Wireless Speaker Sharing System (WSSS)

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Design Document

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1. Introduction

1.1 Problem and Solution Overview

Having a single loudspeaker at parties is uncomfortable at times. The music is too loud if one’s close, but the volume attenuates as he/she moves further away. The conventional way of solving such issues, for example, in theatres, is by connecting the audio output to multiple speakers using audio cables. This wired solution, though reliable, limits the mobility of the playing device. It is particularly undesirable when the playing device nowadays usually are phones, which people carry around all the time.

The project introduces a novel design, a standalone plug-and-play wireless audio sharing system that interfaces with the standard 3.5mm audio jack. There will be one broadcasting dongle and multiple receivers, all of which are powered by Li-Po battery embedded in the design. Users can plug the broadcaster to any of their music players (phones, computers, or even game consoles), and plug in the receivers to an arbitrary amount of playback devices in proximity without any pairing or registration procedure. Then, they are ready to “stream” music to all speakers wirelessly over 2.4GHz radio frequency (RF). All audio signals will be in sync, so users can enjoy an immersive acoustic experience created by a series of speakers placed around the room.

1.2 Background

It’s often to have parties where it's deafening standing beside the main speaker but not loud enough further from the speaker, so not all people can enjoy those beats. A calculation applying the inverse square law [1] shows that an 85 dB sound pressure at a distance of 0.2 meters from the sound source can attenuate to 51 dB at 10 meters. The former sound level is considered harmful to humans while the latter one is quieter than typical background music. [2] Purchasing a large loudspeaker is also an extra expenditure for the party host. So, it will be great if people can utilize their existing small personal speakers and easily sync them up for a song for everyone to enjoy. That is why the WSSS (Wireless Speaker Sharing System) is developed. It allows people to gather the power of multiple generic small speakers and host a great party.

Our main selling point is its ease of use, as absolutely no pairing or setup will be needed. It should behave like an ordinary wired Audio AUX cable but without the wire. There are several commercial attempts at wireless audio sharing system. Comparing to existing commercial solutions:

1. **Chromecast® audio** requires online registration and Wi-Fi connection. Thus, it can't be used in the wild. Our proposed solution is an entirely standalone audio sharing system.

2. **Qualcomm® broadcast audio/Apple® Air-Play audio share** uses proprietary technologies and thus requires expensive supported devices with Bluetooth pairing with individual speakers. The proposed design can work with any music playing and playback device so long as they support the universal 3.5mm audio interface.

3. **Anker® Soundsync A3352 Bluetooth Receiver** has device count limits and still requires a Bluetooth pairing procedure. The proposed solution doesn't have device limits since the RF signal is broadcasted and it doesn't require pairing procedures.

1.3 Example Use Case

Figure 1 demonstrates a typical usage of WSSS where we have a mobile device as a transmitter and multiple audio output devices which we want to pair them and make them synchronously playing the music from our mobile device. In this case, we simply plug in transmitter WSSS to mobile and receiver WSSS to speaker devices and turn them on. After that, the mobile device could start playing music and transmitting and all speakers should start receiving signals via RF and synchronously playing the track. Beautiful!

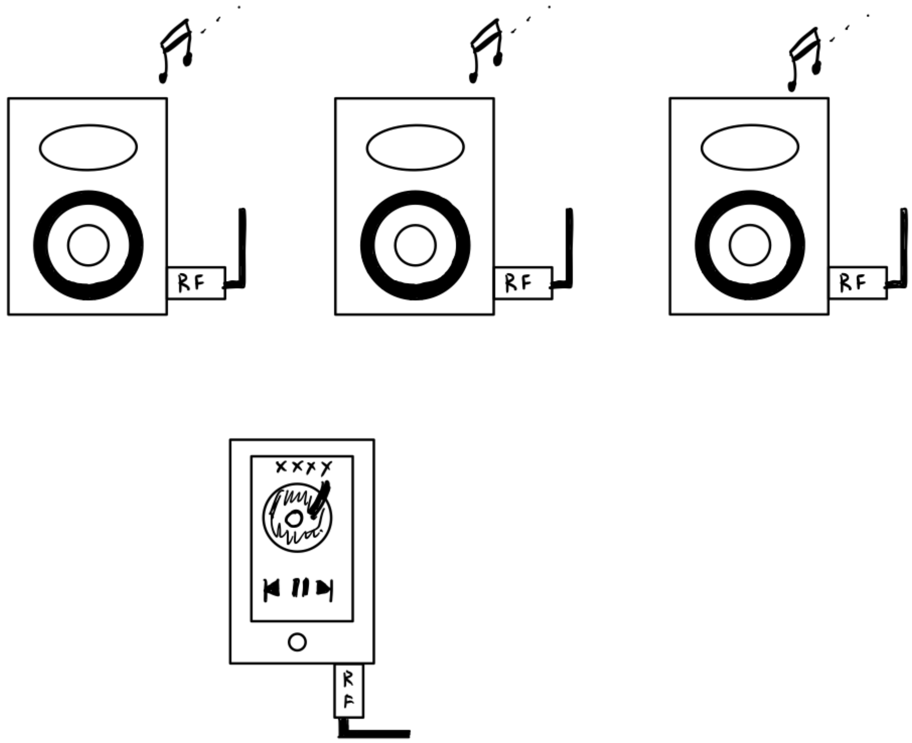

Figure 1 Example use case

1.4 High-level Requirements

1. Users must be able to successfully play music through our WSSS with more than two speakers.
2. Both transmitter and receiver should work without any setup process. Turn on power switches and plug-in both transmitter and receiver to start the transmission right away.
3. The receiver should pick up the signal instantaneously upon powering up, making it behaves like a wired connection.
4. The audio signals from different speakers should be in sync, with indiscernible latencies among them (typically < 15ms) [3].

2. Design

2.1 Block Diagram

The design can be divided into three separate systems, namely, the power system, the signal processing system, and the RF transceiver system. The power system features a rechargeable Li-Po battery with corresponding charging and regulator circuits to power the rest of the design. The radiofrequency (RF) module can sustain a bandwidth of 1Mbps, within 100 meters in open space without any interference. While the range is expected to be lower indoor, where more radio interference and obstacles are present, it should be well above the area of a typical use scenario. We target a 10m range in-doors with all other Wi-Fi, Bluetooth, and other common 2.4Ghz interferences. The signal processing system is responsible for converting analog audio input to digital signals suitable for transmission over RF, and vice versa on the receiver end.

The circuitry is the same for both transmitter and receiver. The difference is only in the microcontroller code that controls the RF module to go to RX/TX mode.

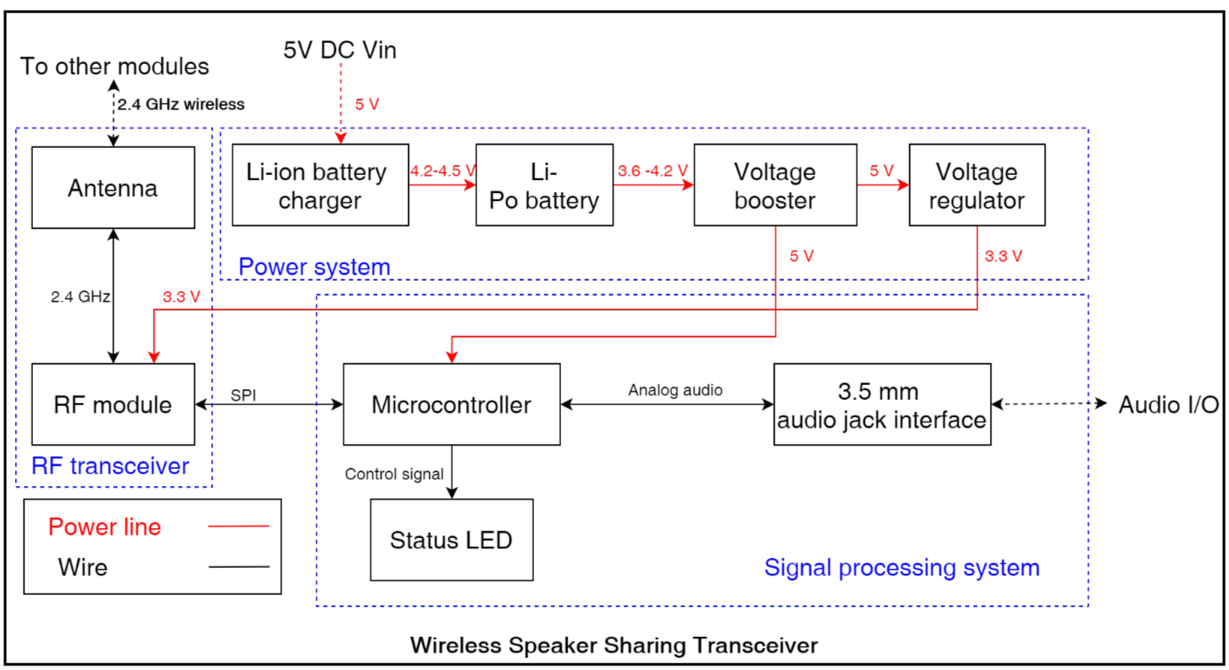

Figure 2 Block diagram

2.2 Physical Design

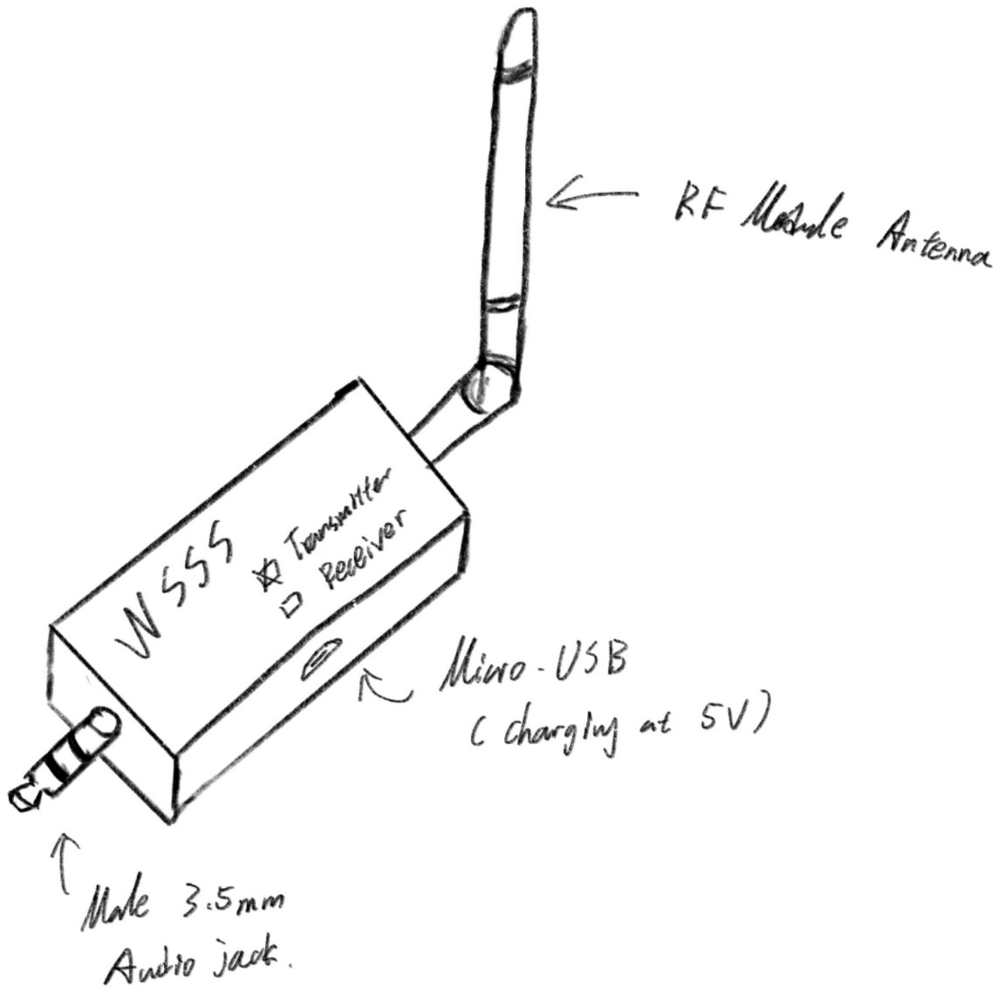

Figure 3 Physical design

2.3 Power subsystem

2.3.1 Li-Po battery charger

Charge the Li-Po battery so that it can power the whole system. This charger circuit is needed as we have to prevent Li-Po overcharge, which can cause a safety hazard if not careful. This charger circuitry will ensure the proper handling of a Li-Po battery.

Requirement	Verification
Must charge the Li-Po battery to 4.2 V ± 50 mV per cell, which is the nominal full-charge voltage for this kind of battery cells	(a) Discharge a li-Po battery cell to ~3.3 V (b) Charge the battery using a Li-Po charging IC with 5V input voltage. (c) When the charging process is finished (indicated by the charger IC), connect a voltmeter to check that the battery is at *4.2 V ± 50 mV* per cell

2.3.2 Li-Po battery:

The battery must keep the system powered. We choose a Li-Po battery because of its great energy density. Using a 1Ah battery allows us to achieve a ~10hr uptime per charge, which is ideal.

Requirement	Verification
1. The battery must store 1Ah charges, which is enough to power the system at 100mA for 10 hours. *2. During the discharging period, the battery provides power at voltage 3.6V to 4.2V* *3. The battery's temperature should stay below 50℃ when discharging*	(a) Charge the battery to full capacity, use a multimeter to ensure that the voltage across it is <= 4.2V (b) Connect the battery to a 40-ohm resistor and discharge the battery at ~100mA for ten hours. (c) Use a multimeter to measure the battery voltage again after discharging, it should remain above 3.7V (d) During verification steps (a)-(c), use an IR thermometer to ensure the battery stays below 50°C

2.3.3 Li-Po Battery Voltage Booster:

To achieve stable operation of our 16MHz ATMEGA-328P Arduino microcontroller, we need to supply it with a stable 5V power. This is achieved by using a switch power booster circuit that can boost the Li-Po batteries voltage to a constant 5V.

Requirement	Verification
Must be output a clean and stable 5V DC at a sustained the current draw of ~ 200mA	(a) Connect a lab bench power supply to the boost circuitry input. (b) Attach 25 ohms resistor as load (200mA load) (c) Attach a voltmeter across the load (d) Sweep the supply voltage from 3.5 to 4.2 V (e) Ensure the output voltage always stays at 5.0 ± 0.1V

2.3.4 Voltage Regulator

This integrated circuit supplies the required 3.3V to our relatively power-hungry nRF24 module during receiving. A good 3.3V power source is crucial to the stable transmission and nRF24 can't be powered by the same 5V that Arduino uses.

Requirement	Verification
Must be able to handle the 5V input from the battery boost circuit *at the peak current draw (~200mA when transmitting/receiving w/ amplifying circuit).*	(a) Attach 25 ohms resistor as load (200mA load) (b) Attach a voltmeter across the load (c) Supply regulator with 3.7 V ± 0.4V DC (d) Ensure output voltage remains 3.3 ± 0.1V

2.4 Signal processing subsystem

2.4.1 Microcontroller

The microcontroller is essential to do the A/D, D/A conversions to ensure usable audio quality and also send control signals to communicate with our RF modules, as RF modules transmit digital signals instead of analog voltages.

Requirement	Verification
Must be able to do A/D at 8-bit resolution and 44kHz sampling rate.	1, A/D verification: (a) Use a 20kHz sine wave as the input to the A/D submodule on the microcontroller. (b) Save the output digital signals and use an ideal DAC (with a reconstruction filter) to theoretically reconstruct the analog signal and get the original 20kHz sine wave back.
Must be able to do D/A at 8-bit resolution and 44kHz sampling rate.	2, D/A verification: (a) Once A/D verification passes, we can directly use the digital signal output from the A/D submodule and make that as the input of the D/A submodule. (b) Verify that the output analog signal is a reasonably clean 20kHz wave. (Not a sine wave as Arduino cannot output a real sine wave. However, the output should sound similar)

2.4.2 Status LED

Display the status of transmission via some red LED, this would allow users to see the working state of the transmitter and receiver.

Requirement	Verification
The status LEDs must be flashing when the RF module is transmitting or receiving payloads.	(a) Put one RF module in transmission mode and the other in receiving mode. (b) Ensure LEDs on both nodes are flashing. (c) Turn off the transmission mode on the first RF module. (d) Verify that both LEDs are no longer flashing.

2.5 Radio Frequency Transceiver Subsystem

2.5.1 Antenna

An antenna will be connected to our RF modules. This greatly enhanced the effective range of our RF module, which in turn gives us a better reception and audio signal.

Requirement	Verification
An omnidirectional antenna with a gain rating at about 5dBi will be used. This allows our RF module to have a ~10m range for indoor usage with no positioning requirements.	(a) Use both transmitter and receiver without connecting the antenna. (b) Verify that the status LED is not flashing properly when these two modules are 10 meters apart. (Indicating a bad reception) (c) Install 5dBi omnidirectional antennas on both transmitter and receiver. (d) Verify the usefulness of the Antenna by placing them 10m apart and look for the constant

	flashing of both status LEDs to ensure that a good connection is established.

2.5.2 RF module

RF module should reliably transmit and receive digital audio signals via the antenna and send them to the signal processing module. It must operate in the 1Mbps Bandwidth mode consistently within a 10m radius to ensure proper transmission.

Requirement	Verification
The module should use the 2.4 GHz band and it can sustain a single-direction wireless transmission bandwidth of 350 kbps (calculated in Tolerance Analysis) consistently within a 10m radius.	(a) Use the nRF24 library on Arduino to set both transmitter and receiver to use the 1Mbps bandwidth mode. (b) Program the timer interrupt to send a 32-bytes counter packet at a frequency of 1367 Hz. (c) On the receiver side, constantly check if there's data to be read and store the received data in memory (d) Place the two nodes ~10m apart. (e) Start program on both nodes and keep running for 1 minute (f) Dump the received packets to a file and verify that it is below a BER of 0.1%

2.6 Circuit Schematics

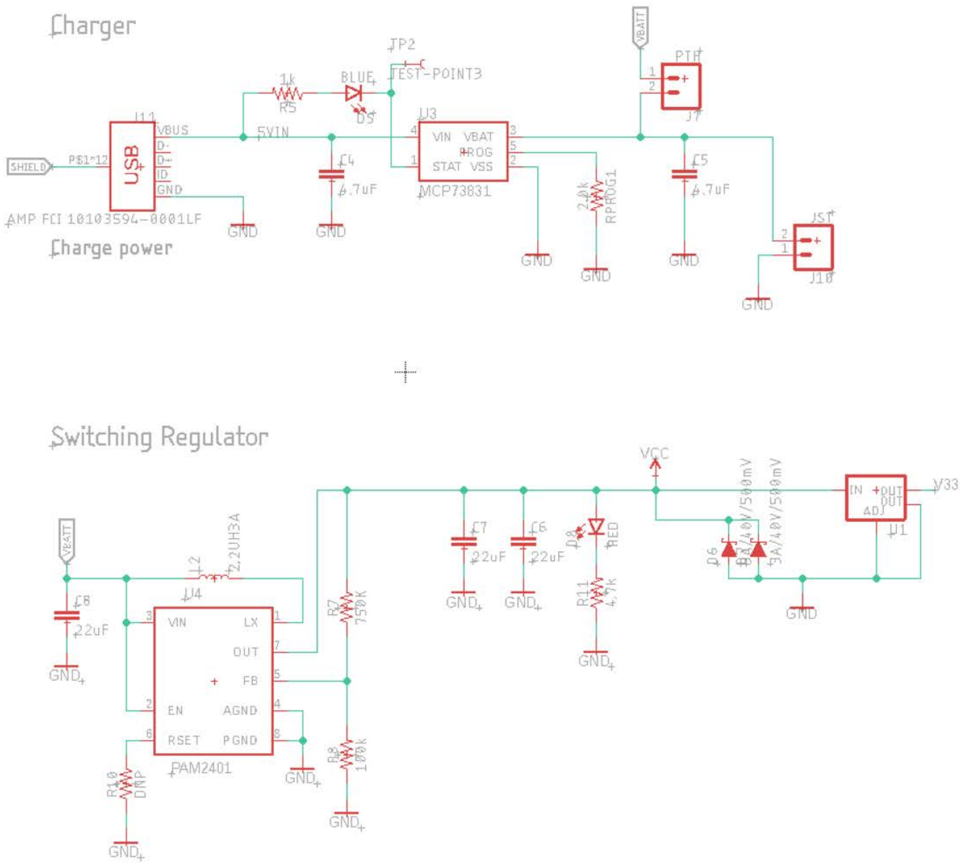

Figure 4 Battery Charger/Booster/Regulator Schematics [4]

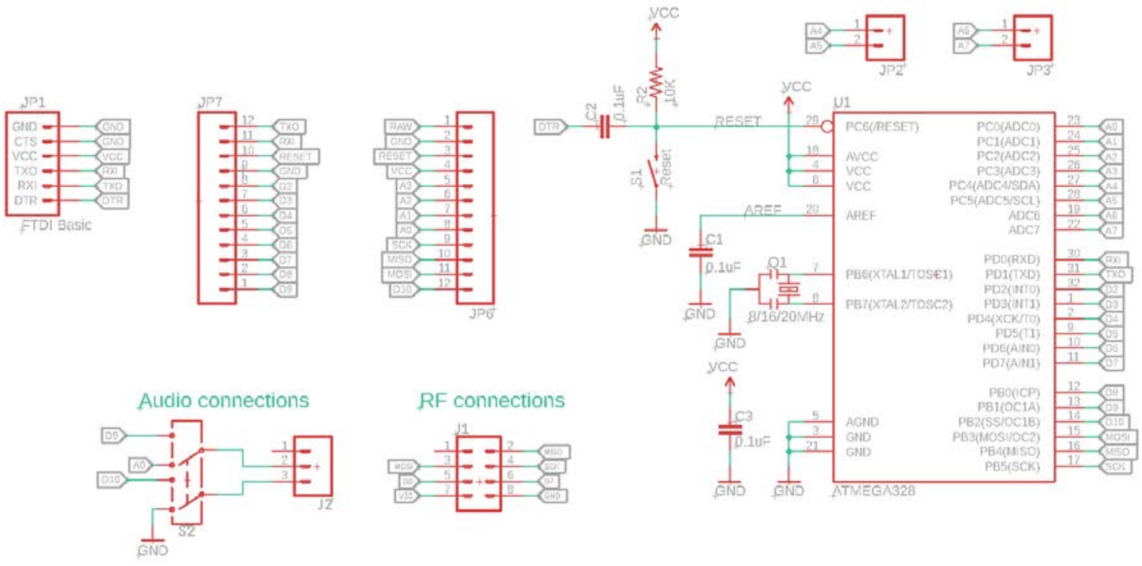

Figure 5 Microcontroller Schematic [5]

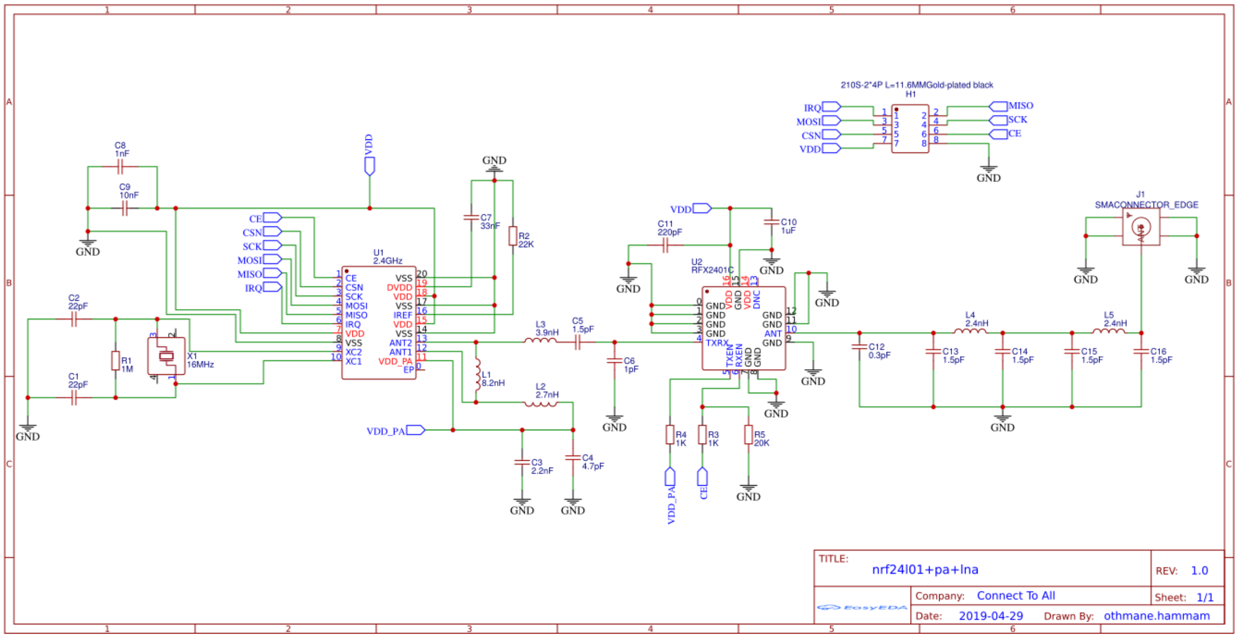

Figure 6 RF Schematic (For RF module, we are directly using the commercial product) [6]

2.7 Board View

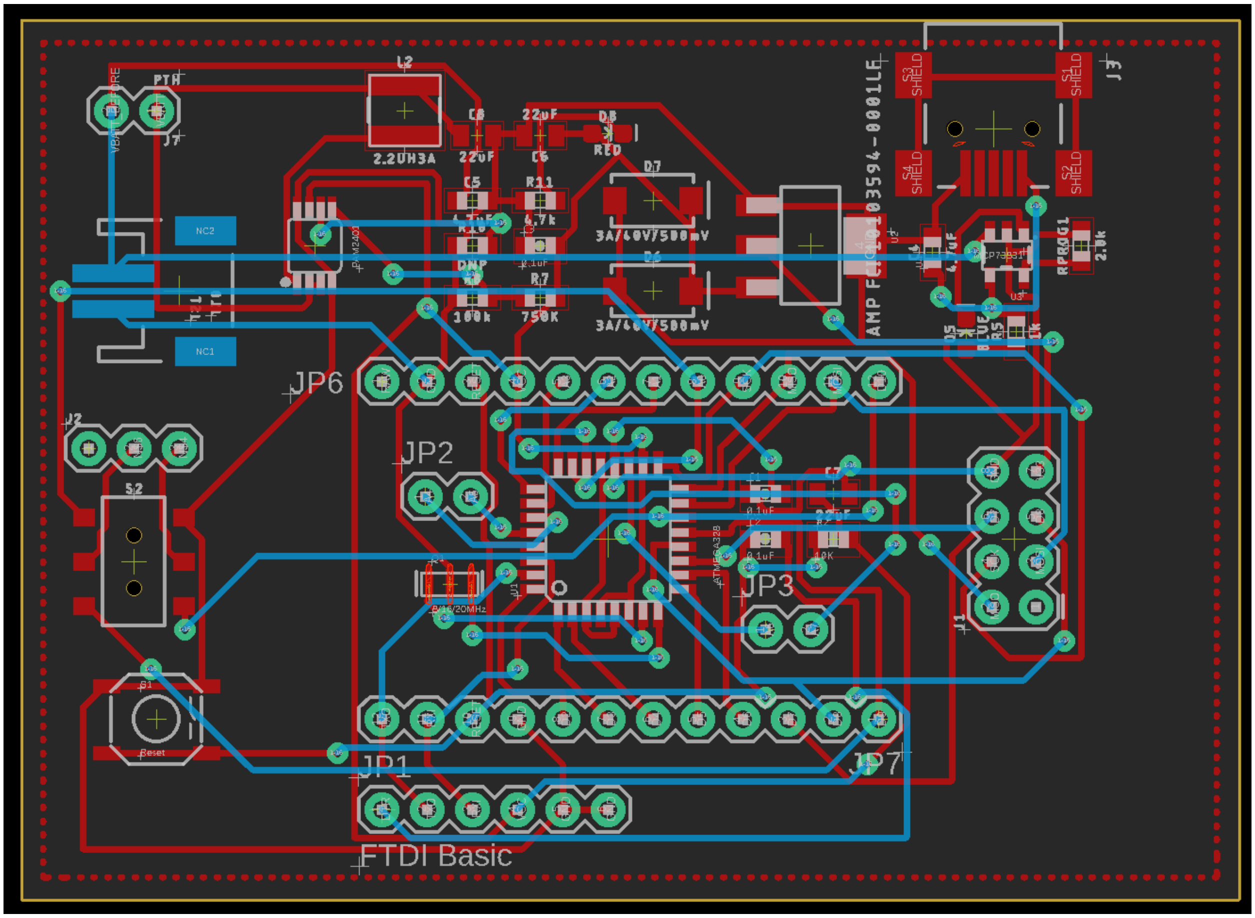

Figure 7 Board View

2.8 Software

The software we run on our microcontroller can be divided into three parts: software-defined analog-to-digital converter (ADC), RF driver, and a software-defined digital-to-analog converter (DAC). The transmitter units will have the ADC module and the RF driver. The receiver units will have the RF driver and the DAC module. The high-level diagram for all software components is outlined in Figure 7 Software diagram. This diagram is created from the perspective of the microcontroller software, so the RF module hardware and wireless signal transmission are both omitted.

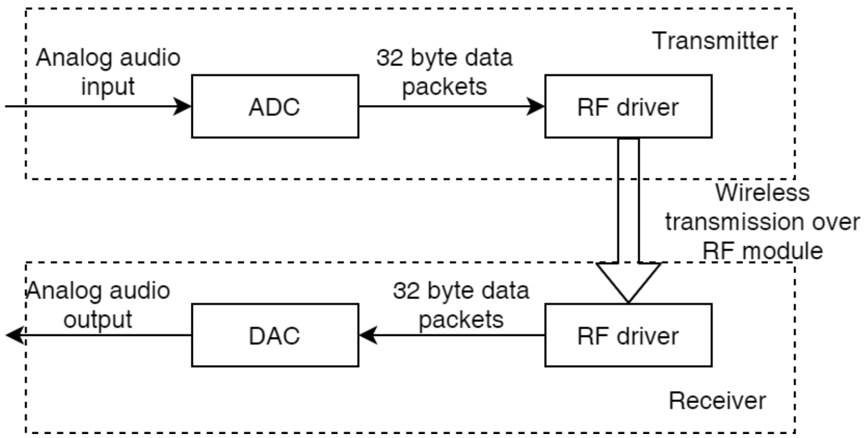

Figure 8 Software diagram

2.8.1 Software-defined analog-to-digital converter

The ADC uses the TIMER1 on the ATMega328 microcontroller. The compare register A is set to a value calculated by $\frac{\text{timer frequency}}{\text{sampling frequency}}$. An interrupt handler is created that whenever the counter values match the compare register value, the microcontroller will read from the analog input pin, an 8-bit number, and store it into the 32-byte buffer. In this manner, the ADC takes periodic samples of the input audio.

The sampling frequency is a programable variable, more samples meaning higher audio quality but stresses the RF bandwidth, and consequently limit the transmission range. Through calculation in Tolerance Analysis, we will determine the optimal value for the sampling frequency.

2.8.2 RF driver

The RF driver utilizes the nRF24 library created by TMRh20. [7] The library supports basic read/write through the RF module, RF channel selection, and RF addresses. The later two functionalities will help us with conflict resolution in the case of two systems being used close together.

The microcontroller will write/receive through the radio driver whenever the 32-byte is full/empty (triggered by timer interrupt). Double buffering is used here to make sure the program is not reading and writing the same buffer at any given time instant.

2.8.3 Software-defined digital-to-analog converter

The DAC uses the same sampling frequency as specified in the ADC section, but instead of reading from the analog pin, the DAC produces a pulse-width-modulation signal, with the value from the buffer, using TIMER1.

2.9 Tolerance Analysis

The tradeoff between audio quality and RF transmission range is inevitable in the development of this system. Sampling the analog audio signal at a higher rate yields better sound quality, a crucial goal of the project. Meanwhile, this means that more data needs to be transmitted over the RF module. The data rate which the RF module can sustain is inversely proportional to the range: we must make sacrifices on audio quality if we want a longer transmission range.

RF transmissions are extremely susceptible to the environment. No authoritative range testing for the nRF24L01 is found. Therefore, we assume the Free Space Path Loss [8] conditions to calculate the signal-to-noise ratio (SNR). While this assumption is ideal, the result would provide an upper bound on the transmission range given a sound quality and is helpful for the testing steps.

The Free Space Path Loss states that:

$$FSPL\ (dB) = 20\log_{10}(d)\ + 20\log_{10}(f)\ + 20\log_{10}(\frac{4\pi}{c})$$

Where *d* is the distance between the transmitter and the receiver in meters, *f* is the transmission frequency in Hz and *c* is the speed of light in vacuum. In the case of RF, the transmission frequency is in the 2.4 GHz band, simplifying the equation to be:

$$FSPL\ (dB) = 20\log_{10}(d)\ +\ 187.60\ - 147.56$$

$$= 20\log_{10}(d) + 40.05$$

The RF24L01 datasheet states that it supports three bandwidth modes: 2Mbps, 1Mpbs, and 250kbps. The receiver is capable of sustaining sufficient transmission bandwidth at a bit error rate (BER) below 0.1% when the SNR is at the typical value stated.

Datarate	Symbol	Parameter (condition)	Notes	Min.	Typ.	Max.	Units
	RX_{max}	Maximum received signal at <0.1% BER			0		dBm
2Mbps	RX_{SENS}	Sensitivity (0.1%BER) @2Mbps			-82		dBm
1Mbps	RX_{SENS}	Sensitivity (0.1%BER) @1Mbps			-85		dBm
250kbps	RX_{SENS}	Sensitivity (0.1%BER) @250kbps			-94		dBm

Table 1 Receiver operation [9]

Combining the FSPL equation and the receiver specification would produce the following table:

Data rate	Typical SNR (dBm)	Maximum range (m)
2Mbps	-82	125.2
1Mbps	-85	176.8
250kbps	-94	498.3

Table 2 Transmission range under FSPL at different data rates

The range obtained is an overestimation of the actual value because of higher background noise power and more obstacles, both of which reduce the SNR at the receiver.

The sampling frequency of CDs is 44.1 kHz at 16 bits, yielding a bit rate of 705.6 kbps. Our microcontroller can support the 44.1 kHz sampling rate, but the analog input resolution is limited at 8 bits, producing a bit rate of 352.8 kbps. Evaluating all information above, the system is going with the 1Mbps data rate as an optimal point in terms of both transmission range and audio quality.

2.10 COVID-19 Contingency Plan

We already have plenty of lab equipment available including the soldering iron, multimeter, etc. Safety concerns of a home lab are addressed in Discussion of Ethics and Safety. If the course transfers fully online, we are planning to continue working on the project, purchasing necessary tools as needed. They might not be as fine as the ones in the lab and might cause our end products to have a slightly worse audio quality, but they should still do the job.

3. Cost and Schedule

3.1 Cost Analysis

We have an estimated labor cost of $3, 000 given by $3 \times \$40/hr \times 10hr/week \times 10\ weeks \times\ 2.5\ =$

$\$3000$ where we estimate $40/hr. salary and overall 100 hrs. work for three people.

Our parts cost is estimated at $20.87 each as follows:

Part Name/#	Description	Manufacturer	Quantity	Cost(per unit)	Cost(Total)
10103594-0001LF	Micro-USB female connector	Amphenol ICC (FCI)	10	$0.67	$6.7
MCP73831	Battery Management Charge management controller	Microchip Technology	10	$0.56	$5.6
PAM2401	Step-Up DC to DC Converters	Diodes Inc	10	$0.40	$4.0
LM1117MPX-3.3	LDO Voltage Regulator	Texas Instruments	10	$0.94	$9.4
ATMEGA328	Microcontroller	Microchip Technology	10	$1.83	$18.3
54-00036	Audio connector	Tensility International Corp	10	$2.45	$24.5
DTP603450	Lithium Ion Battery - 1Ah	SparkFun Electronics	10	$9.95	$99.5
NRF24L01+ Wireless Transceiver Module	2.4G Wireless Transceiver Module	HiLetgo	10	$1.97	$19.7
Assorted resistors, capacitors, ICs, crystals	Assorted resistors, capacitors, ICs, crystals	Any	Many	$0.1	$10
PCB	PCB	PCBWay	10	$2.0	$20
Total				$20.87	$217.7

Table 3 Cost Analysis

Since we are planning to build ten prototypes in total, this gives us a grand total cost of $3, 217.7

3.2 Schedule

Week	Task	Responsibility
9/14	Project Proposals Due	ALL
	Finalize project proposal	Michael, Hammer
	Prepare for DDC concepts	Bernard
9/21	DDC Due	ALL
	Finalize DDC	Michael, Hammer
	Prepare DDC presentation	Bernard
9/28	DD Due, DR signup	ALL
	Finalize DD	Michael, Hammer
	Prepare DR zoom meeting and logistics	Bernard
10/5	DR week	ALL
	Finalize DR document	Michael, Hammer
	Prepare for DR zoom meeting	Bernard
10/12	First PCB order	ALL
	Finalize PCB design and schematics	Michael, Hammer
	Upload and order PCB	Bernard
10/19	No Due, work on individual soldering assignments	ALL
10/26	Final round PCB order	ALL
	Finalize PCB design and schematics	Michael, Hammer
	Upload and order PCB	Bernard
11/2	Individual progress report Due	ALL
11/9	Mock demo Due	ALL
	Finalize all demo details together	ALL
11/16	Project DEMO	ALL
11/23	Thanksgiving week	x
11/30	Mock presentation & real presentation	ALL
	Finalize all presentation details together	Michael, Hammer
	Prepare for presentation	Bernard
12/7	Final papers	ALL

Table 4 Schedule

4. Discussion of Ethics and Safety

The power subsystem could be a potential safety hazard. As we are going to use Lithium batteries as the major power source in the system, which can explode if overcharged or brought to extreme temperatures. We are thus planning to purchase a set of quality lithium battery modules from reputable sources like Sparkfun.com to minimize the risk. We are also only buying RoHS certified batteries to minimize toxic metal usage and less environmental impact. They are batteries that have a reduction in lead and other harmful materials in electronics. [10]

Regarding our home lab safety, the major concern is related to soldering. Soldering indoor can cause harmful gas [11] to get inside the human body via breathing. To address this concern, we purchased a soldering fume air filter and we will always open windows to ensure good ventilation.

The Wireless Transmission Subsystem in the design uses the nRF24L01+ single-chip radio transcriber for the worldwide 2.4 GHz ISM band. ISM bands refer to the industrial, scientific, and medical bands, which are defined by the ITU Radio Regulations. The 2.4 GHz ISM band is permitted for unlicensed operations here in the United States. [12]

On the ethics side, according to the IEEE Code of Ethics, #1: “To accept responsibility...” [13], we might have an ethical breach on I.1, which states that we have to paramount the safety, health, and welfare of the public. This is because our wireless transmission subsystem emits radio waves, which might affect the general public’s health. As a result, we will strictly restrict our wireless transmission power limit and make sure all wireless transmissions are within the FCC spec. [14] This will keep that our public health impact to a negligible degree and thus avoid ethical breaches.

The data stream transmitted between the transmitters and receivers is protected data according to ECPA. [15] Due to limited processing power, we cannot encrypt/decrypt the data packets on the microprocessor. We will ensure that the RF address for each set of devices we produce is unique and immutable. The nRF24 library [7] enforces that the receiver can only receive packets addressed to itself. The unique and immutable

RF address mechanism prevents users from wiretapping on others’ wireless traffic when they are using our product.

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