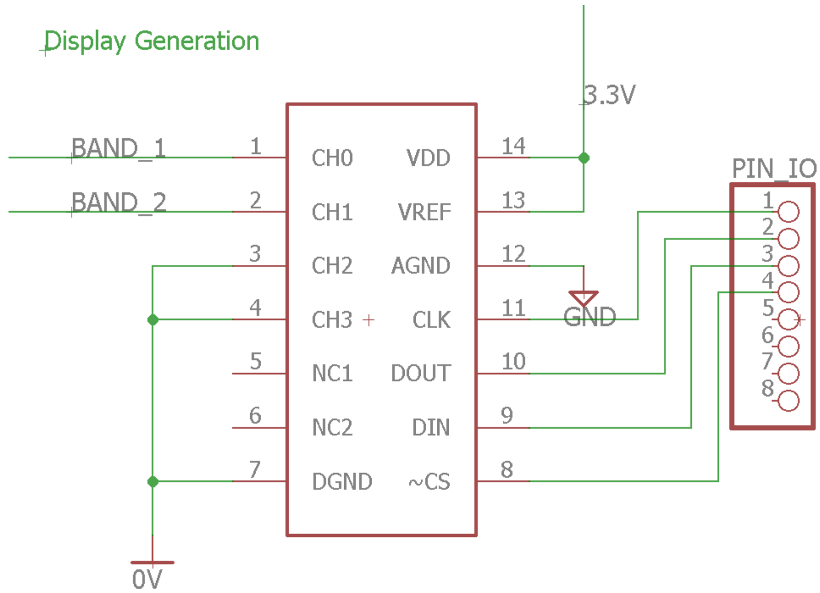

Figure 13: Display Module schematic

Table 2: Pin Assignments from PIN_IO to Raspberry Pi

PIN_IO Pin Number	Signal Name (from Raspberry Pi)
1	SCLK
2	MISO
3	MOSI
4	CE0 (Chip Enable 0)

We can then setup the Raspberry Pi as the master unit in this master-slave configuration, which tells the slave unit (MCP3004 ADC) to sample voltages according to the flowchart in Figure 14.

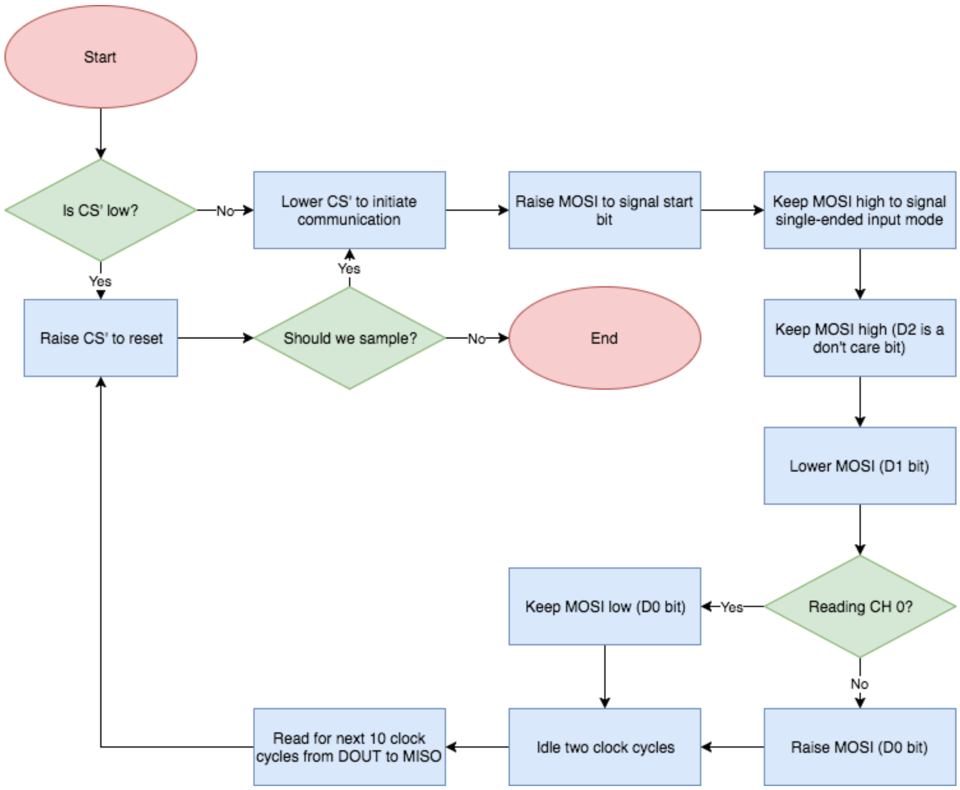

Figure 14: Sampling MCP3004 with SPI communication

3. Design Verification

3.1 Power Supply Module

We performed all of our testing by probing the output of the devices of interest directly on the PCB with a multimeter. We expect 12 V output from our purchased wall adapter, and consistently receive between 12 V to 12.1 V when probing the output of the adapter under various loads, which meets our expectations. With this output then going into the 3.3 V regulator, we see that the output is, as expected, 3.3 V with a margin of error on the order of a couple of millivolts. For our 5 V regulator, we observed the range is between 5 V and 5.05 V, which also satisfies our requirements.

3.2 RF Module

The antenna was tested by connecting it to an oscilloscope and using another antenna from the ECE 445 lab to transmit a +10 dBm signal from a nearby signal generator at various frequencies. The receiving antenna's reading on the oscilloscope varied by less than 1.5 dBm across our effective range of 700 MHz - 1.9 GHz, satisfying our requirements. Additionally, the antenna provided 5 dBm of attenuation at FM radio's 250 MHz, allowing us to get added filtering below our lower band.

The bandpass filter was tested after soldering the components onto our PCB. The input was connected to a signal generator, and the output was connected to an oscilloscope. The lower bandpass filter's output varied by only .5 dBm across our range of 700 – 850 MHz. At 250 MHz, the output was attenuated by 8 dBm. At 1.5 GHz, the output was attenuated by 4.5 dBm. This satisfies our requirements. The upper bandpass filter's output varied by .3 dBm across our range, performing slightly better. At 800 MHz, the signal was attenuated by 1.5 dBm. This also satisfies our performance requirements.

The RF amplifier was tested after soldering it to our PCB after our bandpass filter. Again, the input was connected to a signal generator and the output was connected to an oscilloscope. We measured the strength of the output signal compared to the output of the signal during the bandpass filter testing (no RF amplifier). We saw a gain of 22 dBm at 700 MHz and a gain of 20.5 dBm at 1.9 GHz, meeting our design standards.

The half-wave rectifier was tested by feeding in an input signal via a high-frequency signal generator and then probing the output voltage of the capacitor. The rectifier was fed an 800 MHz signal with a peak voltage 1 V, and yielded 0.93 V across the capacitor (as read on the multimeter).

3.3 Notification Module

This module was tested both block-by-block and as a whole. To test the DC amplifier, it was soldered onto a breakout board and connected to a breadboarded circuit of a resistor biasing network, two power supplies, and a digital multimeter. The first power supply provided the 5 V supply to the amplifier, and the second provided the input DC signal which was first set to 50 mV. The resistor network was composed of R_f of 10kΩ and R_g of 1kΩ, which yields a gain of 11 according to Equation 5. This is above our minimum required gain of 6.67, and produced satisfactory results.

The comparator was also tested with a breakout board and breadboarded circuit of supplies and a multimeter. Two supplies were fed into the differential inputs and one was set to 3.3 V while the other was varied across a small range centered on 3.3 V. The switching voltage level was low, on the order of 1 mV. This was then used to trigger an LED which was connected to the corresponding voltage divider. The LED was triggered and visible as expected when the comparator outputted high impedance.

When testing the entire module, a variable input signal was fed into the DC amplifier and the LED switched accordingly. A high signal resulted in the LED turning off, and a low signal resulted in the LED turning on. This is expected behavior since, as mentioned previously, the differential comparator inputs were such that the LED turns off with a higher-than-reference signal.

3.4 Display Module

The general procedure for testing the display module relied on feeding in known DC voltage inputs to the two channels of the analog-digital converter, and cross checking their values on the bar graphs shown on the LCD screen. This makes the testing procedure end-to-end for this module. From 0 V to 3.5 V, the display represented the source input within a 10mV margin of error. The values also updated within 0.5 seconds of changing the input, which makes this a real-time display, thus satisfying all of our requirements. Figure 15 shows sample results for feeding in 1.5 VDC for *Band 1* and 3.3 VDC for *Band 2*.

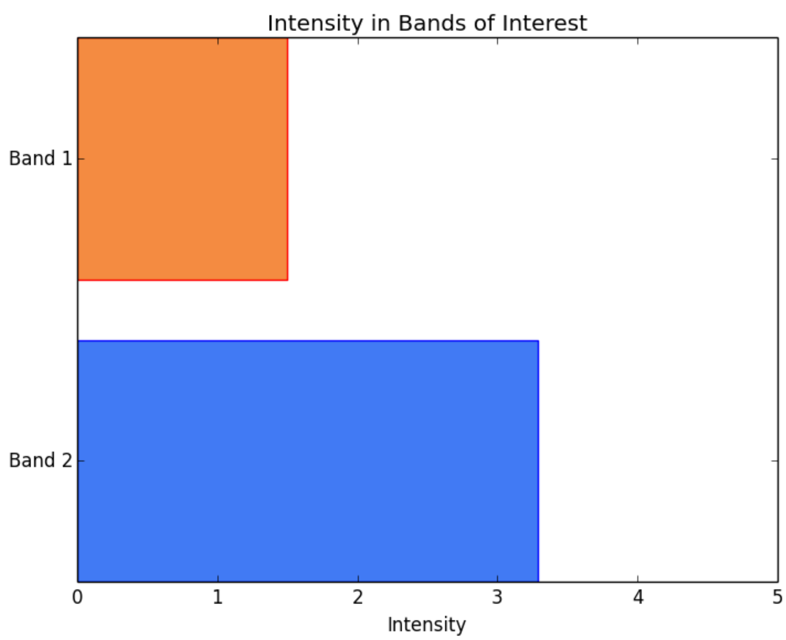

Figure 15: Display of Sample DC Voltage Input

4. Costs

4.1 Parts

Table 3: Parts Cost

Part	Manufacturer	Retail Cost ($)	Bulk Purchase Cost ($)	Actual Cost ($)
Wideband Antenna	Pulse Electronics	16.84	10.18	16.84
SMA Connector	Cinch Connectivity	8.85	5.77	44.25
LCD Screen	Waveshare	45.99	35.99	45.99
Raspberry Pi 3 Model B	Raspberry Pi	35.00	35.00	35.00
SD Card w/Raspbian	LoveRPi	15.00	15.00	15.00
BAT63-02V Diode	Infineon Technologies	0.43	0.01	0.86
12V AC/DC Wall Adapter	TMEZON	15.99	15.99	31.98
3.3 V Reg. (LM1117-3.3)	Texas Instruments	1.11	0.38	1.11
5.0V Reg. (LM1117-5.0)	Texas Instruments	1.11	0.38	2.22
DC Amp. (LMC6022)	Texas Instruments	1.75	0.60	3.50
Diff. Comparator (LM339)	Texas Instruments	0.29	0.08	0.29
RF Amp. (TQP3M9008)	Qorvo	4.79	2.14	9.58
10-bit ADC (MCP3004)	Microchip Technology	2.20	1.58	2.20
Green LED	Kingbright	0.18	0.04	0.36
Assorted resistors	Various	0.14	0.01	1.40
Assorted capacitors	Various	0.28	0.07	3.08
Assorted inductors	Various	0.40	0.09	1.60
Total				**215.26**

4.2 Labor

A typical ECE Illinois graduate can earn around $40 an hour in the industry, so we assume this wage. We estimate that a working prototype can be completely finished within the 16 weeks of the course. We also assume that this work would require a consistent 15 hours per week of work. This leads us to a final labor cost calculated by:

$$\frac{15[hrs]}{[week]} \times 16[weeks] \frac{40[\$]}{[hr]} \times 2.5 = \$24,000 \quad \textbf{(7)}$$

As seen from our calculations, the initial cost of producing our first prototype and working device is our labor cost plus our individual parts cost: $215.26 + $24,000 = $24,215.26. From there, disregarding maintenance and assembly, we could produce additional units at $166.61 per device.

5. Conclusion

5.1 Accomplishments

Our project was able to perform everything that was necessary in order to constitute a successful project. Our main success was the RF module's ability to output a measure of high signal strength during active cellular transmission. Other notable successes included real-time visualizations of the aforementioned measure of signal strength, and a functioning LED notification element. Ultimately, our project was able to perform active cellular transmission detection from a range of up to 3m, surpassing our original requirement.

5.2 Uncertainties

Our only uncertainty with our project lies in the behavior of the LED that is present in the notification module. Due to the sporadic communication nature of cellular phones, the signal is never smoothly captured or stable. This leads to rapidly varying voltage levels at the output of the RF module, which means that the LED tends to flicker in the presence of active transmission. In this project, we strived to create an excellent user interface/visual interpretation of these signals, but the current state of the LED does not create this frontend that we desire. In Section 5.4, we propose a method to create more stable behavior for the LED.

5.3 Ethical considerations

There are a couple things we needed to keep in mind when designing this project, the most important of which lies in the power supply side. We will be powering various elements of our circuit with a wall outlet, thus we need to take extra caution when converting the 120V AC wall outlet to 12V DC with our AC-DC converter so that we avoid possible electric shock and other forms of bodily harm in accordance with Section 1 in the IEEE Code of Ethics [17]. Buying quality wall adapters resolves these issues.

We must also abide by FCC regulations. This is not an issue if we are only receiving RF signals, however we must still take precaution to not arbitrarily transmit waves. This could result in problems such as jamming signals, which is not only illegal, but would defeat the purpose of the detecting RFI in the first place.

A key ethical point we deal with stems from the nature of this project, namely that we are "to improve the understanding of technology; its appropriate application, and potential consequences;" (IEEE Code of Ethics #5) [17]. One of the goals of this project is to visually educate the visitors of the Arecibo Observatory about the effects of RFI, which affects the measurements carried out by researchers.

5.4 Future work

In order to remedy the issue of having a rapidly switching LED, we propose that in the future we allow the LED to remain on throughout the entire duration of cellular transmission. We can do this by replacing the notification module with the Raspberry Pi, allowing the computer to control when the LED lights up via software signals. To ensure stability, we would hold the LED high for three seconds after which the Raspberry Pi will then give a low and turn the LED off. However, while holding the signal high, we could still check if there is still significant signal strength coming from the RF module. If so, then we restart the timer. This method would help mask the volatile nature of the incoming cellular signals.

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Appendix A Requirement and Verification Table

Table 4: RF Module Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. <u>Detection distance of 1 m</u> **a. Minimum Discernible Signal of –50 dBm**	1. Connect antenna to signal generator, transmit +15 dBm signal. Move device 1 m away from transmitting antenna and ensure DC output >50mV a. Change transmitter power to –50 dBm and ensure DC output	Y
2. <u>Attenuate unwanted signals</u> **a. 3 dB drop for FM radio (250 MHz) with lower BPF** **b. 3 dB drop for Bluetooth/Wifi (>1.5 GHz) with lower BPF** **c. 1 dB drop for U.S. signals (<800 MHz) with upper BPF**	2. Connect antenna to signal generator, transmit +15 dBm 720 MHz (lower test) and 1.7 GHz (upper test) signal. Probe output of BPF. a. Change transmitter frequency to 250 MHz. Observe lower BPF output power relative to 720 MHz. b. Repeat (a.) for 1.5 GHz transmitter frequency. c. Change transmitter frequency to 800 MHz. Observe upper BPF output power relative to 1.7 GHz.	Y
3. <u>Output a usable DC signal</u> **a. 50 mV DC output from halfwave rectifier**	3. Connect input of HW rectifier to signal generator. Generate typical (720 MHz, -10 dBm) incoming signal. Connect output to oscilloscope. a. Measure DC output voltage of rectifier	Y

Table 5: Power Supply Module Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. <u>3.3 V regulation within 10 mV</u> **a. Maximum load of 500 mA**	1. Connect AC-DC adapter to wall outlet and DC jack on PCB at the input of the regulator. Probe the DC output on a multimeter. a. Vary load resistances to draw up to 500 mA	Y
2. <u>5.0 V regulation within 200 mV</u> **a. Maximum load of 2 A**	2. Connect AC-DC adapter to wall outlet and DC jack on PCB at the input of the regulator. Probe the DC output on a multimeter. a. Vary load resistances to draw up to 2 A	Y

Table 6: Notification Module Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. <u>DC Amplifier capable of >6.67x amplification</u>	1. Power DC amplifier correctly and provide an input voltage. Change bias resistances and measure input-output gain on multimeter.	Y
2. <u>Comparator switches states within 10 mV of reference voltage (3.3 V)</u>	2. Power and bias comparator correctly. Change compared input to within –15, -10, -5, 0, +5, +10, and +15 mV of reference voltage.	Y

3. <u>LED visibly switches on/off when a signal is detected</u>	3. Assemble entire DC amplifier – comparator – LED circuit. Provide comparator compare voltage such that it switches. Observe LED state change.	Y

Table 7: Display Module Requirements and Verifications

Requirement	**Verification**	**Verification status (Y or N)**
1. <u>Display 2 distinct bands on screen</u> **a. Display lower, USA band and higher, PR band**	1. Connect RPi to LCD screen. Ensure plots appear. a. Switch 150 mV signal at input of ADC channels on/off. Ensure plot updates.	Y
2. <u>Update plots in real time</u> **a. Maximum delay of 0.5 s**	2. Employ same setup as Verification 1. a. Switch 150 mV signal off, time the response on the screen.	Y
3. <u>Precise signal strength information</u> **a. Represent output of HW rect. within 10 mV**	3. Employ same setup as Verification 1. a. Increase ADC channel input by 5 mV increments. Observe plots.	Y