Final Report

Team 5: Com 1 Com All

Joe Gluvers, Justin Slocum, Josh Velthouse
Friday, May 09, 2008
# Final Report Table of Contents

**Team 5 – Com 1 Com All**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TABLE OF FIGURES</strong></td>
<td>- 6 -</td>
</tr>
<tr>
<td><strong>TABLE OF TABLES</strong></td>
<td>- 7 -</td>
</tr>
<tr>
<td><strong>INTRODUCTION</strong></td>
<td>- 8 -</td>
</tr>
<tr>
<td>1.1 SENIOR DESIGN</td>
<td>- 8 -</td>
</tr>
<tr>
<td>1.2 THE PROJECT</td>
<td>- 8 -</td>
</tr>
<tr>
<td>1.3 TEAM DESCRIPTION</td>
<td>- 8 -</td>
</tr>
<tr>
<td>1.3.1 Joe Gluvers</td>
<td>- 9 -</td>
</tr>
<tr>
<td>1.3.2 Justin Slocum</td>
<td>- 9 -</td>
</tr>
<tr>
<td>1.3.3 Josh Velthouse</td>
<td>- 9 -</td>
</tr>
<tr>
<td>1.4 PROBLEM STATEMENT</td>
<td>- 10-</td>
</tr>
<tr>
<td>1.5 THIS DOCUMENT</td>
<td>- 10-</td>
</tr>
<tr>
<td><strong>2.0 PROJECT OBJECTIVES</strong></td>
<td>- 10-</td>
</tr>
<tr>
<td>2.1 AFFORDABILITY</td>
<td>- 10-</td>
</tr>
<tr>
<td>2.2 SIMPLICITY (TRANSPARENCY)</td>
<td>- 11-</td>
</tr>
<tr>
<td>2.3 INSENSITIVE TO AC POWER FLUCTUATIONS</td>
<td>- 11-</td>
</tr>
<tr>
<td>2.4 EASILY MANUFACTURABLE</td>
<td>- 11-</td>
</tr>
<tr>
<td><strong>3.0 CHRISTIAN PERSPECTIVE</strong></td>
<td>- 11-</td>
</tr>
<tr>
<td>3.1 PRODUCT’S PURPOSE</td>
<td>- 11-</td>
</tr>
<tr>
<td>3.2 SPECIFIC DESIGN NORMS</td>
<td>- 12-</td>
</tr>
<tr>
<td>3.2.1 Transparency</td>
<td>- 12-</td>
</tr>
<tr>
<td>3.2.2 Integrity</td>
<td>- 12-</td>
</tr>
<tr>
<td>3.2.3 Stewardship</td>
<td>- 13-</td>
</tr>
<tr>
<td>3.2.4 Cultural Appropriateness</td>
<td>- 13-</td>
</tr>
<tr>
<td>3.2.5 Trust</td>
<td>- 13-</td>
</tr>
<tr>
<td>3.2.6 Caring</td>
<td>- 13-</td>
</tr>
<tr>
<td>3.2.7 Justice</td>
<td>- 14-</td>
</tr>
<tr>
<td><strong>4.0 DETAILED DESIGN REQUIREMENTS</strong></td>
<td>- 14-</td>
</tr>
<tr>
<td>4.1 PROTOTYPE REQUIREMENTS</td>
<td>- 14-</td>
</tr>
<tr>
<td>4.1.1 Functionality</td>
<td>- 14-</td>
</tr>
<tr>
<td>4.1.2 Power</td>
<td>- 17-</td>
</tr>
<tr>
<td>4.1.3 Size</td>
<td>- 18-</td>
</tr>
<tr>
<td>4.1.4 Environmental</td>
<td>- 18-</td>
</tr>
<tr>
<td>4.1.5 Cost</td>
<td>- 18-</td>
</tr>
<tr>
<td>4.2 PRODUCTION REQUIREMENTS</td>
<td>- 19-</td>
</tr>
<tr>
<td>4.2.1 Functionality</td>
<td>- 19-</td>
</tr>
<tr>
<td>4.2.2 Power</td>
<td>- 19-</td>
</tr>
<tr>
<td>4.2.3 Packaging</td>
<td>- 19-</td>
</tr>
<tr>
<td>4.2.4 Environmental</td>
<td>- 20-</td>
</tr>
<tr>
<td>4.2.5 Cost</td>
<td>- 20-</td>
</tr>
<tr>
<td>4.2.6 FCC Compliance</td>
<td>- 20-</td>
</tr>
<tr>
<td><strong>5.0 ALTERNATIVE SOLUTIONS</strong></td>
<td>- 21-</td>
</tr>
<tr>
<td>5.1 “WIRELESS” WIRED SYSTEM</td>
<td>- 21-</td>
</tr>
<tr>
<td>5.2 WIRED SYSTEM</td>
<td>- 21-</td>
</tr>
<tr>
<td>5.3 RF WIRELESS SYSTEM</td>
<td>- 22-</td>
</tr>
</tbody>
</table>
6.0 INTELLECTUAL PROPERTY CONCERNS/OPPORTUNITIES ........................................... - 22 -
6.1 WIRELESS INTERCOM PATENTS ........................................................................... - 23 -
6.2 DESIGN COMPONENT PATENTS ........................................................................ - 23 -
6.3 INTELLECTUAL PROPERTY PROTECTION AND POSSIBILITIES ...................... - 24 -
7.0 MARKET STUDY ........................................................................................................ - 24 -
7.1 COMPETITION IN THE MARKET .............................................................................. - 24 -
7.1.1 Home Power Circuit Intercom Systems ................................................................. - 25 -
7.1.2 High-end Wired Intercom Systems ...................................................................... - 25 -
7.1.3 Wireless Intercom Systems .................................................................................. - 26 -
7.2 TCOM’S PLACE IN THE MARKET .......................................................................... - 27 -
7.3 SALES PROSPECTS ............................................................................................... - 27 -
8.0 PRELIMINARY DESIGN ............................................................................................ - 27 -
8.1 SYSTEM DESIGN ..................................................................................................... - 27 -
8.1.1 Modular Unit Network Implementation ................................................................. - 27 -
8.1.2 Modular System Design ...................................................................................... - 28 -
8.2 SOFTWARE DESIGN ................................................................................................ - 30 -
8.2.1 Auto Setup ......................................................................................................... - 31 -
8.2.2 Network ............................................................................................................. - 31 -
8.2.3 Update ............................................................................................................... - 31 -
8.2.4 Top Menu .......................................................................................................... - 32 -
8.2.5 Call and Receive ................................................................................................. - 32 -
8.2.6 Talk and Listen ................................................................................................... - 32 -
8.2.7 Alarm and Clock Set .......................................................................................... - 32 -
8.2.8 Watchdog ........................................................................................................... - 32 -
8.3 NETWORK PROTOCOL ........................................................................................... - 32 -
8.3.1 Call Request and Monitor .................................................................................. - 33 -
8.3.2 Talk Start, Talk End, and Call End ..................................................................... - 33 -
8.3.3 New Module Request and New Module Return .................................................. - 33 -
8.3.4 Update ............................................................................................................... - 33 -
9.0 HARDWARE SELECTION ........................................................................................ - 34 -
9.1 PRELIMINARY BLOCK DIAGRAM ....................................................................... - 34 -
9.2 WIRELESS TRANSMISSION TECHNOLOGY ......................................................... - 35 -
9.3 MICROCONTROLLER ............................................................................................. - 37 -
9.4 SIGNAL PROCESSING SOLUTION ....................................................................... - 38 -
9.5 LCD DISPLAY .......................................................................................................... - 38 -
9.6 USER KEYPAD AND SCROLL WHEEL CONTROL .................................................... - 39 -
9.7 REAL TIME CLOCK ............................................................................................... - 39 -
9.8 MICROPHONE ........................................................................................................ - 39 -
9.9 SPEAKER ................................................................................................................ - 40 -
9.10 ANTENNA ............................................................................................................ - 40 -
9.11 ADDITIONAL ANALOG CIRCUITRY .................................................................. - 40 -
9.12 POWER SUPPLY ................................................................................................. - 40 -
9.12.1 Prototype Supply ............................................................................................... - 40 -
9.12.2 Final Production Supply ................................................................................... - 41 -
9.13 CIRCUIT BOARD LAYOUT .................................................................................... - 41 -
9.14 PRODUCT PACKAGING ....................................................................................... - 41 -
9.15 CURRENT BLOCK DIAGRAM ................................................................................ - 42 -
10.0 HARDWARE DESIGNS PROCESS .......................................................................... - 43 -
10.1 PIC DEVELOPMENT BOARD .................................................................................................................. - 43 -
10.2 AUDIO CODEC PROTOTYPE BOARD .................................................................................................... - 44 -
10.3 BREADBOARD PROTOTYPING ........................................................................................................... - 45 -
10.4 CHANGING TO THE PIC18F45J10 ..................................................................................................... - 45 -
10.5 PIC18F45J10 PROGRAMMING CIRCUIT ............................................................................................. - 46 -
10.6 TRANSCEIVER PROTOTYPING ............................................................................................................ - 46 -
10.6.1 Initial Prototype Boards ..................................................................................................................... - 46 -
10.6.2 Surface Mount Difficulties ............................................................................................................... - 48 -
10.6.3 Antenna Design ................................................................................................................................... - 49 -
10.6.4 Antenna Ground Plane ..................................................................................................................... - 49 -
10.6.5 Development Boards ....................................................................................................................... - 50 -
10.7 LCD CIRCUIT DESIGN ....................................................................................................................... - 50 -
10.7.1 Backlight Control ............................................................................................................................. - 51 -
10.7.2 Setting LCD Contrast ....................................................................................................................... - 51 -
10.8 ADDITIONAL CODEC OPTIONS ......................................................................................................... - 51 -
10.8.1 XE3005 ............................................................................................................................................. - 51 -
10.8.2 320AIC .............................................................................................................................................. - 52 -
10.9 ADC AND DAC AUDIO SOLUTION .................................................................................................... - 52 -
10.9.1 Internal Analog to Digital Converter ............................................................................................. - 52 -
10.9.2 External Digital to Analog Converter ............................................................................................. - 52 -
10.10 HUMAN INTERFACE DESIGN ......................................................................................................... - 53 -
10.10.1 Scroll Wheel Control ...................................................................................................................... - 53 -
10.10.2 Buttons .......................................................................................................................................... - 53 -
10.11 AUDIO INPUT CIRCUIT ..................................................................................................................... - 53 -
10.11.1 Microphone Selection .................................................................................................................... - 53 -
10.11.2 Signal Amplitude Issues ............................................................................................................... - 54 -
10.11.3 Input Audio Filtering ...................................................................................................................... - 54 -
10.12 AUDIO OUTPUT CIRCUIT .................................................................................................................. - 55 -
10.13 PROTOTYPE SCHEMATICS ................................................................................................................ - 56 -
10.14 CIRCUIT BOARD DESIGN ................................................................................................................ - 56 -
10.14.1 Four Layer Board Design ............................................................................................................. - 57 -
10.14.2 Two Layer Board Design ............................................................................................................ - 58 -
10.15 SINGLE BREADBOARD PROTOTYPE ............................................................................................... - 59 -
10.16 CIRCUIT BOARD PROTOTYPE .......................................................................................................... - 60 -

11.0 SOFTWARE DESIGN PROCESS ............................................................................................................ - 61 -

11.1 ITERATIVE APPROACH ....................................................................................................................... - 61 -
11.2 DEVELOPMENT SOFTWARE ............................................................................................................... - 61 -
11.3 SYSTEM PROTOTYPES ..................................................................................................................... - 61 -
11.3.1 The Hello World Program ................................................................................................................ - 61 -
11.3.2 Subroutines ...................................................................................................................................... - 61 -
11.3.3 Hello World 2 for the PIC18F45J10 ............................................................................................... - 61 -
11.3.4 Liquid Crystal Display and Random Access Memory Tables ....................................................... - 62 -
11.3.5 Transceiver Boards ....................................................................................................................... - 62 -
11.3.6 Codecs and Converters .................................................................................................................. - 62 -
11.3.7 Transceiver Modules ..................................................................................................................... - 63 -
11.3.8 Audio Test Egg ............................................................................................................................. - 63 -
11.3.9 Flash Reading and Writing ............................................................................................................. - 63 -
11.3.10 Timer ............................................................................................................................................ - 63 -
11.3.11 Watchdog ..................................................................................................................................... - 64 -
11.4 COMBINING SYSTEM SOFTWARE ..................................................................................................... - 64 -
11.4.1 ADC and TxRx Prototypes .............................................................................................................. - 64 -
11.4.2 LCD and Timer ............................................................................................................................. - 64 -
11.5 THE FINAL PROTOTYPE SOFTWARE ............................................................. - 64 -
11.5.1 Proto.asm ....................................................................................... - 64 -
11.5.2 Proto1.asm .................................................................................... - 66 -
11.5.3 Proto2.asm and Proto3.asm ............................................................ - 67 -
11.5.4 Proto4.asm .................................................................................... - 67 -
11.5.5 Proto5.asm and proto6.asm ............................................................ - 67 -
11.5.6 Proto7.asm .................................................................................... - 68 -
11.5.7 Proto7board.asm ........................................................................... - 68 -
11.6 MANUFACTURE’S SOFTWARE DESIGN ................................................ - 68 -
11.6.1 Rx during menus and more interrupt uses ...................................... - 69 -
11.6.2 Networking Changes ..................................................................... - 69 -

12.0 FINAL PROTOTYPE DESIGN .................................................................... - 69 -
12.1.1 Final Design Schematics ................................................................. - 70 -
12.1.2 Circuit Board Design ....................................................................... - 73 -
12.2 PARTS LIST/BOM ................................................................................ - 74 -

13.0 BUSINESS STUDY AND PLANS ............................................................. - 76 -
13.1 PRODUCT DESCRIPTION ...................................................................... - 76 -
13.2 BUSINESS STRUCTURE ....................................................................... - 76 -
13.2.1 Goals ............................................................................................. - 76 -
13.2.2 Purpose .......................................................................................... - 77 -
13.2.3 Foundation ..................................................................................... - 77 -
13.3 MARKETING PLAN ............................................................................ - 77 -
13.3.1 The Typical Customer and Marketing Strategy ............................... - 78 -
13.3.2 Expanding Customer Base .............................................................. - 78 -
13.3.3 Long Term Marketing Strategy ....................................................... - 78 -
13.4 RESEARCH AND DEVELOPMENT ..................................................... - 78 -
13.4.1 Product Growth Brings Business Growth ......................................... - 79 -
13.4.2 Additions to the t\textsuperscript{com} Product Offerings ...................... - 79 -
13.4.3 New Market and Product Research ................................................ - 79 -
13.4.4 New Product Development ............................................................ - 79 -
13.5 MANUFACTURING ............................................................................. - 79 -
13.5.1 The Infant Company ....................................................................... - 80 -
13.5.2 The Young but Growing Company .................................................. - 81 -

14.0 FEASIBILITY STUDIES .......................................................................... - 83 -
14.1 AUDIO QUALITY STUDY ...................................................................... - 83 -
14.1.1 Bit Depth ....................................................................................... - 83 -
14.1.2 Frequency Range ........................................................................... - 84 -
14.1.3 Noise ............................................................................................. - 84 -
14.1.4 Audio Quality of Design ................................................................ - 85 -
14.2 DATA TRANSFER ANALYSIS .............................................................. - 85 -
14.2.1 Transceiver ................................................................................... - 85 -
14.2.2 Codec ............................................................................................ - 85 -
14.2.3 Microprocessor ............................................................................... - 86 -
14.3 POWER CONSUMPTION ANALYSIS ................................................. - 86 -
14.3.1 Total Power Usage ......................................................................... - 86 -
14.3.2 Components of Interest ................................................................. - 87 -
14.4 ECONOMIC ANALYSIS ...................................................................... - 89 -
14.4.1 Parts List and Bill of Material ......................................................... - 89 -
11.4.2 Manufacturing Costs ...................................................................... - 90 -
Table of Figures

Figure 1: Team Photo ........................................................................................................ - 9 -
Figure 2 - GE/Jasco TL97600 ...................................................................................... - 25 -
Figure 3 - GE SmartCom Module .................................................................................. - 26 -
Figure 4 - Westinghouse WHI-4CUPG ....................................................................... - 27 -
Figure 5 - System Level Functionality ......................................................................... - 28 -
**Figure 6 - Initial Design Concept** ............................................................................. - 30 -
Figure 7 - Software Block Diagram .............................................................................. - 31 -
Figure 8 - Initial Hardware Block Diagram ................................................................... - 34 -
Figure 9: Designed Usage of Set Frequency Channels ...... .................................... - 36 -
Figure 10: Product Packaging ....................................................................................... - 42 -
Figure 11: Current Hardware Block Diagram .............................................................. - 43 -
Figure 12 - Pinout for AD74111 Audio Codec ............................................................... - 44 -
Figure 13 - AD74111 Prototype Board Layout ............................................................. - 45 -
Figure 14 - Required Circuit for In Circuit Serial Programming (PICkit 2 17) ......... - 46 -
Figure 15 - Schematic for nRF24L01 Circuit ............................................................... - 47 -
Figure 16 - Example Board Layout for nRF24L01 ....................................................... - 48 -
Figure 17 - Transceiver Prototype Board Layout ........................................................... - 48 -
Figure 18 - nRF24L01 QFN Package and Pinout ......................................................... - 49 -
Figure 19 - Antenna Image in Reference to Ground Plane ........................................... - 50 -
Figure 20 - Circuit Schematic for XE3005 Audio Codec ............................................... - 51 -
Figure 21 - Prototype Board Layout for XE3005 ........................................................... - 52 -
Figure 22 - MCP4822 Package Pinout ......................................................................... - 53 -
Figure 23: Inverting Amplifier ..................................................................................... - 54 -
**Figure 24: Low Pass Multiple Feedback Architecture (Texas Instruments)** .......... - 54 -
Figure 25: Second-Order 3-dB Chebyshev Filter Frequency Response (Texas Instruments) ........................................................................................................... - 55 -
Figure 26: Analog Output Stage .................................................................................... - 56 -
Figure 27 - Four Layer Board Top Layer ..................................................................... - 57 -
Figure 28 - Four Layer Board Bottom Layer ............................................................... - 58 -
Figure 29 - Four Layer Board Outside Layers with Drill Holes ................................... - 58 -
Figure 30 - Full Two Layer Board Design .................................................................. - 59 -
Figure 31 - Sinlge Breadboard Prototype ..................................................................... - 60 -
Figure 32 - Assembled Printed Circuit Board Prototype ............................................... - 60 -
Figure 33: Schematic of PIC Control Circuit ............................................................... - 70 -
Figure 34: Audio Input Circuit ..................................................................................... - 71 -
Figure 35: Audio Output Circuit ................................................................................... - 71 -
Figure 36: LCD Module Circuit .................................................................................. - 72 -
Figure 37: Transceiver Circuit ....................................................................................... - 72 -
Figure 38 - Two Layer Board Component Layer ....................................................... - 73 -
Figure 39 - Two Layer Board Bottom Layer ............................................................... - 74 -
Figure 40 - Signal Approximation with Bit Resolution (zone.ni.com) ...................... - 84 -
Table of Tables

Table 1 - Available Intercom Examples .............................................................. - 25 -
Table 2 – Network Protocol Instruction Set ..................................................... - 33 -
Table 3 - Decision Matrix for Wireless Protocol ........................................... - 35 -
Table 4 - Decision Matrix for Transceiver Selection ..................................... - 36 -
Table 5 - Microcontroller Decision Matrix ..................................................... - 37 -
Table 6 - LCD Decision Matrix ..................................................................... - 38 -
Table 7 - Microphone Decision Matrix ......................................................... - 39 -
Table 8: Bill of Materials .............................................................................. - 74 -
Table 9 - Component Power Requirements .................................................... - 86 -
Table 10 – Power Usage of the nRF24L01 Transceiver .................................. - 88 -
Table 11 - Cost For Purchased and Needed Parts ......................................... - 90 -
Introduction

This document is the compilation and documentation of the work done by 2008 Calvin College Senior Design Team 5: Com 1 Com All. This section introduces the reader to the context in which this project will be completed including: the class, the team, the project, and what will be found in the remainder of this report.

1.1 Senior Design

Calvin College is a small liberal arts college in Grand Rapids, MI which offers an Accreditation Board for Engineering and Technology (ABET) accredited engineering degree in chemical, civil, electrical, and mechanical concentrations. As the core capstone of this major Engineering 339/340 Senior Design requires students to form a team to research and design a solution to a problem or fill a need.

1.2 The Project

Intercoms allow a person to communicate with another person or all persons within earshot of an intercom module when circumstances prohibit face to face communication. Unfortunately, installation of a wired intercom system is an arduous task because it involves running communications wires between all points that require communication. These wires can be a major eyesore if great care is not taken to run them through walls, ceilings and floors, so the obvious solution is to do away with the new communication wires. Two main solutions exist for this: power line communication, and wireless radio frequency (RF) transmission. Com 1 Com All has decided to design a wireless RF intercom solution called t\textsubscript{COM}.

1.3 Team Description

Com 1 Com All is a design team made up of three senior engineers in the electrical and computer concentration: Joe Gluvers, Justin Slocum and Josh Velthouse. Members of the team can be seen below in Figure 1.
1.2.1 Joe Gluvers

Joe is a senior engineer in the electrical concentration, and has a broad taste within the field of electrical engineering. This summer he worked for Twisthink LLC in Holland, MI as an intern and developed his skills in test development and reporting. Joe is originally from Sacramento, CA where he attended Rocklin High School before coming to Calvin College. He is also a four year varsity swimmer for Calvin and a team captain this year. He recently celebrated his first wedding anniversary and will be working mostly on the overall visual design and human interface of the device.

1.2.2 Justin Slocum

Justin is focused on hardware design and board layouts for digital and analog electrical systems; he is working on an engineering degree of electrical concentration and a math minor. While working at DornerWorks Embedded Systems Engineering in Grand Rapids, MI this summer and through this year Justin worked on development and testing of embedded hardware systems as well as gained experience in reverse engineering. He hails from suburban Detroit where he attended Oscar A. Carlson High School before coming to Calvin College. When not engineering, Justin is also a member of the Calvin College Capella. He worked on the board layout, RF communication, and other various support tasks.

1.2.3 Josh Velthouse
Josh is a programming-focused engineer with an electrical and computer concentration and will receive an additional math minor. He worked as an intern at Gentex Corporation in Holland, MI where he gained valuable experience in a manufacturing environment. Josh is originally from Holland and attended Holland Christian High School prior to attending Calvin College. He also enjoys singing, reading, and creating. It is likely he will be working on much of the programming and related functionality of the design.

1.4 Problem Statement

In the home intercom market there are three prevalent products: low-cost systems that transmit through the house’s power lines, low quality wireless radio frequency intercom systems that offer little more than simple communication similar to walkie-talkies, and advanced wired intercoms that mesh with home security systems. These high-end systems offer video communication and surveillance, home control features, and cost upwards of a thousand dollars per module. Both of the more economical options suffer from signal degradation, and the power line transmission method is hindered by interference from the household power grid. Our goal is to provide reliable and feature-rich wireless communication to both do-it-yourself home improvers and new home builders to fit in the niche between the represented extremes.

1.5 This Document

This document details the engineering design and prototyping progress made by the team this year. It begins with the broad objectives we intended to achieve in our design. Next we describe how our Christian faith informs our design. At the beginning of the project we explored alternate solutions and they are discussed next, then intellectual property concerns with our chosen solution. After that the results of or competition survey are presented. Then we get into the specifics of our design starting with the specific design requirements, and next showing our final prototype progress. Then we move into the production and business plans, followed by the feasibility studies conducted last semester and our testing plans and results for both prototype and final manufactured product. Finally we report the task breakdown, schedule, and our conclusion followed by acknowledgements, references and appendices.

2.0 Project Objectives

This section will outline the major objectives which Com 1 Com All hoped to accomplish in the design and testing of the tCOM intercom system. Project objectives include: affordability, simplicity and transparency, AC (alternating current) power fluctuation insensitivity, and Manufacturability.

2.1 Affordability

At the core tCOM is a commercial product and therefore must turn a profit when sold, however, in a competitive market if the product is not worth the asking price customers will ignore it and it
will never turn a profit. Therefore, the tCOM system must be affordable to manufacture, so that it can be affordable to own, in that it does not have an exorbitant initial cost, nor unrealistic maintenance and operating costs.

2.2 Simplicity (Transparency)

Each tCOM station needs to be extremely easy to use so that the entire family including children and disabled persons whom might need the system the most can benefit from the installation of a home intercom system. Device setup and programming also should be easy, so it will appeal to all people not just the tech savvy. With these two objectives complete tCOM will appeal to the widest possible user base, directly impacting the number of units sold.

2.3 Insensitive to AC Power Fluctuations

Fluctuations in the AC line voltage can cause damage to a system’s components if the voltage is not properly regulated. In addition to component damage the talk over the power lines intercom systems, fluctuations in the AC line voltage cause pops and buzzes in the communication line. This would cause the users to turn off the intercom and forget to turn it back on. An intercom is not useful when it cannot transmit and receive data, so our device will have communications isolated from the AC line, thus lowering the noisy interference, and protecting sensitive components.

2.4 Easily Manufacturable

To improve production cost and compete commercially tCOM must be able to make the transition from prototype single board builds to mass manufacture. Mass production procedures such as automated board fabrication, automated testing, and automated final assembly and packaging bring down the per-unit cost.

3.0 Christian Perspective

Since we are all Christian engineers, our faith undoubtedly will have a significant impact on both our final system design in addition to how we go about our design process. Although this project at first glance may not seem to have specific applications for “Christian life” or “outreach”, the final product would impact everyday living which is itself an offering to God. Also, community and relationships are central to human life for people of all religious perspectives and an intercom system is one way to further enable communication between friends, families, and coworkers. What could be seen as a somewhat insignificant gadget could have significant impact on how people live with each other in worship to their creator.

3.1 Product’s Purpose
The overall aim of the tCOM is to enable communication within a home or business. This is done by enabling verbal contact between areas/rooms which were previously physically separated by walls or physical distance. Although not a necessity, having an intercom system offers a simple way to save time and physical energy communicating between different locations in a building. In addition, the intercom system would also provide added safety to the home environment. Extra features like a “Listen Mode” (baby monitor type feature) would allow parents to monitor young children who are sleeping or playing in another room. We see our intercom system as a very useful addition for many homes and businesses.

3.2 Specific Design Norms

Design norms are a collection of ethical principles which engineers or other professionals can use as a framework on which to base the design of a product or process. They can be used effectively to remind the engineer what is needed by the end user and thus help to provide a better serve their client. In addition to affecting the end design, many of these design norms also apply directly to the design process itself and how the engineer carries out their work. Throughout our design process, we have and will continue to use design norms as a way of guiding choices for tCOM’s final system design. These will be explained in the context of our project in the following sections.

3.2.1 Transparency

It is essential for the intercom system to be intuitive for the user and easy to program and use. If the customer has difficulty learning how to use the system, it will not at all be useful. Additionally, young children may potentially have to use the intercom in the home setting. This means that small children must be able to easily learn and use the intercom as well as adults.

This will affect our design most noticeably in the area of the user interface. We want to provide the robust system features (“Com 1/Com All”, module naming, automatic network setup and upkeep, hot button communication, synchronized system clock, alarms) using only as many buttons as is necessary. Extra buttons would cause a cluttered and confusing exterior for the user resulting in something similar to a common remote control where the use is forced to hunt through the button labels to find the desired function.

3.2.2 Integrity

In addition to providing a product that is easy to use, we feel it is also extremely important that we provide the customer with a product that looks attractive, works well and respects their privacy concerns when using the intercom. Because of this the audio quality delivered to the end user should be of sufficient both in possible volume and audio quality with reduction of electrical noise. Other systems became functionally useless due to the problem of noise on the signal. So, it will be of key importance in the final integrity of our product. Also, the system should provide reliable functionality for the end user, secure communication kept within the home network, and not become quickly obsolete due to other technology changes. All of these are expectations of potential customers that must be met if our product is to serve them well.

Integrity also covers the area of how we work on the project and develop our designs. We are called to honesty in the amount and source of our ideas and eventual designs and should always give credit to those who have given us their valuable input.
3.2.3 Stewardship

We believe that it is extremely important to provide a high quality final product while making good use of our and the consumer’s resources. Solid technical functionality and low cost to the consumer should take precedent over flashy features that would drive up the final system cost. Many of the existing products on the market have a large financial cost for an intercom with robust functionality and wireless or dedicated wired audio transmission. It is our hope to be able to dramatically lower the final cost of our intercom while still providing robust features the consumer will find desirable, by using a more cost effective wireless transmission scheme. This will make it a more easily accessible product for those who may have ignored the product due to the high prices in the past.

3.2.4 Cultural Appropriateness

The fact that tCOM may be used in light commercial/business environments in addition to the residential environment adds another layer of complexity to the design tasks. Usage in a small business would be very different from in a home and thus requires a slightly different or more flexible design to account for these differences. For example, a monitor or listening mode may be a critical feature for a couple with a new baby but would probably be looked upon negatively in the work environment. As a result, our design must take into account the fact that the user may wish to prevent other intercoms from listening in on them by making some sort of blocking feature available.

Also, the possibility of this product being used in other countries must be considered in the final production design. This may not change the technical functionality offered by the tCOM, but it would have a major impact on how the product would be packaged and marketed in those countries, and affect the power supply design. It would be extremely short sighted to think that someone who only spoke or read French for example would be quick to buy a product which only used English. Exterior packaging should have varying markings based on the native language of the country in which it is being sold. In addition, the interactive menus displayed should have the option of changing the language to the user’s language of choice. Finally, each country will most likely have a slightly different view of the product in the marketplace and would require varying strategies in marketing and distribution.

3.2.5 Trust

The consumer being able to find the tCOM as a reliable and useful product will be critical to it finding a permanent place within the intercom market. In the past, many consumers were completely disappointed with the functionality of inexpensive systems which claimed wireless capability while the functionality depended completely on the wires within the building. Some of these consumers may have had their thoughts of purchasing an intercom greatly reduced and the tCOM will have to work at rebuilding the sense of trust in these products. As designers, we must be open and honest about the capabilities and functionality of the final design and portray it as such to the customer. If this is not done, the customer will feel betrayed and would be unlikely to look to our products in the future because of such a deception.

3.2.6 Caring

We want to design this product in such a way that we serve the customer’s needs by creating a product that will improve their everyday life. Every aspect of the design should look to improve the way it serves the end user’s immediate community. Caring for the customer encompasses all of the other design norms and is at the core of the design and design process.
3.2.7 Justice

We believe that Justice is applicable to our design and is supported by our inclusion of stewardship and transparency. Stewardship contributes to justice because if the product is affordable for all people we will not be discriminating against those who have less monetary wealth. Also our focus on transparency supports justice in our goal to make the device easy for all to use including young children and elderly people who may not be as technologically adept as the younger generations.

4.0 Detailed Design Requirements

The final intercom system should adhere to the requirements as listed below. Section 4.1 details the requirements for our final prototype design which will be tested on actual prototypes next semester. Requirements for the full scale production design are given in Section 4.2 as additions to the prototype requirements which will already have been met.

4.1 Prototype Requirements

As a means of solidifying the high level system design and focusing the design process, the requirements for the prototype system in terms of functionality, power usage, size, environmental concerns, and final cost are discussed.

4.1.1 Functionality

The final prototype design for the tCOM will:

1. Network no less than 255 intercom modules.

   One byte of data will be used to indicate the intended intercom to receive and carry out a given system instruction. Eight bits would allow for a maximum of 256 modules to be addressed. One of these addresses will allow for a message to be intended for all intercoms on the network. This makes the maximum number of intercoms 255 on a given network.

2. Provide and keep track of separate data transmission frequency channels dedicated to or being used for networking tasks, calling other modules and network detail updates, and direct audio transmission.

   Having a consistent knowledge of which frequency channels are being used by the tCOM network will be crucial to the final functionality. There will a dedicated RF (radio frequency) channel for all tCOM intercoms used for initial network setup and later intercom additions to the network. Another dedicated but changeable channel should be used to facilitate communication requests and updates of intercom station and network information. This information would include new intercoms on the network, updated intercom names, system clock changes, and channels and intercoms being used in audio
transmission. Any number of additional channels can then be used for audio transmission between intercom stations once the requests are facilitated.

3. Have a range no less than 300 m (1000 ft).

In our market study, available range from wireless intercom systems was one of our main areas of interest. Most wireless systems claimed a range of either 150 m (500 ft) or 300 m (1000 ft). Designing for a range of 1000 ft would keep us on the same level as existing competition and also make the t_{COM} much more flexible for physical network configurations.

4. Provide RF (radio frequency) audio transmission from one intercom to one or more other intercom stations.

The transmission should send audio in one direction at a time but the audio signal should be receivable by multiple stations within range of the output signal.

5. Provide the user a button to initiate conversation with a single module or group of intercom stations.

This will be called the “Com One” button and will be the general call button for conversation with any set of intercoms smaller than the whole network. After indicating which intercom(s) will receive the audio, pressing this button will allow the user to begin talking directly to the other intercoms.

6. Provide an audible busy signal when requesting another intercom already in conversation.

The user should not be able to initiate conversation and send audio to another station already in conversation. This would corrupt the signal being sent for the preceding audio transmission.

7. Provide the user a button to request conversation and transmit audio with all other modules.

The “Com All” button will be used as a general purpose call to all the network intercoms. When pressed, the user can begin talking with all the other intercoms.

8. Provide transition from initial “Com All” request to continued audio response from another intercom to all network intercoms or just the original “Com All” requester.

After initial audio is sent from the original requester, another user could press the “Com All” button on their intercom to send audio back to the entire network. Pressing the “Com One” button would end the entire network audio transmission and initiate a single conversation with the original requester.

9. Provide the user a button to end an intercom call.
Pressing this button would transmit a message to the other intercom(s) indicating that the current call has ended. Then the intercoms should return to the frequency channel dedicated to facilitating com requests.

10. Provide a monitor function which will receive and play audio from another intercom station.

This must also be subject to the end call button. The audio transmission must therefore provide gaps to allow the monitoring intercom to send the end call message to the intercom sending the audio. This is equivalent to a baby monitor.

11. Provide automatic network initialization upon initial startup.

When a \text{tCOM} is first opened and plugged in, it will be configured to receive data on the dedicated channel for network setup. If it does not receive a message from another intercom already on a network, it will then begin the process of initializing a network. This entails creating a network address, producing an encryption key, determine the network frequency channel used for facilitating com requests and network information updates, and then send this data to any other intercom that powers up within at most 5 minutes of its initial power up. All of these intercoms will be assigned an initial name to distinguish them on the network and address for network instructions.

12. Provide 128 bit data encryption for secure data transmission.

An exclusive-or operation will be done to all data sent over the transceiver with the encryption key produced during the automatic network initialization. This can be undone on the receiver side by an additional exclusive-or operation with the same network key which will be saved in each intercom.

13. Provide a process to add additional intercom units after the initial automatic network initialization process has completed.

There may be the need to add additional intercoms to a network after its initialization. This process should provide that new intercom with all the required network information from requirement (11) above and inform the intercoms on the network of the new intercom details (address and initial name).

14. Provide for module naming and renaming after initial network setup.

The naming feature will allow the users to easily determine which intercom they wish to communicate with due to a descriptive name.

15. Provide programmable hot buttons for one or more intercoms.
These buttons will be used to quickly select which intercoms will be used under an upcoming “Com One” call. They should be able to be reprogrammed by adding or removing an intercom from the button list.

16. Provide a system clock showing the time and date and also allows for synchronous updates among the entire network.

The clock should be set by the user and then be kept through the use of a real time clock or software routine. Any changes in the clock from any intercom station should be sent to the other stations which will update their own time based on that information.

17. Provide alarm options based on the system clock.

These alarms should cover single intercoms only and not to the entire network.

18. Provide a graphical (visual) interface to display an interactive menu system used to help the user control the intercom.

This menu will provide access to clock updates, setting alarms, programming hot buttons, adding additional intercom units, volume control, backlight control, monitor function, accessing network information on intercom names, and selecting a custom list of intercoms to call.

19. Provide a physical interface (buttons) to allow control of the module and system.

These will include the “Com One”, “Com All”, end call, four “hot buttons”, and the control for the interactive menu.

20. Provide a means of volume adjustment within existing buttons.

Volume must be able to be adjusted without adding additional buttons to the system. It should be controlled through the menu system when not transmitting audio and through the menu control buttons during audio transmission.

21. Have programmable backlight feature on the display for nighttime use based on the system clock.

The user must be able to turn the backlight off and adjust the brightness. Additionally they can program the time during the day in which the backlight will be used at all.

4.1.2 Power

For power supply requirements the tCOM prototype will:

1. Provide a nominal DC voltage above 5V using an AC to DC converter to convert standard outlet power.
The requirement of a voltage above 5V is due to the fact that we will need to regulate supply voltages at a 5V maximum for some integrated circuits. If the provided voltage is not adequate we will not be able to provide the required voltages.

2. Provide nominal voltages of 5V and 3V for integrated circuits in the design.

This should be done through integrated voltage regulators if possible. 5V and 3V were selected because they are the two commonly used supply voltages for almost all integrated circuits.

3. Use less than 5W in total power.

For an estimated ten year life, the cost of the power used if permanently receiving audio should remain less than the cost of purchasing the system.

4.1.3 Size

The prototype board should fit within the following size restraints:

1. Total dimensions no greater than – 5” by 8”

Based on the market study, this dimension will make the prototype board only a few inches in each direction larger than most available intercom packages. Assuming the final production design will be able to be made a few inches smaller in each direction, this should be an good requirement for the prototype.

4.1.4 Environmental

The prototype should adhere to the following environmental requirements:

1. All parts should be RoHS (reduction of hazardous substances) compliant.

$t_{\text{COM}}$ modules will comply with reduction of hazardous substances (RoHS) standards, this includes lead free components and soldering in the prototyping and production stages. The product must comply with these regulations in order to be marketed in Europe, and it will add to the safety of the product for the end user and community.

4.1.5 Cost

The final cost for an assembled prototype design shall:

1. Not exceed $100.

For adequate testing of the system, a minimum of three prototypes will be necessary. With the current project budget of three hundred dollars, each prototype will have to be assembled for a total cost to the team of less than $100.
4.2 Production Requirements

The production design must adhere to the requirements of the prototype design above and any additional requirements listed in this section.

4.2.1 Functionality

In addition to the prototype functionality, the production design must also:

1. Provide the option of changing the displayed language of the interactive menu system.

   In order to make the product marketable in other countries and non-English speakers, the options of additional display languages must be included.

4.2.2 Power

The power system of the production design must:

1. Convert AC power from the outlet with an on board AC to DC conversion circuit.

   The further regulation should be implemented on board as in the prototype design. This requirement helps to make the product more marketable due to the lack of an external power converter that will be used for prototyping.

4.2.3 Packaging

Intercom packaging for the production design must:

1. Have a maximum allowable size of 5” by 8” by 1.5”.

   This was determined based on comparisons to available wireless intercoms in the market study.

2. Have a maximum allowable circuit board size of 4.5” by 7.5” by 1.25”.

   This is based on the maximum size of the product packaging. The circuit board must be able to fit inside the exterior packaging.

3. Provide the capability to be wall mountable, flush mountable, and free-standing within the same package design.

   These options would further improve the marketability and flexibility of the tCOM for the end user. Wall mountable entails the intercom being hung from a nail like a picture frame. Flush mountable entails the package being embedded within the wall so the face is roughly even with the wall. Free standing entails standing on a desk or counter with some sort of support system to make the intercom easier to use.
4. Provide rounded corners and edges

This will add to the safety of the final design for small children in the homes.

5. Provide durability to retain system functionality after a ten foot drop onto a hard surface.

This will be essential to the final marketing and distribution of the product. If it breaks easily, then there will be significant cost in replacing or fixing this problem.

6. Provide easy cleaning without harming the interior electronics.

Users should be able to clean their systems without worry of breaking the product.

4.2.4 Environmental

The production design must adhere to the following environmental requirements:

1. Any additions in the product packaging or on board power supply must comply with RoHS standards.

This follows the reasoning explained in the prototype environmental requirements section.

4.2.5 Cost

Manufacture the production design must:

1. Be able to produce a single intercom unit for under $20.

To sell for a preliminary target market price of around $80 per unit, the manufacturing cost must come in under $20. This is assuming that the price per unit will double for each link in the distribution chain until the product is brought to the end user. That would bring the wholesale cost to $40 and the consumer cost to $80 per unit.

4.2.6 FCC Compliance

The final production design must:

1. Be able to pass FCC compliance testing.

Commercially available products to be marketed in the United States must comply with FCC (Federal Communications Commission) regulations part 15 for intentional and unintentional radio frequency radiators. Since our product will operate in the unlicensed industrial, scientific and medical (ISM) radio frequency bands at the 950 megahertz, 2.4 gigahertz, or 5.8 gigahertz frequency range. The FCC has set maximum output power in these frequency ranges is one watt or thirty decibels referenced to one milliwatt and defined the exact frequency range available in each area, our product must comply with
those regulations. In other countries similar organizations control the use of the radio frequency spectrum with similar rules. Worldwide the 2.4 gigahertz band is available for unlicensed communication, however, the specifically allowed frequencies vary slightly, so our system will have to be flexible if it is to be marketed worldwide.

5.0 Alternative Solutions

In order to deliver basic intercom functionality, the designer must, at minimum, be able to transmit the audio from one intercom to another. There are four basic means of audio transmission used in intercom systems: sending the signal through the building AC power lines, additional wires between the intercom stations, the use of the telephone wiring system, or an RF (radio frequency) connection between intercom stations. These each have their own strengths and weaknesses that should be considered when implementing an intercom system or any other audio link.

5.1 “Wireless” Wired System

In this implementation, the audio signal is sent over the building’s AC power lines by impressing a low frequency, frequency modulated carrier signal which carries the audio. The carrier signal also must have a small amplitude so it will not significantly change the existing 120 V\text{AC} power signal. This is a functionally low cost option since the transmission medium is already implemented within the building. All the intercom system has to do is to create the modulated carrier and demodulate and the receiver side to recover the original audio. The savings on additional wiring or RF connections would likely be significant thus dramatically reducing the cost of the intercom system.

Unfortunately, some fairly serious problems for audio transfer come with the power lines within your home. IEEE (Institute of Electrical and Electronics Engineers, Inc.) member Luis Montoya, in his article, “Power Line Communications: Performance Overview of the Physical Layer of Available Protocols”, points to several problems with implementing communication over power lines. First, power lines were only designed to be used for transmission of power at a frequency of at most 400 Hz. Additionally, it is difficult to produce dependable results since power lines are extremely “electronically contaminated” and signal attenuation is high at the frequencies used. The results of these problems could be heard from many people who have used these systems. Many complained of noise demodulated from the wiring when audio was not being transmitted causing unacceptable audible noise being produced at the intercom speaker. Others also criticized these systems for having unreliable behavior in which configurations which worked one day would not on another. Finally, these systems can only transmit data between intercoms which are connected to the same physical circuit within the house. Otherwise the receiving intercom wouldn’t even see the audio signal being sent making the pair useless.

5.2 Wired System
These audio transmission systems use either additional dedicated wiring or existing telephone wires to transmit audio and other data between a number of intercoms. Twisted pair, coaxial, and Ethernet wires are the most commonly used for intercom systems. Ethernet is more prevalent among the newest systems. After the initial cost of implementing all the wiring and setup within the home, these systems can provide extremely fast data transmission with very few concerns for noise tainting the audio signal. Because of the additional bandwidth, these systems have much more flexibility to add additional features in addition to the basic intercom functionality. Many include the option of loading and making available audio from another device which could then be listened to on any of the intercom systems. The increased bandwidth is often dedicated towards video transmission as well in intercoms implemented as part of a security system.

Cost is the obvious drawback for choosing a dedicated wiring system. In addition to the installation and materials cost for the wiring, there is also the additional cost of implementing a high speed transmission protocol like Ethernet or otherwise. The task of determining where all of these signals need to be sent as well sending these large amounts of data is extremely daunting. If done well though, improvements in system quality would be obvious.

5.3 RF Wireless System

RF or true wireless systems would implement the audio transmission through the means of RF communication between a transmitter and receiver. In RF communication a base frequency is selected and that signal is then modulated to include the data that is to be transmitted. How this is done varies based on the given RF protocol being used. Wireless data transmission is desirable because it is wireless and would require no installation of additional wires just the like “wireless” wired systems. Unlike those systems though, RF intercoms would not be dependent on a physical system and less likely to have data corrupted by noise.

There are drawbacks to the wireless implementation. While there isn’t a physical wire which would encounter noise on, additional RF signals may be present at the frequency of choice making it difficult or impossible to receive the data signals. Bandwidth is also significantly reduced by going to a wireless connection with any range. Additionally, RF communication is also contingent upon the receiver being within the physical range of the transmitter. The signal loses power as it travels further from the transmitter and becomes harder for the receiver to successfully receive the signal. Range is a function of the transmitter output power, receiver sensitivity, and any signal gain on the antennas used. So, range of a given system can be improved by using a more powerful antenna. If the two RF intercoms are in range and are not encountering significant noise signal on the frequency, a wireless connection should be able to provide effective and dependable data transmission.

6.0 Intellectual Property Concerns/Opportunities

All projects must keep patent infringement and opportunities for new intellectual property in mind. With wireless technology at the forefront of today’s market, there are many patents to be
aware of and look over. Patents are also a source of information and ideas to help projects get on the right track. Unfortunately, although patents are intended to teach others about your invention, many try to cover as broad a spectrum as possible while giving away as few specifics about design as possible.

6.1 Wireless Intercom Patents

Several wireless patents of interest were found that were relevant to tCOM’s design. The first patent, US 7,103,392 B2, describes a wireless microphone of the sort that might be used in a restaurant. It mentions other units which include a headset model and a unit with a remote switch. This patent references patents as late as 1969. No detailed circuitry is provided since the patent is primarily for the housing. Because the circuitry needed for the design is patented over 20 years before the patents 2002 date, there was no infringement for the design. Likewise tCOM’s design will incorporate only circuitry such as filters that no longer are covered by patents.

The second patent, US 7,120,388 B2, describes a wireless hub for attaching multiple wired intercoms to a wireless headset device. This patent shows a fairly complicated analog circuit that is used to implement the wireless transmission.

US Patent 5,903,322 describes an intercom system that could transmit both video and audio. The video was transmitted on the 2.4/5.8 GHz spectrum while the audio was modulated on the UHF band. tCOM will not allow for video communication and is using the 2.4 GHz band for audio rather than the UHF frequencies. However, the approach for a single portion of this invention is similar to our system, since there is no main base with several satellites, and the information is taken from its natural analog form and transmitted digitally, then transformed back into analog form. There is also a similar video and audio transmitter that has single directional video and bidirectional audio transmission, which uses 2.4 GHz communication for the video/audio direction and UHF for the returning audio signal.

We also found several patents including US2003/0013503, US 5,574,775, US 6,256,303 B1, and US 5,784,685 that detail wireless speaker systems which transmitted both analog and digital information. Since these systems only send data in a single direction, they are dissimilar to tCOM in intended function, but due to only being able to transmit or receive tCOM is similar to two of these platforms which take turns talking to each other. Similar to these wireless speaker system is a wireless monitoring system similar to a baby monitor that uses the unlicensed 900 MHz, in fact this is a feature that we hope to incorporate into tCOM’s functionality, but, baby monitors have been around a long time and our implementation will be unique mostly in its enfolding into a larger intercom system.

6.2 Design Component Patents

While most of the components in tCOM’s design are integrated circuits available for purchase, there was no manufacturer that sold scroll wheel packages like the ones used in mice. This is due to the fact that there are two extremely large mouse manufacturers, Microsoft and Logitech. Together they manufacture most mice, with third party original equipment manufacturers.
buying Microsoft and Logitech equipment to be rebranded. While investigating patents surrounding computer mice and their scroll wheels we discovered US Patent Number 5,952,997 detailing an encoder wheel arrangement. This patent details a mouse wheel arrangement that uses an optical sensor and a slotted wheel to detect movement. There were also other numerous patents for the ergonomics of mice and the ribbed rubber grip found on scroll wheels. Since our scroll wheel will use neither photo sensor nor be attached to a mouse, the packaging and mounting will require invention of our own and thus not infringe on the decorative, photo array, or whole mouse system patents.

6.3 Intellectual Property Protection and Possibilities

t\text{COM}'s design does not use extensive analog circuitry, instead relying on integrated circuits produced by companies such as Microchip and Nordic. The analog circuits that are used can be found in an advanced textbook, so there is no real opportunity for patenting circuitry. Our code for the t\text{COM} that ties the whole system together and establishes the communication protocol is new intellectual property belonging to the Com 1 Com All team. In order to protect this information our micro processor has an available option to encrypt the information on it to prevent reverse engineering, while the assembly code used to program the modules can be protected by US copyright law.

7.0 Market Study

Prior to the development of our product, thorough knowledge of the existing intercom market was necessary. This information would be used to help determine desired features, final product target cost, technology usage, and marketing strategies. An adequate sampling of the products currently available were compiled and compared to determine the market status. In addition to product offerings, data was also collected on annual home construction in the United States. This along with general commercial sales would make up the majority of possible sales for the t\text{COM}.

7.1 Competition in the Market

A brief compilation of information on a variety of intercoms available online is shown in Table 1 below. The full table of intercom data from our market study is available in Appendix B. These intercoms show the wide range of technology, quality, and price available to consumers on the market today. Each of the options represented will be explained in the sections to follow.
Table 1 - Available Intercom Examples

<table>
<thead>
<tr>
<th>Name</th>
<th>Transmission Type</th>
<th>Range</th>
<th>Size</th>
<th>Price (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio Shack</td>
<td>200 - 270 kHz (FM)</td>
<td>-</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>Reporter Wirefree Intercom</td>
<td>900 MHz</td>
<td>1000 ft</td>
<td>4&quot;x5.5&quot;x2&quot;</td>
<td>89</td>
</tr>
<tr>
<td>Flush Reporter Wirefree Intercom</td>
<td>900 MHz</td>
<td>1000 ft</td>
<td>6&quot;x7&quot;</td>
<td>99</td>
</tr>
<tr>
<td>Outdoor Reporter Wirefree Intercom</td>
<td>900 MHz</td>
<td>1000 ft</td>
<td>6&quot;x3.5&quot;x2&quot;</td>
<td>79</td>
</tr>
<tr>
<td>Westinghouse WHI-4CUPG</td>
<td>FM</td>
<td>500 ft</td>
<td>-</td>
<td>62.5</td>
</tr>
<tr>
<td>Westinghouse WHI-2C</td>
<td>FM</td>
<td>1500 ft</td>
<td>5.5&quot;x5.5&quot;x1.75&quot;</td>
<td>20</td>
</tr>
<tr>
<td>Westinghouse WHI-3C</td>
<td>FM</td>
<td>1500 ft</td>
<td>6.75&quot;x5&quot;x1.75&quot;</td>
<td>27</td>
</tr>
<tr>
<td>Westinghouse WHI-4C</td>
<td>FM</td>
<td>1500 ft</td>
<td>6.25&quot;x5.5&quot;x1.25&quot;</td>
<td>35</td>
</tr>
<tr>
<td>Nutone IMA110</td>
<td>200 - 290 kHz (FM)</td>
<td>500 ft</td>
<td>7&quot;x5.75&quot;x1.875&quot;</td>
<td>43</td>
</tr>
<tr>
<td>GE/Jasco TL97600</td>
<td>Home Wiring</td>
<td>Same Circuit</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>GE SmartCom</td>
<td>Wired (Ethernet)</td>
<td>Cable Length</td>
<td>-</td>
<td>2200 (four module system)</td>
</tr>
<tr>
<td>M&amp;S DMC1</td>
<td>Wired (Ethernet)</td>
<td>Cable Length</td>
<td>-</td>
<td>500 (master only)</td>
</tr>
</tbody>
</table>

7.1.1 Home Power Circuit Intercom Systems

This type of intercom system, represented by the GE/Jasco TL97600 in Table 1 and Figure 2 below, was the source of the problem which created this project idea. While these intercom systems are extremely inexpensive, they are functionally restrictive due to their means of audio transfer. Intercom modules in one of these systems send their audio data through the home’s wiring system by modulating the standard AC signal. Unfortunately, this requires that two intercoms which hope to communicate must be plugged into the same circuit within the building. Otherwise they will be unable to communicate and the intercom will be completely useless. Additionally, the audio signal is sensitive to fluctuations in the AC power signals which can cause noise on the audio output. These systems still are bought due to their low prices but are disappointing for those unaware of their wiring requirements.

7.1.2 High-end Wired Intercom Systems

Another type of wired intercom system does not use the building’s power circuits but additional wires connecting each of the intercom modules. The GE SmartCom and M&S DMC1 are two examples of this type of system. GE’s SmartCom module is shown in Figure 3 below. These intercoms provide much greater reliability in data transfer and include additional features like home audio distribution from
traditional audio devices (i.e. CD players, radios, etc). Along with the superior functionality and features of these systems comes the overwhelming cost of implementing them in a home or office. In addition to costing in excess of one hundred dollars for each module and more for master or hub modules, there is the additional material and installation cost for wiring these systems. There are extremely impractical for existing homes but are a viable option for new construction or renovation projects.

Figure 3 - GE SmartCom Module

7.1.3 Wireless Intercom Systems

The remaining intercoms, those listed first in Table 1, represent systems technically similar to the proposed tCOM. All of these use RF data transmission to send audio between intercoms modules. All of the systems we found made use of transmission on either the 200 kHz or 900 MHz frequency ranges. This does not seem to be the only indicator of final system cost even though the 900 MHz systems are the most expensive systems listed. Additionally the number of channels available for communication seems to have a direct relationship with the intercom cost. The Westinghouse intercoms show this as each intercom increases in cost due to the addition of another channel for communication between intercoms. The most expensive version, the WHI-4CUPG shown in Figure 4 below, includes five channels the user can set for a module’s communication. Two intercoms hoping to communicate must be placed on the same channel for transmission to take place. Additional channels provide flexibility for the user but also force the modules to be manually placed into the correct channel to communicate with a specific module. Westinghouse’s least expensive model provides only two channels for communication. None of these systems provided additional features available on the higher end wired systems like a graphical interface to provide clock, alarms, or other information to the user.

Figure 4 - WHI-4CUPG
7.2 **T\text{COM}'s Place in the Market**

Due to t\text{COM}'s proposed RF transmission, we believe the t\text{COM} will fit into the market as a mid-priced but fully featured wireless intercom system. The presence of its LCD screen will allow it to offer additional features not offered on most wireless intercom systems. In addition, the automatic frequency or channel setup for talking modules will make the system much simpler for the user. The t\text{COM} will be more expensive than the low end intercom systems but should provide superior functionality to even those systems more expensive than our projected selling costs. Because of this, it should be a successful product within the existing intercom market.

7.3 **Sales Prospects**

While data on yearly sales of comparable intercom systems seem to be relatively difficult to procure, there are still other methods to determine a possible sales market for the t\text{COM}. Our device will be most useful in the home market and to a lesser extent the smaller office environment. Because of the t\text{COM}'s ability to be wall mounted or even placed into a wall, an excellent target market would be for new home construction. According to the National Association of Home Builders (NAHB), there were just over 1.8 million new homes started in 2006. Some percentage of these, assumingly the more expensive homes, probably included intercom/home audio systems comparable to the GE SmartCom. The t\text{COM} would provide a low cost alternative, both in system and installation cost, compared to expensive wired systems which could be offered to new home construction companies and contractors. Additionally, the lower system cost would make it a more feasible option for less expensive homes. Making a conservative estimate, t\text{COM} could prospectively be used in about half a million new homes in America each year alone. In addition, the t\text{COM} could be marketed to retailers as a higher quality alternative to less expensive systems like the one found at Radio Shack. Retail sales in addition to possible direct online sales would further increase possible sales.

8.0 **Preliminary Design**

Our preliminary design shows how the t\text{COM} is to be implemented and will fulfill the requirements for the system. The system level, hardware, software, and any additional system protocol designs will each be explained along with any internal components or subroutines used to fulfill the higher level design. Decision criteria for each component will be explained along with the eventual selection and any key information about that component or subroutine.

8.1 **System Design**

This section will describe the top level system design for the t\text{COM}. The intention is to show the various areas of the entire system design and how they are connected and work together to provide the intercom functionality.

8.1.1 **Modular Unit Network Implementation**
One of the first decisions made was to design the intercom system using several identical modular units. This design choice would simplify the design and manufacturing process and also allow for a more consistent experience for the end user. Instead of having several different unit types for the user to understand, each intercom module would provide identical functionality to be mastered. This would also allow for network setup and other system functions to be carried out from any location rather than at a central hub or mother intercom which would most likely control all setup and most of the audio transmission as well. Most wireless intercom systems similar to our design employ a similar design but also provide a simpler module version for outdoor locations like the front door. This would be another addition to possibly consider after the main module design is complete.

8.1.2 Modular System Design

The block diagram in Figure 5 below shows the five main systems of the tCOM module design. Along with the various connections between each system, the general features supplied by each are also listed. Further description of each system is provided in the sections to follow.

![Figure 5 - System Level Functionality](image)

8.1.2.1 Module Control System

The control system is the brain of the intercom module. From this point all data from the other systems will be processed and additional messages sent out to implement the various system functionalities. Upon initial power up, the control system will have to configure all of the other system components and initialize the network connections between modules through the network system. It will also store a variety of network information that will be used to keep track of network activity and ensure successful communication and functionality between the various modules.

8.1.2.2 Networking System
In order to connect and transfer data between the various modules, a networking system had to be implemented. Because of our choice to use wireless RF data transmission this system will consist of only our transceiver integrated circuit and additional external hardware necessary including an antenna. Such an integrated circuit would implement an RF transmission and receiving protocol to consistently send data between the modules over the required range of 300 m (1000 ft). The controller will have to configure this circuit through data messages and also upload and download the data messages being sent and received on the intercom network.

8.1.2.3 Audio System

This system will implement the audio input and output functionality. For audio input, it will take an audio input from a microphone, provide this analog signal at the proper amplitude to be converted to a digital signal, and then transmit the digital audio data to the control system to be transmitted over the network. On audio output, it will receive digital audio data from the control system, convert this back into an analog audio signal which will be amplified so that it can be used to drive a speaker and provide audible sound back to the user. This system will consist of some means of conversion between the analog and digital audio formats and additional analog hardware to provide amplification and output power to the speaker.

8.1.2.4 User Interface System

The user interface system is the tool that allows the user to interact with the intercom module and network as a whole. A graphical display will be used to show the system clock and interactive menu used control some of the intercom functionality. User input will be provided through a series of buttons which will control the menu and thus also the functions of the intercom. Buttons for the “Com 1 Com All” functionality will be independent of the graphical display menu and will automatically begin conversation with the other modules. The volume will be controlled through the menu control buttons if the module is talking with another module. Otherwise it will be changed through the settings under the displayed menu.

8.1.2.5 Power System

The power system provides the necessary voltages to all of the components within the tCOM module. It will have to convert standard power from a electrical outlet to a DC (direct current) voltage. From this point the system will use voltage regulators to reduce the initial DC values to those required by any integrated circuits and other components in our design.

8.1.2.6 Design Conceptualization

Early in the design process tCOM required an initial visual design concept, this early concept can be seen below in Figure 6. The design has since been refined to include a two like LCD display, scroll wheel interface and different sized audio components.
8.2 Software Design

The preliminary design’s software is best represented in sections or routines that focus on certain aspects of the Intercom’s functionality. These routines frequently incorporate the other devices controlled by the microprocessor. The preliminary design’s routines and their interfaces can be seen below in Figure 7.
8.2.1 Auto Setup

A key feature of tCOM is its ability to automatically detect and set up a wireless network without any user programming. This feature will be implemented in the Auto Setup routine with the help of the Network routine. The Auto Setup will look to connect to an existing open network. If detected, the routine will obtain network information including addressing, module names, and the encryption key. If no open network is available, the routine will assume a preprogrammed encryption key. A generic module name will be assigned if none exists in the memory. The Auto Setup directly interfaces with the power supply in that upon powering up, the Auto Setup is initiated. The watchdog routine may also restart the software by calling Auto Setup. The Auto Setup is also responsible for reestablishing the network in the case of a power failure.

8.2.2 Network

The network routine directly interfaces with the transceiver. It sends data and network info requests to and from other routines and implements the data protocol. The network routine must establish a network frequency when communicating with other modules in order to avoid collisions with other module requests.

8.2.3 Update
The Update routine is a relatively simple routine that updates key network information such as module name changes, new module connections, and clock updates. This routine is intended to synchronize information on the network and provide features like timeSYNC and nameSYNC.

8.2.4 Top Menu

The Top Menu routine is the interface control center. It updates the clock by directly interfacing with the LCD and allows for user interaction by interfacing with the buttons and scroll wheel. The Top Menu runs most of the other routines allowing access of the many features of tCOM to the end user. As its name implies, Top Menu is menu based to facilitate use. Menu options include call, clock, change name, and hot buttons. Hot button changes are stored in memory and in registers. Other selections run their respective routines. This is the default routine after periods of disuse.

8.2.5 Call and Receive

The Call and Receive routines directly interface with the transceiver to control the flow of data during module communication. Like the Network routine, they implement the data protocol and work in conjunction with the Talk and Listen routine to transfer audio. It is extremely important to make these sections as efficient as possible as they will be the most processing intensive and poorly written code could reduce audio quality.

8.2.6 Talk and Listen

The Talk and Listen routine directly interfaces with the audio codec. It will be able to control the volume settings as well as any of the other features available through the codec. Should the Talk and Listen routine when combined with the Call and Receive routines become too processor intensive, a second microprocessor dedicated to interfacing the codec will be added to separate these tasks.

8.2.7 Alarm and Clock Set

The Alarm and Clock Set routine directly interfaces with the Real Time Clock to change clock settings and also sets control registers for the alarm. Changes to the clock can be sent across the network through the update routine.

8.2.8 Watchdog

While much of the watchdog is in fact separate hardware on the microprocessor, the control of this automated function will be set with the Watchdog routine. This routine will reset a watchdog timer to indicate that the entire program is functioning correctly. If the program should freeze for some reason, the watchdog will reset the program and initiate the Auto Setup routine. The Watchdog routine will also be used to periodically send the program to sleep during periods of inactivity in order to conserve power.

8.3 Network Protocol

Network protocols are extremely important for wireless systems. They provide the means for communication and transmission validation between wireless transceivers. In the case of a tCOM network, the network protocol enables important feature such as updating the network, adding new modules, and making calls. The protocol is 32 bytes long and includes a section for instruction, address, and data. While many protocols include handshaking within the instruction set, tCOM’s transceiver can automatically be set to acknowledge transmissions. Because of this automatic handshaking, there is no need for a
separate handshaking instruction. The complete instruction set for tCOM’s network protocol can be seen below in Table 2.

Table 2 – Network Protocol Instruction Set

<table>
<thead>
<tr>
<th>Instruction(1B)</th>
<th>Addr(1B)</th>
<th>Data(28B)</th>
<th>EN(1B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Call Request</td>
<td>0hXX</td>
<td>Frequency(1B)</td>
<td>Empty(28B)</td>
</tr>
<tr>
<td>Monitor Request</td>
<td>0hXX</td>
<td>Frequency(1B)</td>
<td>Empty(28B)</td>
</tr>
<tr>
<td>Talk Start</td>
<td>0hXX</td>
<td>Empty(29B)</td>
<td>End(1B)</td>
</tr>
<tr>
<td>Talk End</td>
<td>0hXX</td>
<td>Empty(29B)</td>
<td>End(1B)</td>
</tr>
<tr>
<td>Call End</td>
<td>0hXX</td>
<td>Empty(29B)</td>
<td>End(1B)</td>
</tr>
<tr>
<td>New Module Request</td>
<td>0xFF</td>
<td>Addr(1B)</td>
<td>Empty(28B)</td>
</tr>
<tr>
<td>New Module Return</td>
<td>0xFF</td>
<td>0</td>
<td>Network Frequency(1B)</td>
</tr>
<tr>
<td>Update</td>
<td>0hXX</td>
<td>1</td>
<td>Addr(1B)</td>
</tr>
<tr>
<td></td>
<td>0hXX</td>
<td>1</td>
<td>Addr(1B)</td>
</tr>
</tbody>
</table>

8.3.1 Call Request and Monitor

Perhaps the most important instructions in tCOM’s instruction set are the Call Request and Monitor instructions. These instructions tell other modules when to expect audio data packets and where to expect them. The Call Request instruction sends information to all of the other modules on the network. The address portion communicates to each module if they are the intended recipient of the request. The frequency portion tells each module on which frequency the audio data will be transmitted. Similarly, the Monitor Request also communicates which module is being monitored and on which frequency the module should send its audio data. The Monitor Request instruction must be resent after every second to continue audio reception from the destination module.

8.3.2 Talk Start, Talk End, and Call End

Because the audio data sent from module to module is usually continuous and for undefined lengths of time, it is necessary for each module to communicate when they would like to talk and when they are done talking. The Talk Start and Talk End instructions achieve this goal. Likewise, the Call End instruction alerts the other module that the entire conversation is over and that the module should return to the network frequency. If for some reason an instruction or data packet is not received by the module for an appropriate length of time, the module assumes that the transmission has been terminated and returns to the network frequency automatically.

8.3.3 New Module Request and New Module Return

The New Module Request instruction is only used during the Auto Setup routine for a module that has not already been networked. After the New Module Request has been sent, a New Module Return is sent back to the requesting module if a module already on the network has been set to accept new modules by the user. If no New Module Return is received after 15 requests, the module assumes that there is no network available and sets up its own network based on preprogrammed randomized values. The Network Module Return sends key network information including the network frequency, network address, 128 bit encryption key, and network clock. The Network Module Return can also send the addresses and names of the other modules on the network after which it can indicate the end of transmission. Both instructions use the 0xff address for speaking to all modules because neither module knows the other’s address.

8.3.4 Update
The Update instruction allows a module to make changes to the network clock, frequency, and the modules own name. The instigating module sends this instruction to each module on the network and must try again if the some of the modules are unavailable.

\textbf{9.0 Hardware Selection}

A large portion of the functionality for the t\textsubscript{COM} will be provided using hardware which will then be controlled through software. Due to their low power consumption and ease of use for prototyping, integrated circuits (ICs) were used wherever possible for our hardware design. This choice would significantly simplify the design process as large portions of required functionality could be covered by a single IC.

\subsection*{9.1 Preliminary Block Diagram}

The first conceptualization for the hardware required for the t\textsubscript{COM} is shown in \textbf{Figure 8} below. Based on the system level design of the most previous section, the following components were selected: a microcontroller, transceiver (TX/RX), digital to analog converter (DAC), analog to digital converter (ADC), LCD (liquid crystal display), external buttons, power supply unit (PSU), external memory, microphone, speaker, antenna, and line in/out.

\begin{center}
\textbf{Figure 8} - Initial Hardware Block Diagram
\end{center}

From this point we began the task of selecting components for the intercom system.
9.2 Wireless Transmission Technology

The wireless transmission technology is arguably the most essential component to the basic functionality of a wireless intercom system. If the transceiver is unable to provide the necessary data rate, range, or cost effectiveness then the system will not be able to meet its requirements. When selecting this device, the first task was to decide on an RF protocol which the transceiver would use to transmit the data. For this decision, we compared six major wireless protocols in the areas of available data rates, range or transceiver sensitivity, price for implementation, and overall practicality of development cost and time. In addition to manufacturer specific protocols on the 2.4 GHz and 900 MHz spectrums, ZigBee, Wi-Fi, Bluetooth, and Wireless USB were considered for this application. Our decision matrix in Table 3 below shows the ratings for each protocol type and the total score to determine the eventual choice.

Table 3 - Decision Matrix for Wireless Protocol

<table>
<thead>
<tr>
<th>Criteria</th>
<th>2.4 GHz RF</th>
<th>900 MHz RF</th>
<th>ZigBee</th>
<th>Wi-Fi</th>
<th>Bluetooth</th>
<th>Wireless USB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Rate</td>
<td>4</td>
<td>3</td>
<td>12</td>
<td>2</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Range/Sensitivity</td>
<td>4</td>
<td>3</td>
<td>12</td>
<td>4</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td>Price</td>
<td>5</td>
<td>5</td>
<td>25</td>
<td>5</td>
<td>25</td>
<td>4</td>
</tr>
<tr>
<td>Practicality</td>
<td>4</td>
<td>5</td>
<td>20</td>
<td>4</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>16</strong></td>
<td><strong>69</strong></td>
<td><strong>15</strong></td>
<td><strong>65</strong></td>
<td><strong>12</strong></td>
<td><strong>52</strong></td>
</tr>
</tbody>
</table>

A general 2.4 GHz transceiver was our choice for the type of wireless transmission protocol. Although they provide a slightly slower over air data rate than some of the specific protocols, they were much less expensive to implement and more practical for our specific project. This was due mostly to the cost of individual ICs which are much more expensive for ZigBee, Bluetooth, and especially Wireless USB transceivers. Limited range further eliminated Wireless USB (3-10 meters) and Bluetooth (10 meters) from being a viable option for the iCOM.

With 2.4 GHz transceivers selected as the general wireless protocol, a decision still had to be made as to the specific transceiver to use in the iCOM. The main criteria for this decision were data transfer rate, transceiver sensitivity and output power, and the amount of available frequency channels. Without adequate data transfer rates to cover the task of streaming the audio, a transceiver would be functionally worthless. Preliminary data transfer analysis showed that to transfer the audio data without any associated protocol overhead would take a transfer rate of 576 kbps. Considering the protocol addressing and overhead that the actual data rate would have to be at least 1 Mbps or perhaps even more to be considered. Transceiver sensitivity and output power are the main components to calculating possible data transmission range. A larger range of output power to receiver sensitivity would provide a larger transmission range. The use of our expected transceiver design also required that it use a wide range of transmission frequencies for the various types of communication taking place between modules. This can be seen in our frequency usage diagram in Error! Reference source not found. below.
The intercom software will be designed so that specific frequencies will be allocated for specific types of
network tasks such as the initial network setup and additional module additions, network updating,
mapping of requested intercoms for communication, and the actual audio transmissions during secure
talking. Every tCOM module will be programmed with the same network setup frequency where network
information will be dispersed to the various modules before they can work as a viable network. From this
point, the modules will shift transmission frequency to a “waiting channel” in which the modules will
share updated network information and send requests to talk with specific modules. Finally any number
of the remaining channels can be used for connections between talking modules which need to stream
audio data. Additional channels would allow for the transceiver and/or microcontroller to find a clear
channel within the operating frequency range, by sampling the traffic. So, the transceiver must be able to
allow easy changes to the operating frequencies for data transmission.

After a thorough search of available 2.4 GHz transceivers, five possibilities, each from a different
manufacturer, were compared to determine which would provide the best functionality for our project.
Four of the options were available in individual parts while the RFW3M from Vishay was a module only
product. Module designs could be soldered onto the existing circuit board design greatly simplifying the
eventual board layout unfortunately they are also much more expensive than implementing the full design
on the board with the rest of the design.

Table 4 - Decision Matrix for Transceiver Selection

<table>
<thead>
<tr>
<th>Criteria</th>
<th>ATMEL ATR2406 Rating</th>
<th>Nordic nRF24L01 Rating</th>
<th>Transceiver Type Rating</th>
<th>Texas Instruments CC2400 Rating</th>
<th>Vishay RFW3M Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Rate</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Range/Sensitivity</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Price</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Packaging/Size</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Available Channels</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>19</td>
<td>69</td>
<td>19</td>
<td>71</td>
<td>15</td>
</tr>
</tbody>
</table>

- 36 -
The choice for the transceiver to be implemented, the nRF24L01 from Nordic Semiconductors, provided all of the necessary features and capabilities for the tCOM technical requirements. Its top data rate of 2 Mbps was double that of the initial 1Mbps estimated requirement. Available channels will not be an issue as it allows 126 different transmission frequencies. The only slight drawback was a slightly lower sensitivity than the other options when operating at the highest data rate. In addition to the main design criteria, it also provided a standard Serial Peripheral Interface (SPI) for transmission of data to and from the microcontroller. This will decrease the burden on microcontroller software for transmitting data to the transceiver. Although more expensive than some of the other options, the transceivers were only $2.05 each and provided excellent functionality to implement in the tCOM system.

9.3 Microcontroller

There are a multitude of different microprocessors available on the market. Not only do they come with a variety of costs, features, and speeds, but also offer a variety of development kits and support software. Com 1 Com All considered a number of popular low cost microprocessors to potentially use for tCOM’s controller. The microprocessor’s decision matrix can be found below in Table 5.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Weight</th>
<th>PIC</th>
<th>AVR</th>
<th>SX</th>
<th>Freescale</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAM</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>Cost</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Flash</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Speed</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Features</td>
<td>3</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Prototyping</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Weighted Total</td>
<td>67</td>
<td>37</td>
<td>42</td>
<td>42</td>
<td>42</td>
</tr>
</tbody>
</table>

The most important category for the choice of microcontroller ended up being the cost and ease of prototyping. This is primarily because of the limited funds available for spending on development kits which were as high as $300. The two second most important categories were the production cost of each microprocessor and their functionality. The cost was important to keep tCOM’s pricing in its desired market and the functionality was necessary for communicating with the peripherals. The last three categories were important for performance, but all possible microcontrollers were chosen to have at least as much flash, RAM, and speed as was necessary for functionality of the final design. The relative scoring was based on a scale of ten where 10 was given to the most favorable of the possible microcontrollers and the others were given proportional scores based on their proportional performance. The PIC processor ended up with the highest score.

With a PIC selected as the microprocessor of choice, there were two possible choices which maximize necessary features and minimize cost. The PIC18F45J10, which was the most inexpensive PIC available with two Serial Peripheral Interface ports necessary for communicating with the transceiver and audio codec, is barely capable of fulfilling the controller needs. It has the advantage of coming in a plastic dual inline package for easy prototyping. Should the microcontroller need additional peripheral interfaces, a second microcontroller the PIC24FJ16GA004 can provide an additional two Inter-Integrated Circuit ports for possibly communicating with the LCD and real time clock. The PIC24FJ16GA004 is only available in surface mount parts.
9.4 Signal Processing Solution

Because the speaker and microphone are analog and the transceiver requires digital transmission, some signal processing must take place. To keep cost down, the pulse wave modulation capabilities of the PIC processor could approximate the digital to analog conversion and use its own 10 bit analog to digital converter for the conversion of analog into a digital signal. Unfortunately this conversion was would require careful timing management in the code making it difficult to allow for the other features desired for t_COM and limited the bit depth of the audio to only slightly better than that of the tradition telephone. In addition, using pulse wave modulation to emulate a digital to analog converter is clumsy and causes unacceptable distortion. Instead, a relatively cheap codec was found that provided the same functionality but allowed for a much higher bit depth. The AD74111 codec supports 16-24bit signal processing. Using the AD74111 also allows for digital control of the volume along with a lower signal to noise ratio than the PIC as both have a bit accuracy rating of .5, making the 24 bit codec many times more accurate. 16 and 20 bit codecs available for purchase did not provide an appreciable cost reduction.

9.5 LCD Display

For the LCD display Com 1 Com All decided to use the Crystalfontz CFAH1602O-YYH-ET sixteen character, double line, yellow/green, transflective, backlit, super-twisted nematic (STN), LCD display that will display the time, desired calling address, and menu structure. The t_COM system requires a sixteen character field because module names can be up to sixteen characters long, and Com 1 Com All felt that horizontal scrolling must be avoided. It also became apparent during research that single line LCDs are actually more expensive than double line modules. Another requirement that became apparent was that the LCD display must be backlit for the t_COM system to be useful in the dark.

Alternate solutions included modules from Lumex Opto. These units seemed very similar to offerings from Crystalfontz, however, Lumex modules were available via Digikey and Mouser, so the single price was much better than Crystalfontz’s, but the bulk discounts were not as deep. Lumex also does not supply good documentation for their product, and while it could be inferred that they operated similarly to the Crystalfontz the designers would not know. Details of the design criteria and results of each option are displayed below in Table 6. As you can see bulk pricing and documentation were the most important criteria, with single or prototype pricing also having a large effect on the outcome.

Table 6 - LCD Decision Matrix

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>crystalfontz CFAH1602O-YYH-ET</th>
<th>crystalfontz CFAH1602O-TFH-ET</th>
<th>crystalfontz CFAH1602D-TMI-ET</th>
<th>Lumex Opto LCM-S01602DSF/C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Documentation</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Color/Image*</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Price (Single)</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Price (Bulk)</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Packaging/Size</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>51</td>
<td>45</td>
<td>48</td>
<td>30</td>
</tr>
</tbody>
</table>

Originally there was some resistance to a yellow/green display color, however, the more attractive color arrangements held a cost penalty of a dollar a piece in bulk pricing. The same happened to the film compensated super-twisted nematic (FSTN) display; the added crispness was not worth the added cost.
9.6 User Keypad and Scroll Wheel Control

The graphical user interface of the tCOM system will be menu driven system which needs to be navigated. This navigation can be accomplished using arrow keys and an enter button, however, arrow keys are not very well suited to navigating long lists of menu options. A more elegant solution to menu navigation would be to use a scroll wheel such as found in any modern mouse device. This scroll wheel could incorporate all three previous buttons into a single intuitive feature. Module programming will also be controlled via the scroll wheel interface. tCOM will also feature four “Com 1” buttons which when programmed by the user call a specified module on the network. Finally, there will be a “Com All” button which will call all modules currently connected to the network, to enable broadcasting of messages with no particular recipient. This feature is found in all commercial intercoms.

9.7 Real Time Clock

In order to relieve the microcontroller of the burden of counting out time, tCOM will include a real time clock chip that will count the seconds, minutes, hours, days, months and years to be displayed on the LCD display when the system is not actively communicating. The design criteria for this device were price, and compatibility with the rest of the system. The Philips PCF8563 Real time clock/calendar was chosen because it provided: year, month, day, weekday, hours, minutes and seconds based on 32.768 kilohertz quartz crystal and communicates with a 400 kilohertz two-wire I2C-bus interface, for the best price of $0.67.

9.8 Microphone

Initially a member the team purchased a small board mounted condenser microphone element (Model: 270-090) from a local Radio Shack so that the team could have the equipment immediately for testing and demonstration purposes. For the final prototype and production model a bulk purchasing solution was investigated. On Digikey.com there were two manufacturers of omni-directional condenser microphones in the frequencies that matched the response of the speaker. Details of the design criteria and results of each option are displayed below in Table 7. The most important design criterion was the bulk pricing since all microphone options met minimum required quality standards. Secondary considerations were single pricing and audio quality considerations.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Rating</th>
<th>Score</th>
<th>Rating</th>
<th>Score</th>
<th>Rating</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response Range</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>4</td>
<td>12</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>3</td>
<td>4</td>
<td>12</td>
<td>3</td>
<td>9</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Price (Single)</td>
<td>3</td>
<td>3</td>
<td>9</td>
<td>4</td>
<td>12</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Price (Bulk)</td>
<td>5</td>
<td>5</td>
<td>25</td>
<td>4</td>
<td>20</td>
<td>3</td>
<td>15</td>
</tr>
<tr>
<td>Packaging/Size</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>18</strong></td>
<td><strong>61</strong></td>
<td></td>
<td><strong>17</strong></td>
<td><strong>57</strong></td>
<td><strong>17</strong></td>
<td><strong>53</strong></td>
</tr>
</tbody>
</table>

Table 7 - Microphone Decision Matrix
The Horn EM9765P-42 was the cheapest unit when bought in bulk, coming down below $0.15 when purchased in quantities greater than 10,000 units, and while its response range was less than the other options the sensitivity was just as good as the more expensive Panasonic model.

9.9 Speaker

Initially a member of the team purchased a small .1 watt (W) speaker from a local Radio Shack so that the team could have the equipment immediately for testing and demonstration purposes. In testing this circuit element the team discovered that the speaker did not have enough power to output a clear and audible signal when in a crowded and busy room. Com 1 Com All decided that a louder speaker with a broader response range was needed, after some research a 2W solution was found from CUI Inc. The GF0771 speaker covers a range of 180 hertz to 10 kilohertz at a sound pressure level of 92 decibels per watt. The speaker also fits within the space constraints of a tCOM module.

9.10 Antenna

Based on our range requirement feasibility study the antenna gain, transceiver output power, and transceiver sensitivity dictate that a tCOM module will need an antenna gain of between two and three decibels of gain. The antenna module chosen is a Pulse Engineering W1027 high gain antenna that provides 3.2 decibels of amplification on the transmit power and receive sensitivity. The W1027 utilizes a one-quarter wavelength dipole configuration to provide a uniform radiation pattern in the horizontal plane with the only meaningful nulls on its south and north poles. This radiation pattern means that the modules will have maximum range across a vertical plane and will only have trouble when two modules are situated directly above one another; however, the distance between levels in a home is considerably lower than our maximum transmission distance requirement of 105 meters.

9.11 Additional Analog Circuitry

Additional circuitry will be required to maximize the utility of components, including tuning networks for the transceiver, capacitors to mitigate pin capacitances, and filters and amplification for analog audio. These components are not projected to have a large impact on the final cost of tCOM modules, and the total scope of the required additional circuitry is still an unknown and will be fleshed out during the prototyping stage of the design.

9.12 Power Supply

Some intercoms run on expensive but convenient batteries, tCOM runs on the cheap power available from home power lines. There are two versions of this power supply. One is intended for prototyping and the other is for production. This separation will allow Com 1 Com All to focus more on digital system design and less on analog design.

9.12.1 Prototype Supply

The prototype design uses a power adapter to handle most of the power regulation. The use of the adapter allows for minimal on-board components to regulate the remaining direct current voltage. The power adapter also reduces the heat of internal components. It is quite likely that the end user desires the flexibility of plugging the tCOM into a wall outlet, so this functionality is also available on the production
supply as well. This setup does not integrate well with a wall mountable design which encouraged a change for the final production design.

9.12.2 Final Production Supply
The final production supply incorporates the power adapter’s functionality into on-board circuitry. This incorporation is far more practical in production because the use of surface mount parts make the product less expensive and space intensive. The on-board transformer still requires significant space, but the other components reduction from using surface mount equivalents should help offset the space. The advantage of an on-board adapter is that the units would become wall mountable for a superior integration in homes. A plug would still be provided for the option of plugging into an electrical outlet.

9.13 Circuit board layout
During the preliminary stages of our design, there is no need for a full circuit board design until all parts have been selected and preliminary testing on individual system components is completed. Until that point, there is still some preliminary board design work for testing purposes of individual components. For testing of the audio codec and transceiver control with our PIC microcontroller development kit, it will be necessary to create a daughter boards for each of these surface mount chips to interface with the breadboard on the microcontroller development board. Although relatively small designs, these will be important initial steps towards a final board design as well as a necessary addition for initial testing of the components. These designs will be completed over the Christmas break and ready to be used for testing at beginning of January.

9.14 Product packaging
Prototype versions of the tCOM system will not include a packaging solution however for the production model the packaging will likely be constructed of a polymer or resin for ease of mass manufacture and their lesser effect on RF transmissions than a metal case. RF interference properties of the selected material will have to be taken into account when tuning the antenna. Polymers and resins can also be made in several colors at creation, rather than having to paint the final product. Initially tCOM will be available in a range of colors suitable for interior use, including: white, beige, and black. Special attention will be paid to the texture of the plastic, as it will have an effect on the perceived quality of the product as well as the ease of cleaning. To simplify assembly of the modules components and the PCB will be mounted on the face of the module so that the back can simply be closed in the final assembly step.
Figure 10: Product Packaging

9.15 Current Block Diagram

Below in:

Figure 11: Current Hardware Block Diagram
is the current hardware block diagram displaying our hardware design choices and the communications protocols between communicating blocks.

![Current Hardware Block Diagram](image)

**Figure 11: Current Hardware Block Diagram**

### 10.0 Hardware Designs Process

With our preliminary prototype hardware design in hand, the second semester was used for taking this proposed design and implementing it in a prototype to prove that all required functionality could be provided with the design. This prototyping and design process took place in the order of the perceived importance to the design starting with the PIC microprocessor, audio codec(s), transceiver, and LCD (liquid crystal display). Without these hardware components working correctly, the design would not meet any of the system’s basic requirements. So, they were treated as the highest priorities in the prototyping process and other less significant hardware designs were left until after the main hardware functionality was achieved in the prototype. The rest of this section documents the circuit design and development of each of the t\textsubscript{com}’s different hardware components.

### 10.1 PIC Development Board

Since software development would make up the majority of the engineering development during this project, the first priority was to begin learning the PIC assembly language and programming PIC microcontrollers. A PIC development board for eight bit microprocessors, which included a USB programmer, was purchased to begin both the hardware and software development. This board included a twenty pin PIC microcontroller (PIC16F690) which could be used to start writing assembly code and learning some of the useful features of the PIC microcontrollers. From the hardware perspective, these twenty pin microcontrollers did not have the number of necessary peripheral interface pins which would be required for a full prototype. Still, the PIC16F690 included a single serial interface module which could be used to learn how to use the serial peripheral interface (SPI) or inter-integrated circuit (I\textsubscript{2}C) bus which would later in the design to connect the PIC microcontroller with the audio codec and transceiver.
circuits. Through software development and testing, this board was able to confirm the behavior of the SPI which was the serial interface used on our audio codec and transceiver.

### 10.2 Audio Codec Prototype Board

The first prototype board to be designed and fabricated was for the AD74111 audio codec from Analog Devices. This was the device selected to provide ADC and DAC functionality for the audio input and output circuits respectively. The circuit design included a microphone to input an audio voltage and a speaker to output the audio from the microphone after being converted to digital form and reconverted back to an analog form. The pinout for the AD74111 is shown in Figure 12 below.

Following the requirements in the datasheet a freehand circuit schematic showing connections off each of the various pins was completed prior to board layout. A full formal schematic was never created but the freehand documentation for this circuit can be found in Justin Slocum’s notebook. Pins of interest on the AD74111 which would interface with the microprocessor included pins one through four which were the SPI pins and a frame synchronization signal which indicated when a new audio packet was being sent. Additionally, a master clock signal which ran all of the internal hardware and a reset signal would have to be provided by the microcontroller. With all of the necessary connections placed on the circuit board, along with all of the necessary capacitors and power connections, the prototype board layout was created as shown in Figure 13.
Two of these boards were successfully fabricated and assembled during the prototyping process. The first included microphone input and speaker output in addition to the main required parts for component operation. When this prototype board was tested for functionality with appropriate software, a troubling problem was revealed. Although all internal registers could be written to and read successfully with the microcontroller, the ADC and DAC functionality appeared non-operational on the AD74111. With this problem being seen, the second board was fabricated without the microphone input and speaker output. This allowed for voltages to directly into the Vin pin and see corresponding changes in the ADC values based on variations in the input voltage. Similarly, the output voltage could be monitored directly while the values being written to the DAC were being changed. Testing on this new minimalist board produced identical behavior as with the original prototype board. After extensive software testing, the team decided to abandon the AD74111 as the necessary encoding and decoding functionality could not produced. The replacement process for this design component is covered in Sections 10.8 and 10.9 below as parallel paths were pursued to replace this piece of hardware.

### 10.3 Breadboard Prototyping

The majority of the hardware design was developed through the use of breadboard prototyping. After initial testing on the PIC development board it was decided that a more flexible development platform would be necessary. Efficient connections from prospective prototype circuit boards for audio codecs and other components to the PIC development board would have been nearly impossible due to a single set connection header. Using a breadboard platform allowed for circuits to be rapidly built, tested, and changed based on the testing results. Additionally connections could be easily made and changed with wires from prototype boards to the microcontroller or other circuits.

### 10.4 Changing to the PIC18F45J10

Along with the change to the new breadboard prototype platform, it was decided to forgo further testing with the PIC development board and center all further prototyping around our choice for our microprocessor. Sample PIC18F45J10 microprocessors in both PDIP and TQFP packages were ordered from Microchip at no cost to the team. Both of these packages made use of 44 pins and included two serial communication modules to connect to the nRF24L01 transceiver and audio encoding and/or decoding circuit. The PDIP, or Plastic Dual Inline Package, had through-hole pins which could be plugged into our prototype breadboard and be used for the first level of prototyping. Once prototyping moved past the breadboard stage and onto a printed circuit board prototype, the PDIP would be replaced by the TQFP (Thin Quad Flat Pack) which would provide identical pinout connections with a much small board landing space. Other than the space used by each package the external hardware required was identical for either version of the PIC18F45J10.
10.5 PIC18F45J10 Programming Circuit

In order to prototype effectively with the PIC18F45J10, it was necessary to provide a circuit to interface the PIC microcontroller programmer with the required programming pins. PIC microcontrollers and the PICkit2 programmer use a feature called In Circuit Serial Programming (ICSP) to initialize program memory on the microcontroller. The datasheet for the PICkit 2 programmer included the example circuit shown in Figure 14 which was used to interface the programmer with the microcontroller for reprogramming during all further prototyping.

![Isolation Circuitry: Resistor or Schottky-type diode](image)

There are several changes which we made to the ICSP circuit for our prototyping application. It was decided to use the 470 Ω resistor for the isolation circuit instead of the diode due to the smaller cost of resistors compared to diodes. The 5V supply was also reduced to 3V to match the operating voltage used on the microcontroller. This decision would give a reduction in power consumption in the programming circuit.

10.6 Transceiver Prototyping

With the PIC microcontroller and programming circuit implemented on the initial breadboard prototype, the first component to prototype was the Nordic nRF24L01 transceiver. Because the transceiver itself only came in surface mount parts, it would be necessary to either fabricate prototype circuit boards or to purchase development boards sold by several Nordic suppliers. In order to reduce development cost, it was decided to order the necessary surface mount parts, fabricate an appropriate circuit board, and assemble prototype boards which could then be plugged into the breadboard to be tested with appropriate software.

10.6.1 Initial Prototype Boards

Nordic Semiconductor provided an application example for their nRF24L01 transceivers which indicated all of the necessary components, a circuit schematic and example board layouts for use in development. This example circuit information was actually the circuit and circuit board layout used for the
development boards which could have been purchased. Figure 15 below shows the suggested circuit schematic. This circuit only required sixteen surface mount parts, a connector, and an embedded or external antenna with 50Ω resistance. An example board layout which includes a 4 x 2 connection header and embedded antenna is shown in Figure 16. This board layout was used as a reference design for the initial prototype boards.

Figure 15 - Schematic for nRF24L01 Circuit
There are two significant changes in the circuit as shown in Figure 15 above. The 16 MHz crystal selected for transceiver operation operated with a load capacitance of 10pF, which required a matching change in the values of capacitors C1 and C2. This selection also had a change in the board layout as the crystal had a slightly different PCB footprint than the reference crystal. Additionally, the 4x2 connection header was replaced with a single row header with 8 pins, which would be more easily interfaced with our breadboard prototypes. The circuit board layout for this prototype board was designed using the ExpressPCB board layout program and can be seen in Figure 17 below. White areas on this board correspond to copper areas on the board. The pattern included two boards since two would be needed to properly test the circuit’s functionality. This board was fabricated at Calvin using a chemical etching method.

10.6.2 Surface Mount Difficulties
The use of extremely small surface mount parts, including the transceiver itself, led to many challenges in board fabrication, assembly, and testing. First, the surface mount parts required extremely thin trace widths which were prone to difficulties when exposing the photo resist to UV light. Close traces would often overlap and blur together with the slightest movement of the board image. Furthermore, the small traces also proved to be somewhat prone to being scratched or peeled from the board materials. Once suitable circuit boards were fabricated the process of assembling the circuit on the board proved extremely difficult. The nRF24L01 is only offered in a single package known as a QFN or quad flat pack with no leads. Its package shape and pinout is shown in Figure 18. This package only had connections on its bottom and was meant to be placed with more advanced soldering techniques like a reflow oven or wave soldering. It was nearly impossible to properly solder these components even when they seemed to be securely connected to the board traces. This became more obvious during testing.
prototyping the transceiver was to successfully communicate with the internal registers with a SPI serial connection. Communication took place as expected with values being written to and read from a number of registers. Eventually this behavior became sporadic and could be made successful again by pressing down on the transceiver package. This indicated that the transceivers were not soldered well enough with the tools available to the team.

10.6.3 Antenna Design

In an effort to give the transceiver prototype boards additional flexibility during prototyping, an unconventional antenna design was made on the board which included an embedded trace antenna and a pad for connecting an SMA connector and external antenna. The transceiver circuit was designed to feed a 50Ω monopole antenna in either the external or embedded form. An external antenna was specified for the design in the preliminary hardware design but an embedded antenna design was not. For an embedded monopole antenna, the length of the antenna should be ¼ of the target RF frequency wavelength. According to Nordic, an antenna for their 2.4 GHz transceivers should have been approximately 23 mm long or ¼ of a 92 mm wavelength for a 2.45 GHz signal (Feescale). The embedded antenna on the prototype board was not designed to this requisite and was slightly longer. All indications were that this itself would not be an issue with receiving RF signals. Unfortunately, neither of these connections on its own would behave properly due to a lack of knowledge in basic antenna design theory at the time of design.

10.6.4 Antenna Ground Plane

For any single ended monopole antenna, in order to have proper RF transmission and reception, a proper ground plane must be included in the hardware design. Monopole antennas provide radiation patterns similar to dipole antennas despite only having a single actual trace due to a phenomenon known as “antenna imaging”. Figure 19 below shows the principal of how an antenna image is physically oriented.
The presence of a continuous conductive ground plane near the feed point of a monopole antenna causes the RF radiation to be mirrored on the opposite side of the plane. For an external antenna with an SMA connector, this would require a conductive ground plane directly beneath the connector and antenna with breaks in the plane only for the feeding trace and other components. An embedded trace antenna, on the other hand, must have no ground plane in the area directly around the antenna itself. In this case, the ground plane should extend as a full plane from the feed point away from the antenna as shown in the example board layout in Figure 16 above. A representative from Nordic Semiconductor who was contacted for assistance with the prototype board design confirmed this technical requirement.

The transceiver prototype we designed was not outfitted with either of these ground planes as it was originally designed. In order to possibly get proper behavior from the already fabricated boards, ground planes would have to be added to enable one of the antenna configurations. Due to the extensive amount of rework around the embedded antenna trace for an externally connected antenna to work properly, it was decided to add a ground plane for the trace antenna. The proposed solution was to add a conductive plane in either the form of a piece of solid copper or copper tape on the back side of the boards beneath the existing components as in the demonstration board layout. Due to the ease of use, it was decided to use conductive copper tape for the makeshift ground plane. All of the connecting vias for ground signals were soldered to the copper tape using short jumper wires between the bottom and top layers.

After these boards were reworked, they were tested once again with the initial transceiver prototype code. There were still the previously reported issues with some of the connections to the transceiver chip itself which limited confidence in any testing done on these boards. Successful transmission between the two prototype boards had not been achieved when we were informed that we would soon be receiving important additional development hardware from Nordic Semiconductor.

10.6.5 Development Boards
Jay Tyzzer, the engineering representative from Nordic Semiconductor, who had offered some expertise with the ground plane issue also offered two development boards free of charge for the project. This removed all doubts about our circuit board manufacturing abilities and ground plane designs as these boards were the other original option for transceiver prototyping. With these boards, the functionality dependent on the transceivers could be developed with confidence in the hardware design and quality.

10.7 LCD Circuit Design
Although the majority of the display functionality was already developed on the LCD module which was selected for the initial design, there were still two additional circuits which would have to be designed to provide useful functionality to the user interface. The first would provide control of the LCD backlight through a single signal from the microprocessor. Second, a nominal voltage would have to be provided to set a usable contrast level on for the characters displayed on the LCD. Each would require a simple and efficient hardware design for the module to fulfill its design requirements.
10.7.1 Backlight Control
To control turn on the backlight a resistor had to be tied between the A port on the LCD module. However, we did not want the backlight to be continuously on, so a MOSFET (2N7000) switch was added with its gate driven by a logic pin from the PIC Microprocessor. When the processor sends a logic “1” to the gate the FET turns on allowing current to pass through the resistor to ground, powering the backlight, while a “0” completely turns the backlight off. In the future, this FET could be rapidly switched and with pulse width modulation (PWM) used as a resistor itself to dictate the intensity of the backlight.

10.7.2 Setting LCD Contrast
Currently the LCD contrast is controlled by a resistor between port VO and ground. The value of this resistor determines the reference voltage that the LCD module uses to control its contrast. This function could also be controlled with a switched MOSFET, allowing the user to adjust the contrast through software if it were programmed into the menu interface.

10.8 Additional Codec Options
As was noted in section 10.2 above, the original audio codec to be implemented in the hardware design. Due to the large amount of time lost during the debugging and testing process of the original codec, multiple parallel paths were taken to provide a possible solution to the necessary audio encoding and decoding functionality. The desired solution was to replace the AD74111 with another comparable audio codec which would be controlled through one of the standard serial communication buses without bringing a significant increase in the component cost. Two audio codecs were selected and ordered to be developed and tested as a possible replacement to the originally selected component.

10.8.1 XE3005
The XE3005 audio codec from Semtech provided a sixteen bit analog to digital and digital to analog converted controlled through two separate SPI interfaces. Optimally, only one serial communication bus would have to be used so the transceiver could maintain a dedicated communication bus. Sampling frequencies could also be selected based on the given application. A prototype circuit board to hold the surface mount package and some additional circuitry was designed, fabricated and assembled based on the application schematic given in the part documentation. This circuit schematic is shown in Figure 20 and the designed board layout is shown in Figure 21 both seen below.

![Figure 20 - Circuit Schematic for XE3005 Audio Codec](image-url)
The circuit used for the board layout was slightly different than the one shown in the figure above because we were working with the XE3005 which had limited functionality compared to the XE3006. The “Sandman output” pins did not exist on the XE3005 and the SPI only allowed writes to control registers and not reads. This eliminated three pins from the connection header. Additionally, the audio output circuit was not included as a means of simplifying the board layout and testing of the circuit. During the initial testing of the completed circuit, a clock signal with a voltage with amplitude higher than the maximum allowable signal was applied to the “Master Clock” pin. This caused the internal circuitry to fail and the part no longer functioned without this clock input for all of the internal hardware. This stopped further software prototyping until additional parts could be obtained from Semtech.

10.8.2 320AIC
The final Codec option was a TLV30AIC from Texas Instruments. This integrated circuit was a sixteen bit codec with a set sampling rate of twenty-six thousand samples per second which was controlled through another serial communication protocol known as I2C (Inter-Integrated Circuit). Although the sample rate would have been increased on this chip, it still would have been implementable in the tCOM design. There was a limited amount of design work on this option as another solution had been implemented successfully at the same time this design was being considered.

10.9 ADC and DAC Audio Solution
While the development of audio codec solutions continued to be laborious and challenging, two simpler pieces of hardware, the actual internal circuits within an audio codec, were being developed simultaneously within the design to replace the AD74111. This working solution made use of the internal ADC on the PIC microprocessor and an external DAC from Microchip. Using the internal ADC allowed for the audio codec to be replaced by a simple digital to analog converter.

10.9.1 Internal Analog to Digital Converter
One of the features included in most PIC microcontrollers was an internal analog to digital converter module with several input pins which could be selected to provide the input voltage. The ADC on the PIC18F45J10 was a ten bit converter controllable and readable through internal registers. This solution had the advantage of adding no additional space to the eventual board layout and a reduction in prototype cost due to the difference in cost between an audio codec. Unfortunately the reduction in bit depth from twenty four or even sixteen bits to ten or eight bits would also result in a comparable loss in audio quality during the conversion process. Since the converter was working correctly, it was decided that this loss of quality was acceptable for the prototype design.

10.9.2 External Digital to Analog Converter
In order to decode the digital audio stream provided by the ADC, an external DAC also had to be added to the design. For the prototype, free samples of the MCP4822 from Microchip were received and used to implement the functionality. A pinout of the DAC is shown in Figure 22 below.
The samples came in the convenient PDIP package so they could be easily prototyped on the breadboard. These chips were controlled through a partial SPI bus which allowed the device to be written to only. With pin five (LDAC) set low, writing any eight bit value on the SPI caused the output voltages on pins 6 and 8 to be updated. Only one of these pins (8) was actually used in the prototypes. The MCP4822 required no additional external components and was obviously extremely simple to use. It, along with the internal ADC, proved capable of recreating audio or any other signals using only eight bits of data.

### 10.10 Human Interface Design

The input hardware for the user interface would provide several signals to the microprocessor to indicate various desired actions from the user. Two types of user input devices were specified to allow for control of the system: a scroll wheel with clicking action like that usually found in a mouse and regular push button switches. The signaling behavior of a push button switch was extremely familiar but the scroll wheel system was a less familiar process, which, required additional research. In order to gain knowledge of a typical circuit design for a scroll wheel, several computer mice were procured from Bob DeKraker and disassembled to investigate the circuit. During this process several push button switches were also removed to be used for prototyping purposes.

#### 10.10.1 Scroll Wheel Control

The scroll wheel is elegant in its simplicity and intuitiveness, to go up, you roll up, to go, down you roll down, and to select, you push. Our original scroll wheels were scavenged from old mice, but when we ran out of these we scoured various parts supply websites to find one workable mechanical quadrature encoder the EC10E. This quadrature encoder provides the same logic signal as the original from the mouse and is a mechanical component freeing us from the patent literature documenting the optical scroll wheel solutions. Unfortunately, we did not have accompanying wheels, so we made our own using a disposable pen which had the same click feel we were after. The final product a scroll wheel would be created along with the packaging to fit the 2mm hexagonal key of our quadrature encoder.

#### 10.10.2 Buttons

Our buttons are also the result of the mice we received from the engineering department. The current implementation has the input pins held high on the pick and pressing a button draws the voltage down to zero indicating to the processor to do the function the button is tied to. We have had difficulty sourcing another supplier for our buttons. We think this is similar to the way cables are overpriced at consumer electronics stores, thus as we make contacts with suppliers we could procure more buttons.

### 10.11 Audio Input Circuit

In order for our prototype to get data to transmit we needed a way to detect the analog sound coming from the user. The simplest way to do this is to use a microphone, therefore we kept it simple with a microphone design which amplified the signal and filtered out the high frequency components so that we would not have aliasing sent across the network.

#### 10.11.1 Microphone Selection

The key concern in picking a microphone was that it works with the rest of our system and be simple to implement. An electrets condenser microphone is both of these and also cheap. The circuit required for
electrets operation is a ground on the ground pin, and on the other pin is a resistor going to power and a capacitor to block the DC voltage and allow the signal to pass.

10.11.2 Signal Amplitude Issues

Due to the miniature signal amplitude and even more limited current we needed to amplify the signal. To achieve the required strength we chose a standard inverting amplifier using an operational amplifier (op-amp). The circuit topology is a common one and can be seen in Figure 23 below.

![Inverting Amplifier](image)

The original solution featured a 741 type op-amp, however, the required gain was too high for the 741, and the input impedance was insufficient, resulting in a lost signal. Therefore, we changed to a 3140 Bi-Mos type op-amp. The 3140 has an input resistance of 1.5 teraohms versus the 6 megaohms (typ) of the 741. The figure also shows that the gain is just over 70 or 37 decibels, this boosts the signal into an acceptable level.

10.11.3 Input Audio Filtering

Once the audio signal was amplified to the correct level the signal must be filtered with a cutoff frequency of 10 kHz. This is due to our analog to digital converter sampling at a rate of 20,000 times per second. The Nyquist Theorem predicts that frequencies above 10 kHz will be alias back at our sampling rate. To prevent the aliased signal from distorting the true signal we needed to attenuate the components above 10 kHz. We chose to use a second order 1dB ripple chebyshev low pass filter of the multiple feedback architecture seen in Figure 24.

![Low Pass Multiple Feedback Architecture](image)

\[
\begin{align*}
H(f) &= \frac{-R_2}{R_1} + \frac{R_2}{R_1} + 1 + \frac{R_2}{R_1} + 1
\end{align*}
\]

Figure 24: Low Pass Multiple Feedback Architecture (Texas Instruments)
This topology produces a superior attenuation at high frequencies to the Sallen-Key topology as seen in Figure 25 below.

![Figure 25: Second-Order 3-dB Chebyshev Filter Frequency Response (Texas Instruments)](image)

The decision to use an active filter was originally so that the filter could provide gain as well as filter the signal. Unfortunately, the addition of gain made the filter unstable and caused it to oscillate when given a signal.

### 10.12 Audio Output Circuit

Likewise on the output side of the system the digital to analog converter could not produce the power required to drive the speaker, driving us to look for an amplifier. From our analog design classes we realized that we needed a type AB output stage to mitigate the diode drop associated with using bipolar junction transistors. Rather than use diodes to achieve this we used a follower amplifier with the output of the transistor push-pull pair as a negative feedback loop. Our chosen design can be seen below in Figure 26.
You can also see the reactive network on the input of the amplifier follower circuit, this causes our signal to react about zero potential, and dissipate any charge left on the amplifier when the signal stops. The design also features matched PNP and NPN transistors, which should balance the push-pull dynamic, so that the positive or negative amplitudes are accurately represented.

10.13 Prototype Schematics

With working circuits for each of the necessary functional stages, it was necessary to compile all of these circuits into a set of circuit schematics to document our prototype design. This was also a necessary step in order to design a full prototype circuit board. The team was offered the use of the Mentor Graphics PADS schematic entry and circuit board layout software by DornerWorks Embedded Systems Engineering. Final prototype schematics as shown in section 12.1.1 were created using this software.

10.14 Circuit Board Design

After all circuits were designed and prototyped on the breadboard platform, the next stage in the prototyping process was to design circuit boards for the final prototype design. This would give a specific measure of the actual amount of space required for each intercom module. Additionally, the physical implementation of a prototype on circuit boards would make for a cleaner system without the general clutter inherent with breadboard prototyping. The circuit board design would also be a necessity in order to provide a fully manufacturable design. Without a circuit board to carry all of the hardware components and electrical connections, the design would simply be a prototype with no usefulness beyond proving the system functionality.
For this design, two separate board designs were completed using Mentor Graphics PADS Layout and Router. PADS Layout allows for creation of a board outline, setup of board layer properties, placement of component footprints based on schematic data, and manual routing of traces for electrical connections. With all components placed on the circuit board, PADS Router then automatically routes as many of the traces as possible following design rules set in Layout and connections in the circuit schematics. The following board designs created were based on schematics which still included several incorrect and even missing connections. Schematics were later updated to reflect the proper circuits but the board designs were not updated due to time constraints on the project.

10.14.1 Four Layer Board Design

The first board design completed was a four layer design with top and bottom component layers and solid internal layers for the +3V supply and ground signals. Using direct connections to the internal power planes for the two networks, the number of traces on the component sides could be greatly reduced. This also provides greater signal integrity since other traces have a much smaller effect on the large ground or power plane as they would on a trace running on the outside layers. Pictures of the two outside layers and a combination of both layers with drill holes are shown in Figure 27, Figure 28, and Figure 29 below. The interior layers were not shown as they were continuous conductive planes throughout the entirety of the board. One area of interest is the additional poured planes around the transceiver circuit on both sides of the board to ensure proper antenna imaging for an external antenna.
10.14.2 Two Layer Board Design

Due to the high cost of fabricating a four layer printed circuit board on a short lead time, this second board design with only two external layers was designed as a less expensive alternative. While this board would not have the same signal quality as the four layer board, it would still be provide all of the required connections for a full module within the same board outline. This design was sent to Advanced Circuits...
in Aurora, CO in the form of fabrication gerber files to be fabricated. Four of the finished boards were received three days later ready to be assembled and tested.

![Full Two Layer Board Design](image)

**Figure 30 - Full Two Layer Board Design**

### 10.15 Single Breadboard Prototype

With all of the prototype circuits developed and tested for functionality, another full prototype was assembled on a single circuit board. The initial prototype circuits were developed on several different breadboards with appropriate connections for power and ground supplies between all of them. This second prototype would have identical circuits but would be much more compact, simpler, and would give an indication of the space needed to lay out all of the circuit components. A picture of this full functional prototype is shown in Figure 31 below.
The final step in the prototyping process was to take the fabricated two layer circuit boards and have them assembled into fully functional prototypes which could interact with any of the other module prototypes (breadboard or circuit board). Unfortunately, all of the circuits could not be fabricated on the boards using the technology available at Calvin. The transceiver package was once again too difficult to solder correctly to the pads on the circuit board. As a result, the entire transceiver circuit was left unassembled on the circuit board prototypes but the demonstration modules could still be soldered in to complete the prototype. A picture of the semi-assembled circuit board prototype is shown in Figure 32 below running the final prototype software.

**10.16 Circuit Board Prototype**

The final step in the prototyping process was to take the fabricated two layer circuit boards and have them assembled into fully functional prototypes which could interact with any of the other module prototypes (breadboard or circuit board). Unfortunately, all of the circuits could not be fabricated on the boards using the technology available at Calvin. The transceiver package was once again too difficult to solder correctly to the pads on the circuit board. As a result, the entire transceiver circuit was left unassembled on the circuit board prototypes but the demonstration modules could still be soldered in to complete the prototype. A picture of the semi-assembled circuit board prototype is shown in Figure 32 below running the final prototype software.
11.0 Software Design Process

11.1 Iterative Approach
In an effort to subdivide the massive undertaking that would be the software portion of the design and to provide a framework for basic testing of functionality, the software was broken up into smaller, more manageable portions based on the system design and component parts such as the graphic user interface and PIC microchip to transceiver communication. After obtaining minimal working functionality, more components and software were added in a repetitive process known in the software world as iterative programming. The iterative programming allowed for more thorough testing than could otherwise be done because assembly code does not lend itself well to writing self testing code. Test driven development, a process that utilizes self testing code, is much easier to implement on higher level languages where language constructs such as classes and variables greatly increase the ease and speed of developing good tests. Because these constructs are missing in assembly, and take a great deal of time to implement subroutine replacements, the iterative approach combined with frequent functional testing helped keep poorly written code or small errors from hindering the development of the final prototype software.

11.2 Development Software
The PICkit2 development board came with two important pieces of software used for developing code. The first was the PICkit2 hardware software which interfaced with the PICkit2 programmer. The second software was MPLab IDE (Integrated Development Environment) which compiled the assembly into binary code and provided register names instead of numbers for the special function registers. These special function registers controlled most features of the device and names greatly reduced confusion about which register was which. The MPLab IDE software also allowed for commenting which greatly reduced the burden of documentation while programming.

11.3 System Prototypes
11.3.1 The Hello World Program
After Com 1 Com All received the programmer and small development board, the first bit of software to be developed was the infamous hello world program (see APPENDIX A, Software: Hello World). This program normally displays “Hello World!” as a means of testing that the compilation and set up of software is correctly configured. As the PIC has no means of displaying characters, the functionality of the hello world program was achieved through blinking light emitting diodes already on the development board. Using the iterative approach explained in the section Iterative Approach, the PIC was further modified to blink at different rates and change speed according to various potentiometer settings. While the hello world program was useless for future software and no light emitting diodes were used on the final design, the hello world program played an important role in introducing Com 1 Com All to the PIC assembly language which had not been used prior to this project by any member of the team.

11.3.2 Subroutines
The next program explored the use of subroutines in the PIC assembly language. Subroutines are functions in software that allow sections of code to be inserted anywhere else with the instruction CALL. Not only do subroutines allow for simpler code, but also reduces the total amount of code and the chance of mistakes during code revision. Because Com 1 Com All knew that subroutines would be a significant portion of the code, the subroutine program was given enough time to familiarize the team with subroutines in assembly.

11.3.3 Hello World 2 for the PIC18F45J10
While developing software for the PIC16F690, the PIC intended for the final prototype was selected and purchased. The PIC18F45J10 had several improvements over the stock PIC that came with the development board and because it was 16bit word processor as opposed to the 690’s 14bit, the
programming and setup were different. A new hello world program was written and tested on a breadboard (see APPENDIX A, Software: Hello World 2). The 16bit chips cannot be directly programmed by the MPLab IDE, instead the software was first converted into .hex files which the PICkit2 hardware interface software could force write to the microcontroller.

11.3.4 Liquid Crystal Display and Random Access Memory Tables

The first peripheral integrated with the microcontroller was the Crystalfonz LCD. Along with eight data lines, the microchip also needed to supply RS, RW, and Enable control lines. The LCD was initialized using the code provided by the datasheet and the message “Hello Prof’n VanderLeest” was displayed (see APPENDIX A, Software: LCD). Two problems were discovered while programming the LCD and PIC. First, when the PIC reset and reran the initialization instructions, the LCD lost the bottom half of the screen. The second was the LCD ran equally well on the four data pin mode which freed up four pins for interrupts. While the missing bottom row was a concern, Com 1 Com All felt that the controlling wire to the regulator which would be able to turn off the power to the LCD would provide the necessary reset to insure a proper double row initialization. This issue was further resolved by the final circuit board design as the re-initialization no longer caused the bottom of the screen to blank on the boards.

A RAM table was implemented to display the characters to the screen. The RAM Table cut down on code by allowing a subroutine to use a loop to step through each character instead of loading the literal to the working register and then sending the data to the LCD. The initialization of the RAM table was quite lengthy and far from transparent, but would be improved with the use of flash reading later on.

After the four pin and RAM table iterations, a modified computer mouse was attached to Input/Output pins on the PIC. By observing the signals from the quadrature encoder, subroutines were written to decode the transmissions into directional “clicks” of the wheel. At first the arrow which moved through the menu would occasionally go in the wrong direction. The error was fixed with a longer debouncing delay. An extra long delay after a read click slowed down the scrolling to a more controllable speed.

11.3.5 Transceiver Boards

When the transceiver boards were completed, software was developed as quickly as possible to get the boards working (see APPENDIX A, Software: Transceiver). The transceivers were important because they were not only the most unfamiliar peripheral, but also a core part of the main functionality. The transceiver programming did not go as planned. Firstly, only one of the boards communicated with the PIC sending back meaningful and correct register information. The working board would also sometimes stop communicating which could be remedied by applying pressure to the transceiver chip. This raised suspicions that the leadless transceiver chip was not fully soldered on to the prototype board. With the transceiver pressed into working, the initialization sequence for the chip was able to cause the interrupt request (IRQ) line to go high indicating that the chip was in listen mode. However, the IRQ would drop indicating a received signal that was never sent. This false indicator was stopped with the addition of the CRC bytes to the package. While this seemed to fix the transceiver, Com 1 Com All later determined that the boards were missing a sufficiently large ground plain for accurate transmission and reception of signals. The addition of the ground plain stopped the false IRQ triggers even without the CRC bytes, but the boards were later abandoned for the better made transceiver modules generously donated by Nordic Semiconductor.

11.3.6 Codecs and Converters

11.3.6.1 Initial Failures

While waiting for the professionally manufactured transceiver modules, the codec boards were built and software written for their implementation (see APPENDIX A, Software: Codec). Unfortunately while the registers were writable and readable, the codec did not present a voltage on the output pin nor send the digital representation of a voltage applied to the input pin. After spending hours setting registers and adjusting the timing, there were still no results. Instead of spending more time on the audio codec which was apparently not working, the team bought two other codecs and a digital to analog converter (DAC). The first codec was blown by using a too high of voltage (5V) on the communication lines between the
PIC and codec. The DAC, however, was successfully integrated with the PIC and provided accurate voltages for the 12bit representations (see APPENDIX A, Software: DAC).

11.3.6.2 Adding the ADC

If the DAC was to be used for the final prototype, the PIC’s own analog to digital converter (ADC) would need to be integrated. Using the commands given by the PIC datasheet, subroutines were developed to start the ADC conversion, sample the data, and handle the two byte but 10bit representation. To test the accuracy of the ADC and the coherency of the combined ADC and DAC, a sign wave was presented to the ADC and compared with the output of the DAC. Other than a small delay, the small digitized step representation of a sign wave, and a difference in amplitude inherent to the system, the two signals were identical.

11.3.7 Transceiver Modules

Unlike the transceiver boards, the modules were programmed with relative ease (see APPENDIX A, Software: Transceiver). More importantly the transceivers were checked for the exact data being sent to the receiving transceiver. A number of different single byte data packets were sent and seen to transmit correctly to the transceiver. Expanding upon the success of the single byte transmission, registers were changed to send two byte packages, then four, then eight all the way to the full 32byte packet length. While the lengthening of the packets went smoothly, the immediate transmission of multiple packets originally did not work. The oscilloscope showed the same packet being received by the transceiver repeatedly. The reason for this turned out to be that the transceiver needed to leave Rx mode in order to clear the IRQ and receive new packets. Likewise, the transmitting transceiver needed to be cleared outside of Tx mode before the next transmission would be sent. With these two changes the transceivers were sending multiple 32byte packets correctly.

11.3.8 Audio Test Egg

To further show the capabilities and quality of the speaker and output stage, an arrangement of the familiar and historic Mario Brother’s Theme was digitally represented into code and programmed into the chip (see APPENDIX A, Software: DAC). The result was clear and quite loud midi music. The software showed that the unamplified output of the DAC was large enough to fit our needs. Our representation was later shown to be too generous as the lower power contained in a sign wave compared to a square wave caused a noticeable sound reduction. The audio testing program was also useful as a delightful Easter egg on the final prototype for the purpose of pleasing the audience during senior design night.

11.3.9 Flash Reading and Writing

While the RAM table was a convenient way to move data to the LCD and transceiver, storing the data in the code as instructions was wasteful of memory resources. A much more efficient way to store the data would be to append the binary code after the end of the program. The PIC not only provided a special register for reading data stored in this manner, but also added the functionality of being able to permanently write to the flash from code. This software would be later used to remember module names, network addresses, the network encryption key, and other important information even after a power outage. The subroutines necessary for reading, writing, and finding the appropriate location for names from the blocks of memory were written but not tested until their integration with the final prototype (see APPENDIX A, Software: Flash).

11.3.10 Timer

With Senior Design night approaching ever closer, team 5 determined that the integration and purchase of a real time clock would be too costly in terms of time for the additional functionality. Instead, the basic functionality was developed with software using on-chip timers (see APPENDIX A, Software: Timer). The timers on the PIC were actually counters with prescales to the main program clock. This would unfortunately cause the timers to fail not only during power outages, but also during sleep mode. This hurdle would need to be overcome when the correctly functioning simple timer program was integrated with the final prototype.

- 63 -
11.3.11 Watchdog
A key component to the transparency and integrity of our design was the ability to setup and reset automatically. Not only would these autonomous features ease the use of the tCOM, but also remove some frustration if the product was not functioning because of improper setup. To support these features software was developed to prototype the watchdog function on the PIC (see APPENDIX A, Software: Watchdog). The watchdog is a timer set on a separate internal oscillator. The timer counts and when it overflows, causes the PIC to reset. If for some reason the PIC gets stuck in a loop or stops running code, the watchdog timer would reset the PIC allowing it to restart and function correctly. With the watchdog in place the PIC could reset and continue functioning without the consumer ever knowing. The timer included a prescale for selecting the length of time it took to reset if no clearing of the watchdog took place.

11.4 Combining System Software
Before beginning the final prototype software, a couple of prototypes were combined to double check timing issues and concepts. Com1 Com all would have liked to combine more of the software before the final prototype, but simply ran out of time.

11.4.1 ADC and TxRx Prototypes
While transmission appeared to be good when sending sign waves from one transceiver to the other, separate testing of the quality of sound capable of being transmitted with the addition of the microphone, preamp, output stage, and speaker allowed for some tweaking of application resistor values and the addition of more hardware if needed. The software was written and tested using the new configuration (see APPENDIX A, Software: Transceiver Audio). The tests showed that the output from the preamp circuit would need to be biased with a DC voltage to prevent a potentially damaging negative voltage on the PIC ADC input pin. Software to increase and control volume was considered but was unnecessary for the final prototype and redundant for the manufacturing version as the use of a codec would also provide the same functionality.

11.4.2 LCD and Timer
To allow the tCOM to sleep during the clock screen while not in use, it was necessary to provide a timeout mechanism for the menus and other screens that would return the software to the clock screen. To solidify this functionality before the final prototype the LCD and Timer prototypes were combined and new software was written to periodically check the timer0 for overflow conditions (see APPENDIX A, Software: Timer). This was achievable partly because timer0 (one of three timers available on the PIC) included up to a 256 prescale which meant that the timer only increased every 256 instruction cycles and partly because the timer was a 16bit timer. Thus even longer subroutines such as those that displayed 32 characters to the LCD were able to safely pole the upper byte of the timer for overflow while maintaining little variation in time length.

11.5 The Final Prototype Software
Before any code was written or integrated into the final prototype, a general outline of the code that would make up the final prototype was written up. This outline included the main menus, LCD initialization, Com1 and ComAll subroutines, and most of the basic functionality. The code also contained comments as to what each subroutine would do and a rough outline of how the code would eventually be written. As code was written in to replace comments, some subroutines were added and some suggested approaches were disregarded. The outline served as a guide and helped break up the code for the iterative design approach.

11.5.1 Proto.asm
Proto.asm was software written for the final prototype for senior design. It was the first of many iterations for the final prototype and therefore includes only some of the functionality. Proto.asm can be found electronically in APPENDIX A under the Software section in the Final Prototype folder.
11.5.1.1 Main Menu

The first section of code to be written for the final prototype was the main menu. This seemed appropriate since the end user would be using the menus to access the features of the t\textsubscript{COM} and by writing the menus first, the following software could be tested through the menus. The main menu starts with setting the TBLPTR special function register in the PIC to point at the location in program memory of the string that makes up the main menu. This is followed by the initializing of menu variables MENUSIZE which sets the length of the menu and MENUARROW which sets the position of the screen in the menu. With the TBLPTR and menu variables set up the REFRESHMENU subroutine could be called which displayed the menu to the LCD which was modified from the LCD prototype code. Also included were the LCD initialization, delays for timing, and the WAITFORBF which made sure the LCD was ready for the next instruction.

11.5.1.2 Clock Screen

After the main menu was completed, work was started on the clock screen which displayed the time and was also the default screen for the t\textsubscript{COM} when not in use. Like the main menu the clock screen begins with setting the TBLPTR and menu variables and calling the REFRESHSCREEN subroutine. Instead of writing the large number of possible screens that might be displayed, a blank menu was called to clear the screen and the individual numbers for the hours and minutes along with the Am or Pm were written to the screen individually. To write these numbers and letters to the screen a new subroutine was coded borrowing the SENDLCD subroutine from REFRESHSCREEN.

11.5.1.3 Sleep

Since the clock screen was completed, it seemed logical to add the sleep functionality that would save the t\textsubscript{COM} energy when waiting for calls or user inputs. The addition of the sleep command was extremely straightforward, but required that the watchdog be active to interrupt the sleep and continue running code. The watchdog was set to a prescale of 128 which when combined with the approximately four millisecond clock cycle of the internal oscillator gave a total delay of 660ms. This delay was important since it would determine how long the PIC would take to react to a set alarm. The sleep command was apparent on the power supply and resulted in an approximate 9mA drop (27mW).

11.5.1.4 Scroll Wheel Scrolling and Clicking

To more easily test further menus and subroutines it was convenient to program the scrolling and clicking of the scroll wheel of the modified mouse. The subroutine MENUNAVIGATION was written to fill this role and modified appropriate menu registers to give the illusion of scrolling and also modified the timeout register to indicate when the wheel had clicked. Because the scrolling was signaled with two input pins, the possibility of both signals being high or low had to be taken into account. By testing which signal changed first, the direction could be deciphered. While oscilloscope tests predicted that only both high and both low would occur during normal scrolling, the testing done during the combined LCD and Button prototype revealed that occasionally the signals would alternate during a half click. To accommodate this possibility and stop the PIC from thinking the wrong direction had been scrolled, the labeled sections SCROLLUPDOWN and SCROLLDOWNUP were added.

A timeout subroutine was also written as the main menu timed out to the clock menu and could be tested. While there was many places to place the timeout subroutine CALCTIMOUTS, the convenient place to put it was in the MENUNAVIGATION subroutine. By placing CALCTIMOUTS there, no additional work would need to be done on the existing menus. The CALCTIMOUT set the timeout to occur after about thirty seconds of inactivity, giving the user plenty of time to think about the next instruction but not too much time to risk not being able to receive calls.

To allow for the selection of different subroutines from the main menu, a hash table or switch statement like method was used. The position of the arrow on the screen determined by MENUARROW and ARROWTOP was added to the program counter with an appropriate multiplier to jump to a list of goto
instructions which further pointed to a subroutine call or set of instructions. As somewhat tricky as it was to determine the correct multiplier to add to the program counter, this method was much quicker and much shorter than the multi-branch if statement like the one used for the audio test egg prototype.

11.5.1.5 Name Menu

With the framework in place for standard menus and with the scrolling and clicking working, the more irregular name menu could be developed. The name menu needed to provide an interface for the user to select names by scrolling through the alphabet and give the user the option of changing the module name to the new name or canceling the name change. To achieve this functionality a basic menu with a blank top line and "Select  Cancel" on the bottom line was given to REFRESHSCREEN to print on the LCD. Then like the clock screen, individual characters could be written to the top of the screen forming the new name. The characters for this new name were selected in the CALLADDCHARACTER section of CHANGENAMEMENU and added to the MOD_NAME RAM array. To provide the arrow selection functionality of adding another character or selecting or canceling the new name the menu was given a size of three to trick the already written menu navigation into scrolling three times and a new subroutine was written to display the arrow to the screen. This arrow subroutine was called ADDNAMETOSCREEN and not only displayed the arrow in the correct location but the original module name to the screen before the new name was started. While the programming went smoothly and a hash table format was used to select which of the three possible locations the arrow should go, the prototype software began to behave in unexpected ways. It was eventually determined that the number of lines of code written before the ADDNAMETOSCREEN subroutine determined whether or not the program behaved correctly. With a little thought, this problem was tied to the hash table, which is the only code that could change based on its location, and it was found that the hash table did not take into account when the program counter carried to the upper byte of the sixteen bit register. Before rewriting the hash tables to behave correctly at any location, the entire grouping of iterations was saved as proto.asm and a new copied project and assembly file was started to preserve the working code in case future programming broke what had already been written.

11.5.2 Proto1.asm

Proto1.asm can be found electronically in APPENDIX A under the Software section in the Final Prototype folder.

11.5.2.1 Fixing the Hash Tables

Fixing the hash tables so that they worked even when straddling a carry to the upper byte took a bit more code than the original as seen in proto1.asm. However, the approach wasn’t complicated and required only one more variable to hold the current program counter value. During programming, some research resulted in useful commands to the PIC assembly compiler. Instead of using a set location in memory to store the menus and referring to that location statically, the compiler could use labels at the menu’s location to dynamically tell the compiler where to set the TBLPTR register. The menu setups found in proto1.asm reflect this change.

11.5.2.2 Set Time Menu

The set time menu subroutine SETTIME was developed shortly after the fixing of the hash tables. Set time is in essence a modified change name menu. The loop of the CHANGENAMEMENU was modified to display only numbers and adjust for impossible combinations such as eliminating possibilities 3-9 if a preceding 1 was entered on the hours. The user could then select the change or cancel options as before on the name menu. Because each choice of number was similar, a subroutine was also written to take care of the selection process and reduce code. The subroutine for displaying names was replaced with ADDTImETOSCREEN and the loading and saving of the time was taken care of through the LOADTIME and STORETIME subroutines respectively. The coding was straight foreword except for the handling of the inverted binary coded decimal format of the hours and minutes.
11.5.2.3 Integrating Flash

While the reading of flash to ram was a simple setting of the destination register TBLPTR, writing to flash was a much more complicated matter. The flash writing was not only important for bonus functionality such as module naming, but was also imperative for joining networks and remembering network information on power up. Since the software was written by one team member and added to the prototype by another, some misunderstandings occurred on exactly how the prototyped but untested software was intended to run. Besides these issues, the complexity created from inherent requirements both to writing and erasing data in flash as mentioned in the system design section also made the software subroutines more complex.

The first use of the flash would be in the change name menu as it was already written and functional unlike the networking subroutines. With a selection of “Change” the NAMECHANGEMENU called the CHANGENAMEFLASH subroutine. This routine simply setup and called the flash routines and was written to separate all flash calls and coding from the menu subroutines for organizational purposes. The subroutine stores a one in the UPDATE_MOD register telling the UPDATE_F_MODNAME subroutine to move the contents of the MODNAME_BUF into the first name location.

The UPDATE_F_MODNAME used the subroutines FIND_MOD_SPOT and FIND_BLOCK to pinpoint the exact location of the first modules name. Then the subroutine determined to which block the pinpointed module name belonged. Depending on the block (in this case the first block), UPDATE_F_MODNAME called the appropriate COPY_F subroutine. This subroutine copied the entire block to the copy block after erasing copy. After COPY_F, the WRT_UPDATE_BUF_MOD was called to create the 64byte modified section in the update ram buffer. With the ram buffer created and the block copied, the subroutine could call the correct UPDATE_F subroutine to erase the destination block and replace it with the combined contents of the UPDATE_BUF and copy block. The writes to flash included a specific ordering of instructions provided by the PIC datasheet and required the PIC to halt all other activities while suspended for writing.

11.5.3 Proto2.asm and Proto3.asm

Proto2.asm and proto3.asm further develop the networking data locations in program memory and assigns labels for future ease of use (see APPENDIX A, Software: Final Prototype). Because no change to running code was intended, new projects were started to insure working code could be obtained if instructions were accidentally modified while working on the network layout. The TxRx prototyping functions have been moved into code at this point, but have not been implemented by any usable menus.

11.5.4 Proto4.asm

Proto4.asm can be found electronically in APPENDIX A under the Software section in the Final Prototype folder.

11.5.4.1 Integrating the Interrupt Service Routine

After noticing that the timer would not work outside of the display clock screen (expected software execution), a timer based counter of seconds was prototyped and then added to the prototype. This simple counter was complicated by using the interrupt on overflow capabilities of the PIC. The interrupt functionality would not only be easy to add to the existing software, but also allowed the future use of interrupt signals on PORTB to immediately bring the PIC out of sleep and into the main menu or interrupt on the IRQ pin from the transceiver. There was some concern that interrupting during the middle of a write to the LCD screen might cause erratic behavior, but testing showed this not to be the case. Further testing would have had to of been done to prove no erroneous behavioral issues on a manufactured product, but the lCOM would be using a real time clock at that point making the issue a mute point.

11.5.5 Proto5.asm and proto6.asm

Proto5.asm and proto6.asm can be found electronically in APPENDIX A under the Software section in the Final Prototype folder.
11.5.5.1 Integrating TxRx
Because the software represented well the basic menu, naming, flash writing, and time functionality and
because team 5 realized that remaining time would only allow the addition of select features,
programming the most important element, the transmission of audio from one module to the next, became
top priority. While the code was already present by this point, adding the subroutine calls in the
TALKLISTEN and newly created CHECKFORCALL subroutines were done separately and tested with
their prototyped counterparts. After their initial success, the TX_AUDIO and RX_AUDIO subroutines
replaced TX_1 and RX_1. These routines added reads from the ADC creating for the first time a static
channel with audio transmission using identical programs.

11.5.5.2 Button Incorporation to Clock Screen
Team 5 next added the ability to end transmission and call the MAINMENU subroutine with a click of
the scroll wheel. Both were implemented without difficulty by adding a check to PORTC,0 input pin
once every loop and adding debouncing and waiting until the button was released. While simple, the
functionality added by this small change allowed for transmission in either direction without restarting the
program (only once, see next section).

11.5.6 Proto7.asm
Proto7.asm can be found electronically in APPENDIX A under the Software section in the Final
Prototype folder.

11.5.6.1 Ignore Lack of Reception
A problem with the reception subroutine in proto6.asm was that there was no testing for valid data after
the initial IRQ trigger. To correct for this problem, which disabled the ability to leave the display clock
screen, a WAITFORKIRQ subroutine was written which would delay for 2500us (over one packet
transmission) and check for a drop in the IRQ. The status of the second counting register COUNT2
indicated an IRQ detect or timeout. This in turn allowed RX_AUDIO to finish and the PIC to sleep
conserving energy as intended after the transmission was no longer being sent. Com 1 Com All felt that
the now statically functional intercom would genuinely represent a proof of concept for the manufacturing
version of the tCOM.

11.5.6.2 Integrating the Easter Egg
For effect and to the delight of the audience on Saturday night, the Mario Easter egg was added as the
called subroutine of REMOVEMENU. There was no changes to the prototyped code so the integration
was quickly completed. The design night ran smoothly from a software perspective and Mario proved to
be a good choice for additional features as the proto boards did not lend well to displaying the changing
of names, or time.

11.5.7 Proto7board.asm
Proto7board.asm was developed to fix errors on the printed circuit boards. This was mostly needed due
to the inversion of switch outputs. The fix was simple and can be found electronically in APPENDIX A
section Software in the Final Prototype folder.

11.6 Manufacture’s Software Design
As expected, many changes would need to be applied to the software of the final prototype to satisfy the
requirements of a fully functional manufactured module. Many of these changes are slight or already
well frameworked and the Mario Easter egg would of course need to be removed. However, some
changes that would require more work or are not proven well are given below along with suggested
approaches for implementing the software. These suggestions are only helpful hints as the actual
implementation would be up to the style and whim of the engineer responsible for its development.
11.6.1 *Rx during menus and more interrupt uses*

While the final prototype demonstrated the ability to use interrupts, it would be very useful to extend the ISR to handle the IRQ line from the transceiver and button inputs. This would allow a module to receive calls and make hot button calls even while on a menu screen. To insure correct behavior while running the program, tests would need to be done to demonstrate whether the interrupts could interfere with LCD signals. If they were found to be an interference, a simple turning off and on of interrupts would allow for correct timing while maintaining the detection of the interrupt.

11.6.2 *Networking Changes*

To make the manufacturable module work correctly, a great deal of work would need to be done on networking. First, the random networking address and channels would need to be programmed and used during network communications. Second, all communication except for the add module request would need to be encrypted or decrypted with the network key. Thirdly, networking subroutines would need to be added for the instruction set to send information, receive calls, or ask for updates. Fourthly, the network will need to assign module numbers to new modules and incorporate automatically resending update capability to ensure that all modules receive the new network information. This would seem to be most easily implemented during the display clock screen where a variable might track which modules are still pending for authenticated transmissions. Fifthly, all calling modules would need to test a series of channels for activity to avoid collisions with other communicating intercoms or noise and switch to this channel after the initial handshaking between modules. This testing would apply to new networks setting up when no open networks are detected, testing before sending any request on the network channel to avoid creating excess noise when already in use, and may be applied to existing networks were a once clean network channel becomes too noisy for optimum use. Sixthly, all non-audio communications should be done with acknowledgement to ensure no dropped packets. Lastly, audio transmission should indicate when transmissions are over and receivers should timeout when data has not been sent for an appropriate amount of time.

11.6.2.1 *RTC*

Software would also need to be implemented to communicate with a selected real time clock. A simple change in the UPDATETIME subroutine should be sufficient. The change time menu would need to be improved to include week, month, and year along with visual indication of the information on the display clock screen.

11.6.2.2 *Flash improvements*

To improve the life of the flash and time to write, the program could be made to test for information already present in the memory. If this memory already matched the new or if the entire 64bit block was already empty, no erasing would be necessary. This improvement is most likely unnecessary as the flash typically gets over 1000 erase/write cycles (APPENDIX) unless the modules were constantly changing the network channel due to noise.

11.6.2.3 *Communicating with the Codec*

Like the RTC, new software would need to be written for communication with the codec. Some old software subroutines such as TX_AUDIO may be simplified by detecting a sample ready line or command greatly reducing the focus on timing for audio sampling. While this signal may be used to interrupt the program, Com 1 Com All would suggest polling instead as the timing is quite long and occurs predictably. Naturally, the subroutines dealing with the DAC in the prototype would also need to be redone using the format of the codec. The codec may also need to be initialize on power up.

12.0 *Final Prototype Design*
12.1.1 Final Design Schematics

12.1.1.1 PIC Control Circuit

The schematic above shows the PIC control circuit. The surface mount PIC chip can be seen in the middle of the picture as a large square. On the lower left hand corner the programming pins connect to the PIC and above them is the Com All button. Labeled wires above and to the right of the Com All button are SPI and control lines used to communicate with the LCD, DAC, and transceiver. The upper right contains the scroll wheel encoder and button and just bellow them the oscillator circuit for the program clock. The last four buttons connect to the PIC directly and indirectly to the PIC interrupt pin through the four input NOR gate.

Figure 33: Schematic of PIC Control Circuit

12.1.1.2 Audio Input Circuit

The audio path begins at the microphone which is powered by the voltage though a thousand ohm resistor. The generated signal passes through the blocking capacitor leaving the bias voltage behind. It then goes through an inverting amplifier with a gain of 70 and a Bi-Mos operational amplifier. From here the second order multiple feedback 1dB ripple chebyshev lowpass filter attenuates the high frequency components to eliminate aliasing.
12.1.1.3 Audio Output Circuit

Below in Figure 35 the audio output circuit, you can see the Digital to Analog Converter being fed digital audio data by the PIC. The data is converted into analog sound waves and passes through the capacitor, which block DC current and has a resistor to ground to drain any lingering charge left by the signal. The signal then hits a 741 op amp follower which adds power to the system and negates the diode drop associated with the push-pull transistor output stage that follows, and feeds the boosted signal to the 8 ohm speaker.

12.1.1.4 LCD Circuit

As you can see in Figure 36 the LCD module gets its data and control signals from the PIC microcontroller, while the backlight operation is a current setting resistor to ground which is switched by the PIC via a MOSFET. The contrast of the screen is also controlled with a resistor to ground.
12.1.1.5 Transceiver Circuit

The transceiver circuit shown above depicts the transceiver and supporting circuitry. At the bottom lies the oscillating circuit for the transceivers internal clock. The transceiver is the large square above the oscillation circuit. To the right lies the antenna tuning and stabilization circuit with antenna. At the very top a current referencing resistor and noise reducing capacitors connect to ground. Lastly to the left are the lines to the pins for transceiver module attachment and continuing lines to the PIC.
12.1.2 Circuit Board Design

The other necessary piece of design necessary to create a complete prototype module was the circuit board design. This set of gerber files could be provided to a circuit board manufacturer to tell them the exact design specifications for all traces, pads, vias, and drilled holes on the circuit board. As was noted in a previous section, there were two circuit board designs made during the hardware design process. It was decided to include the two layer board as the design for the final prototype due to the reduced cost of two layer boards compared to four layer boards.

12.1.2.1 Two Layer Board Design

An electronic pointer to the full set of design documents for the two layer board design is given in Appendix B. Final dimensions for the circuit board were 6.652” by 3.821”. This was near the desired size for the entire module of 6” by 4” and well within the maximum required module size. With further minimizations due to full use of surface mount components and tighter component layout, the board design could easily fit within the module size requirements. The layout of all hardware components can be seen on the top layer board design as shown in Figure 38 below.

![Figure 38 - Two Layer Board Component Layer](image)

The components were laid out in groups according to their functions as follows:
- LCD circuits – top left
- Transceiver circuit – top right
- Audio input circuit – bottom right
- Audio output circuit – bottom left
- PIC and buttons – center right
- Programming circuit – bottom center

The bottom layer of the board is also shown in Figure 39. Other components were kept away from the transceiver circuit and ground plane to limit the effect the electromagnetic fields could have on other components or vice versa.
12.2 Parts List/BOM

Below is a compiled bill of materials for the final prototype. For the final design, parts would be further distilled to homogenize the design.

<table>
<thead>
<tr>
<th>Part</th>
<th>Part #</th>
<th>Manufacturer</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCB</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Case Front</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Case Back</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Buttons</td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Scroll Wheel</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>LCD Module</td>
<td>CFAH-16020YYHET</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Pic Processor</td>
<td>PIC18F45J10</td>
<td>Microchip</td>
<td>1</td>
</tr>
<tr>
<td>470 Ω resistor</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>10 kΩ resistor</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1 MΩ resistor</td>
<td></td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>20 pF cap</td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>1 uF cap</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>.1 uF cap</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>switches</td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Encoder</td>
<td>EC10E</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Component</td>
<td>Type</td>
<td>Quantity</td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>----------</td>
<td>----------</td>
<td></td>
</tr>
<tr>
<td>10 MHz Crystal</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Or Gate</td>
<td>SN74LS32N</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Transceiver</td>
<td>NRF24L01</td>
<td>Nordic</td>
<td>1</td>
</tr>
<tr>
<td>22 kΩ resistor</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1 MΩ resistor</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>22 pF cap</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>2.2 nF cap</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2.7 pF cap</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1.5 pF cap</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1 pF cap</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>33 nF cap</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1 nF cap</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>10 nF cap</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>8.2 nH inductor</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2.7 nH inductor</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>3.9 nH inductor</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Antenna</td>
<td>W1027</td>
<td>Pulse</td>
<td>1</td>
</tr>
<tr>
<td>16 MHz Crystal</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>N-channel MOSFET</td>
<td>2N7000</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>20 Ω resistor</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>4.7 kΩ resistor</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>DAC</td>
<td>MCP4822</td>
<td>Microchip</td>
<td>1</td>
</tr>
<tr>
<td>Op-Amp</td>
<td>ua741</td>
<td>any</td>
<td>1</td>
</tr>
<tr>
<td>47 kΩ resistor</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1 uF cap</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>npn transistor</td>
<td>2N3904</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>pnp transistor</td>
<td>2N3906</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Speaker</td>
<td>GF0771</td>
<td>Cui inc</td>
<td>1</td>
</tr>
<tr>
<td>BiMos Op-Amp</td>
<td>CA3140E</td>
<td>Intersil</td>
<td>1</td>
</tr>
<tr>
<td>Op-Amp</td>
<td>ua741</td>
<td>any</td>
<td>1</td>
</tr>
<tr>
<td>47 kΩ resistor</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>330 kΩ resistor</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>641 Ω resistor</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>10 kΩ resistor</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>.1 uF cap</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>.01 uF cap</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>microphone</td>
<td>EM9765P-42</td>
<td>Horn</td>
<td>1</td>
</tr>
<tr>
<td>1 kΩ resistor</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1 uF cap</td>
<td></td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
13.0 Business Study and Plans

13.1 Product Description
This product is a digital wireless intercom system. Our intended market is mid to high range residential and small to mid range commercial applications. The intercom system will:

- Consist of several modular intercoms with identical design
- Communicate using a wireless proprietary protocol connection
- Communicate over one of the unlicensed radio frequency spectrums
- Provide secure communication within its given system
- Convert the analog audio input to digital data prior to transmission
- Be simple and understandable for the end user

13.2 Business Structure
The basic structure of Interpersonal Communication Corporation (ICC) will be that of a privately held corporation that will attempt to achieve the following goals, fulfill our purpose, and adhere to the stated foundation. The company will attempt to develop multiple distribution channels including a web portal, direct selling to home developers, and retail placement with home improvement and electronics stores.

13.2.1 Goals
Interpersonal Communication Corporation’s actions will be focused toward achieving the following overarching company goals.

13.2.1.1 Growth

We and our employees will seek to expand the business to offer our products the widest audience that can make effective use of them. Growth is essential to any business’s to thrive.

13.2.1.2 Efficiency

Strive to be the most efficient at everything we do, through this constant effort we can support all other goals, have the greatest ability to fulfill our purposes and faithfully serve our foundations.

13.2.1.3 Advancement
We will constantly push the boundaries on a technological front in order to be ahead of the market in new technologies and products that use those technologies.

13.2.2 Purpose
Interpersonal Communication Corporation is guided in its actions by the purposes that bind its employees together and give reason for work.

13.2.2.1 Communication

We want to bring people together with simple and reliable communication available to the widest set of users.

13.2.2.2 Quality

We strive to provide the highest quality product to the customer, ensuring that our product is durable and attractive for its entire life.

13.2.3 Foundation
Interpersonal Communication Corporation is built on a foundation that supports the company, and provides guidance.

13.2.3.1 Safety

First and foremost public and private safety is a huge concern, we cannot have our products cause harm to our customers.

13.2.3.2 Customer Focus

As a company that sells a product we are directly dependent on the customer for our continued success. As such our principle concern is the customer

13.2.3.3 Positive Impact on Community

The Interpersonal Communication Company does not operate in a vacuum and will be a part of the surrounding community. As such we will strive to give back to the community that supports our business through thing such as the chamber of commerce and or charitable enterprises.

13.3 Marketing Plan
An integral part of the success of any business or product line is a strong marketing plan to pinpoint potential customers and grow the product recognition. Because of this, the tCOM and
other future products will have specific customer profiles and strategies for expanding sales. Once a solid customer base is in place, the long term marketing strategy can then go into effect to bring further consistent growth to the company as a whole and other product that would come into the market.

13.3.1 The Typical Customer and Marketing Strategy
The initial tCOM design and functionality makes it a great option for many mid to large scale residential and some small to mid range commercial/business settings. Intercoms are already a more accepted feature in the residential market and there are more potential sales in the residential sector compared to small businesses. So, the typical base customer will be 3 to 5 person homes (3 or 4 bedrooms) which would each require 4 to 5 intercoms for the household. Based on the size of their home (which is a key in making the tCOM useful for a home), these families will usually be fairly well off financially which will make buying a luxury item like an intercom a possibility.

Due to the various products already available on the market, most of the marketing will focus on comparisons between the tCOM and other intercom systems on the market. Because the tCOM offers robust functionality and quality comparable to many of the more expensive wired intercom systems, it can be marketed to people who want the latest technology and quality in the products they buy. In addition, the tCOM could be marketed towards more frugal customer because it will provide a system cost far less than the better systems on the market. That is even before the additional costs of installation for wired systems. Finally, the flexibility offered by the design also makes the product very marketable to existing homeowners, new home builders, and even to potential business customers. The tCOM can be used in any room, location, and situation as long as there is an electrical outlet. This combination of quality technology, very competitive cost, and system flexibility make the tCOM an extremely marketable product to offer to a hopefully growing potential customer base.

13.3.2 Expanding Customer Base
With a quality product and strategy for growing sales to the standard customers in place, additional steps must be made to add other customers to increase product sales. At the beginning of the business life, an aggressive strategy of business contacts would have to be made in order to develop sales opportunities.

13.3.3 Long Term Marketing Strategy
After a large and varied base of customers is in place, the next goal in the marketing plan will be to cement the company’s name recognition and market identity.

13.4 Research and Development
While initial sales of the tCOM system will have to be the initial growth source for the business, all products have a limited life cycle and there will need to be new products to offer and continue growth into the future. Research and development will be the driving force behind the expansion of product offerings and thus business opportunities. Updates to the initial product designs will
have to be made through its life cycle and new products must be added as technology, demand, and new areas of opportunity require.

13.4.1 Product Growth Brings Business Growth
Even with a great product to offer the customer, once someone buys your product, they are essentially removed from the pool of potential customers for that product. A single product offering can last for a short time but eventually business will dwindle due to a shrinking potential customer base and changes in technology. As a result, the long term success of this company will hinge on the ability to bring in new sources of revenue through additions to existing product lines and development of new products.

13.4.2 Additions to the tCOM Product Offerings
The basic tCOM module offers significant functionality but there are still several additions which could be made to the product line. Other intercoms, even the less expensive wireless modules, often offer outdoor modules which can be used as doorbells and other remote outdoor locations. This would be a simple addition since it would be a scaled back version of the current design. As technology improves and associated costs drop, improved functionality can be added like music streaming, video communication, and touch screen control which would greatly improve the marketability against the more expensive systems on the market. These upgraded modules should be compatible with the earlier versions to make them a viable addition to customers who already have bought tCOM systems.

13.4.3 New Market and Product Research
Some portion of the business efforts should additionally be placed into research for new technologies, market opportunities, and new products to meet those market opportunities. Although this business would start in the communication electronics it would be possible to move into other business areas. Once these business opportunities are found in our existing or another market, additional research will go into finding solutions to fill those market needs.

13.4.4 New Product Development
Once finances allowed, the company would need to support a group of engineers dedicated to developing new products and improving existing product designs. Our own expertise could cover this for a short time but would require a much more significant focus to continue meeting the companies development needs. Some of this work could be outsourced to a consulting firm during our first few years of operation.

13.5 Manufacturing
Manufacturing is perhaps the most important part of a business plan. No matter how much money or developed a structure one has, without manufacturing there is no product to sell and no client to serve. Our business plan foresees three phases in our manufacturing. The first phase is as a small and developing company. The second phase is for higher production runs as a young but developed business. Our last phase is for the established company with a large customer base and larger financial resources.
13.5.1 The Infant Company
Because there is a lot of risk with young companies and little financial resources available, most of the manufacturing will need to be outsourced. Outsourcing will adversely affect the products final cost and limit profits, but will allow the flexibility needed to develop a market and evaluate the viability of a full blown operation. The initial phase will likely last until the company is capable of selling 10,000 modules a year or roughly creating $130,000 in profits a year.

13.5.1.1 Assembly
Initially, the machinery and man power needed to produce circuit boards and final assemblies will be cost prohibitive and too risky for ICC. To reduce risk and the financial burden of large fixed costs, ICC plans to outsource the fabrication of the printed circuit boards and module housing. Assembly of parts cannot be outsourced efficiently at low volumes so the placement and soldering will have to be done in house.

13.5.1.2 Machines
Since placement and solder will have to be done by ICC, machines will be needed to facilitate assembly. ICC will need a reflow oven, a part placer, and a solder paste dispenser. Other assembly such as enclosure attachment and packaging can be done with standard tools. The lack of initially expensive machines is intentional to limit the startup cost of ICC.

13.5.1.3 Testing
With the small number of parts being sold, phase one will test modules before sale. The test will be functional and limited. While the limited testing may cause some customer dissatisfaction, ICC will not have the resources for individual PCB testing until phase two.

13.5.1.4 Shipping
The shipping of ICC’s products will be through a third party such as FedEx or UPS like many small businesses. Shipping would be a charge added to purchases and incurred by the customer to encourage bulk orders.

13.5.1.5 Costs

13.5.1.5.1 Fixed Costs
The fixed cost for phase one will include the purchasing of machines, business creation fees, and working space. The expected cost for each of these factors can be seen in the following table.
Variable Costs

The variable costs for the t\textsubscript{COM} include parts, assembly, testing, and shipping. The BOM for the t\textsubscript{COM} can be found in the table below followed by a table of variable costs.

13.5.2 The Young but Growing Company

When ICC develops a market and establishes a customer base, ICC will be ready for implementing phase two. Phase two will require larger quantities of parts, enough to necessitate outsourcing of assembly. This outsourcing will allow ICC to focus more on sales and R&D as the company grows and develops. Phase two will likely last until production grows to 100,000 parts a year or $950,000.

13.5.2.1 Assembly

Because assembling over 10,000 complete modules will require more manpower then the three original team member can supply and can be done nearly as cheaply through a third party, PCB assembly will be outsourced to a general assembly company. Some minor assembly such as speakers, microphone, buttons, and enclosure will still need to be completed.

13.5.2.2 Machines

The outsourcing of assembly will require no addition machines. However the large number of modules being sold and a developed market will require more stringent testing then in phase one. A tester will be purchased or built capable of rigorously testing the PCBs.

13.5.2.3 Testing

A tester will be used to check each PCB before final assembly. The final functional test will be used as a quality check for parts such as the LCD which cannot be tested well by the PCB tester.
13.5.2.4 Shipping

The shipping of ICC’s products will be through a third party such as FedEx or UPS like many small businesses. Shipping would be a charge added to purchases and incurred by the customer to encourage bulk orders.

13.5.2.5 Costs

13.5.2.5.1 Fixed Costs

The fixed cost for phase one will include the purchasing of machines, business creation fees, and working space. The expected cost for each of these factors can be seen in the following table.

<table>
<thead>
<tr>
<th>ICC's Fixed Cost Estimation for Phase One</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Machines</strong></td>
<td>Cost ($)</td>
</tr>
<tr>
<td>Small Reflow Oven (used)</td>
<td>1000</td>
</tr>
<tr>
<td>Vacuum SMT Part Placer</td>
<td>??</td>
</tr>
<tr>
<td>Solder Paste Screen printer</td>
<td>2000</td>
</tr>
<tr>
<td>Solder Paste Screen</td>
<td>20</td>
</tr>
<tr>
<td>Computer</td>
<td>700</td>
</tr>
</tbody>
</table>

**Business Creation**

| State Registration                       | ??     |
| Drafting Fees                            | ??     |
| Name Registration                        | ??     |

**Work Space**

| Machine room                            | ??     |
| Computer Space                           | ??     |

13.5.2.5.2 Variable Costs

The variable costs for the $t_{\text{COM}}$ include part costs, assembly, and shipping. The BOM for the $t_{\text{COM}}$ can be found in the table below followed by a table of variable costs.

<table>
<thead>
<tr>
<th>BOM</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
<td>Description</td>
</tr>
<tr>
<td>PIC18F45J10</td>
<td>PIC</td>
</tr>
<tr>
<td>AD74111YRUZ</td>
<td>Codec</td>
</tr>
<tr>
<td>P9925</td>
<td>Microphone</td>
</tr>
<tr>
<td>GF0771</td>
<td>Speaker</td>
</tr>
<tr>
<td>nRF24L01</td>
<td>Transceiver</td>
</tr>
<tr>
<td>w1027</td>
<td>Antenna</td>
</tr>
<tr>
<td>PCF8563</td>
<td>Real Time Clock</td>
</tr>
<tr>
<td>CFAH1602O-YYH-ET</td>
<td>LCD</td>
</tr>
<tr>
<td>Human Interface</td>
<td>Buttons and</td>
</tr>
<tr>
<td>Devices</td>
<td>Scroll</td>
</tr>
<tr>
<td>-------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Boards(4&quot;x6&quot;)</td>
<td>Final Boards</td>
</tr>
<tr>
<td>3V Reg</td>
<td>3V 1500 mA REG</td>
</tr>
<tr>
<td>5V reg</td>
<td>5V 100 mA REG</td>
</tr>
<tr>
<td>NX3225SA</td>
<td>16MHz Xtal</td>
</tr>
<tr>
<td>ECS-100-S-1</td>
<td>10MHz Xtal</td>
</tr>
<tr>
<td>901-9877-RFX</td>
<td>SMA Male</td>
</tr>
<tr>
<td>PSU</td>
<td>Power Supply</td>
</tr>
<tr>
<td>Analog Components</td>
<td>12</td>
</tr>
<tr>
<td>Enclosure</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable Cost</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parts</td>
<td>39.16</td>
<td>24.608</td>
<td>17.3308</td>
</tr>
<tr>
<td>Assembly (75)</td>
<td>7</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Testing</td>
<td>0.4</td>
<td>0.17</td>
<td>0.12</td>
</tr>
<tr>
<td>Final Cost</td>
<td>46.56</td>
<td>31.778</td>
<td>20.4508</td>
</tr>
<tr>
<td>Profit</td>
<td>13.968</td>
<td>9.5334</td>
<td>6.135240</td>
</tr>
<tr>
<td>Total</td>
<td>60.528</td>
<td>41.3114</td>
<td>26.5860413</td>
</tr>
</tbody>
</table>

**14.0 Feasibility Studies**

**14.1 Audio Quality Study**

While some of the competition may incorporate minimal quality audio systems in order to reduce cost, because t\textsubscript{COM} is targeting upper middle class and commercial markets that desire increase in functionality, audio quality will be a significant factor for sales and design. Other similar devices have very poor audio quality to the point of user annoyance or even information loss. Such devices include walkie-talkies, phones, and low quality toys. On the opposite spectrum DVD’s and CD’s are known for their excellent audio quality. For these reasons, the goal of the t\textsubscript{COM}’s audio quality is to exceed that of a phone and approach that of a CD.

**13.1.1 Bit Depth**

Audio quality is a difficult thing to define even though it is very apparent to the sensitive human ear. One measure of the quality is the bit depth of the signal. Bit depth refers to the divisions of sound levels in the signal. For instance, a signal with a bit depth of one would have $2^1$ sound levels. This signal would only be able to produce square waves at one volume. A signal with a bit depth of three would have $2^3 = 8$ different sound levels and one with sixteen would have $2^{16} = 65536$. Since natural occurring signals are produced by vibrations in the air, desired signals...
have a sine wave shape. This shape is far better approximated by the sixteen bit signal then by the three or one bit as seen below in Figure 40 below.

![Signal Approximation with Bit Resolution](zone.ni.com)

This differentiation becomes more important and noticeable with smaller signals and with approximating complex frequencies like voices that have many frequencies present as the same time. The necessity of having more than 16 bits or even just 8 bits of depth for a signal may seem excessive, but even moving from 16 to 24 bit signals can improve overtones and nuances (extremetech.com). The bit depth of a common telephone is 8 bits and a CD frequently has 16 bits.

### 13.1.2 Frequency Range

A second measure of audio quality is the frequency range of a signal. The human ear can differentiate frequencies from 20-20,000Hz. To perfectly replicate audible sounds, these frequencies must be covered and sometimes sub-audible signals are included to feel sounds like those of a jet engine. When converting an analog signal into digital, the frequency range of the result is determined by the sample rate. This sample rate is exactly twice as fast as the fastest frequency in the desired range. This is why CD’s which cover the entire audible spectrum must sample at a rate of 44.1 kHz. The telephone’s frequency range of 180-3.2 kHz is a clear indicator of its far lower quality. In general, frequency range is far more noticeable then bit depth and is a far greater factor in total audio quality. Unfortunately, increasing the frequency range of an audio system is far more expensive then increasing its bit depth. It is especially expensive for small sized systems, because larger speakers are needed for producing lower frequencies and space is sometimes too limited for multiple speakers.

### 13.1.3 Noise
Even more apparent than a reduced frequency range is the introduction of noise to a signal. Noise often is heard as a crackling or whining sound. Noise can occur from a multitude of different sources including the supply lines to speaker, microphone, or codec, crosstalk between lines, electromagnetic pollution, and poor data transmission. In fact, it is noise induced from home power lines that inspired the conception for the tCOM. In terms of noise, a digital system has significant advantages over analog. However, any audio system will need to incorporate at least some analog circuitry. Because tCOM’s data will be transmitted over RF, poor signal reception may cause intermittent connections. This makes the transceiver the most crucial component effecting audio quality.

13.1.4 Audio Quality of Design

tCOM incorporates all of the audio quality issues mentioned above to provide for affordable but high quality sound. By using slightly more expensive parts, tCOM is designed to have a bit depth of 24, a frequency range of 180-12,000Hz, and as little noise as possible especially when the speaker is not being used during listen mode. Bottlenecks for tCOM’s designed bit rate are the transceiver and microprocessor. These components must be able to handle the 576kb/s required to move a 12kHz signal with a bit depth of 24. Any further range extension will only increase the bit rate and subsequently the transceiver’s and microprocessor’s necessary performance. The chosen components account for the desired bit rate to ensure the desired audio quality. This expected quality is far better than a telephone’s 180-3.2kHz 8b signal but not quite as good as that of a CD’s 20-20kHz 16 bit depth sound.

14.2 Data Transfer Analysis

To achieve the desired audio quality mentioned in the Audio Quality Study section above, all of the components must be able to transfer at the necessary data rate. A failure of a component to comply with this rate would lower the quality of sound and if unaccounted for, cause unacceptable distortion. These data rates must be carefully calculated because data rates given in data sheets can be very misleading. The needed transfer calculations can be found in Appendix C and result in a rate of 576,000 bps (bits per second).

14.2.1 Transceiver

According to the transceiver data sheet, the nRF24L01 transmits at 2 Mbps or 1Mbps. Based on prior experience we are allowing for some packaging inefficiencies expected to add up to 50% of the data transmitted, it initially appears to more than cover the desired bit rate even at low speed. A more careful analysis of the data sheet showed that this assumption was not true. As seen in the calculation found in Appendix C, the actual maximum rates are closer to 584 kbps and 906 kbps respectively. These results make using the lower transmission rate too risky and leave no room at the higher rate for acknowledgement of individual packets.

13.2.2 Codec

The codec is designed to convert analog and digital signals at sample rates of 48 kHz and up to 24 bits of depth. Thus the theoretical bit rate for the codec is 1.1152 Mbps. Not only is this well
above the needed rate, but also indicates that the device will not reduce quality to keep pace with the data transmission of the transceiver.

13.2.3 Microprocessor

The microprocessor has two methods of data transfer with different transmission rates. Using only the general input-output ports, the processor can transfer raw data at a rate over 1MHz. However, tCOM’s other features make using the processor’s computing power inefficient and undesirable. The SPI (serial peripheral interface) capabilities of the PIC18F45J10 allow for up to 10 Mbps autonomous transfer. Both codec and processor were chosen to coordinate in their peripheral support of SPI to facilitate the requirements of data transfer and ease of programming.

14.3 Power Consumption Analysis

Because tCOM is designed for quality and functionality, the power supply must provide adequate power to all of the components without overheating. Integrated circuits were the most common choice for components partially because they reduce the total need for power.

14.3.1 Total Power Usage

A list of the components used in tCOM’s design can be found Error! Reference source not found. in Error! Reference source not found.. Together all of these will determine the total power usage of the individual tCOM modules. Data below was taken from the various component datasheets for the individual parts.

<table>
<thead>
<tr>
<th>Device/Component</th>
<th>Max Power (mW)</th>
<th>Sleep (mW)</th>
<th>Active (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIC Processor</td>
<td>1000.0</td>
<td>0.7</td>
<td>568</td>
</tr>
<tr>
<td>Audio Codec</td>
<td>35.0</td>
<td>1.9</td>
<td>35.0</td>
</tr>
<tr>
<td>Microphone</td>
<td>5.0</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Speaker</td>
<td>1000.0</td>
<td>1.0</td>
<td>500</td>
</tr>
<tr>
<td>Transceiver</td>
<td>60.0</td>
<td>0.1</td>
<td>36.9</td>
</tr>
<tr>
<td>LCD</td>
<td>868.0</td>
<td>7.5</td>
<td>868.0</td>
</tr>
<tr>
<td>Real Time Clock</td>
<td>4.4</td>
<td>0.0</td>
<td>4.4</td>
</tr>
<tr>
<td>Additional Circuitry</td>
<td>200</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>Total</td>
<td>3172.4</td>
<td>14.3</td>
<td>2114.6</td>
</tr>
</tbody>
</table>

While over three watts of power is may seem like a large power requirement for an intercom, it is a value that will likely never be needed. To max out all of the components, the end user must be receiving a transmission with the backlight on at a constant full volume. The PIC’s maximum assumes that the output pins are providing their max total output current of 200mA. This will never happen because tCOM does not require the PIC to drive any of the surrounding circuitry. A more accurate estimation, the active power, is a better indicator of tCOM’s power needs until prototypes can be built and tested for consumption rates. An expected maximum power usage of 1.25 W is far below our 5.324W requirement.
14.3.2 Components of Interest

A number of the components listed in the previous section will use varying amounts of power based on how they are used and specific modes of operation. These modes are audio communication mode, network setup mode, module settings mode, and idle mode. This section will detail the ways in which each component was used to minimize power usage in the design of the tCOM.

14.3.2.1 PIC

The PIC processor not only controls most of the surrounding circuitry, but also uses a significant amount of power when it is at maximum power according to the datasheets. During the active modes of operation (audio communications mode, network setup mode, and module settings mode) the PIC must process instructions and send signals to the other integrated circuits and is theoretically able to use one watt of power. However, current and voltage values from the datasheet show that the PIC’s I/O ports can sink or source 860mW and that the values were calculated with the PIC Vdd-Vss at 4.3V. Since tCOM’s PIC will be powered at 3V, the theoretical maximum of the microchip is 698mW. This maximum will be further reduced since the PIC is only driving communication pins which require around 3-30uW for a total pin wattage of .960 mW, far less than the 600mW possible. Typical PIC performance at 40MHz with all pins tristated is only 11.5mW which indicates a range of 11.5-99mW for an active PIC. To further reduce the power consumed by the PIC during normal use, the PIC is instructed to sleep when the tCOM module is in idle mode. This sleep is programmed to wake up after ((<.5s>) NEEDDATA) of time has gone by or an interrupt is generated by ((<the transceiver or>) NEEDDATA) button. The datasheet indicates that the PIC uses only far less power in sleep mode so a significant reduction in power is expected.

14.3.2.2 Speaker

Of all of the components necessary for tCOM’s many functions, the speaker and driver circuitry has the highest power consumption when in use. The power needed by the speaker depends on many factors including the volume setting of the codec, the loudness of the sound received by the transceiver, and whether or not the speaker is currently in use. The speaker is rated for 2W of power, however a 5V supply will have a maximum of 1.5W. Because of the factors that affect the actual power used during audio play, the actual power is expected to be far less. On a muted power level or during the network communication, idle, and module settings modes, the speaker and driver will use considerably less power. This idling power could be nearly eliminated by using a class B output stage, but a class AB output stage reduces clipping distortion.

14.3.2.3 Transceiver
The power consumed by the transceiver varies greatly depending on its five modes of operation, data air speed settings, and output power for the transmitter. Although the total power consumed by the transceiver is much less than some of the other components, it represents a larger portion of the consistent power used when audio is not being received and the backlight is not in use. According to the nRF24L01 datasheet, a maximum of 60 mW of power can be used when running at its highest operating temperature (85°C). In the tCOM design however, it is unlikely that the transceiver will ever be operating at such high ambient temperatures. More realistic power values for the transceiver operation are given in Table 10 below.

### Table 10 – Power Usage of the nRF24L01 Transceiver

<table>
<thead>
<tr>
<th>Mode of Operation</th>
<th>Typical Current</th>
<th>Typical Power (3V supply)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transmit @ 0dBm output power</td>
<td>11.3 mA</td>
<td>33.9 mW</td>
</tr>
<tr>
<td>Transmit @ -6dBm output power</td>
<td>9 mA</td>
<td>27 mW</td>
</tr>
<tr>
<td>TX settling time</td>
<td>8 mA</td>
<td>24 mW</td>
</tr>
<tr>
<td>Receive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Receive @ 2 Mbps</td>
<td>12.3 mA</td>
<td>36.9 mW</td>
</tr>
<tr>
<td>Receive @ 2 Mbps and LNA low current</td>
<td>11.5 mA</td>
<td>34.5 mW</td>
</tr>
<tr>
<td>RX settling time</td>
<td>8.4 mA</td>
<td>25.2 mW</td>
</tr>
<tr>
<td>Idle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Down</td>
<td>900 nA</td>
<td>2.7 µW</td>
</tr>
<tr>
<td>1.5 mS crystal oscillator startup</td>
<td>285 µA</td>
<td>855 µW</td>
</tr>
<tr>
<td>Standby-I</td>
<td>22 µA</td>
<td>66 µW</td>
</tr>
<tr>
<td>Standby-II</td>
<td>320 µA</td>
<td>960 µW</td>
</tr>
</tbody>
</table>

Power usage will be at a maximum when the transceiver is in transmit (TX) or receive (RX) mode. Using the highest possible output power, which will increase the possible range, a transceiver in transmit mode will use about 34 mW. Receiving RF data transmissions requires slightly more power than transmission but is comparable when the LNA (low noise amplifier) is turned off. This feature allows the transceiver to consume less current by giving up 1.5 dBm in sensitivity. This design needs all of the possible sensitivity to increase transmission range and thus will use the mode with increased power demands. Two other modes of operation listed are the settling times to Transmit (TX) and Receive (RX) modes. This mode occurs during a 130 µS startup time prior to entering Receive or Transmit mode. The transceiver uses slightly less power while it is preparing to handle the RF communication in the active modes.

The idle modes of operation will provide times of minimal power usage by the transceiver. In Power Down mode, which is the first mode entered when power is supplied, register values can be written to and read through the SPI interface but transmission cannot take place. Upon setting the Power_Up bit in one of the control register, the transceiver starts its external crystal oscillator so it can enter into the initial Standby-I state. From this point, the transceiver can be placed into TX or RX modes after only a short settling time delay. Standby-II is reached after the transmit data pipe is emptied but the transceiver remains in active transmit mode.

In order to reduce the amount of power used, the transceiver should be kept in idle modes whenever possible. This had to be weighed against the obvious need to be run in RX mode in
case an incoming transmission was coming from another module. To balance the desire for reduced power consumption with the need for readily available and consistent communication, a system of polling in RX mode will consistently check for incoming messages from other modules. This will allow for minimal delays in communication without using a consistently large amount of power.

14.3.2.4 LCD

The Crystalfontz CFAH1602O-YYH-ET LCD module provides the visual interface for the tCOM and will at times be a major source of power consumption. Its power usage is entirely dependent on the use of its available backlight. With the backlight off, the module will use less than 10 mW of power but this jumps to over 850 mW of power with the backlight turned on. The brightness of the backlight under its normal conditions was excessive and offered a chance to lower the power consumption with changes to the drive circuit to limit the current to the backlight.

14.3.2.5 Audio Codec

This section will be updated once we have a new solution to the audio issues.

14.3.2.6 Real Time Clock

The PCF8563 real time clock presents minimal power demands to the system. While its I²C interface is active and communicating with the microcontroller, the maximum power it could require is only 4.4 mW with a 5V supply. This design will have it connected to a 3V supply which will cause it to consume even less power. When the interface in inactive, the power levels drop again causing expected power consumption to range between 1 and 2 µW. Power consumption should be on the lower end of that range for tCOM’s expected usage.

14.4 Economic analysis

Cost estimates are important for determining the marketability and the budget of a design. As already mentioned in the Detailed Design Requirements, tCOM needs to cost 20$ or less to manufacture to reach its goals. This requirement is extremely tight and a small amount of overshoot may be deemed acceptable for additional features. In terms of budgeting, Com 1 Com All has only $300 to spend on resources. Therefore $300 is the desired total spending unless additional funding from other senior design allotments can be redistributed to tCOM’s development.

14.4.1 Parts List and Bill of Material
The total amount of money expected to be spent on \( t_{\text{COM}} \) including projected bulk pricing can be found below in Table 11.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Sing. Cost($)</th>
<th>Multi Cost($)</th>
<th>Qty Needed</th>
<th>Qty Bought</th>
<th>Sing. Sub Tot</th>
<th>Multi Sub Tot</th>
</tr>
</thead>
<tbody>
<tr>
<td>DV164120</td>
<td>DEV KIT</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>PIC16F685-I/P</td>
<td>PIC</td>
<td>3</td>
<td>1.14</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>1.14</td>
</tr>
<tr>
<td>PIC18F45J10</td>
<td>PIC</td>
<td>0</td>
<td>1.79</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1.79</td>
</tr>
<tr>
<td>PIC24FJ16GA004</td>
<td>PIC</td>
<td>0</td>
<td>1.84</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1.84</td>
</tr>
<tr>
<td>AD74111YRUZ</td>
<td>Codec</td>
<td>5</td>
<td>2.66</td>
<td>1</td>
<td>2</td>
<td>15</td>
<td>2.66</td>
</tr>
<tr>
<td>EM9765P-42</td>
<td>Microphone</td>
<td>0.98</td>
<td>0.147</td>
<td>3</td>
<td>0</td>
<td>2.94</td>
<td>0.1479</td>
</tr>
<tr>
<td>GF0771</td>
<td>Speaker</td>
<td>3.6</td>
<td>1.92</td>
<td>3</td>
<td>0</td>
<td>10.8</td>
<td>1.92</td>
</tr>
<tr>
<td>nRF24L01</td>
<td>Transciever</td>
<td>2.05</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>8.2</td>
<td>1</td>
</tr>
<tr>
<td>w1027</td>
<td>Antenna</td>
<td>4.65</td>
<td>1.97</td>
<td>3</td>
<td>0</td>
<td>13.95</td>
<td>1.97</td>
</tr>
<tr>
<td>PCF8563</td>
<td>Real Time Clock</td>
<td>1.33</td>
<td>0.6625</td>
<td>3</td>
<td>0</td>
<td>3.99</td>
<td>0.6625</td>
</tr>
<tr>
<td>CFAH1602O-YH-ET</td>
<td>LCD</td>
<td>19.24</td>
<td>3.3</td>
<td>3</td>
<td>0</td>
<td>57.72</td>
<td>3.3</td>
</tr>
<tr>
<td>Human Interface Devices</td>
<td>Buttons and Scroll</td>
<td>5</td>
<td>1.5</td>
<td>3</td>
<td>0</td>
<td>15</td>
<td>1.5</td>
</tr>
<tr>
<td>Boards</td>
<td>Final Boards</td>
<td>25</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>75</td>
<td>1</td>
</tr>
<tr>
<td>Packaging</td>
<td>Packaging</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Contingency</td>
<td>Contingency</td>
<td>50</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>PSU</td>
<td>Power Supply</td>
<td>10</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Shipping</td>
<td>Shipping</td>
<td>25</td>
<td>0.1</td>
<td>0.72</td>
<td>0.28</td>
<td>25</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>78.2</strong></td>
<td><strong>330.6</strong></td>
</tr>
</tbody>
</table>

Table 4 clearly shows that \( t_{\text{COM}} \)'s total cost with a $50 contingency is $330.6 which is more than the goal. While goal can be reached if the contingency is unneeded, it is far more likely that Com 1 Com All will require additional funding. The total under the multi subtotal calculates the cost of a single module’s materials using only the PIC18F45J10. This total is very close to the goal of $20 per module, but costs are based on actual bulk rates available online and it may be possible to negotiate better deals in an actual business setting. Bulk pricing was unavailable for the transceiver so a conservative half pricing was assumed.

11.4.2 Manufacturing Costs

 Additional cost such as labor, shipping, and machine maintenance make the actual cost of production higher than merely the cost of materials. These rough estimates and assumptions can be found in Appendix D. Added to the estimated cost of materials, the total production cost comes out to $19.8915. This is below our goal of $20 and is conservative because of the lack of availability of certain bulk prices and production costs.

15.0 Test Plans and Testing Results

During and after the design process, testing provided a means to measure the proper functionality and, in some instances, the quality of the designs made. This section provides a description of the testing which took place during the prototyping process and details the final prototype test plans and subsequent testing results.
15.1 Prototype Test Plan

Informal testing was the basis for progressing from the simplest microcontroller circuits to more complicated circuits with our other hardware components and eventually to the final prototype design. As a given functionality was produced and confirmed through various test processes, the designs were then saved and expanded to provide greater and more robust functionality. Further description of the various testing taking place during prototyping is given in the hardware and software testing sections below.

15.2 Power Consumption Testing

Part of our completed system testing would be to take measurements of system power consumption for each module under various operating conditions. This testing would confirm the theoretical power consumption calculations in the previous section and give more precise power consumption values. These measurements will be taken using a DC power supply with a built in ammeter to power the modules and take real time current measurements used to calculate power consumption.

15.2.1 Idle State Power

This measurement will take place with the tCOM in its idle state by not attempting to send or receive any data. In this state, the usage of the PIC microcontroller will be minimal as it will be placed into its lowest power state and only removed to make minimal updates to the system information and check for incoming RF transmission.

15.2.2 Module Settings (Menu) Power

In this measurement, the user was working with the tCOM menu system but not taking any actions which would cause data to be transmitted over the RF connection. This gives an indication of the power consumed when the microcontroller was active and the LCD screen was being frequently updated.

15.2.3 Audio Communications Power

The amount of power used by both the transmitting and receiving modules will be of significant interest. Maximum amounts of power will be used during the audio transmission process in which data will be consistently sent with intensive workload on the microcontroller, transceiver, codec, and speaker for the receiving module.

15.2.4 Networking Communications Power

This mode of operation is similar to the when audio is being transmitted but the codec and audio circuitry will not be in operation. Only network data will be transmitted causing a much lower power consumption level.
15.2.5 *Addition of Backlighting*

The backlight can be turned on from the menu system. Its impact on system power consumption should be consistent no matter what mode of operation is taking place. Varying brightness level measurements may also be taken based on the final backlighting features (adjustable brightness).

**16.0 Conclusion**

To conclude, we believe that the prototype was an unqualified success. It could transmit and receive audio messages, navigate menus, keep time, write to its own memory, use interrupts and play digital audio data stored in program memory. This current list of features proves that with more time the features detailed in our requirements could be implemented. In completing this project the team learned many things about working on a project of this magnitude which we did not know prior to the senior design class, even though we had all had industry experience in the form of internships. Among these lessons that we take away is the importance of manufacturer support, when there was good manufacturer support such as with Nordic we were able to succeed with their help, while Analog was not help full and we were stuff floundering for quite a long time. We also learned the importance of active project management. In the beginning of the project and to a degree throughout the project, we worked on whatever was next with little to no regard to the project as a whole, this resulted in us taking too much time on non-essentials or stumbling block early on such as the codec, when we should have cut our losses and worked out an alternate solutions so as not to lose momentum. Next we learned about manufacturing quality, and how professionally manufactured printed circuit boards are far superior to the prototype boards created in the lab. Finally we learned the additional complexity and special issues that radio frequency circuits bring to the design.

Also during this class we came across numerous things which we would do differently if we were given the chance to start again. The first change would be to work more at getting over the first semester hump and realize how huge the project actually is. When the team realizes the magnitude of the project it will drive them to use less time researching and more time designing and prototyping, in this way we would design systems, and then when a system has been designed the parts would be ordered and prototyping and documentation of design and prototype can begin. To this end we feel that we need to set out a project that has hard due dates for certain systems and then it needs to be kept with frequent team progress meetings. Also when the system is designed it should be documented, this really hurt our team as in the last weeks of both semesters we scrambled to provide documentation for all of the work we had done that semester. Finally we now understand why the default team size is four people, there were many times when we just did not have the available man hours to do all that we wanted to do, such as both prototype and document.

In all Senior Design class has been a growing experience, in which we have all learned a great deal about truly working as a team to overcome self set challenges, and quite a bit about ourselves in the process.

**17.0 Acknowledgements**

- Steve VanderLeest – Our indispensable advisor
- DornerWorks Embedded Systems Engineering – For support in creating our PCBs
  - Andy Wallner – For help learning PADS software
- Jay Tyzzer, Nordic Semiconductor – For assistance with transceiver modules
- Tim Theriault, GE Aviation – Our industrial consultant
- Chuck Holwerda – For electronics support
• Bob DeKraker – For ordering parts and fixing our computer
• Paulo Ribeiro – For help debugging our circuit boards
• Ned Nielson – For the inspiration behind our project

18.0 References


Appendices

APPENDIX A
Appendix A contains the electronic locations of files created by team 5 during the design and creation of the tCOM.

**Software:**
Hello World  
X:\Engineering\Teams\Team5\PIC\02 Blink
Hello World 2  
X:\Engineering\Teams\Team5\Software\JMS\Blinky
Codec  
X:\Engineering\Teams\Team5\Software\Codec
X:\Engineering\Teams\Team5\Software\XE300
DAC  
X:\Engineering\Teams\Team5\Software\DAC
Flash  
X:\Engineering\Teams\Team5\Software\Flash
Interrupt  
X:\Engineering\Teams\Team5\Software\interrupt
LCD  
X:\Engineering\Teams\Team5\Software\LCD
Final Prototype  
X:\Engineering\Teams\Team5\Software\Prototype
Timer  
X:\Engineering\Teams\Team5\Software\Timer
Transceiver  
X:\Engineering\Teams\Team5\Software\TXRX
Transceiver Audio  
X:\Engineering\Teams\Team5\Software\TX_RX_AUD
Watchdog  
X:\Engineering\Teams\Team5\Software\Watchdog

**Schematics:**
Gerber File  
X:\Engineering\Teams\Team5\Electronic Notebooks\Justin Slocum\Design\Tcom\Gerber Files
APPENDIX B

Appendix B contains datasheets for the parts used or considered for use in the tCOM.

Antenna X:\Engineering\Teams\Team5\Data Sheets\Antenna
DAC X:\Engineering\Teams\Team5\Data Sheets\DAC
Demo Boards X:\Engineering\Teams\Team5\Data Sheets\Demo Boards
Codec X:\Engineering\Teams\Team5\Data Sheets\Codec
Crystals X:\Engineering\Teams\Team5\Data Sheets\Crystal
LCD X:\Engineering\Teams\Team5\Data Sheets\LCD
Microprocessor X:\Engineering\Teams\Team5\Data Sheets\MCU
Microphone X:\Engineering\Teams\Team5\Data Sheets\MICS
NOR Gate X:\Engineering\Teams\Team5\Data Sheets\NOR Gate
Operational Amplifier X:\Engineering\Teams\Team5\Data Sheets\Op Amp
PIC Microprocessor X:\Engineering\Teams\Team5\Data Sheets\PIC Stuff
Regulator X:\Engineering\Teams\Team5\Data Sheets\Regulator
SMA Connector X:\Engineering\Teams\Team5\Data Sheets\SMA Connectors
Speaker X:\Engineering\Teams\Team5\Data Sheets\Speaker
Scroll Wheel and Switches X:\Engineering\Teams\Team5\Data Sheets\Switches and Buttons
Transformer X:\Engineering\Teams\Team5\Data Sheets\Transformer
Transceiver X:\Engineering\Teams\Team5\Data Sheets\TxRx