Bone Conduction Discrete Communicator

ECE 445 Design Document

Team 63

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https://github.com/magicmomo123/WBCS

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I. Introduction

Hearing loss is a condition that affects about 2 to 3 out of every 1.000 children born in the US[1]. Common types of hearing loss are Conductive Hearing Loss (CHL) or Single Sided Deafness (SSD) are two different types of hearing loss, the former being a dysfunction in one's ability to transfer sound through either the outer ear, the ear drum, or the middle ear , and the latter being a total dysfunction of the ear, including the cochlea. In people with Single Sided Deafness or Conductive Hearing Loss, a different method of transmitting sound must be employed to give the user an auditory understanding of their surroundings. Conductive Hearing loss, which is characterized by a dysfunction of the ear to transmit pressure waves for interpretation by the cochlea, commonplace solutions might not be as readily available. For people afflicted by CHL, bone conduction based hearing aids might be a suitable alternative to traditional hearing aids.

Another motivating area for our project is the field of discreet communication. The ability to communicate without providing visual cues of communication might prove valuable in fields such as entertainment and defense.

Inspired by these two primary use cases, our group chose to work on a wearable bone conduction device mounted on the palate in the mouth. The idea was for the bone conduction transducer to maintain contact with the back two molars on the upper set of teeth, so that a resonant channel for transmission would be maintained to the cochlea. As this is a wearable device, there must be no dangling wires, meaning the device should be battery powered. To support long-term usage, the battery must be rechargeable, and should have a sufficient battery life to limit the need for constant recharging. To receive some signal, the device connects to an audio stream from an http server. As for the mechanical requirements for the device, it is necessary that the electronics fit into an area small enough to not impede speech, an area we decided to be $400mm^2$.

To summarize the functionality of the device, three separate subsystems are enumerated: the power/charging subsystem, the signal subsystem, and the transducer subsystem. The power/ charging subsystem is comprised of the usb connection and the battery. It should be able to support charging of the battery, be able to switch the PCB's main power line depending on

[1] "Quick Statistics about Hearing." National Institute of Deafness and Other Communication Disorders, U.S. Department of Health and Human Services, https://www.nidcd.nih.gov/health/statistics/quick-statistics-hearing

which components are present, and output a regulated 3.3 Volt output. The signal subsystem should receive this regulated power output, connect to an http server to fetch an audio stream, and output audio for processing by the transducer unit. The transducer unit should then receive this audio, which is sent in the I2S format, demodulate and apply some gain, and send the analog signal to the transducer. As speech is the primary type of signal that we aim to support with the device, the output to the transducer should be clearly intelligible at 2Khz. According to Nyquist sampling theory, the ESP32 should then send digital data at a minimum rate of 4Khz, as shown in Eq. 1.

$$f_{sample} >= 2 * Bandwidth \tag{1}$$

The high level block diagram for all three components is shown below.

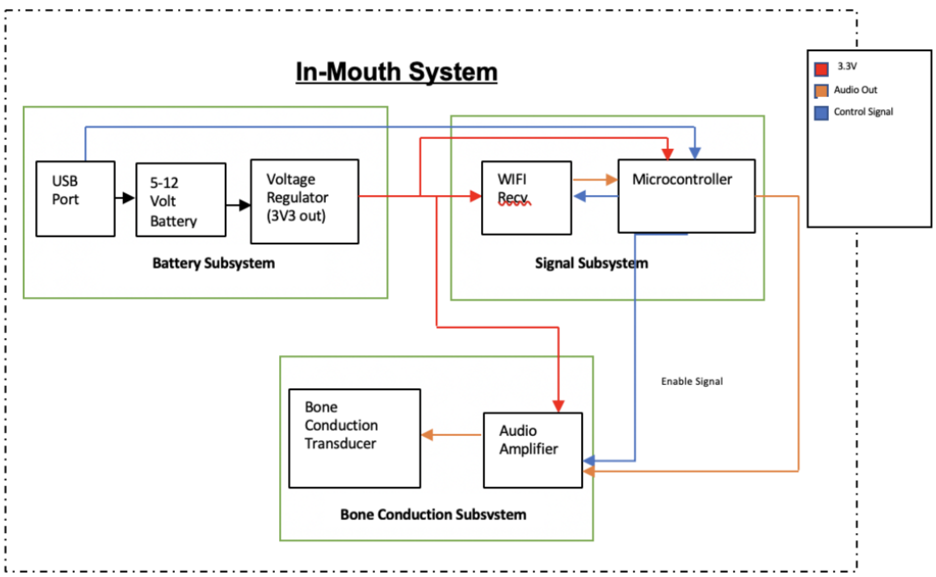

Fig. 1. While the high level functionality of our device has stayed the same throughout the semester, our choices for components has significantly changed from the design document. Our charging subcircuit is largely the same, but our signal subsystem, instead of being comprised of an ESP8266 for Wifi and an ATTiny for demodulation, is now just an ESP32, which was chosen because of its built in wifi antenna and I2S bus functionality. Our transducer unit, because of the addition of the I2S bus, also had to change, originally being an op-amp based component, and then changing to an I2S DAC IC, the MAX98357.

II. Design

A. Design Procedure

1) Charging/Power Subcircuit:

For the charging subcircuit, a couple of main functionalities needed to be achieved. First, we needed to be able to recharge the battery in a short amount of time. Second, we needed to be able to output a constant 3.3V to the microcontroller and DAC. Finally, we needed to have some way to select which source would be used to power the circuit. One alternative to this would be just having the USB supply voltage for charging the battery instead of to the rest of the circuit. The issue with this design was that when the USB was plugged in, we were blocking voltage to the microcontroller unit, which needed to be powered on in order for us to flash a program on to it. In order to fix this problem, we decided on including a diode so that the USB would also supply power to the microcontroller, and that no current would flow back through the USB voltage line. One design choice that ended up costing us was not having a USB-UART converter on the chip. UART is the recommended way to flash a serial program onto the ESP32, but we decided not to add a UART IC in order to save space on the PCB. We ended up having problems flashing onto the microcontroller, requiring us to buy a usb-uart breakout board for assistance. Also, for ease in soldering, a microUSB port would have been a better option than USB C. In the next section, we will go into more detail about specific components and their functionalities.

2) Signal Subcircuit:

For the signal subcircuit, there were three main functionalities that we needed to address. The first was size; we knew that whatever microcontroller we used needed to be small enough to fit onto a board of $400mm^2$, while still leaving enough space for the rest of the components of the circuit. The second was communication. We wanted a microcontroller that had an antenna already attached to it, so that we could be confident that it would support the signal communication of our choosing. Finally, the microcontroller needed to be able to support low energy audio by having enough memory to support circular buffering of an audio stream, while also outputting the audio in some standard digital format. At first, we were going to use two microcontrollers, the ESP8266 for wifi communication and circular buffering, and the

ATTiny as a pwm dac. We soon realized that this approach didn't make much sense, as we could get a single microcontroller that could support the entire intended functionality in a small physical footprint. We eventually decided to use the ESP32 -C3, first using the N4 footprint, and then transitioning to the WROOM footprint for ease of soldering. One final requirement was that the microcontroller had to output data at twice the bandwidth of our signal according to Nyquist, in our case, a minimum of 4 kHz, which is far lower than the maximum sampling rate of the ESP32, 2 MHz.

3) Transducer Subcircuit:

For the transducer subcircuit we had to tackle two main issues. How should we would convert the Digital Signal transmitted through WiFi to convert to an Analog Signal. In addition, we also needed to determine the gain required to amplify the signal to an intelligible sound that the wearer can understand. We decided to use the MAX98357AETE+ for our Digital to Analog converter (DAC) because it fit our design requirements to be very small, and had a very simple design that could easily be integrated into the system as a whole. This DAC also has a built in gain that we can modify depending on the voltage feeding into the gain input pin. Lastly, the MAX98 is supposed to output the new analog signal to the Bone Conduction Transducer, which will vibrate accordingly to the actual audio sent via the WiFi signal.

B. Design Details

1) Charging/Power Subcircuit:

Starting from the USB unit, we chose to use a USB C receptacle, which has more output pins than a microUSB. Two of these pins, the CC1/CC2, are used for sensing a device on the bus; the pairing device should have two pull down resistors in Figure 2 to form a voltage divider with corresponding pull up resistors on the source. If a voltage divider is formed, then serial communication can begin. The USB C also sends D+ and D- to GPIOs 18 and 19 on the ESP32, the GPIO pins specified for serial communication. Finally, the VBUS (denoted by the VBUS flag in Figure 2) is routed to the VDD pin of the charging IC and the Gate input for the P Mos transistor. The charging IC that we use is the MCP73831, which changes the current output to the positive terminal of the battery according to the voltage of the battery versus the rated voltage of the IC. Refer to APPENDIX I. A test of this functionality was carried out as part of our requirements and verifications, discussed later in this document. The bypass capacitors and pulldown resistor are selected in accordance with the sample application circuit given in the document. A large part of the functionality of the charging circuit comes from the PMOS logic, shown by the circuitry in the top right corner of Figure 2. When VBUS is high, then the voltage from the battery does not flow through the drain of the PMOS, while a biased line from VBUS becomes the main power line for the PCB. When VBUS is low (not plugged in), then the VBAT becomes the main power source for the PCB. Regardless of which power source is chosen, before it can flow to the rest of the circuit, it goes through a linear dropout regulator, the AP2120, which maintains a constant voltage at 3.3V. As we would later come to see, while the AP2120 did regulate voltage properly (verified by multimeter), it also limited the current output to the ESP32, causing a power brownout. To solve this problem, we soldered a wire between VIN and VOUT, effectively shorting the linear dropout regulator. While this is obviously not a permanent solution, for the demonstration, it allowed us to finally boot up the program on the ESP32.

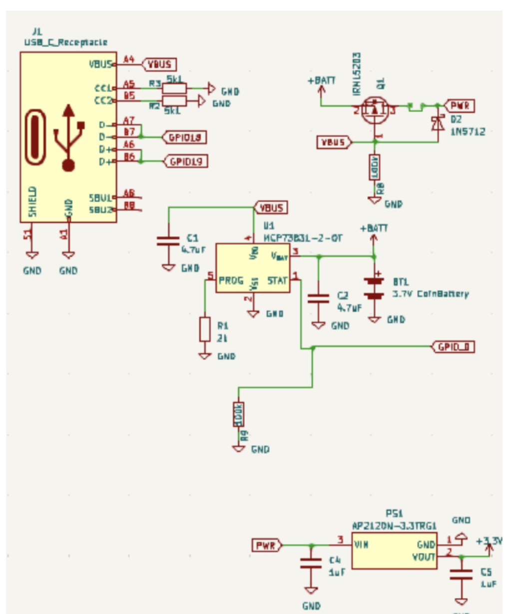

Fig. 2. Charging Schematic

2) *Signal Subcircuit:*

Displayed in Figure 3is the circuit schematic for the signal subsystem, which is basically just an implementation of the ESP32 on a pcb. The design is largely based off of Espressif's Devkit, with the configuration of the switches kept the same as the schematic. The switches are sent to the enable and GPIO9 for a very specific reason. First, the Enable port must have a switch so that the reset can be toggled on the microcontroller to rerun the program. GPIO9 on the ESP32 C3 is the 'boot' GPIO pin. It must be toggled low in combination with the enable pin to flash a program onto the ESP32, and then left in a debounced state to boot the program, as it has an internal pullup resistor. To ensure proper serial behavior, GPIO8 must also be pulled up. This was a problem for us originally, as the resistor connected to GPIO8 was actually grounded instead of pulled up, leading to incorrect booting. To fix this problem, we directly soldered on a resistor to pull up the GPIO. The microcontroller connected to a audio stream hosted on the LAN, and output the digital audio onto three pins to create the I2S bus.

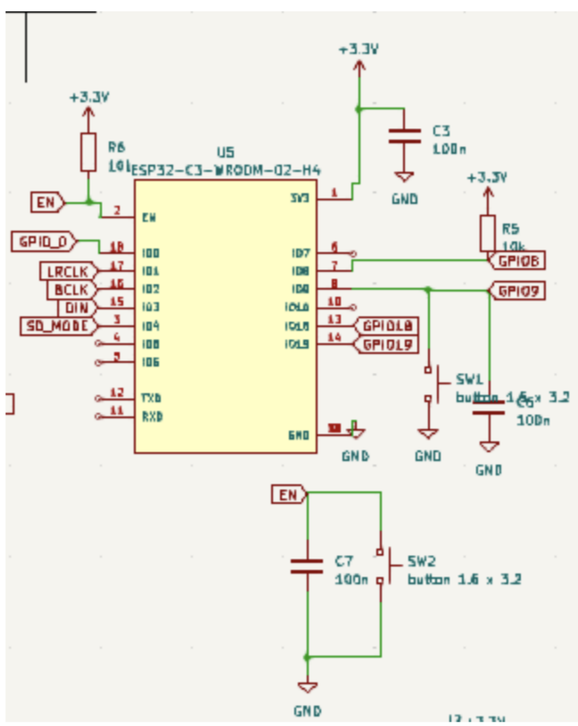

Fig. 3. Signal Subsystem Schematic

3) *Transducer Subcircuit:*

Displayed in Figure 4 is the circuit schematic for transducer subsystem, which is an implementation of the MAX98+ on the PCB. Two of the pins, BCLK and LRCLK are both clock signals that are derived from the ESP from the signal system which means their is no need for an external clock. The DIN pin simply feeds the Digital Signal received from the ESP32 and the SD MODE is used for turning the DAC on or off while the VDD and GND lines in the schematic is just powering the device itself. As shown in Figure 4 there are also only two output pins as to complete the circuit with the external bone conduction transducer attached to the PCB.

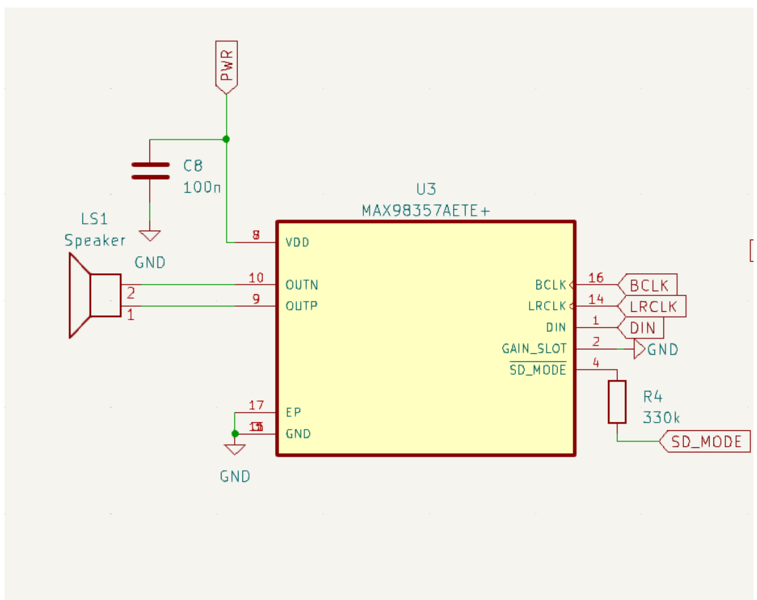

Fig. 4. Transducer Subsystem Schematic

III. Verification

1) Charging Verification:

For our charging subcircuit, we got one of the two requirements along with the listed verification as shown in Fig 8 APPENDIX II. However, we added an extra test during the testing phase of our project, which should further serve as evidence of a functional subsystem. For the first verification, we first dissipated the charge on our battery by attaching a large resistor across its terminals. We also monitored the discharge by monitoring the voltage reading across the battery. In this test, we discharged our battery to 2 volts, then attached the battery to the PCB and plugged in the USB. If the charging circuit was working, then current should be flowing from the MCP charging IC to the battery, and the voltage should increase. Upon carrying out this test, we indeed did see a quite rapid increase in voltage across the battery, increasing to 4 Volts, higher than the rated voltage of the battery, in about 2 minutes. In the future, we should take care to choose a charging IC with a rated voltage equivalent to the voltage of our battery. The second test carried out in the charging subcircuit was an additional test added after the design document, a test meant to check the functionality of the state machine of the charging circuit. By attaching a simulated load to the PCB on the battery terminals when the USB is plugged in, we should be able to observe a relationship between the simulated load and the current output to the battery terminals. This relationship is displayed in the graph Figure 5. As for the requirement of alerting the user that the device is in a low battery state, we were not able to get a full implementation by the time of the presentation. We recognize that this functionality is important for an effective product. Future work on this project will definitely add this functionality.

2) Signal Verification:

For our signal subsystem, we enumerated three tests a shown in Fig 9 APPENDIX III, one testing secure data communications, and two testing the intelligibility of the output of the I2S bus. Our first test details secure communication between the server on the LAN and the microcontroller. By adding a private key for authentication by the http server, we were able to make sure that only the ESP32 could connect to the local server, and any user with malicious intent could not sabotage the communication channel between the microcontroller and the

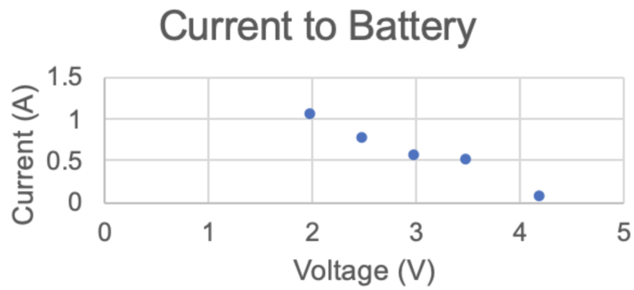

Fig. 5. Graph of Current vs Voltage delivered to the battery

server. Our second test involved a reading of the output from the DAC with an ADC. Originally, the idea was to reroute the analog output to the ADC of the ESP32. However, this did not work sufficiently as the sampling frequency of the esp32 was not high enough to resample the analog signal. Initially, the ADC(analog digital converter) was low resolution, at only 12 bits. To deal with this, we used a raspberry pi with an ADC hat with 32 bit resolution and 38 kHz sampling rate. According to Nyquist, the maximum bandwidth of our signal would then be 19 kHz, more than enough for intelligibility of speech. The STFT of the resampled audio is shown below, where the y axis represents evenly spaced frequency buckets from 0 to 20000 kHz, and the x axis is number of samples. As one can see, there is a significant amount of noise introduced in the transmission channel from the microcontroller to the transducer, but audio is still intelligible at frequencies of interest for speech.

3) Transducer Verification:

Our final test builds off of the last one, and is a simple listening test for the output of the transducer. If the transducer is able to induce vibration causing an audible, intelligible signal to be perceived, then we know that the transmission channel correctly outputs audio. When inducing the DAC with the output of the I2S bus, we were able to perceive an intelligible signal of the original input, meaning that the signal unit works as intended which was also demonstrated during the demo as well as a video on the presentation.

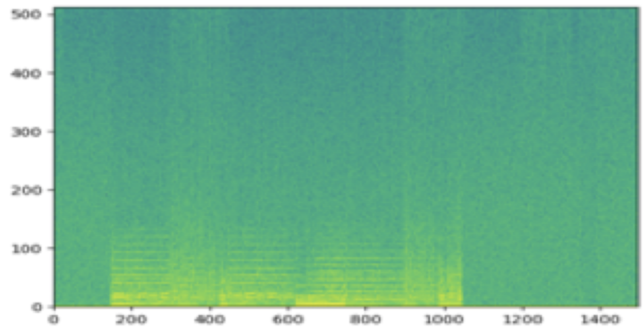

Fig. 6. STFT of sampled AUDIO signal sent to ESP32

IV. Cost and Schedule

A. Electrical Components

Item No	Quantity	Manufacturer	Part No	Distributor	Distrib Part No	Description	Cost
1	1	Espressif	ESP32-WROOM-32E-N16	Digikey	3647-Ai-ThinkerESP-01SESP8266-ND	Wifi Transceiver	$3.60
2	1	HiLetGo	3-01-0103-B	Digikey	MCP73831T-5ACI/OTDKR-ND	USB to Uart	$7.30
3	1	Adafruit Industrial LLC.	MAX98357	Digikey	1528-1696-ND	I2S to Audio Amplifier	$5.95
4	1	GCT	USB4125-GF-A-0190	Digikey	2073-USB4125-GF-A-0190CT-ND	USB-C Connector	$0.67
5	1	Microchip Technology	MCP73831T-2DCI/OT	Digikey	MCP73831T-2DCI/OTCT-ND	PMIC for battery	$1.19
6	1	Diodes Incorporated	AP2120N-3.3TRG1	Digikey	AP2120N-3.3TRG1DITR-ND	IC Linear Regulator	$0.39
7	1	Generic	1674	Adafruit		Bone Conduction Speaker	$9.74
8	1	Cornell Dubilier	RJD2048ST1	Digikey	1572-1629-ND	LiPo Battery	13.22
						Total	$42.06

B. Other Materials

For the electrical components above we ordered multiple versions of many of the components for testing purposes, while the actual cost comes to 42.06 for the electrical components necessary we paid 76.75 for the number of the parts we ended up ordering.

Material	Quantity	Manufacturer	Cost
Tooth Mold	1	East Bay Dental	$0.00
Plaster of Paris, 4lbs	1	Home Depot	$10.78
Acrylic(PMMA), 1 gal	1	Home Depot	$70.81
PCB	3	PCBway	~$55.00
		Total	~$136.59

V. Safety and Ethics

As any interface which directly interacts with the human body, safety is of paramount importance. This requirement is compounded by the fact that electrical and battery components are being placed in the mouth for this particular project. As such, to address these concerns, we will insulate the pcb and the associated components with great care, and run the system at low power values. To help determine the ideal materials and methodology to insulate such components we have been in contact with a professional dentist, Dr. Shilpa Khatavkar who works for East Bay Dental. Poly(methyl methacrylate) (PMMA), also known as acrylic resin, has many favorable properties in such an application. First off, using equipment provided by the dental office, we are able to create plaster molds of an individual's upper palette, teeth and jaw. Using such a mold in combination with acrylic, it is possible for the aforementioned material to be poured directly into the mold and over the circuit components to assure a personalized fit to an individual that will not prove to be an impediment. This material is ideal for electrically insulating the components of our PCB as well, as it has an extremely low electrical conductivity. In regards to its inert nature, the material has had numerous studies that have demonstrated its safety in the oral cavity. Acrylic resin has the property of maintaining its hardness even in the presence of materials commonly found in foods. In one such study, published in the National Library of Medicine, the material was tested thoroughly through continuous immersion over a 30 day period in substances such as weak acids, ethyl alcohol, and water. The results indicated that, over various commonly used brands of acrylic resin, there was at most a 20 percent change in hardness.9 While this may, at face value, seem significant it is an unrealistic situation for the material to be placed in, as, commonly coffee is not held in a stagnant position in the mouth for 30 days at a time. This is corroborated through studies as well. It is estimated, 30 days of immersion in coffee is equivalent to 2.5 years of continuous wear10. Due to the nature of the Bone Conduction Discrete Communicator needing to be removed from the mouth for charging for example, it is possible to make a theoretical estimate and assume the acrylic's lifespan in this specific application could be even longer. Despite this, the slow degradation of acrylic is something to be taken into consideration and an additional layer of insulation could be necessary. While we have found the ideal insulator material to encase our design in the mouth to prevent hazards, we still must address the ethical issues presented by placing electrical components in a systematic fashion. As such we have designed the project in accordance with the International Safety Organization 14971 safety standard. This standard defines the risk as "the probability of occurrence of harm, and the consequences of harm, that is, how severe it might be".2 To ensure that the circuit components do not short, we will also follow ISO 14971, which details practices such as using specific connectors for each component (correct ports on the PCB), removing features that can be mistakenly selected, such as extraneous GPIO pins. To alert the user that the battery is near low battery, we have indicated low battery with an LED. This will ensure that the user does not wear the component while it is not capable of transmitting, or create unintended problems for the circuitry. We will also ensure that no piece of conductive material is exposed to the user by first creating a plastic housing for our components, and then melting a layer of acrylic over the housing. In conclusion we have found the best housing for the BCDC as well as minimize the risk to the user with compliance with a well known safety standard. While extensive testing is necessary in order to deploy this concept, this is a good starting point for further research.

VI. Conclusion

Bring together, concisely, the conclusions to be drawn. It may be appropriate, depending on the nature of the project, to begin or end with a two- or three-sentence executive summary. The reader needs to be convinced that the design will work. Summarize your accomplishments. If uncertainties remain, they should be pointed out, and alternatives, such as modifying performance specifications, should be spelled out to deal with foreseeable outcomes. Use words, not equations or diagrams. Devote a section to ethical considerations with reference to the IEEE Code of Ethics and any other applicable code (e.g., the AMA Code of Medical Ethics for certain bioengineering projects). Either here or in the background discussion of your introduction, provide a paragraph addressing the broader impacts of your project in terms of global, economic, environmental and/or societal contexts.

In conclusion our project combines the WiFi capabilities of the ESP32, a bone conduction transducer, and incredibly efficient PCB design to create a microchip with the potential to serve as one of the most discrete communication devices created. We were able to place the entire thing in a footprint with an area of $400mm^2$ which required us to solder quite difficult connections with incredible precision. Along with this we set up an entire front end for communication with the device, and if given a server hosted site it is possible to communicate with the device from far greater ranges given an intermediary such as a phone. This design however has far more potential. Given the opportunity to machine solder the chip it is possible to reduce the footprint by many magnitudes, dissolving any doubts one may have of the feasibility of comfortable placement within the oral cavity. Furthermore, with the usage of extensive testing and calibration of the software on the esp32 it is possible to extend the estimated battery life by great lengths by simply toggling on and off the bone conduction transducer itself. The potential is endless and the current design serves as an exciting proof of concept for further testing and manufacturing.

With the aid of machine soldering the footprint has the potential to shrink far more and the tests show the effectiveness of bone conduction should not be put into question.

VII. Citations

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VIII. Appendix

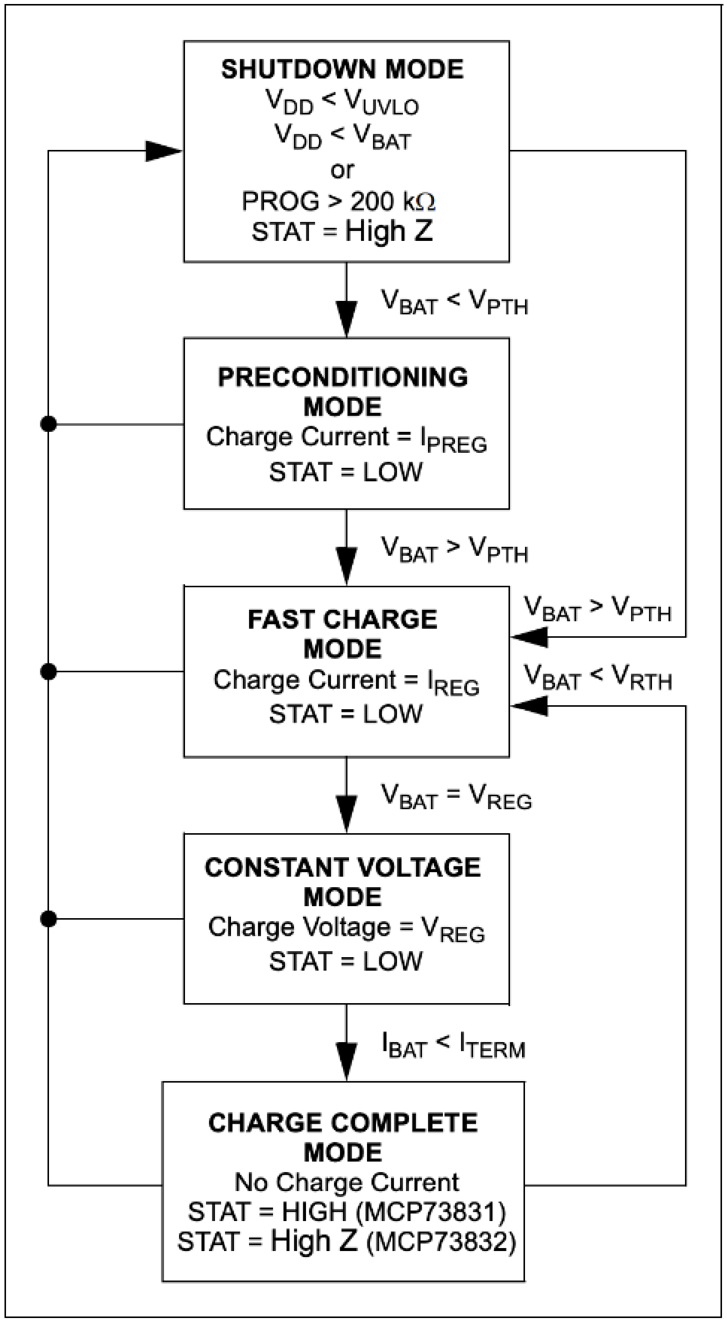

Fig. 7. Appendix I

Requirements	Verification
The MCP73831 can charge the battery	• We will test this by using a voltmeter to measure the voltage on the battery. If the component is working properly the dead/low battery will have a lower reading on the voltmeter vs when it is fully charged.
Flashing LED when low battery	• We will use the STAT pin to create a threshold voltage to send a signal to an LED to indicate low battery. We will test this by measuring the voltage across the battery and then checking if the LED flashes after a set voltage.

Fig. 8. Appendix II

Requirements	Verification
The ESP01 must be able to receive data via HTTPS on a secure server.	• ESP will be assigned an IP Address upon connection to University network. In order to communicate, the sender must be authenticated so that a malicious user will not be able to hack into data stream. • Acting as a malicious user, we will try to send data through this channel without verification. Successful implementation of this requirement will entail not being able to send or receive data on this channel.
The ATTiny must output intelligible audio at a minimum frequency of 4Khz.	• After audio is output from the AT Tiny, in testing it will be received by the GPIO pins of a raspberry pi, where it will be analyzed using a Short Time Fourier Transform. If speech is intelligible at 4Khz, the Spectrogram will output non-noise energy at 4Khz.
The ATTiny must output analog signals for use by the Bone Conduction Subsystem.	• We will initially verify by connecting a small piezo speaker to the GPIO output of the ATTiny. Intelligibility of the output audio will indicate completion of this requirement.

Fig. 9. Appendix III