High Fidelity Signal-Processing (HFS) Headphones

ECE4012 Senior Design Project

HFS 4011s
Jennifer Hasler

Carter Culwell, cculwell6@gatech.edu
Connor Hawley, chawley8@gatech.edu
Nitish Katta, nkatta7@gatech.edu
Matthew Kern, mkern8@gatech.edu
Alexander Meyer, ameyer30@gatech.edu
Karthik Praturu, kpraturu@gatech.edu

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Executive Summary

The purpose of this project was to design, build, test, and refine a set of noise-cancelling headphones. These headphones have the ability to wirelessly connect to a user's Bluetooth compatible device and receive an audio signal from the device. They process the incoming noise from the environment to create a noise-cancelling signal and integrate this signal with the audio signal from the user to play music without interference from the noise of the environment.

We to differentiated our set of noise-cancelling headphones from those that are currently on the market by building the headphones using a Field-Programmable Analog Array (FPAA). Thus far, no commercially available headphones have been built with an FPAA. They are advantageous to current designs as they have the capability to use less energy which translates to a potentially longer battery life and provides a solution to the typical trade-off required between using a digital audio driver or an analog audio driver. A digital audio driver provides more flexibility but requires higher power while an analog audio driver operates on low power and can instantly react to changes in noise but requires more precise tuning. The utilization of an FPAA allowed us to retain the benefits of low power and instantaneous reactions provided by an analog audio driver without giving up the flexibility the digital audio driver provides.

The cost of this project was $1000 in order to create the desired end goal of a working pair of noise-cancelling headphones that can connect to any device via Bluetooth and adequately play music. The final design was a pair of over-the-ear headphones with circuitry housed externally as we were not able to fit all the relevant parts inside the headphones themselves.

1. Introduction

High Fidelity Signal Headphones (HFS Headphones) are noise cancelling headphones that utilize Field-Programmable Analog Arrays (FPAAs) to reduce the power consumption of the real time signal processing system. The HFS system is comprised of an FPAA, a Bluetooth microcontroller, microphone, active noise cancelling hardware, speaker and battery.

1.1 Objective

The team developed a system that, when placed over the user's ears, would theoretically only allow sound from the local stereo speakers. This system communicated over bluetooth with a mobile device. Outside sounds were recorded with a microphone that was placed on one headphone, which was fed through the field-programmable analog array, where its computation produced an output signal intended to synthesize the noise-cancellation component with the desired audio output. Batteries in the headphones took advantage of the low power consumption of the field-programmable analog array to power the system for a day of average use on a full charge with only a small solution size.

Motivation

Noise-cancelling headphones are nominally a mature technology. Many varieties are commercially available, and collectively they cover a broad market. However, recent developments in field-programmable analog arrays, as a kind of programmable mixed-signal processor, enable new design possibilities [1]. This new generation of field-programmable analog arrays consumes a thousand times less power than comparable processors, which could lead to a noise-cancelling headphone design with lighter batteries, more sophisticated or entirely novel computation, or a combination of both. Choosing either flavor of design will cater to a different set of people. If the lighter battery design is pursued, a more cost-effective low-end set of headphones could be realized, appealing to cost-sensitive markets, like college students. If the more sophisticated computation design is pursued, these headphones could prove superior to current high-end headphones in noise-cancellation, which would appeal to music enthusiasts.

1.2 Background

Active noise cancelling (ANC) headphones work by incorporating circuitry that measures acoustic noise from the environment through a microphone, combines it with the music being played, and outputs a new signal that compensates for the measured noise. If this process is fast enough, feedback from the output can be sent back to the input to more finely tune the amount of noise cancellation. In particular, Bose designs headphones with multiple stages of feedback and feedforward circuitry that can be tuned by a user, allowing for a controllable level of noise cancellation [1]. Over the past two decades, extensive research has been devoted to determining which algorithms work best for different environments [2], exploring techniques for combining different types of designs [3], and measuring their performance [4].

Modern noise cancelling headphones, however, do more than just block out acoustic noise. They tend to have a long battery life, lasting for about 20-30 hours, and incorporate many features that take advantage of a connected device. For example, the Sony WH-1000MX has an adjustable sound profile, and the amount of noise cancellation can be tuned through an app [5]. The Bose QuietComfort 35 II has volume-optimized equalization while also incorporating voice command functionality [6].

Field-programmable analog arrays (FPAAs) will be the technological keystone of this project. Reconfigurable computing has been commonplace and commercially viable in the digital domain for years, given the success of devices like field-programmable gate arrays, but with recent technological advances, FPAAs promise huge savings in both size and energy consumption used in computation [7]. Since the early ‘90s, FPAAs have been an academic interest, with limited applications [8]. However, a new generation of FPAA SoCs has recently been realized by researchers at Georgia Tech by using both analog and digital components to enable richer, lower-power computation, with success already demonstrated in important applications, like recognizing speech trigger words [9].

2. Project Description and Goals

The team designed a pair of noise-cancelling headphones, utilizing a Field-Programmable Analog Array (FPAA) to increase the digital signal processing power from what is currently available from existing noise-cancelling headphones. The designed headphones have use over-the-ear speaker drivers with the circuitry housed externally due to space constraints. In addition, they are wireless and utilize Bluetooth to connect with any Bluetooth compatible device to allow the user to play audio through the headphones. The design will have an internal rechargeable battery to power the circuitry. Project goals include the following:

- Provide passive noise-cancellation
- Provide active noise reduction for low frequency
- Compatible with all standard Bluetooth devices
- Average battery life of 20 hours
- Weighs less than 0.5 lbs
- Headphones contain physical UI controls for direct control
- Comfortable to wear

3. Technical Specifications

Table 1 contains the specifications for the High Fidelity Signal Headphones. The average human ear size was used to determine the measurements for the width and height of the earcup [10]. The minimum sampling rate of the microphone allows for all possible noise frequencies to be detected and provides compatibility of the noise signal acquired from the microphone with the audio signal to allow ease of processing and merging of the two signals [11]. In addition to the specifications listed in the table, the headphones successfully operate in real-time and the wireless communication of the headphones with a device exceeds a minimum operating range of five meters.

Feature	**Specification**	**Result**
Headphone Ear Cup Width	> 30 mm	90 mm
Headphone Ear Cup Height	> 70 mm	110
External Supply Voltage	< 5 V	3.7 V

Impedance	< 32 Ohms	4 Ohms
Battery Capacity	> 15 hours	25.2 hours
Weight	< 0.5 lbs / < 0.23 kg	1.1 lbs

Table 1: Table of product features and their accompanying design specifications.

4. Design Approach and Details

4.1 Design Approach

Overall, two systems were developed in parallel. One of these systems was the prototyping system, which was built with breakout boards from adafruit and sparkfun. The other system was the custom PCB design. The schematic for this PCB can be viewed in Figure 1 below. In retrospect, each team member should have spec-ed a part for each aspect of the system block diagram, then the group should have designed the schematic and laid out the PCB together. Utilizing GitHub worked to the group's advantage.

PCB Design

During the assembly of the PCB, many parts were fried. Thankfully, we order at least twice the quantity necessary for each part of the assembly, preventing complete failure when a single component was compromised. Another consideration for future PCB assembly is the type of solder paste used for reflowing. The group's custom PCB had to be reflowed 7 times because of a solder paste with an unknown heating curve, resulting in two shorts on the board. These shorts took many hours to debug. The back of the board, however, was much easier when hand-flowed with a heat gun.

The FTDI chip was not working after assembly, so it became necessary to take it off of the board and program the ESP32 pins with a FTDI cable. The battery charger also appeared not to be hooked up correctly. The part let out some magic smoke when the USB and battery were simultaneously plugged in, so the battery charger had to be removed from the board.

When the board was interfaced with the I2S DAC, there was an esoteric issue that could only be resolved when the connection was reduced to 1 jumper wire instead of two. This connection was the bit clock. In retrospect, it was a mistake to put the I2C DAC on the board. The better decision would have been to instead put a I2S DAC on the board which would have been more useful for future board revision.

All in all, almost all of the problems we had were a result of assembly issues with the custom PCB. In hindsight, it would have been better to have an external manufacturer fabricate and assemble the board for us. This would have allowed us more time to focus on fine-tuning our design.

FPAA Design Techniques

After some time working with the FPAA, it became clear how important it was to follow all of the instructions on Dr. Hasler's website, as there are not any other resources out there on the subject. It is important to understand that the FPAA is not a digital computer, but a programmable analog computer. This means that it requires a different paradigm for computation. Another important realization was that during virtual machine boot-up, it was necessary to always update the RASP tools. Looking back, it would have been better to lean more heavily on the lab's PhD students and Dr. Hasler for advice on the details of FPAA technology. For example, they are the only people that know which FPAA boards have the best performance.

When putting signals on the FPAA pins, choosing signals between 0 and 2.5V is very important. It is also noteworthy to be patient when programming the FPAA, as programs may sometimes take 20 or more minutes to load. Whenever connection issues appear, it is a good idea to reset the FPAA several times and unplugging it and plugging it back in. Also, it is helpful to check the rx and tx LEDs on the back of the FPAA to see if it is alive.

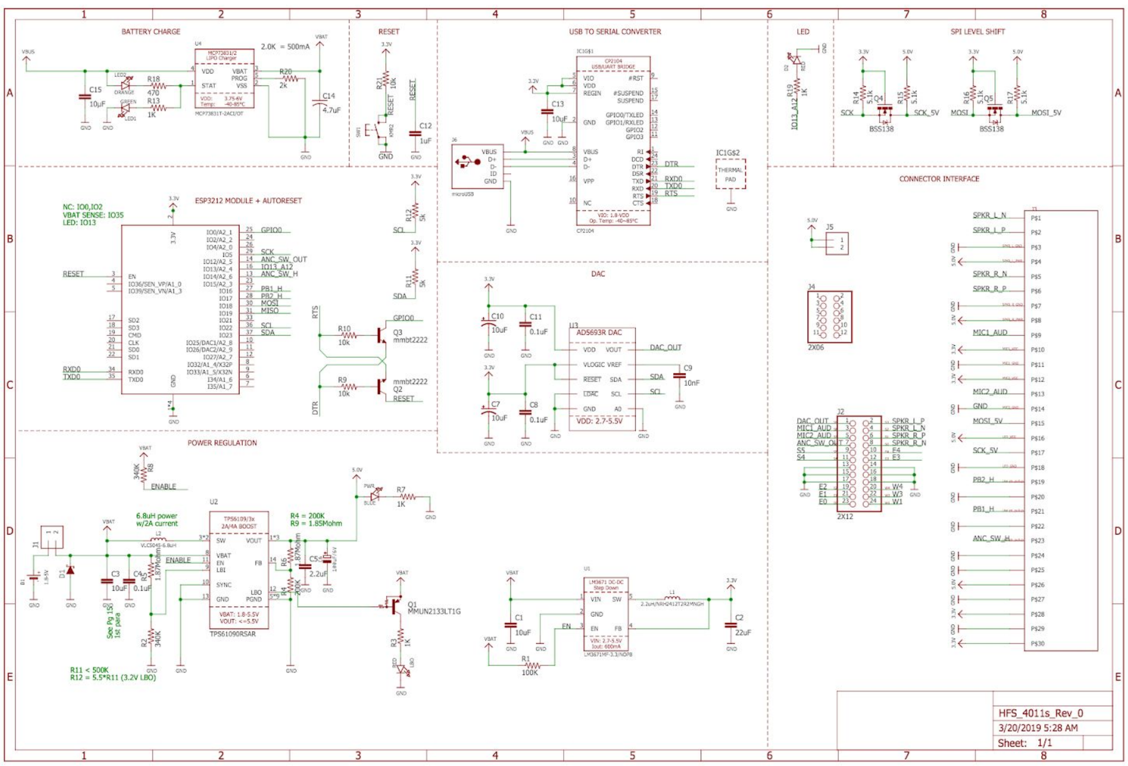

Figure 1: Custom PCB Schematic.

4.2 <u>Codes and Standards</u>

The applicable standards to this project range from broad, system-level standards to specific, technical standards. On the broader side, standards like NIST 8118 were applicable [13]. NIST 8118 covers basic electrical and electronic equipment compliance standards in the United States, along with IEC 60950-1, which provides wiring, power supply, and other hazard safety for information technology equipment [14]. Diving into the audio equipment domain, IEC 62368-1:2018, also guided the project design with specific safety requirements for audio and video information and communication technology equipment [15]. After the audio system was built, there there were applicable codes for testing it as well. For example, ISO 11904 lays the groundwork for how to determine sound emission from sound sources placed close to the ear, which would have been important for measuring system performance and user experience had we had the time to fully test the product [16].

Technical codes like the Bluetooth 5.0 Core Specification were relevant during the implementation of bluetooth communication for the project [17]. The project relies on codes like this as a reference to debug and design communication systems, whether they be wireless or on the board itself, like serial peripheral interfaces for sending commands to the FPAA.

4.3 Constraints, Alternatives, and Tradeoffs

Constraints

The design was constrained by the material needed to provide passive noise cancelling. Certain materials naturally act like different types of noise filters and impact how the noise sounds to the user; therefore, these are the materials that must be used when designing the headphones. The amount of material used affects the weight and comfort of the headphones with the possibility of additional materials added solely to provide comfort. The material impacts the amount of noise-cancelling circuitry and the type of digital signal processing required. The physical size and weight of the headphones determines the amount of circuitry and size of battery that can be used.

Alternatives

An alternative to the design decision to utilize the FPAA to handle the work of sensing noise in the outside environment and applying signal processing algorithms to calculate anti-noise signals was utilizing the FPAA only for sensing the noise from the outside environment and then sending the signals to be processed by a separate digital signal processor (DSP). This decision to have the FPAA handle all aspects of the signal receiving and processing was influenced by the separate DSP needing an additional software development kit that would need to be learned and integrated into the project. The system would also consume more energy due to the two separate devices, potentially causing issues of excess heat and battery life length. Furthermore, there is a possible latency between the FPAA outputting the appropriate signals and the DSP receiving them, which would impact the ability of the system to operate within the real-time constraints required. The major advantage of having the separate DSP was to simplify the debugging and testing procedures as each system could be developed simultaneously while the design in which the FPAA handles all tasks would be linear in its development and provide possible complications while debugging. This problem will be addressed and overcome with a pre-defined development and testing schedule to allow for each individual task performed by the FPAA.

Tradeoffs

The tradeoffs associated with our design revolved around the Active Noise Cancelling (ANC) hardware circuitry design and the ANC software design. The hardware design focused on the different options of either a feedback, feedforward, or hybrid ANC circuit design. The designs differed in both the amount of time they would add to the system, the complexity of each design and their ability to produce a quality signal. Therefore, our design had to sacrifice some of the quality of the signal processing while still maintaining an acceptable level in order to ensure that the complexity was feasible for the team to be able to design as well as operating within the real-time constraints of the system. This tradeoff was mimicked in the software design decision process as the complexity and quality of the digital signal processing algorithms directly conflicted with the speed at which the algorithm could run. Due to the real-time constraints, some software complexity was eliminated.

5. Schedule, Tasks, and Milestones

The GANTT chart is shown in Appendix A. The necessary project tasks, as well as the schedule for start and completion of each task is listed. The individual team member task assignments are listed in a chart in Appendix B.

The relative contributions to the overall project by each team member are as follows:

All Team Members - All members took a part in writing the project proposal and project summary draft, designing the high level system for the noise cancelling headphones, researching and selecting prototyping components and materials, conducting system level testing, attending capstone expo, and writing the final project summary and report.

Carter - Designed, built and tested the speaker driver circuitry, and debugged any audio I/O issues.

Connor - Submitted the weekly email reports, programmed the FPAA, helped test the FPAA module, soldered components onto the custom board, designed and prototyped the power circuitry, and set up the demos for capstone expo.

Nitish - Researched signal processing algorithms useful for active noise cancellation, managed work on submission documents and debugged the overall system.

Matt - Programmed and tested the ESP to receive and output audio from a Bluetooth device, managed work on selecting project components and materials, and set up the demos for capstone expo.

Alexander - Researched the FPAA programming tools, programmed the FPAA, tested the FPAA module and debugged the overall system.

Karthik - Managed work on selecting project components and materials, designed the custom board, soldered components onto the custom board, and built and tested any remaining circuitry.

Major project tasks in which the team encountered technical difficulties are as follows:

Custom Board Design - Designing the custom board was difficult because it's dimensions had to fit within the design specifications we determined while also including all the logic needed to connect the various project modules together. This logic included a DAC, input/output pinholes, usb connector, ESP32, etc.

Programming the FPAA - FPAA technology is still in development, and FPAAs are only accessible inside the ICE laboratory in the TSRB. Some FPAAs were fully functional and some did not operate correctly. Each version of the FPAA had to be programmed differently and did not always consistently operate under our tests. Finally, the RASP programming tools could not compile Scilab code on some laptop computers. These made programming and testing the FPAA functionality brittle and inconsistent.

Testing the Speaker Drivers - The purchased speaker drivers had difficulty outputting bass frequencies from music audio without distortion, which greatly diminished the audio quality. Additional time was required to reprogram the ESP32 and rebuild the speaker driver circuitry to reduce audio distortion enough to demo the speaker drivers during capstone expo.

6. Project Demonstration

6.1 Demonstration

The final project demonstration was comprised of two parts:

- The first part demonstrated that the ESP32 can receive music audio from a bluetooth device and output to the, uncovered, speakers driven by a simple audio amp. A smartphone was first connected to a standalone ESP32 device, music audio ("Seven Nation Army" by The White Stripes, and "Welcome to the Black Parade" by My Chemical Romance) was then broadcasted to the ESP32, which outputted the audio signal to a DAC, and finally a class D audio amplifier drove the resulting audio signal to the speaker drivers. Interested persons at expo would then listen to the music audio by holding the speaker drivers close to their ears

- The second part demonstrated that the overall headphone system with noise cancellation was functional. Interested persons at expo first fit the headphones on, connected to the headphones with a smartphone, and sent music audio to the headphones. This demonstrated that our project specifications were met: putting on the headphones showed that the ear cups were large enough to fit over one's ears, playing music showed that the impedance of the headphones was low enough to provide clear audio, and using a battery to power the headphones showed that the supply voltage was low enough to prevent damage to electrical components and that the battery life of the headphones was long enough to last throughout expo without recharging.

The final results of our headphone specifications against our proposed specifications are listed below. All of the specifications were met, except for the total weight of the headphones. Most existing noise cancelling headphones are around 0.23 kg in weight, but this specification was not met because the final HFS 4011 headphones contained a heavy battery pack as well as many jumper wires and electronic components. The feature that exceeded its proposed specification was in regards to the battery capacity. The final headphones were able to accomplish 25.2 hours of continuous usage, a 168% increase over the proposed battery life.

Feature	Proposed Specification	Final Specification
Headphone Ear Cup Width	> 30 mm	90 mm
Headphone Ear Cup Height	> 70 mm	110 mm
External Supply Voltage	< 5V	3.7 V
Impedance	< 32 Ohms	4 Ohms
Battery Capacity	> 15 hours	25.2 hours
Weight	~ 0.23 kg	0.50 kg

6.2 Testing

- **Noise Cancelling:** A series of square and sine waves of amplitude 1 V and frequencies from 50 Hz to 20 kHz were swept through a waveform generator, the Discovery 2 device paired with WaveForms software, and inputted to an operational FPAA device in the ICE laboratory programmed to implement the final iteration of a noise cancelling algorithm. A reference signal was sent cleanly through the FPAA without the noise cancelling algorithm using the FPAA I/O pads, and a second, identical signal was simultaneously inputted to the FPAA with the noise cancelling algorithm. The resulting waveforms were captured using an oscilloscope in the WaveForms software, and compared to determine whether the noise-cancelled signal was reduced in amplitude.
- **Power Consumption:** The battery pack was fully charged, and then connected to the entire headphone system while turned off. The headphones and the noise cancellation feature were turned on and an arbitrary background noise input (AC, heating, etc.) in the ICE laboratory was used for ninety minutes. The initial charge of the battery was measured using an amp-hour meter and then remeasured after five minutes. The remaining battery charge was then compared against the starting battery charge and extrapolated to calculate the total battery life with the headphones.

7. Marketing and Cost Analysis

7.1 Marketing Analysis

There are two general price markets for noise-cancelling headphones. The lower-end has a price range of about $150 - $500 while the high-end market has a price range of $1500+. Noise-cancelling headphones generally have high-end audio output as it is expected that consumers who are willing to pay for the enhanced noise-cancellation technology will also place a high value on audio quality. We intend to target the same consumer market as is targeted by headphones made in the $150 - $500 range. There are many noise-cancelling headphones within this range, so we will briefly describe the features and prices of three of the top-rated headphones in this segment [TechRadar]. The first is the Sony WH-1000XM2, which retails for approximately $350. These headphones boast great noise-canceling abilities, a 30-hour battery life, and incredible audio quality. Next are the Bose QuietComfort 35, which are equipped with excellent noise cancellation and sound quality, and are pre-built with Google Assistant. The Bose QC35s retail for around $300. Lastly, are the Sennheiser PXC 550s, which, based on customer reviews, have the best audio quality and noise-cancellation, but lack useful touch controls.

It is difficult to compete with well-established, well-funded, and mass-produced products that are the result of years of research and development conducted by some of the top sound engineers in the world. In terms of the quality of sound and noise-cancellation, we can only expect to perform at the same level as the leaders in the industry, at best. To that end, we will cater our headphones to early adapters and technophiles who revel in being able to claim they are trying out the newest technology. Our headphones will have the distinct advantage of being powered by field-programmable analog arrays which is a novel technology and unique in the industry. We will price the HFS 4011s towards the higher end of the spectrum, around $500, to account for the nature of the product. As a luxury good targeted towards early adapters, the demand curve will actually have a tipping point where demand goes up as price goes up.

Marketing the product properly would also be instrumental in maximizing returns on our investment in developing the headphones. To effectively reach our target market of early adapters and headphone technophiles, we would place resources towards digital advertising on platforms frequented by such parties. These websites would include technology review sites and high-tech newsletters and magazines. By strategically marketing through these platforms we would be able to efficiently reach our target market and encourage them to try our noise-cancelling headphones for a pleasurable music experience.

7.2 Cost Analysis

To calculate the cost of each headphone, the estimated cost of each component and part was researched and then aggregated. A spreadsheet in the appendix lists the itemized costs for the various parts needed to make noise-cancelling headphones, along with links for some parts that provide pricing estimates. The total parts cost estimate is $454, including estimated labor costs to outsource to a third-party to solder the FPAA chips to the PCB. It was estimated that the collective report preparations, meetings, research, development, assembly, and testing would take a collective 720 man-hours to create the final product. This, split over 6 team members, provided a means to estimate the cost of labor for production of these noise-cancelling headphones. A 35% rate of fringe benefits and overhead costs was added to the labor cost, along with a 5% addition for marketing and sales costs. The rates were derived from research online amongst companies with publicly available financial data creating similar products. The total cost of labor needed to be recouped over the five years is $36,348.48 to account for the development of HFS 4011s specifically. At a desired pricing point of $500 based on headphones mentioned in the previous section, this comes out to a margin per item of $46. To break even, the company must sell at least 158 items per year. Assuming that additional sales do not incur significant additional miscellaneous costs, each additional item sold past the 158 item threshold would yield $46 of profit per item. At an itemized cost of $454, this would come out to 10.1% profit.

8. Conclusion

Although the team did not accomplish its end goal of developing fully-functional noise-cancelling headphones, a great deal of progress was made in terms of working with the FPAA and many important lessons were learned. Designing, building, testing, verifying, and demonstrating an intricate piece of hardware is a lot of work. Specific design methodologies and lessons learned are laid out in this report in section 4. Overall, the team learned a few key pieces of engineering wisdom for future projects. The approach to designing the board was good, but definitely could have been improved. The prototyping system and custom PCB were developed in parallel which proved to be slightly challenging. The PCB had to be based on a best guess schematic as not all of the requisite prototyping of the system had been done prior to when the design needed to be sent in for manufacturing. Much of the project's progress came in the last few weeks before the senior design expo. It would have been useful to be more proactive in the prototyping/design stage so that parts could have been ordered earlier, received earlier, and used earlier. In retrospect, each member of the team should have identified and spec-ed a part for each aspect of the system block diagram. The group should have then designed the schematic and laid out the PCB together. One early decision the team made that proved to be an excellent decision was the use of Github as a repository for schematics and code that were shared by the team.

The final result of the project was a proof-of-concept of noise-cancelling headphones with a field-programmable analog array. There is definitely quite a bit of work to be done to get the headphones up to par in both the noise-cancelling and audio playing realms, but the team laid the groundwork for this throughout the semester.

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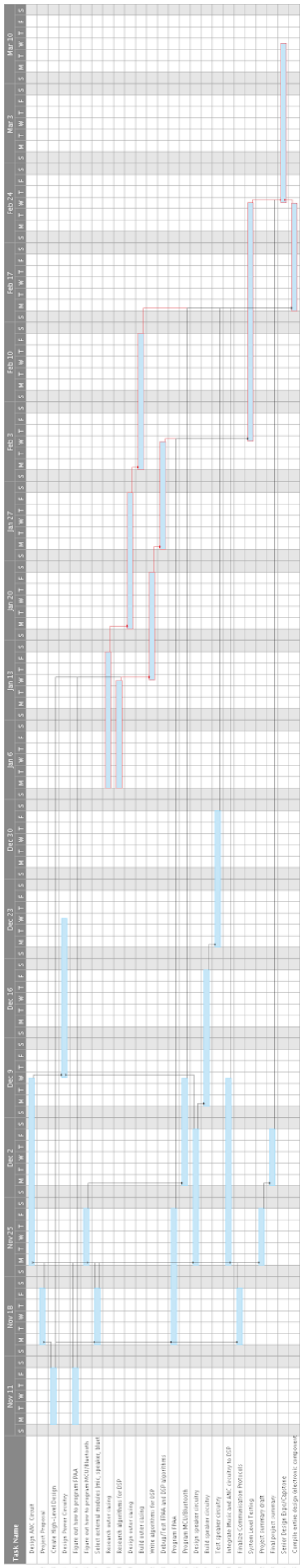
Appendix A - GANTT Chart



Appendix B - Task Assignments

Task	Team Member
Design Active Noise Canceling Circuit	Karthik
Submit project proposal	All
Create high-level design	All
Design power circuitry	Karthik
Learn how to program FPAA	Alexander
Learn how to program MCU/Bluetooth	Alexander, Matthew
Select external modules (speaker, microphone, bluetooth)	All
Research algorithms for DSP	Nitish
Research outer casing	Matthew
Design outer casing	Connor
Build outer casing	Nitish
Write algorithms for DSP	Alexander, Nitish
Debug/Test DSP algorithms/FPAA	Alexander, Nitish
Program FPAA	Alexander, Connor
Program MCU/Bluetooth	Alexander, Matthew
Design speaker circuitry	Carter
Build speaker circuitry	Carter
Test speaker circuitry	Carter
Integrate music and Active Noise Cancelling circuitry to DSP	Carter, Karthik, Connor
Finalize communication protocols	Matthew, Connor
System level testing	All
Submit project summary draft	All
Submit final project summary	All
Senior design expo/capstone	All

Compile entire design (electronic components and casing)	All