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

A. Problem and Solution

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. Bone Conduction is a commonly used technology to assist in hearing for those that experience hearing loss, working by directly vibrating one's skull to pressurize the cochlear fluids in the cochlea (organ in charge of hearing)[2]. Bone Conduction hearing aids come in a few main categories, surgically implanted to directly vibrate the skull, percutaneous implants, which lie directly beneath the skin and use the skin as a medium to transmit waves to the skull [3]. In this document, we will explore an alternative treatment, an in mouth wearable in which surgical implantation is not required.

Another use case of our proposed device are applications requiring discreet communication. An in mouth wearable is a good solution, as communication will not be apparent to an outside observer. In modern espionage settings, the ability to receive and transmit information while retaining secrecy is desirable. Classic methods, such as “wearing a wire”, or tiny in-ear headphones are popular, however, there is still the risk of being exposed by a suspicious onlooker. The ability to retain discretion while in a high stakes situation can prevent the user from being discovered by a belligerent force, thus saving the user from dire consequences.

To aid in applications of espionage and hearing aid technology, we propose a Wearable Bone Conduction Microphone affixed to the molars of the bottom teeth. Previous attempts at a wearable bone conduction speaker have proven that the molar provides sufficient access to the

[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

[2]Ellsperman, Susan E., et al. “Review of Bone Conduction Hearing Devices.” Audiology Research, vol. 11, no. 2, 2021, pp. 207–219., "https://doi.org/10.3390/audiolres11020019."

[3]Ellsperman

jawbone, making it a suitable location for bone conduction. In our implementation, we will aim to use either NFMI, Bluetooth, or AM signals to transmit to a receiver on a pcb inside an insulated case. On this pcb will also be a microcontroller for controlling the receiver and routing audio to an audio amplifier. This audio amplifier will then be routed to a bone conduction transducer. These components will be sufficiently tiny so as to not be an impediment to the wearer.

B. *Visual Aid*

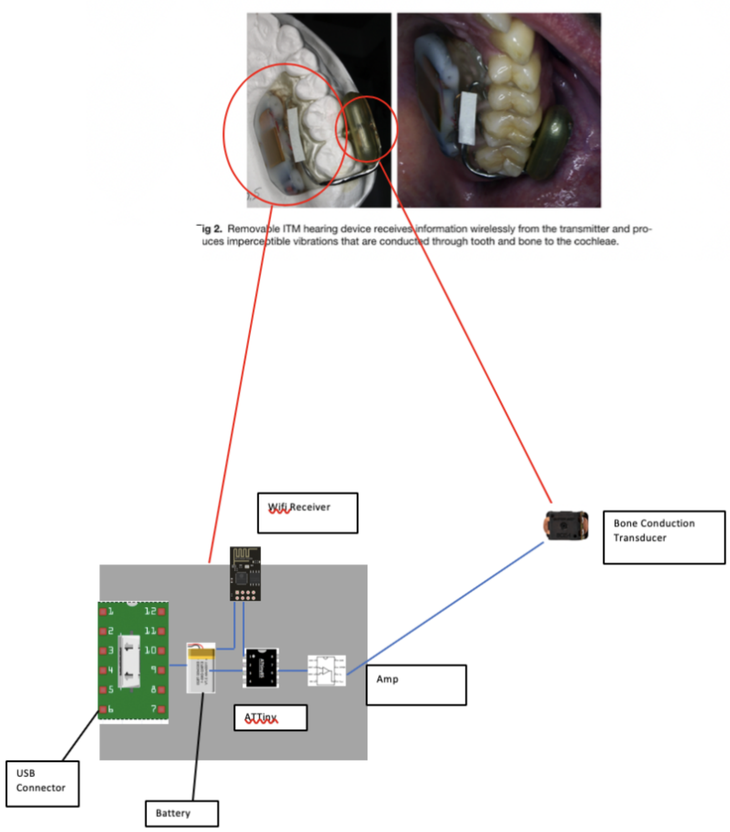

Fig. 1. The visual aid is based on a previous attempt at in ear bone conduction where most of the electronics are housed on the palette of the mouth, and the bone conduction transducer is placed on the cheek side of the back two molars. The electronics on the palette side are first housed in a plastic encasing and then coated with acrylic to create a tight fit with the palette of the wearer. It is kept in contact with the transducer and in place in the palette by orthodontist grade titanium wire to the transducer on the cheek side.

C. *High Level Requirements*

1) The pcb, fitted with all components, must fit in a 20 mm^2 area.
   - According to Dr. Shilpa Khatavar, if the wearable is too large in the palette it might evoke a gag reaction in the wearer. Therefore, to minimize risks of harm to the user, we will aim to make the pcb a 20 x 20 mm board.
2) Upon fitting the speaker in the mouth, normal speech must be intelligible.
   - The user must be able to understand the output speech from the speaker. Speech transmitted through the bone conduction must be minimally intelligible at 2 khz.
3) While talking, the speaker should not be visible to an onlooker without close inspection.
   - Speech transmitted through the bone conduction must be minimally intelligible at 2 khz.
4) All circuit elements must be heavily insulated, so as to not create a risk for the wearer.
   - Extreme care must be taken in design to ensure that multiple layers of insulation are kept between the circuitry and the wearer.
5) While talking, the speaker should not be visible to an onlooker without close inspection.
   - All the components should be fit into the mouth without providing any visual cues to an onlooker.

II. Design

A. Block Diagram

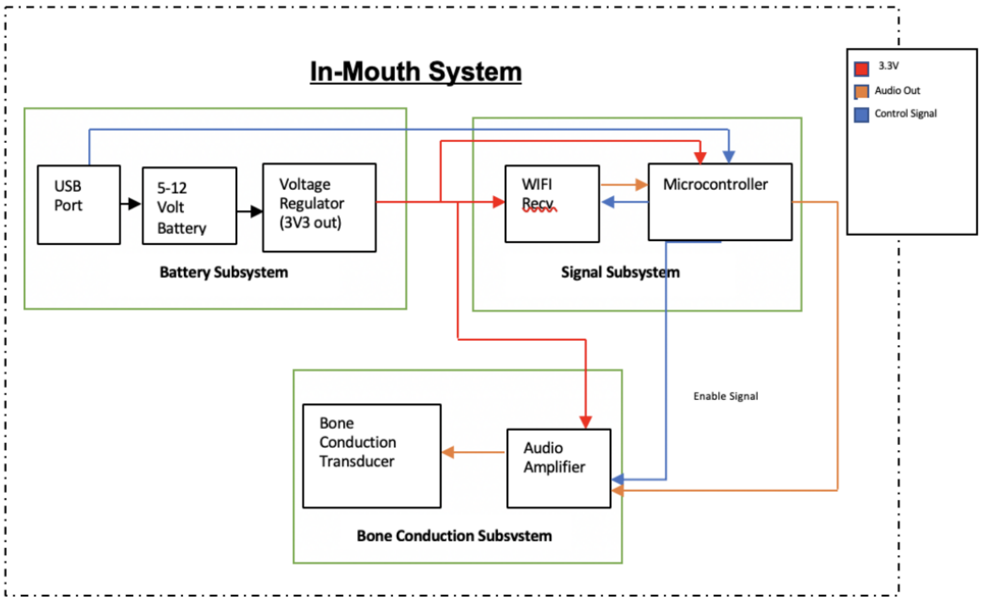

Fig. 2. Three main subsystems are enumerated in the block diagram, the Battery Subsystem, the Signal Subsystem, and the Bone Conduction Subsystem. The Battery subsystem will support rechargeable battery and will provide VCC to the rest of the circuit. The Signal Subsystem will receive signal via http and output it through the ATTiny. The Bone Conduction Subsystem will amplify the received signal and stimulate the user's jawbone.

B. Subsystem Overviews

1) Battery Subsystem:

This subsystem is responsible for proving the input voltage to the ICs as well as the microcontrollers that we are using in our project. As we have a size constraint for our project (roughly 20 square millimeters), the battery must not take up too much space on our PCB. Our battery will then be a Lithium Ion coin battery which will not be more than 6mm in diameter. The voltage output for batteries like this are not usually more than 3V, thus our ICs for the entire circuit will also not have an operating voltage higher than 3V. This battery will be connected to a voltage regulator to ensure stable voltage output from the battery unit. Additionally, the battery will be rechargeable through a covered USB C port connected to a linear regulator. As shown in the Figure 6 the circuit diagram of the USB4125-GF-A-0190 the USB-C port we will use two pins, the V_BUS and the GND to recharge the battery. We connect this to the MCP73831. This device is a highly advanced linear charge management controller for use in space limited, cost-sensitive applications. Along with their small physical size, the low number of external components required make the MCP73831 ideally suited for portable applications. For applications charging from a USB port, the MCP73831 adheres to all the specifications governing the USB power bus. The MCP73831 employs a constant-current/constant-voltage charge algorithm with selectable preconditioning and charge termination to accommodate battery charging requirements. The constant current value is set with one external resistor. The MCP73831 devices limit the charge current based on die temperature during high power or high ambient conditions. This thermal regulation optimizes the charge cycle time while maintaining device reliability. This will make sure our pcb never heats up to temperatures capable of melting the acrylic.

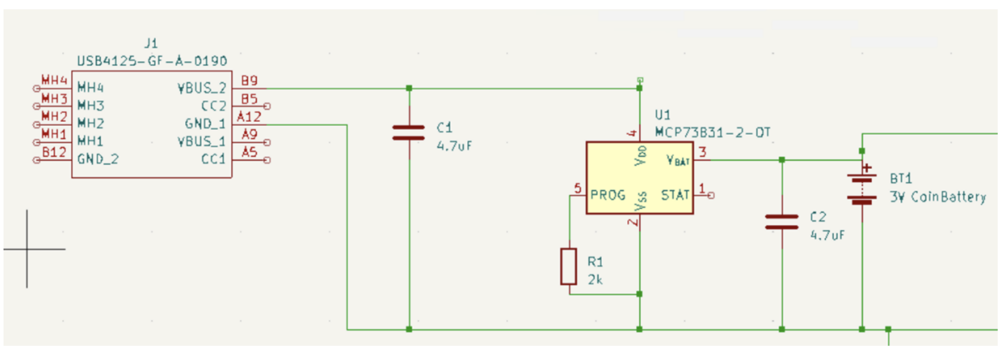

Fig. 3. Battery Subsystem Schematic

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.

2) *Signal Subsystem:*

This subsystem will be responsible for receiving a signal from a WIFI receiver, relaying it to a microcontroller, and outputting the audio to the bone conduction subsystem. The Wifi receiver that we are using is the ESP01, which will be pre programmed by connecting to an Arduino Uno. The transmitter and receiver will connect through HTTPS with SSL to ensure that communication cannot be interfered with by a malicious third party. It is given a supply voltage of 3.7V from the battery subsystem. The received signal is then relayed to the microcontroller, the ATTINY85. The ATiny then sends the audio out through a GPIO after being modulated from a PWM signal that is also produced from the AT Tiny. The output from the inbuilt DAC is then sent out through the GPIO to the Bone Conduction Subsystem.

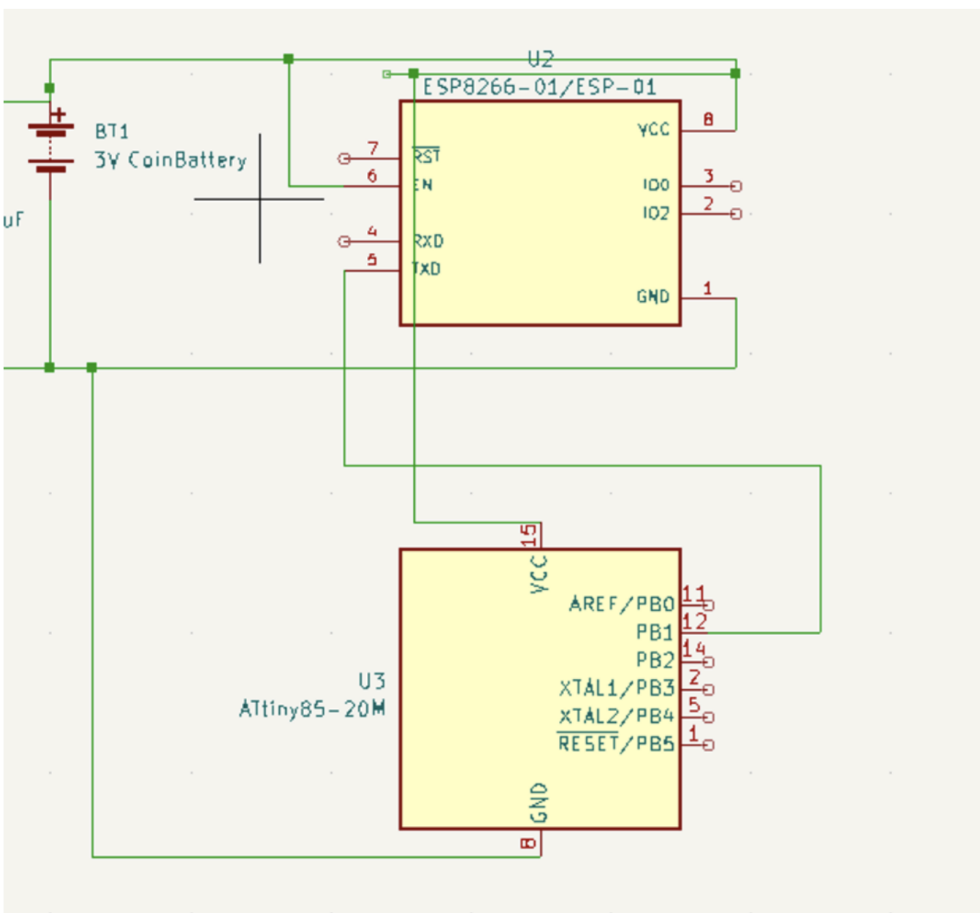

Fig. 4. Signal Subsystem Schematic

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. 5. Signal Requirements and Verification

3) Bone Conduction Subsystem:

This subsystem converts a digital signal output from the microcontroller into vibrations of the magnetic coil of the bone conduction transducer. The purpose of the audio amplifier is to amplify the signal to the required power input of the bone conduction transducer, 1 Watt. The Bone Conduction transducer is exposed to the back two molars of the upper set of teeth, where it is heard through the cochlea via the jawbone. This specific circuit displays the amplifier which takes the analog 8 bit signal output by the ATtiny85 and amplifies it, the first capacitor is to decouple the dc signal from the analog signal. The first two resistors, reading from left to right, shift the up, essentially the signals voltage is increased to a range at which the gate for the transistor can create a valid output signal. The transistor and the resistors connected to its source and drain determine the amount of gain for the signal, these values are dependent therefore on the output of the ATtiny as well as R1 and R3. The C1 capacitor serves to denoise the signal and the C2 capacitor serves as a second denoising capacitor. The goal then, taking the 8 ohm transducer and supplying it with the requisite current to make sure the total power consumed is 1 watt.

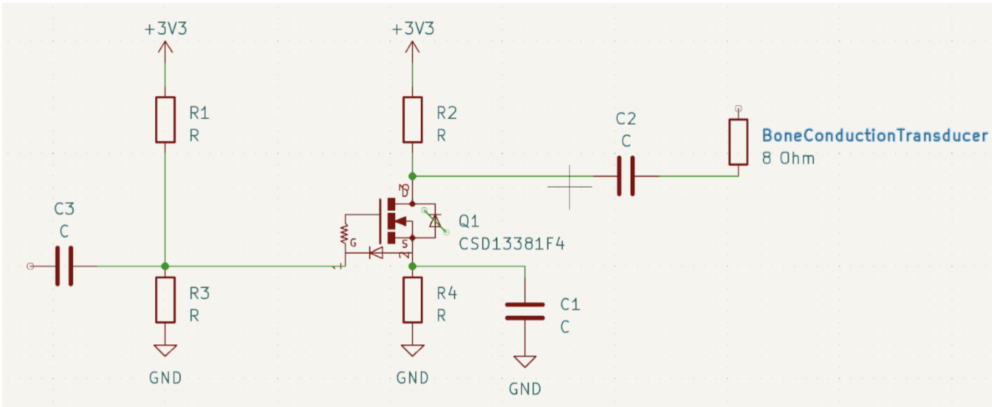

Fig. 6. Bone Conduction Subsystem Schematic

Requirements	Verification
There must be 1 watt power being supplied and consumed by the bone conduction transducer.	• Before casing the system in acrylic we can check the voltage and power across the transducer to make sure it is functional.
The amplifier must produce a signal identical to the original DC output.	• Plot the input signal on an oscilloscope and the output signal on an oscilloscope and test the amount of noise introduced and other such inaccuracies.

Fig. 7. Signal Requirements and Verification

C. Tolerance Analysis

The average oral temperature of humans is 98.6° F(37° C). According to doctors any temperature value over 110° F(43° C) can cause superficial burns to the inner lining of the cheeks. Anything over 160° F(71° C) will cause severe burns to the mouth and can cause long term damage. In our block diagram, the component that will dissipate the most heat will be the voltage regulator. We plan on using one 5V battery and using a voltage regulator to regulate the voltage to 3.3V. To determine the heat dissipated by the regulator we have to find the difference between the source and the regulated voltage and then multiply that by the total amount of power dissipated by the entire PCB. Going part by part to calculate the total power dissipated by the circuit, first we have the AM receiver which has a power dissipation of 25 mw. Next is the ATiny85 which has an approximate power dissipation of 10 mw. After which comes the Amplifier which has a power dissipation for a 4 ohm speaker (in our case 4 ohm transducer) of 400 mw. Finally the transducer has a power dissipation, if run at 3.3 volts of 2.7 Watts. As of right now the expected power required for the circuit will be approximately 3W. The voltage drop across the voltage regulator is 3 volts. Since the circuit is powered at 3.3 volts, this means the power dissipated by the voltage regulator is slightly less than 1 Watt. Reading the datasheet for the voltage regulator, it has a thermal resistivity of 115 Celsius per watt. Thus the temperature of the voltage regulator would be approximately 100 Celsius which would cause severe burns within the mouth of the wearer. To address this issue extensive testing must be done to find the optimal power required by the transducer for comprehension by the user and lowering the voltage supplied to the transducer to match this value.

Fig. 8. Acrylic Cross Section

$$Q = k * A(T_{mouth} - T_{pcb})/W_{Acrylic} \tag{1}$$

$$q = mc\Delta T \tag{2}$$

In addition to the analysis of energy loss, it is very important to maintain a stable environment with respect to heat in the oral cavity. This is a sensitive area of the human body and with electronic components come the possibility of burns. Thus, since we plan on insulting our electronic components with PMMA, or dental acrylic it is paramount to note the thermal properties of the material with respect to the conditions that will be placed upon this material.

PMMA has a thermal conductivity of 0.167 W/(m*k) and has a specific heat of 1466 J/kg/K. 11 Using these two values, let's assume the PCB components have overheated to 80 degrees celsius, a temperature which is at the edge of the operating range for a majority of the components. The acrylic is at the average temperature of the mouth at 37 degrees Celsius. Given the PCB has an area of 25 mm and the acrylic has a thickness of 5 mm, we can use formulas relating heat transfer through a specific material. In Eq. 1, where Q is in units of joules/seconds and k is the thermal conductivity. Doing this we can calculate Q to be 35.9 Joules/seconds. Now relating this heat transfer through the acrylic to its own changing temperature the formula in Eq. 2 where q is Joules, m is the mass of the object and c is the specific heat. Using the assumed sizing of the acrylic, given its density is 1180 g/mm3, we can calculate its volume, since already having known the specific heat we get the result dT/dt being 0.000167 C/s. This is obviously a very slow rate of temperature change, over the course of an hour the temperature of the acrylic will have changed 0.6 degrees Celsius. This means that despite our initial concerns, given the chemical properties of PMMA, heat will not be a danger to the user of the BCDC.

III. Cost and Schedule

Electrical Components

Item No	Quantity	Manufacturer	Part No	Distributor	Distrib Part No	Description	Cost
1	1	Ai_thinker	Ai-Thinker ESP-01S ESP8266	Digikey	3647-Ai-ThinkerESP-01SESP8266-ND	Wifi Receiver	$3.30
2	1	Microchip Technology	MCP73831T-5ACI/OT	Digikey	MCP73831T-5ACI/OTDKR-ND	USB to Lipo battery	$0.76
3	1	Texas Instruments	CSD13381F4	Digikey		Mosfet for Amplifier	$0.44
4	1	Microchip Technology	ATTINY85-20PU	Digikey	ATTINY85-20PU-ND	Microcontroller	$1.77
5	1	GCT	USB4125-GF-A	Digikey	2073-USB4125-GF-ADKR-ND	USB C adapter	$0.67
6	1	Cornell Dublier	RJD2048ST1	Digikey	1572-1629-ND	LiPo Battery	$13.22
7	1	Generic	1674	Adafruit		Bone Conduction Speaker	$9.74
						Total	$29.90

Fig. 9. Acrylic Cross Section

Material Costs

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
Injection Molding	2	Form Labs	~$100.00
		Total	~$182.00

Fig. 10. Acrylic Cross Section

Total Cost, based on Labor Cost + Material Cost + Electrical Components is roughly $14,600. However, ignoring the Labor Cost, we should be able to build this device for about $200.

Labor Cost

Group Member	Hours Per Week	Hourly Pay	Salary Per Week
Arya N.	15	$20	$300
Yash K.	15	$20	$300
Raahim A.	15	$20	$300
			$14,400

Cost Estimate Based on 16 weeks per semester

Fig. 11. Acrylic Cross Section

IV. Discussion of Ethics and Safety

This project will be designed in compliance with safety standards as defined by International Safety Organization 14971 (ISO 14971), which is a document discussing methods of risk management in wearable medical devices. [4] The document defines generally the concept of risk as "the probability of occurrence of harm, and the consequences of harm, that is, how severe it might be". [5] Based on this definition, we identify sources of risk in our project:

1) Current short for any reason, i.e. overheated circuit components, loose wire connections, etc.
2) Circuit overheating leading to melting of acrylic material.
3) Insecure communication to ESP01 unit.

We will discuss how to mitigate these risks in order. 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 will modulate the output signal with a series of beeping to indicate that the device is nearing low battery. 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

[4] Benedict, Amanda. "ISO 14971:2019." ISO, 10 Dec. 2019 , https://www.iso.org/standard/72704.html.

[5] Benedict

plastic housing for our components, and then melting a layer of acrylic over the housing. More details regarding acrylic materials will be discussed later in the document.
Circuit overheating discussed in tolerance analysis.
In order to ensure that communication between the transmitter and receiver is not compromised, a secure socket for communication will be established between these components. This will be accomplished with a standard SSL certificate to ensure that communication will not be compromised by a malicious third party. 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 addition to insulting electrical components, the material has to also be heat resistant and unreactive when coming into contact with the various chemicals that exist in the mouth such as saliva, food particles, weak acids, ethyl alcohol etc. Therefore, on the recommendation of the office, we have decided on a material commonly used in dental practices in applications such as dentures, the material being acrylic resin. 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% change in

hardness.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. Next we must consider the thermal capacity of acrylic resin. In addition, we are in contact with a dentist, Dr. Shilpa Khatavkar, to address concerns regarding, materials which can safely be placed within the mouth, materials which can interface with teeth, and ideas to aid the insulations of requisite electrical components.

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