CubiCom: Noisy Office Environment Communication Device

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Abstract

The CubiCom is a system that enables secure and clear communication between users in a noisy office space. It can function in any small cubicle within a 12 foot radius. The system consists of a series of wireless headsets for 6 users to transmit and receive audio, and a communication box that facilitates this process. These headsets are noise-dampening, preventing ambient sounds from interrupting conversation and making sure that all parties can hear each other clearly. Line-of-sight (L.O.S.) with each headset is required to have proper communication between users. This feature ensures no one outside of the room can eavesdrop, which establishes privacy. The headsets also require pairing to the communications box to transmit audio to other users, which adds another layer of security. The CubiCom also has features that prioritize ease-of-use. Each headset incorporates both accessible and adjustable volume controls for the microphone and headphones. Additionally, the installation process features minimal connections to make setup quick and convenient.
Chapter 1: Introduction

In a noisy office environment, it can be difficult to engage privately in conversations. Particularly in open office environments with cubicles, many different conversations occur simultaneously. The Department of Veteran Affairs (the VA) is looking for a device which would allow multiple users to communicate in such an environment. This device would provide high quality face-to-face communication between multiple people in a noisy office environment with emphasis on security. Some products currently exist for aiding in better face-to-face communication, most notably the EarTec Hub [1] as shown in Fig. 1.1. The Hub operates on the digital enhanced cordless telecommunications (DECT) band, specifically from 1920 to 1930 MHz, and it can allow full-duplex communication among up to 8 devices. However, due to its high range, it does not provide the security that the VA is seeking, nor does it fit the cost constraints the VA described.

Fig. 1.1: EarTec Hub Full-Duplex Communication System [1]

Another product with similar function is Sensear's two-way radio communication headsets[2]. These headsets require a radio connection to operate, and provide good noise cancellation and face-to-face communication between two people in a noisy office space. However, as with the EarTec Hub, Sensear's device does not provide a medium for secure communication, as it only operates on radio frequencies. Additionally, it only has a two person capacity, while the VA has expressed a need for six inputs.

The concept of the CubiCom is to use Bluetooth and Infrared (IR) technology to provide more secure conversations in a noisy and open office space. Bluetooth pairing provides security on the transmit side through frequency hopping spread spectrum, so that no outside sources can detect the carrier frequency used to transmit data [3]. On the other end, an IR transmitter broadcasts a signal for all users to pick up on their headphones. Because IR frequencies are unregulated and provide a very large bandwidth, it is unlikely interference from other infrared signals will occur. In addition, since IR communication
depends on line of sight (L.O.S.), it would be difficult for anyone outside the cubicle to tap into the channel [4]. Adequate integration of Bluetooth and IR technology will provide a high level of security and audio quality.

This idea of integrating Bluetooth (BT) and Infrared (IR) technologies to provide secure face-to-face communication in an open office environment originated from a previous senior project team. Their product, the CubiConvo, could communicate with two headsets [5]. This design can be seen in Fig. 1.2 below. Using a microphone with a Bluetooth transmitter, each user transmits modulated audio over the air. A 3D-printed central box interfacing Bluetooth receivers, one paired to each user’s transmitter, receives and demodulates the transmitted signal to convert it back to the desired audio signal. The central communications box contains summing circuitry to add the mono audio signals of each user together [6]. This summed signal is modulated again and broadcast over the Infrared band using an IR transmitter which is also mounted on the communications box (shown separately in Fig. 1.2 for a clear visual). The IR receiver on each user’s headset receives and demodulates the broadcast signal, allowing each user to hear every other user linked to the CubiConvo.

![CubiConvo Design](image)

**Fig. 1.2: CubiConvo Design [5]**

With our product, the Cubicom, we will extend the functionality to support six headsets. We will also seek to improve significantly upon the quality of the audio received. Standards exist for defining a good quality microphone, a necessity when ensuring good sound quality[7], [8], [9]. We also will be using a printed circuit board (PCB), to improve audio quality and use space efficiently inside the 3D-printed case which will contain the combiner circuit [10]. Additionally, we aim to improve upon the user interface, both in ease of setup, and ease of use [11].
### Table 2.1: Customer Requirements and Engineering Specifications

<table>
<thead>
<tr>
<th>Customer Requirements</th>
<th>Engineering Specification</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1. 4-5kHz cutoff frequency</td>
<td>Intelligible speech requires a broad enough spectrum to encompass all vocal sounds [9].</td>
</tr>
<tr>
<td>A</td>
<td>2. The SNR of the microphone should be at least 40 dB to ensure good quality sound.</td>
<td>The SNR must be high enough to ensure sufficient sound pressure above the noise floor. SNR should be high enough to extend from the noise floor (dependent on mic) to 1 Pascal (94 dB$_{SPL}$) [8].</td>
</tr>
<tr>
<td>C</td>
<td>4. IR system bandwidth must accommodate 2-6 lines.</td>
<td>Sponsor specified that they want the system to accommodate up to 6 users. Certain products currently exist on the market that allow communication between multiple users [1], [2].</td>
</tr>
<tr>
<td>D, G</td>
<td>5. Battery life of at least 6 hours</td>
<td>As specified by the sponsor, conversations are generally about an hour. Headsets should have</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>E</td>
<td>6. Connection distance from outside room, target: 0 ft, max: 15ft. Test by setting up device inside a small variety of rooms and measure how far from the threshold of the room the headset can still connect.</td>
<td>The sponsor specified that the types of conversations that would be carried out using the CubiCom would involve sensitive details that need to be kept private. This metric ensures that anyone outside the room and thus the conversation cannot eavesdrop using any receivers.</td>
</tr>
<tr>
<td>G</td>
<td>7. 12 V AC adapter used for powering all components on central communications box.</td>
<td>The communications box must be powered from a single AC wall plug adapter.</td>
</tr>
<tr>
<td>G</td>
<td>8. Single Supply Op Amp capable of operating from 0 to 12 V.</td>
<td>The Op Amp must be able to operate on a single supply due to 12 V power source [6]</td>
</tr>
<tr>
<td>F</td>
<td>9. CubiCom box containing summing and interface circuitry should be manufactured to dimensions 6” x 3” x 2”.</td>
<td>Previous design was 4”x 3” x 2” [5]. The new design should be large enough to allow for more Bluetooth receivers.</td>
</tr>
<tr>
<td>F</td>
<td>10. CubiCom box should weigh no more than 15 oz.</td>
<td>Previous design was roughly 5 oz. Due to the increased size of the combiner box, 15 oz is allowed for.</td>
</tr>
</tbody>
</table>

**List of Customer Requirements:**

A: Clear sound quality
B: Wireless operation
C: Multi-line communication (2-6 people)
D: Sufficiently Long Battery Life
E: Secure communication medium
F: Size & Weight
G: Convenient Power Supply

<table>
<thead>
<tr>
<th>Spec. #</th>
<th>Parameter</th>
<th>Target (units)</th>
<th>Tolerance *</th>
<th>Risk (H, M, L)</th>
<th>Compliance (A, T, S, I)</th>
<th>Test Equipment Needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Passband Filter Cutoff Frequency</td>
<td>5 kHz</td>
<td>Min</td>
<td>L</td>
<td>A, T, S</td>
<td>Single Tone Test over audible range</td>
</tr>
<tr>
<td>2</td>
<td>Noise filtering for mic (SNR)</td>
<td>40dB</td>
<td>Min</td>
<td>L</td>
<td>A, T</td>
<td>Single Tone Test over audible range</td>
</tr>
<tr>
<td>3</td>
<td>Wireless Range</td>
<td>20 Ft</td>
<td>±50%</td>
<td>H</td>
<td>A, T, I</td>
<td>~ Determined by Product</td>
</tr>
<tr>
<td>4</td>
<td>Simultaneous Users</td>
<td>6 Users</td>
<td>4-6</td>
<td>H</td>
<td>T</td>
<td>Oscilloscope, Power Supply</td>
</tr>
<tr>
<td>5</td>
<td>Battery life</td>
<td>6 Hr</td>
<td>Min</td>
<td>M</td>
<td>A, T</td>
<td>Multimeter</td>
</tr>
<tr>
<td>6</td>
<td>Signal Breach Distance</td>
<td>0 Ft</td>
<td>0-6 Ft</td>
<td>H</td>
<td>A, T</td>
<td>Oscilloscope</td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td>Voltage</td>
<td>Accuracy</td>
<td>Units</td>
<td>Measurements</td>
<td>Equipment</td>
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<td>-------</td>
<td>--------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>7</td>
<td>DC Power Supply</td>
<td>12 V</td>
<td>±0.1 V</td>
<td>L</td>
<td>A</td>
<td>Multimeter</td>
</tr>
<tr>
<td>8</td>
<td>Op Amp Supply limit</td>
<td>12 V</td>
<td>±2 V</td>
<td>L</td>
<td>A</td>
<td>Multimeter</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Electronic Load</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Oscilloscope</td>
</tr>
<tr>
<td>9</td>
<td>Size</td>
<td>6”x3x2”</td>
<td>Max</td>
<td>L</td>
<td>I, A, S</td>
<td>Scale</td>
</tr>
<tr>
<td>10</td>
<td>Weight</td>
<td>15 oz</td>
<td>Max</td>
<td>L</td>
<td>I, A, S</td>
<td>Scale</td>
</tr>
</tbody>
</table>

*min, max, range (or %)
Chapter 3: Functional Decomposition

Fig. 3.1 below depicts a high level view of the CubiCom system. The various inputs and output to the system, and the signals within the system, are shown, and further elaborated upon in Table 3.1.

![CubiCom Level 0 Functional Decomposition](image)

**TABLE 3.1: Level 0 Function Inputs/Outputs**

<table>
<thead>
<tr>
<th>Functional Element</th>
<th>Input</th>
<th>Specs</th>
<th>Output</th>
<th>Specs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headset</td>
<td>Battery power</td>
<td>$V_{DC} = 3$ V</td>
<td>Headphone audio signal (output of IR transmitter)</td>
<td>BW: 100Hz - 4kHz</td>
</tr>
<tr>
<td></td>
<td>Microphone audio signal</td>
<td>BW: 20 Hz - 20 kHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Combiner audio IR signal</td>
<td>$f_c$: ~2 to 4 MHz*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication Box</td>
<td>AC Adapter Power</td>
<td>$V_{DC} = 12$ V</td>
<td>Combiner audio IR signal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transmitted BT Audio Signal</td>
<td>BW: ~1.5 MHz $f_c$: 2.4 GHz</td>
<td></td>
<td>$f_c$: ~2 to 4 MHz*</td>
</tr>
</tbody>
</table>

*Central frequency of IR signals depend on Channel used (4 different passband frequencies)*
Fig. 3.2 gives more insight into the various functions which make up the Headset and Communication box. Table 3.2 gives the specific details for system level I/O, as well as the I/O of the various function blocks that make up the system.

**TABLE 3.2: Level 1 Function Inputs/Outputs**

<table>
<thead>
<tr>
<th>Functional Element</th>
<th>Input</th>
<th>Specs</th>
<th>Output</th>
<th>Specs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bluetooth Transmitter</td>
<td>Microphone Audio Signal</td>
<td>BW: 100Hz-10kHz</td>
<td>Modulated BT Audio Signal</td>
<td>BW: ~1.5 MHz f₀: 2.4 GHz</td>
</tr>
<tr>
<td></td>
<td>Battery Power</td>
<td>3.7 V_{DC} 400 mAh</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bluetooth Receiver</td>
<td>12 V AC Adapter Regulated Power</td>
<td>12 V_{DC}</td>
<td>Demodulated BT Audio Signal</td>
<td>BW: 100Hz-10kHz</td>
</tr>
<tr>
<td></td>
<td>Modulated BT Audio Signal</td>
<td>BW: ~1.5 MHz f₀: 2.4 GHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Summing Circuit

<table>
<thead>
<tr>
<th>Component</th>
<th>Power Supply</th>
<th>Output Voltage</th>
<th>Output Signal Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Adapter Power</td>
<td>12 V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td></td>
<td>Summed Audio Signal BW:~100Hz-1kHz V&lt;sub&gt;p&lt;/sub&gt;:~50 mV-5 V</td>
</tr>
<tr>
<td>Demodulated BT Audio Signal</td>
<td></td>
<td>5 V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>5 V Regulated Power</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Voltage Regulator

<table>
<thead>
<tr>
<th>Component</th>
<th>Power Supply</th>
<th>Output Voltage</th>
<th>Output Signal Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Adapter Power</td>
<td>12 V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>5 V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td></td>
</tr>
<tr>
<td>5 V Regulated Power</td>
<td></td>
<td></td>
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</table>

## Infrared Transmitter

<table>
<thead>
<tr>
<th>Component</th>
<th>Power Supply</th>
<th>Output Voltage</th>
<th>Output Signal Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summed Audio Signal</td>
<td></td>
<td>12 V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>Modulated IR Audio Signal f&lt;sub&gt;o&lt;/sub&gt;:~2 to 4 MHz* V&lt;sub&gt;p&lt;/sub&gt;:~2 V</td>
</tr>
<tr>
<td>12 V AC Adapter Power</td>
<td></td>
<td>12 V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td></td>
</tr>
</tbody>
</table>

## Infrared Receiver

<table>
<thead>
<tr>
<th>Component</th>
<th>Power Supply</th>
<th>Output Voltage</th>
<th>Output Signal Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulated IR Audio Signal</td>
<td></td>
<td>5 V&lt;sub&gt;DC&lt;/sub&gt;</td>
<td>Demodulated IR Headphone audio signal (to user) BW: 100Hz - 1kHz V&lt;sub&gt;p&lt;/sub&gt;:~1 V</td>
</tr>
<tr>
<td>Battery Power</td>
<td></td>
<td>V&lt;sub&gt;DC&lt;/sub&gt; = 3 V</td>
<td></td>
</tr>
</tbody>
</table>

*Central frequency of IR signals depend on Channel used (4 different passband frequencies)*
Chapter 4: Cost Estimates

This Chapter discusses the various predicted costs of the project, the estimated time required, the material costs and wages. For material costs of the project, please see Table B.1 and Table B.2 in Appendix B.

Labor Cost:

According to Salary.com the median hourly wage for entry-level Electrical Engineers in California is $40 [12]. This project also assumes that each team member will work during the six hours of provided lab time every week. This project takes place over the course of three quarters which are ten weeks long each. This can be used to estimate a labor cost of $7,200 per person over the course of the project, since there are 3 people then the total labor cost would be $21,600.

In Chapter 5 Gantt Charts labor hours are calculated for each task. Using Program Evaluation Review Technique (PERT), an approximate effective time to completion for each task is found. Based on PERT analysis, it was determined that roughly 543 hours would be required for completion of the Cubi-Com. The total labor cost divided by the hourly rate yields the labor hours.

Table 4.1 shows the effective total duration when compared to the labor cost is virtually equal. All stakeholders know what they are paying for, the cost of each unit is clearly depicted and shows transparency in labor and cost. Optimistic value shows that Cubi-Com can be produced ~7.5% faster than the predicted 540 labor hours.

<table>
<thead>
<tr>
<th>Labors Hours</th>
<th>$t_o$ [Hours]</th>
<th>$t_m$ [Hours]</th>
<th>$t_p$ [Hours]</th>
<th>$t_e$ [Hours]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gantt Chart</td>
<td>500</td>
<td>540</td>
<td>600</td>
<td>543.33</td>
</tr>
<tr>
<td>Labor Cost [$]</td>
<td></td>
<td></td>
<td></td>
<td>$\approx$ 21,733.20</td>
</tr>
</tbody>
</table>

\[ t_e = \frac{t_o + 4t_m + t_p}{6} \]

where $t_o$ = most optimistic duration

where $t_m$ = most likely duration

where $t_p$ = most pessimistic duration
Chapter 5: Gantt Charts.

Each major task in the project has been broken down into subtasks and put on display in the Gantt Charts below, one for each 3 month period that the project takes place over. PERT (Program Evaluation and Review Technique) is commonly used to give the stakeholders a probable estimation for time of completion for each task. The Critical Path Method is also used to identify key tasks that can be done in parallel with other tasks and tasks that can cause delays in the overall project completion. For example, the architectural design 1 selection in Fig. 5.1 is dependent on a full functional decomposition, however, it does not rely on the completion of Monte Carlo analysis of a level 1 component that may be used in the CubiCom’s design.

The Gantt Chart progress for each task does not reflect the current progress for each task. Arbitrary values are used to convey the procedure and reflect the progress and dependency of certain tasks from the critical path method.

1. Fall Quarter 2022

Fig. 5.1 below shows a tentative Gantt Chart for the initial and planning phase of the EE460/463/464 Senior Project Sequence. This quarter is perhaps the most important phase of the project because if planning is done correctly we can expedite phase two and three. Saturdays and Sundays are shown explicitly to convey a full work week but are not part of actual labor hours.

2. Winter Quarter 2023

At least 2 design iterations are shown in Fig. 5.2. It reflects a general interim milestone for EE 463. Component selection and shipping are accounted for.

3. Spring Quarter 2023

Fig. 5.3 below shows the final phase of the Senior Design sequence. 3 weeks of product validation and delivery of the product are shown. This window accounts for delivery, final report and spring demo preparation.
Fig. 5.1: Gantt Chart Fall Quarter 2022
Fig. 5.2: Gantt Chart Winter Quarter 2023
Fig. 5.3: Gantt Chart Spring Quarter 2022
Chapter 6: Revised Gantt Charts

Since the Winter Quarter schedule didn’t line up with the corresponding Gantt Chart, a new one was made that is more aligned with how time was actually spent rather than ideally spent and is shown in Fig. 6.1. In addition, with this new experience the Spring Quarter Gantt Chart was also revised to a schedule that is more practical shown in Fig. 6.2. These revisions still follow the guidelines outlined in Chapter 5. More detailed changes are below.

1. Winter Quarter Gantt Chart Changes
   a. Replaced the Design 1 section with Analysis of Previous Design
      i. This time was spent looking over the old design and figuring out any issues
   b. Added sections for Prototype 1 and 2
      i. Functionally identical to Design 1 and Design 2 sections on original but subsections were altered to be more accurate. Timeframes were also adjusted to be more accurate
   c. Replaced Validation section with Documentation
      i. Ideally, this time would’ve been spent making the final design but time constraints and documentation took priority

2. Spring Quarter Gantt Chart Changes
   a. Replaced Final Design section with more testing and construction of a 2nd stage
      i. There wasn’t enough time during Winter Quarter to achieve this, but this won’t take more than a week
   b. Added Prototype 3 section
      i. This section is primarily for moving the design onto a PCB and constructing the chassis, since there are no major design changes this will realistically be lumped in with the final design
   c. Moved Final Build and Final Test together into Final Design
      i. This section ensures that if any major changes need to take place after Prototype 3 then there will be designated time to account for it
   d. Added Documentation section
      i. This time is designated for writing reports and preparing for presentations as well as writing instructions and basic debugging fixes for the customer
   e. Added Demo section
      i. This section accounts for the time needed to actually present the project and to ensure this time doesn’t get mistaken for additional time to work
Fig. 6.1: Revised Winter Quarter Gantt Chart
Fig. 6.2: Revised Spring Quarter Gantt Chart
Chapter 7: Test Definitions and Protocols

Throughout the design process, the following tests were used to either assess the relative performance of each design, or the performance of components which would be used in the final design. They are described in further detail later in this section. See Chapter 9 for the data gathered using these tests.

Test 1: Maximum Achievable Bluetooth Output Test

This test monitors the voltage output of the bluetooth receiver which will be used in the final design. The test seeks to obtain the largest possible voltage output from the receiver, which will be used in various other tests for determining edge-cases or “worst-case” scenarios. The procedure is as follows:

1) Pair the bluetooth microphone to the receiver by following the instructions provided in Appendix E: Troubleshooting.
2) Press the “+” button on the microphone repeatedly to turn up the input volume as much as possible.
3) Using either an alligator clip or a TS female audio jack connector, monitor the voltage produced across the tip and sleeve on an oscilloscope

![TS Connector Reference Diagram](image)

Fig. 7.1: TS Connector Reference Diagram

4) Using the “Single” setting on the oscilloscope and setting the trigger to an appropriate level, speak loudly into the mic and record the voltage level
5) Being mindful of the environment, attempt to create as loud of an audio signal as possible, trying various means such as speaking loudly, tapping the mic on the desk, or blowing into the mic. Record the voltage level of the loudest signal that was achieved.
6) Press the “+” button a few more times and repeat Step 4 to ensure the input gain is turned up all the way and the results match those previously obtained.
**Test 2: Nominal Operating Level Bluetooth Output Test**

This test determines the normal voltage range of operation of the Bluetooth receiver. The procedure is as follows:

1) Pair the bluetooth microphone to the receiver by following the instructions provided in Appendix E: Troubleshooting.
2) Press the “+” button on the microphone repeatedly to turn up the input volume as much as possible.
3) Using the “Single” setting on the oscilloscope and setting the trigger to an appropriate level, speak normally into the mic and record the voltage level
4) Repeat step 2 multiple times to ensure the voltage level is consistent

**Test 3: Maximum Input Test**

This test serves the simple purpose of finding the maximum input voltage which can be applied to the op amp before saturation occurs. The procedure is as follows:

1) Using a function generator, apply a sinusoidal tone in the passband (1 kHz will suffice) to Input1, leaving the other inputs open, as indicated in Fig. 7.2. Ensure that proper power is supplied to the circuit as well.
2) Connect oscilloscope probes to Input1 and V_Out and measure the peak-to-peak voltage of the input waveform.
3) Increase the amplitude of Input1 until clipping can be observed in the output waveform and record the amplitude at which this occurs.

![Fig. 7.2: Test Setup for Maximum Input Test](image)
Test 4: Voltage Regulator Noise Analysis Test

This test serves to assess the spectral content of the voltage regulator output. The steps are as follows:

1) Apply 12 V DC to the input of the Voltage Regulator (pin 1 in Fig. 7.3 below)
2) Connect pin 2 to ground
3) Monitor output voltage (pin 3) on an oscilloscope
4) Run an FFT on the output voltage
5) Export the data to a CSV file
6) Use MATLAB to square the voltage values of the FFT (proportional to power) and compute the non-DC power

![Fig. 7.3: Voltage Regulator Pin Reference Diagram](image)

Test 5: Chirp Test

The Chirp Test is a qualitative test to observe any filtering effects introduced by loading the summing circuit. This test informs the closed circuit single tone test. By inputting a chirp signal, the frequency response can be observed qualitatively in the time domain. The procedure is as follows:

1) Using a function generator, generate a chirp signal to sweep the entire audio frequency range ($f_{\text{low}} = 20$ Hz, $f_{\text{high}} = 20$ kHz) and connect to Input1 as seen in Fig. 7.4 below.
2) Monitor the Input1 and $V_{\text{Out}}$ on an oscilloscope and capture at least one full sweep cycle to observe the frequency response over the entire audio range.

![Fig. 7.4: Test Setup for Chirp Test](image)
Test 6: Open Circuit Single Tone Test

The Open Circuit Single Tone Test is used to determine the open circuit frequency response of the summing circuit. It is used to ensure the circuit is providing the expected gain over the desired audio range.

The procedure for conducting this test is as follows:

1) Using a function generator, apply a sinusoidal tone at 20 Hz to Input1, leaving the other inputs open as indicated in Fig. 7.5. Ensure that proper power is supplied to the circuit as well.
2) Connect oscilloscope probes to Input1 and V_Out and record the open circuit gain.
3) Increment the frequency and repeat until reaching the end of the audio range (i.e. 20 kHz)

A properly functioning summing amplifier will provide the programmed gain over the entire audio range.

![Fig. 7.5: Test Setup for Open Circuit Single Tone Test](image)

Test 7: Loaded Circuit Single Tone Test

This test further expands on the open circuit test by determining what effect the introduction of the load has on the frequency response of the summing amp. The goal of this test is to ensure expected gain is being provided by the op amp over the audio range. The procedure is identical to that listed in the procedure above, with the exception of connecting the load (IR transmitter) to the output as shown in Fig.
7.6. A successful test should give the passband, stopband, and cutoff regions within a reasonable precision (100 Hz).

Test 8: Open Circuit Six-Tone Test

The Open Circuit Six-Tone Test serves multiple purposes. It simulates 6 inputs to the circuit simultaneously, which the final product must be capable of handling. The tones used are harmonics of each other, so that they constructively sum together. By using the maximum input voltage (determined by Absolute Maximum Bluetooth Test), the circuit can be tested not only for the nominal signal amplitude of the Bluetooth Microphone, but also for the edge case of the loudest sound occurring in every microphone simultaneously. The non-linearities introduced by the circuit can be observed for the saturation and nominal cases to inform any degradation upon performance.

The test is conducted as follows:

1) Use function generators to generate 6 tones which are harmonics of a fundamental frequency and reside in the audio range (100 through 600 Hz was used). These tones should operate at a nominal amplitude of 1 V to prevent saturation (when the signals interfere constructively, their combined amplitude shouldn’t exceed the offset of the op amp and cause it to saturate). Connect these tones to the inputs of the summing circuit as shown in Fig. 7.7 and ensure the circuit is powered.

2) Monitor the V_Out on an oscilloscope

3) Perform an FFT across the audio range (20 Hz - 20 kHz) on the output waveform to observe the spectral content of the signal
4) Measure the voltage level of the most significant tone introduced due to non-linearities (i.e. not one of the desired tones)

5) Repeat the process using the absolute maximum voltage measured in the Absolute Maximum Bluetooth test for each input to simulate the edge-case scenario (i.e. maximum constructive interference at the highest voltage).

![Fig. 7.7: Test Setup for Open Circuit Six-Tone Test](image)

**Test 9: Loaded Circuit Six-Tone Test**

The Loaded Circuit Six-Tone Test introduces the IR transmitter load to observe any added effects which were not present in the open circuit test, such as filtering or more significant non-linearities. The procedure is identical to that described in the Open Circuit Six-Tone test, with the load being introduced as shown in Fig. 7.8.
**Test 10: Voice Filter Analysis Test**

This test is a qualitative test to ensure proper selection of the cutoff frequency due to high-pass filtering effects at the output observed from previous tests (i.e. chirp test, tone tests). The absolute lowest cutoff frequency is the most ideal however this test is used to determine a higher and more practical cutoff frequency while maintaining audio quality. The test seeks to determine whether good audio quality can be maintained by using an ideal high-order high-pass cutoff filter. Since our circuit’s filter can be modeled as first order, if a higher order filter is used and maintains quality then a low order filter will as well. For justification of the cutoff frequency used, see Chapter 8 & 9.

The test is conducted as follows:

1) Record audio of the members of the team saying the same sentence, “With tenure, Suzie’d have all the more leisure for yachting, but her publications are no good”. This sentence was chosen because it contains a large number of the syllables in the English language so the impact a filter would have on each syllable can be clearly observed

2) Using the program Audacity, implement a 5th order high-pass filter to run the audio through with a given corner frequency

3) Verify that the audio still sounds the same quality

**Test 11: Qualitative End-to-End Test**

The Qualitative End-to-End Test investigates the quality of audio which is delivered to the user. It is dependent upon the opinion of each user, and requires a consensus by the team to determine whether
high enough quality has been achieved. It also serves the purpose of assessing the security provided by
the system. This is done by verifying limited range and line of sight (LOS).

The procedure is as follows:
1) Pair all available Bluetooth microphones and receivers, and connect to the inputs of the circuit.
2) Connect the IR transmitter to the output
3) Ensure proper power is supplied to the circuit
4) Give each available user (preferably 6 for complete test) a bluetooth microphone and IR headset.
   Ensure the IR headsets and transmitter are set to the same channel (A or B).
5) Have the users hold a conversation amongst each other, whilst keeping in mind the quality they
   observe.
6) Walk around the room to determine an approximate radius for which the IR headsets maintain
   connectivity
7) Cover the IR transmitter with a box and observe the effect on the ability to hear the conversation.
8) Have one user go behind a wall and observe the effect on the ability to hear the conversation.
Chapter 8: Design History

This Chapter outlines each distinct version of the circuit as it changed throughout this project, primarily describing the circuit schematic, implementation and reasons for changes. Each outline is in chronological order.

CubiConvo:

The CubiConvo is the circuit handed to this team as the result of the previous team’s efforts shown in Fig. 8.1 below. It is an inverting summing amplifier utilizing a LM386 for its op amp, tuned potentiometers for its input resistors and a voltage divider for its voltage offset. In addition, the circuit only supports two inputs. These can all be seen in the schematic shown in Fig. 8.2.

![CubiConvo Physical Circuit](image1.png)

**Fig. 8.1: CubiConvo Physical Circuit**

![CubiConvo Circuit Schematic](image2.png)

**Fig. 8.2: CubiConvo Circuit Schematic**
When used end-to-end, the audio quality did not sound very good. We believe this is due to the IC the previous team selected, the LM386, as it cannot handle any input voltage swing larger than 0.8V_pp which the Bluetooth Microphones are more than capable of producing. In addition, the potentiometers have three terminals to determine what resistance is used, the intent was to use them to get as close to 10k Ohms as possible then lock it in so both inputs have the same gain. However, the way it was implemented in the circuit gave each signal a path to ground which when combined with the very large coupling capacitors degraded the audio quality.

These factors played large roles when developing the first prototype and were the driving forces behind the redesign.

Prototype 1:
The first prototype was constructed on a breadboard which allowed great flexibility to swap parts out and test different versions before settling on a design, the schematic for our first design is shown in Fig. 8.3. One of the first major changes is the op amp, the LM741. This IC allows for a much larger voltage swing, up to 15 V_pp but for this project only 12 V was used. There is also the inclusion of a 5 V Voltage Regulator at the noninverting input of the opamp to offset the input signals.

![Prototype 1 Schematic](image-url)
The frequency range of human speech has been determined as approximately \(~100\text{ Hz - 3 KHz}\), while the range of frequencies that can be heard by the human ear is about 20 Hz-20 kHz. The amplifier bandwidth must accommodate 3 kHz at the very least, though most amplifiers have a sufficiently high GBW so that this is not a problem.

The relationship between input and output of an inverting Summing Amplifier is as shown:

\[
V_0 = AC_1 \left( \frac{-R_f}{R_1} \right) + AC_2 \left( \frac{-R_f}{R_2} \right) + \ldots + AC_n \left( \frac{-R_f}{R_n} \right) + V_p
\]

where \(AC_n\) is an arbitrary analog signal, \(R_f\) is the feedback resistor, and \(V_p\) is the DC voltage applied to the non-inverting terminal. \(V_p\) is necessary to prevent clipping when the input signal drops below 0 V, since the amplifier must run off a single 12 V supply. \(V_p\) is also contained by the coupling capacitors, C1-C7 so that the DC current doesn’t flow back into the inputs or the output and potentially damage other components. The gain of each input is determined by \(R_n\).

The LM741 is an operational amplifier capable of operating from a single supply, and was selected as the summing amplifier. Adding a 5V offset at the non-inverting terminal allows the signals to be approximately centered at the power supply swing.

The LM340 is a monolithic positive voltage regulator with an output of 5V, and was selected to provide a consistent 5V DC offset to the positive terminal of the LM741. The LM340 is internally equipped with thermal shutdown, short circuit protection and overcurrent protection. Additionally, it provides line regulation of 0.01%, making it reliable for any slight fluctuations in input voltage. (See the Voltage Regulator Noise Analysis Test in Chapter 7 & 9 for further justification of the LM340).

Coupling capacitors are necessary to ensure no backwards DC current flow through the circuit, so that the 5 V non-inverting input is maintained. However, simple circuit analysis techniques show that introducing coupling capacitors at the input creates a high-pass filtering effect, changing the transfer function from:

\[
H(s) = \frac{-R_f}{R_{in}}
\]

to

\[
H(s) = \frac{-R_f}{R_{in}} \frac{s}{s + \frac{1}{R_{in}C_{in}}}
\]
This is further confirmed by frequency analysis performed on Fig. 8.4 below and shown in Fig. 8.5.

**Fig. 8.4: Circuit for Illustrating High Pass Effect due to Introduction of Coupling Capacitors**

Selecting 1 μF coupling capacitors and 10k resistors sets the corner frequency of the high-pass filter at about 16 Hz, allowing for the entire audible range from 20 Hz and above to be unattenuated. To maintain the unity gain, a 10k resistor was selected for the feedback resistor.
Prototype 2

Prototype 1, while providing better audio quality than the previous year’s design, contained many loose or unreliable connections which contributed to undesired noise observable at the input and output. For this reason, a second prototype was constructed on a development board as seen in Fig. 8.6 and 8.7 below. For testing, leads were clipped directly onto the capacitor leads to measure and feed signals into and out of the circuit.

Fig. 8.6: Prototype 2 Top Side View

Fig. 8.7: Prototype 2 Bottom Side View
Later on, TRRS connectors were soldered to some of the coupling capacitors for ease of qualitative testing with the Bluetooth receivers.

Though the circuit architecture was identical to Prototype 1, the feedback resistance of 10kΩ was justified by the Nominal Operating Level Bluetooth Output Test and the Maximum Input Test (discussed in Chapter 9 as tests 1 & 2 respectively). Based on this information, a gain of 1 was selected to ensure there would be no scenario where the amplifier would ever enter saturation under normal operating conditions. The reasoning was conducted as follows:

Given a max input of roughly 8 V<sub>pp</sub>, if all six users happened to be speaking at the same time, and each user’s average Bluetooth receiver voltage was about 720 mV, the maximum constructive interference that could occur would be 4.32 V<sub>pp</sub> for a gain of 1. Normally, all users will not be talking over one another, and in the unlikely event that they are, it is unlikely that a concerning amount of constructive interference will occur as the fundamental frequency of each user’s voice will not be a harmonic of the others. A gain of 1 thus ensures that the summing amp never enters saturation.

The team contemplated the addition of a second stage to the Prototype 2 design, as it was initially thought that loading via connecting the circuit to the IR Transmitter was an issue. However, after performing various tests (chirp, single tone, and six tone tests specifically), it was determined that loading was not the issue, but rather the output coupling capacitor in conjunction with the internal resistance of the IR transmitter was creating a first order high pass filter. This realization informed future design decisions, and allowed the team to scrap the second stage design entirely.

**Prototype 3**

Prototype 3 was the first design to be implemented on a PCB, a render of which can be seen in Fig. 8.8. As this was the intention for the final design from the beginning, this prototype was a significant step toward the final product. As mentioned above, it was determined that the summing circuit was followed by a RC high-pass filter. Single tone testing showed that this filter was first order, and allowed us to calculate the internal resistance of the IR transmitter based on the observed cutoff frequency. From this knowledge, it was determined that the output coupling capacitor would need to be increased from 1 uF to 4.7 uF such that the desired audio range would be contained in the passband. This effectively sets the corner frequency at ~100 Hz, allowing for the entire human vocal range to exist in the passband.

For modularity, Prototype 3 also incorporated Molex connectors for the audio I/O and the power supply. In the event that a redesign was necessary for the PCB, these connectors allow the hardware to easily be swapped between versions without having to make copies or desolder any connections.
Altium, a PCB layout software used in industry for various electronic applications, was used for Prototype 3 and the final design. Using a PCB was deemed essential even for a relatively low frequency application, as connections would be much more reliable than on the development board. A 2 layer 1 oz copper board was used to minimize signal coupling and stray currents, and improve noise reduction and current carrying capacity. The top layer was used to connect all Vcc connections and the bottom layer for all ground connections. This method is sufficient because of the low frequency and current demand, since the dielectric of the PCB does not introduce any noise or signal coupling at low frequencies. Table 8.1 below shows the measurements used in the PCB.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Trace Thickness</td>
<td>0.25mm</td>
</tr>
<tr>
<td>Solder Joints Diameter</td>
<td>0.45mm</td>
</tr>
<tr>
<td>Board Dimensions</td>
<td>125mm x 90mm</td>
</tr>
</tbody>
</table>

Fig. 8.9 below shows the assembled board. Board dimensions were not a design constraint, but the board needed to fit inside the Cubi-Com chassis. This design took up much more space than was necessary but it was functional. After running through all the tests, the team decided to make one last revision to reduce cost and materials, and to fix an error where the input Molex ground port was left floating rather than connected to the ground plane.
Final Design:

Fig. 8.10 shows the final Altium schematic and Fig. 8.11 shows the changes made to the board layout.

---

Fig. 8.9: Rev 1 PCB construction

Fig. 8.10: Final Design Altium Schematic
The final design was nearly identical to Prototype 3, except that the surface area of the PCB was significantly reduced 85mm x 85mm for cost and space efficiency. Solder joints were increased by 0.02mm in diameter for ease of construction. The specifications laid out in Table 8.2 were the ones used in the final design.

**Table 8.2: Final Design PCB Specifications**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trace Thickness</td>
<td>0.25mm</td>
</tr>
<tr>
<td>Solder Joints Diameter</td>
<td>0.47mm (Rounded Rectangle)</td>
</tr>
<tr>
<td>Board Dimensions</td>
<td>85mm x 85mm</td>
</tr>
</tbody>
</table>
Chapter 9: Test Results

The following chapter shows the various test results obtained from performing the tests described in Chapter 7. Note that Prototype 1, though described in the Design section (Chapter 8), does not have any test results displayed. It is not included for two reasons:

1) Prototype 1 had many loose and unreliable connections due to the many jumper wires in the circuit, and because it was implemented on a breadboard, making it difficult for testing.
2) Prototype 2 used an identical circuit design to Prototype 1 (all values and components implemented were the same), but had stronger connections for easier testing.

Test 1: Maximum Achievable Bluetooth Output Test

After trying various methods, it was determined that blowing into the microphone created the loudest possible voltage level. The recorded voltage was 3.20 V as shown in Fig. 9.1. This information was used for testing the summing circuit in the worst case scenario, where each input is at its loudest possible level, and each input is a harmonic of a fundamental frequency such that the signals have maximum constructive interference. This can be observed in the saturation case of tests 8 & 9 later in this chapter.

![Image of a waveform analysis with a peak of 3.20V]

Fig. 9.1: Maximum Achievable Voltage with Bluetooth Microphone
**Test 2: Nominal Operating Level Bluetooth Output Test**

Following the procedure outlined in Chapter 7, the average operating voltage of the Bluetooth receiver was found to be about 720 mV as shown in Fig. 9.2. This information was used for determining the gain of the summing circuit, as this is the normal range in which the Bluetooth receivers operate.

![Fig. 9.2: Average Operating Level of Bluetooth Microphone](image)

**Test 3: Maximum Input Test**

**Prototype 2:**

Following the procedure in Chapter 7, the maximum input for the Prototype 2 was determined to be about 7.9 V. This data, in conjunction with the nominal operating voltage of the Bluetooth receivers (obtained in Test 2), allowed the team to determine an optimal gain at which to program the summing circuit (discussed in Chapter 8).

**Prototype 3:**

The maximum input for Prototype 3 was determined to be approximately 7.8 V, at which point the summing amplifier entered saturation. This was consistent with the maximum input found in Prototype 2 and confirmed that no changes to the gain of the circuit would need to be made.

**Final Design:**

The maximum input for the Final Design was determined to be approximately 7.94 V, at which point the summing amplifier entered saturation. This was consistent with the maximum input found in Prototype 2 and 3, and confirmed that no changes to the gain of the circuit would need to be made.
Test 4: Voltage Regulator Noise Analysis Test

The power spectrum of the voltage regulator output in Fig. 9.3 below shows that the non-DC power is negligible. The total power over the frequency range (excluding DC) was found to be 6.1249e-05 W. This confirms that the regulator is providing a reliable 5 V DC voltage to the non-inverting input of the summing amplifier, and that no significant noise is being introduced to the circuit.

![Power Spectrum of Voltage Regulator Output](image)

Fig. 9.3: Power Spectrum of Voltage Regulator Output

Test 5: Chirp Test

Prototype 2:

The yellow signal in Fig. 9.4 below is the input chirp signal, and the green signal is the output (see Chapter 7, Fig. 7.4 for the procedure). This qualitatively shows the high pass response of the Prototype 2 circuit. The stopband and transition band were quantitatively determined in the Single Tone Loaded Test. Additionally, the passband gain is clearly less than 1. This suggests that some amount of loading occurs due to the output.
Prototype 3:

Similar to Prototype 2, the chirp test in Fig. 9.5 signifies a high pass response. However, the passband gain is unity, contrary to the loading observed in Prototype 2. Additionally, the high pass response appears less pronounced than in the previous prototype. This is consistent with the change in the output coupling capacitor value between Prototype 2 and 3, which lowered the cutoff frequency.
**Test 6: Open Circuit Single Tone Test**

The open circuit single tone test shows the expected high pass response due to the input capacitors. The predicted corner frequency of 16 Hz (discussed in Chapter 8) is consistent with the results shown in Fig. 9.6 below, which contains the overlaid frequency responses of all tested designs. Any variations in gain can be attributed to the tolerance of the capacitors and resistors used in the circuit, as well as precision errors on the part of the data collector.

For Prototype 2, the slew rate was exceeded at approximately 160 kHz, though the op amp still provided a gain of 1. This is well outside the intended operating range for the summing circuit (20 Hz - 20 kHz), showing that the op amp provides sufficient bandwidth and slew rate for the audio range. Prototype 3 and the Final Design yielded similar slew rate results.

![Open Circuit Frequency Response](image)

**Fig. 9.6: Open Load Frequency Response of Summing Circuit**

**Test 7: Loaded Circuit Single Tone Test**

Fig. 9.7 below shows the improved high pass response from Prototype 2 to Prototype 3 and the Final Design due to the replacement of the 1uF capacitor with the 4.7 uF capacitor at the output of the summing amplifier (described in Chapter 8). The corner frequency which was previously at about 500 Hz was improved to about 100 Hz, encompassing the entire human vocal range.
As anticipated by the Chirp Test, Prototype 2 experienced some loading, as the gain in the passband was only about 0.86. This placed the corner frequency gain at about 0.608. The corner frequency is thus about 500 Hz, as seen in Fig. 9.7.

![Loaded Circuit Frequency Response](image)

**Fig. 9.7: Loaded Frequency Response of Summing Circuit**

**Test 8: Open Circuit Six-Tone Test**

Fig. 9.8 below overlays the FFTs of all the tested designs operating with no load (open circuit) and a nominal input value (1 V). The three FFTs are all very similar, consistent with the identical input impedances in Prototype 2 and 3, and the Final Design. The open circuit operation provides a difference of roughly 50 dBV between the desired inputs and the undesired harmonics introduced by non-linearities in the op amp.

Note: dBV is not to be confused with dB for a power spectrum. The conversion of Volts to dBV is as follows:

$$dBV = 20 \times \log_{10}(V_{\text{RMS}})$$

Where $V_{\text{RMS}}$ is the RMS voltage of the measured signal.
Fig. 9.8: Six Tone Open Circuit Test for 1V Input

Fig. 9.9 below overlays the FFTs of the various designs operating with no load (open circuit) and a maximum input value (3.2 V), obtained from Test 1. Due to the high input voltage and constructive interference of the harmonics, the circuit enters saturation. As a result, the non-linearities present are much more significant than before.

Fig. 9.9: Six Tone Open Circuit Test for 3.2 V Input (Saturation)
Test 9: Loaded Circuit Six-Tone Test

Fig. 9.10 below overlays the FFTs of the various designs operating with the IR transmitter load and a nominal input value (1 V). Prototype 3 and the Final Design have nearly identical FFTs, while Prototype 2 has a much more visible high pass response. As discussed in Chapter 8, Prototype 3 replaced the 1 uF output coupling capacitor with a 4.7 uF coupling capacitor. This effectively lowered the cutoff frequency of the high pass response to roughly 100 Hz. Notice also how there is again a 50 dBV difference between the desired tones and the undesired non-linearities. This confirms that under normal operation, the non-linearities introduced by the summing amplifier are negligible.

![Six Tone Loaded Circuit Test - Nominal](image)

Fig. 9.10: Six Tone Loaded Circuit for 1 V Input

Fig. 9.11 below overlays the FFTs of the various designs operating with the IR transmitter load and a maximum input value (3.2 V), obtained from Test 1. Not shown is the output waveform in the time domain. The waveform in Prototype 2 did not experience clipping. This is because the high pass corner frequency in Prototype 2 was at about 500 Hz, so all tones below this experienced attenuation. The resulting constructive interference did not exceed the maximum input limits. This is consistent with the less significant non-linearities seen in Fig. 9.11. Prototype 3 and the Final Design, on the contrary, do enter saturation as the high pass response cutoff frequency was shifted down to 100 Hz. Fig. 9.11 shows the more significant non-linearities present in Prototype 3 and the Final Design compared to Prototype 2.
Test 10: Voice Filter Analysis Test

Fig. 9.12 below shows the combined frequency spectrum of each team member’s voice (recorded in Audacity) when reading the same sentence: “With tenure, Suzie’d have all the more leisure for yachting, but her publications are no good.”
Next, a 5th order high pass filter with a cutoff frequency at 100 Hz was introduced. The resulting spectrum is shown in Fig. 9.13 below. Listening to the filtered audio content, each team member deemed the audio to be high quality. There were no distinguishable differences to the human ear between the filtered and unfiltered audio signals, confirming the placement of the high pass corner frequency at roughly 100 Hz.

![Fig. 9.13: Filtered Combined Spectral Content of Team Members’ Voices](image)

**Test 11: Qualitative End-to-End Test**

Contrary to other tests, the Qualitative End-to-End Test was used to assess the audio quality from the user’s perspective. This test is thus of a more subjective nature than the other tests. By handing each team member an IR headset and a Bluetooth microphone, the quality of each design was tested. It should be noted that in all the designs, the circuits were nearly identical. This made it somewhat difficult to distinguish too many significant differences in audio quality between the subsequent designs. However, Prototype 3 and the Final Design were both deemed to have higher quality than Prototype 2 for normal conversation between users. This was consistent with the improved high pass response of the circuit as discussed in the Six-Tone Loaded Circuit Test above.

Aside from this distinguishable feature, all designs performed very well, in that all team members expressed that the system facilitated clear conversation. Additionally, the team walked around the room in which the test was performed, and estimated that connection was consistent within a 10 foot radius of the IR transmitter before the IR connection was lost. The team also verified that line-of-sight (LOS) needed to be maintained, as covering the IR transmitter with a box or walking behind a wall cut off connection with the IR headsets.
Chapter 10: Overall Construction

This chapter outlines each major part of the project and how they physically fit together and electrically connect to other components.

The final PCB features 0.25mm trace clearance. 0.8mm trace thickness is enough to carry up to 100mA per trace. Vias were used in several of the input signals and the output signal in order to minimize board size and maintain signal integrity. Fig. 10.1 shows the 6mm mounting holes in the corners with screw chamfer to allow screws to sit flush to the board plane and mount onto the chassis.

![Fig. 10.1: Final Unassembled PCB](image1)

Fig. 10.1: Final Unassembled PCB

Fig. 10.2 shows the final assembled PCB. An 8 pin IC Socket was used in the event that the LM471 breaks and needs to be replaced. Component labels were added to help streamline the assembly process.

![Fig. 10.2: Assembled PCB](image2)
Fig. 10.3 shows the assembled PCB screwed into place with the Audio Input (bottom), Power Input Splitter (right) and Audio Output (top) plugged in which will be gone over in further detail.

![Fig. 10.3: Final Assembled Cubi-Com with Chassis](image)

Shown in Fig. 10.4 is the construction of the Audio Input cable, which connects each of the TRRS connectors to the PCB. The TRRS connectors interface with the Bluetooth Microphones outside the chassis, the ports of which are shown in Fig. 10.5. The microphones only have two electrical connection points, the audio and ground. Since they all share the same ground, the TRRS connectors have their corresponding ground pins soldered together and fed into the same pin in the 2x4 Molex connector using the black wire. Each of the red wires correspond to the audio for one input and all have their own pin in the 2x4 Molex connector. These wires were zip tied together for organization. The TRRS connectors were superglued in place and reinforced with paper in the back to reduce the chances of it breaking off as much as possible. Some super glue residue can still be seen in Fig. 10.5 as a layer of light gray over the black plastic of the connectors.
The Power Input Splitter seen in Fig. 10.6 takes power from an external source from the chassis and splits it between the PCB and IR Transmitter. This is functionally identical to a standard Barrel Splitter such as the one seen in Fig. 10.7 except one of the outputs was modified to interface with a 1x2 Molex connector.
The Audio Output cable can be seen circled in red in Fig. 10.8. Functionally, it carries the audio signal from the PCB to the IR Transmitter with one caveat. The IR Transmitter uses stereo audio (as in separate signals for left and right audio) and the microphones only produce mono audio, so the left and right audio wires within the cable were soldered together before being crimped within the 1x2 Molex connector to resolve this issue. The extra length of cable was bundled together to keep it organized.

Fig. 10.8: Output Audio Cable

Fig. 10.9 displays everything within the bottom half of the chassis assembled.
The IR Transmitter fits within the top half of the chassis as shown in Fig. 10.10. Underneath the back half is a large hole that feeds into the interior of the chassis and allows the audio and power cables to plug into the back of the transmitter. This keeps all the wires hidden from view for aesthetics and ease of use.

Fig. 10.10: IR Transmitter Chassis Assembly

Fig 10.11 and 10.12 show the fully assembled final product of this project with all the Bluetooth Receivers plugged in.

Fig. 10.11: External View with the Top Removed
Fig. 10.12: External View of the Fully Assembled Product

Specifics on the design of the 3D Printed chassis are given in Appendix D.
Chapter 11: Retrospective

This chapter serves the purpose of looking back at the requirements and specifications determined at the beginning of the project cycle (reference Table 2.1 & 2.2 in Chapter 2), and justifies the requirements and specifications that were met by the final product, and also to reflect upon any requirements or specifications that were deemed not necessary. Additionally, this section discusses future improvements which could be made to the project.

Spec 1: Passband Filter Cutoff Frequency

Initially, the team specified a low pass response for the circuit which would attenuate frequencies above 4-5 kHz. However, after performing the Qualitative End-to-End test, all team members came to the consensus that the sound quality was sufficient to meet the customer needs without the addition of a low pass filter. To reduce circuit complexity, this requirement was deemed unnecessary as the team moved forward with the design process.

Spec 2: Noise Filtering for mic (SNR)

The initial Engineering Specifications required a 40 dB SNR for the Bluetooth Microphone. However, because the team was limited to a specific microphone model, the team also deemed this requirement unnecessary to measure. Additionally, the Voice Filter Analysis Test performed in Audacity (Test 10 in Chapter 9) determined that the sound quality provided the mics was acceptable.

Spec 3: Wireless Range

The Engineering Specifications placed a high emphasis on a wireless range of operation between 10-30 ft. The End-to-End test performed on the Final Design verified that this constraint was met, with a 10-12 ft connection range for locations within LOS of the IR transmitter.

Spec 4: Simultaneous Users

Another Engineering Specification which was considered of utmost importance throughout the project was the ability for the CubiCom to facilitate conversation between up to 6 users. Again, the End-to-End Test verified that this specification was met, as the team tested for all 6 microphones paired simultaneously, with the conclusion that the system provided high audio quality. The CubiCom was tested at the Senior Project Expo numerous times, with the general consensus of participants being that the CubiCom provided high audio quality, and promoted better conversation.
Spec 5: Battery Life

Battery life was a significant specification, as the sponsor required that the CubiCom provide communication for at least an hour long conversation. Though the team set out to make the product operational for at least 6 hours without needing a recharge, this was unrealistic due to the limited battery life of the IR headsets. However, during the Senior Project Expo, the CubiCom was operational for all 3 hours, without the need for recharging or replacing batteries.

Spec 6: Signal Breach Distance

Signal Breach Distance was a key specification as it was a measure of how secure the system would be. The End-to-End Test performed on the Final Design verified that the constraint fell within the maximum 6 ft breach distance specified, as the second the user walked behind a wall, the signal was cut off.

Spec 7: DC Power Supply

The initial requirements specified that the CubiCom should be able to entirely run off a DC power supply. As the entire system is run off of a 12 V AC wall adapter, this requirement was met.

Spec 8: Op Amp Supply Limit

Initial Engineering Specifications required that the Op Amp operate off a single 12 V supply. As the entire circuit runs off a single 12 V AC wall adapter, this requirement was also met.

Spec 9: Size

Initially, the size specification for the chassis allowed a max size of 6”x3”x2”. However, after designing the PCB, it became clear that the width of the chassis would need to be larger, as the PCB was square. Additionally, the height of the chassis needed to be larger to allow enough space for standoffs and through hole components to be soldered onto the board, and to house the IR transmitter at the top. The final dimensions were 5.74“x5.51”x2.717”.

Spec 10: Weight

Weight was allocated at most 15 oz in the original Engineering Specifications. However, because the team was limited to the type of plastic used (courtesy of Innovation Sandbox on campus), and because the size was immutable due to the reasons previously specified, weight became an irrelevant requirement.
Future Improvements:

Though the project was an overall success in providing secure, high quality, wireless communication to 6 simultaneous users, the following improvements could be made for future designs:

- Adding an On/Off switch for the overall system, as the current design requires unplugging the AC adapter to turn off the system.
- Adding a 5V USB charging system for the Bluetooth receivers to allow for longer conversations.
- Selecting headsets with better noise dampening (or potentially noise canceling technology) for improved performance in a noisy office environment.
- Combining the Bluetooth Microphones and Infrared Headphones into one cohesive unit including merging the batteries and On/Off switches for ease of use.
Annotated List of References:


Appendix A: ABET Analysis of CubiCom

Summary of Functional Requirements
The CubiCom is a communication device that facilitates face-to-face conversations between multiple users in an open office environment. Open office environments, such as cubicles, do not naturally promote good face-to-face conversation. This is because multiple conversations are taking place simultaneously, making for a noisy environment. The CubiCom is able to provide noise dampening for each user, while also transmitting the desired signal. What makes this project unique is its use of dual technologies. Bluetooth is used to transmit audio from each user, while Infrared (IR) is used to broadcast this audio to all users on the desired channel. Due to the device pairing capability of the CubiCom, it provides secure audio transmission, so that no undesired parties can interfere or disrupt the conversation. On the receiver end, the broadcast signal, which resides in the Infrared band, requires line-of-sight (L.O.S.) and has limited range. Hence, the CubiCom also provides secure reception, as only the people within the cubicle or room will be able to hear each other.

Primary Constraints
The most significant challenge of designing the CubiCom was selecting the proper components, specifically for the PCB. This involved reordering parts on a couple occasions to ensure successful interfacing with the board. Another unexpected challenge was meeting the noise dampening requirement, as the available headphones were too small and did not fit over the ears.

Economic
An economic analysis of the product requires examining the capital, costs, and benefits of the product and how they affect the product life cycle. Human capital consists of knowledge in regard to signal processing and operational amplifiers. This generally requires an education in Electrical Engineering. In order to design and build the CubiCom, the company must hire Electrical Engineers, which will require offering a salary which competes with other companies’ job offers. The concepts themselves implemented in the design of the CubiCom are well-known among most Electrical Engineers and do not require much specialization beyond the general education required in obtaining a degree. Therefore, the salary should be mainly entry level, which in the United States is about $75,000 [1].

In regard to financial capital, as open office environments are wide-spread among businesses, this is a very unique product not currently on the market, and would initially pull a lot of equity from shareholders. The manufacturing of this product, if produced on a wide scale, would require real capital such as PCB board printers and 3D printers. The product requires natural capital such as silicon to manufacture the PCBs, but uses little else in regard to natural resources aside from the materials used in the plastic which is used in the construction of the CubiCom.

Most of the cost is accrued in the manufacturing process, which includes the cost of Bluetooth and IR transmitter and receiver components. Operational expenses should be little to none as the PCB printers and 3D printers generally have a long life time. The main manufacturing cost is the plastic to print the CubiCom Chassis. The total cost to buy the required headsets, IR transmitter, and Bluetooth transmitters and receivers, along with the manufacturing of the central communications box, is estimated to cost about
$412.76. The product is marked up by 10% to $330 for the market price. The majority of the benefits occur at the selling of the product, as this product is not a good or service which requires monthly leases or subscriptions. Though the company selling the CubiCom makes the majority of the profits, it can be argued that the customers who purchase the product will experience profit gain due to increased productivity in the work environment.

Testing of individual components requires the use of lab equipment, including oscilloscopes, and spectrum analyzers, which also contributes a large portion of real capital owned by the company. Integrating and system testing is mainly qualitative, using a sample of the population. At the closeout of the product, the company will document lessons learned through the design, manufacturing, and operation of the product in the market. This will include common customer complaints, as well as struggles experienced in the design, manufacturing, and testing phases.

**Commercial Estimates**
CubiCom is anticipated to be popular among companies with commercial buildings. There are an estimated 5.7 million commercial buildings in the US [2]. With approximately 18.2% of these buildings being offices, that is roughly 1.04 million office buildings in the US. Under the assumption 1 in 50 companies will want to buy our product each year, this is about 20,800 companies that will buy our product yearly. If we assume each of these companies buys 10 products, this is about 208,000 devices sold per year. Each device costs $300 to manufacture and sells for $330. This yields a net revenue of approximately $6.24 million, not including operational expenses. As the CubiCom consumes relatively little power and is fairly robust, there is little to no risk of any cost in regard to operation of the device.

**Environmental Impact**
In its operation phase, CubiCom has little environmental impact. The manufacturing of the CubiCom requires a fair amount of plastic for its various components. This is mainly a concern at the end of the product’s lifetime, since most plastic is not recycled. However, if the proper plastic filament is used, it can reduce the waste due to each product at the end of its lifetime. The main ecosystem the product could affect is marine ecosystems, including marine life, so reducing plastic waste is a priority.

**Manufacturability**
The main challenge associated with manufacturing was the 3D-printing of the chassis and microphone mount. These had to be designed for a sleek appearance and user friendly operation, and required careful attention to detail. Additionally, the required electronic components must be soldered manually onto the PCB board, which is time consuming, particularly when producing the product on a mass scale.

**Sustainability**
No main challenges associated with maintaining the completed device exist. The main issue is recyclability, as the product uses a fair amount of plastic, which is environmentally unfriendly. Plastic is very hard to recycle, and is not always a renewable resource. Future upgrades to the system would include making the communications box smaller, such that it uses less plastic. The main issue with this is all the Bluetooth receivers and IR transmitter need to fit on the box, in which case smaller products would likely need to be bought or manufactured. Regarding economic sustainability, the CubiCom not only profits the seller, but increases work productivity of office environments, yielding profits for all parties involved. For
this same reason, it improves social sustainability by improving the quality of life and work efficiency of those in the office work environment.

**Ethical Implications**
There are little to no unethical implications associated with the product. As mentioned previously, it is very hard for anyone to tap into private conversations due to the double layered security of CubiCom. It is thus hard to use in an unethical way. The CubiCom seeks to improve quality of life according to the IEEE Code of Ethics, by holding the safety, welfare, and health of the public and environment as an utmost priority. The CubiCom is designed with the good of the user in mind, though self-interest also plays a role, as a higher user satisfaction rate will result in higher revenue. This is a healthy medium between utilitarianism and ethical egoism, which fosters ethical decision-making.

**Health & Safety**
As the CubiCom consumes relatively low power and is non-invasive to the environment and emits few health and safety threats. The primary safety concern is that the CubiCom might be mounted on a ceiling, such that if installed improperly, it could fall and potentially injure someone. The other concern is in regard to a healthy sound level for each user. We don’t want unsafe decibel levels being received by the users. The system was designed to prevent such hazards from happening. A holder on the 3D printed chassis was made to secure the IR transmitter so as not to fall out and hit someone if mounted on the ceiling. Additionally, the gain of the circuit was selected to prevent the user from being exposed to harmful decibel levels and frequencies.

**Social and Political Impact**
This project mainly impacts the quality of work in the work environment, contributing to the social well-being of the employees and their customers. The main stakeholders are Cal Poly and the US Department of Veteran affairs (VA). If the project fails, it will mainly affect the VA as the current office environment is noisy and hard to interact with veterans. The main beneficiary is the VA, as they are the primary stakeholder and will be receiving the completed product. The product promotes equity by facilitating conversation with veterans, as many veterans have disabilities that inhibit their ability to communicate in noise-filled environments. While CubiCom seeks to facilitate face-to-face conversation with veterans, there is always a risk that some veterans may not want to try new technology, as it is unfamiliar to them. Fortunately, while some veterans may reject using the product, it will not prevent others who need or want to use the product from using it. This product also seeks to counteract environmental injustice by minimizing waste such as plastic which is often dumped illegally near the residential areas of poorer communities. This indirectly counteracts what is referred to in a famous essay as “the tragedy of the commons”, where users can selfishly use a product without considering the consequences of whom it may impact, in regard to environmental injustice in this specific case.
Development
A main tool used in the analysis of the project was Pugh Matrix, which was taught in the lecture section and learned individually by each team member. The Pugh Matrix allows convergent thinking to take place, and allows one to assess the best design alternatives. Some tools that the team used in the development of the project included Altium for designing the PCB, TinkerCad for 3D printing of the chassis, LTSpice for circuit design, and Audacity for audio analysis.

References


## Appendix B: Vendors, Parts List and Cost

### Table B.1: Estimated List of Parts and Costs

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# Appendix C: Vendors Supplied Component Specifications

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| LM741 Amplifier                  | ● The LM741 can be operated in either single supply or dual supply. This application is configured for dual supply  
                                 |   ● with the supply rails at ±15 V  
                                 |   ● improved performance over industry  
                                 |   ● standards like the LM709. It is intended for a wide range of analog applications. The high gain and wide range of  
                                 |   ● operating voltage provide superior performance in integrator, summing amplifier, and general feedback  
                                 |   ● applications  
                                 |   ● GBW ≈ 1.5MHz (Typical)  
| LM340 Voltage Regulator          | ● Available in Fixed 5-V, 12-V, and 15-V Options  
                                 |   ● Line Regulation of 0.01% / V of at 1-A Load  
                                 |   ● Load Regulation of 0.3% / A (LM340A)  
                                 |   ● Output Capacitance Not Required for Stability  
                                 |   ● Output Voltage Tolerances of ±2% at TJ = 25°C  
| LM358 Op-Amp                     | ● Wide supply range of 3 V to 36 V (B, BA versions)  
                                 |   ● GBW = 1.2MHz (Typical)  
                                 |   ● These devices consist of two independent, high-gain frequency-compensated operational amplifiers designed to operate from a single supply over a wide range of voltages.  
                                 |   ● Max Input Voltage up to 40V  
| 1 µF ±10% 50V Ceramic Capacitor  | ● 50V Rated Voltage  
                                 |   ● 10% Capacitance Tolerance  
                                 |   ● Lead (Pb)-free, RoHS and REACH compliant  
                                 |   ● X7R temperature stable dielectric  


| **10 kOhms ±5% 0.25W, 1/4W Through Hole Resistor** | ● ¼ Watt Power Rating @70° C  
● 350V Working Max Voltage  
● 600V Max Overload Voltage  
● 5% Ohmic Range Tolerance  
| **3.50mm (0.141", 1/8", Mini Plug) - Headphone Phone Jack Stereo (4 Conductor, TRRS) Connector Solder** | ● 3.50mm (0.141", 1/8", Mini Plug) - Headphone Phone Jack Stereo (4 Conductor, TRRS) Connector Solder  
| **20 kOhms 0.2W, 1/5W Through Hole Slide Potentiometer Top Adjustment Type** | ● 0.2W Max Power Rating  
● 20% Tolerance  
● 20kOhms, 30mm travel range  
| **Simolio 4-Pack of Vehicle IR Headphones** | ● 11cm Adjustability  
● AAA Battery Power  
● 20 Hours Battery Life  
● 3.5mm TRRS Aux Jack  
● -20 Passive Noise Canceling  
● [Amazon Hyperlink](https://www.amazon.com) |
| **SIOCEN 3 Pack DC Power 1 Female to 2 Male 5.5 mm x 2.1mm DC Power Supply Splitter Cable COOrd** | ● Material: Our Cable is made of great High-quality copper, and covered with PVC material.  
● Color : Black;Connector : 2.1mm x 5.5mm Length: 11.8inch/30cm Weight : 41g  
● Product Name : DC 1 Female to 4 Male Power Splitter Cable  
● Compatible with 12V DC Components for camera power connecting supply and led strip light single color 3528 5050, Bars, and other low voltage accessories, Avoid Soldering with easy-plug 5.5x2.1mm DC Jack connector.  
● [Amazon Link](https://www.amazon.com) |
| **12 V 5A Power Supply, Waysse Power Supply Adapter** | ● AC/DC Power Adapter  
● Input: AC 110-220V 50/60Hz  
● Output: DC 12V 5A max  
● 60 watts Max  
● DC Connector: 5.5mm x 2.1mm  
● [Amazon Link](https://www.amazon.com) |
| **Simolio Dual Channels IR Transmitter with Optical in** | ● IR Frequency Channel:  
  ○ Channel A: L-2.3MHz R-2.8MHz  
  ○ Channel A: L-3.2MHz R-3.8MHz  
● Effective Range up to 30 feet  
● RCA to 3.5mm audio cable  
● 3.5mm to 3.5mm audio cable  
● [Amazon Link](https://www.amazon.com) |
<table>
<thead>
<tr>
<th>Car Lighter:</th>
<th>Bietrun UHF Wireless Microphone Headset</th>
</tr>
</thead>
<tbody>
<tr>
<td>● Car Lighter:</td>
<td>● Built-in high sensitivity condenser microphone, transmission distance upgrade to 160 Feet</td>
</tr>
<tr>
<td>○ Output: DC 12V/400mA</td>
<td>● Built-in 400 mAh rechargeable lithium-ion batteries that can offer about 6 hours working time.</td>
</tr>
<tr>
<td>○ DC Plug 4.0x1.7mm</td>
<td>● The USB cable has two micro USB V2.0 to charge the transmitter and receiver simultaneously. Fully charged is only 2.5 hours.</td>
</tr>
<tr>
<td>● Dual Channel</td>
<td>● The plug on the receiver is 3.5mm. For 6.35mm amplifiers, please use the additional 6.35mm adapter (included) to connect more equipment.</td>
</tr>
<tr>
<td>● Amazon Link</td>
<td>● Use up to 15 microphone headsets at the same time.</td>
</tr>
</tbody>
</table>
Appendix D: Chassis Design

The chassis was designed in TinkerCad in two halves, designed to be connected with screws. Starting with the bottom half, seen in Fig. D.1 there are six indents and holes on the front face of the chassis, these are for each of the Bluetooth Receivers and are roughly in the same shape as their front faces. This was designed to be an obvious place to plug the receivers into the TRRS connectors which also have slots as seen in Fig. D.2 which are designed to be mounting positions that provide structural stability for these connectors. Also considering that these are the parts that will be interacted with most frequently and most roughly by the user, extra care was taken to provide as much strength as possible so these will not be the first point of failure. Also seen in Fig. D.1 is the hole on the right side, this is designed to be the entry point for power into the chassis which has a female port mounted on it that should the chassis fall and have the power cord yanked, it should unplug from the box before causing any tears on wires within.

![Fig. D.1: Chassis Bottom Half Front and Side-View](image)

The last details about the bottom half are the standoffs and screw holes. The four columns in the center empty part of the box correspond to where screw holes would be on the PCB which was an agreed upon design aspect between the designers. This serves as a mounting spot for the PCB using screws which allows it to be removed in case repairs are needed but also a stable spot so that the PCB won’t rattle around loosely inside the chassis. The size of the holes in the standoffs correspond to be just a mm smaller than the thread width of the chosen screw so that holes wouldn’t need to be drilled and so that there is space for the screws to be manually threaded. The location of the holes on the four corners in Fig. D.2 also has some additional reinforcement so they won’t break out the sides and also correspond to the location of the holes on the top half of the chassis as seen in Fig. D.3.
Fig. D.2: Chassis Bottom Half Top-View

Fig. D.3: Chassis Top Half Top-View
The top half of the chassis was designed to contain the IR Transmitter while also keeping any wires hidden for aesthetics and so end users don't need to do as much while setting up the device by keeping wires plugged in and maintaining one cohesive unit. As seen in Fig. D.4 there is a small compartment to contain the IR Transmitter, this space was designed so that the transmitter could slide in and be both secure and keep the front half exposed as line-of-sight is needed for its functionality. The functional parts are the bar in front which prevents it from sliding out and the wings inside which prevent it from falling backwards into the chassis. The last point of note is the hole within the compartment that leads to the interior of the bottom half of the chassis, this is meant to route the cables for power and audio to the IR Transmitter while keeping it from view.

Fig. D.4: Chassis Bottom Half Front-View
## Appendix E: Troubleshooting

### Table E.1: Troubleshooting for Bluetooth Pairing & Operation

<table>
<thead>
<tr>
<th>Issue</th>
<th>Solution</th>
</tr>
</thead>
</table>
| 1 Pairing Bluetooth Microphones and Receivers   | All Bluetooth Microphones and Receivers should already be paired with each other. To verify this do the following:  
1. Turn on the Microphone  
2. Within 10 seconds turn on the Receiver  
If the blue light on both devices stays on (not flashing) then they are paired. If either light is flashing, refer to Issue 5 below. |
| 2 No Sound At All                                | Ensure the following:  
- Power to the Communications Box is plugged in and secure  
- Bluetooth receivers plugged all the way in  
- Bluetooth receivers are turned on and paired  
- Headphones are switched on to Channel A  
- The Headphones have L.O.S. with the communications box  
- Sunlight is not in direct contact with the Headphones  
If issues persist then recharge the Bluetooth Receiver and Bluetooth Microphone and/or replace the batteries in the Headphones. |
| 3 Sound Only on One Side of Headphones          | This is a known issue caused by low power on the headphones, replace the AA batteries located in the left earmuff to resolve the issue. |
| 4 Warbling Interference and Sound Distortion    | This issue is caused by multiple microphones being paired to the same channel. Locate the correct microphone by turning them off one at a time until the interference stops. Turn said microphone and receiver back on and hold down the “+” button for several seconds until a beep is heard over the headphones. Repeat until the issue is resolved. |
| 5 Flashing Blue Light on Bluetooth Receiver     | This indicates that the receiver is not paired with its respective microphone. If the issue does not resolve itself within 20 seconds then do the following:  
1. Turn off all Bluetooth Microphones and Receivers  
2. Turn on the Microphone then the Receiver and wait for the flashing to resume  
3. Hold the “+-” button on the microphone for 10 seconds or until the Microphone’s light flashes  
4. Wait for both lights to stay on, indicating they have been paired |
| 6 Low Volume Sound                              | This can be caused by a few things:  
- Ensure that the user is speaking directly into the side of the Microphone  
- Press the “+” until desired volume is reached (multiple beeps after pressing the button once indicates that the maximum volume has been reached)  
- Locate the volume knob on the right earmuff of the |
| 7 | Red Light on Bluetooth Microphone and/or Receiver | This is the low battery warning, recharge the corresponding Receivers and Microphones |