Phone Audio FM Transmitter

ECE 445 Design Document

Team 18
James Wozniak (jamesaw)
Madigan Carroll (mac18)
Dan Piper (depiper2)

TA:
Abhisheka Mathur Sekar

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Table of Contents

1 INTRODUCTION

1.1 PROBLEM

In cars with older stereo systems, there are no easy ways to play music from your phone as the car lacks Bluetooth or other audio connections. There exist small FM transmitters that circumvent this problem by broadcasting the phone audio on some given FM wavelength. A significant safety flaw with these devices arises when the user enters an area in which a radio station is transmitting on the same frequency they are using. While operating the vehicle, the user must manually scan through the channels, identify an open frequency, and set the transmitter to that frequency, taking their attention off of driving.

1.2 SOLUTION

We will build upon these preexisting devices, adding the functionality of automatically switching the transmitter's frequency, creating a safer and more enjoyable experience. For this to work, several components are needed: a Bluetooth connection to send audio signals from the phone to the device, an FM receiver and processing unit to find the best wavelength to transmit on, and an FM transmitter to send the audio signals to be received by the car stereo.

1.3 HIGH LEVEL REQUIREMENTS

These are further defined technically with methods of verification in the subsystem requirements and verification tables.

1. *Device will connect and receive audio data via Bluetooth.*
2. *Device will transmit audio via FM.*
3. *Device will scan FM stations and automatically select one with minimal interference.*

1.4 VISUAL AID

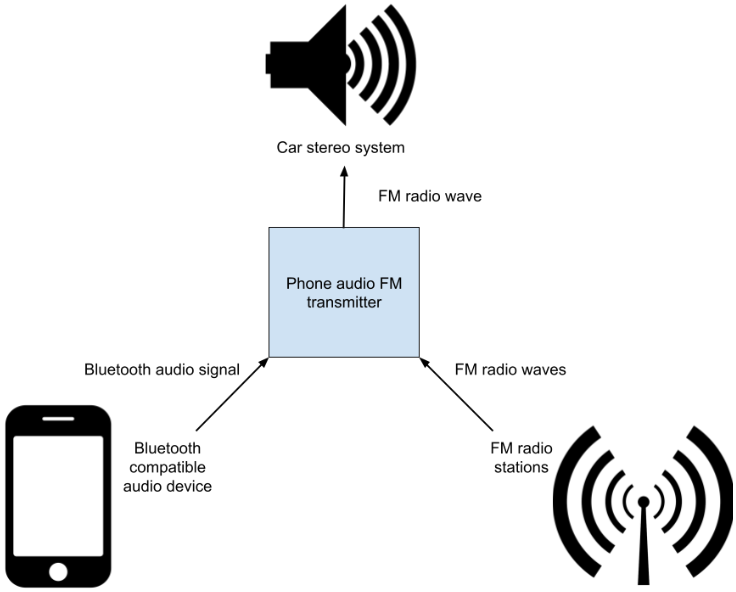

Figure 1: Phone Audio FM Transmitter Visual

2 Design

2.1 Block Diagram

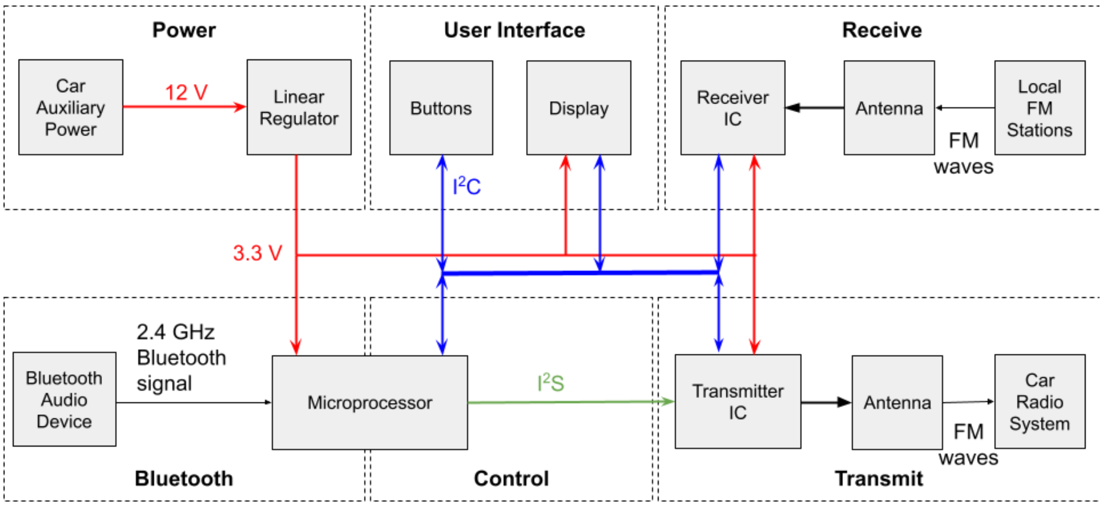

Figure 2: Block Diagram

2.2 Physical Design

The physical design of our project is similar to current designs already on the market and other accessories for car auxiliary power ports. It is a two-piece design containing a front faceplate cut out to provide access to the display and pushbutton and a back plug to insert into the port. These pieces are held together with external screws through the back. The dimensions were chosen to provide enough space for the LCD display and to provide a wide perimeter for the FM transmit and receive antennas. These values may change as the PCB design is finalized and exact dimensions can be provided, however, the basic form factor will likely stay the same.

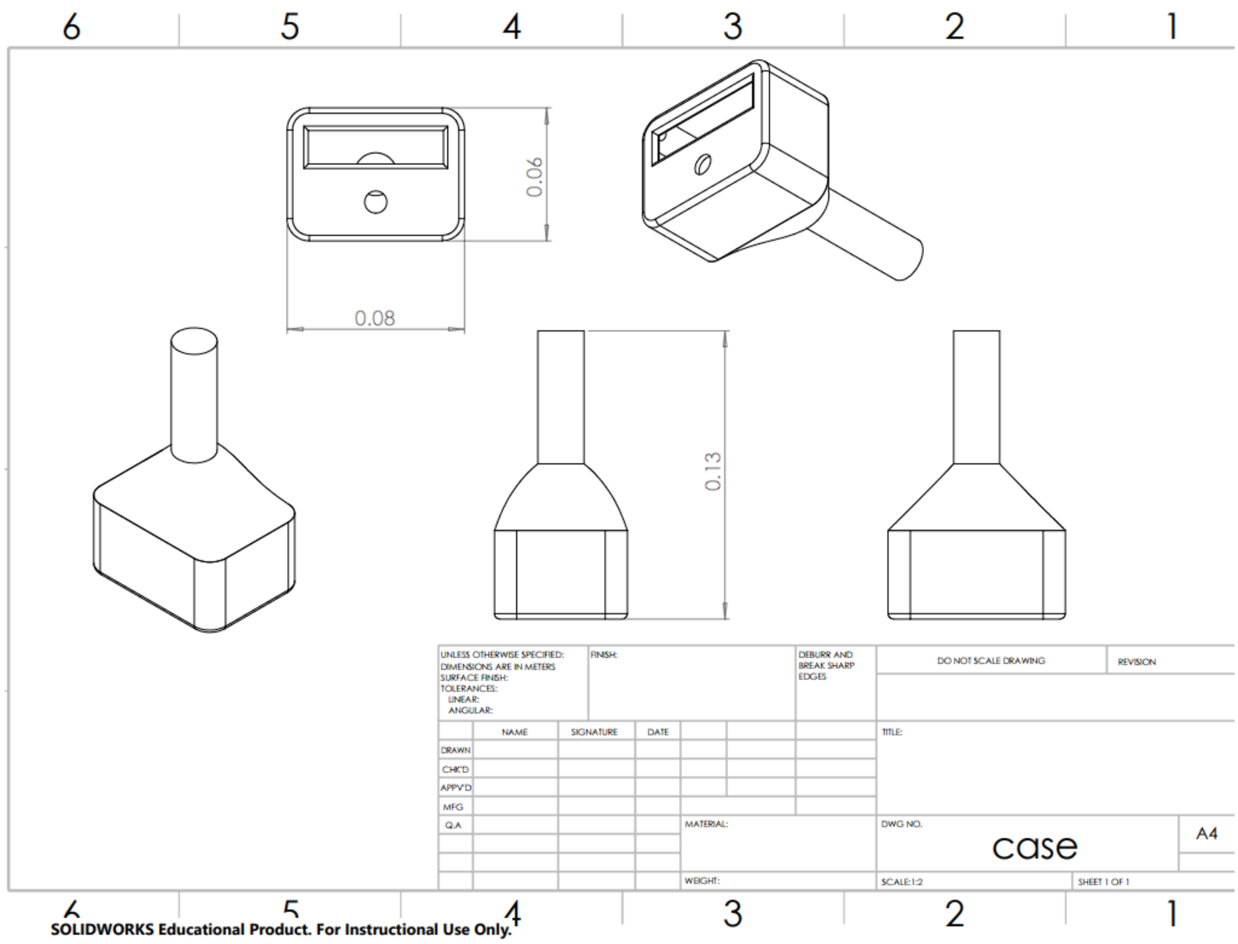

Figure 3: CAD Model of Current Design

2.3 Subsystems

2.3.1 Control

The control system will consist of a microcontroller and surrounding circuitry. It will be capable of communicating over I^2C and I^2S and will take input from the user. It will set up and control all other IC's over the I^2C bus and transmit the audio data to the transmitter via the I^2S bus. When the user requests, it will implement the protocol to scan the FM band and select the most suitable frequency to play over. It will then output a signal to the FM transmitter to adjust the transmitting frequency to the band determined above. The ESP32-S3-WROOM-1 [1] will be used as the microcontroller. Additionally, the system will interface with a computer via the included micro-USB port for programming and debugging.

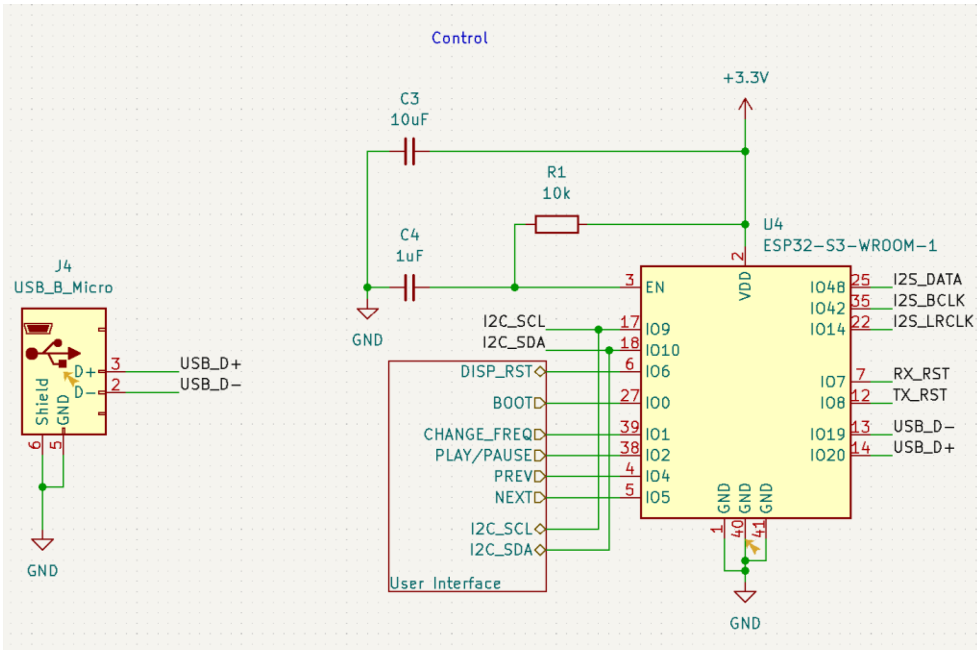

Figure 4: Control Schematic

Design decisions

- *The ESP32-S3-WROOM-1 was selected because our group is familiar with the ESP32 line, the module provides a useful Bluetooth, I^2C, and I^2S interface, and it has the necessary transmission and reception hardware for Bluetooth built in.*
- *There are multiple options for programming the microcontroller. We opted to directly interface with it over micro-USB because it will require less hardware than other options. Additionally, if we were to use an additional IC to implement a USB-UART interface we would need to manage a 5V rail in addition to 3.3V and our chosen implementation negates this need.*
- *On startup, the ESP32 relies on strapping pins to start in the correct mode. Pin IO0 determines if we are booting on internal memory or if we are flashing the device from an external computer. It has an internal pull-up resistor setting it to boot from memory, but we included a button in the user interface to pull the pin low for when we flash the device. All the other strapping pins have weak internal pull-up/down resistors that are set to the parameters we require so we opted to leave them disconnected so that they cannot be in the incorrect state on startup.*
- *The microcontroller must be fully powered up before the EN pin is brought high so we included a RC circuit that will delay the enable signal for ~10ms which is enough time according to the device's datasheet.*
- *The microcontroller can be programmed using the Espressif IDF provided by the manufacturer or with a library for the Arduino IDE. Both options offer most of the functionality we require except the Arduino library is limited to a 16kHz sampling rate for I^2S which is not acceptable for our use. Therefore, we decided to use the Espressif IDF for programming.*

Requirements	Verification
Can write and read data from the I^2C bus	Writing to bus: 1. Flash a program to the board which writes a singular byte to the bus repeatedly. 2. Read the data on the bus using a digital signal analyzer. Reading from bus: 1. Flash program to board that reads data from the bus and outputs it to the serial connection. 2. Using a function generator, send SDA and SCL signals as inputs to the bus pins. 3. Using a serial client, check the data output by the microcontroller against the input.
Can write audio data to the I^2S bus	1. Flash a program to the board which writes a 2kHz sine wave to the bus and outputs each sample to the serial connection. 2. Read the data on the bus using a digital signal analyzer. 3. Using a serial client, check the data output to the bus.
Takes input from the user interface	1. Flash program to board that reads data from the user interface and outputs it to the serial connection. 2. Provide inputs to the user interface. 3. Using a serial client, check the data output by the controller against the input.

2.3.2 Bluetooth

This system will interface with the user's audio device. It will connect wirelessly with the device using the Bluetooth protocol. The device will transmit audio data which the subsystem will parse and convert to PCM to be sent to the control subsystem. Because the microcontroller offers Bluetooth functionality, this subsystem will be entirely housed within it.

Design decisions

- *As described above in the control subsystem, we selected the ESP32-S3-WROOM-1 for its integrated Bluetooth functionality and built in Bluetooth transmission and reception circuitry.*

Requirements	Verification
Device is discoverable and able to pair to a separate Bluetooth audio device.	1. Flash a program to the board that configures the Bluetooth system with a unique name and writes Bluetooth data to the serial connection. 2. Using a smartphone, find and connect to the appropriately named Bluetooth device. 3. Check on the smartphone and a serial client for a successful connection.
Bluetooth audio signal from connected device is properly received at the microcontroller.	After Bluetooth connection is established, via serial connection to the microcontroller: 1. Flash program to board which uses functions within the ESP library to extract AVRCP data, specifically song metadata and writes it to the serial connection. 2. Connect to the microcontroller with PuTTY or other serial client and check output data for correctness.

2.3.3 FM Transmitter

This module will receive the audio signal digitally from the control unit (both on the PCB) and then transmit the audio via the FM radio frequency chosen by the control unit. This module will use an integrated circuit, the Silicon Labs Si4711 [2] integrated FM transmitter. The Si4711 is a smart modulation chip; it is able to receive digital audio via the I^2S protocol, and communicate digital control signals using the I^2C protocol, and can be powered by the 3.3V system power supply we will use. It uses onboard digital signal processing to modulate the signal. For our antenna, we will use a wire loop embedded in the enclosure, as recommended by the Antenna design guide [3].

The control unit will send the audio data digitally via I^2S to the transmitter IC to the Once the control unit and the main algorithm decide on a transmission frequency, the control unit will send a command via the I^2C bus to the IC to set the transmission frequency, and then an argument containing the frequency.

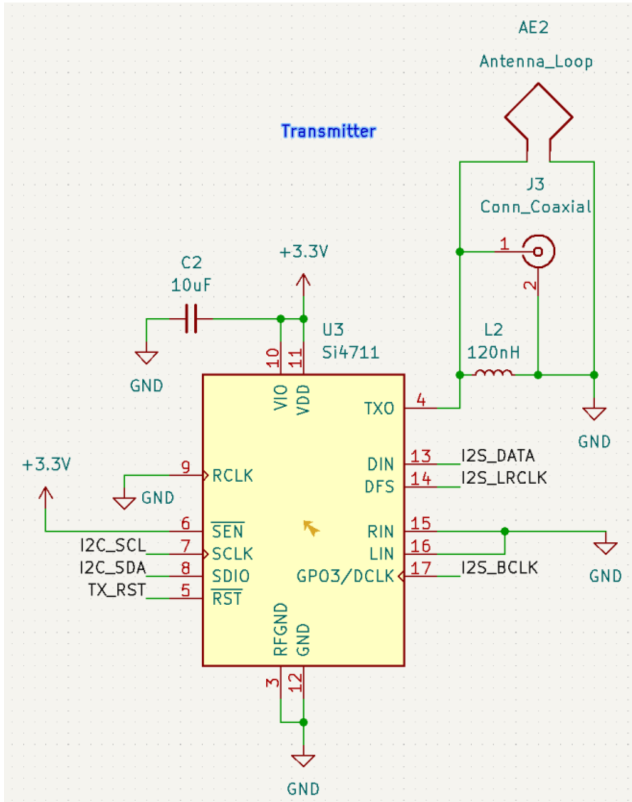

Figure 5: Transmitter Schematic

Design decisions

- We chose the Si4711 for our FM transmitter because it contains almost all of the necessary hardware fully integrated in the chip. I^2S was a convenient protocol to use with our MCU, and the fact that it contains the ADC and DAC makes it simple to include in our design.
- For our Antenna, the antenna design guide for Si47xx specifies that embedded antennas can be used with this IC. We will use a 24AWG wire of length ~ 6-13 cm as recommended by the design guide, in a loop configuration. The Antenna will run along the outer edge of the enclosure to maximize length, and therefore transmission power. Using a wire antenna, as opposed to a PCB trace minimizes parasitic capacitance and makes it more convenient to avoid other components on the board.
- For verification, we included pads to attach an SMA connector to the antenna input of the receiver. This will allow us to attach the connector while we are testing the device but remove them to save space and cost in the final product.

Requirements	Verification
The transmitter IC is able to transmit a signal at a frequency specified by the control unit. The	With the antenna not connected to the PCB: 1. Connect the output SMA port to a spectrum analyzer. 2. Flash the board with a program to change the transmission frequency at specified intervals.

	3. Program sends command to set frequency. 4. Program sends frequency argument. 5. Measure the output frequency at the spectrum analyzer.
When the control unit is transmitting digital audio via the I2S data channel, the transmitter IC is able to receive that data, modulate it, and transmit it at the chosen frequency.	1. Connect the output SMA port to a spectrum analyzer. 2. Flash the board with a program to send various single-frequency audio tones to the transmitter at a predetermined transmitting frequency. 3. Program selects transmitting frequency. 4. Program sends tone frequency via I^2S. 5. Observe the output on the spectrum analyzer.

2.3.4 FM Receiver

This module will be responsible for determining the RF power being transmitted at the frequencies specified by the control unit. This module will use an integrated circuit, the Skyworks Si4706 [4] integrated FM receiver. The receiver IC can send and receive digital communication signals via the I^2C protocol and can be powered by the 3.3V system power supply we will use. It also has the capability to make signal quality measurements including measuring the signal strength of the received signal. We will use the same embedded loop antenna design used for the transmitter module.

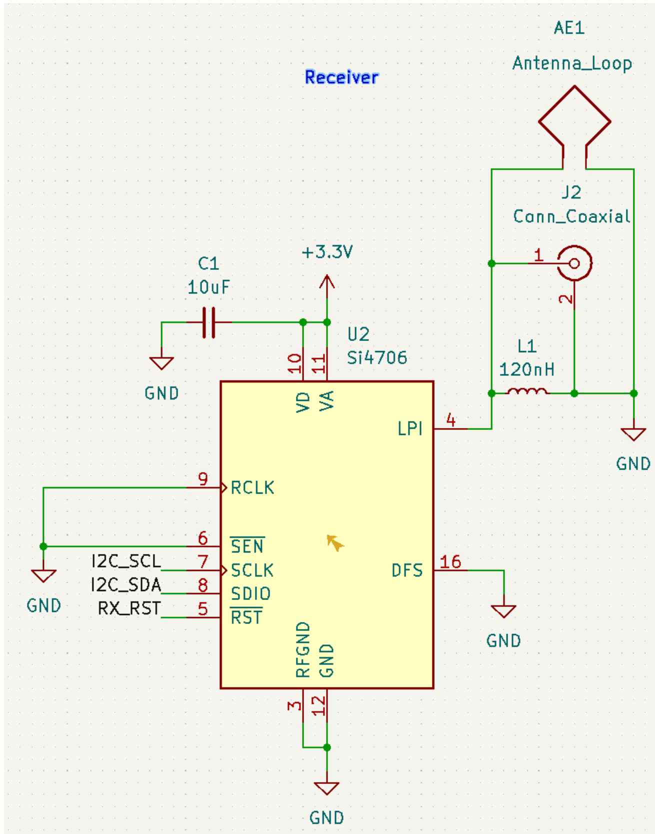

Figure 6: Receiver Schematic

The control unit will send a command on the I^{2}C bus to the receiver IC to set the receiving frequency. Upon changing the receiving frequency, the receiver IC will take signal quality measurements and store them on internal registers, after a minimum of 300µs, as specified by the programming guide [5]. The control unit will then send a command that queries the status of these registers, and the receiver IC will send the status over the I^{2}C bus,

Design decisions

- We chose the Si4706 for our FM receiver because of the signal quality measurement capabilities. Choosing a chip that can communicate digitally over I^{2}C is convenient because all our components can communicate on a single bus. The received signal strength measurement enables the main functionality of our goals for the project.
- For verification, we included pads to attach an SMA connector to the antenna input of the receiver. This will allow us to attach the connector and input signals to the receiver while we are testing the device but remove them to save space and cost in the final product.

Requirements	Verification
The receiver IC must be able to measure the signal strength of an FM channel specified by the	With the antenna not connected to the PCB: 1. Connect the input SMA port to a spectrum analyzer

control unit, and communicate that back to the control unit	2. Set up a signal generator to output a low frequency tone ~ kHz, Modulated to a specified FM channel. 3. Flash the board with a program to measure the signal strength at that frequency, and at another frequency with much lower power • Control unit sends command to set receive frequency. • After waiting a minimum of 300µs control unit sends command to query the signal quality indicators • Control unit sends signal strength measurements to serial port, to be read on the PC. 4. Compare received power indicated at the frequency output by the signal generator against the power indicated at the other frequencies.

2.3.5 Power

The device will be used in a car auxiliary port. Therefore, it will have an input voltage ranging from 12-15V. It will not require any active control so it will have no inputs other than the external power source and its output will connect to all power inputs of other subsystems.

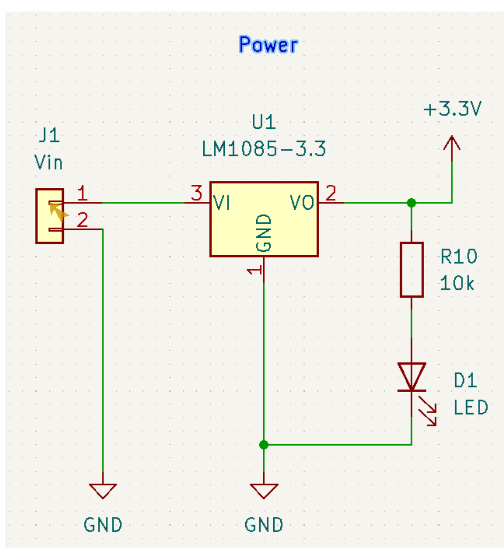

Figure 7: Power Schematic

Design decisions

- The LM1085-3.3 voltage regulator can output 3A and we only require 600mA from our voltage regulator, so we looked at other options. The other choices were either out of stock, could not put out the desired current, or could not handle the 12-15V input so we chose this IC.
- We considered protection circuitry such as a fuse or diode but decided they were unnecessary for our implementation. If there is some sort of fault that draws too large of a current in our device there the worst that would happen is some component destructing and opening the circuit, there is nothing flammable or dangerous. Additionally, the vehicle will have a 10-20A fuse limiting the current on the power port. The datasheet discusses possible needs for a protection diode but stated one is only necessary when the load capacitance is greater than 1mF which our load is less than.

Requirements	Verification
Output 600mA continuously at 3.3V ±0.3V	1. Solder the power supply to PCB before all other components. 2. Connect an oscilloscope in parallel with a 5Ω resistor across the output voltage rail and ground. This will draw a minimum of 600mA across the entire acceptable voltage range. 3. Measure the output voltage for at least 5 minutes and ensure it remains within the acceptable range.
Interface properly with an automotive auxiliary power port	1. Plug the device into the port. 2. Ensure the power LED illuminates.

2.3.6 User Interface

This system will provide the controls and feedback to the user. This includes buttons to switch to a clear frequency and song controls (play/pause, skip, and previous), and a display to show the broadcast frequency being used. The display will be the Newhaven Display C0220BiZ LCD [6] which provides the advantages of displaying text for debugging or song metadata, and the inclusion of a backlight for nighttime driving. The display module directly connects to the I^2C bus and includes a built-in font table which simplifies the process of writing to the screen. The buttons used are generic pushbuttons which are tied high by default. A debouncing circuit is included to prevent multiple signals from being sent for a single press. The buttons are connected directly to GPIO pins on the microcontroller, so the main program will need poll these pins continuously.

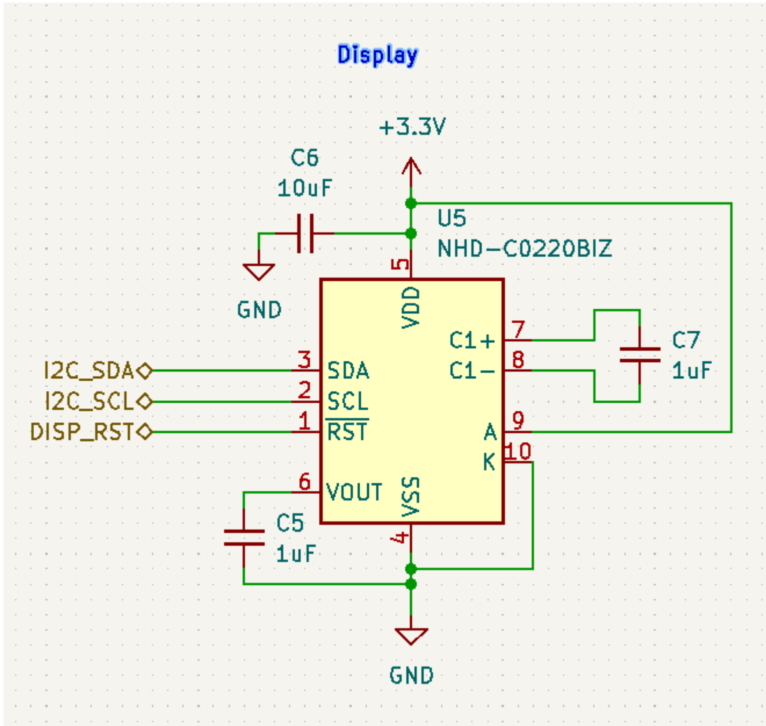

Figure 8: Display Schematic

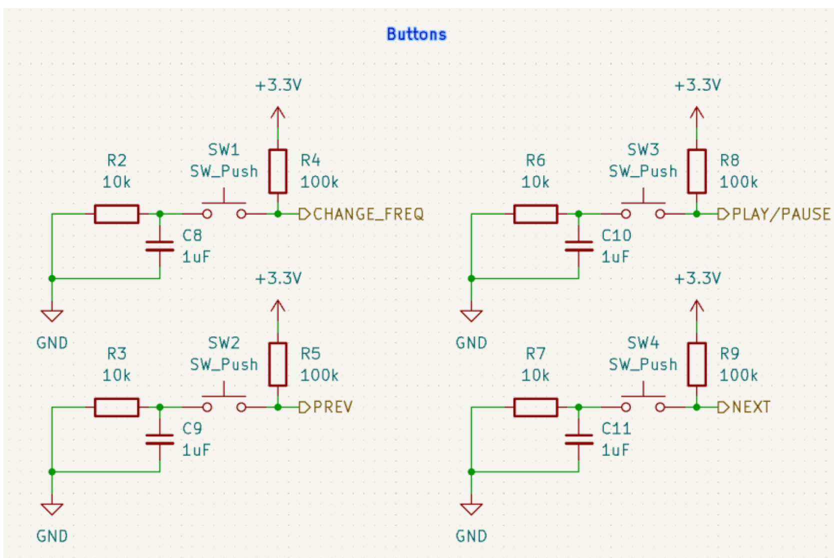

Figure 9: Button Schematic

Design decisions

- The two-line display was selected to offer enough characters to display the frequency and any additional content we may decide in the future we want to include.
- A debounce circuit was built into each button. The microcontroller most likely offers configurable pull-up/down resistors for the pins but the datasheet for the module does not specify so we decided to include external pull-up resistors for each button.

Requirements	Verification
LCD displays alphanumeric characters received on the I^2C bus.	1. Flash a program to the board that writes a character or sequence of characters to the I^2C bus (i.e., "Test"). 2. View the LCD display for correct characters.
Buttons provide a clear signal when pressed/depressed. Once the signal falls below 30%±5% of the maximum, it doesn't increase until the button is released.	1. Measure the outputs of each button on an oscilloscope. 2. Press each button and check the voltage curve for adherence to the mentioned requirements.

2.4 Tolerance Analysis

As discussed in the power section, our power system must output 600mA at 3.3V. 3.3V is within the ideal operating range of our chosen transmitter and receiver ICs as well as the MCU we have chosen.

However, this is not likely to be an issue. The potential failure points are downstream of the transmitter and upstream of the receiver. The following RF design points pose risk to the success of the project.

- *We must transmit sufficient power to be detected by a typical car FM radio receiver.*
- *The SNR of our transmission must be sufficient to achieve a clean audio signal at the output of the radio.*
- *There is likely a maximum measured signal strength from our receiver that will be required for transmission without interference.*

It is difficult to answer these questions at this point in the process because they depend so much on the design and measurements we will need to make in the lab. For instance, the power transmitted and signal strength we receive depend on the antennas we will use. Both of the ICs we have selected support embedded antennas. We will need to design the antennas, either PCB traces or wires embedded in our enclosure, and characterize the impedance and frequency response of the antennas.

Our transmitter IC has an output signal to noise ratio of 58 dB, which should be more than sufficient. We will match our antennas to the transmitter and receiver to ensure maximum power transfer for optimal transmission. Because we are transmitting such a short range (from inside the car) we should not need a large amount of power. However, should the power available from the IC be insufficient, we may use a low power amplifier to boost the signal.

3 Cost and Schedule

3.1 Cost Analysis

Item	Part No.	Manufacturer	Unit Price	Quantity	Price
MCU	ESP32-S3-WROOM-1-N8	Espressif Systems	$3.52	1	$3.52
Transmitter	SI4711-B30-GM	Skyworks Solutions, Inc.	$5.32	1	$5.32
Receiver	SI4706-D50-GM	Skyworks Solutions, Inc.	$6.00	1	$6.00
LCD Display	NHD-C0220BIZ-FSW-FBW-3V3M	New Haven Display Int.	$12.73	1	$12.73
Voltage Regulator	LM1085IS-3.3	Texas Instruments	$3.60	1	$3.60
Button	B3FS-1010P	Omron	$0.78	4	$3.12
10k Resistor	Generic	Generic	$0.28	6	$1.68
100k Resistor	Generic	Generic	$0.39	4	$1.56
10uF Capacitor	Generic	Generic	$0.74	4	$2.96
1uF Capacitor	Generic	Generic	$0.40	7	$2.80
Inductor	Generic	Generic	$0.31	2	$0.62
24 AWG Wire	Generic	Generic	$7.03	1	$7.03
3D Printed Case	We will print	Custom	$2.00	1	$2.00
Red LED	Generic	Generic	$0.84	1	$0.84
Micro USB Connector	10118194-0001LF	Amphenol ICC	$0.46	1	$0.46
Molex Connector	1718563002	Molex	$1.46	1	$1.46
Header Pins	22102101	Molex	$2.21	1	$2.21
PCB	Custom manufactured	PCBWay	$0.50	1	$0.50
Hours			$40.00	120	$12,000.00
				Total	$12,058.41

3.2 Schedule

Week	Expected Schedule
26-Feb	Finish schematic
	Order parts
	Begin layout
	Begin CAD model for enclosure
5-Mar	Finish layout
	Get layout audited – 3/7
	Submit PCB order – 3/7
12-Mar	Finish first software prototype
	Finish CAD model
	Print enclosure
19-Mar	Assemble first prototype
	Test functionality and debug
26-Mar	Finish second software prototype (if necessary)
	Finish revised layout
	Get layout audited – 3/28
	Submit PCB order – 3/28
	Begin final report
2-Apr	Assemble final product
	Test functionality and debug
	Begin verification
9-Apr	Finish verification
16-Apr	Finish final product
	Finish final report

4 Ethics and Safety

In creating a device related to an activity as inherently risky as driving, it is imperative that throughout our design and production process we act ethically, using the IEEE [7] and ACM [8] Codes of Ethics as our guiding principles. First and foremost, we will meet the requirements of IEEE I.1 regarding safety and public welfare, which is also succinctly represented in ACM 1.2 to “Avoid harm” which they define as any negative consequence.

This device is meant to allow drivers to operate their vehicles more safely by automating the frequency selection process of the FM transmitter. This means if any aspect of our device causes the driver to be less safe or aware of their surroundings, we are not solving the problem we set out to. Therefore, we must ensure that we do not add any other steps or distractions than what the current systems on the market already have. To comply with this, the user interface system is kept as simple as possible, consisting of only 4 buttons and an LCD screen. An LCD display poses the risk of distracted driving, so text will be used sparingly on the display, allowing the user to focus more on the broadcast channel.

Additionally, the electromagnetic spectrum is subject to the regulations and oversight of the Federal Communications Commission here in the United States and we must meet the standard of ACM 2.3 to know and respect the rules relating to our work. We know that ignorance is no excuse to break rules and will ensure that we consult the FCC requirements and meet them.

4.1 FCC Regulations

Under the FCC rules, no license is required for this project given it is not sold commercially and that we follow the parameters for our transmitter specified by Part 15 [9]. These rules state we are allowed a maximum bandwidth of 200 kHz within the 88-108 MHz frequency range. Additionally, the maximum emitted power is 250 $\frac{mV}{m}$ at 3 meters away. To adhere to these specifications, our signal will be properly filtered to add minimal interference outside our operating bandwidth, and the output power will be monitored. These values will be tested in the lab using the RF station using a spectrum analyzer and additional antennas.

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