Portable Bluetooth Amp for Home Speakers

Design Document

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1 Introduction

1.1 Objective

With our observations, we believe that there are no battery-powered amplifiers for regular home speakers on the market. Our objective is to create a device that allows people to repurpose their home speakers to become portable Bluetooth speakers. We define portable as something that can be easily moved, for example by carrying it in your hands or storing it in a backpack. We want a user to be able to unplug their speakers and connect it to this device to bring their own speaker on the go. They would be able to connect it via Bluetooth or a 3.5mm audio jack. As the device has its own battery, the user can use it anywhere, for example at the park or at a dance practice. Because speaker connections are common, the device gives the user the freedom to purchase their own speakers or use their existing home speaker system. As we plan to design the device to be usable with power from a DC power adapter, the user can also use the device as a standalone desktop amplifier. Therefore, if they want to use the device on the go all they must do is unplug the device.

1.2 Background

Bluetooth speakers are increasingly more common as people find convenience in a wireless and portable speaker [1]. However, the market lacks more powerful and affordable Bluetooth speakers for those who need them for larger applications, such as theatrical and dance rehearsals. Large companies such as Bose and JBL have boombox style speakers, however their price point is over $300 [2][3]. As speakers have become more common in households in the past couple of decades we seek to create a portable Bluetooth amp that can convert these household speakers into a Bluetooth speaker. As users can repurpose their speakers, they can purchase our device to use with their own speakers rather than be locked into the speaker and amp all in one provided by other companies at a much cheaper price point.

1.3 High-Level Requirements List

- The device must be able to output at least 20 watts continuous for an 8Ω speaker.
- The device must operate a minimum of 3 hours on battery with the amp outputting 20 watts continuous.
- The device must be small enough to be carried in a backpack or in one's hand (more details in Section 2.2).

2 Design

2.1 Block Diagram

The project consists of three blocks. There is the Power Unit (PU), which handles the charging of the battery and supply of the necessary voltages for all the other modules. The Digital Logic Unit (DLU) handles the initialization of the device's chips, Bluetooth with the user's device, and volume control. Finally, the Audio Output Unit (AOU) accepts the audio signals from the Bluetooth module or an external AUX input, amplifies the signal, and outputs sound to an external speaker. The high-level block diagram is shown in Figure 1.

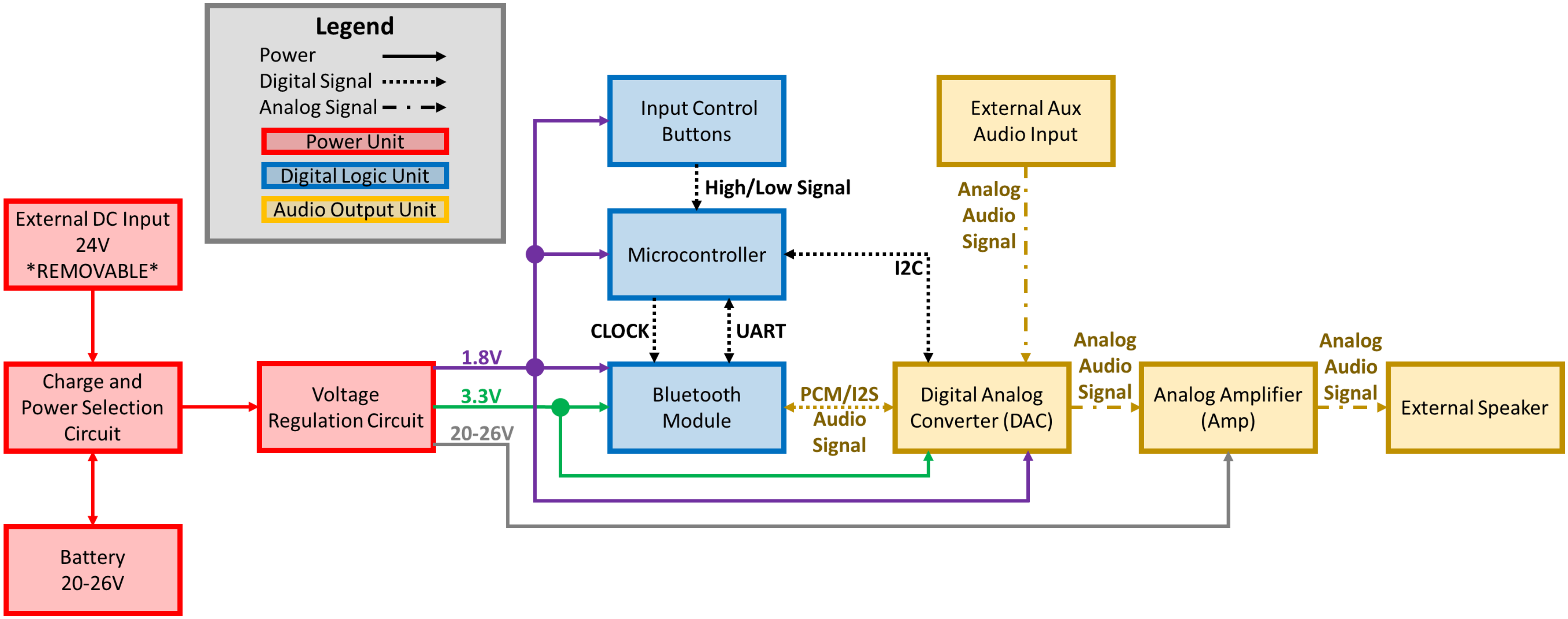

Figure 1. High-Level Block Diagram

2.2 Physical Design

The proposed physical format of the device consists of a rectangular box. The components will be secured within the chassis. The rear of the box will house the banana plug connections for the speaker output, a 3.5mm audio input, and the DC power supply input. The front of the device will house the input buttons for easy accessibility. To yield a portable product, we have determined the appropriate dimensions to be approximately 10in. x 5in. x 5in. Most backpacks will hold this volume comfortably.

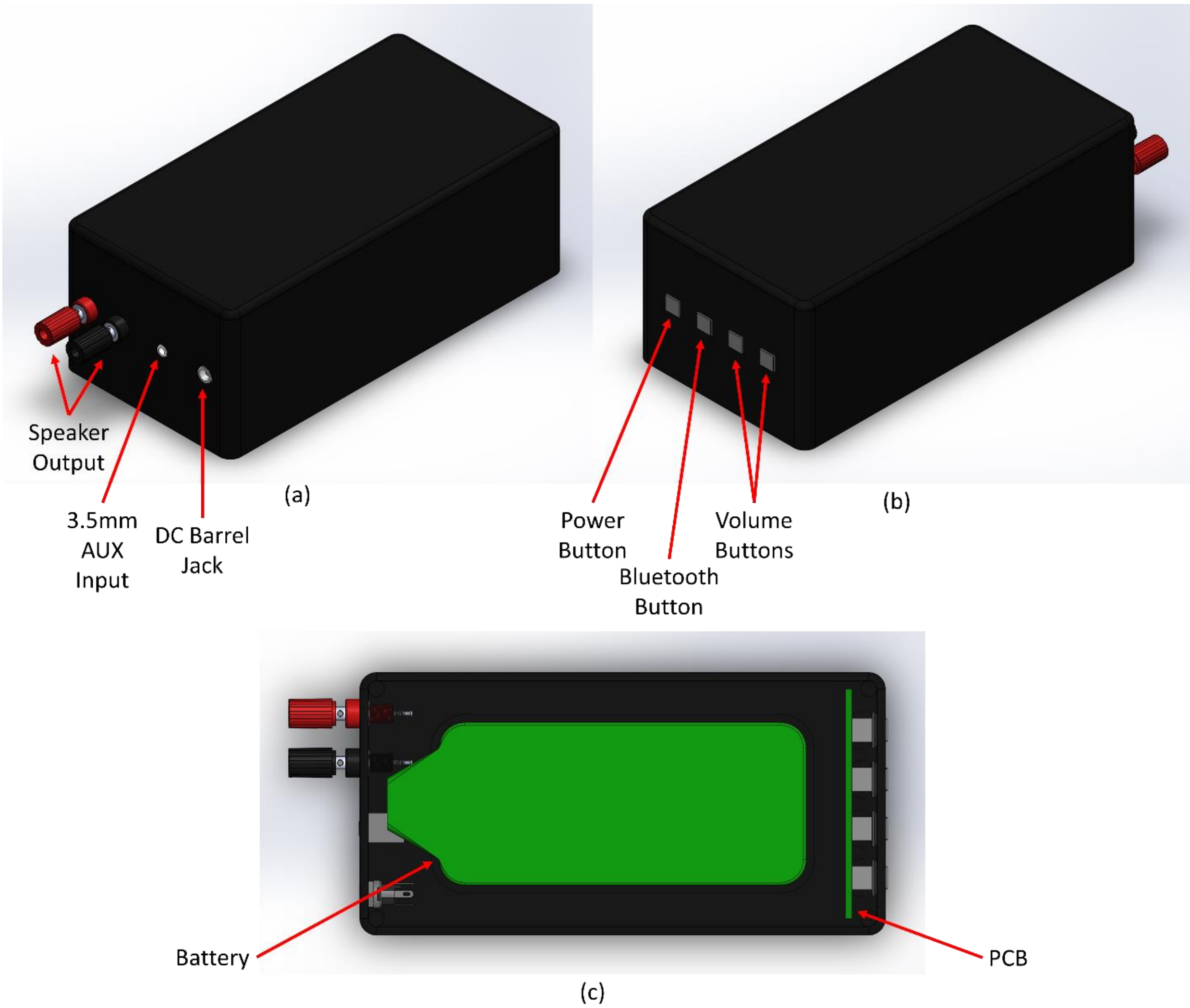

Figure 2. High-Level Physical Design Model of the (a) Rear View, (b) Front View, and (c) Top View (with Lid Removed)

2.3 Overview and Requirements

2.3.1 Power Unit

This block consists of all the power management for the digital logic unit and audio output unit, including supplying 20-26V for the amplifier, 3.3V for the microcontroller and Bluetooth module, and 1.8V for the Bluetooth module. The external DC Input is used to charge the battery and supply power to the system, so as to not drain the battery while charging it. The power supply that is used will be removable so that the device is portable when not being charged. The charge circuit will charge the battery when the external DC input is connected and switch which power source will be applied to the rest of the modules. The battery will supply the power to the system when the external DC input is not connected. The voltage regulation circuit takes the 20-26V supplied from the battery, or the 24V supplied from the external DC input (if connected) and regulate the voltage to 3.3V and 1.8V for all the other modules. It also passes the unregulated 20-26V (or 24V) supply to the amplifier. The circuit schematic of the power unit is shown in Figure 4. Figure 3 shows the typical charging profile for lithium chemistry batteries, which is internally controlled by the charging IC circuit [8].

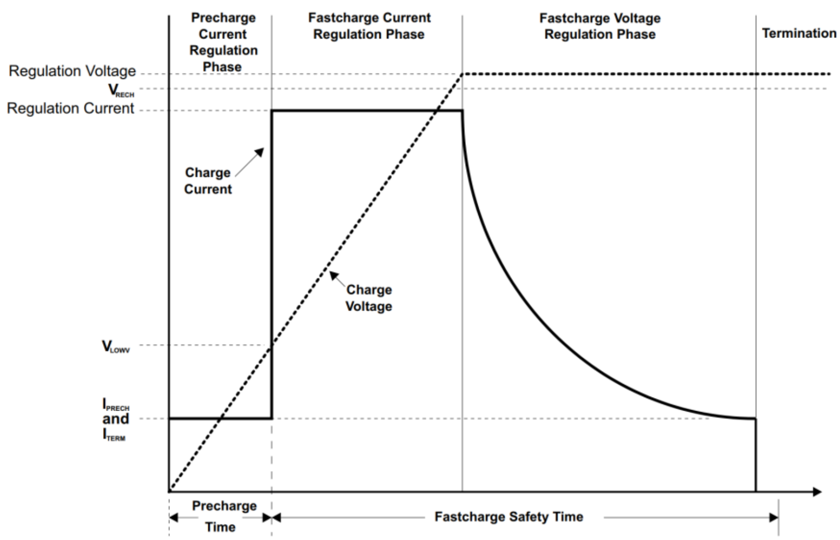

Figure 3. Battery Charging Profile [8]

2.3.1.1 External DC Input

Requirement:	***Verification:***
1. Must be able to supply 24V ±1V at 3A to the charge circuit and to the voltage regulation circuit.	1. Connect the supply to a DC Electronic Load in constant current mode and increase the current to 3.0A. Measure the voltage to confirm it is between 23.0V and 25.0V.
2. Must be removable from the system for portability.	2. Confirm that the output plug of the external supply is a common DC barrel jack connector.

2.3.1.2 Battery

Requirement:	***Verification:***
1. Must have a fuse between the battery and the rest of the circuit to prevent damage to the battery in the case of a short-circuit.	1. Place a fuse with a voltage rating above 26V and a current rating less than 80A immediately after the battery in the circuit.
2. Must supply 20-26V at 3A to the voltage regulators and amplifier.	2. Connect the battery to a DC Electronic Load in constant current mode and increase the current to 2.0A. Measure the voltage to confirm it is between 20.0V and 26.0V.
3. Must have a capacity large enough for at least 3 hours of runtime.	3. Connect the battery to the system and follow verification 3 of Section 2.3.3.2 to put the system under load. Run until the battery voltage drops below 21V and record the time.

2.3.1.3 Charge and Power Selection Circuit

Requirement:	***Verification:***
1. Must be able to stop the battery from charging once the battery has reached full charge.	1. Connect the battery to the charge circuit and measure the current applied to the battery with a multimeter. Confirm that the current going into the battery is below 10mA when battery voltage is greater than the external supply voltage.

2.3.1.4 Voltage Regulation Circuit

Requirement:	***Verification:***
1. Must be able to supply 3.3V ±0.2V at 2A to the Digital logic and Audio Output Units.	1. Connect the 3.3V output to a DC electronic load in constant current mode and increase the current to 2.0A. Measure the voltage to confirm that it is between 3.1V and 3.5V.
2. Must be able to supply 1.8V ±0.2V at 500mA to the Bluetooth module.	2. Connect the 1.8V output to a DC electronic load in constant current mode and increase the current to 500mA. Measure the voltage to confirm that it is between 1.6V and 2.0V.

2.3.2 Digital Logic Unit

This block consists of a complete Bluetooth module communicating with a compatible microcontroller via 4-wire UART transmission. The microcontroller will handle the initialization and shutdown the Bluetooth module and the DAC. The Bluetooth module will transmit incoming audio data directly to the DAC module via some form of pulse-code modulation (PCM) transmission such as I2S. The microcontroller also receives user inputs via buttons for volume control, Bluetooth connection, and power. The microcontroller will then send the appropriate signals to the Bluetooth module, DAC, and Amp.

2.3.2.1 Bluetooth Module

Requirement:	***Verification:***
1. Bluetooth module/stack must be Bluetooth qualified and must be compatible with the advanced audio distribution profile (A2DP) and audio/video remote control profile (AVRCP) [4].	1. Find the necessary documentation to prove that the module we use is Bluetooth qualified and compatible with both profiles. Run the Bluetooth stack in both profiles, verifying they work separately and simultaneously.
2. Bluetooth module must be able to transmit PCM data via I^2S with: a. a sampling frequency of at least 44.1 kHz b. and a 16-bit frame width.	2. Steps: a. Verify under an oscilloscope that the bit clock signal has a frequency of 705.6 kHz mono or 1.4112 MHz stereo b. View the I2S signal with an oscilloscope and verify that the frame is 16 bits wide + start/stop sequence.
3. Device should support a range of at least 20 feet in unobstructed sight. Passed maximum distance means constant interference/drop-out occurs; finite/unpredictable interference/drop-out is acceptable.	3. Connect to the device and play audio. Increase distance from the device until consistent interference or drop-out occurs. Measure distance.

2.3.2.2 Microcontroller

Requirement:	***Verification:***
1. The controller must transmit a 3-wire UART signal with speeds >1 Mbps for fast control responsiveness.	1. View the UART signal in an oscilloscope, locate a start and stop sequence, and calculate the transfer speed of the sample packet.
2. The controller must be able to initialize and shutdown the device from a switch.	2. Initialize device and measure with multimeter current drawn from power source to each module. Shutdown device with switch and verify with multimeter that current to all modules is 0.
3. The controller must be able to adjust the gain of the amp via Bluetooth UART and the physical volume buttons.	3. Probe the i/o pins to the gain control pins on the microcontroller. When the volume button is pressed, the oscilloscope should show a spike for increasing the gain.

2.3.2.3 Input Control Buttons

Requirement:	***Verification:***
1. Must be tactile for the user to input functions.	1. Press the button and confirm that there is physical feedback when the button is pressed.
2. Must be momentary type buttons.	2. Check the resistance across the button terminals when pressed and not pressed to confirm that the resistance is low (less than 10Ω) only when the button is pressed.

2.3.3 Audio Output Unit

This block consists of the DAC and Amp. The block accepts 2 types of signals: a digital PCM data signal (I2S_SDOUT) from the Bluetooth module and an analog signal from a local 3.5mm connection. These are the audio sources. The digital signal will be converted to analog via the DAC by using I2S_SDOUT and a bit clock from the Bluetooth module (I2S_BCLK). A switch, for example a mux built into the DAC, will switch between the audio source depending on what the microcontroller signals it to.

2.3.3.1 Digital Analog Converter (DAC)

Requirement:	***Verification:***
1. The DAC must be able to receive and convert PCM data via I^2S to an analog signal.	1. Connect the I^2S from the Bluetooth module and play a 1kHz sine wave from your audio device. Measure the outputs of the DAC and verify that the frequency of the wave it outputs is 1kHz.
2. The DAC must be able to switch between an analog input and a digital input (PCM data from I^2S) from a switch.	2. Play a 100 Hz sine wave through the Bluetooth device, and a 1 kHz sine wave through the analog input of the DAC. Probe the outputs of the DAC with an oscilloscope. Flip the pin associated to the switch on the DAC from i/o level high (1.8V) to GND and verify that the output wave frequency changes between 100 Hz and 1 kHz.

2.3.3.2 Analog Amplifier (Amp)

Initial Setup: We need an 8Ω resistive load that can dissipate more than 25W of heat, a signal generator that will generate a 1 kHz or 100 Hz sine wave, and an oscilloscope. Due to the amplifier have a bridge-tied load output, a differential probe must be used when measuring the output with an oscilloscope.

Requirement:	***Verification:***
1. The amp must be able to playback an analog signal.	1. Connect the amp's output into the resistive load and probe the output of the amp with an oscilloscope. Use a signal generator and generate a 1kHz sine wave into the amp's audio input. Verify that the amp outputs a 1 kHz sine wave through the oscilloscope.
2. The amp must be able to reproduce audio between the frequency ranges of 20Hz and 20kHz with response variation 4dB or less.	2. Connect the resistive load to the amp's output and probe the outputs with a vector signal analyzer. Connect the source output of the vector signal analyzer to the input of the amp. Perform a sweep from 20Hz to 20kHz. Measure the maximum and minimum amplitudes within the 20Hz to 20kHz range and verify that it is within 4dB of each other.
3. The amp must be able to output 20 watts ±2 watts continuous signal with an 8Ω load using a 1kHz sine wave input.	3. Connect the resistive load to the amp's output and probe the outputs with an oscilloscope. Generate a 1kHz sine wave to the amp's input. Measure the cycle RMS voltage of the output wave and record this value as voltage. Input the voltage into Power = V^2/8Ω and increase the input level and gain until the power is between 18 and 22 watts.
4. The amp must be able to keep a THD of less than 1% with an 8Ω load using a 1KHz sine wave input.	4. Connect the amp's output into the resistive load and probe the output of the amp with a spectrum analyzer. Use a signal generator and generate a 1kHz sine wave into the amp's audio input. Follow the steps found in verification 3 of this section to set the output power to 18 to 22 watts. Enable the oscilloscope FFT function to view the frequency spectrum. Record the amplitudes as volts RMS of the distorted sine wave.

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} V_{n_{rms}}^2}}{V_{fund_{rms}}} \text{ [7]} \quad (1)$$

- V_{n_rms} is the RMS voltage of the n^{th} harmonic
- V_{fund_rms} is the RMS voltage of the fundamental frequency

2.3.3.3 External Aux Audio Input

Requirement:	***Verification:***
1. Input jack must be a 3.5mm (⅛”) headphone port.	1. Connect a 3.5mm connector from the device to a phone. Ensure that the ring and tip pins on the jack are receiving a signal by probing the pins with an oscilloscope.
2. Input jack must have a switch that detects if a 3.5mm jack is inserted.	2. Probe the GND and switch pins on the input jack with a multimeter and start a continuity check. Insert and remove a 3.5mm jack into the input. Continuity should switch.

2.3.4 Chassis

Our chassis for the components will be 3D-printed with the proposed dimensions in the physical design diagram in Figure 2. We chose to 3D-print the chassis for its low cost and to have the ability to quickly prototype new iterations. Also, although metal case may be somewhat sturdier, it also could interfere with the Bluetooth signal and increase costs.

Requirement:	***Verification:***
1. Cannot decrease the functional Bluetooth signal range below 20 feet.	1. Enclose the device in the case. Power it on, connect to it and play audio. a. Increase distance from the device until consistent interference/drop-out occurs. Measure distance.
2. The dimension of the chassis must be less than 10in. x 5in. x 5in.	2. Measure the chassis with a ruler and verify that the dimensions are under 10in. x 5in. x 5in.
3. The weight of the device must be under 10lbs.	3. Measure the chassis with all its internal components and verify that the device is under 10lbs.

2.4 Schematics

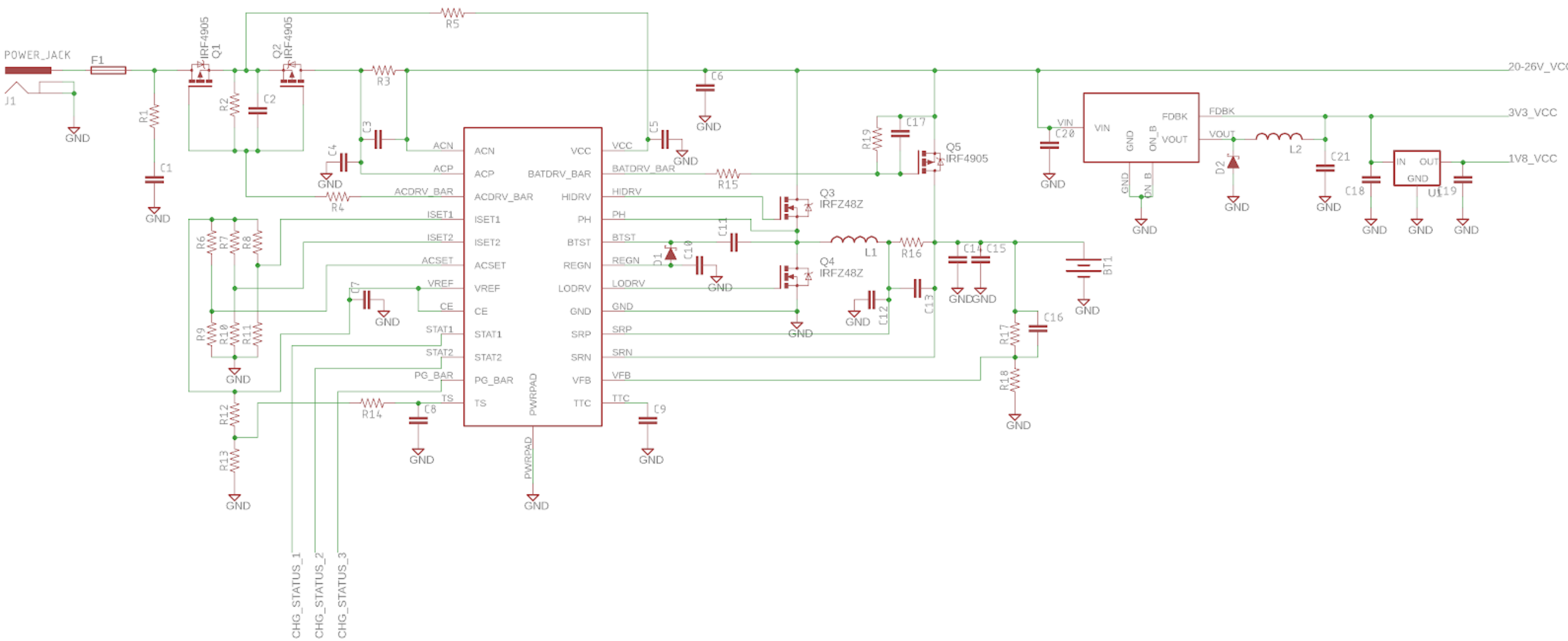

Figure 4. Power Unit Schematic

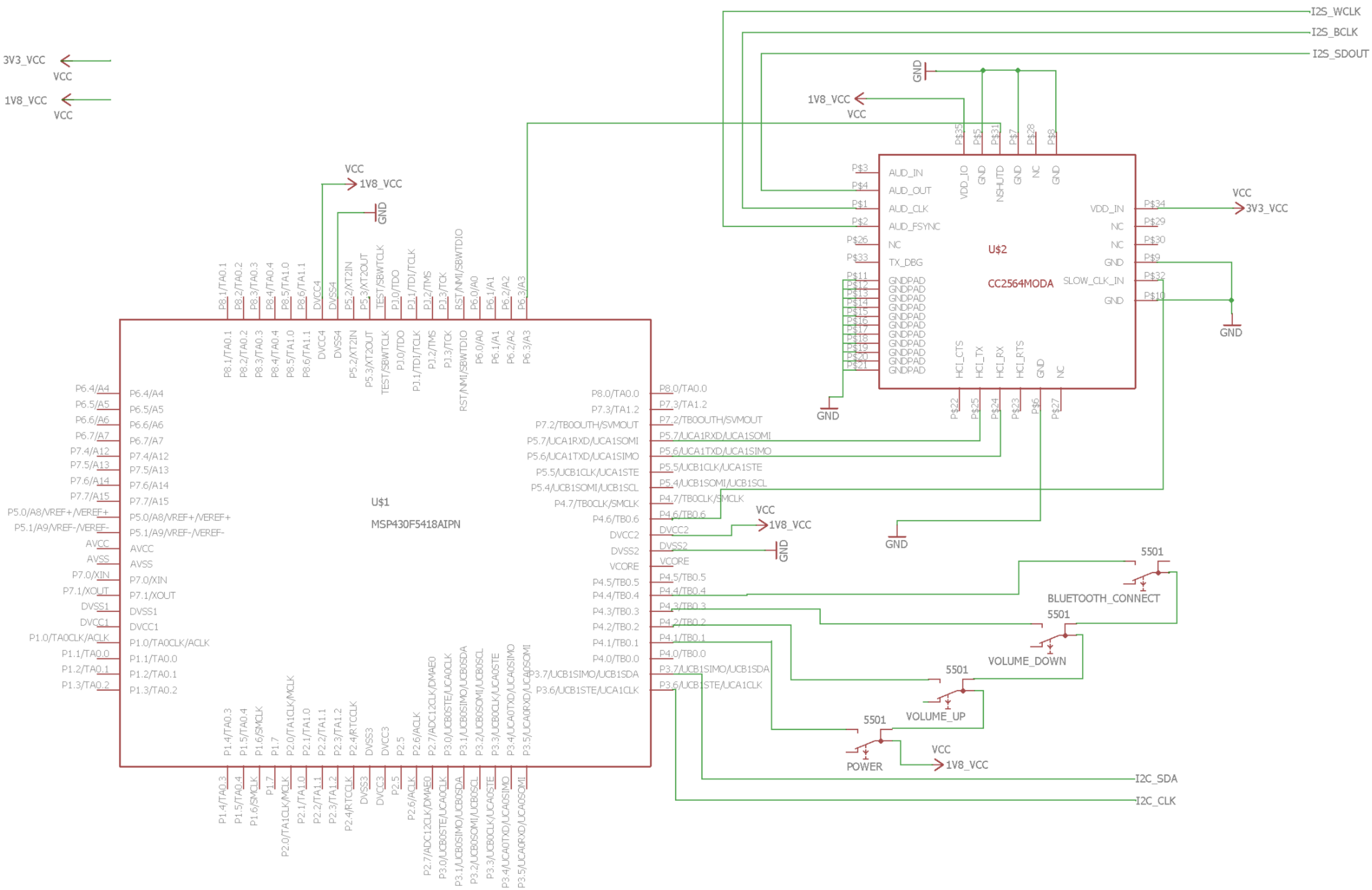

Figure 5. Digital Logic Unit Schematic

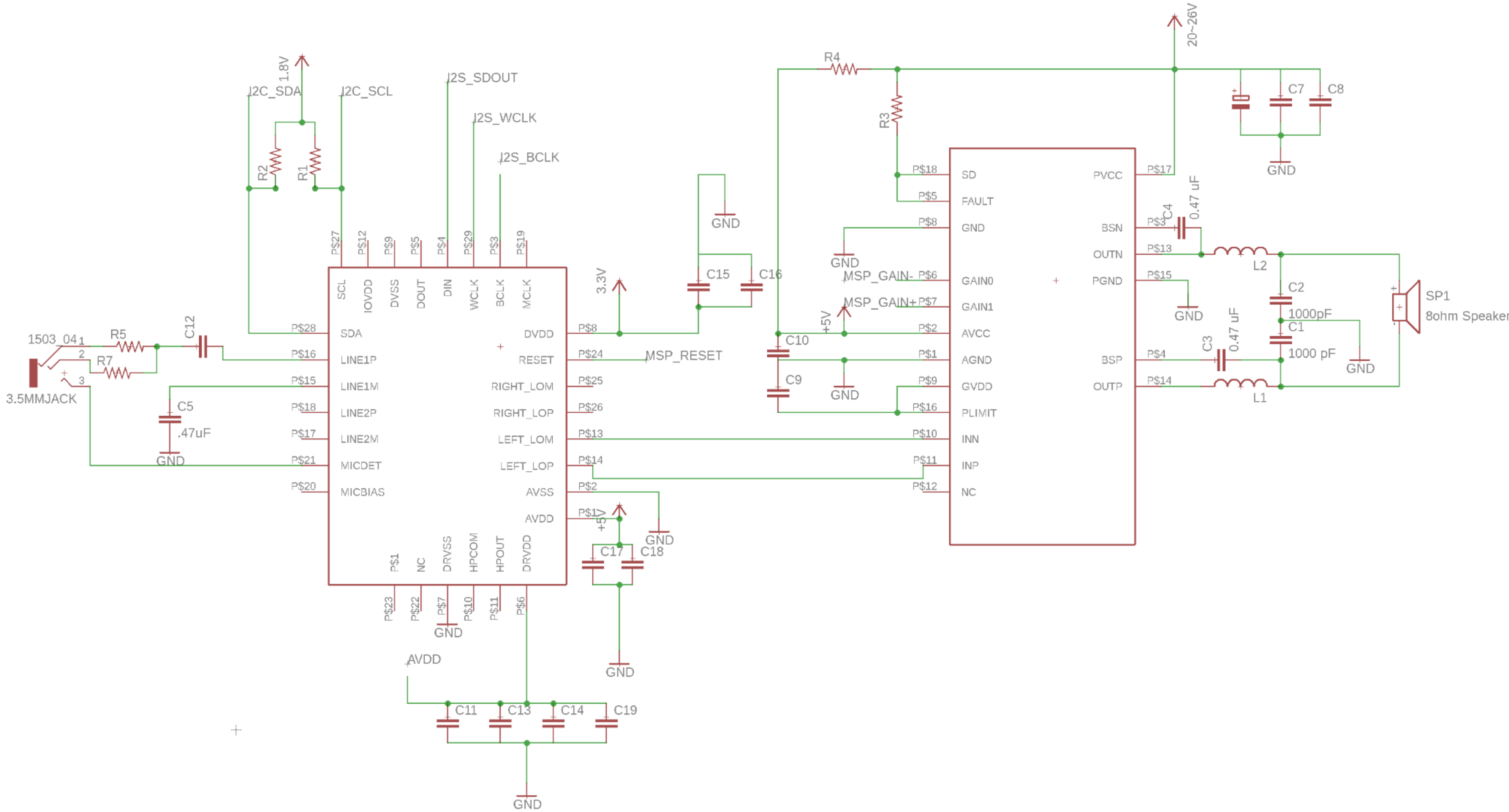

Figure 6. Audio Output Unit Schematic

2.5 Tolerance Analysis

Because this device needs to be portable and last at least 3 hours when outputting 20 watts of audio power continuously, battery life becomes a major design factor. Too small of a battery capacity, and the device will not last the full 3 hours; too large of a battery, and the weight and size of the device may make it not as portable as we had defined in Section 2.2 as well as costs would be unnecessarily high since lithium batteries become much more expensive at higher capacities.

In order to determine the appropriate battery capacity for the device, the power requirements needed to first be determined. There are four significant IC devices in the circuit: amplifier, DAC, Bluetooth module, and Microcontroller. These ICs will collectively pull the most power from the battery during operation. Using the datasheets for each IC, the maximum current at a specified voltage can be determined.

- Amplifier: 1.2A at 24V (Figure 12 of [11])
- DAC: 1.2A at 3.3V and 2.45mA at 1.8V (Listed in Section 6.5 of [12])
- Bluetooth: 112.5mA at 3.3V and 100mA at 1.8V (Listed in Section 4.5.1 of [13])
- Microcontroller: 500mA at 1.8V [14]

From these maximum values, the current requirements at each voltage can be calculated. Since the 1.8V voltage regulator is powered from the 3.3V supply, the total power from the 1.8V is added to the 3.3V summation as shown in Equation 4. Similarly, because the 3.3V voltage regulator is powered from the 24V supply, the total power from the 3.3V is added to the 24V summation, as shown in Equation 6. It is also assumed that there is a 75% efficiency for each voltage regulation, which was determined to be a lower efficiency value than what was listed in any of the IC datasheets.

$$1.8V: \quad 2.45mA + 100mA + 500mA = 602.45mA \tag{2}$$

$$1.8\text{V}: \quad 1.8\text{V} \cdot 602.45\text{mA} = 1.084\text{W} \tag{3}$$

$$3.3V: \quad 4.31mA + 112.5mA + \left(\frac{1.084W}{3.3V} \div 75\%_{efficiency}\right) = 554.790mA \tag{4}$$

$$3.3V: \quad 3.3V \cdot 554.790mA = 1.831W \tag{5}$$

$$24V: \quad 1.2A + \left(\frac{1.831W}{24V} \div 75\%_{efficiency}\right) = 1.302A \tag{6}$$

$$24V: \quad 24V \cdot 1.302A = 31.248W \tag{7}$$

From Equation 7, a maximum power draw of 31.248W will be required from the battery. Since lithium batteries (specifically lithium polymer) have a nominal voltage of 3.7V per cell, a 6-cell battery would be an ideal choice for obtaining a voltage between 20V and 26V. At 6 cells, the nominal voltage of the battery would be 22.2V based on Equation 8.

$$3.7V_{per\ cell} \cdot 6\ cells = 22.2V \tag{8}$$

Using a minimum voltage of 22.2V, the maximum current draw from the battery can be calculated, as shown in Equation 9.

$$31.248W \div 22.2V = 1.408A \quad (9)$$

1.408A is the worst-case tolerance maximum current draw pulled from the battery. Since we want the battery to last while at continuous full load, we will assume the worst-case maximum current is being pulled continuously. As a requirement that the device must operate at least 3 hours under full load, as stated in Section 1.3, the optimal battery capacity in milliampere hours (mAh) can be calculated, as shown in Equation 10. To account for inefficiencies in the circuitry as well as the inconsistency of manufacturers' battery capacity ratings, a 60% efficiency factor is added, which is shown in Equation 11.

$$1408mA \cdot 3hours = 4224mAh \quad (10)$$

$$4224mAh \div 60\%_{efficiency} = 7040mAh \quad (11)$$

Based on Equation 11, the optimal battery capacity is 7040mAh at 6 cells, but since battery capacities are usually in intervals of 1000mAh for capacities above 1000mAh, the capacity will be rounded up to 8000mAh. Hence, the optimal battery capacity is 8000mAh for this device taking into consideration all the tolerancing of the circuitry.

3 Costs

3.1 Labor Costs

Using the average salary of an EE graduate at the University of Illinois at Champaign-Urbana [15], we can determine a reasonable hourly rate for labor to be $32.21 an hour.

($67,000 / 52 weeks · 40 hours) = $32.21 an hour

$32.21 · (3 Members) · (10 hours/week) · 16 weeks = $15,460.80

3.2 Single Unit Cost

Our parts and manufacturing estimate for one unit.

Part Name	Quantity	Unit Price	Total Cost
Texas Instruments MSP430F5418AIPN Microcontroller	1	$6.02	$6.02
Texas Instruments TPA3112D1 Analog Amp	1	$2.54	$2.54

Texas Instruments **CC2564MODA** **Bluetooth CS**	1	$11.27	$11.27
Texas Instruments **6PAIC3109-Q1** **DAC**	1	$4.25	$4.25
CUI INC **SJ1-352xN 3.5mm Jack**	1	$0.76	$0.76
SparkFun **PRT-09739 Binding Post Red**	1	$0.35	$0.35
SparkFun **PRT-09740 Binding Post Black**	1	$0.35	$0.35
Texas Instruments **BQ24610** **Li-Polymer Battery Charger**	2	$5.76	$11.52
PCBWay **18 in² PCB**	1	$6.80	$6.80
Texas Instruments LM1117 **1.8V Linear Regulator**	1	$1.14	$1.14
Texas Instruments **LM2576SX-3.3** **3-A Step-Down Voltage Regulator**	1	$2.86	$2.86
Mouser Electronics **CAPACITOR TANT 10UF 6.3V 20% 1206**	5	$0.34	$1.70
Multistar 8000mAH Battery	1	$49.99	$49.99
Miscellaneous Capacitors, Resistors, ferrite beads, and Wires (estimate)	N/A	$10	$10

Generic 24V DC AC Power Supply	1	$22.99	$22.99
Chassis Print Filament	1	$3.00	$3.00
PCBWay PCB Shipping	1	$20.00	$20.00
HobbyKing Battery Shipping	1	$8.55	$8.55
Digi-Key Shipping	1	$7.49	$7.49
		Total	$171.58

4 Schedule

Week of:	***Anthony:***	***Nicholas:***	***Austin:***
Feb. 19	Compose Design Document, Breakout Amp Pins, Verify calculations for capacitors/inductors/resistors	Compose Design Document, calculate resistors/capacitors/inductor values for charge circuit, create initial chassis design	Compose Design Document, create *DLU* Eagle packages
Feb 26	Integrate DAC and AMP to prepare for Bluetooth integration	Assemble charge and voltage regulation circuits	Verify Microcontroller and Bluetooth Module, integrate via UART, initialize Bluetooth chip
Mar. 5	Integrate amp with Bluetooth, Design PCB Layout	Test power with components, Design PCB Layout	Verify I^2S output signal, integrate Bluetooth with amp, Design PCB
Mar. 12 **Milestone: Modules work individually**	Verify PCB Layout, Integrate gain control from the Microcontroller.	Verify PCB Layout, Begin Chassis Design	Verify PCB Layout, create control button logic, Integrate power, Bluetooth, and volume control buttons logic

Mar. 19 [SPRING BREAK]	Spring Break [Begin Final Report]		
Mar. 26 Milestone: Modules are integrated	Integrate components with PCB, begin designing PCB v2	Integrate components with PCB, begin designing PCB v2, print or order chassis	Integrate components with PCB, begin designing PCB v2, Debug microcontroller
Apr. 2 **Milestone: Device operates within specifications with all modules**	Stress test amp and assemble components in chassis	Assemble components in chassis, design new chassis if necessary.	Assemble components in chassis and begin physical testing of buttons
Apr. 9	Integrate components with PCB v2 and new chassis if necessary. Test audio circuit.	Integrate components with PCB v2 and new chassis if necessary. Verify charging circuit.	Verify Bluetooth stability, initialization, shutdown, and button logic with new PCB.
Apr. 16	Write Final Papers and prepare for Mock Demo Presentation		
Apr. 23	Continue Final Papers and prepare for Presentation		
Apr. 30	Complete Final Papers and Present		

5 Ethics and Safety

The user’s safety and the safety of his/her belongings are of great importance to us; the user trusts our product to boost an audio signal to a safe level for an external speaker for hours at a time. We intend to follow rule #1 of the IEEE Code of Ethics [5] by assuring that the boosted audio signal cannot damage the user’s property by limiting the amount of achievable gain, and more importantly by implementing a fuse between the battery the rest of the circuit to minimize the damage of a short in the battery.

Working with lithium batteries is inherently dangerous, especially during prototyping. We must keep in mind the danger of batteries and the possibility of shorting. While not in use, the battery will be kept in a safe storage location away from people so as to prevent any injury of others [5]. When the battery is in use, we will ensure that it is protected against damage and kept at a safe distance away from any person.

Being a Bluetooth device, there are several regulations that it must adhere to in order to maintain safety and legality. The Bluetooth module and stack must be qualified with Bluetooth SIG; however, a qualified, unmodified module can be used, which is what we plan to do [4]. Also, the Bluetooth module (and hence the device as a whole), must be using the correct “Bluetooth SIG”-approved profiles, namely the advanced audio distribution profile and the audio/video remote control profile.

Although every engineer should remember to cite sources and credit contributors properly [5], this project requires some software, so we especially must remember to check if any code we use or modify has been trademarked or requires licensing or appropriate credit. So far, the Bluetooth module we are considering using comes with royalty-free stack software for specific microcontrollers. We will continue to thoroughly examine the terms of use for any software or hardware we use and meaningfully credit any contributions to our project.

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