

Add-on box for old stereo systems

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1 Introduction

1.1 Objective

While online music stores and streaming services have significantly changed how people listen to music, many people still own large collections of CD and vinyl records, and prefer to enjoy them with existing stereo systems rather than purchasing digital copies. Though many of these old stereo systems are working properly, they often lack modern features like remote volume control and equalization, making them inconvenient compared to newer devices. For example, a user sitting in sofa has to stand up and come close to the CD player to turn the volume knob.

Our goal is to bring user-friendly features to existing stereo systems, so users can play their existing music collections with their existing audio equipments, at the same time control volume, equalization, etc. wirelessly. In order to do this, we propose an USB powered low cost add-on box together with an iOS app. The add-on box will be inserted into the signal path of existing stereo system to route and alter the analog audio signal, and the iOS app will be used to control the add-on box wirelessly via Bluetooth. The combination adds wireless volume control, equalization, left/right balance, input selection and a sleep timer to user's existing audio equipments. The add-on box will use RCA for inputs and output, so it will be compatible with most audio equipments on the market.

1.2 Background

Compared to the existing commercial wireless audio receivers which stream audio files, our device can satisfy the needs of those people who enjoy using the CD player or turntable. For example, those CD collectors can enjoy the modern features such as wireless control and equalizer without ripping their CDs into the digital files.

1.3 High-Level Requirements

- User must be able to use the iOS app to adjust volume and set equalization level of the input audio signal.
- Add-on box must not significantly decrease input audio quality.
- Add-on box must be able to operate on 5V USB bus power.

2 Design

The whole system contains two parts: the iOS app and the add-on box. The app serves as the user interface to control the functionality of the add-on box wirelessly via Bluetooth Low Energy (BLE). The add-on box routes and processes analog audio signal to apply input selection, volume control, and equalization to the audio signal. It connects to other audio devices via RCA connectors, and is powered by 5V USB bus power through a micro USB connector.

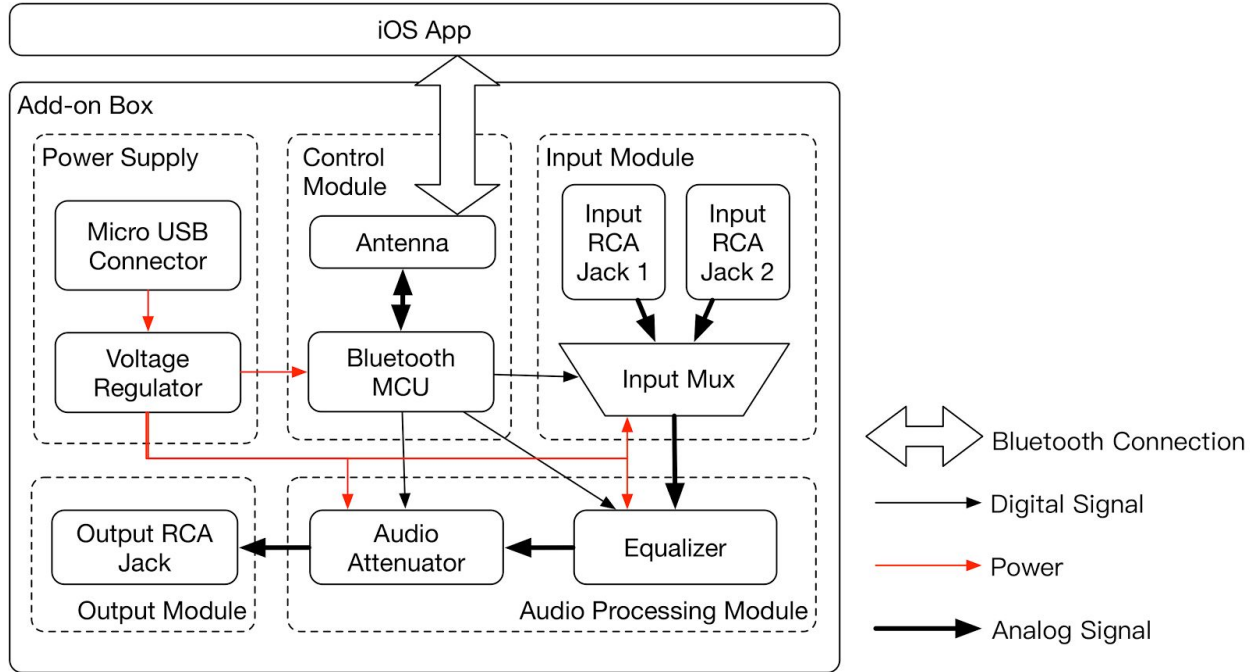


Figure 1. Block Diagram

2.1 Power Supply Module

This module powers the whole add-on box. Some components of the add-on box are powered by 5V USB power directly, while others draw power from a 5V to 3.3V voltage regulator.

2.1.1 Micro USB Connector

5V USB bus power is drawn from the micro USB connector, and powers the TS5A23159 analog multiplexer and the LM1972 audio attenuator directly. The USB specification requires USB bus power to be within $5V \pm 5\%$. Using USB power reduces cost because USB chargers and micro USB cables are cheap and widely available as common accessories of consumer electronics like smartphones and tablets.

Requirements	Verifications
Must output $5V \pm 5\%$ from a valid USB bus power input at 300mA.	<ol style="list-style-type: none"> 1. Connect a micro USB cable with $5V \pm 5\%$ bus power to the micro USB connector. 2. Connect a 11Ω resistor load to the output of the micro USB connector. 3. Measure the output voltage with a multimeter and make sure it's within $5V \pm 5\%$.

2.1.2 Voltage Regulator

A Texas Instruments LM3940 5V to 3.3V linear voltage regulator regulates the 5V USB power and powers the nRF51822 Bluetooth MCU and the AD5144 digital potentiometers. Since audio quality is critical to this project, linear regulator is chosen for its lower high frequency noise compared to switching regulators.

Requirements	Verifications
Must output $3.3V \pm 5\%$ from 5V USB power input at 300mA.	<ol style="list-style-type: none">1. Connect the voltage regulator's input to a 5V power source2. Connect the voltage regulator's output to a 11Ω resistor load.3. Measure the output voltage with a multimeter and make sure it's within $3.3V \pm 5\%$.

2.2 Control Module

This module controls all functionalities of the add-on box. It gets user commands from the iOS device wirelessly via BLE, and controls Input Module and Audio Processing Module accordingly.

2.2.1 Bluetooth MCU

The Nordic nRF51822 Bluetooth Low Energy MCU manages BLE communication with the iOS device. It acts as a BLE peripheral device and sets up a GATT profile to receive commands from the iOS device. It then sends corresponding control signals to the input multiplexer, equalizer or audio attenuator. Table 1 lists all commands the MCU processes.

User command	Action
Set volume level to [x]dB	Set volume level of the audio attenuator to [x]dB
Set equalizer band [x]Hz to level [y]dB	Set the corresponding digital potentiometer value ¹
Set input to [jack1 jack2]	Set the input multiplexer to [jack1 jack2]
Set sleep timer to mute after [x]s	Set audio attenuator to mute after [x]s
Set left/right balance to left:[x]%, right: [y]%	Convert [x] and [y] to dB and set the audio attenuator accordingly

Table 1. MCU Command List

Requirements	Verifications
Must be able to receive and process 5 user commands per second.	<ol style="list-style-type: none"> 1. Program the MCU with a test program which logs the command every time a command is received and processed. 2. Run a test program on iOS device which sends 5 random commands per second to the add-on box for 30 seconds. 3. Retrieve the log from MCU. Make sure every log entry matches the command sent by the iOS device.

2.2.2 Antenna

A 2.4GHz PCB trace antenna is matched to 50Ω and connected to the Bluetooth MCU. Its design follows Nordic nRF51822 Reference Layout [1] for best performance.

2.3 Input Module

This module receives audio signals from RCA connectors and routes them to the Audio Processing Module.

2.3.1 Input Jacks

2 CUI RCJ-2223 RCA connectors receive stereo analog audio signals from 2 different audio sources. RCA connector is chosen because it is supported by many consumer audio equipments, especially CD players, turntables and powered amplifiers.

¹ Details are discussed below in 2.5.1 Equalizer.

2.3.2 Input Multiplexer

A Texas Instruments TS5A23159 analog multiplexer selects one of the 2 input signals to send to the audio processing module. It is controlled digitally by the MCU.

2.4 Audio Processing Module

This module applies volume control, equalization and left/right balance to the audio signal. Parameters are set by the user using the iOS app.

2.4.1 Equalizer

The analog equalizer alters the sound signature to user's preference by boosting/attenuating certain frequency bands of the analog audio signal. The 5 band analog equalization circuit controlled by the MCE is described below. The equalizer outputs equalized audio signal to the audio attenuator.

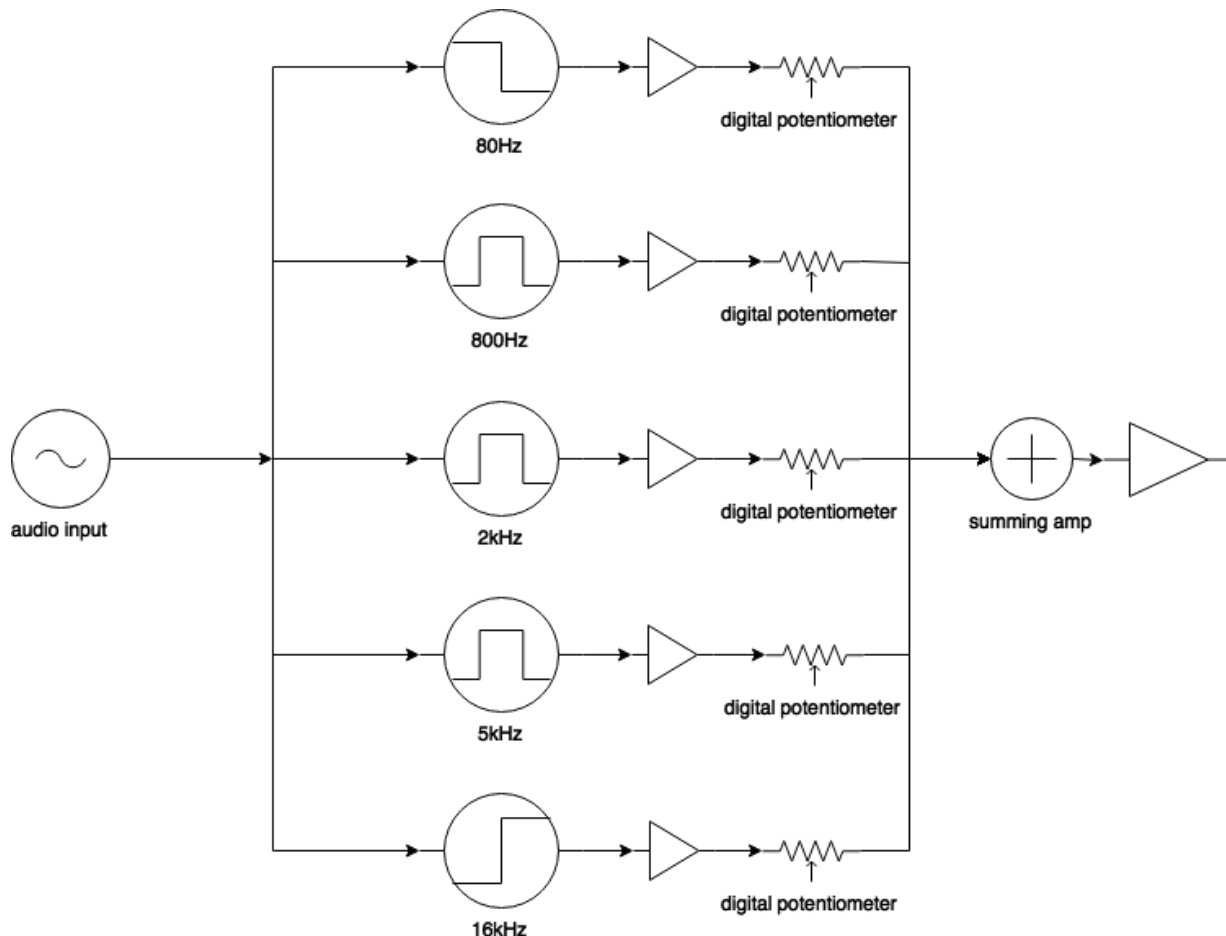
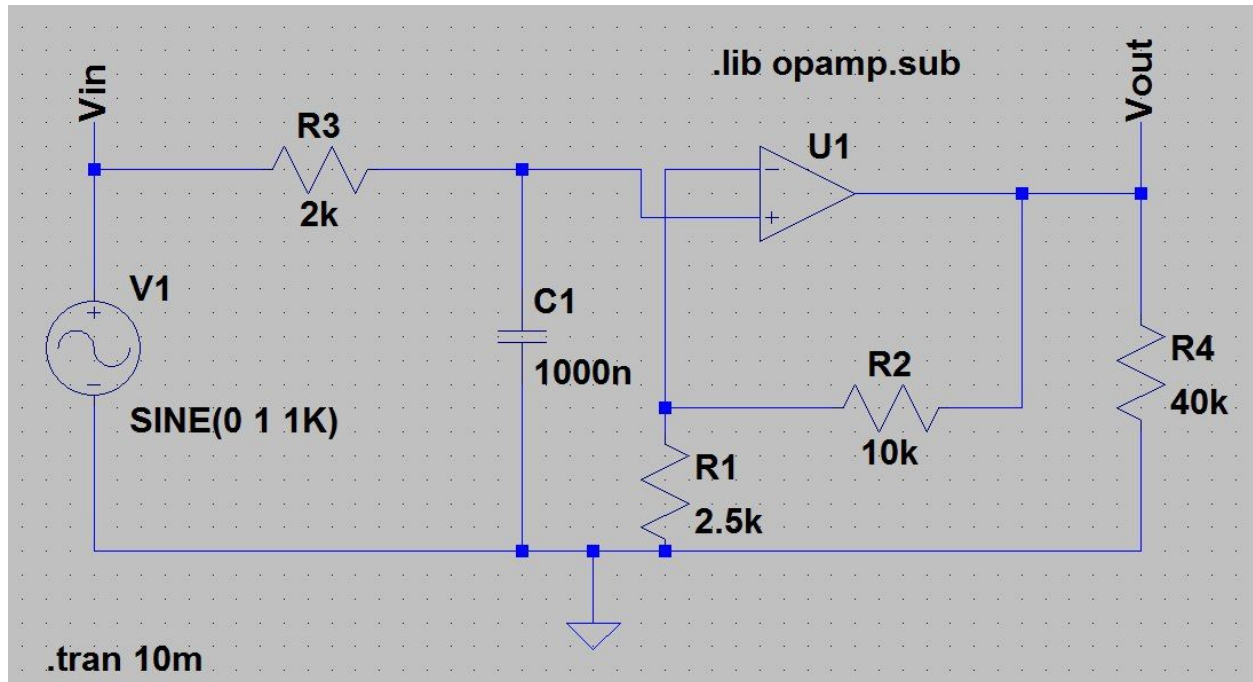


Figure 2. High Level Design of the Equalizer

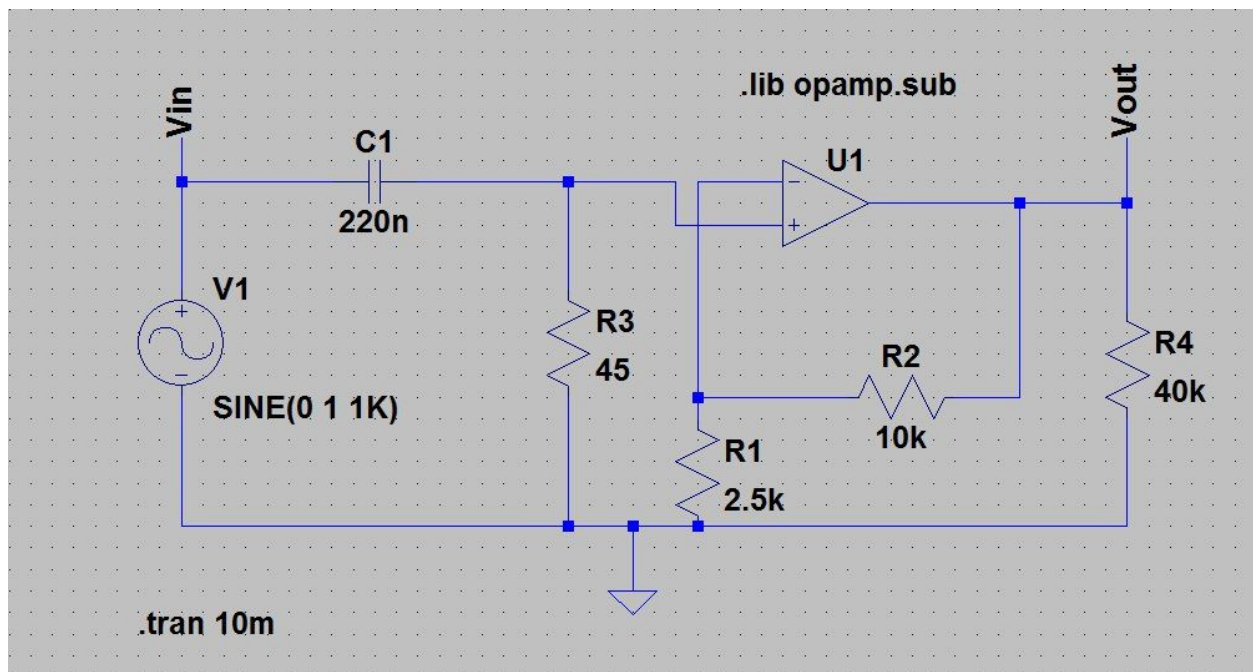
For the design of the equalizer, the input audio signal will be splitted into five different

frequency bands centered at 80Hz, 800Hz, 2kHz, 5kHz, and 16kHz respectively. The lowest frequency band goes through the low pass filter, the highest frequency band goes through the high pass filter, and the three frequency bands in the middle go through band-pass filters. The reason that separate amplifier will be applied on the each filter is that the cut-off frequency of every filter will depend on the resistor and the capacitor in the circuit of the filter, which means the op-amp will function as the buffer between the output signal of the filter and the actual output signal. Based on the equations of the cut-off frequency of each filter, the parameters such as the resistance and capacitance of the filter circuit can be determined based on the simple calculations. To ensure the consistency of the audio signal, the bandwidths of the other three bandpass filters will be divided into three frequency bands: 250Hz to 1.2kHz, 1.2kHz to 3kHz, and 3kHz to 9kHz based on calculations. Three Analog Devices AD5144 digital potentiometer ICs with the maximum resistance of 10k Ω controlled by the MCU control the voltage gain of the amplifier. To provide $\pm 3\text{dB}$ adjustment for each frequency band, the maximum voltage gain of the amplifier is set to 5. Finally, the output audio signals will add up through the summing amplifier, and the output will be connected with the digital attenuator with the input impedance of 40k Ω . The summing amplifier sums outputs from all filters into a single output. Ceramic capacitors are chosen instead of electrolytic ones because of their lower equivalent series resistance which makes it good when bypassing high frequency noise in the circuit. In this case, the ceramic capacitors can ensure the sound quality of the audio signals in the high frequency range. Because output signals of filters with different frequency bands have different peak amplitudes, to maintain the audio quality, the voltage gain of each op-amp is tuned to guarantee that peak amplitudes are around the same level. And all the waveforms and circuits are simulated on the LTSPICE.



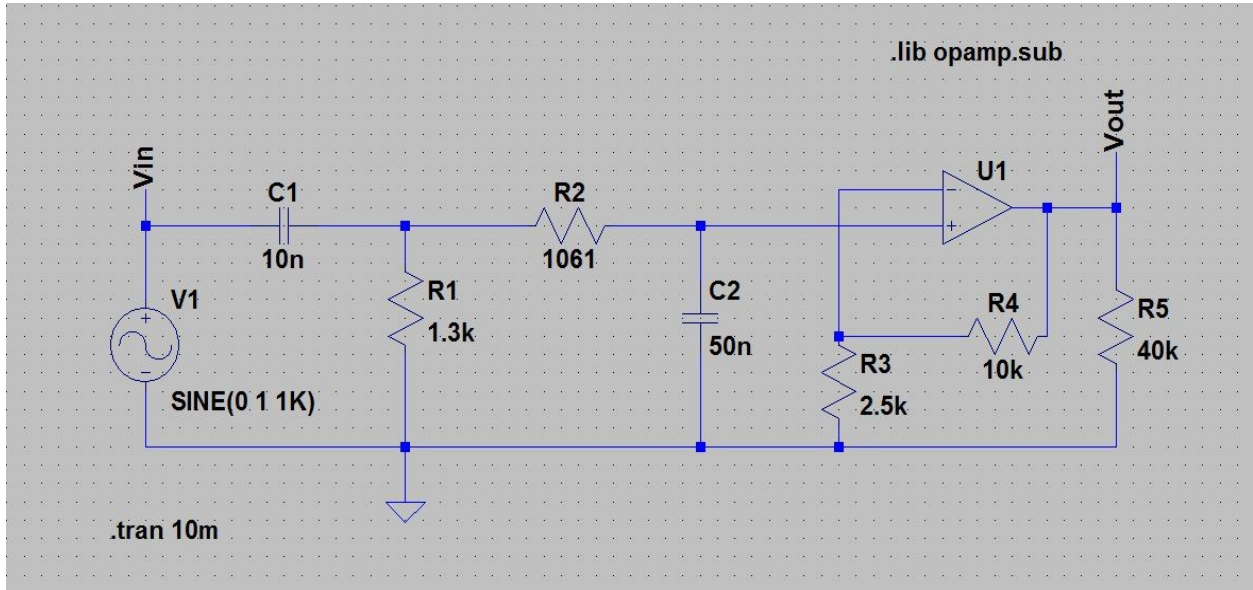
*R2 is the digital potentiometer with the maximum of 10k Ω

Figure 3. Schematic of the Active Low Pass Filter (80Hz) with Amplification



*R2 is the digital potentiometer with the maximum of 10k ohm

Figure 4. Schematic of the Active High Pass Filter (16kHz) with Amplification



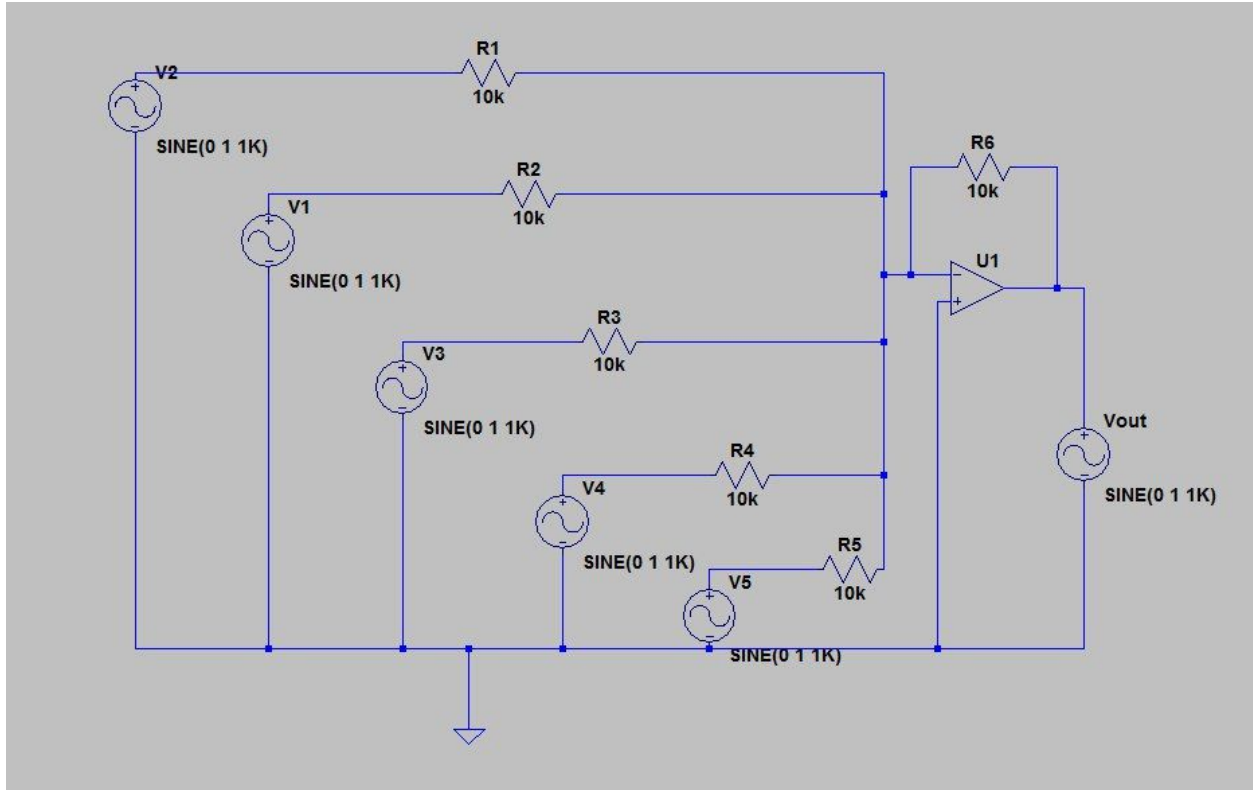
*R4 is the digital potentiometer with the maximum of 10k Ω

Figure 5. Schematic of the Active Band-Pass Filter (2kHz) with Amplification

Since the same bandpass filter circuit will be used on the other two frequencies, the parameters of all the band pass filters are listed in the following table:

Central Frequency (Hz)	Resistor (ohm)	Capacitor (F)
800	R1= 6.4k Ω R2=1.3k Ω	C1=10nF C2=10nF
2000	R1= 1.3k Ω R2=1061 Ω	C1=10nF C2=50nF
5000	R1= 350 Ω R2=45 Ω	C1=50nF C2=220nF

Table 2. Parameters of the Band-Pass Filters



$$V_{out} = -(V1 + V2 + V3 + V4 + V5)$$

Figure 6. Schematic of the Summing Amplifier

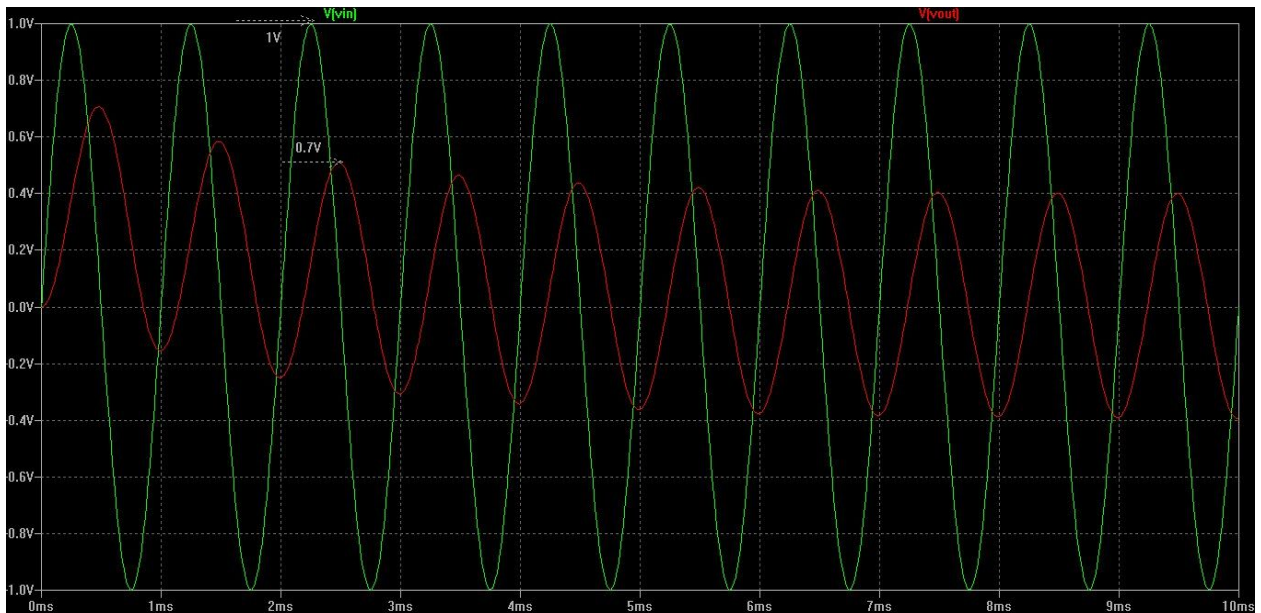


Figure 7. Waveform of the Active Low Pass Filter with Amplification

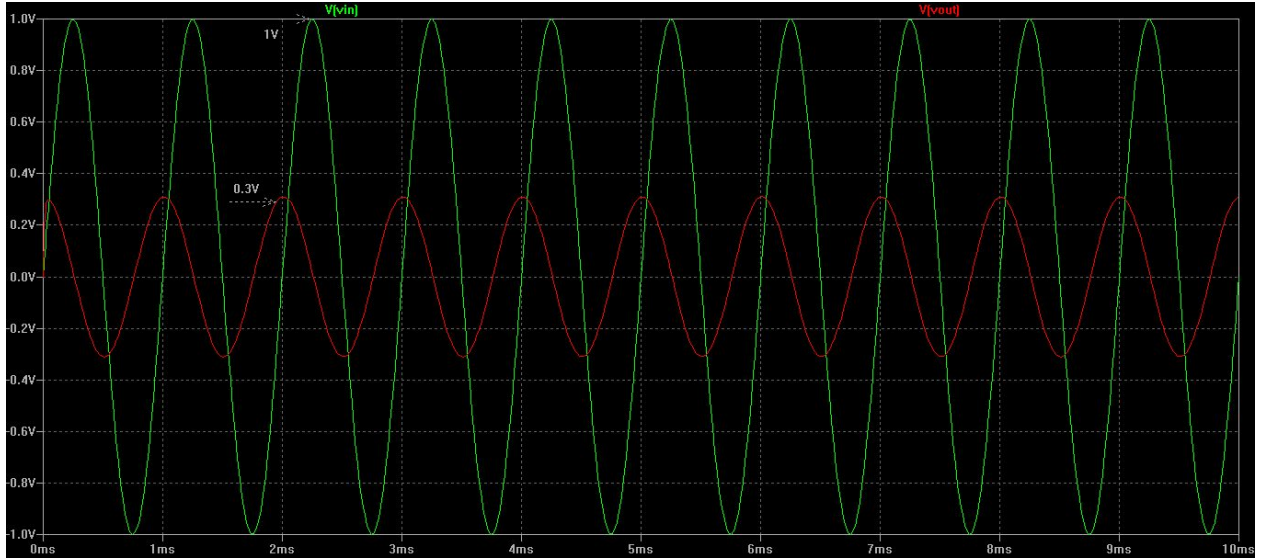


Figure 8. Waveform of the Active High Pass Filter with Amplification

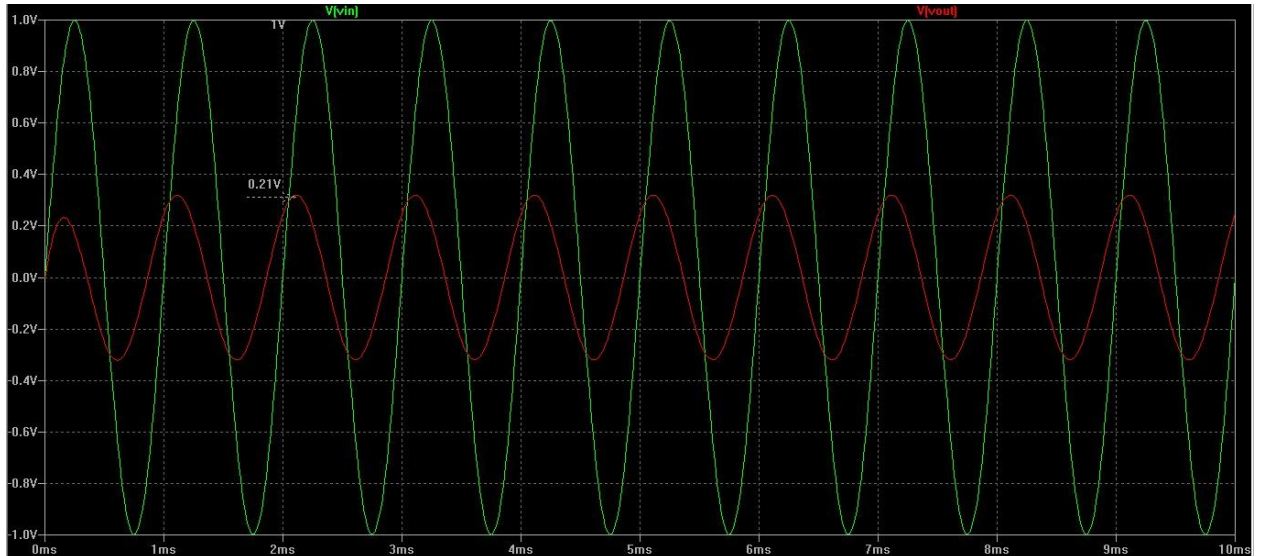


Figure 9. Waveform of the Active Band Pass Filter with Amplification

The following equations will be applied for the filters and amplifiers:

For the active low-pass filter, the cut off frequency of the filter will be

$$f_c = \frac{1}{2\pi R_1 C_1}$$

And the Voltage gain of the amplifier will be

$$\text{VoltageGain}(A_v) = \frac{V_{out}}{V_{in}} = \frac{A_F}{\sqrt{1 + \left(\frac{f}{f_c}\right)^2}}$$

Where:

A_f is the low pass band gain of the filter:

$$1 + \frac{R_3}{R_2}$$

f is the frequency of the input signal in Hertz;

f_c is the cut-off frequency of the low pass filter;

Similarly, for the active high-pass filter, the cut off frequency of the filter will be

$$f_c = \frac{1}{2\pi R_1 C_1}$$

And the Voltage gain of the amplifier will be

$$VoltageGain(A_v) = \frac{V_{out}}{V_{in}} = \frac{A_f \left(\frac{f}{f_c} \right)}{\sqrt{1 + \left(\frac{f}{f_c} \right)^2}}$$

Where:

A_f is the low pass band gain of the filter,

$$1 + \frac{R_3}{R_2}$$

f is the frequency of the input signal in Hertz;

f_c is the cut-off frequency of the high pass filter;

And for the active band pass filter, we can derive the center frequency of the filter will be:

$$f_r = \sqrt{f_L * f_H}$$

where f_L is the cut-off frequency of the low pass filter;

f_H is the cut-off frequency of the high pass filter;

Requirements	Verifications
Must provide $\pm 3\text{dB}$ adjustment for 5 frequency bands centered at 80Hz, 800Hz, 2kHz, 5kHz, and 16kHz respectively.	<p>For each frequency band:</p> <ol style="list-style-type: none"> 1. Set level of the this frequency band to +3dB and levels of all other frequency bands to -3dB. 2. Connect the input to a function generator, and run a frequency sweep from 20Hz to 20kHz. 3. Analyze the frequency response from the output with an oscilloscope. Make sure amplitude of the central frequency of this frequency band is +3dB relative to the input, and amplitude of all other frequency bands are -3dB.

2.4.2 Audio Attenuator

A Texas Instruments LM1972 audio attenuator adjusts volume and left/right balance of the analog audio signal. It also alters the left/right balance by adjusting volumes of left and right channel independently. It outputs the attenuated audio signal to the output module.

Requirements	Verifications
Must attenuate input audio signal to -60dB or lower at 1dB or smaller steps	<ol style="list-style-type: none"> 1. Set the audio attenuator to its lowest volume level. 2. Connect input of audio attenuator to a function generator and generate a sine wave. 3. Measure the amplitude of the output signal with an oscilloscope, make sure the amplitude is -60dB of the input signal or lower 4. Program the audio attenuator one level higher 5. Measure the amplitude again and make sure the amplitude increases less than 1dB.

2.5 Output Module

This module outputs processed audio signal.

2.5.1 Output Jack

A CUI RCJ-2223 RCA connector outputs the processed audio signal to devices which accept RCA input.

2.6 iOS App

The app is the only user interface to control the functionality of the add-on box. It acts as a BLE central device and transfer commands to the add-on box by reading and manipulating the GATT profile set by the Bluetooth MCU.

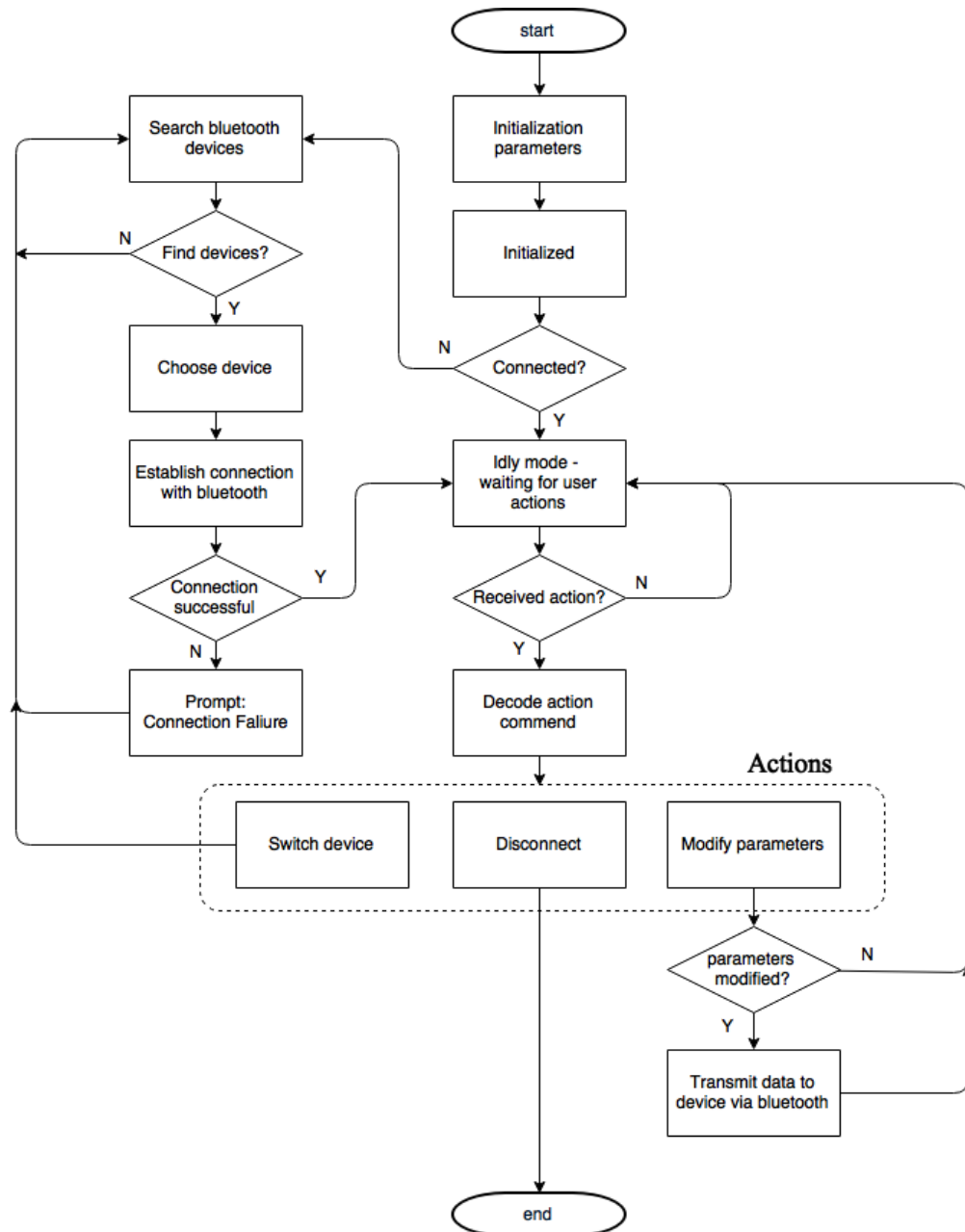


Figure 10. iOS Application Flowchart

The iOS App is built following the above flowchart. This app connects with the add-on box via Bluetooth Low Energy and transmits data and signals to it. Current volume, left/right balance and level of each equalizer band are set and stored by the App. Each of them is modified by users and the app detects changes and transmits the updated values to the add-on device. This app is compatible with iOS 10.0 and higher version.

Requirements	Verifications
1). Correct bluetooth connection and possess device-selection functionality 2). Valid data transmission 3). Compatible with iOS 10.0 and higher version	1). Use multiple devices to test and verify the ID of connected device. 2). Use simulation program to visualize the transmitting data. 3). Run and test in all versions of iOS from 10.0 to the latest.

2.7 Schematics

will be 1% and the tolerance of the capacitors will be around 10%. Taking the schematic of the active low pass filter as an example, we are using the 2k Ω resistor with 1% tolerance and 1000nF with 10% tolerance, which means the product of the RC will determine the location of the resonant frequency.

	Frequency (Hz)	Voltage Gain
Max RC	71.6	0.707
Exact RC	80	0.7
Min RC	89	0.78

Table 3. Parameters of the LPF with exact and extreme values the RC product

Also, the tolerance of the resistors will also affect the voltage gain of the op-amp behind each filter.

	Voltage Gain of the amplifier
Max $\frac{R2}{R1} = 1.02$	2.02
Exact $\frac{R2}{R1} = 1$	2
Min $\frac{R2}{R1} = 0.98$	1.98

Table 4. Parameters of the op-amp with exact and extreme values of R2/R1

The requirement for the output of the equalizer is that the peak amplitudes of all the filters should be around the same level after the audio signal go through the amplifiers, so that all the output audio signals will be added through the summing amplifier. Therefore exact values of resistance and capacitance of the components should be measured before the amplifiers are implemented.

3 Cost

3.1 Labor

We estimated our development costs based on \$40/hour, 10 hours/week for three people. By the end of this semester, we expected to spend around 16 weeks on this project:

$$3 \times \frac{\$40}{hr} \times \frac{10hr}{wk} \times 16wk = \$19,200$$

3.2 Parts

Part	Cost (prototype)	Cost (bulk)
Bluetooth MCU (Digikey;1490-1024-ND)	\$4.85	\$2.87
TI Analog Switch ICs 1-Ohm Dual SPDT Ana Sw Mult/DeMult (Mouser; TS5A23159RSER)	\$0.88	\$0.51
3x RCA connector	\$5.01	\$2.47
3x Digital Potentiometer IC (Mouser: 584-AD5144BCPZ10-R7)	\$25.56	\$12.06
Attenuators Micro-Pot 2CH 78dB Audio Attenuator (Mouser;926-LM1972MX/NOP B)	\$4.61	\$2.87
PCBs	\$4.3	\$0.2
Resistors, capacitors (Digikey;est.)	\$8	\$0.3
Total	\$53.21	\$21.28

4 Schedule

Week	Tong Zhao	Chutian Shao	Ziyang Liu
2/19/17	Buy components	Buy components	Buy components
2/26/17	Software programming on connection between bluetooth and microcontroller	Design and generate PCB blueprint	Construct iOS app frame
3/5/17	Continue on programming	Simulation on PC	Research on data transmission and bluetooth protocols
3/12/17	Finish programming and embed in iOS app	Produce PCB and design equalizer	Finish app programming integrate bluetooth device.
3/19/17	Continue on software integration	Build actual circuits and assemble hardware components	Continue on software integration
3/26/17	Assemble hardware and software	Assemble hardware and software	Assemble hardware and software
4/2/17	Simulation on real device	Simulation on real device	Simulation on real device
4/9/17	Fix software bugs and evaluate performance	Fix hardware bugs and evaluate performance	Fix software bugs and evaluate performance
4/16/17	Continue on bugfix	Continue on bugfix	Continue on bugfix
4/23/17	prepare final presentation	Compose final report	Compose final report

4. Ethics and Safety

Incorrect connection of audio cables, like connecting two outputs together or connecting the device to power amplified audio source may cause short circuit and potentially overheat and fire. We must inform users clearly on how to safely use the product by providing instructions of how to connect the cables correctly and warn users the danger of not doing so. Otherwise, this product should be relatively safe because we only deal with low power analog audio signal. The product

doesn't process any power amplified signal.

Few potential ethics issues might affect the project. During our development, we are committed to follow the IEEE code of Ethics. We will instruct users on how to safely use the product according to the IEEE code of Ethics, #1: "to accept responsibility in making decisions consistent..." [2]. When we are programming our iOS application, we might cite and imitate some online source code. We assure that proper citation would be included in our project which is consistent with IEEE code of Ethics, #7: "..... credit properly the contributions of others" [2].

References

- [1] Nordic Semiconductor, 'nRF51 Series Reference Layout', 2017. [Online]. Available: http://infocenter.nordicsemi.com/topic/com.nordic.infocenter.nrf51/dita/nrf51/pdflinks/ref_layout.html?cp=3_6. [Accessed: 24-Feb-2017]
- [2] Ieee.org, "IEEE IEEE Code of Ethics", 2017. [Online]. Available: <http://www.ieee.org/about/corporate/governance/p7-8.html>. [Accessed: 7-Feb-2017].
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