

ECE 445 Final Report

Wireless Guitar Pedal / Fagen Scooter BMS

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Abstract

A guitarist's ability to move around on stage is limited by their ability to access their guitar effects stomp board; to fix this, lots of research on how to move these controls to a more mobile platform. The previous solution by ECE 445 students was to send both pedal controls and the audio signal through a secure, ultra high-frequency radio. Instead, our revision transmits the pedal controls over secure bluetooth, opting to transmit audio via a normal cable to ensure the audio signal can't be lost if the transmitter fails or is damaged.

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Chapter 1: Motivation

1.1 Problem Statement

Performing live at a concert often requires musicians to move around constantly on stage. Whether it be to crowd surf, mosh, or just to move to the rhythm of the music they're playing, the actions of a musician on stage can make or break a performance. Traditionally, guitars are connected to sound equipment, using pedal boards to control effects like distortion, echo, reverb, filtering, etc. [1]. Pedals are typically daisy chained together, and contain control knobs to adjust different parameters on each pedal [2]. This means that if the musician wants to make real-time adjustments, they need to be standing near the pedal and are forced to adjust parameters with their feet. There are existing devices on the market that allow for the modulation of certain effect parameters wirelessly, however, there are no devices on the market that allow a guitar player to remotely control several effect parameters on a pedal [3].

This pedal would be desired by musicians because it will increase the musical freedom of the musician on stage. Being able to adjust signals live from a device that is mounted directly onto a guitar is something that a lot of musicians are moving towards. For example, Matt Bellamy, the lead guitarist of Muse has incorporated a MIDI X-Y control pad into his guitar so that he can modulate his guitar during performances [4]. Music is moving in a direction that combines acoustic and digital elements, which would make a guitar-mounted controller very appealing to musicians.

1.2 Solution

Our solution to this problem is to create a transmitter unit that can be placed on the guitar. This device will be able to turn effect(s) on/off, and will have several potentiometers to give the user control over effect elements. The transmitter will communicate with a receiver unit that will take an analog guitar input, apply the effect/process the audio data digitally based on parameters coming from the transmitter, and then convert it back into an analog output. This receiver can be daisy chained to a guitar pedal board and is set up exactly like any other guitar pedal.

1.3 High Level Requirements

1. If a 1V peak to peak analog sine wave is inputted to the receiver, the receiver's output must be an identical signal that has a latency less than 13 ms with a Signal-to-Noise Ratio (SNR) greater than 20dB

2. Bluetooth transmitter must be able to send 12-bit digital potentiometer values to the bluetooth receiver at a distance of 10 feet
3. Receiver microcontroller must be able to process audio data (data from the guitar) at a sampling rate of at least 48 kHz and a bit resolution of 16-bits

1.4 Visual Aids

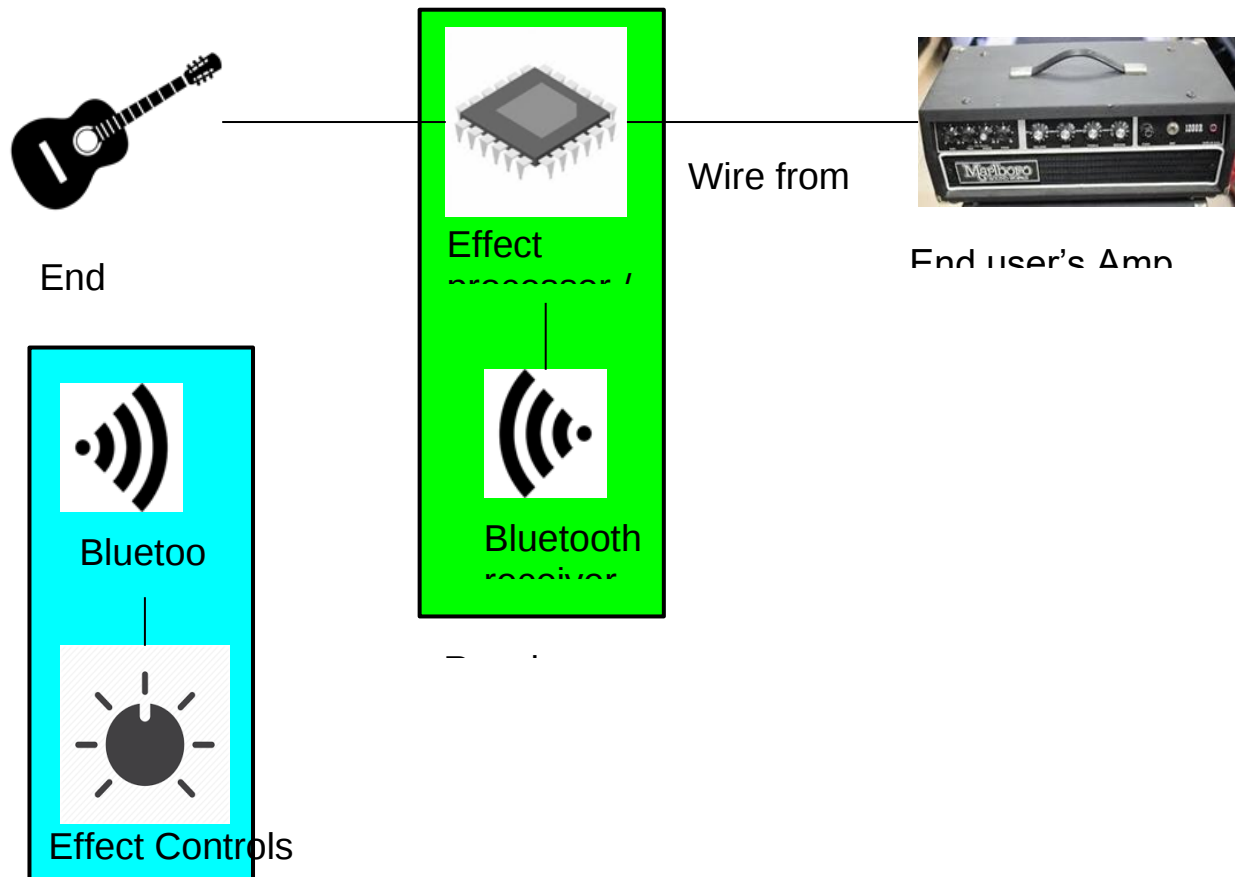


Figure 1. Physical layout

1.5 Block Diagram

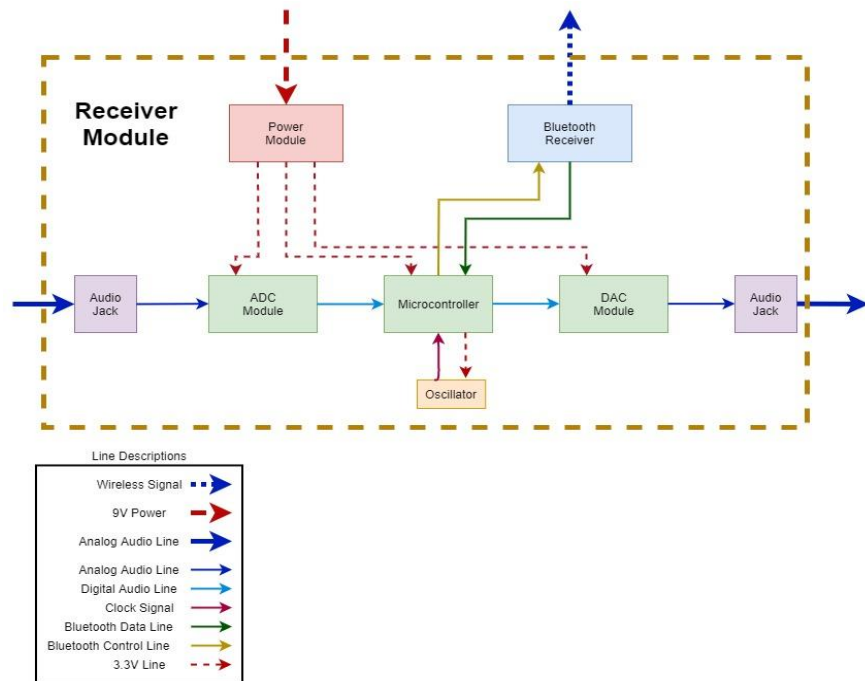


Figure 2. Block Diagram of Receiver Module

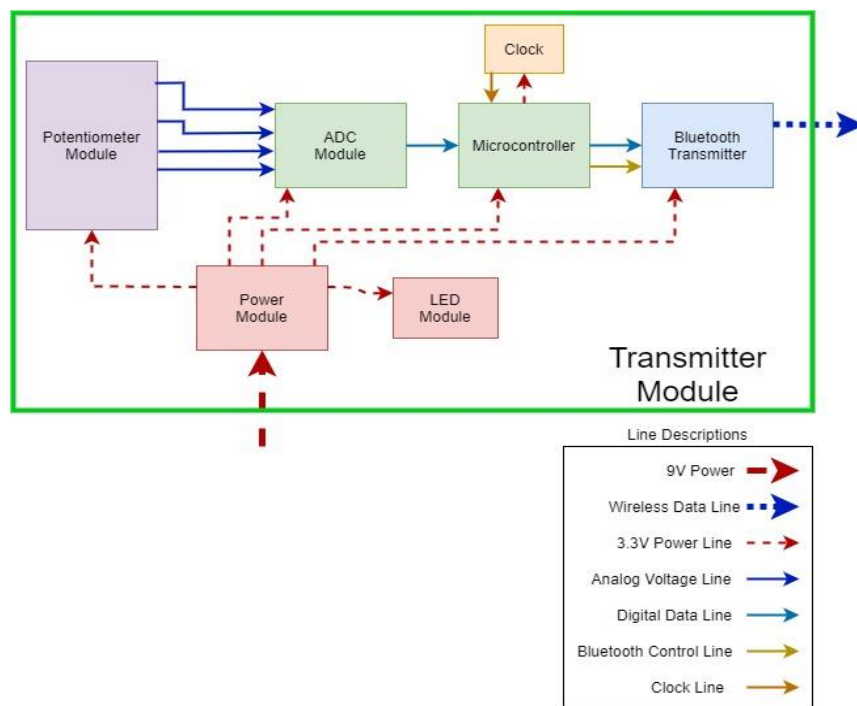


Figure 3. Block Diagram of Transmitter Module

Chapter 2: Implementation

2.1 Submodule Details

In the scope of this semester, we planned on developing a bill of materials and PCB design for the receiver of the guitar pedal. This section will describe the different sections and considerations during the design of the PCB and will analyze the overall costs and manufacturing of a single receiver unit. This section will also discuss the algorithm used to pass audio through the microcontroller. The implementation of bluetooth on the microcontroller software will not be discussed in this section. The following section will describe the subsections of the receiver.

2.1.1 Microcontroller

The microcontroller will be in charge of data flow. This includes controlling the Oscillator module for proper clocking, managing the data transfer protocol to move data from the ADCs to the DAC and data from the Bluetooth receiver to itself. Additionally the microcontroller will control pairing and receiver timing for the bluetooth system.

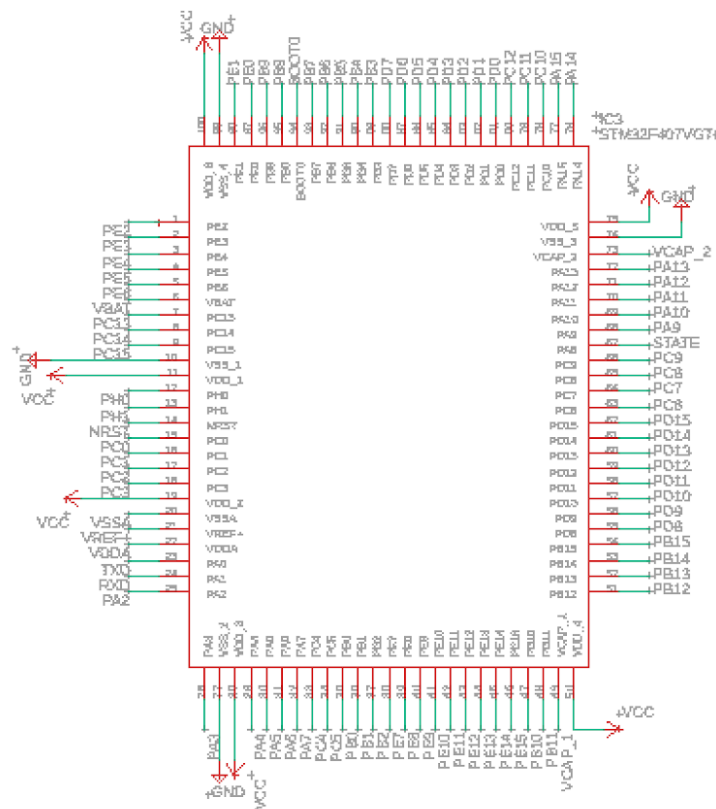


Figure 4: Microcontroller

The power module is responsible for supplying a consistent 3.3 volt signal to power the microcontroller. To ensure consistent power supply a voltage regulator circuit is placed immediately after the power source.



Figure 6: Microcontroller Supporting Components

2.1.3 LED Module

The LED module is used to show proper pairing. When the LED is on, the receiver is paired to the transmitter and able to receive data. The LED will also blink similar to the transmitter if the power module drops below 3.3V, indicating damage to the power module.

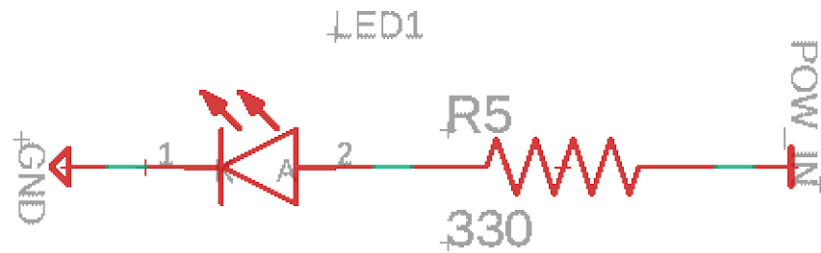


Figure 7: LED Module

2.1.3 Oscillator Module

The Oscillator module will be the clocking source for the receiver system. The clocking speed is governed by the microcontroller and used to dictate the speed of data transfer and how often bluetooth data is received and how fast the guitar's sound signal is sampled. This will need to be a very fast clock because audio processing is very time consuming. For our design, we went with.

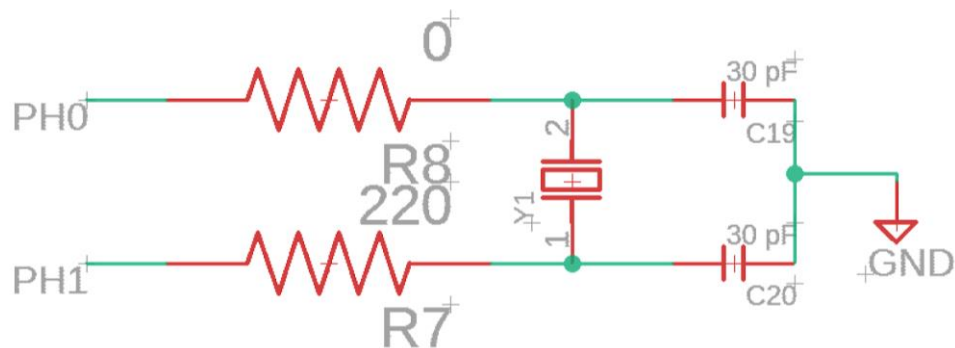


Figure 8: Oscillator Module

2.1.3 ADC/DAC Module

The ADC and DAC modules will use the AK5720 and AK4430 ADC and DAC. These devices were picked because of their dynamic range of controls and for their high audio quality. The ADC converts the audio input to digital I2S serial data and the DAC converts I2S data back into an analog signal. See appendix item 1 for an enlarged copy of ADC and DAC schematic.

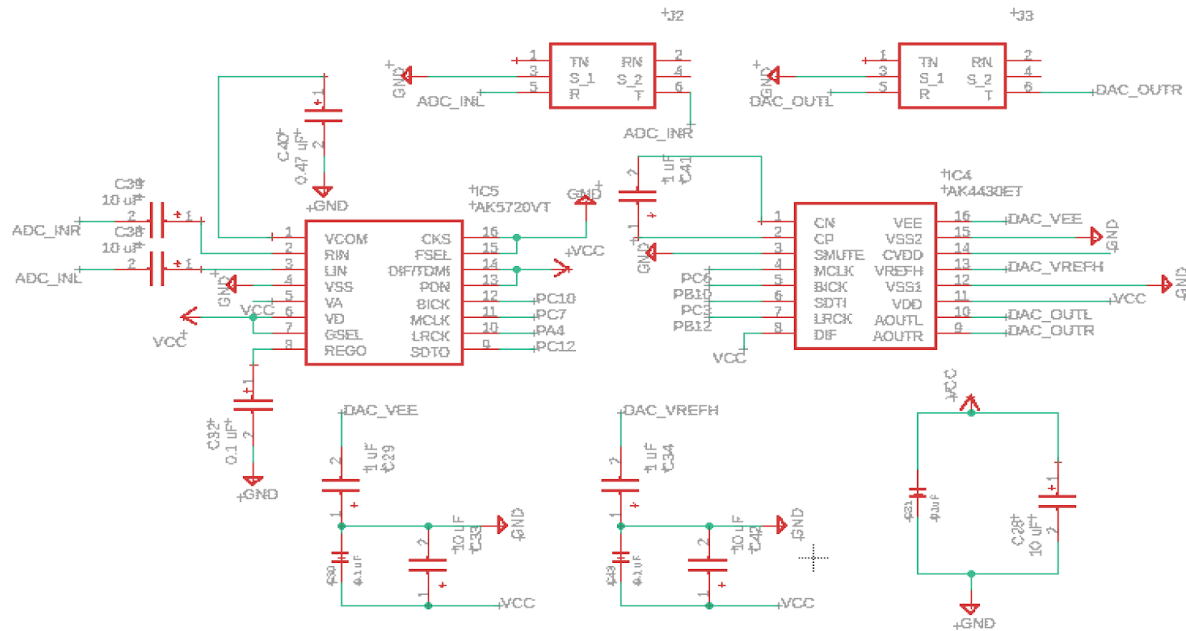


Figure 9: ADC/DAC Modules

2.1.3 Bluetooth Module

The bluetooth module will receive wireless data from the bluetooth module on the transmitter. The RXD chip will then transfer data serially to the microcontroller. This module has several GPIO pins that can be used to adjust the state and to press a button to pair the device to the transmitter. There is also an LED connected to this that will glow when the module has successfully paired.

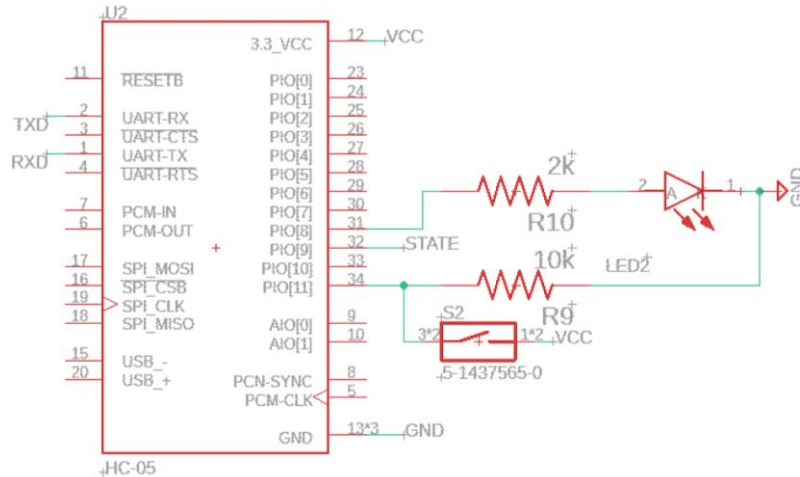


Figure 10: Bluetooth Module

2.2 Software

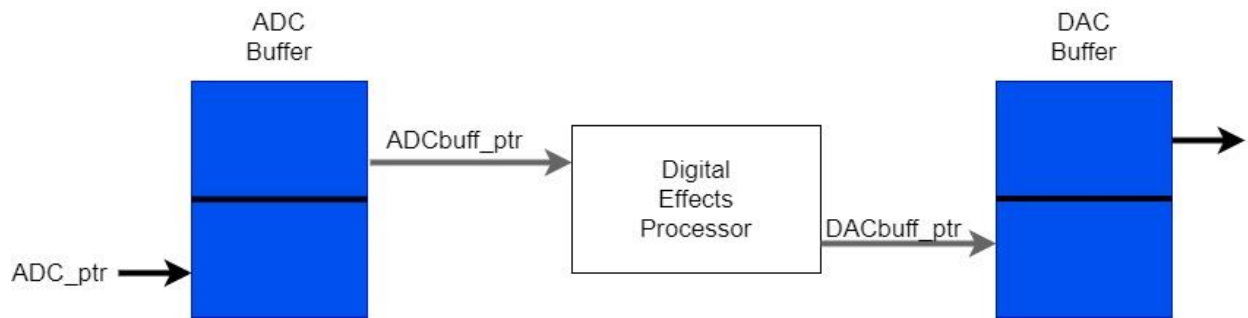


Figure 11: Software Flowchart

The software will be solely done using the free STM32 IDE. This compiler does all the low level configuration for you and provides a GUI to set the settings for clocks on the microcontroller and pinouts on it. All the pin and clock settings are set up in the .ioc file, and then an embedded C code is created by the IDE. This code can then be adjusted according to the desired use of the microcontroller.

The goal of our initial software is just to obtain audio from the ADC, process it in some way, and then output it to the DAC. The bluetooth module would be added later and the parameters being sent by the controller will adjust variables that are being used to process the signal. The way our code works is by using 2 DMA buffers, 2 buffers, and a processing function. a pointer is cyclically placing data into the DMA buffer from the ADC. Using this pointer, our software moves this data into a 256, 24-bit word buffer. When this buffer is filled halfway, the program is interrupted and data is processed and stored into another 256, 24-bit word buffer. Another pointer will then continuously grab data from this buffer until it is halfway filled. Attached above is a flowchart of the software architecture. The Digital Effects Processor

function is a simple distortion effect. This function multiplies each audio data point by some value, then it clips the signal with a conditional statement.

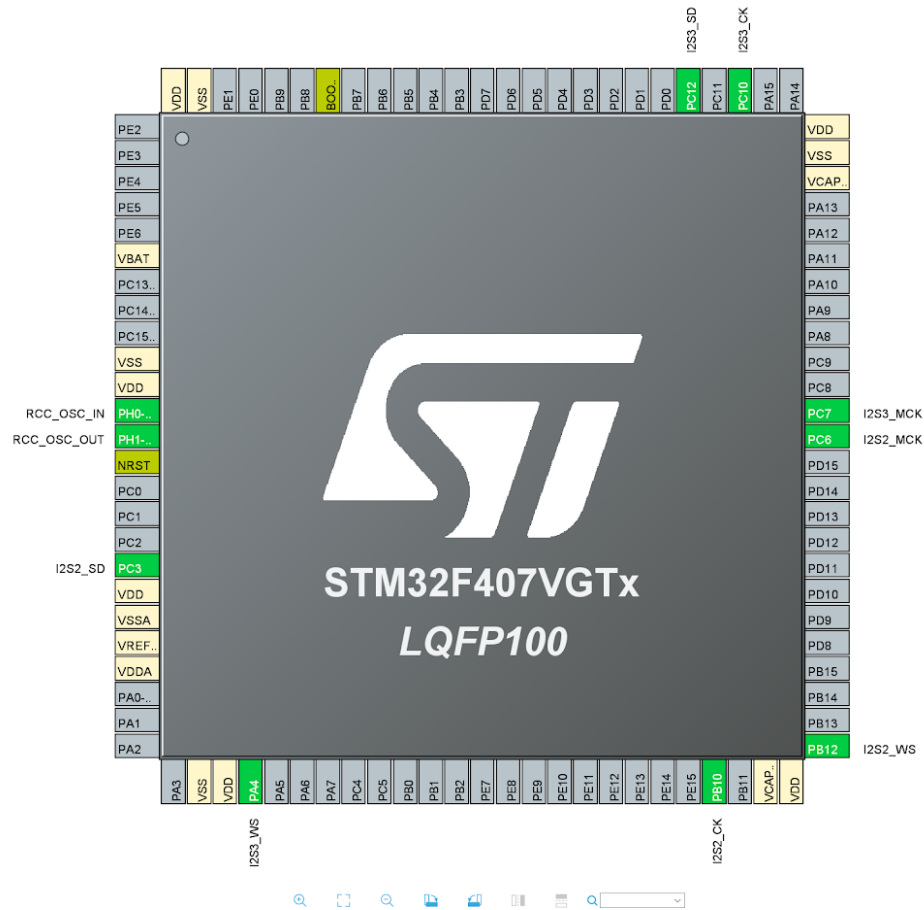


Figure 12: Pin Configuration for Microcontroller

2.3 Prototyping With Audio Board

To test the developed software on an ARM processor, we used an STM32F407DISCOVERY board. This device contains an STM32F407 processor on it. This processor is specifically designed for audio applications. To emulate the ADC and DAC setup, I used a board that has an external ADC/DAC on it. This board has all the required architecture to power an AK ADC and DAC, along with pinouts of all the different digital signalling. The developed software will be booted onto the microcontroller using UART, and then we can test the software by hooking up a guitar to the input of the audio board and hooking the output to an amp. If the audio signal is coming out clean, then the software is a success. To see the setup of this experiment, see appendix item 3.

2.4 Analysis of Noise in Receiver

The most important section of our design will be the system in charge of ensuring audio data playback. This includes all the modules that will be inputting analog audio, converting it to digital data, processing it, then converting it back into an analog signal, and outputting it. This section of the design is the audio jacks, ADC/DAC module, and the microcontroller. This section is vital because, without this system working, it cannot be effectively determined whether the rest of the pedal is working properly. If a clean signal cannot be outputted in the first place by the pedal, and everything else is working perfectly, the device is completely useless to a consumer. The most important specification of this system that needs to be analyzed to ensure a clean audio signal is the overall SNR of the system, and all the elements of the system that can potentially produce error. Our high level requirements outline that we need an SNR of 20 dB or greater, so this analysis will ensure that this requirement will be satisfied using an ADC and DAC with a bit resolution of 24 bits.

The largest amount of noise that will enter our audio signal will occur during the transition from analog to digital data and vice versa. So long as no data loss occurs during reception, processing, and transmission inside of the processor, there will be no noise added by the microcontroller. This can easily be done using a 32-bit MCU that can process more than 40 instructions per second [5]. ADCs and DACs will naturally add noise to your signal due to the effect known as quantization error. This error occurs because any ADC or DAC must round the value of an analog signal by some degree[6]. This error is reduced as you increase the bit resolution of your audio signal. Below is a bar chart that shows the relationship between the SQNR, which is the SNR created due to quantization error, and bit length in an ADC with a 5V voltage span [6].

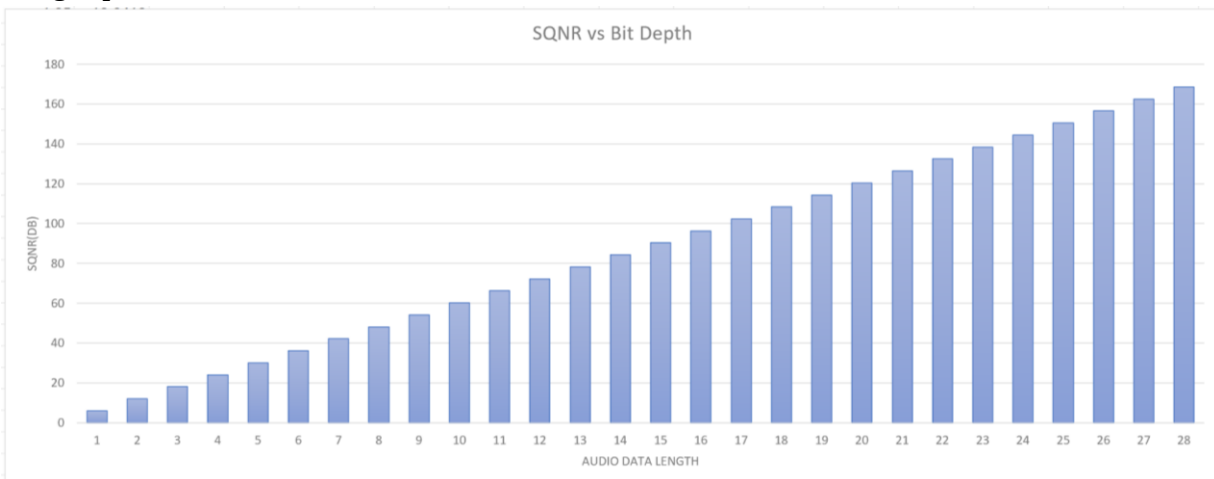


Figure 13. SQNR vs Bit Depth

This graph shows that the SQNR (in dB) is linearly related to the bit depth, and that a 4-bit data length will give us adequate SQNR; however, since quantization error is not the only form of noise that can be introduced into the system, we have selected a bit resolution that will give a much higher SQNR than needed. Even though a bit depth of 16 is plenty for our ADC, we have

chosen 24 bits for marketability purposes; people typically affiliate a higher bit-depth with higher audio quality.

Another thing to consider when making design decisions for the ADC and DAC is their jitter. Jitter is a phenomena that is caused by sampling clocks being unideal. These clocks can sometimes produce error due to there being an uncertainty about when samples are recorded [6]. Jitter is dependent on the frequency of the audio and on the bit depth. The time uncertainty $\Delta t < \frac{1}{2^q \pi f_o}$, where f_o is the frequency of your signal and q is the bit depth of your audio. Since we will be using a sine wave for testing purposes, we can model our audio signal as being $s(t) = A \sin(2\pi f_o t)$. According to wikipedia, the error that corresponds to the jitter of a audio signal corresponds to the following inequality: $E_j \leq |s'(t)\Delta t|$. Thus, with the sine wave we are using for testing, $E_j \leq 2A f_o \Delta t < \frac{A}{2^{q-1}}$. With this equation, we can calculate the maximum noise created by jitter, assuming we are passing in a sine wave with an amplitude of 1 Volt. A plot of Δt is also attached to ensure that jitter is relatively small at frequencies below 48 kHz. This has been plotted for several standard audio bit depths [7]. These charts show that a 24-bit data value will give minimal jitter in the range of 0 Hz to 48 kHz, and this makes sense because jitter takes major effect at extremely high frequencies [6].

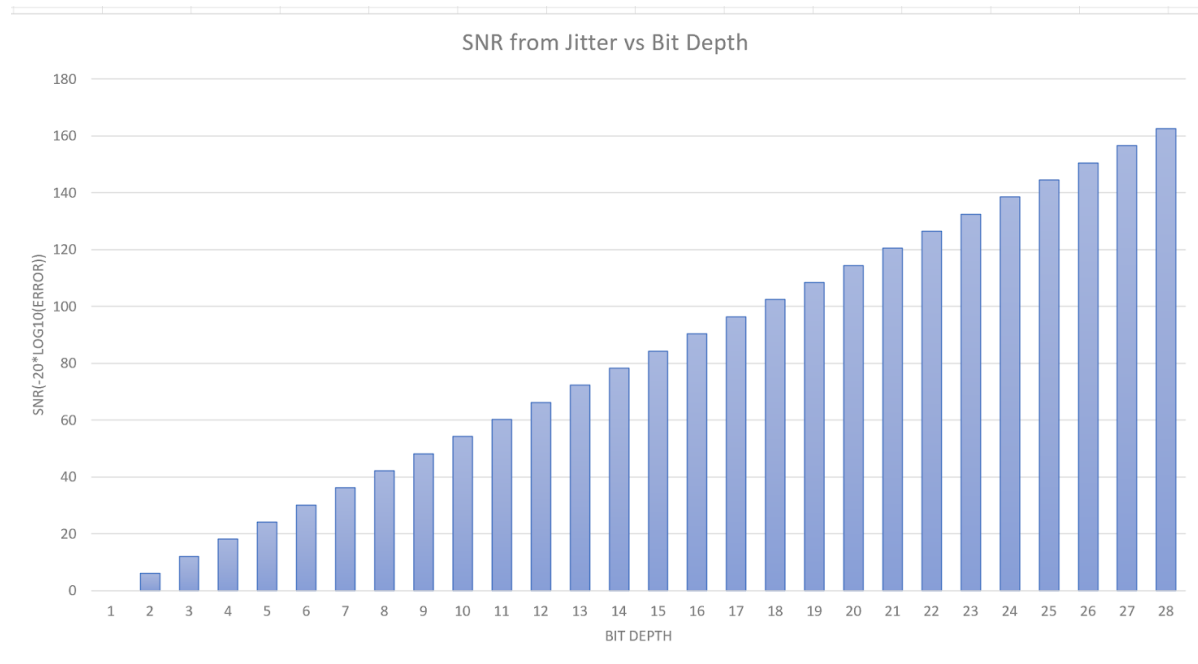


Figure 14 Jitter SNR vs. Bit Depth

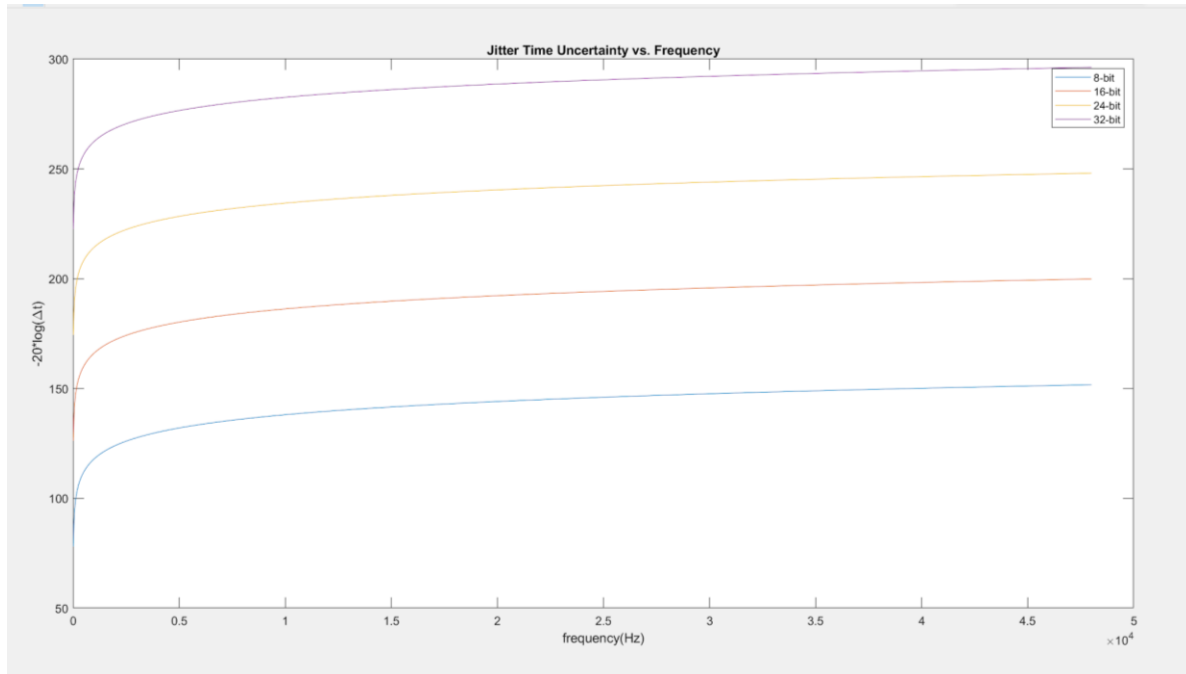


Figure 15: Δt vs. Frequency

2.5 Analysis of Noise in Receiver

A provided bill of materials has been included in the appendix as appendix item 4. This spreadsheet contains all the components necessary to build the receiver. The total cost of a single unit, along with Digikey links to the relevant components are included in the spreadsheet.

Chapter 3: Conclusion

3.1 Summary

From what we've developed in *Chapter 2: Implementation* we expect our design to be ready to function and just needs to be built. The only major hic-up possible is the Bluetooth transmitter receiver combination, which is discussed in the below Unknowns, Uncertainties, Needed Testing section. We were able to create code that minimized/eliminates any noise from the microcontroller. The I2S configuration and chosen frequencies with the ADC/DAC minimizes the noise bar low level noise from the mechanical switching in the ADC/DACs. This is then further eliminated as the low level noise is too weak to play through the end user Amplifier. Thus we can within reason say high level requirement #1 is achieved / expectedly achievable. By inspection our research indicates that by using our chosen ADC/DACs, clocking speeds, and I2S data protocol High Level requirement #3 should be met, we have no reason to believe this requirement would not be met as it is majorly hardware / hardware configuration dependent.

3.2 Unknowns, Uncertainties, Needed Testing

Having built a similar project before we are confident in our receiver system bar the bluetooth system, using the lessons from the receiver we also expect our transmitter to be easily made functional. Bluetooth is the major uncertainty, and requires a large amount of testing to verify proper linking and secure connectivity. The testing of both the receiver and the transmitter needs to be done during production. While we believe that everything is configured correctly from the documentation we can not guarantee this without producing the pcb and attempting to connect. Not having access to the lab/pcbway makes it so we can not produce the physical system and thus can not properly test pairing.

Another issue that we ran into during the development of our design occurred during the testing of our software. Unfortunately, the initial test failed. We set up the test outlined in section 2.3, and it failed to output a clean audio signal. There are some hardware elements that could be causing this circuit to fail. The pinouts or the audio board may have been damaged or a clock/data signal is not correctly being transmitted to/from the microcontroller. Since I don't have access to an oscilloscope, we can't test to see if the audio board hardware is the issue. This ambiguity prevents us from determining if the software is working correctly.

3.3 Ethics and Safety

After careful consideration, there are only a few ethical and safety concerns regarding the pursuit of this project. One potential safety/security risk that could be considered is the ability for the bluetooth communications between the transmitter and the receiver to be maliciously intercepted. A malicious attacker attempting to disturb a band/musician's performance could intercept and/or alter the data being sent to the receiver resulting in unwanted/bad sounding output from the amplifier. However, because this device only deals with guitar effect parameter data, a compromise in this data transmission would not be as detrimental as if other wireless bluetooth data was intercepted such as a classified document. Nevertheless, in this case, we will work to ensure that statement 9 of the IEEE Code of Ethics is satisfied, in the fact that we will work to ensure that there is no injury in reputation to any person or their property in the event that important data is not compromised from the use of our device [8]. In the event that our device's bluetooth transmissions are being tampered with, we can always switch the transmitter/receiver system off and continue to allow the guitarist to change effects manually.

Another concern that comes to mind with a system like this is equipment damage. We would not want our device to cause an amplifier to be overdriven to the point of failure. However, after reading through several guitar forums [9], we have come to the conclusion that this will not be a problem. At its worst, an incredibly distorted signal would be simply that: a distorted signal. Guitar amplifiers are designed to handle a ton of feedback and distortion, unlike a standard public address speaker system. Because of this research, we have concluded that our device will be compliant with statement 3 from the IEEE Code of Ethics in the fact that the available data tells

us honestly and realistically that an end user's guitar amp will not be damaged from the possibility of an immensely distorted signal. Our device will also be in accordance with statement 9 from the Code of Ethics in the fact that no injury of property will occur from the usage of our device.

Finally, in regards to environmental ethics, we will fully comply with statement 1 from the IEEE Code of Ethics by ethically designing our system and developing it with sustainability in mind [10]. For this reason, it is important to discuss and be aware of the resources required to manufacture the Integrated Circuits found in our design. Stanford University reported that, "it takes roughly 10 gallons of water to make a single computer chip" [11]. When developing our system, we will try to be conscientious of waste and try to minimize it throughout. Although, because of the fact that we are not actually building this system physically, environmental factors are not really an issue.

3.4 Project Improvements

When we went through the process of picking an old project to redesign, this one stood out to us because there were so many things that could be done in a different (and better) way.

Group 42's project from Spring 2003 did a good job at addressing the problem they introduced and finding a realistic and feasible solution. They decided that the best way to implement this wireless guitar effect system was by way of standard Ultra-High Frequency (UHF) radio transmission. In addition, the IC that they decided to base their project around (the Motorola MC13190) was a really good option that was capable of doing exactly what they wanted to do.

Their plan was to run the guitar's "dry" output directly into a transmitter unit. Within this transmitter unit, their guitar signal went through a low pass filter (to ensure that aliasing of the signal would not happen), into an ADC, into a microcontroller, and transmitted to the receiver via the Motorola RF IC. Their transmitter's microcontroller was responsible for receiving the data from the guitar's output and receiving data from the end user's adjustments of the effect parameter potentiometers.

The transmitter's output was then received by the receiver, where it went into another Motorola RF IC, into a second microcontroller, into a DAC, into a "Routing Unit", and finally out to an amplifier or PA system. This second microcontroller in the receiver unit was responsible for receiving the digital signal from the transmitter containing the guitar's dry output and the user's effect parameter settings. The microcontroller sent the dry guitar signal to the DAC, but it sent the user's effect parameter settings to the "Effects Loop," which Group 42 said would "mix and route the analog signal out of the DAC to different effects loops, and eventually out to the speaker output. The routing is determined by the signals that the MCU reads in from the transmitter [12]."

There are several key differences between Group 42's proposed solution and ours:

First, Group 42's solution relied on standard UHF radio transmission. We believed that this method of transmission was inherently problematic due to the possibility of interference, as well

as the possibility of transmission interception or hacking. In a big concert venue, there can be catastrophic impacts because of RF signal interference, bad reception, and loss of connection between transmitter and receiver. Because of these things, we decided that transmitting and receiving data via Bluetooth was a far better option. Bluetooth establishes a secure transmission channel between master and slave. For our purposes, the receiver would be the master, and the transmitter would be the slave. Once two devices are paired via bluetooth, they only listen to each other. This makes interference problems with Bluetooth significantly less than interference problems with RF.

The next difference between the 2 projects is that Group 42's design required an uninterrupted connection between the transmitter and the receiver. Again, this is a problematic approach due to the fact that RF is susceptible to interference. However, because we cannot completely rule out interference between Bluetooth transmission either, we opted to split up the guitar's dry output connection and the effect parameter transmitter. This way, even if our bluetooth receiver and transmitter lose connection, the end user will still be able to output their guitar's signal to the effect board/receiver unit. The only thing they will lose is the ability to change effect parameters wirelessly, but this is a significant improvement from Group 42's design where their device would fail all together.

The next difference is the transfer protocols between the 2 projects. Group 42 chose to use a Motorola RF IC to transmit data. This IC also required data to be encoded using a "Manchester" encoding. Our group decided to transfer data via Bluetooth and the I²S transfer interface.

Another difference between the 2 projects is that Group 42's design required a separate "Routing Circuit" to mix effects with guitar signal. Our group thought that this decision was a bit too complicated and created an inflexible hardware design and decided that the guitar signal could be mixed with the desired effects by the microcontroller alone, rather than requiring a separate unit. This will allow for our hardware to be able to support any kind of guitar effect instead of just a single effect.

Finally, Group 42's design did not include a method to monitor system connectivity status. We decided that an LED module to monitor whether or not the transmitter and receiver were connected was a really important feature to include.

Modular Battery Management System (Extra Credit)

We spent the first half of the semester working with Fagen Scooters in Champaign, IL to assist owner Tom Dillavou by designing a new battery system and battery management system (BMS) for a faulty scooter that he had purchased from a vendor. The original battery system was a Sealed Lead-Acid Battery that had become severely deformed because of overheating and was completely destroyed. We decided to implement a new Lithium Ion battery pack made from 18650 cells. This new pack had many advantages over the old one, including weight reduction and life-span. Unfortunately, due to COVID-19, we were unable to reach the end goal of building a new battery system and BMS for the scooter. However, we were able to build a modular version of the BMS that could be upscaled. The BMS that we were able to make could easily be upscaled for use in larger applications up to 72 V.

To begin, we needed a way to connect the 18650 cells together (circuit-wise) so that the pack would supply the energy the load required. We decided on using pure nickel strips in a spot welded four series, three parallel configuration. Since each cell's nominal voltage is 3.6 V, our pack voltage is 14.4 V. We decided to use three cells in parallel for a pack capacity of 10.8 Ah (3600 mAh/cell). We chose 14.4 V because it is close to 12 V which is a common battery voltage used in many different applications.

We implemented our BMS design around the Texas Instruments BQ77915 IC. This chip is specifically designed for BMS systems, so it was perfect for our project. It has 24 I/O pins for reading specific voltage values, so it can determine things like current draw by the load, thermal runaway (via thermistor), and pack overvoltage/undervoltage, among other things.

This BMS system has 2 major components: a set of data lines and a power line. These data lines are in place in many different locations. You can find a data line between each cell bank in series. These data lines are needed to monitor voltage between each cell bank in series. We also needed data lines on the charge and discharge MOSFETs. When the BQ77915 detects a load in the circuit, it can change the MOSFETs' respective gate signal (high or low) and allow the circuit to charge the battery pack or draw current from the battery pack.

In order to make everything as safe as possible, we wanted to incorporate quick disconnect connectors in as many places as possible. We added them on the ends of every cable that was responsible for delivering power. We also tried to add connectors to the data lines in case of problems with the BQ77915, but the ones purchased for the project were not of good quality and broke quickly and made very intermittent connections at best.

To conclude, under the circumstances, the project was very successful. Because of limitations due to COVID-19, this circuit stands more as a proof of concept, but this system could easily be upscaled to larger battery packs and higher voltage systems for bigger applications up to 72 V.

See Photos in Appendix (items 5-12)

References

- [1] Unknown Poster, “How are guitars hooked up to speakers at concerts?” Accessed: 1APR2020. [Online]. Available: https://www.reddit.com/r/Guitar/comments/1ta0nn/how_are_guitars_hooked_up_to_speakers_at_concerts/
- [2] Hugo, Strymon, “Setting Up Your Effect Signal Chain” 29FEB2016. Accessed: 1APR2020. [Online]. Available: <https://www.strymon.net/setting-up-your-effect-signal-chain/>
- [3] “Source Audio Hot Hand 3 Wireless Effects Controller Pedal,” Accessed: 1APR2020. [Online]. Available: https://www.sweetwater.com/store/detail/HotHand3--source-audio-hot-hand-3-wireless-effects-controller-pedal?mrkgadid=3331289787&mrkgcl=28&mrkgen=gpla&mrkgbflag=0&mrkgcat=guitars&&acctid=21700000001645388&dskeywordid=92700046934877524&lid=92700046934877524&ds_s_kwgid=58700005283398557&ds_s_inventory_feed_id=97700000007215323&dsproductgroupid=373037010169&product_id=HotHand3&prodctry=US&prodlang=en&channel=online&storeid=%7bproduct_store_id%7d&device=c&network=g&matchtype=&locationid=%7blocation_id%7d&creative=332063179833&targetid=pla-373037010169&campaignid=1709882817&gclid=EAiaIQobChMI3dPf4LPG6AIVWPfjBx12jAtEEAQYAyABEGljcvD_BwE&gclsrc=aw.ds
- [4] Dave Burrluck, “Manson Guitars MB-1 Standard Matt Bellamy Signature Guitar Review,” 12APR2010. Accessed: 2APR2020. [Online]. Available: <https://www.musicradar.com/reviews/guitars/manson-guitars-mb-1-standard-matt-bellamy-signature-guitar-241595>
- [5] Lee H. Goldberg, “Choosing The Right MCU For Your Audio Applications,” 05MAY2012. Accessed: 14APR2020. [Online]. Available: <https://www.digikey.com/en/articles/choosing-the-right-mcu-for-your-audio-application>
- [6] “Analog-to-Digital-Converter,” Accessed 14APR2020. [Online]. Available: https://en.wikipedia.org/wiki/Analog-to-digital_converter#Resolution
- [7] Bonnie Baker, “Jitter and the Ins and Outs of SNR,” 21JAN2010. Accessed: 14APR2020. [Online]. Available: <https://www.edn.com/jitter-and-the-ins-and-outs-of-snr/>
- [8] “IEEE Code of Ethics,” *IEEE*. [Online]. Available: <https://www.ieee.org/about/corporate/governance/p7-8.html>. [Accessed: 01-Apr-2020].
- [9] *Can you overload/damage an amp with too much distortion?* [Online]. Available: <https://www.soundonsound.com/forum/viewtopic.php?f=22&t=56495&p=507054&hilit=>. [Accessed: 01-Apr-2020].

[10] Concerning Reality. "How Does Bluetooth Work?," YouTube, September 16, 2019. [Video file]. Available: https://youtu.be/cxP0Mdoz_Bo. [Accessed: April 11, 2020].

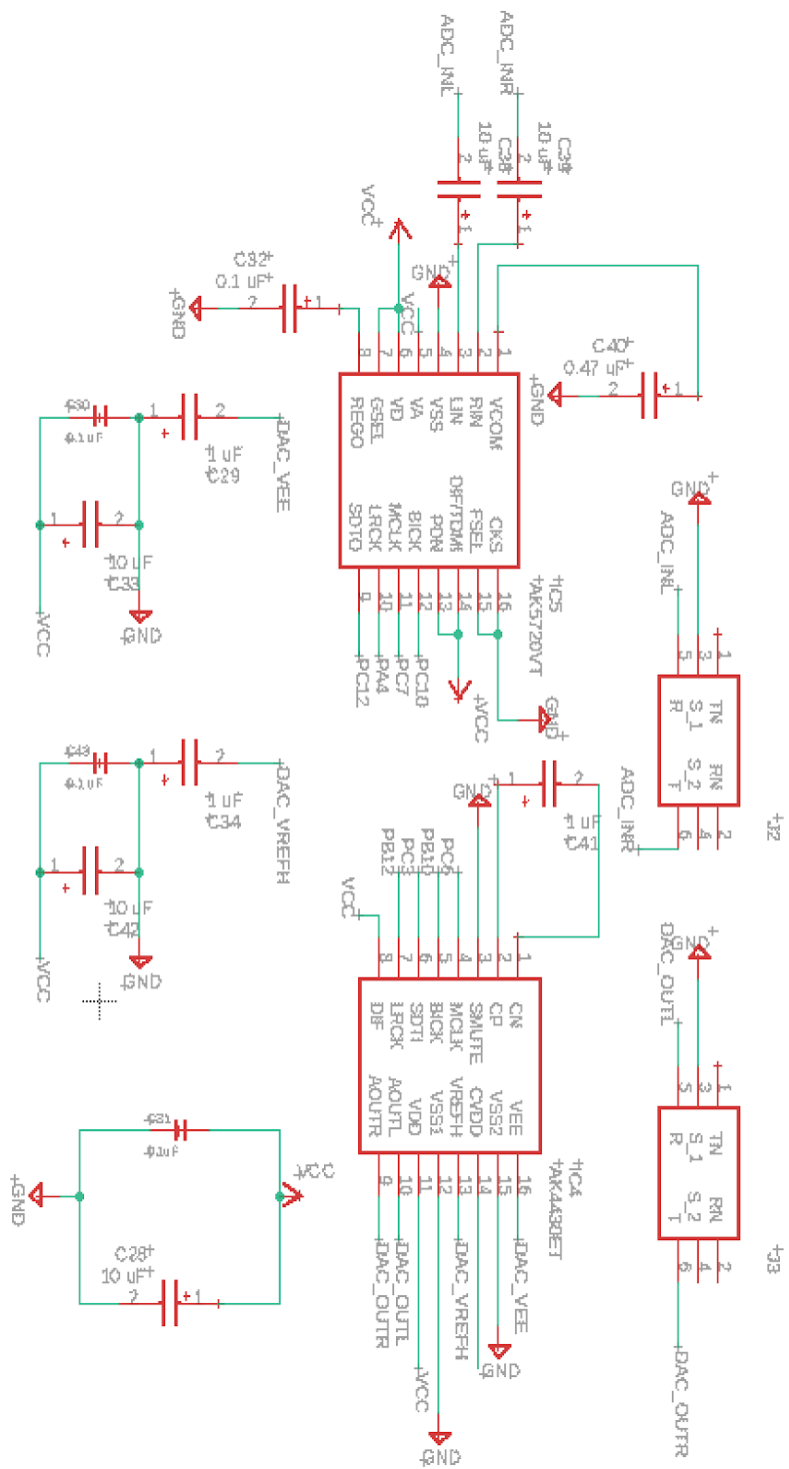
[11] *Can computer chip makers reduce environmental impact?* [Online]. Available: <https://news.stanford.edu/pr/96/960605chipsenvir.html>. [Accessed: 01-Apr-2020].

[12] J Miller, J Smith, E Bellas, "Wireless Guitar Unit," 12FEB2003. Accessed: 1APR2020. [Online]. Available: <https://courses.grainger.illinois.edu/ece445/projects.asp>

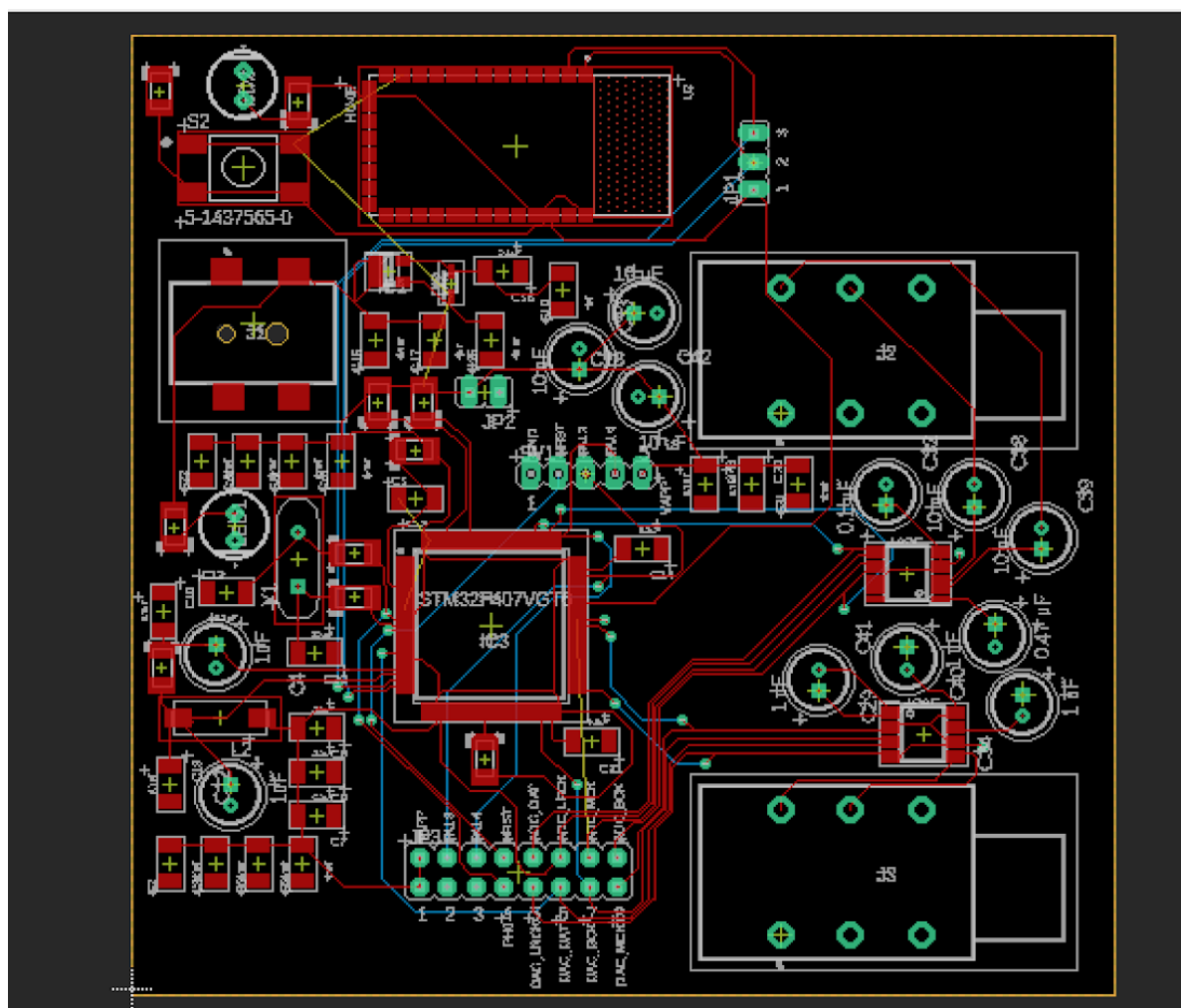
R. Singh, P. Singh, and K. Yadav, "Wireless Communications Enlargement: A Review of Advancement in Technologies," International Journal of Current Engineering and Technology, vol. 4, no. 4, Aug. 2014.

F. Vergès, "Free Space Path Loss Diagrams," SemFio Networks. [Online]. Available: <https://www.semfictionetworks.com/blog/free-space-path-loss-diagrams>. [Accessed: 14-Apr-2020].

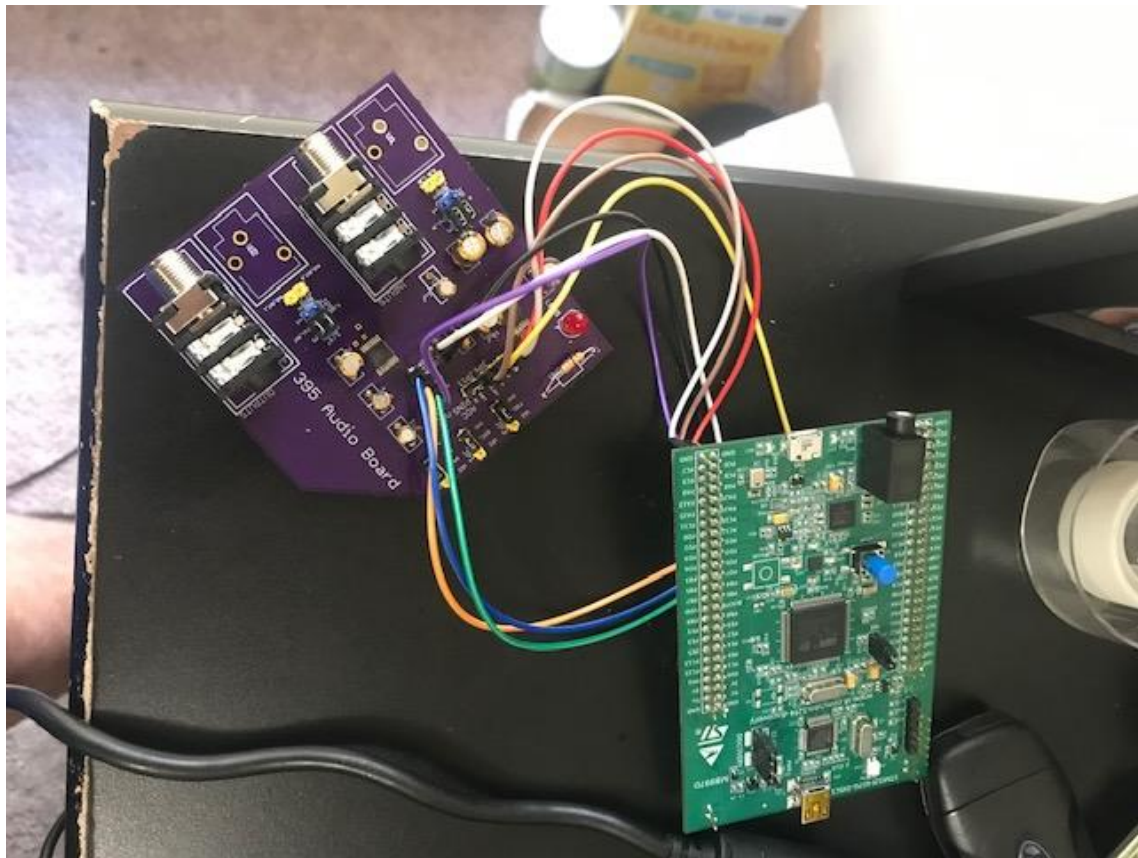
Appendix



Item 1: Enlarged ADC/DAC Modules



Item 2: Enlarged Receiver PCB Board

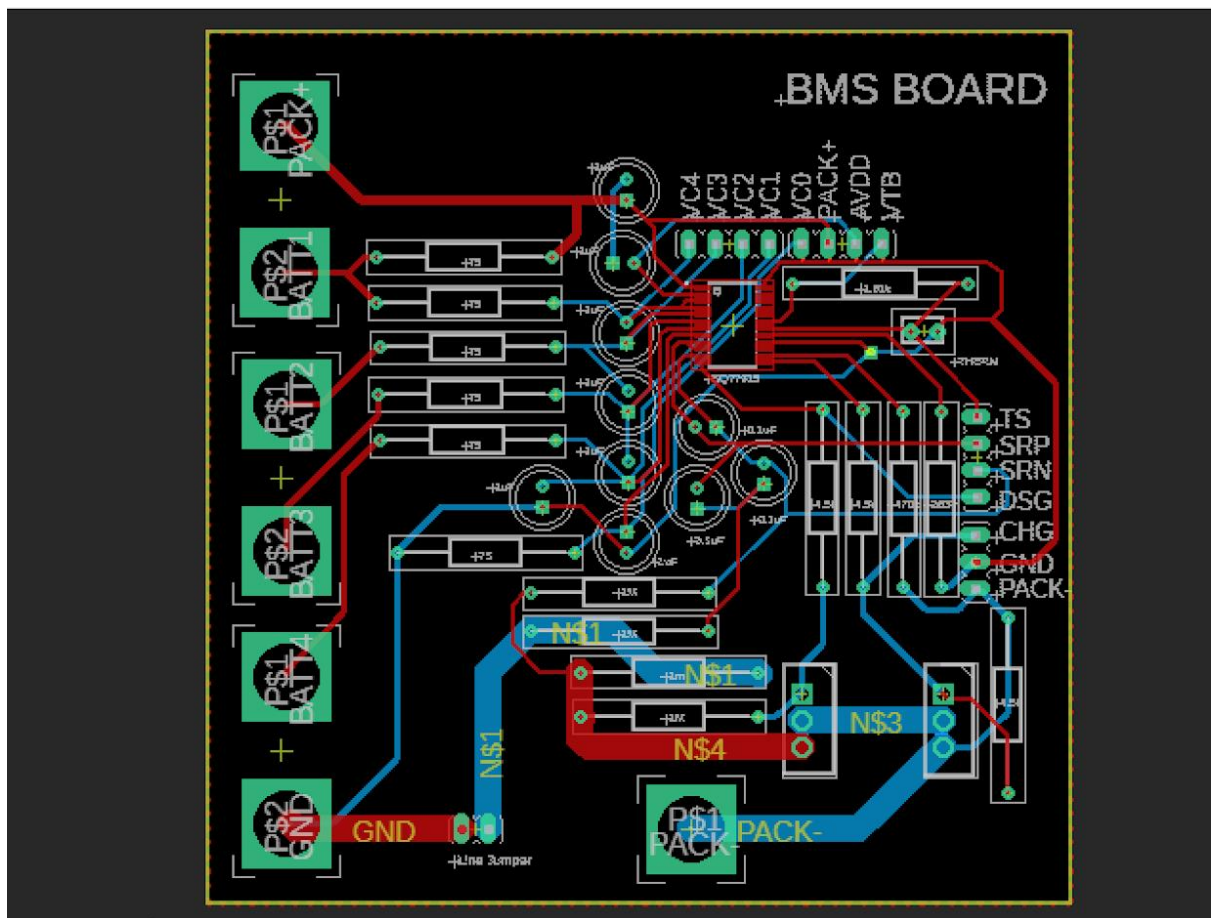


Item 3: Experimental Setup

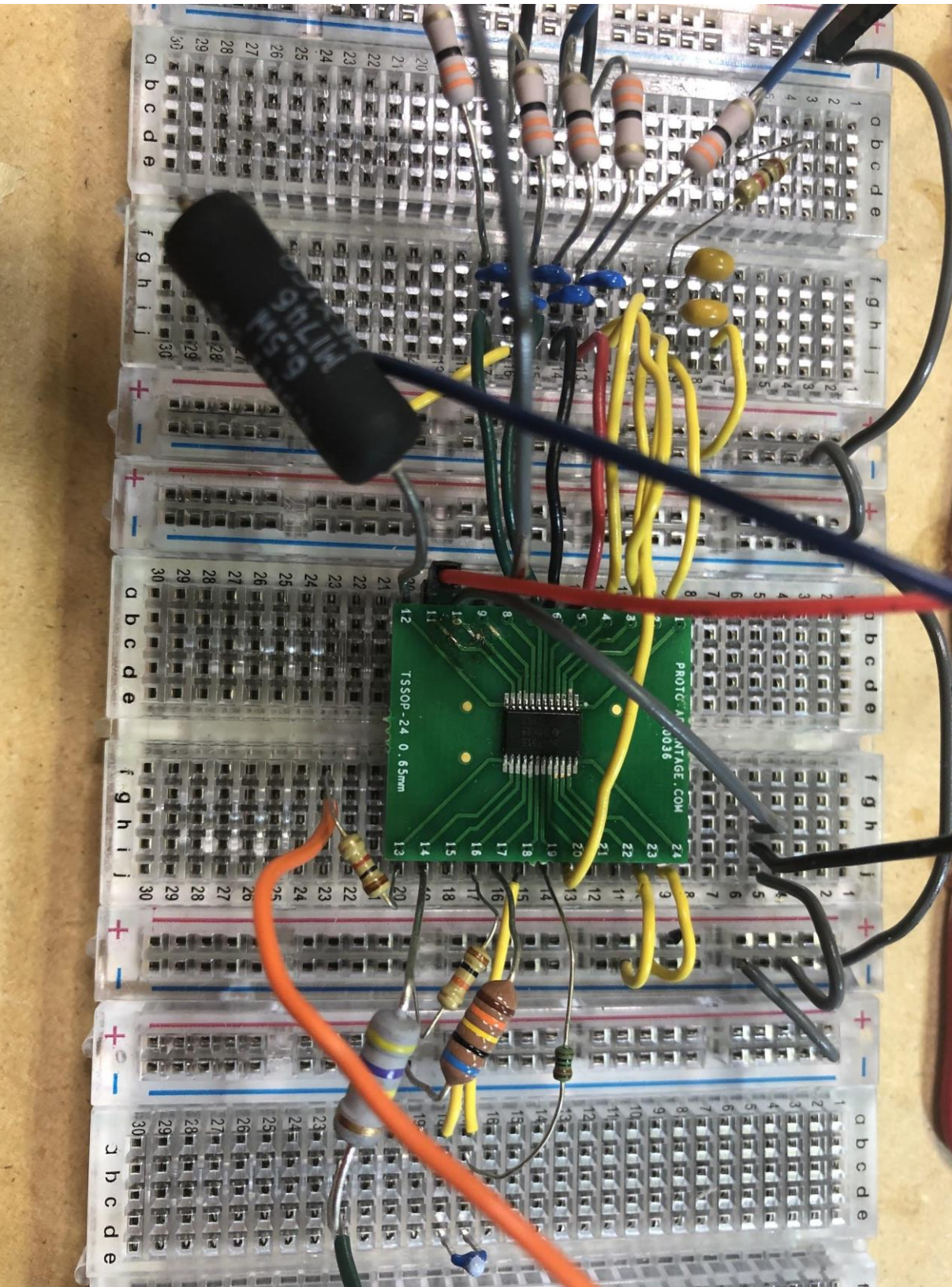
1	Device	Value	Quantity	Unit Cost(\$)	Total Cost	Link
2	AK5720 ADC	N/A	1	1.3	1.3	https://www.digikey.com/product-detail/en/akm-semiconductor-inc/AK5720VT/974-1069-1-ND/5180420
3	AK4430 DAC	N/A	1	1.52	1.52	https://www.digikey.com/product-detail/en/akm-semiconductor-inc/AK4430ET/974-1017-1-ND/233403
4	Mono Guitar Jack	N/A	2	1.25	2.5	https://www.digikey.com/products/en?keywords=ACLS-MHOM
5	Crystal	24 MHz clk	1	0.37	0.37	https://www.digikey.com/product-detail/en/cds-frequency-controls/ATS2454/CTX910-ND/2292888
6	Voltage Regulator	5V - 3.3V	1	0.6	0.6	https://www.digikey.com/product-detail/en/smicrelectronics/LD3985M33R/497-3504-1-ND/669344
7	BAT501FILM	diode	2	0.29	0.58	https://www.digikey.com/product-detail/en/smicrelectronics/BAT501FILM/497-3707-1-ND/686425
8	DC Power Jack	5V	1	0.6	0.6	https://www.digikey.com/product-detail/en/cui-devices/PI-002A/CP-002A-ND/96962
9	Red LED		2	0.14	0.28	https://www.digikey.com/product-detail/en/cree-inc/CSSMF-RLE-CTOW08B1/CSSMF-RLE-CTOW08B1-ND/4793808
10	STM32 Processor	N/A	1	11.65	11.65	https://www.digikey.com/product-detail/en/stmicroelectronics/STM32407G16/497-11605-ND/2747117
11	Resistor	330 ohm	1	0.1	0.1	https://www.digikey.com/product-detail/en/bourns-inc/CR1206-FX-3300ELF/CR1206-FX-3300ELFCT-ND/3767682
12	Resistor	47 ohm	2	0.1	0.2	https://www.digikey.com/product-detail/en/stackpole-electronics-inc/RMCF1206JT47R0/RMCF1206JT47R0CT-ND/1942760
13	Resistor	10k ohm	2	0.1	0.2	https://www.digikey.com/product-detail/en/stackpole-electronics-inc/RMCF1206FT10K0/RMCF1206FT10K0CT-ND/1942707
14	Resistor	4.7k ohm	2	0.1	0.2	https://www.digikey.com/product-detail/en/bourns-inc/CR1206-FX-4701ELF/CR1206-FX-4701ELFCT-ND/3767651
15	Resistor	0 ohm	1	0.1	0.1	https://www.digikey.com/product-detail/en/stackpole-electronics-inc/RMCF1206ZTOR00/RMCF1206ZTOR00CT-ND/1942835
16	Resistor	220 ohm	1	0.1	0.1	https://www.digikey.com/product-detail/en/bourns-inc/CR1206-FX-2200ELF/CR1206-FX-2200ELFCT-ND/3767699
17	Resistor	2k ohm	1	0.1	0.1	https://www.digikey.com/product-detail/en/panasonic-electronic-components/ERA-8AE8202V/P2-0K/BCT-ND/3069645
18	Capacitor	0.1uF	19	0.11	2.09	https://www.digikey.com/product-detail/en/w%C3%BCth-elektronik/885012208009/732-8086-1-ND/5454713
19	Capacitor	2.2uF	2	0.29	0.58	https://www.digikey.com/product-detail/en/yageo/CC1206KXSR88925/311-3516-1-ND/7164537
20	Capacitor	1uF	2	0.19	0.38	https://www.digikey.com/product-detail/en/kemet/C1206C105M4RACTU/399-8150-1-ND/3471873
21	Capacitor	10nF	1	0.19	0.19	https://www.digikey.com/product-detail/en/kemet/C1206C103IARACTU/399-7174-1-ND/3439312
22	Capacitor	30 pF	2	0.52	1.04	https://www.digikey.com/product-detail/en/kemet/C1206C3005GAC/800/399-17472-1-ND/6570439
23	Pol-Cap	1uF	5	0.29	1.45	https://www.digikey.com/product-detail/en/nichicon/UPS2C010MED1TD/493-5383-1-ND/3129720
24	Pol-Cap	10uF	5	0.24	1.2	https://www.digikey.com/product-detail/en/nichicon/USWLE100MDD/493-16044-ND/2539311
25	Pol-Cap	0.1uF	1	0.24	0.24	https://www.digikey.com/product-detail/en/nichicon/UVR2A081MD01TD/493-12812-1-ND/4328496
26	Pol-Cap	0.47uF	1	0.27	0.27	https://www.digikey.com/product-detail/en/nichicon/UVR2ER47MED/493-1187-ND/588928
27	2-row header	N/A	1	1.79	1.79	https://www.digikey.com/products/en?mpart=PRPC040DFBN-RC&v=35
28	1-row header	N/A	5	0.39	1.95	https://www.digikey.com/products/en?mpart=PRPC0105ACN-RC&v=35
29	Ferrite Bead	N/A	1	0.63	0.63	https://www.digikey.com/product-detail/en/w%C3%BCth-elektronik/7427931/732-2393-1-ND/2268595
30	Pushbutton	N/A	1	0.41	0.41	https://www.digikey.com/product-detail/en/te-connectivity-alcoswitch-switches/F5SM65MATR/450-2058-1-ND/4569748
31	HC-05 Bluetooth Module	N/A	1	7.99	7.99	https://www.amazon.com/Hitegro-Wireless-Bluetooth-Transceiver-Arduino-dp/B0715G80R
32	PCB	N/A	1	5.5	5.5	
33						
34				Total Receiver Unit Price	46.11	

Item 4: Wireless guitar pedal bill of materials

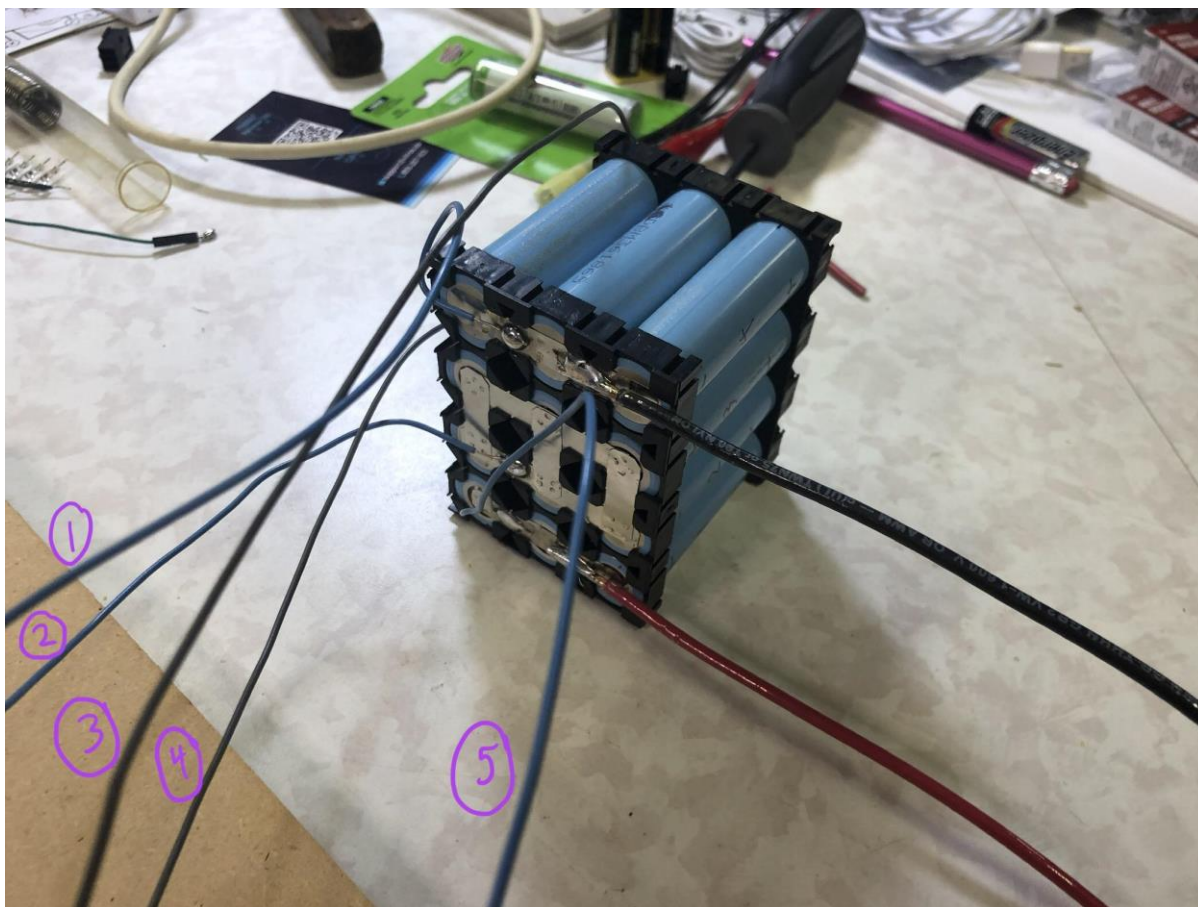
Item 5: BMS Schematic



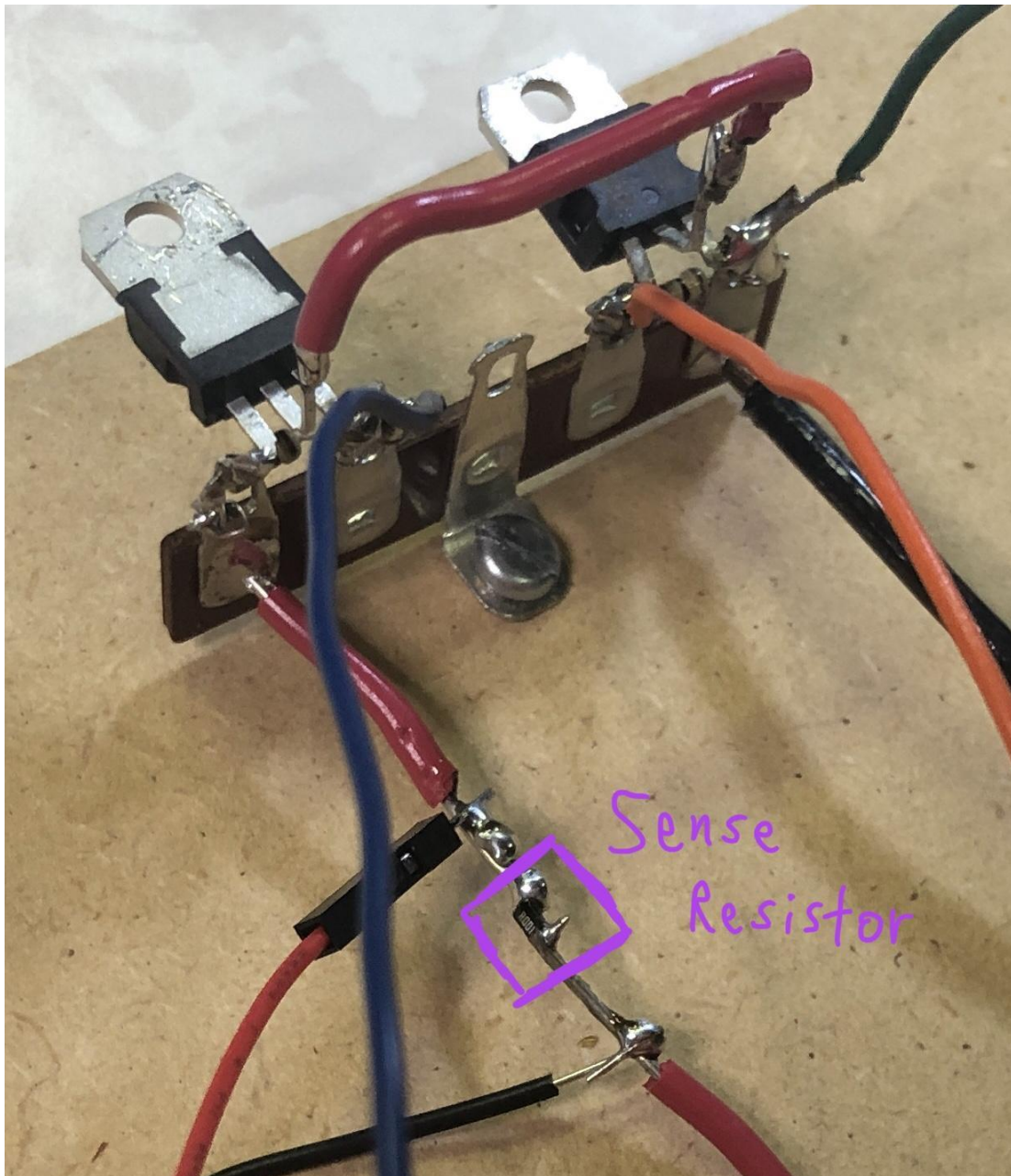
Item 6: BMS PCB



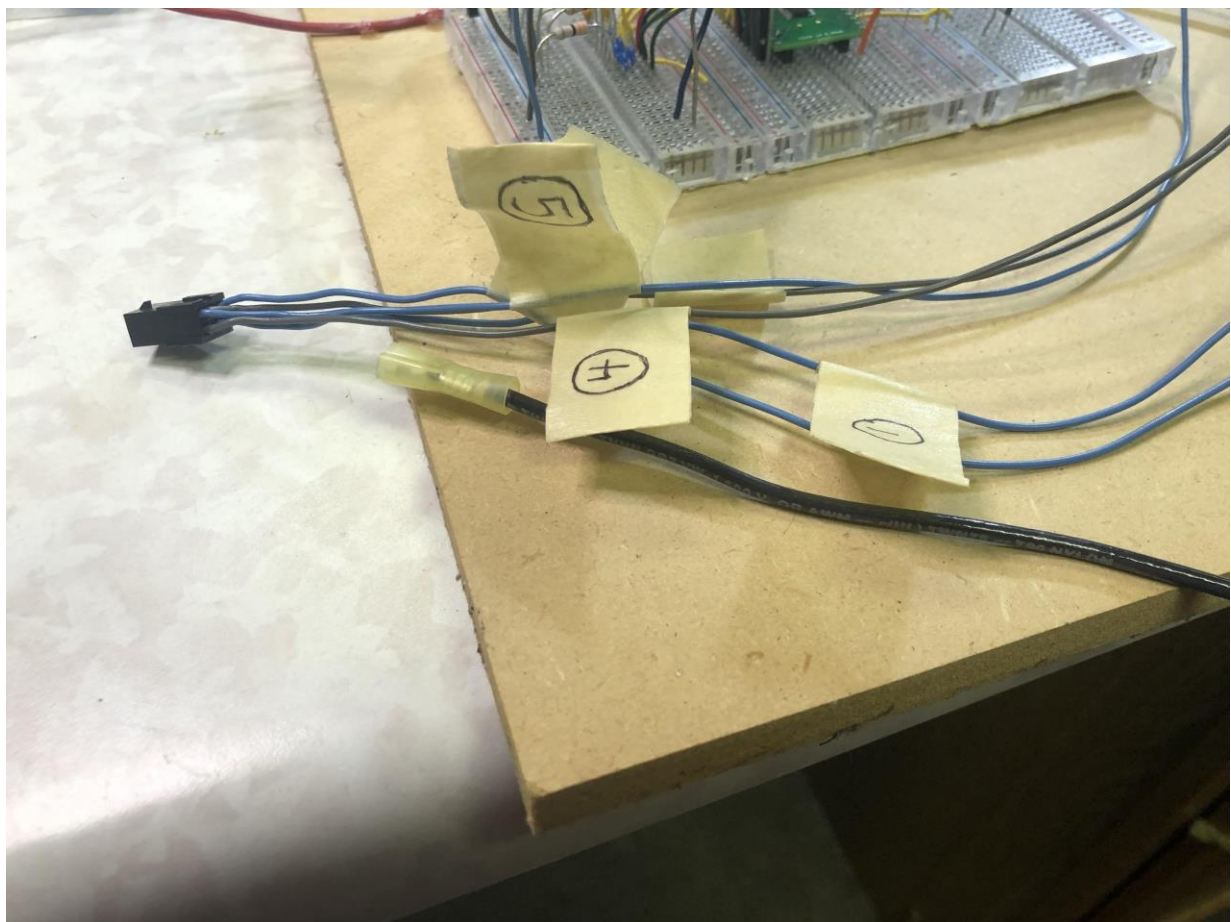
Item 7: Breadboarded assembly of BMS



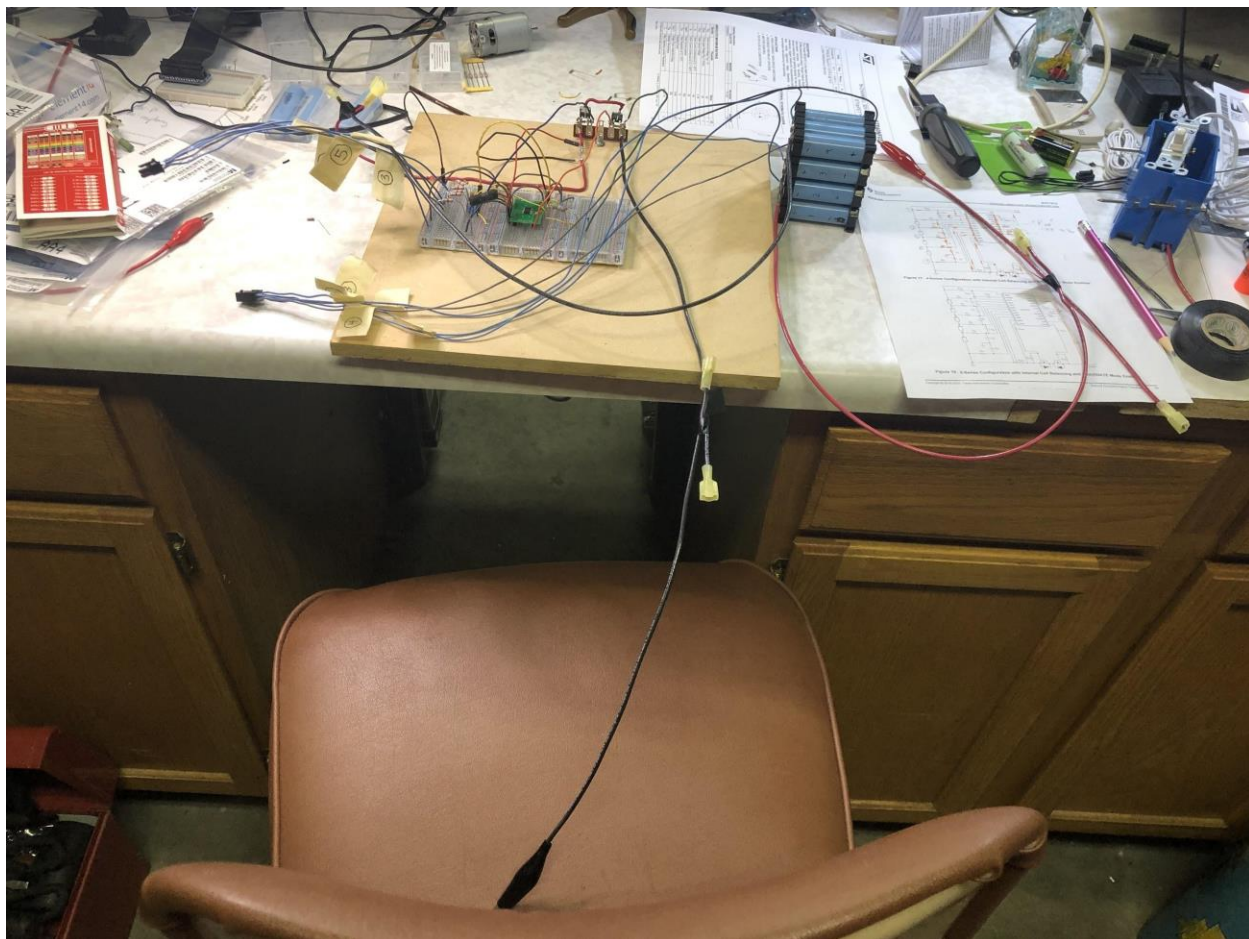
Item 8: Spot welded 14.4 V battery pack with 5 data lines attached



Item 9: Charge/Discharge MOSFET breakout with sense resistor



Item 10: Quick disconnect male connector for data lines from the battery pack (female end was connected to breadboard)



Item 11: Complete assembly of BMS connected with battery pack



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Shipping Method: FEDEX 2 DAY

Order Date: Mar 16 2020

Customer Number:

Contact Name: CHRISTIAN SCHEURER

Purchase Order Number:

LN

Mouser Part Number
Manufacturer Part Number
Description

Customer Part Number

Date Code
Lot Code

Quantity
Ordered

Quantity
Shipped

Quantity
Pending

001	954-103AT-2 103AT-2 Semitec NTC (Negative Temperature Coefficient) Thermistors 10kohm 1% RoHS: compliant through exemption	Taric: 8533401000 ECCN: EAR99	19-1114	3	3	0
002	903-QH05TZ600 QH05TZ600 Power Integrations Diodes - General Purpose, Power, Switching H-Series 600V 5A RoHS: compliant	Taric: 8541100000 ECCN: EAR99	1707 M3U217F	5	5	0
003	S11-STP40NF03L STP40NF03L STMicro MOSFET N-Ch 30 Volt 40 Amp RoHS: non-compliant	Taric: 8541210000 ECCN: EAR99	1931	5	5	0
004	660-MOS1CT528R330J MOS1CT528R330J KOA Speer Metal Oxide Resistors 33 ohm 5% 1W RoHS: compliant	Taric: 8533210000 ECCN: EAR99	1840 14162903	10	10	0
005	588-PCS1206FR0010ET PCS1206FR0010ET Ohmite Current Sense Resistors - SMD 1W 0.001 Ohms 1% RoHS: compliant	Taric: 8533210000 ECCN: EAR99	1927	5	5	0
006	756-MFR3-10KFC MFR3-10KFC TT Electronics Metal Film Resistors - Through Hole 10K ohm 1% 0.4W RoHS: compliant	Taric: 8533210000 ECCN: EAR99	1937 11662657	4	4	0



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Purchase Order Number:

LN

Mouser Part Number
Manufacturer Part Number
Description

Customer Part Number

Date Code
Lot Code

Quantity
Ordered

Quantity
Shipped

Quantity
Pending

007	603-RSF100JB-73-470K RSF100JB-73-470K Yageo Metal Oxide Resistors 1W 470K Ohm 5% RoHS: compliant	Taric: 8533210000 ECCN: EAR99	1825 33H2530180	4	4	0
008	71-CCF60-604K-E3 CCF60604KFE36 Vishay Metal Film Resistors - Through Hole 1/2watt 604Kohms 1% RoHS: compliant	Taric: 8533210000 ECCN: EAR99	1749 0070495589	4	4	0
009	80-C333C105MSU C333C105MSU5TA KEMET Multilayer Ceramic Capacitors MLCC - Leaded C333 1uF 50volts RoHS: compliant through exemption	Taric: 8532240000 ECCN: EAR99	1813 1813GC64	4	4	0
010	810-FG18XSR1H105KRT0 FG18XSR1H105KRT00 TDK Multilayer Ceramic Capacitors MLCC - Leaded RAD 50V 1uF RoHS: compliant	Taric: 8532240000 ECCN: EAR99	1919 0812353601	10	10	0
011	71-CW5-4.5K CW0054K500JB12 Vishay Wirewound Resistors - Through Hole 5watts 4.5Kohms 5% RoHS: non-compliant	Taric: 8533210000 ECCN: EAR99	1746 0070373955	2	2	0

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Item 12: BMS circuit components bill of materials from Mouser

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