Wireless Speaker Sharing System

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Abstract

This report documents the full design process of our Wireless Speaker Sharing System (WSSS). WSSS is an easy wireless audio sharing solution that mainly differentiates itself from existing commercial products by eliminating the need for pairing, network connection, or proprietary software. Our system utilizes an Arduino compatible ATmega328P microcontroller for computing and an nRF24 radio module for digital audio transmission over the 2.4 GHz industrial, scientific, and medical (ISM) band. The final product is a small lithium-polymer battery-powered device that can be directly plugged into any standard 3.5 mm audio output/input jack. With virtually no limits on the number of receivers, it opens a new way of audio sharing for large social gathering events and is proven to be cheap, reliable, and opensource.

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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 is 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 3.5 mm audio jack. There will be one broadcasting dongle and multiple receivers, all of which is powered by a Li-Po battery embedded in the design. Users can plug the broadcaster into 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 2.4 GHz 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 is often to have parties where it is 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 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 a Wi-Fi connection. Thus, it cannot 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 does not have device limits since the RF signal is broadcasted and it does not require pairing procedures.

1.3 Example Use Case

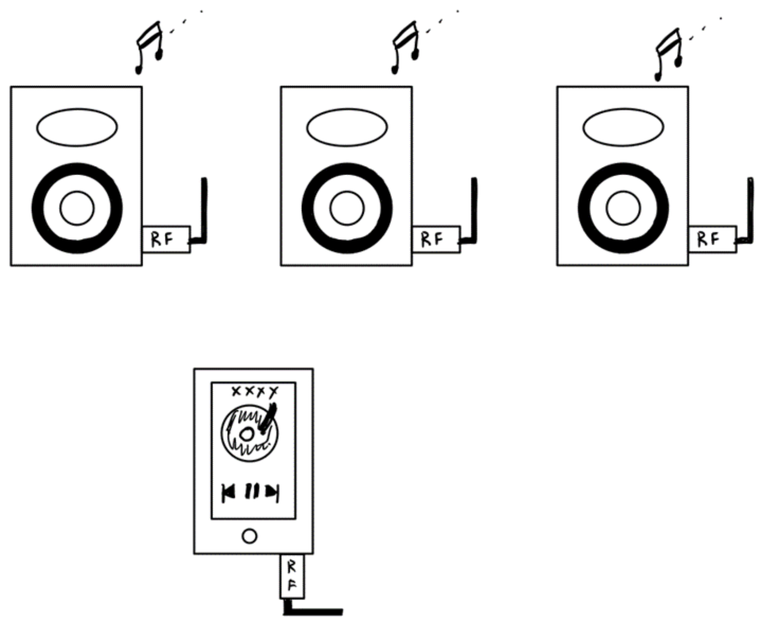

Figure 1 Example Use Case

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 and make them synchronously playing the music from our mobile device. In this case, we are 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.

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 < 15 ms) [3].

2. Design

The design is divided into three separate systems, namely, the power system, the signal processing system, and the RF transceiver system. The block diagram is shown in Figure 2. 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 1 Mbps, 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 10 meters range in-doors with all other Wi-Fi, Bluetooth, and other common 2.4 GHz 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.

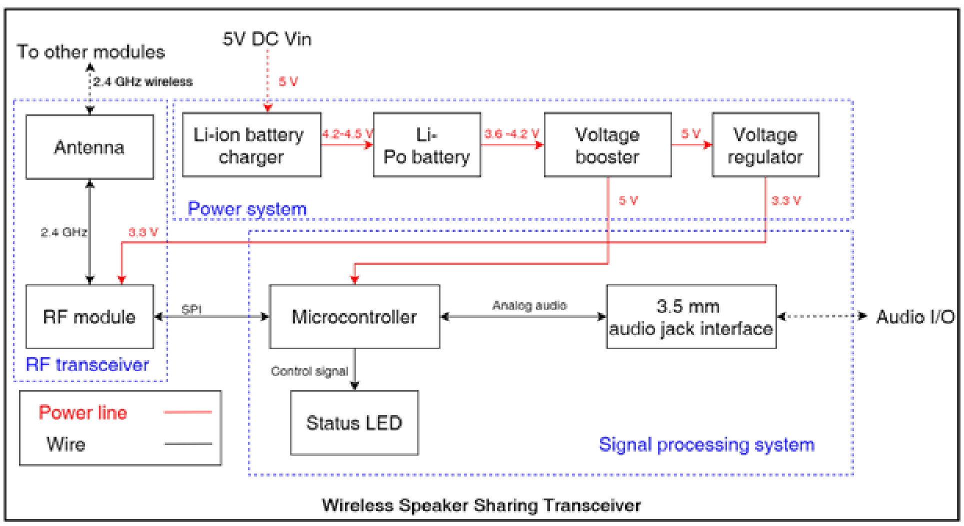

Figure 2 Block Diagram

2.1 Power System

The power system is designed to power the microcontroller operating at 5 V and the RF module operating at 3.3 V. The design includes a voltage booster to step-up the 3.7 V battery output to 5 V. Then the linear voltage regulator is used to step-down the 5 V to 3.3 V for the RF module. A Li-ion battery charger is integrated into the design for recharging. The charging port of choice is the popular mini-USB. The circuit schematics of the entire system is shown in Figure 3.

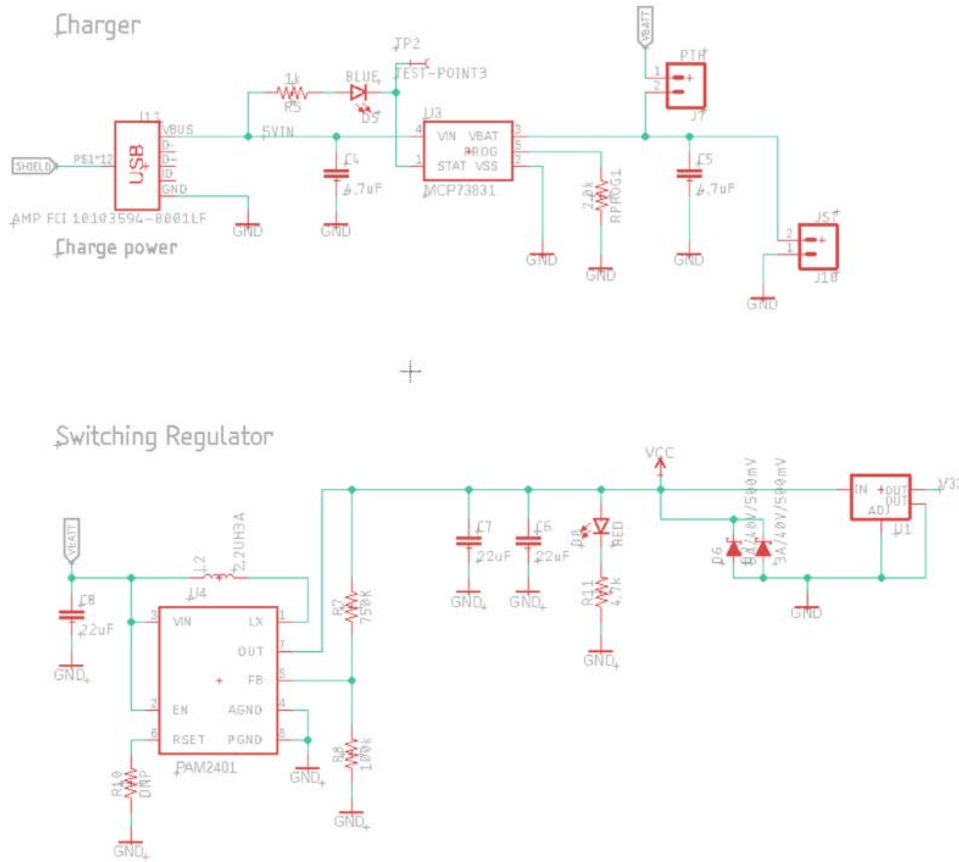

Figure 3 Battery Charger/Booster/Regulator Schematics

2.1.1 Charger IC choice

Lithium-ion polymer battery has all the advantages, but it can also be a safety hazard if not charged properly. [4] To ensure a safe operation, we cannot just feed a constant voltage to this type of battery and hope it will not explode. That is why we opted to use a purposely built Li-ion/LiPo battery charging IC to handle the charging process. We ended up choosing MCP73831/2 from Microchip®. This is a Miniature Single-Cell, Fully Integrated Li-Ion, Li-Polymer Charge Management Controllers that satisfy all my requirements for a charging IC.

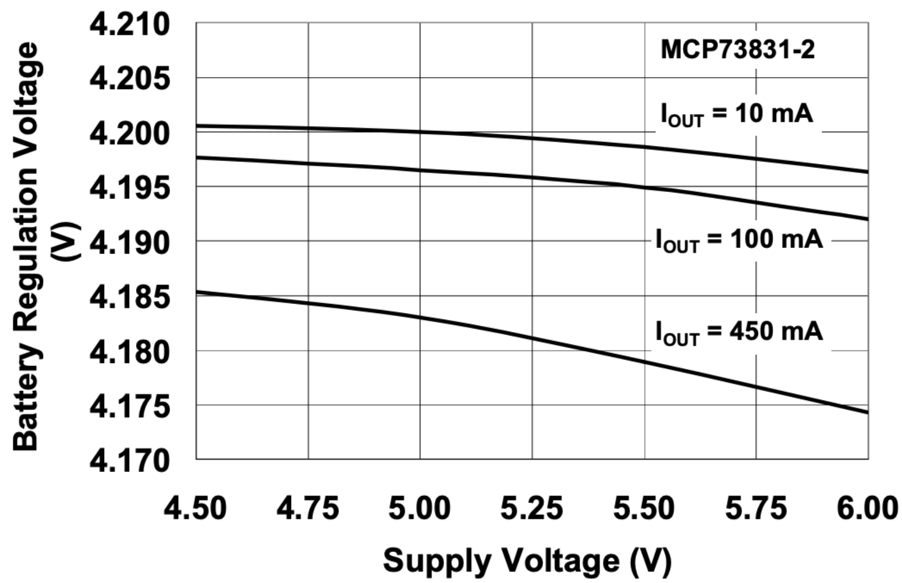

Figure 4 MCP73831/2 Battery Regulation Voltage vs. Supply Voltage [5]

This IC supports a supply voltage of 5 V, which is especially convenient for our system design as it means that it can be powered by a regular 5 V USB connection and utilize the widely available phone chargers. From Figure 4, this IC controls the battery regulation voltage to be constantly below 4.205 V, which is the full-charge voltage of LiPo batteries. The use of this IC essentially eliminates the possibility of overcharging the battery.

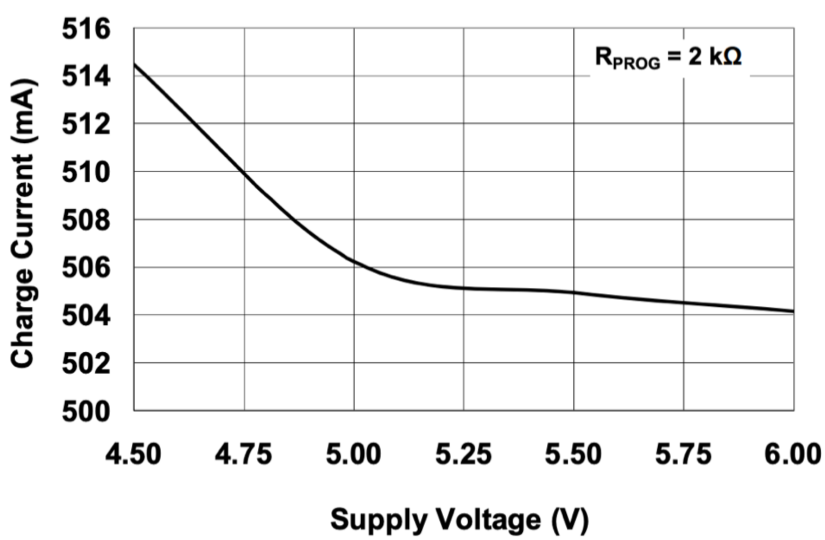

Figure 5 MCP73831/2 Charge Current vs. Supply Voltage [5]

From Figure 5, we can see that with our USB 5 V power supply, MCP73831/2 charges our 1 Ah LiPo battery at about 500 mA when the batter is not full. This is also great for the power subsystem's performance. This kind of fast charging capability makes charging the first 50% of the battery under 1 hour, which means at least 4 hours of using time.

2.1.1 Voltage booster IC choice

Because our Arduino needs to run at a constant 5 V to ensure reliable performance at 16 MHz. A voltage booster circuit is needed. Our system's power is mostly consumed by the Arduino (ATmega328P) and nRF24 module. Arduino at 5 V/16 MHz draws 15 mA by itself [6] while nRF24 can use a maximum of 100 mA during transmission. [7] Combined with some generous margins, we thought the voltage booster needs at least 200mA output capability at 5 V. After meticulous searches, we settled with PAM2401 from DIODES®.

PAM2401 is a high efficiency, current mode, fixed frequency, step-up DC/DC converter with true output disconnect and inrush current limiting. [8] DC/DC conversion ensures its high efficiency, which is especially important for us as our system runs on battery and need as much battery life as possible.

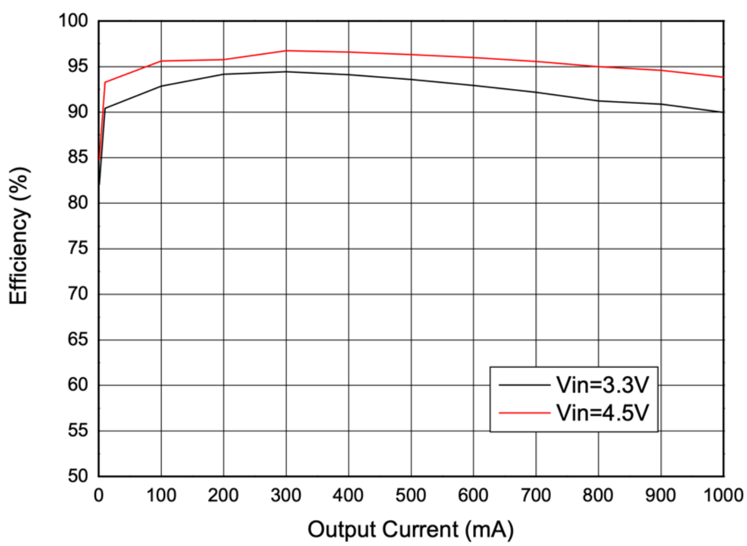

Figure 6 PAM2401 Efficiency vs. Output Current [8]

PAM2401 can handle a maximum of 1 A output, which is more than adequate in our use case. From Figure 6 we can see that at our typical 100 mA~200 mA output current, the efficiency is above 93% percent throughout the 3.3 V to 4.2 V battery output voltage.

2.2 Signal Processing System

The signal processing system can be divided into two parts: the microcontroller circuitry and the transceiver software. Figure 7 shows the circuit schematics for the microcontroller. The power pins are connected to corresponding voltages from the power system and the functional pins are routed to socket connectors for debugging purposes.

A 2-to-4 switch (labeled as Audio Connection in Figure 7) is incorporated into the design. When the switch is in the up position, the system acts as a receiver. When the switch is in the down position, the system acts as a transmitter. This design avoids the extra costs involved in designing and manufacturing two different schematics for the transmitter and the receiver devices.

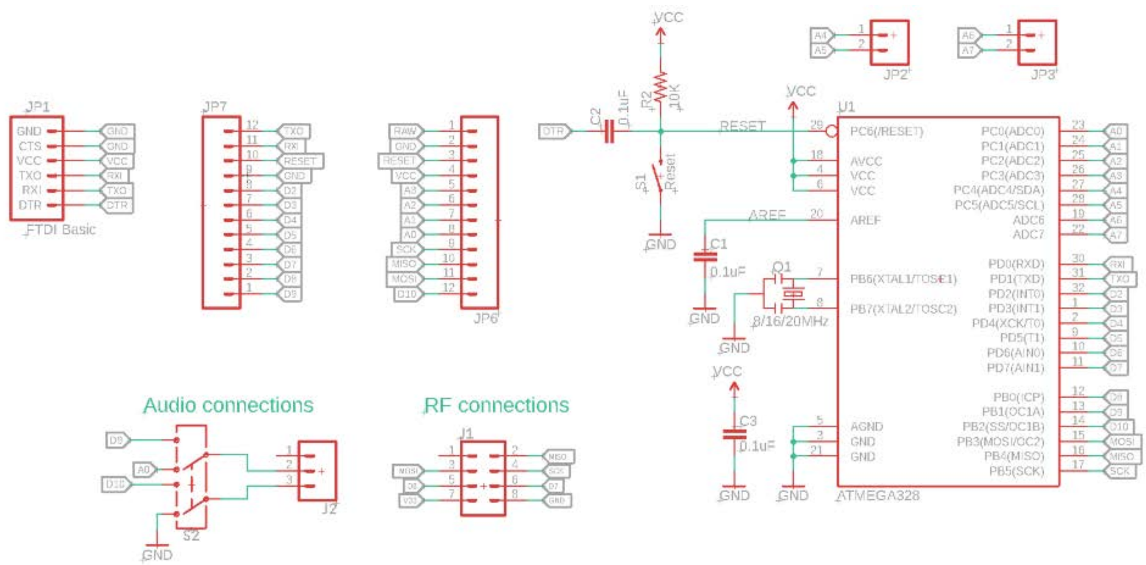

Figure 7 Microcontroller Schematic

The microcontroller software has two variations, namely the transmitter code and the receiver code. The transmitter software periodically samples the analog audio frequency at a predefined rate, discussed in 2.3.1 Tolerance Calculation. It buffers the samples and sends data packets over the RF transceiver once it has collected enough samples. The receiver software, conversely, periodically checks for available data packets in the radio frequency channel and output the audio signal using the timer's pulse width modulation (PWM) mode. This is shown graphically in Figure 8.

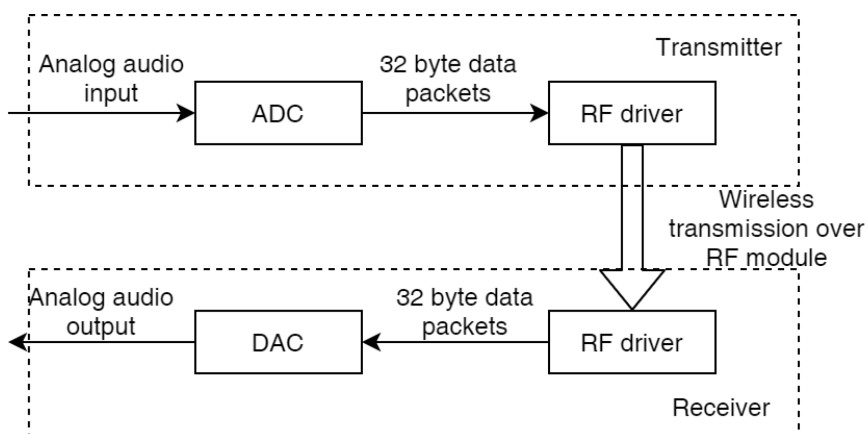

Figure 8 Software Diagram

The transmitter and receivers in a set are configured to operate on the same radio frequency channel and same RF address to allow for multicasting. To avoid RF cross-talking, appearing when two systems are used in the vicinity each other, we assign unique RF addresses to the set of devices. This would prevent cross-talking as the receivers only capture packets addressed to them.

2.3 RF Transceiver

The RF transceiver is available on the market, so we purchased them directly rather than building it from scratch for its sensitivity to tiny inaccuracies. In the circuit schematics and PCB design, a 2×4 socket is reserved for the RF transceiver for easy replacement, as the module is fragile. Figure 9 describes the circuit schematics of the RF module that we obtained from the supplier.

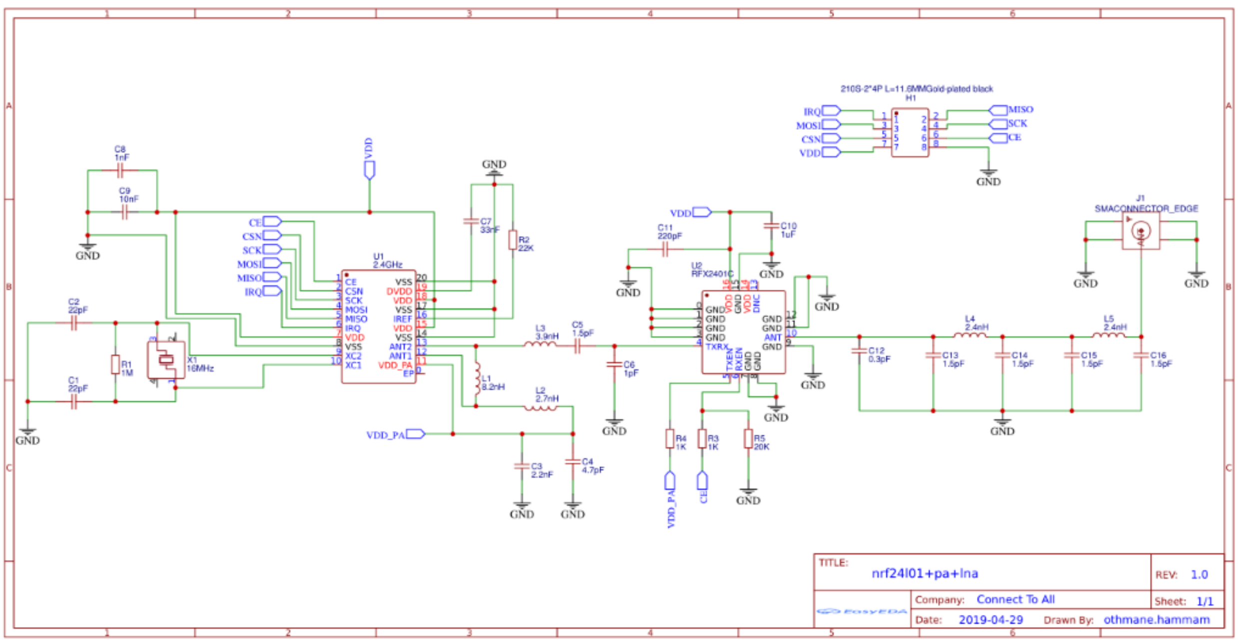

Figure 9 RF Schematic [9]

2.3.1 Tolerance Calculation

The RF24 library [10] is used to interface with the RF transceiver. It supports three transmission bandwidths: 250 kbps, 1 Mbps, and 2 Mbps. The transceiver can stream higher-resolution music with larger bandwidth configurations, but the signal-to-noise ratio requirement is stricter, as described in Table 1. The consequence is a tradeoff between the audio quality and the signal range coverage. To determine the optimal operating bandwidth, sampling frequency, and sample resolution, the following calculations are performed.

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 [11]

First, we assume the Free Space Path Loss [12] conditions to calculate the signal-to-noise ratio (SNR). While this assumption is ideal, the result provides an upper bound on the transmission range on different transmission bandwidths. The Free Space Path Loss states that:

$$FSPL\ (dB) = 20\log_{10}(d)\ + 20\log_{10}(f)\ + 20\log_{10}(\frac{4\pi}{c}) \quad \textbf{Equation 1}$$

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 a vacuum. In the case of RF, the transmission frequency is in the 2.4 GHz band, simplifying Equation 1 yields:

$$\begin{aligned} FSPL\ (dB) &= 20\log_{10}(d)\ +\ 187.60\ - 147.56 \\ &= 20\log_{10}(d) + 40.05 \end{aligned} \quad \textbf{Equation 2}$$

Combining the FSPL equation and the receiver specification produces Table 2

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

Table 2 Transmission range under FSPL at different data rates

ATMega328P, the microcontroller of choice, supports up to 10-bit analog-to-digital conversion. The 10-bit sample resolution is used to fully utilized the microcontroller. The data rate is 220 kbps under a 22 kHz sampling rate and 441 kbps under the standard CD 44.1 kHz sampling rate. While a 44.1 kHz sampling rate would produce better audio, the microcontroller does not have enough computing power for the task. Therefore, we choose 10 bits as the sampling resolution and 22 kHz as the sampling frequency. The bandwidth for the RF transceivers is configured at 1 Mbps, slightly higher than the required one, to account for partial bandwidth utilization due to alignment issues.

3. Requirements and Verification

3.1 Power Subsystem

3.1.1 Li-Po Battery Charger

With all these aspects in mind, we used Table 3 to test our battery charging IC choice. All verifications are successful.

<table>
<tr><th>Proposed Requirements</th><th>Performed Verifications</th></tr>
<tr><td>1. Must charge the Li-Po battery to 4.2 V ± 50 mV per cell, which is the nominal full-charge voltage. This cannot be a higher or lower value.
2. Must have a charging current at about 500mA when the battery is fully discharged.</td><td>1. Discharged the battery cell to about 3.5 V.
2. Charged the battery using the charging IC circuitry with a 5V input voltage from my phone charger.
3. Used a multimeter and measured the charging current.
4. When the charging process has finished (indicated by the charger IC with a peripheral LED), checked battery voltage.</td></tr>
<tr><th colspan="2">Verification Results</th></tr>
<tr><td colspan="2">1. The charging current for a fully discharged battery at about 3.5 V was measured to be 530mA.
2. The fully charged voltage after charging completion cut-off is at 4.208V, which indicates no dangerous overcharging.</td></tr>
</table>

Table 3 Li-Po Battery Charger R&V Table

3.1.2 Li-Po Battery

To achieve both compact form-factor and long battery life, we opted to use the most power-dense battery that we have access to at this time, which is a lithium-ion polymer battery. Aside from power density, this type of battery has numerous advantages including less thickness, lightweight, and customizable shapes. [13] is used for our battery.

<table>
<tr><th>Proposed Requirements</th><th>Performed Verifications</th></tr>
<tr><td>1. The battery must be rated at about 1000 mAh, which is realistically enough to power a constant load of 100 mA for at least 8 hours.
2. The battery is less than 30 grams and has a footprint that is less than 20 cm^2 to reduce the weight and footprint of the whole system.
3. The battery’s temperature should stay below 50°C when charging and discharging.</td><td>1. Charged the battery to full capacity using our charging circuit. Use a multimeter to ensure that the voltage across it is <= 4.2V
2. Connected the battery to our 5V boost circuit with a 50-ohm load for a constant discharge at ~100mA for 8 hours overnight.
3. Used a multimeter to measure the battery voltage again after discharging.</td></tr>
<tr><th colspan="2">Verification Results</th></tr>
<tr><td colspan="2">1. The voltage across a fully charged battery was 4.196 V, which was below 4.2 V
2. 8 hours of constant discharging was successful as the load resistor was still warm and 5 V output was stable.
3. The voltage across the battery about 8 hours of use was at 3.85 V, which was above 3.7 V, indicating a not fully drained battery.
4. The battery cell only got warm to touch, certainly below 50°C.</td></tr>
</table>

Table 4 Li-Po Battery R&V Table

3.1.3 Li-Po Battery Voltage Booster

To achieve stable operation of our 16 MHz ATmega328P 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 5 V. Table 5 shows the requirements and verification.

Proposed Requirements	Performed Verifications
1. Must be output a clean and stable 5 V DC at a sustained current draw of around 200 mA when powered by a range of possible Li-Po battery operation voltages. 2. Must have an efficiency result above 90%	1. Connected a lab bench power supply to the boost circuitry’s input. 2. Attached a 25 ohms resistor as load (200mA load) 3. Attached a voltmeter across the load 4. Swept the supply voltage from 3.5 to 4.2 V 5. Checked the output voltage.

	6. Checked the lab bench power supplies' power output to test efficiency.
Verification Results	
1. Checked the output voltage to be between 5.06 to 4.96 V, which was within Arduino power specs. 2. Power supplies' power output never exceeds 1007mW, which is above 90%.	

Table 5 Li-Po Battery Voltage Booster R&V Table

3.1.4 Voltage Regulator

nRF24 module runs on 3.3 V. Because it is an RF component, power cleanness is also a vital point. Our system needs a constant, clean 3.3 V voltage that can handle at least 150 mA current for the nRF module [7]. With a good consistent 5 V provided by our boost circuit; the problem is simple. We opted to use a simple linear regular that can output a constant 3.3V. Based on my experience, the 1117 series of linear regulators is the most widely used IC for this kind of operation. We used the easiest to find LM1117-3.3 from Texas Instrument® in my design.

According to the datasheet, with a voltage difference of 5 - 3.3 = 1.7 V, the LM1117 will not dropout even when the output current is at 800 mA. [14] This is well above our maximum current need.

Table 6 is thus used, and all verifications are successful.

Proposed Requirements	Performed Verifications
Must be able to handle the 5 V input from the battery boost circuit at the peak current draw (~200 mA when transmitting/receiving at 3.3 V).	1. Attached 10 ohms resistor as load (>200 mA load) 2. Attached a voltmeter across the resistor 3. Supplied the regulator with the 5 V output from my boost circuit. 4. Check output voltage.
Verification Results	
The output voltage is measured to remain at 3.31 V constantly.	

Table 6 Voltage Regulator

3.1.5 Power Subsystem Integration Test

After verifications of all units in the power subsystem, we soldered all parts and did an integration test.

We first used a multimeter to test the continuity of important connections on board to see if our soldering is reliable and there are no shorts in power lines. Then we used a multimeter to check the voltage of the battery to see if it still has enough power. We got a reading of 3.9 V which is good. Then we finally connected/soldered the battery and turned on the power switch. Using a multimeter, we tested the output pin of MCP73831, the output pin of LM1117, and some other inner connections. It turned out it is working perfectly, with the booster providing 5 V output and regulator providing 3.3 V. Lastly, we connected a 5 V USB charger used a multimeter over the voltage of the Li-ion battery and observed a charging rate of 0.01 V/sec approximately, which indicates the charging chip works.

3.2 Signal processing subsystem

3.2.1 Microcontroller

The microcontroller is essential to do the A/D, D/A conversions to ensure usable audio quality and send control signals to communicate with our RF modules, as RF modules transmit digital signals instead of analog voltages. Table 7 shows the requirements and verifications for the microcontroller.

Proposed Requirements	Performed Verifications
Must be able to do A/D at 8-bit resolution and 44 kHz sampling rate.	1. A/D verification: (a) Use a 20 kHz 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 20 kHz sine wave back.
Must be able to do D/A at 8-bit resolution and 44 kHz 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 20 kHz wave. (Not a sine wave as Arduino cannot output a real sine wave. However, the output should sound similar)

Verification Results
1. Input a 20 kHz sine wave to the microcontroller and save the output digital signals to a file. Applying an ideal DAC filter to the saved data and then apply Fourier Transform to the reconstructed analog signals, use pyplot to plot the signals in the frequency domain and observed a peak at 20 kHz, which is the expected result. 2. Getting the input digital signals from A/D submodule output, and then apply Fourier Transform to the reconstructed analog signals, use pyplot to plot the signals in the frequency domain and observed a peak at around 20 kHz, though the curve is not super smooth, which is the expected result.

Table 7 Microcontroller R&V Table

3.2.2 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. Table 8 shows the requirements and verification for the status LED.

Proposed Requirements	Performed Verifications
The status LEDs must be flashing when the RF module is transmitting or receiving payloads.	1. Put one RF module in transmission mode and the other in receiving mode. 2. Ensure LEDs on both nodes are flashing. 3. Turn off the transmission mode on the first RF module. 4. Verify that both LEDs are no longer flashing.
Verification Results	
Status LED is blinking while the RF module is in transmission/receiving mode.	

Table 8 Status LED R&V Table

3.3 Radio Frequency Transceiver Subsystem

3.3.2 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. Table 9 shows the requirements and verifications for the antenna.

<table>
<tr><th>Proposed Requirements</th><th>Performed Verifications</th></tr>
<tr><td>An omnidirectional antenna with a gain rating of about 5 dBi will be used. This allows our RF module to have a 10 m range for indoor usage with no positioning requirements.</td><td>1. Use both transmitter and receiver without connecting the antenna.
2. Verify that the status LED is not flashing properly when these two modules are 10 meters apart. (Indicating a bad reception)
3. Install 5 dBi omnidirectional antennas on both transmitter and receiver.
4. Verify the usefulness of the Antenna by placing them 10 m apart and look for the constant flashing of both status LEDs to ensure that a good connection is established.</td></tr>
<tr><th colspan="2">Verification Results</th></tr>
<tr><td colspan="2">1. The status LED is blinking constantly on both transmitter and receiver within 10 meters range.
2. The status LED is not blinking as often as it is when moving farther than 10 meters, especially when the transmitter and the receiver are set apart beyond 25 meters.</td></tr>
</table>

Table 9 Antenna R&V Table

3.3.3 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. Table 10 shows the requirements and verifications for the RF module.

<table>
<tr><th>Proposed Requirements</th><th>Performed Verifications</th></tr>
<tr><td>The module should use the 2.4 GHz band and it can sustain a single-direction wireless transmission bandwidth of 350 kbps (calculated in 2.3.1 Tolerance Calculation) consistently within a 10m radius.</td><td>1. Use the nRF24 library on Arduino to set both transmitter and receiver to use the 1Mbps bandwidth mode.
2. Program the timer interrupt to send a 32-bytes counter packet at a frequency of 1367 Hz.
3. On the receiver side, constantly check if there’s data to be read and store the received data in memory
4. Place the two nodes ~10m apart.
5. Start the program on both nodes and keep running for 1 minute
6. Dump the received packets to a file and verify that it is below a BER of 0.1%</td></tr>
<tr><th colspan="2">Verification Results</th></tr>
<tr><td colspan="2">1. Place two nodes apart in about 10 meters, do the initial channel setup on both sides.
2. Start the program on both sides and save the transmitted/received data to a file.
3. Running diff tool over the two files, getting a BER of ~0.05 %, which is expected.</td></tr>
</table>

Table 10 RF Module R&V Table

4. Costs and Schedule

The cost of the project is divided into two sections, cost to purchase the electronic components and labor costs.

4.1 Parts

Table 11 describes the costs to purchase all the electronic components in the project.

Part Name/#	Description	Manufacturer	Quantity	Cost (per unit)	Cost (Total)
10103594-0001LF	Micro-USB female connector	Amphenol ICC (FCI)	4	$0.67	$2.68
MCP73831	Battery charging controller	Microchip Technology	4	$0.56	$2.24
PAM2401	DC voltage booster	Diodes Inc	4	$0.40	$1.60
LM1117MPX-3.3	LDO Voltage Regulator	Texas Instruments	4	$0.94	$3.76
ATMEGA328	Microcontroller	Microchip Technology	4	$1.83	$7.32
54-00036	Audio connector	Tensility International Corp	4	$2.45	$9.80
DTP603450	Lithium-Ion Battery - 1Ah	Spark Fun Electronics	4	$9.95	$39.80
NRF24L01+ Wireless Transceiver Module	2.4G Wireless Transceiver Module	HiLetgo	4	$1.97	$7.88
Assorted resistors, capacitors, ICs, crystals	Assorted resistors, capacitors, ICs, crystals	Any	100	$0.10	$10.00
PCB	PCB	PCBWay	4	$2.00	$8.00
Total				$20.87	$83.48

Table 11 Parts Costs

4.2 Labor

We have an estimated labor cost of $3,000 given by $3 \times \$40/hr \times 10 hr/week \times 10$ weeks$\times$ 2.5 = $3000

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

4.3 Schedule

Table 12 describes our development schedule during the semester.

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 12 Schedule

5. Conclusion

5.1 Accomplishments

From the perspective of the design, we've successfully fulfilled our project design. We've completely implemented our system schematics and board design, every subsystem works as intended --- Power subsystem can provide 5 V and 3.3 V power to other subsystems continuously for up to 8 hours; Signal Processing Subsystem can apply the A/D, D/A converting in up to 10-bit resolution at 20 kHz sampling rate at maximum; RF Transceiver Subsystem can transmit/receive digital signals over 2.4 GHz band wirelessly at a rate of 2 Mbps at maximum, reliable within a range of at least 15 meters.

From the perspective of the final deliverable, we successfully built 3 prototype WSSS units consists of 2 receivers and 1 transmitter. As demonstrated in the final demo, we can set up a WSSS by connecting the transmitter to an audio input device (e.g., a smartphone) while the two receivers are connected to audio output devices (e.g., any speaker). As soon as all the components are connected, the output devices will start playing the same audio track coming from the input device/transmitter in sync, with indiscernible latencies among the receivers (< 15 ms). Also, it will work perfectly within 10 meters range, omnidirectionally. This exactly resolves our initial problem statement, it provides the most flexible, reliable, and affordable solution to set up a speaker sharing system to present the best auditory experience.

5.2 Uncertainties

The biggest uncertainty of our design is its A/D, D/A processing capability. Since we do not have a hardware ADC, we accomplish A/D and D/A via sampling over PWM and internal timers of the ATmega328P microcontroller chip. Because this is a software implementation of ADC and DAC as well as the limitation of the processing power of the chip, the sound quality becomes uncertain. And it turns out the final sound quality is unsatisfactory; it is like AM radio quality but not as good/smooth as FM. We can at most achieve a 10-bit resolution/bit-depth at 20 kHz sampling rate for our software ADC and DAC due to the limitation of the chip, whereas a good sound quality may prefer 16-bit bit-depth at 44.1 kHz sampling rate. The limited range of 0-255 of Arduino PWM signals could also impact the sound quality negatively. However, due to fact that we are more familiar with the AVR chipset and Arduino library, the limited amount of cost and fast-paced project development timeline, using an ATmega328P instead of some other more advanced microcontroller chip to achieve a relatively good sound quality is probably the best option. In the future, we are still thinking about upgrading our A/D and D/A by upgrading the microcontroller chip.

5.3 Ethical Considerations

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. [15]

Regarding our home lab safety, the major concern is related to soldering. Soldering indoor can cause harmful gas [16] 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. [17]

On the ethics side, according to the IEEE Code of Ethics, #1: "To accept responsibility..." [18], 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. [19] 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. [20] 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 [10] enforces that the receiver can only receive packets addressed to itself. The unique and immutable RF address mechanism prevents users from wiretapping others' wireless traffic when they are using our product.

5.4 Future Work

We chose the Arduino compatible ATmega328P chip for the project considering the tight development time frame and budget this semester. This chip has limited A/D converting resolution and computing power, limiting the audio quality of our system. In the future, a better performing chip can be adopted for better audio quality. For example, STM32 G4 features a 16-bit ADC, a DAC, and the ARM Cortex-M4F core can operate at a maximum clock frequency of 170 MHz. [21] With a powerful microcontroller like the STM32 G4, the system would stream with much better quality.

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