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EECS 189A and EECS 189B

UCISAT Communications Subsystem

Undergraduate Senior Project

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Abstract

This paper is intended to explain the methods, theories, analysis and experiments that have played a role in the successful completion of the UCISAT-1's communication subsystem, which will insure the safely transmission of the data between the ground station and the satellite. The problems experienced through out this expedition and the solution to those problems will be mentioned. Consisting of a TNC, radio, matching network, balun, and a dipole antenna, this subsystem and its sub-modules' workings will be discussed in this paper.

Background

The CubeSat project was developed through the joint efforts of California Polytechnic State University and Stanford University. It was introduced to world of academia as a means of opportunity for universities throughout the world to enter into the realm of space science and exploration. UCISAT project, being a CubeSat project, is University of California Irvine's (UCI's) effort to enter into the field of space and compete with some of the top universities for producing a satellite with exceptional capabilities. This project consists of about 40 undergraduate and graduate students with 8 major subsystems. Since fall of 2006, Leon and I have joined this project and have been working on the communications subsystem onboard of UCISAT-1[1] (UCI's first satellite) which will be presenting as our senior design project. UCISAT-1's mission is summarized as receiving commands, taking pictures of earth, and transmitting those pictures back to the ground station located at the MSTB building at UCI. This satellite will be launch to a LEO (Low Earth Orbit) at approximately 600 miles above earth. These conditions will introduce exclusive limitations and constraints in the design and analysis of each subsystem. Our focus for the senior design project was to complete a working prototype of the on-board communication's subsystem.

Introduction to the communications subsystem

The goal of UCISAT's communication subsystem is to transmit and receive healthy data to and from the ground station at a speed of 1200 baud. This subsystem consists of three major parts: the TNC/Modem (terminal node controller), the transceiver/radio, and the antenna (Figure 1). The entire system follows the basics of AX.25[2] protocol and the connection between the TNC and the OBC complies with the KISS protocol. The focus of this paper is to review the design and analysis of each of these parts.

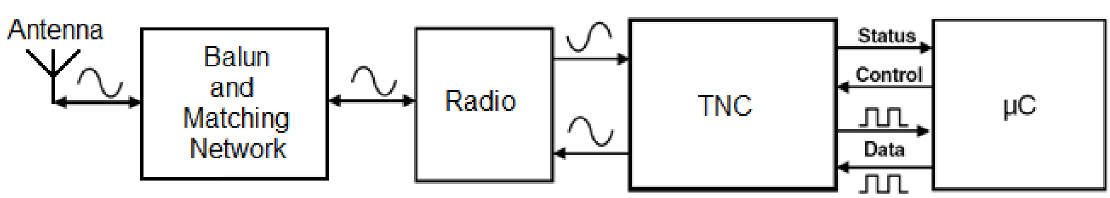


Figure 1 - An overview of the communication subsystem

The TNC

As illustrated above the TNC sits between the radio (off the shelf component) and the onboard computer (OBC).

[1] UCISAT-1 is currently being design and expected to be launched in January of 2009 from an Indian site.
[2]

Objective

The goal of this particular module is to delimit the frames coming from the OBC and convert them to audio and pass it to the radio and vice versa (to capture the audio coming from the radio convert them to packets and open up the packets for the OBC). In order for the TNC to be able to handle this task, it is required to have a microcontroller, a memory module, and a modem. However after some testing we realized that this system will not function properly unless we add an additional filter to the system (which will be discussed later in this paper).

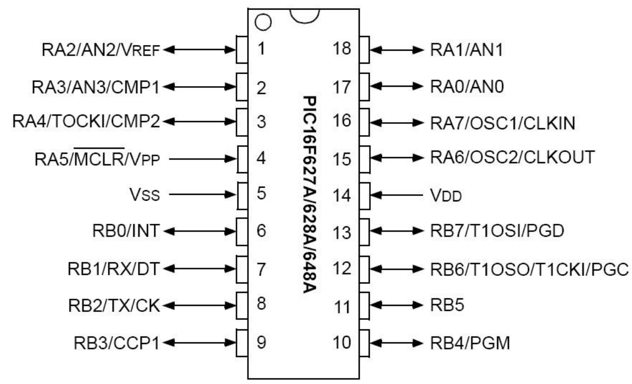


Figure 2 - The pin diagram of the PIC16F628A

Microcontroller (PIC16F628A)

We chose the PIC16F628A as our microcontroller because it was very easy to program and had the number of desirable ports which was a total of 14 (13 ports plus a provision to make the Master Clear pin an addition I/O port). This microcontroller has a very low operation voltage, and economical (being only $2 in price). Figures 2 and 3 and table 1 show PIC's characteristics.

Description		Current (A)	Voltage (V)
Voltage	Operating range		2V to 5.5V
Power Consumption	Operating mode	120uA	5.0 V
	Standby mode	100nA	5.0 V

Table 1 - Characteristics of the PIC microcontroller

The main purpose of the microcontroller is to delimit the incoming frames from the OBC. Pins 7 (RX) and 8 (TX) are used to receive and send data to the OBC accordingly. Pin1 (RA2) is used to send and receive the incoming data from and to the RAM. Although PIC has its own internal clock of 1MHz or 32 kHz, theses frequencies did not match the desirable frequency (), thus we applied an external clock to pins 16 and 15 (CLKIN &CLKOUT). From pin17 (RA0) a serial clock (matching clock) is being applied to the RAM to keep the clocks between microcontroller and the RAM synchronized. The processed data is being send to the modem via pin9

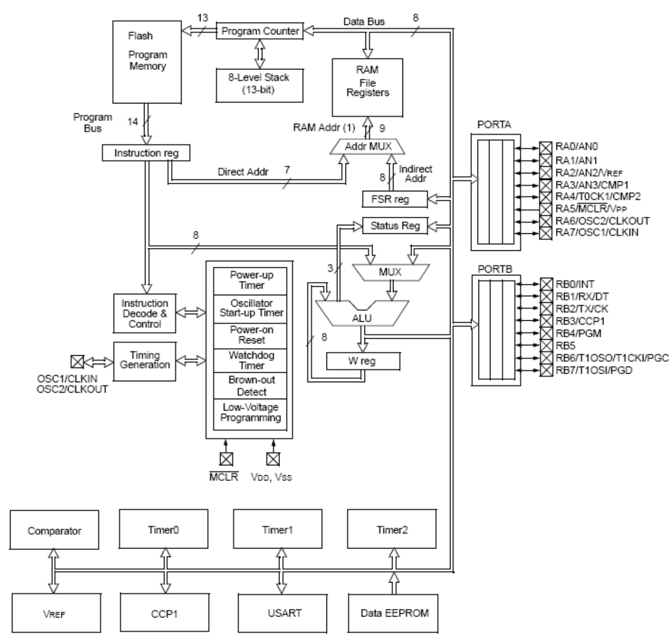


Figure 3 - The Block Diagram of the PIC

(RB3), and pin12 (RB6) is used for receiving packets from the modem.

How it works

The communication between the TNC and the OBC is an asynchronous one. When incoming bits (the makers of a frame) from the OBC arrive to the microcontroller, the PIC will store them inside the RAM and if there are no other task to be done then it will began the process of delimiting the frames. After packetizing the data, the PIC will hand the packet to the modem. PIC delimits the frames using its internal software and with the help of the specific frames sent from the computer. There are four special frames that are signals to the PIC [table 2].

Abbreviation	Description	Hex value
FEND	Frame End	C0
FESC	Frame Escape	DB
TFEND	Transpose Frame End	DC
TFESC	Transpose Frame Escape	DD

Table 2- The special characters in KISS protocol

Each frame is sent as an 8-bit binary data. The asynchronous link is set to 8 bits. Every 8 frames are preceded and ended with an FEND frame which insures the integrity of the packets received by the TNC and also marks the delimiting points. If a FEND or a FESC character appears in the data, it is translated to FESC TFEND or FESC TFESC correspondingly. The FESC puts the PIC into an escape mode which causes the PIC to translate the TFEND back to a FEND. If a TFEND or and TFESC appears in the data by itself then it is treated as normal data. If two FEND characters precede one after the other then those will be ignored. This algorithm seems to be a hard one to implement however it’s very simple once implemented using C++ code. The code has been written by one of the members of UCISAT and is not of importance. The compiler used was the CCS C. After all this each packet (8 frames) will be sent to the modem.

Modem (MX614P)

We researched about the available modem chips in the market and the ones suited for our purpose came down to the TCM3105 made by Texas Instrument and the MX614P made by MX.COM Inc. We chose the MX614P as the modem chip since it was rated by many HAM radio professionals as the best modem available for the packet radio and usage with AX.25. The MX614P has a very low operation voltage and consumes

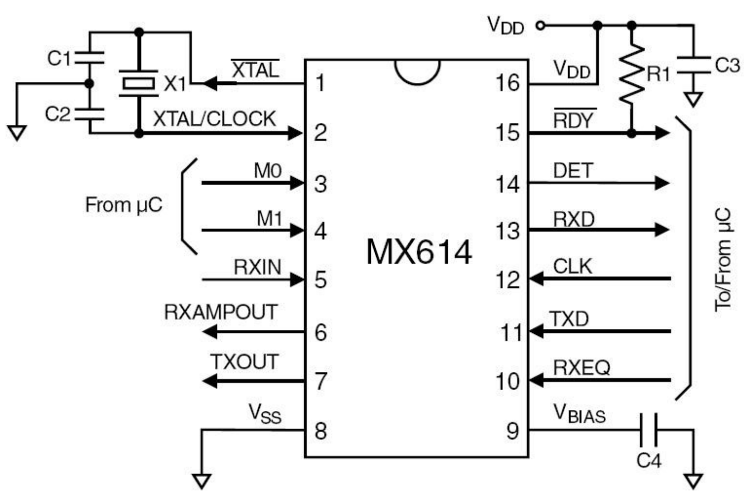


Figure 4 - The pin diagram of the MX614P

low power. Figures 4 and 5 and table 3 show the characteristics of the MX614P modem.

Description		Current (A)	Voltage (V)
Voltage	Operating range	3.3V to 5.5V	
Power Consumption	Operating mode	1mA	5.0V
	Standby mode	1uA	5.0V

Table 3 – Characteristics of the MX614P modem

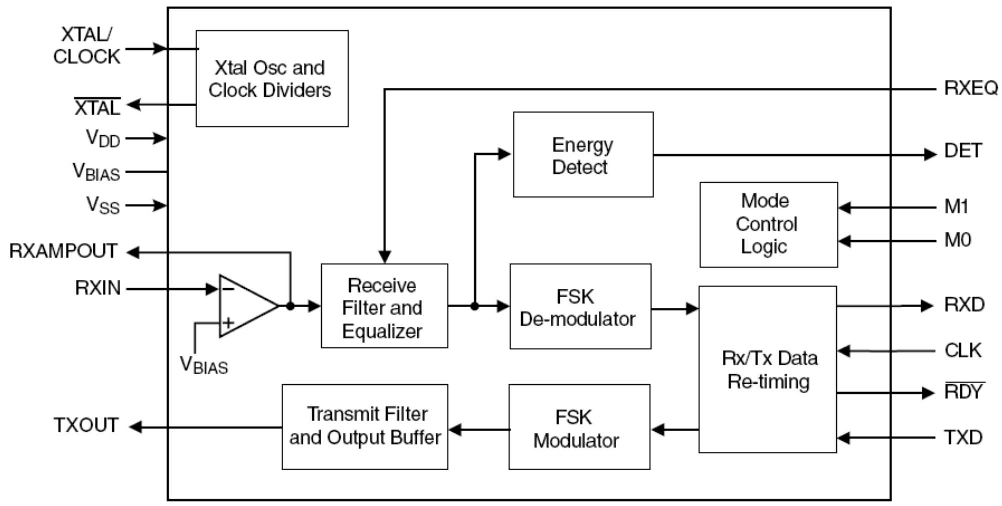


Figure 5 - The block diagram of the MX614P chip

The main task of this MX614P is converting the packets (coming from the PIC) to audio wave, appropriate for transmission via the radio and vice versa. The packets arrive from the PIC on pin11 and get sent to the PIC through pin13. The mode of the modem is set using pins 3 (M0) and 4 (M1) by microcontroller [table 4].

M1	M0	Rx Mode	Tx Mode	Data Retime
0	0	1200 bps	150 bps	Rx
0	1	Off	1200 bps	Tx
1	0	1200 bps	Off / 5 bps	Rx
1	1	Zero-Power		-

Table 4 - The mode control logic of the modem

The manufacturer had provided us with certain values of elements shown in figure3 which we used. The audio will get outputted (to the radio) via pin 7 and inputted (from the radio) via pin 5. By looking at the block diagram of this chip [Figure 5] we realized that pin 6 is designed to filter the received audio. We configured this amplifier as a simple band-pass filter

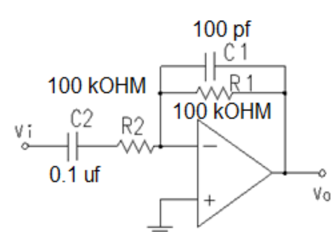


Figure 6 - Our band-pass filter configuration

[figure 6]. This circuit attenuates low frequencies (f<<15 Hz) and high frequencies (f<<1.5 kHz). The center frequency is located at approximately 500Hz [figure 7]:

$$\omega_{high} = \frac{1}{R_1C_1} = \frac{1}{(100k\Omega)(100pF)} = 100000\frac{rad}{sec}$$

$$\omega_{low} = \frac{1}{R_2C_2} = \frac{1}{(100k\Omega)(0.1uF)} = 100\frac{rad}{sec}$$

$$\omega_c = \sqrt{\omega_{high}\omega_{low}} = \sqrt{(100000)(100)} = 3162.27766\frac{rad}{sec}$$

$$\omega_c = 2\pi f_c \rightarrow f_c = \frac{\omega_c}{2\pi} = \frac{3162.27766}{2\pi} = 503.292121Hz$$

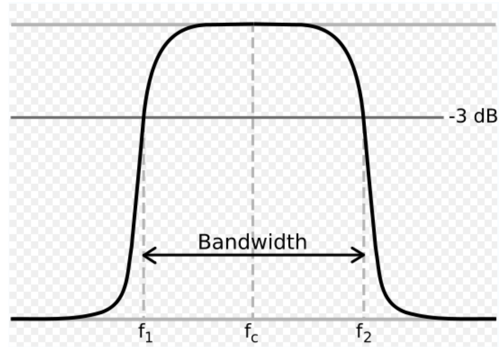


Figure 7 - Gain vs. frequency of the modem's internal filter

Thus the center and corner frequencies f_c ,f_1 and f_2 are:

$$f_1 = \frac{\omega_{low}}{2\pi} = 15.9154943Hz \text{ and } f_2 = \frac{\omega_{high}}{2\pi} = 15915.4943Hz$$

Considering that our radio signal is generated at 1200 baud (1.2 kHz), this filter is suitable for our need.

Problem

After connecting the Modem (MX614P) to the rest of the modules (the PIC and FRAM), we noticed that there are certain audio packets that, if sent to the radio, the TNC is not able to convert them back to the original form and we normally ended up with a wrong bit. When realizing that we suspected that the problem might have been arising either due to the lack of efficient firmware programming (done by other members of the satellite team) or that the data was distorted inside the modem chip itself.

As previously discussed in this paper, we have had purchased a TNC which used a different modem ship (TCM3105) designed by Texas instrument. So what we did was that we ran the same audio packet with the same radio but this time uploaded the written firmware to the TCM chip and we observed that the other TNC converted the audio packet back to the original form and that proved our firmware reliability. Next was to investigate the cause of audio signal corruption inside the modem chip.

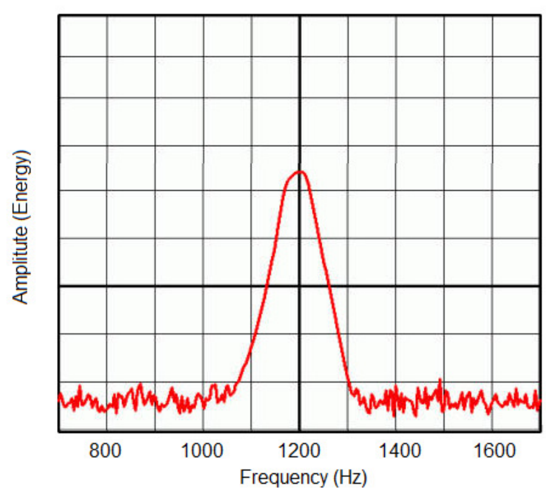


Figure 8 - Audio Spectrum of the good packet

In order to determine the problem of the packet corruption we analyzed the audio sent from the radio and received by the TNC. Using an audio spectrum analyzer, we witnessed that the packets which got decoded with both our TNC and the purchased TNC had a peak at 1200 Hz (as expected) [figure 8] , however, the packets that only the purchased TNC could decode besides the two peaks, contained quite a bit of energy in the 800 – 1000 Hz range [figure 9]. In order to filter that range of frequency we designed a high-pass Butterworth filter using the MCP6023 chip.

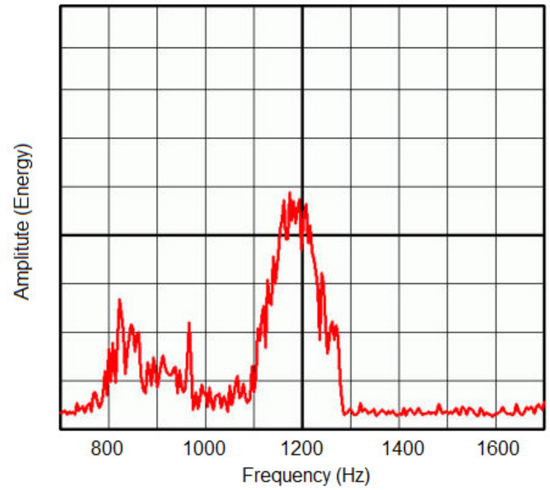


Figure 9 - Audio spectrum of the bad packet

Filter (MCP6023)

This filter was used as a high-pass Sallen-Key Butterworth filter to eliminate the noise existed in the 800 to 1000 Hz frequency range. The characteristics of the chip are given in the table 5 and figure 11.

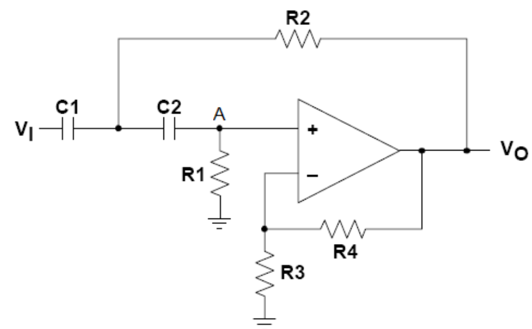


Figure 10 - The filter's configuration

As figure 10 illustrates, the op-amp has a V_{ref} pin (pin 5) that is driven from the internal voltage divider. This node has been used to bias the incoming signal at node A [figure 10].

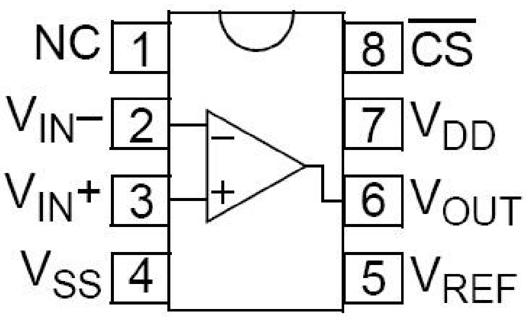


Figure 11 - The pin diagram of the MCP6023

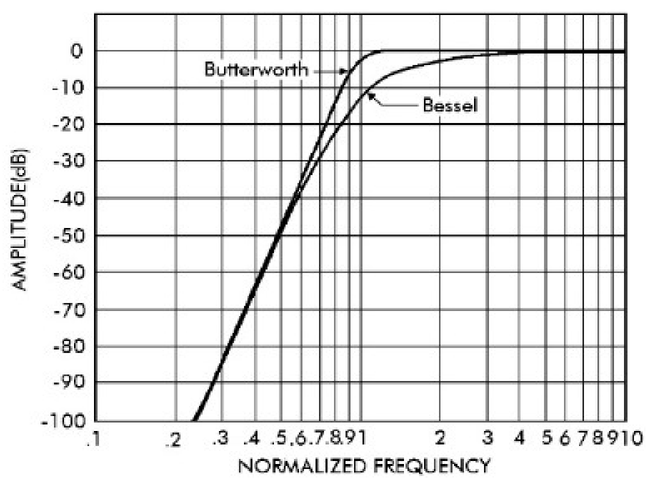


Figure 12 - The filter's transfer function

The transfer function of such filter is shown in figure 12. After adding this filter the packets which modem was not able to decode were decoded and problem solved!! Thus we had a complete TNC. We will not cover the ins-and-outs of the RAM which we used; however, it is an FRAM (Ferroelectric Random Access Memory). This type of RAM is a more reliable than the SRAM provided us with a 10billion read/write cycles and no write delay.

The Antenna

Objective

In terms of the front-end RF performance of the on-board communication system, the objective was to design and implement the method in which the RF signals are most effectively transmitted and received to and from the on-board transceiver. In terms of electrical circuits, the goal is to minimize reflected signals propagating back towards the on-board transceiver and maximize the power dissipated at the load (on-board antenna). This objective must be satisfied at the allocated frequency of the transceiver,

$$f = 437.405 \text{ MHz}$$

Design

Since there is no intermediate amplifier between the on-board transceiver and the antenna, we decided to simply match the theoretical impedance of the dipole antenna, 73 ohms (Schwarz 356) to the 50-ohm coaxial line. Since the transceiver had an internal impedance of 50 ohms, there was no need to match the coaxial line to the transceiver. The block diagram below shows our final design of the RF portion of the on-board communication system.

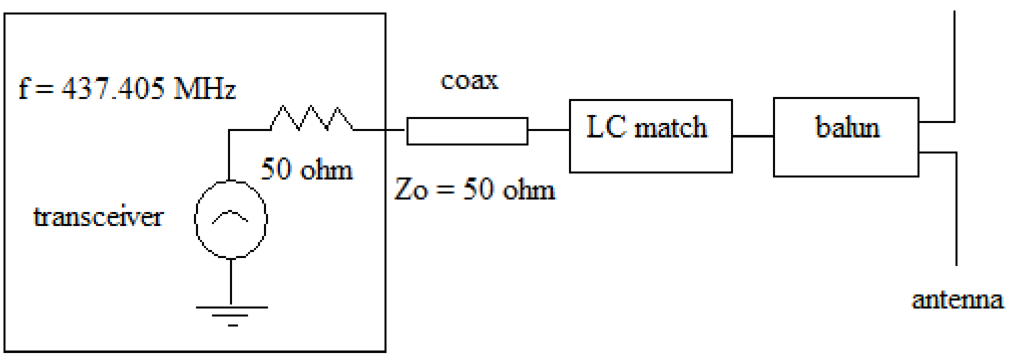


Figure 13 - Diagram of RF portion of on-board satellite

To design a front-end system that meets the mission objective, we first decided on the type of antenna we would use. We selected a ½-wavelength dipole antenna configuration based on its greater area of high gain regions compared to a ¼-wavelength monopole (Schetgen 20.4, 20.20). Also, the fact that the theoretical impedance of the dipole is 73 ohms makes it easier to use smaller values of discrete inductors and capacitors (LC) to match to the coaxial line, 50 ohms, saving valuable space inside the satellite. Furthermore, the reactance of the dipole antenna at the resonant frequency is theoretically close to zero (Schwartz 357), which also facilitates testing and troubleshooting sources of external reactance in regards to matching the antenna load to the 50-ohm coax.

In comparison, the monopole ¼-wavelength antenna is more Omni-directional but has a less area of high gain (Schetgen 20.4, 20.20). After selecting the dipole, we added a balun to interface between the single, unbalanced input of the coax and the two differential lead pairs of the dipole antenna.

Between the coaxial line and the antenna is the balun. The balun matches the unbalanced single input line to the balanced pair of antenna leads, which form a differential signal pair. In terms of circuit topology, there are three different types of baluns used on coaxial cable transmission lines: current balun, coax balun, and sleeve balun (Schetgen 19.14).

We decided to implement the current balun and the coax balun. The current balun is the most convenient since it takes up the least amount of space and we can make a relatively easy baseline measurement for a 1:1 balun configuration. If we want to be more ambitious, we can implement a 2:3 balun to directly match the 73-ohm antenna to the 50-ohm source. The coax balun implements a 4:1 balun, where the coax is 50 ohms and the antenna load would be 200 ohms.

We decided not to implement the sleeve balun because the metal sleeve is not as flexible as the insulating material of the coax, and would therefore take up more space inside the satellite. Also, we would have to insulate the sleeve in order to prevent short circuits on other subsystems inside the cubesat, which would then take up even more space. In the end, we implemented a 1:1 balun, after successfully testing it.

For the matching circuit between the 50-ohm coax and the balun, we decided to implement an LC match. This match features a shunt inductor in series with a capacitor to tune the antenna + balun to the coax.

The design of this configuration was chosen because we thought it would be the simplest design that would match the load (antenna) to the transmission line (50 ohm). Since the generator (in this case, the transceiver) has an internal impedance of 50 ohm, there is no need for a matching circuit (another LC match) between the coax and the transceiver.

In terms of designing around specific restraints, we believe that the block diagram of the dipole antenna, 1:1 balun, LC matching circuit, and 50-ohm coaxial cable is quite thrifty and inexpensive considering earth-bound test conditions. The process of matching the antenna load to the coaxial cable was relatively cheap: the 1:1 balun cost around $20, the discrete LC parts cost less than $5.00.

Since we had access to soldering equipment and the network analyzer, we were in very good hands to begin with. However, when it comes to making the entire RF system “space-ready”, the costs will increase much more due to the firmer PVT (pressure, voltage, temperature) requirements in space. This will be the next step in purchasing hardware that satisfies more extreme PVT conditions of space.

Also, certain types of gas-filled modules must be avoided in order to prevent out-gassing in space. This phenomenon occurs since there is no medium exerting pressure from all sides on a module filled with gas. Therefore, if the temperature of the gas increases, the gas will simply expand and could cause serious structural damage to its host module.

Experiment

When we first started this project, the on-board dipole antenna that was initially mounted by previous members of the Communications Subsystem was actually configured as a ¼-wavelength monopole antenna. One of the antenna wires was connected to ground, while the other was connected to the center conductor of the coaxial cable. A system level test showed that the monopole configuration was functional: transmission and reception of messages and packets was successful.

We then decided to test and see the RF performance of the monopole antenna with a network analyzer, an instrument that measures scattering parameters for at one and two port networks for RF applications (Gonzalez 65). Since network analyzers are quite expensive, we decided to request access to one on the UCI campus. Professor Franco De Flaviis graciously granted the UCISAT team access to his own network analyzer in his research laboratory. Professor De Flaviis's graduate student, Javier De Luis, functioned as an advisor on antenna and RF design and concepts. On the network analyzer, we found that the reflection coefficient S_{11}, was near zero at the transmitting frequency, which was a good sign. Since our system is a single-port network (network analyzer only sees the one-port coaxial cable), the main variable of concern is the reflection coefficient, Γ_S. The monopole antenna configuration and test results are shown below:

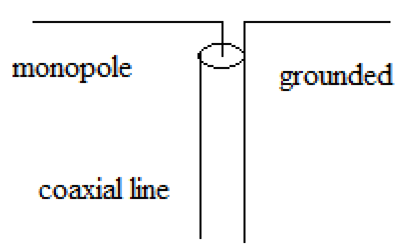


Figure 14 - antenna configuration for monopole

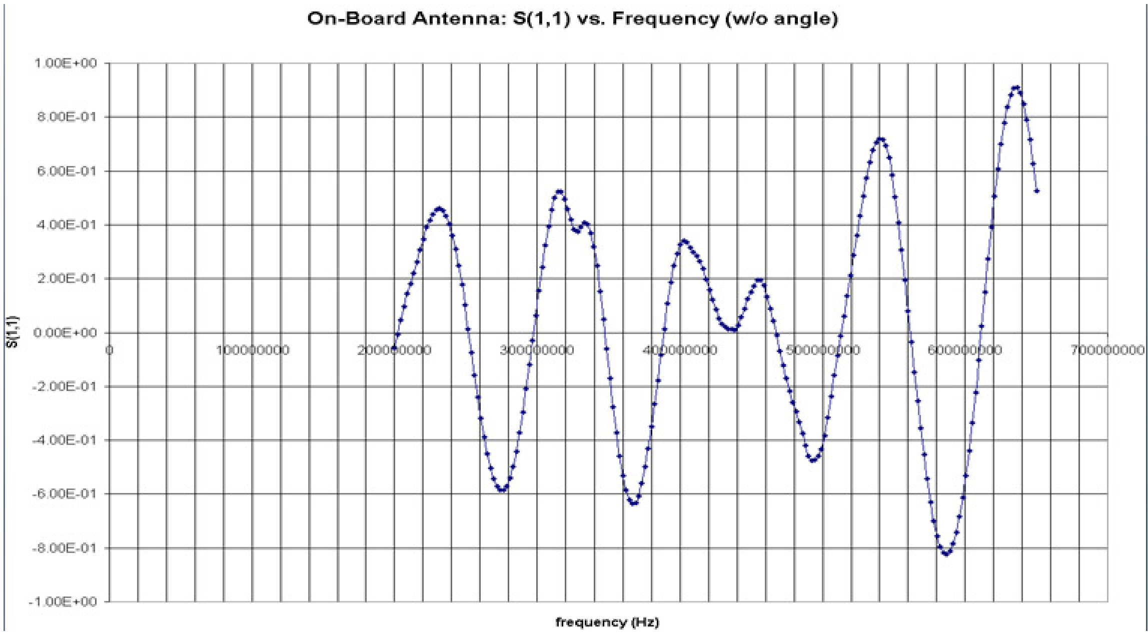


Figure 15 - The reflection coefficient vs. frequency (in the flat position)

The first graph shows the configuration of the antenna in which it is ideally horizontal relative to the mounting plate.

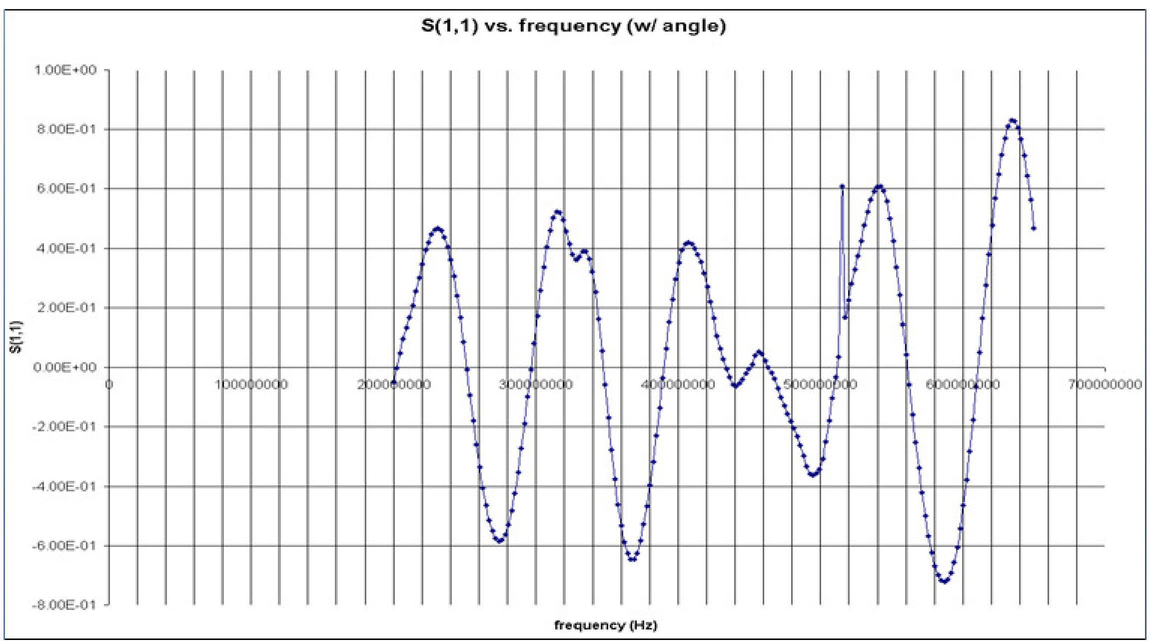


Figure 16 - The reflection coefficient vs. frequency (in the sloped position)

The second graph above shows the reflection coefficient in of the antenna in which it has a slight positive angle relative to the mounting plate. In the second test case, we can see that the reduced capacitance between the antenna and the mounting plate alters the behavior of the reflection coefficient S_{11} near the allocated frequency, 437.405 MHz. In both cases, the reflection coefficient is quite low, much less than +/-1, which represent short and open circuits respectively. This means that most of the signal is transferred to the antenna load, which is exactly what we want. There is a little amount of signal reflected back to the transmitter, but since the length of the coaxial cable is well short of the wavelength, the effect can be neglected as insignificant.

Our conclusion from these results is that the monopole configuration of the antenna is dependable for on-board communication at our allocated frequency of transmission, 437.405 MHz.

Next, we decided to compare the ¼-wavelength monopole antenna to the ½-wavelength dipole antenna. In implementing the balun, we chose to solder on a UHF 1:1 transformer in verifying the RF front-end performance of the dipole antenna, we decided to measure the reflection coefficient with a network analyzer at Broadcom Corporation. Credit must be given to Seon Lee and Seow McIlroy, senior hardware design engineer and hardware manager of BlueTooth Applications in Broadcom respectively, for allowing access to the very expensive RF analysis tool for this project.

The main difference between the network analyzer used at Broadcom and the network analyzer used in Professor De Flaviis's lab at UCI was the Smith Chart feature which provides a clear set of data points on the Smith Chart. The results for dipole antenna with the 1:1 balun are shown below:

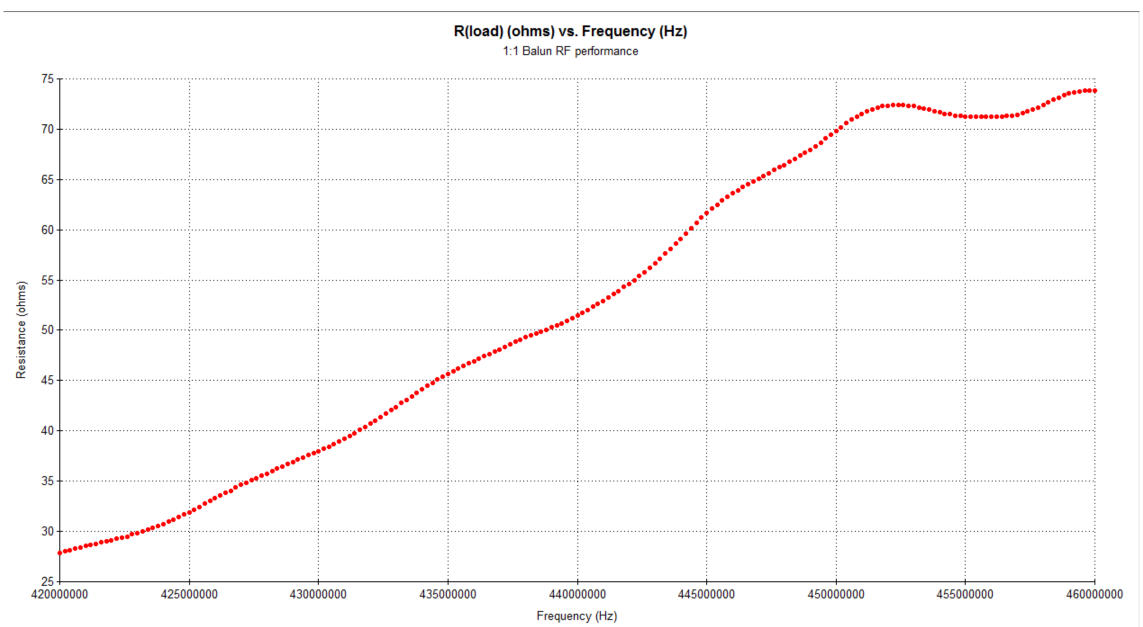


Figure 17 – The load vs. the frequency

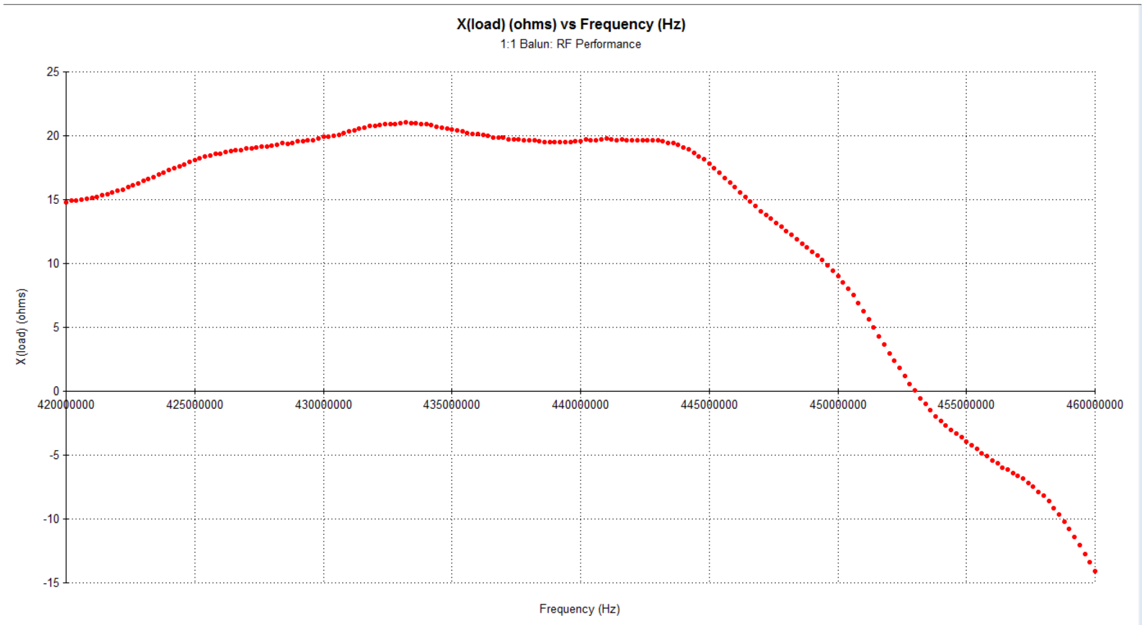


Figure 18 – The load vs. the frequency

The above results verify the functionality of the 1:1 balun: the load resistance at our resonant transmitting frequency is approximately 50 ohms and the load reactance at the same location is approximately 20 ohms. The maintenance of signal integrity from the unbalanced single-ended coax to the double-ended differential pair as well as the maintenance of the 75-ohm impedance, in itself, is a very close match, especially since the transmitting frequency is in the UHF spectrum.

In this case, since a series capacitor with an offset of -j20 ohms is required to match to the 50-ohm impedance, we set $Z_C = -j\ (1/\omega C) = -j20$. Therefore, a series capacitor with value $C = 1\ /\ [2\pi f\ (20)] = 18.2$ pF (setting f = 437.405 MHz) would match the antenna to the coaxial line. Unfortunately, after series of trials, we encountered that there was a phase change that was caused by the length of the coaxial line itself, and the reflection coefficient had to be rotated about the center of the Smith Chart, changing the values and even configurations of the LC matching network (Gonzalez 155). In the end, we obtained a close match from the dipole antenna to the coaxial line, but we believe there should be one final step to make the match even closer, and make the RF performance that much better.

The constraints facing our project

While designing and building this subsystem, there were many requirement and constraints that we faced which will be explained briefly.

Space readiness of the components

Each component that was chosen was to comply with certain rules in regards to outer space. These rules have affected our design dramatically and two name few we should consider characteristics such as out gassing properties of the material used and the temperature range of operation of each component.

All the chosen components have the industrial temperature standard which is between -40^o to 85^o Celsius. The temperature in a LEO orbit is expected to be between -35^o to 100^o C however with the shields designed by the structure subsystem this temperature is narrowed down to -35^o to 65^o Celsius.

Also the total cost of the entire subsystem is estimated to be less than $200.00 which was very well bellow the spending limit of $1000.00 (excluding labor ☺).

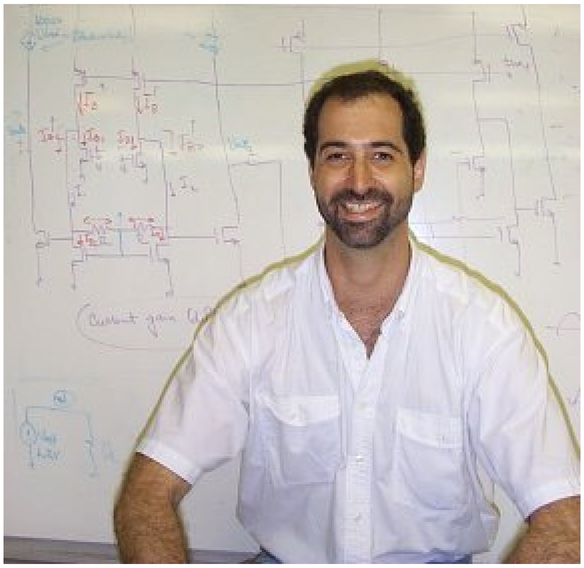
Conclusion

After completing the design of each module, it was time to put the entire components together and proceed with an overall test which was the connection between the ground station and the ob-board communication system. For a quick reminder, this communication system consists of a TNC, a radio, a transmission line, a matching network, a balun, and finally an antenna. This test was done with full success both ways (sending packets and receiving packets) with an accuracy of 99% (every 99 packets received and sent by the TNC, only one was corrupted or missed. As a prompt, this project is an on going project held by the UCISAT club at University of California, Irvine and we will be working on this project for one more quarter to remove any other errors due to possible overlooking of conditions that might be present during launch and after arriving in orbit.

Acknowledgments

At this point it’s time to mention the great people and organizations that supported us through this extensive project and guided us through wrongs and showed us the light to rights.

Professor Payam Heydari, our great mentor and a supporter of our project. Despite his extremely busy schedule, he guided us to success.



Professor Michael Green whom we know for presenting us with the use and different applications of operational amplifiers.

Professor DeFlaviis for helping us in the RF portion of this project.

Our special thanks go to:

Broadcom Corporation for letting us use their equipment for many of our experiments.

UCISAT laboratory for supporting us.

UCI for letting us use its “Center for RF Design and Characterization”…

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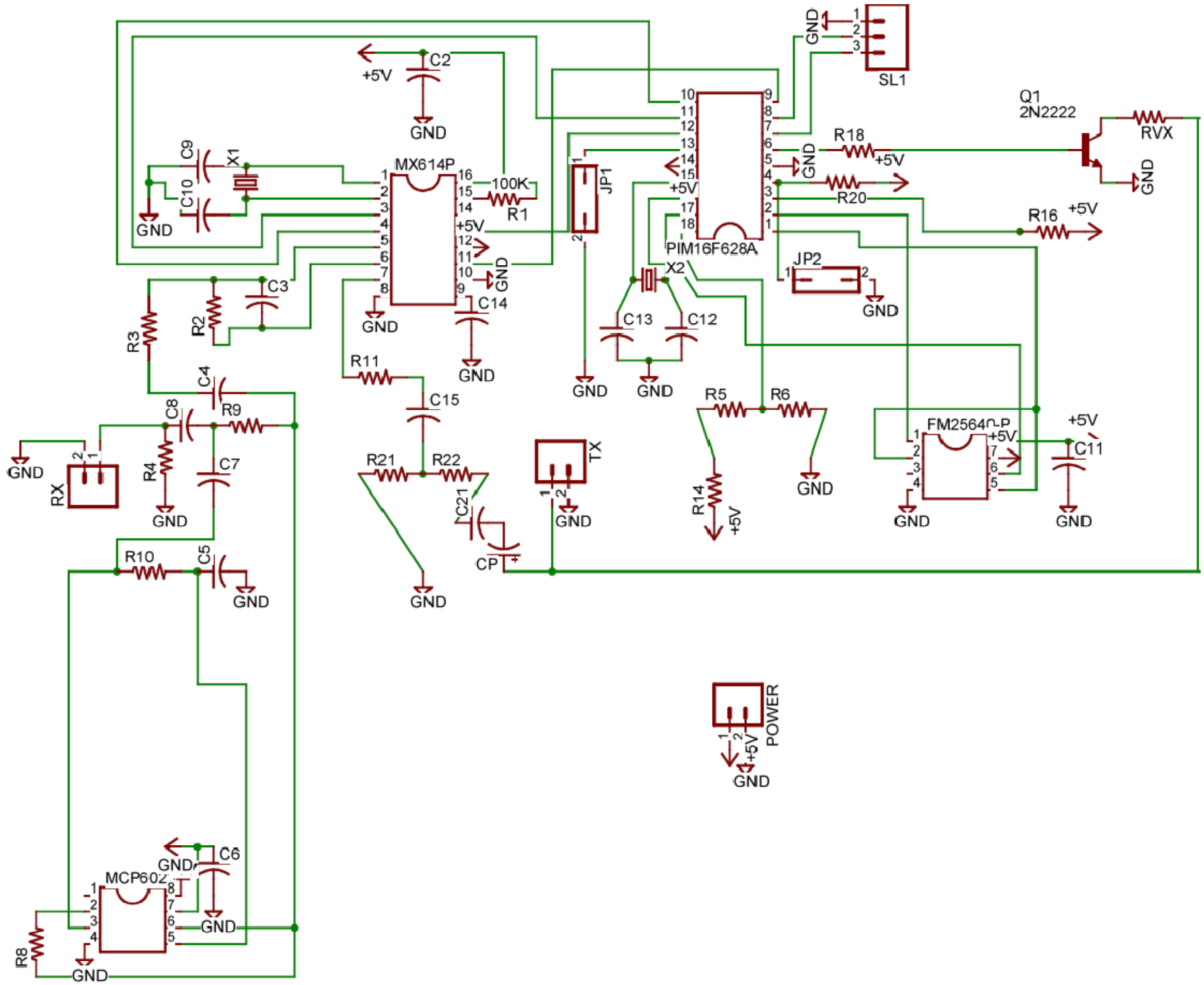
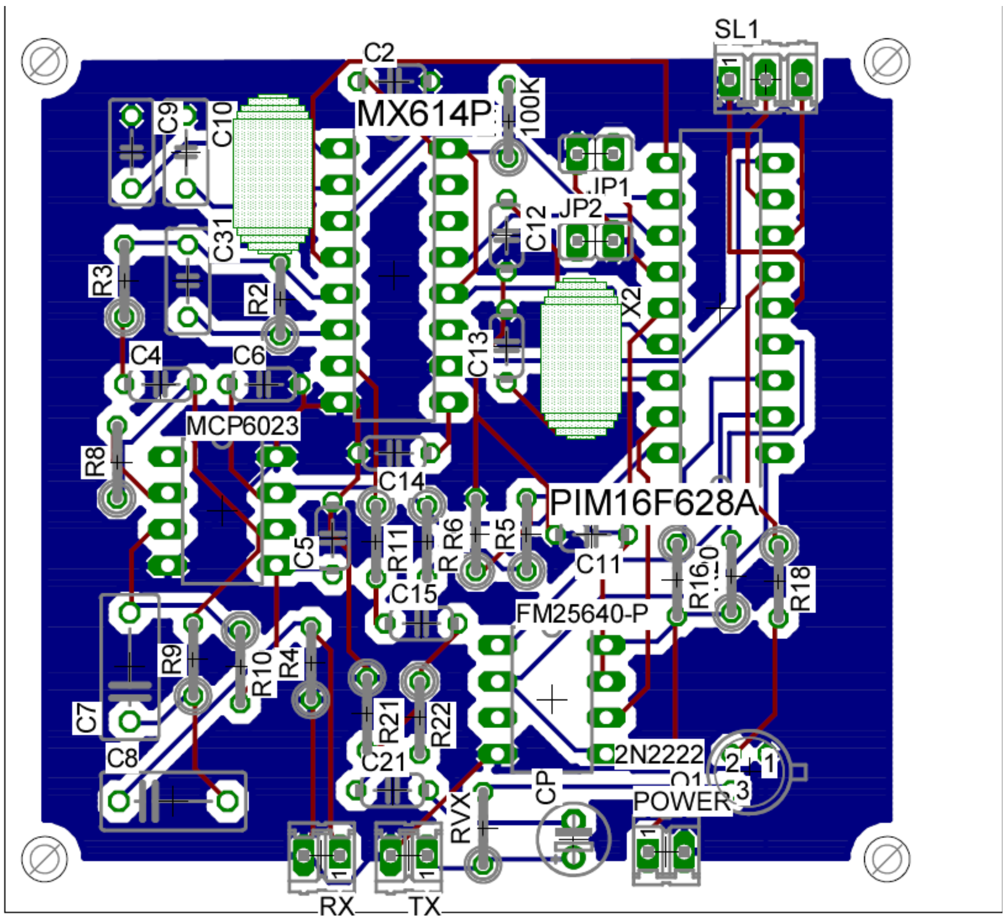
Appendices

TNC

Schematic



Layout



SL1
C2
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100K
C9
C10
JP1
JP2
C12
C31
R3
R2
X2
C13
C4
C6
MCP6023
R8
C14
PIM16F628A
C5
R11
R6
R5
C11
R16
R18
C15
FM25640-P
C7
R9
R10
R4
R21
R22
2N2222
Q1
C8
C21
RVX
CP
POWER
RX
TX