Mesh Network Headphones

ECE445 Design Document 2

Team 12
Aditya Bawankule
David Hickox
Alex Ortwig
Abigail Starr
TA: Dhruv Mathur

04/17/2020

Table of Contents

1 Introduction

1.1 Objective

When using an audio system, it is very difficult to come up with an organized and presentable solution that offers a quality listening experience. Such a system is even more challenging when there is a desire to make it portable and shareable with friends and family. Bluetooth has made its mark on recent technology as the dominant close-range wireless communication protocol in the electronics industry. However, Bluetooth is typically limited to one connection for audio, which means users who wish to share audio with friends are left unable to do so. Our system offers a unique solution to a portable, modular, and shareable audio system that lets consumers take their music where they want to and share it with who they want to, all without the clutter of cables and other hardware restrictions.

The proposed solution allows for multiple headsets to form a mesh network, in order for all of their audio to be completely synced. Only one of the headsets will be connected over Bluetooth, while the rest of them will connect over a proprietary connection, in order to reduce interference with Bluetooth and increase the ease of use.

1.2 Background

One solution would be to simply play the audio out loud, but that isn't always an option. Additionally, many people will share earbuds, but that can be unsanitary, and can actually cause more health problems [1]. This cannot be done with headsets either, because it is not possible for them to come apart, and sometimes it is preferable to use headsets.

The original group that had this project is Team 6 from this semester. The original proposed solution is a Bluetooth audio splitter, like an aux splitter, so any device can connect to the system. This would have the same audio in each of these devices, but both of the devices would have the need to connect separately to the Bluetooth enabled device. This then limits the maximum amount of devices to two, because there are two transmitters in the bluetooth splitter device. On the other hand, the solution proposed in this document has only one Bluetooth connection, which connects to a master headset, whichever headset the user chooses to connect over Bluetooth, as each headset can be connected to over Bluetooth. The headsets are then daisy chained through a separate connection that runs at a different frequency. This allows each headset to connect to each other, with an increased maximum number of devices, and an interchangeable master and slave configuration due to each headset being identical.

Other products exist in the marketplace that function using the same theory as the original group's implementation. Examples would include the Monoprice 109722 [2] and the Anker Soundsync [3], both of which are available commercially and utilize the Bluetooth 5.0 protocol. These commercially available devices do not have the capability to connect to more than two Bluetooth audio devices at the same time. Our product intends to extend the quantity of Bluetooth devices that can be connected to the host audio source by implementing a mesh network instead of utilizing the two-device feature seen in commercial products.

1.3 High-Level Requirements List

- Can support listening for at least 3 slave devices in addition to the master
- Can provide audio at full volume for at least 8 hours on battery charge
- Can support a distance of at least 3m from the Bluetooth device to the acting master headset, as well as from the acting master headset to any one of the acting slave headsets
- System must support high data rate PCM signals (192khz PCM)

1.4 Pictorial Representation

Figure 1. Pictorial representation. This shows 2 users listening to the same song from a single source using a pair of our headphones.

2 Design

The hardware portion of the system consists of a wireless system, a DAC, amp, and driver combination. The wireless system will use both open and closed source protocols to communicate sound, and the battery and battery management circuit handles powering the system while also taking in power from a USB connection. The DAC, Amp, and Driver system handles ensuring all the digital sound provided is converted into a pleasant listening experience for the user.

The Software side handles authenticating headphones, trusted users, trusted devices etc. It will also control the mesh network making decisions as to how to hand off connection order to preserve fidelity if users are moving all while minimizing broadcast bandwidth usage to increase the number of possible users.

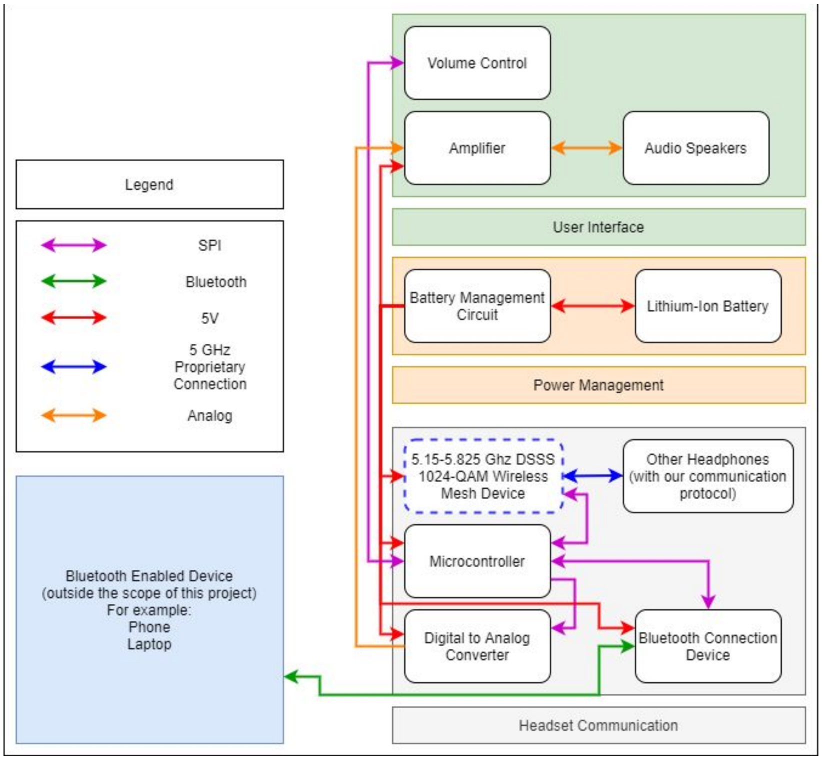

Figure 2. Block Diagram This shows the interactions between systems for our project. There will only be one pcb for this device to make the device as small as possible. The button interface and the battery will be in one ear cup and the other will contain the pcb and antenas.

2.1 Physical Design

Figure 3. Headphone Dimensions. This is a photo of the body of the headphones from the same family as the drivers that we are using, all the measurements for our device will be the same except the ear cup has been adjusted to accommodate the thickness of the electronics as the original model is driver only.

Figure 4. Example of the planned button layout and closed back design for our drivers

2.2 Functional Overview

2.2.1 Lithium-Ion Battery

This is the battery to store charge for the system. The battery must be rechargeable, thus the choice of the lithium-ion battery, as that is commonly chosen for projects that need rechargeable batteries. Lithium batteries are lightweight and have good power density, but can pose some safety concerns that we will have to address.

Given the maximum power draw of 278.22 mW by drivers, a 95 percent efficiency on the amplifier with a base operating power of 6mW making the driver power draw 278.22/.95 + 6 = 298.86 mW. The power draw of the DAC is a maximum of 210mW. The maximum draw from the microcontroller given the expected data rate is 348.47 mW. The total power of the headphones comes out to a maximum of ~855.33mW , a required endurance of 8 hours at full volume, and a battery voltage of 3.7V, with a buck boost efficiency of 95%, the minimum battery capacity needed is equal to $8/95\% * \frac{P}{V} = 1.947Ah$ or 7.20 Wh. This has made us choose the Lithium Ion square battery 103450 (standard size) it is 3.7v and 2ah and some models come with overcharge protection which makes our circuit cheaper.

Requirements	Verification
1. Starting from full charge, the battery is able to output xmW for 8 hours continuously without sagging below xV, the battery’s minimum allowed voltage.	1. a. Connect a fully charged battery to an electronic load set to xmA b. Allow the battery to discharge into the electronic load for 8 hours. c. Ensure that the battery has not fallen below its minimum rated

	voltage with a multimeter.

2.2.2 Battery Management Circuitry

This should allow for battery charging over USB, and should have current protection to make sure that there is no fire or other hazard when charging is happening. Additionally the circuitry should not allow the battery to be discharged below dangerous levels.

The battery management circuitry of the battery will be achieved with the microcontroller and a linear regulator. The linear regulator will be designed to receive a 5V (+/- 0.2V) input and output a constant current of 1A +/- 0.2A. Over voltage protection is not needed as it is built into the battery pack, and the microcontroller will monitor voltage and enter a sleep mode if it detects a battery undervoltage.

Requirements	**Verification**
1. Successfully charges the device without causing harm to the battery, device, or user.	1. a. Connect the linear regulator to a 5V input, and a resistive load on the output. b. Ensure the linear regulator maintains a constant 1A (+/- 0.2A) current output through the load.

2.2.3 Proprietary Connection Hardware

Because there can be interference with Bluetooth, as well as pairing issues, the headsets should be able to talk to each other over a proprietary connection to avoid the user having to do any of this set up. This should be around 5GHz in order to avoid interference with WiFi and Bluetooth, among other common radio frequency applications. Bluetooth and Wifi can both run at 2.45 GHz, which can cause non-negligible interference. However, Wifi can also run at 5 GHz, but this will cause much less interference, so it will not be a problem for this project. Each headset must have this hardware, and up to 3 devices should be able to connect to the master at any one time.

Requirements	**Verification**
1. Can join a mesh network	1. Pair a second pair of headphones to a bluetooth device so it enters broadcast mode

	2. Turn on the pair of headphones and verify enters into the mesh network and mirrors the audio when told to enter the mesh network

2.2.4 Bluetooth Connection Device

There needs to be a Bluetooth connection from the main headset to a cellular telephone or other Bluetooth enabled device, so the user can connect this system to their device with ease. Any of the headsets need to be capable of being the master device, so each one must be Bluetooth compatible.

Requirements	**Verification**
1. Can connect to a modern smartphone	1. Turn on headphones and enter pairing mode 2. Verify the device appears in the smartphone's pairing menu, and select it 3. Verify the device plays Bluetooth audio from the smartphone

2.2.5 Digital to Analog Converter (DAC)

This is an audio grade DAC to take the Bluetooth data and produce a waveform that can be read by the microcontroller. Because Bluetooth is a digital waveform, this cannot be read directly from the microcontroller, so the DAC is necessary for the conversion from Bluetooth signal to an analog signal in the form of a differential pair that can be read by the microcontroller.

Requirements	**Verification**
1. The DAC can convert a digital signal to an analog output.	1. a. Send a known digital signal into the DAC. b. Observe that the DAC outputs the correct analog waveform.

2.2.6 Amplifier

The amplifier takes the audio signal from the DAC and amplifies it, in order to adjust the volume of the analog signal. This will take input from the microcontroller based on the user selected volume level and amplify it accordingly.

Requirements	Verification
1. Have a Total Harmonic Distortion of no worse than -100 db	1. a. Send several frequencies into the amp from the DAC b. Test the integrity of the signal with an oscilloscope and use it to programmatically calculate the Total Harmonic Distortion

2.2.7 Audio Headset

The speakers must be able to output to the ear, and be acceptable quality. The range on the volume control should have a maximum of at least 75 decibels [4], and should be able to go down to 0 decibels with at least 10 increments.

The drivers to be used for our audio headset will be the Sennheiser HD 800 S, which is a 300 ohm driver characterized by a sensitivity of 103.8 dB/V SPL (Sound Pressure Level) [5]. Using the headphone power tool created by digiZoid [6], to meet a requirement of 120 dB a requirement of 6.46 Vrms and 21.53 mA to power the drivers. This yields a maximum power draw of 139.11 mW per driver or 278.22 mW for the pair of headphones at full power.

Requirements	Verification
1. Have a +-3db response from 20hz to 20khz	1. This can be tested using a calibrated microphone and a noise isolation box. This would require a frequency sweep to identify the sound levels. 2. This is not necessary for the most part due to the drivers we purchased guaranteed from the manufacturer to be responsive within 1db for 3hz-30khz.

2.2.8 Microcontroller

The microcontroller is a necessary component in order to connect the Bluetooth and the proprietary connection together, as well as the volume control and the audio output. The MAX32660 can support up to two of each SPI, I2C, UART, and RTC outputs. This gives enough necessary GPIO to support these four functions. Additionally, the microcontroller needs to be low power in order to prolong the battery life.

Requirements	Verification
1. Ensure that the microcontroller works. 2. Ensure that the microcontroller can communicate with each part of the system correctly.	1. a. Connect a programmer to the JTAG breakout for the microcontroller. b. Verify that the microcontroller can be successfully programmed. 2. a. Send a test program that validates each connection independently b. Send final product program that demonstrates all systems working together.

2.2.9 Volume Control

Because different volumes are useful in different scenarios, it is essential for the user to be able to adjust the volume at any point in the listening experience. On the headset, there should be volume adjustment buttons to ensure that the volume is able be set to their desired value.

Requirements	Verification
1. Ensure that the volume button buttons will increase and decrease the volume of the device's sound.	1. a. Press the increase volume button and verify that the output of the media is louder than before. b. Press the decrease volume button and verify that the output of the media is quieter than before.

2.3 Risk Analysis

The hardest part of this project will be ensuring that our proprietary radio transceiver will work properly without being susceptible to interference from other devices that use similar spectrums (ie 5GHz WiFi). We have chosen the 5GHz band due to the wide availability of transceivers that can be purchased allowing us to avoid the tuning and testing of a system which requires equipment not available to us. This will allow us to build a mesh network with a custom protocol over the same widely used bands. The protocol itself is the highest risk item. 5GHz Wifi uses anywhere from 20-160 mhz bands where our solution will need significantly less than that so we cannot use wifi off the shelf. We will also have many more devices that require transmission than most people have wifi routers. This means we will have to find out how to implement narrow band communication over many devices without interference but at data rates higher than bluetooth. With narrow band communication DSSS starts to fail, FHSS may be required which would increase collisions and decrease total number of allowable devices. FHSS though would allow configuration to be easier due to no channel claiming. Also with this many small bands there may be an issue with 5 GHz WiFi not realizing a channel is being used and broadcasting over it, causing interference. We will most likely use QAM1024 encoding since that provides a suitable 5 b/s/hz going any higher will make interference more significant but it would allow more total devices since it allows a narrower band and that is another optimization problem.

2.4 Schematics

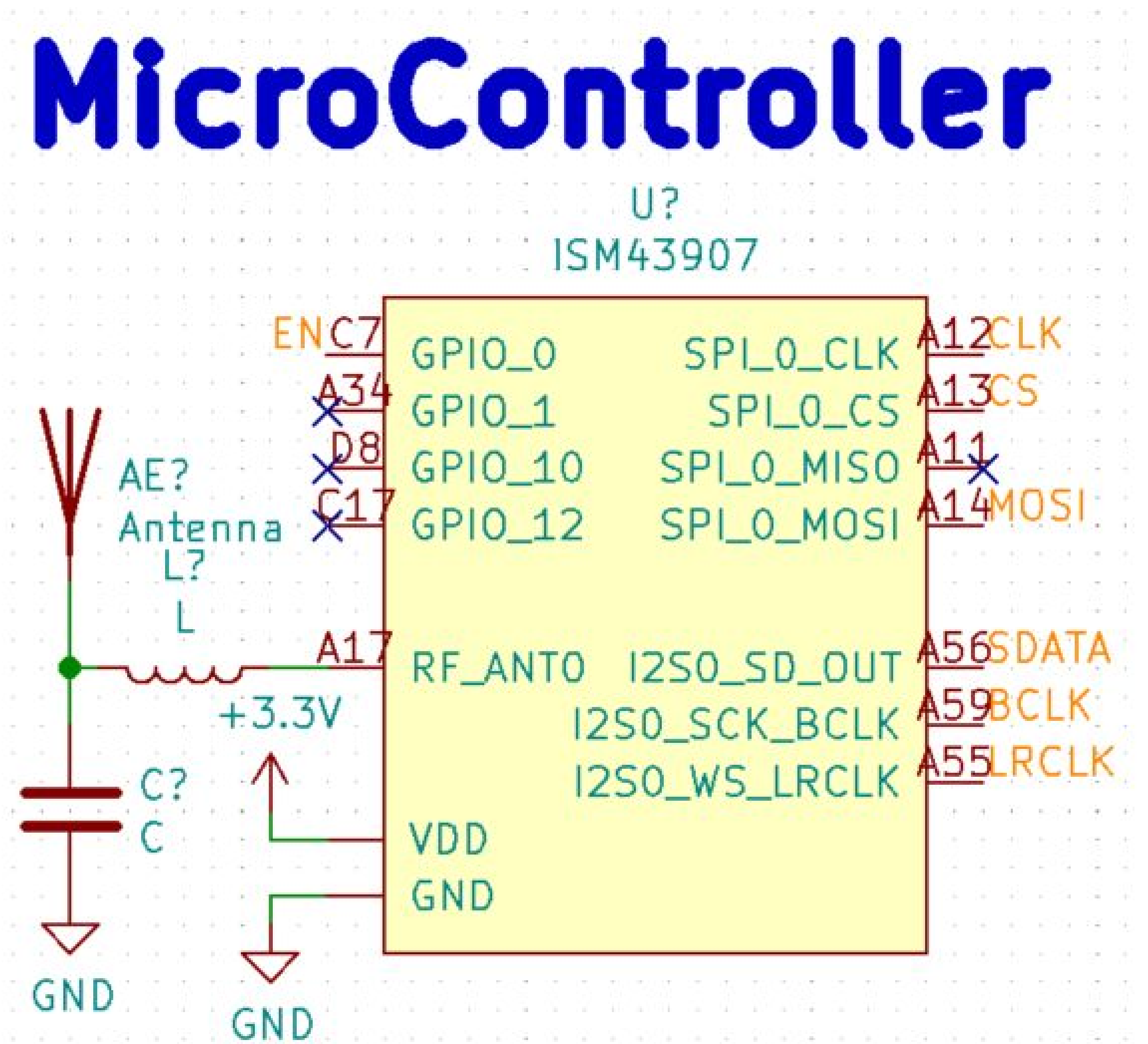

Figure 5: The microcontroller sends and receives data via bluetooth, as well as sends data to the DAC to be processed into an analog signal.

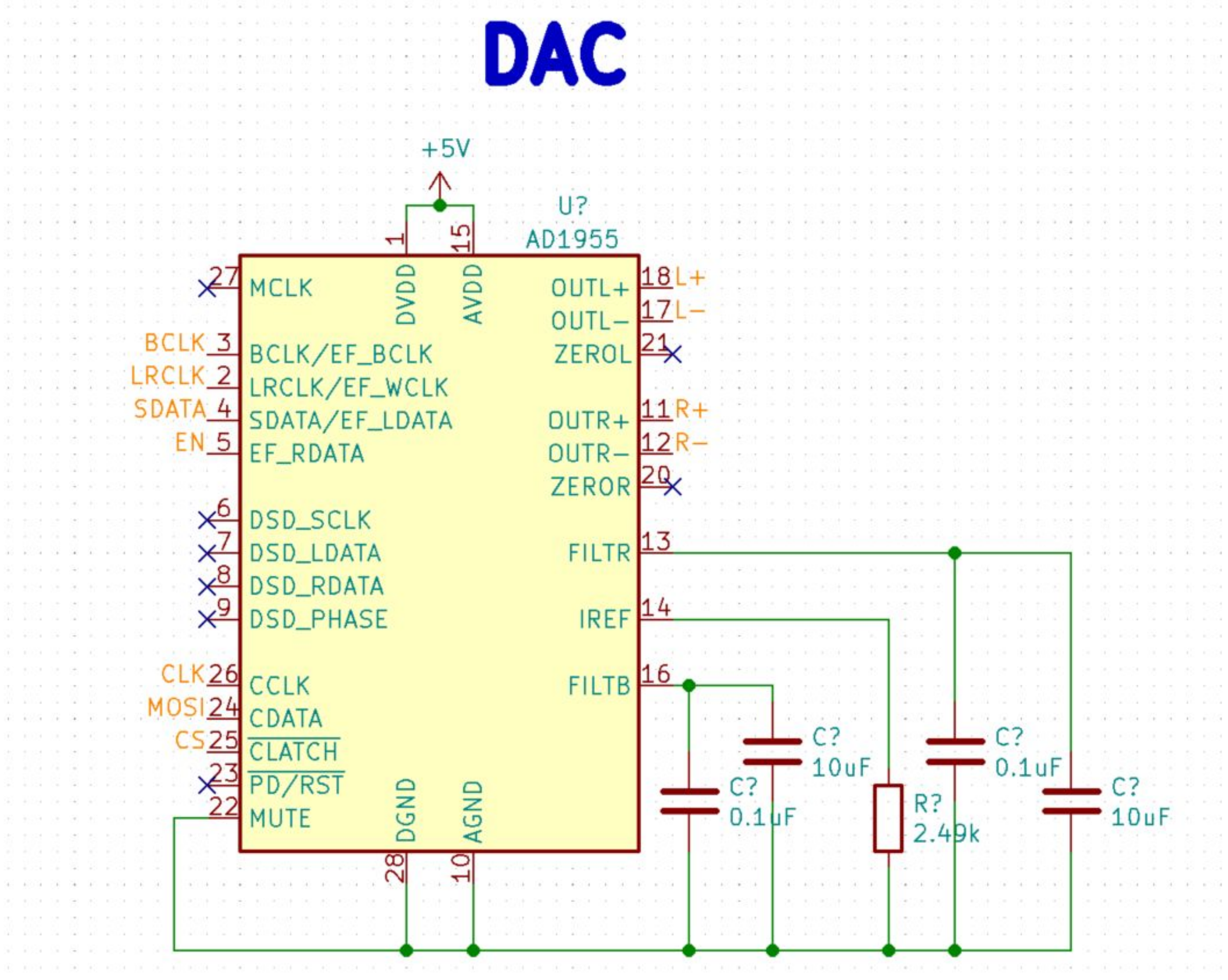

Figure 6: The digital to analog converter, or DAC, converts digital signal received from the microcontroller to an analog output that is amplified before being sent to the headphone drivers.

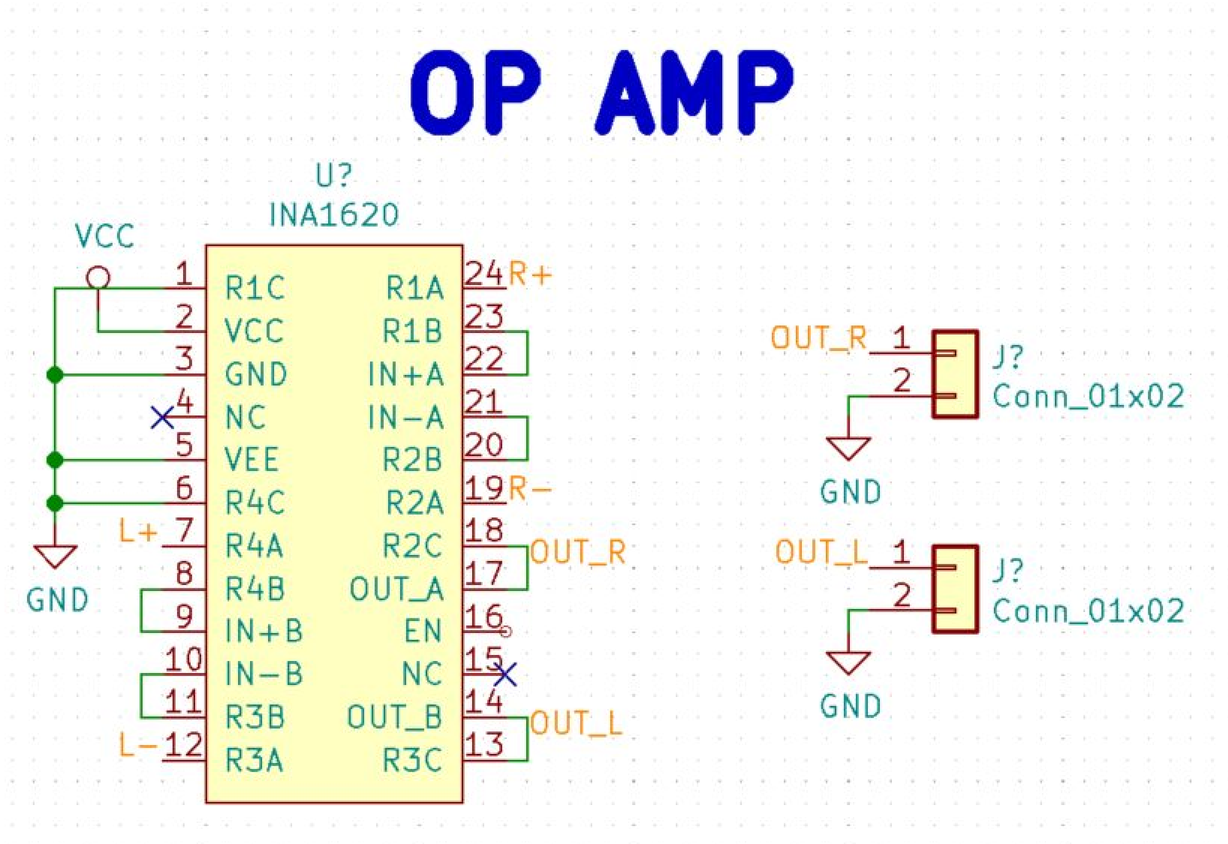

Figure 7: The OP Amp boosts the DAC's input to the 18.5V output needed to achieve the maximum dB output required to meet specifications.

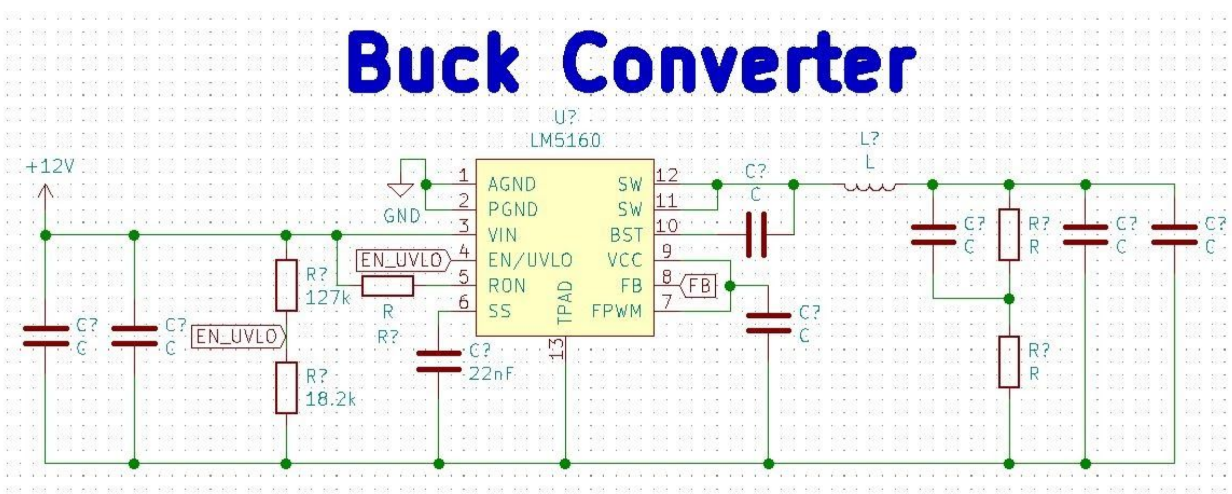

Figure 8: The buck converter will convert the battery voltage to the 3.3V needed for the microcontroller

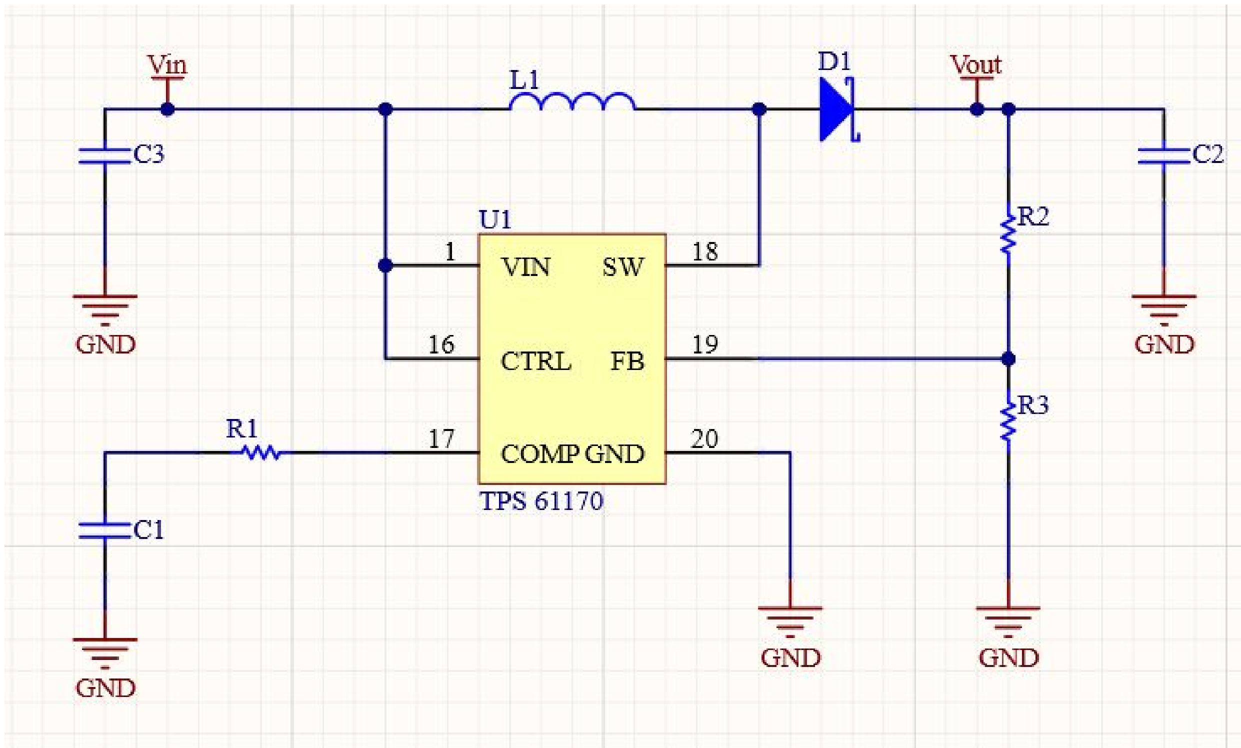

Figure 9: The boost converter is needed to convert the battery voltage to the 5V needed for the DAC and the 18.5V needed for the OP-Amps that drive the headphone drivers.

2.5 Software

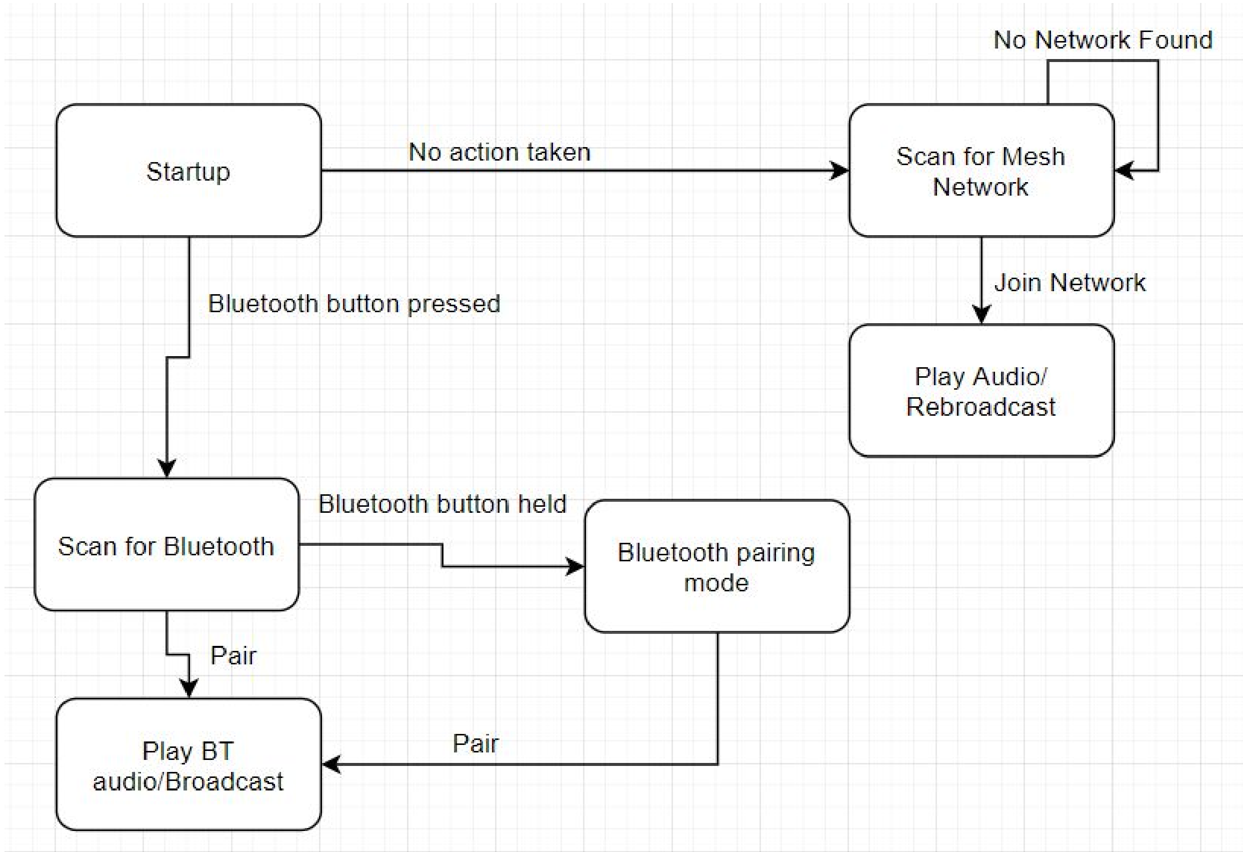

Figure 10:
The Bluetooth portion of our software will be fairly standard, using the well documented Bluetooth protocol to pair and receive audio from a Bluetooth device such as a smartphone.

The mesh network portion of our software will be significantly more involved. The current plan is that as soon as a headphone gets a source, whether it be Bluetooth or another headphone, it will scan for another headphone to connect to and send audio to. On startup, a headphone will look for a headphone in this broadcast mode, and connect to it. That way, there will always be at least one headphone ready to broadcast, and interference will be minimized, as the headphones can negotiate channels based on availability.

3 Costs

The costs for the engineers for this system is \$50 an hour, for approximately 10 hours a week for this semester. This should be also multiplied by 2.5 for the cost of overhead. This comes to \$80,000 [eq.7] in total as a cost of labor.

$$4 * \frac{\$50}{hr} * \frac{10\ hrs}{wk} * 16\ wks * 2.5 = \$80,000 \qquad \text{eq.7}$$

The table below contains the items needed for physical construction:

Item	Price
Tenergy 103450	$10.00
HD 800 HD 820 Headband padding	$31.52
HD 800 and HD 800S pair of Earpads black	$75.66
HD800s Protective grille	$13.65
HD 800 S Capsule 300 ohm (black)*2	$419.34
HD 800 S Acoustic baffle right and left side (1 pair)	$71.45
SUNLU PLA (For headset shell)	$23.99
Total	$645.61

The table below contains the items needed for the PCB:

Item	Price
INA1620	$6.40
ISM43907-L170	$17.77
AD1955	$14.84
TPS61170	$2.45
LM5160QPWPRQ1	$4.95
.1uf Cap, 1uf Cap, 10uf Cap*10	$0.22
Assorted Resistors	$1.57
Total	$645.61

4 Schedule

This schedule is split into two parts to improve readability, as we have four members in our group.

Week	**Abby**	**Alex**
1	Complete main board design and layout	Complete/finalize schematics
2	Order components for main board	Begin PCB Layout
3	Assemble the main user interface board.	Complete PCB Layout
4	Start testing main board	Buck converter testing
5	Finish testing	Boost converter testing
6	Test BT with software	DAC testing
7	Test Mesh Network with software	Op Amp Testing
8	Test Bluetooth with Mesh Network	BMS Testing
	Full system testing	System integration
	Full system testing and preparing for final demo	Full system testing, and Final Demo
	Finish writing final paper	Finish writing the final paper

Week	**Aditya**	**David**
1	Design software state diagrams	Design software state diagrams
2	Start Bluetooth Software	Start Bluetooth Software
3	Finish Bluetooth Software	Finish Bluetooth Software
4	Start mesh network software	Start mesh network software

5	Finish mesh network software	Finish mesh network software
6	Test Bluetooth software with hardware	Test Bluetooth software with hardware
7	Test Mesh Network software with hardware	Test Mesh Network software with hardware
8	Test Bluetooth with Mesh Network	Test Bluetooth with Mesh Network
	Mock Demo, finish up loose ends for demonstration	Mock Demo, finish up loose ends for demonstration
	Demonstration, start on final paper, system testing	Demonstration, start on final paper, system testing
	Finish final paper	Finish final paper

5 Project Differences

The original solution involves a “puck” device that the phone connects to, that rebroadcasts the audio signal to many devices using multiple antennas. This limits the number of headphones that can be connected total, and the previous solution proposed only having two antennas. On the other hand, our solution consists of headphones that form their own mesh network, so that only one Bluetooth connection to the source is required, and then the mesh network allows the original audio to be broadcasted many times. This solves the limitation of Bluetooth antennas. However, our solution will require additional new hardware to be purchased, and users cannot use their existing Bluetooth headphones.

The original problem proposed involved sharing audio with friends in order to experience songs/movies with them. The original solution works well if you only have one friend, but would not work with more people, or would require additional rebroadcaster pucks leading to a high chance of interference. Our solution scales to a much greater number of people, and would easily allow you to watch a movie with your entire social group without disturbing your neighbors. Our solution would theoretically lead to less interference, as different bands could be used, and we would not be using Bluetooth which already is a populated band.

6 Ethics and Safety

We intend to follow the IEEE Code of Ethics 7.8.1-7 and 7.8.9-10 [7]. Some of the Code of Ethics is not applicable due to the nature and methods of our project. In the case of any violations of this code we will take them seriously. Due to the physical nature of our device we do not foresee any sort of physical injury possible without extreme misuse. For this reason we will focus on the nonphysical component when designing and operating our device according to the Code of Ethics 7.8.1 [7].

It is important to ensure that our device will not harm the user's ears, or emit excess radiation as per FCC regulation. Our device is classified as an intentional radiator by the FCC [8]. The chosen frequency is well within the FCC regulations, so any radiation emitted is within the healthy limit [9] that will not negatively impact the users quality of life any more than any other consumer devices. Additionally, as with any battery charging, it is necessary to ensure that the battery will not catch on fire, either when the battery is charging or during normal use. To solve the charging issue, a standard off the shelf charging system will be used that is UL rated in order to limit the amount of power that can enter the system at any one time.

To prevent harming the users ears we will ensure that our internal amplifier is limited to being able to drive any common off the shelf headphone speaker to a maximum of 130dB (roughly the SPL of a rock concert) with a warning at 80dB to alert the user that long term effects could occur. This works out to anywhere from 3mW on earbuds to 16,000 mW for the highest impedance large form factor headphones. This exact value will be chosen based on our voice coil selection specifically [10]. We will also not exceed the maximum voice coil rated power and current in order to prevent destruction of our products and burns to the customer.

6 References

[1] B. Gibson, “Here's Why You Should Never, Ever Share Earbuds with Anyone,” *The Healthy*, 26-Nov-2017. [Online]. Available: https://www.thehealthy.com/ear-nose-throat/never-share-earbuds/. [Accessed: 03-Apr-2020].

[2] Suellen, “Monoprice 109722 Bluetooth Transmitter and Splitter - Other Bluetooth,” *Walmart.com*, 19-Feb-2017. [Online]. Available: https://www.walmart.com/ip/Monoprice-109722-Bluetooth-Transmitter-and-Splitter-Other-Bluetooth/39457824. [Accessed: 04-Apr-2020].

[3]https://www.amazon.com/Anker-Soundsync-Transmitter-Synchronization-Connection/dp/B07BR3FFTB/ref=sr_1_16?dchild=1&keywords=bluetooth+splitter&qid=1585967638&sr=8-16

[4] J. R. Brinson, “What's that? How earbuds can wreck your hearing (especially for young people),” *chicagotribune.com*, 11-Jun-2018. [Online]. Available: https://www.chicagotribune.com/news/ct-earphones-could-be-hurting-your-ears-20160229-htmlstory.html. [Accessed: 03-Apr-2020].

[6] “IEEE Code of Ethics,” *IEEE*. [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html.

[7] “Equipment Authorization – RF Device,” *Federal Communications Commission*, 20-Mar-2018. [Online]. Available: https://www.fcc.gov/oet/ea/rfdevice. [Accessed: 04-Apr-2020].

[8] “Wireless Devices and Health Concerns,” *Federal Communications Commission*, 21-Feb-2020. [Online]. Available: https://www.fcc.gov/consumers/guides/wireless-devices-and-health-concerns. [Accessed: 04-Apr-2020].

[9] “Headphone Sensitivity / Power Requirements Compared” *Head-Fi*, 28-Feb-2003. [Online]. Available: https://www.head-fi.org/threads/headphone-sensitivity-power-requirements-compared.476345/. [Accessed: 04-Apr-2020].