University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Concept Definition Document (CDD)

P4LO - Positioning For Lunar Operations

Project Customers

Name:	Scott Palo	Name:	Nicholas Rainville
Email:	Scott.Palo@colorado.edu	Email:	Nicholas.Rainville@colorado.edu

Team Members

Name: Sam D'Souza Email: sads9574@colorado.edu Phone: (303) 956-4085	Name: Ponder Stine Email: post1579@colorado.edu Phone: (720) 588-6563
Name: Alexander Lowry Email: allo5581@colorado.edu Phone: (979) 267-1188	Name: Dawson Weis Email: dawe5235@colorado.edu Phone: (636) 222-3046
Name: Ruben Hinojosa Torres Email: ruhi9621@colorado.edu Phone: NA	Name: Nathan Jager Email: naja2101@gmail.com Phone: (720) 579-2399
Name: Brendan Palmer Email: Brendan.Palmer@colorado.edu Phone: (702) 595-7846	Name: Ventura Morales Email: vemo8309@colorado.edu Phone: (720) 630-9565
Name: Fernando Palafox Email: Fernando.Palafox@colorado.edu Phone: (720) 666-2131	Name: Ian Thomas Email: Ian.Thomas-1@colorado.edu Phone: (831) 345-6514

Contents

1 Project Description

1.1 Mission Statement

*P4LO (**P**ositioning **F**or **L**unar **O**perations) will be a prototype network of software defined radios demonstrating a foundation for the lunar communication and positioning system LunaNet.*

1.2 Problem Statement

The year is 2040. We have a base for re-fueling on the moon and have an established civilization beginning on Mars. We are beginning to plan missions to venture deeper into our solar system. However, as we continue to expand and explore further into space, astronauts need ways to stay connected. On the Moon, astronauts need to be able to know their position and where they are navigating to in order to explore safely. They need to be able to receive alerts in real-time, warnings for unprecedented space weather, such as solar flares, and incoming asteroids. Eventually, there may be a need for a networking system that expands to the entire solar system. The first step to achieving this is the LunaNet Program.

Figure 1: Handheld Device with GPS and Texting Capabilities [1]

This program calls for handheld communication with astronauts on the lunar surface; however no specific groundwork has been mapped to achieve this goal. Hence, this project focuses on developing a proof of concept system designed to demonstrate the ability to bring a Lunar Positioning System (LPS) similar to GPS on earth, and SMS-like reception and transmission to the moon through a software-defined radio (SDR) platform.

This project will require an orbital analysis of the necessary satellites around the Lunar surface to establish a LPS, where a link budget can be created to determine the effective uplink and downlink power values that satisfy the requirements of the SDR. The designed SDR will then communicate with the orbiting satellites, allowing it to calculate LPS coordinates. Unlike the well defined GPS here on earth, designing a LPS system benefits from not having to account for atmospheric corrections and obstructions from buildings or clouds; however it is still challenged by high orbital velocities and less stable orbits of the satellites transmitting data. These higher speeds give less time for a satellite to transmit data to a ground station before the satellite is out of sight. The stability of the orbits also degrades the accuracy of the positioning due to the way that GPS and LPS work. If the transmitting satellite's position is not known to a certain accurately, then the position of the receiver on the surface cannot be determined accurately.

The final goal is to develop a proof of concept prototype for a handheld device that calculates LPS coordinates to the relative accuracy of a modern cell phone, as well as SMS-like reception and transmission. This prototype will lay the foundation for the work assigned to the CU Boulder professional team affiliated with the NASA LunaNet mission.

1.3 Previous Work

The LunaNet concept was presented by NASA's Goddard Space Flight Center on June 11, 2019, with the goal of developing "a lunar communications and navigation architecture that will bring networking, positioning, navigation and timing (PNT) and science services to the moon" [1]. This highlights the overall grand scope of the project, with the ultimate goal of establishing a communications relay between Earth and the Moon, allowing astronauts on the lunar surface to stay connected with each other and back home. However, NASA is very much still in the early stages of this project. While our project focuses on a much smaller part of this overall mission, the results of this project will allow for continuation of the mission on a larger scale. It is hoped that the team's development of the proof of concept can be used to further expand the system on the moon; from a larger satellite constellation to development of more hardware to be used on the surface.

Furthermore, multiple universities, such as Stanford, California Polytechnic State University, and CSU San Bernardino have devoted time and resources to improve small spacecraft technologies which will provide exploration missions with foundations technologies to deploy communication services and/or GPS-like navigation systems [3]. It has been found that the success of this project is highly dependent on deploying SmallSats with minimal weight, volume, and power usage with the purpose of reducing mass and increasing the number of satellites to be deployed [3]. These are more desirable than larger satellites as they are smaller in size, cost less, and are easier to launch. In terms of positioning accuracy, chip-sized atomic clocks are also included in the satellites to improve accuracy measurements, while the transmitters have been predicted to have a higher power range to reduce satellite orbit altitude restrictions. This research is scalable, as it pertains to the orbital mapping and determination aspect of the team's project. However, certain aspects of this research, such as the final satellite constellations, are out of scope for this project, but the team will be providing high level orbit simulations to lay down the groundwork for the communication systems the CU Boulder professional team will implement.

In addition, a graduate student that works with professor Scott Palo, Evan Bauch, has conducted his own research regarding the orbital geometry of the satellite constellation. Evan agreed to inform us of his current work, and has given the team a baseline model to work off of. The figure below represents the current model he has created:

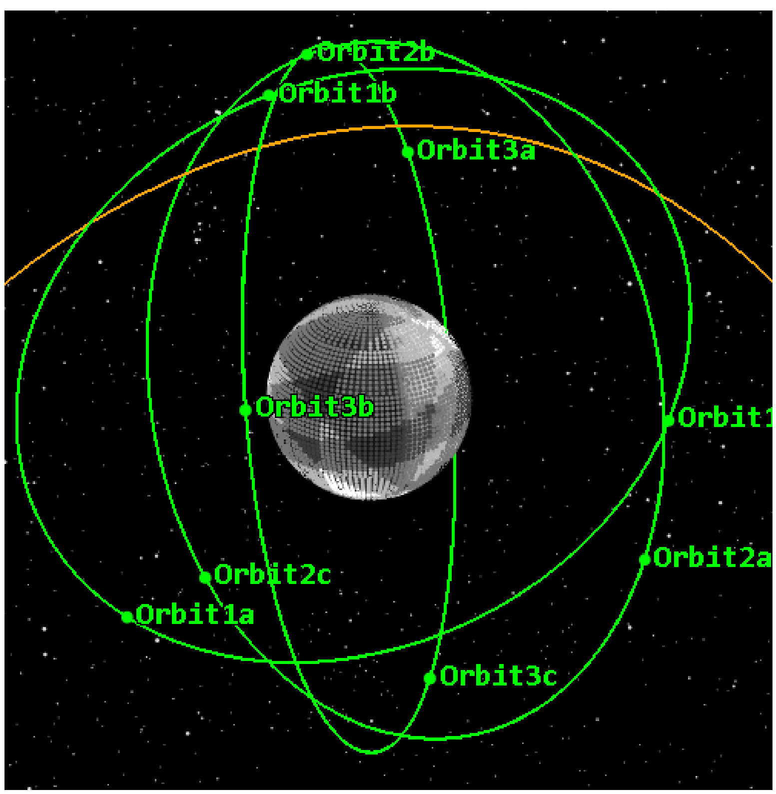

Figure 2: Baseline Satellite Constellation Utilizing the Coverage Package (Courtesy of Evan Bauch)

The model consists of 3 separate orbits, with 3 satellites in each orbit spaced 120^o apart, for a total of 9 satellites. The orange orbit seen in the figure represents the elliptical orbit of the Lunar Gateway, a potential space station to be utilized for the LunaNet Program [1]. In STK, the Coverage Package enables the team to see the coverage on the surface given by the satellites at instantaneous points in time. The shading that can be seen on the Lunar surface in the figure represents the effective coverage of the satellites at that particular instance in time. A lighter shade represents more satellite coverage, while a darker shade represents less satellite coverage. Evan's design meets several of the LPS requirements of the project, including altitudes and coverage percentages, which will be discussed later. The team has obtained the specific values of the orbital parameters, which will help with the initial set-up. One goal for the team is to work with Evan and optimize this satellite constellation to fully meet the requirements of the project. Starting with this baseline model the team will iterate upon it, and explore other potential orbital geometries to reduce error and improve coverage.

1.4 Specific Objectives

The objectives for this project are to design a prototype handheld communication device that demonstrates a path to a viable communication and navigation solution network to be implemented on the lunar surface. Through the development of this prototype, our team will be providing a risk reduction and preliminary analysis for the future implementation of the customer's contribution in the LunaNet system. The team will primarily be focused on building upon a previous LimeSDR prototype provided by CU graduate students to demonstrate the communication link between astronauts on the Lunar surface and orbiting satellites. In order to provide a communication and positioning system on the Lunar surface, the team will analyze and optimize satellite geometry that satisfies our customer positioning requirements of sub 10 (m) positioning and 30 ns $1-\sigma$ transfer times. This includes sufficient coverage on the surface, specifically for the poles due to the presence of ice and other important minerals [4], for extended periods of time, as well as defining the effective orbital parameters in accordance to the customer's requirements. While the team understands the highly unstable orbits present around the Moon, for the scope of this project the team will assume that these orbits are stable and are not subject to 3 body perturbations. Furthermore, an error analysis will be conducted using the built-in Dilution of Precision (DOP) package in STK in order to determine positioning error on the surface. DOP is able to specify error propagation as a mathematical effect of navigation satellite geometry on positional measurement precision [5]. Our role is to provide a customer required 200 bits per second communication link as well as signal acquisition, timing, and positioning solution for a Lunar Positioning System, without the tracking algorithm required to lock onto the signal from moving satellites. This CDD will focus on two integral paths of the overall mission; development of the communication link between the lunar surface and lunar orbiters and a functional prototype to demonstrate communication at the customer specified data rate and a simplified model of the positioning system. More detailed analysis on the SDR power budget, options to implement one-way and two-way ranging, etc. will be covered in the preliminary design review. Table 1 below specifies the levels of success for P4LO:

Level	Hardware	Software	Orbital	Testing
1	LimeSDR achieved communication with a CPU via USB	SDR received signal through hard-wired connection.	Preliminary orbits determined and provided basic orbital parameters for LPS and communication system. Initial link budget completed.	One-way-data transferred and signal detected via hard-wired signal.
2	Single SDR wired to itself, sent and received signals at 200 bits per second	SDR detected and decoded a signal through a wired connection	Modified coverage to 75% around poles, Link budget was refined.	Test message has been detected and decoded at 200 bits per second on a single self connected SDR
3	Implemented wireless communication, signal detection and message decoding between two SDR's.	Successfully read in known satellite orbital data for MATLAB simulation of LPS satellite ranging. Demonstrated two SDRs can communicate simultaneously.	Improved orbital analysis to satisfy progression towards LPS requirements: 50 m positioning error and 90 ns 1-sigma transfer time. Refined linked budget.	Demonstrated MATLAB model that can successfully compute satellite ranging data. Also demonstrated successful wireless communication and signal processing between two SDR's at a distance of 100 meters.
4	Designed and built a system housing that can support an SDR, a microprocessor, a battery module and an antenna	Successfully read in known satellite orbital data for MATLAB simulation of LPS positioning functionality.	Improved orbital analysis to satisfy LPS requirements: 10 m positioning error and 90 ns 1-sigma transfer time. Satellites have 90% coverage around poles. Finalized link budget.	Conducted large scale wireless testing between NCAR and Highway 36 scenic viewpoint. Demonstrated communication between two unit prototypes at 200 bits/second.

Table 1: Levels of Success

1.5 Concept of Operations (CONOPS)

Our mission consists of two sub-projects: a low-rate communication prototype and a lunar satellite-based navigation system. The communication prototype sub-project is intended to allow SMS-like communication between an astronaut on the surface of the moon and a lunar satellite. The lunar positioning sub-project will consist of a GPS-like system with positioning capabilities on the surface of the moon. This sub-project will be heavy on orbital simulations and short range/low power testing in order to demonstrate how a positioning system on the moon would work. The team will use software defined radios (SDR), specifically the customer required LimeSDR, to mimic the proposed communications system and test the functionality and accuracy of the positioning software. The customer defined requirements are to be able to have positioning data accurate to within 10 meters, time data accurate to within 30 nanoseconds, receive signals at 450 MHz, transmit signals at 400 MHz, and a data rate sufficient to send SMS-like messages. Through some baseline calculations for an average typing speed on a phone, the team estimated that a bit rate of 100 bits/second would suffice for text messages, but will aim to have a higher bit rate in testing.

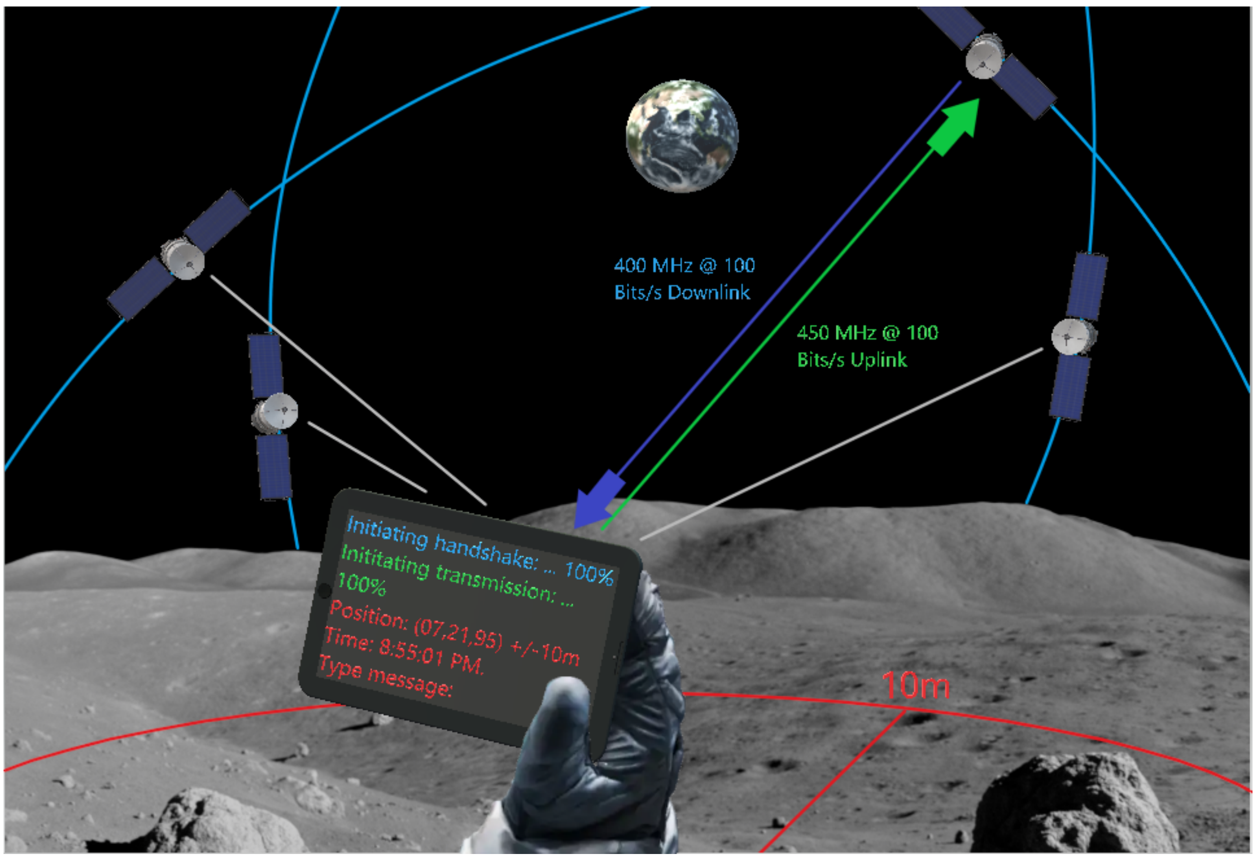

Figure 3: Handheld Device with LPS and Texting Capabilities

1.6 Functional Block Diagram

Below is the functional block diagram for the test setup to demonstrate communication between devices at 400 and 450 MHz. As can be seen, the LimeSDR will be powered by either a laptop or microprocessor at 5V and will be connected to an external amplifier and a signal antenna for transmitting and receiving signals. Within the LimeSDR stack, one can see two processes for receiving and transmitting our signal. For transmitting the signal, the message must be multiplexed in order to account for multiple users on the network. Then the signal is modulated and amplified onto our carrier frequency of 400 MHz with our baseline defined modulation scheme. For receiving the signal, the signal must first be amplified, accounted for phase corrections, passed through a lock filter, demodulated, and finally demultiplexed to determine the transmitted message. This test setup is representative of one single SDR device and will provide a baseline for interactions between multiple SDR's in our final test implementation.

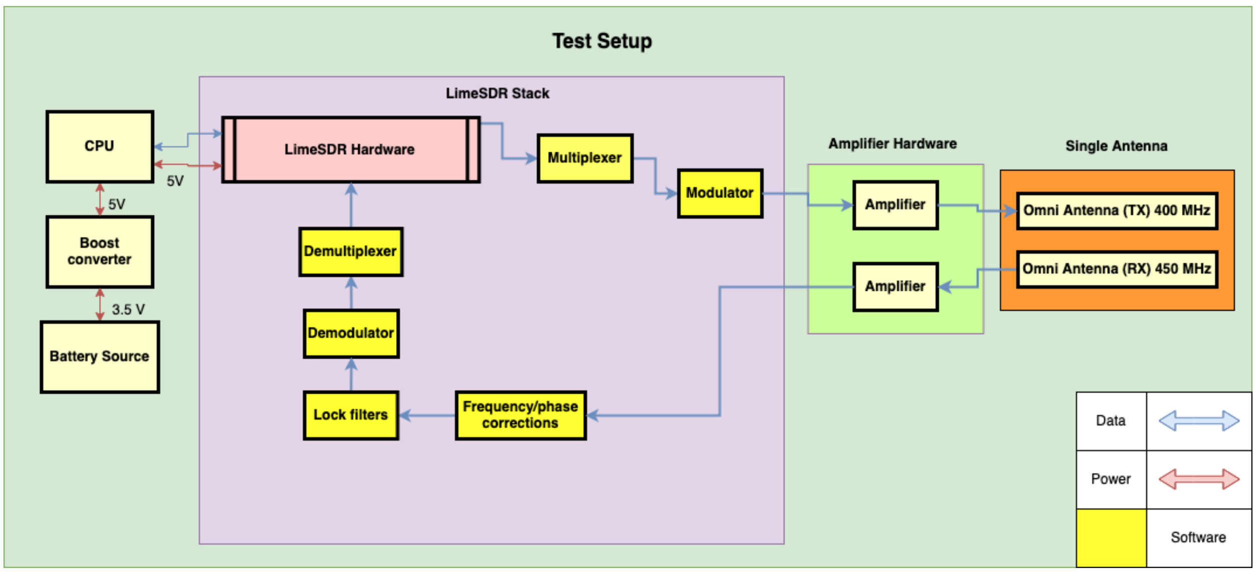

Figure 4: Functional Block Diagram

1.7 Functional Requirements

Our functional requirements (**FR**) for the handheld system (the system) are as follows:

FR1: The system must operate under a scalable LPS model
FR2: The system will provide two-way SMS-like texting capabilities
FR3: The system will be able to provide an architecture for a navigation solution receiver with a 10 meter position accuracy and a 30 nanosecond 1-σ transfer time
FR4: The system will transmit data at 400MHz carrier frequency
FR5: The system will receive data at 450MHz carrier frequency
FR6: The system framework must be extendable to 170 users communicating simultaneously
FR7: The system's communication links must have a channel bandwidth of no more than 1 MHz

2 Design Requirements

2.1 FR1: The system must operate under a scalable LPS model

2.1.1 Design Requirement (DR): Orbits must have altitudes between $4000km$ and $8000km$ when above the desired area to be covered by LPS

Motivation: Orbits within this range of altitudes will give ample coverage, enabling navigation data to be sent/received. Orbits above this range will require unnecessary power requirements and orbits below this range will be too close to the surface to provide adequate LPS coverage.
Verification: Orbits will be created and optimized in STK within these parameters. Using the built-in Coverage Package in STK, the coverage over the Lunar surface can be visualised and then optimized within this range. See description beneath Figure 2 for more in-depth explanation.

2.1.2 DR: Orbits must have inclination between $75^o - 90^o$

Motivation: From the LunaNet program, it was stated that the poles of the Moon are the most important location, due to ice and other important minerals being present there [4]. Orbits with this inclination will have sufficient coverage over the poles, enabling navigation data to be sent/received.
Verification: Orbits will be created and optimized in STK within these parameters. Once again, the Coverage Package will be used to verify high quality coverage over these locations.

2.1.3 DR: The system will operate using the LimeSDR electronics device

Motivation: In order to create the simulation/experimental environment, we must have the hardware and system setup necessary to verify transmission and reception of signal. This system must also be flexible as this project will potentially be scaled up towards a functioning system.
Verification: Software defined radios allow us to transmit and receive signals both in simulation and via hardware. Therefore, both the simulation and hardware aspects of the LimeSDR will be employed in this project.

2.2 FR2: The system will provide two-way SMS-like texting capabilities

2.2.1 DR: Device must demonstrate wireless transmission and reception of data

Motivation: The focus of the project is to provide communication and positioning on the Lunar surface. A functioning part of this goal is to be able to receive SMS-like messages and LPS data, as well as transmit SMS-like messages.
Verification: Demonstrate transmission and reception of text files between two SDR devices between NCAR and US Highway 36.

2.2.2 DR: Demonstrate communication at a data rate of 200 bits/second

Motivation: In order to send and receive communication data to orbital satellites in a timely manner, a 200 bits/s data rate is required to accommodate both SMS-like communication and LPS data simultaneously. This data rate was determined from the relative bit rates required for each task and an acceptable margin of error.
Verification: Transmit and receive 1000 KB text files in less than 40 seconds between two SDR devices.

2.3 FR3: The system will be able to provide an architecture for a navigation solution with a 10 meter position accuracy and a 30 nanosecond 1-σ transfer time

2.3.1 Design Requirement (DR): SDR devices must receive signals at SNR of 23.52 dB

Motivation: Signal-to-noise ratio (SNR), along with bandwidth (B), are intimately related with desired range accuracy by the following formula [6]:

$$\delta R = \frac{c_0}{2B\sqrt{SNR}}$$

We have a desired position accuracy $\delta R = 10$ meters, the speed of light in a vacuum $c_0 = 3 \times 10^8$ m/s, and a bandwidth $B = 1$ MHz, from FR7. This yields an SNR of 225, or 23.52 dB.
Verification: SDR system will be tested receiving a signal at the specified power to noise ratio in order to confirm signal acquisition.

2.3.2 DR: Provide LPS coverage around the Moon Poles for 90% of the time

Motivation: As previously mentioned, the poles are of highest interest on the Moon, and so it can be assumed that astronauts will be spending most of their time at these locations. Thus, it is very important that they will have consistent knowledge of their positioning at these locations.
Verification: In addition to the previously defined orbital geometry, a minimum of 4 satellites must keep coverage around the poles 90% of the time. The minimum of 4 satellites ensures that location and timing can be calculated for the astronaut, while more than 4 would decrease error. This will be simulated in STK using the built-in Coverage Package.

2.3.3 DR: Orbits must provide a Dilution of Precision (DOP) value within the range of 2 to 5

Motivation: For the goal of having precision accuracy to 10 meters, DOP is able to specify error propagation as a mathematical effect on navigation satellite geometry for positional measurement precision [5]. A DOP value within 2 to 5 ensures adequate confidence in positional accuracy.
Verification: Orbits will be created and optimized in STK within these parameters using the built-in DOP Figure of Merit (FOM) to measure the geometry of satellites and the quality of coverage. If a value of DOP less than 2 is achievable, this would signify a better design and more precise coverage.

2.3.4 DR: Demonstrate software model that calculates satellite ranging and ground positioning from known satellite data

Motivation: In order to design a LPS system, a fundamental requirement is that Lunar receivers must be able to calculate ranging to the visible orbital satellites in order to calculate their position.
Verification: Satellite trajectory data will be read in from STK and will be utilized in a MATLAB model to construct a satellite ranging and ground positioning algorithm.

2.4 FR4: The system will transmit data at 400MHz carrier frequency

2.4.1 DR: Demonstrate uplink transmission at 400MHz

Motivation: Communication needs to occur at an agreed upon frequency for transmission and demodulation to occur. Thus, the frequencies are given by the customer for downlink.
Verification: Demonstrate transmission of .txt message from SDR to computer at 400 MHz.

2.5 FR5: The system will receive data at 450MHz carrier frequency

2.5.1 DR: Demonstrate downlink reception at 450MHz

Motivation: Communication needs to occur at an agreed upon frequency for reception and demodulation to occur. Thus, the frequencies are given by the customer for uplink.
Verification: Demonstrate reception of .txt message from computer to SDR at 450 MHz.

2.6 FR6: The system framework must be extendable to 170 users communicating simultaneously

2.6.1 DR: System navigation and communication link must be able to support 170 simultaneous users

Motivation: A customer given requirement is that the system must service 170 users. This allows for the system to provide practical value on the Lunar surface for multiple astronauts.
Verification: Validate multiplexing scheme by demonstrating two or more SDR's communicating to one receiver at 400 MHz and verify both messages were received correctly. Validate architecture scales to 170 simultaneous users.

2.7 FR7: The system's communication links must have a channel 3 dB bandwidth of no more than 1 MHz

2.7.1 DR: Uplink channel must have a maximum bandwidth of 1 MHz

Motivation: Various international organizations, such as the International Telecommunications Union (ITU), have placed restrictions on communication links in different jurisdictions. As a result, the customer requested that our signal take up no more than 1 MHz of bandwidth.
Verification: Validate signal bandwidth by observing the frequency spectrum of modulated transmit carrier signal

2.7.2 DR: Downlink channel must have a maximum bandwidth of 1 MHz

Motivation: Various international organizations, such as the International Telecommunications Union (ITU), have placed restrictions on communication links in different jurisdictions. As a result, the customer requested that our signal take up no more than 1 MHz of bandwidth.
Verification: Validate signal bandwidth by observing the frequency spectrum of modulated receive carrier signal

3 Key Design Options Considered

3.1 Trade Study on Antenna Designs

When selecting hardware for a communications system, the antenna is a critical component that must be selected according to the communication requirements. For example, the most likely scenario for this project is transmitting and receiving from a LimeSDR at frequency ranges of 400-450MHz. Consequently, based on the requirements, several parameters have been selected to define rankings of the antennas:

- SDR Compatibility: The ability of the Antenna to pair with an SDR(connections, interface, etc).
- Unit-Cost: Considering this project has a set budget of five thousand dollars, the selection of the most cost efficient antenna to fulfill the communication requirements is ideal.
- Weight: Effective weight consideration is implemented since sending hardware to space is very expensive. In addition, the handheld prototype should be easy to carry, and thus a lower antenna weight would be more desirable. Hence, the weight selection of the antenna is also a key factor.
- Performance: Quantification of how the antenna works when connected to the SDR under different testing scenarios, gain and bandwidth specifications, etc. This is the ranking that has the highest priority to emphasize the success of the communication system.

After carrying out general research on antennas such as material, shape, bandwidth, low and high gain, omnidirectional and directional antennas, three different configurations of antennas were selected for a trade study. These antennas were though to be ideal candidates for the system set up.

- Externally Mounted Antenna: The antenna is not directly integrated with the handheld device. Instead, the antenna is connected with a long range wire which connects the SDR to the antenna, due to the height and weight of this antenna type. A visual representation is shown below.

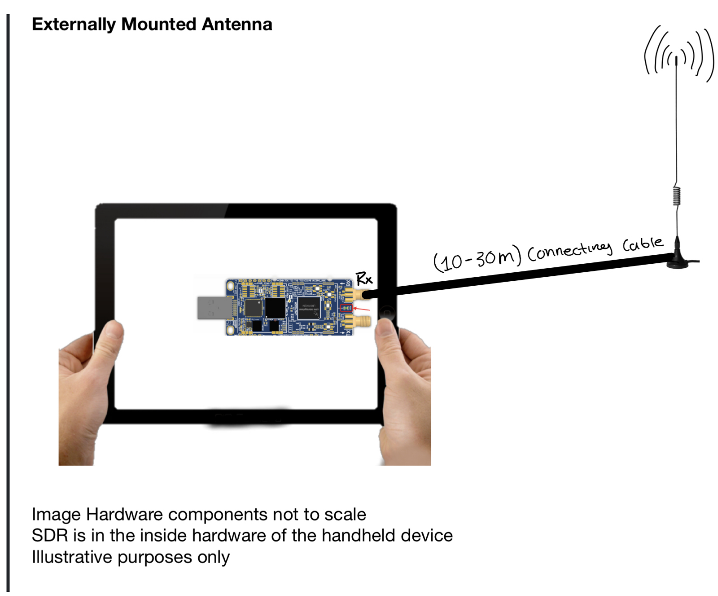

Figure 5: Externally Mounted Antenna

- Attached Antenna: This configuration of an antenna permits integrating the antenna to the handheld device. This is like early cellphones where the antenna was visible and could be extended for use. A visual representation of the set up is shown below,

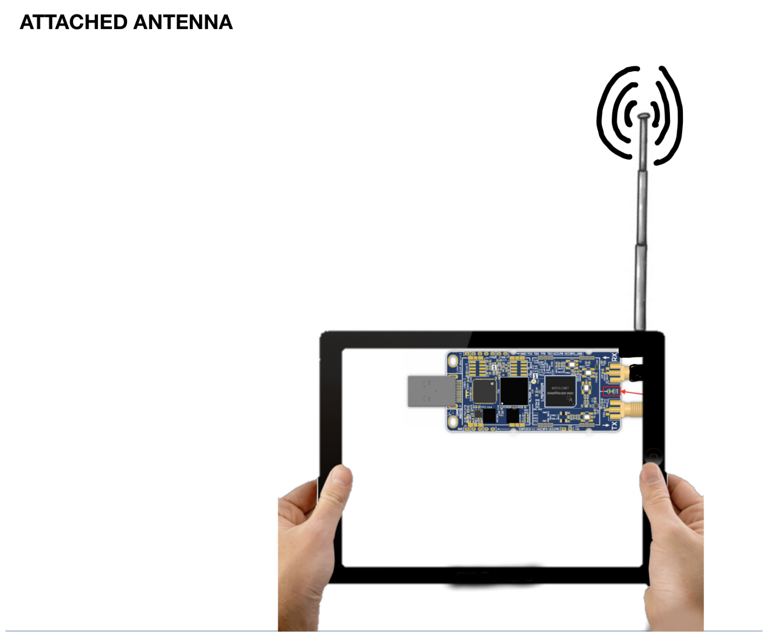

Figure 6: Attached Antenna

- Internally Embedded Antenna: This antenna configuration has all necessary hardware embedded inside the system. This is like modern smart phones where you can't visibly see the antenna since it is encased in the outer shell of the phone. A visual representation is shown below.

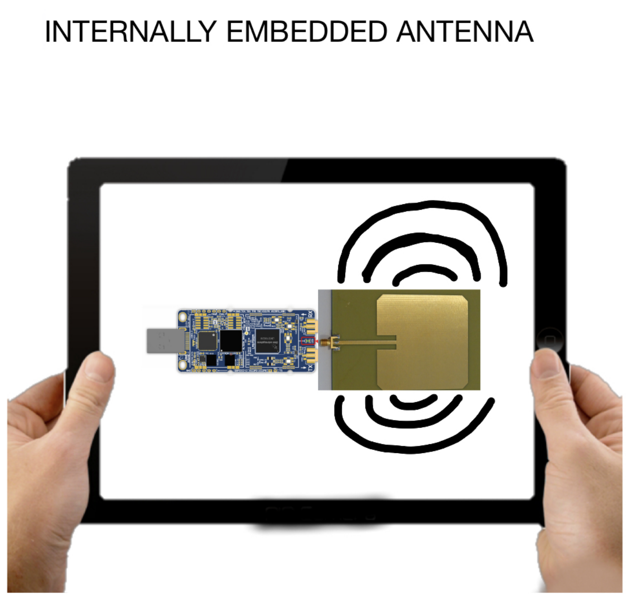

Figure 7: Internally Embedded Antenna Configuration

Based on ASEN 3300 notes, (Aerospace: Electronics and Communication Lecture Notes) the group will need to have 2 different antennas, one for transmitting and another one for receiving signals at frequency ranges of 400 and 450MHz respectively. Gain, which is the parameter that measures the degree of directivity of the antenna's radiation power, is a key factor for selecting these antennas. Another important factor to consider is antenna bandwidth. This is the frequency range occupied by a signal. A high-gain antenna will radiate most of its power in a particular direction, while a low-gain antenna will radiate over a wider angle. The trade off between gain and bandwidth is that the higher the gain, the lower the bandwidth and vice versa. The image below represents this important trade off rank relationship:

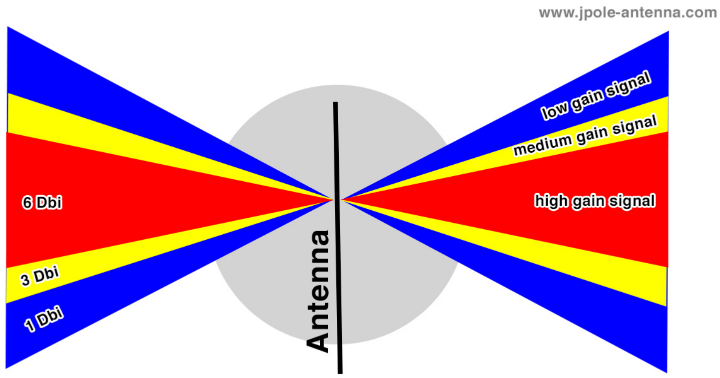

Figure 8: Antenna Gain Vs Bandwidth

After analyzing these ranking factor relationships, different antenna options for each configuration were selected. These include several RF communication company products, which are the Fairview Microwave, Arcadian(Laird) Incorporated, and Molex Electronics/Optics. These companies were considered to find appropriate antennas for this project. The following candidates have been considered in a trade study:

- Laird FG-4507 (Externally Mount Antenna)

Figure 9: Laird Antenna

- FairView Microwave- FMAN51160(Attached Antenna)

Figure 10: Fairview Antenna

- Molex Patch Antenna (Embedded Antenna)

Figure 11: Molex Antenna

3.2 Trade Study on LimeSDR Software Packages

One of the main issues with the transmission and reception of electromagnetic signals via hard-wired electronics is the flexibility which these systems can provide. The team desires a flexible testing/simulation environment in which one electronic component is used to transmit and receive signal consisting of all sorts of coding and decoding schemes. This is where the LimeSDR comes into play. This electronic device, as the name implies, is a software defined radio in which any signal can be received (or transmitted) in the various information schemes currently in use, and hence manipulate this signal via software. This is more beneficial, since the software previously used was a set of electronic components and circuits tasked with processing the incoming or outgoing signal. Naturally, this new approach results in added complexity on the software side, since now, most of these components need to somehow be converted into software. However, this software has multiple solutions which people have developed throughout the years. Because of this, a decision must be reached as to which piece of software is best suited for this project. This aspect of the project engulfs a large part of this project considering most of the testing and development will occur within the capability of our selected software package. To be specific, the objectives influenced by the selection of a software package on our project are found in Section 2-Levels 1, 2, 3, and 4 (Every level of success!).

For all three of our software package candidates we can devise a ranking system such that the most suitable candidate is chosen among the options. This ranking system contains:

- Software Complexity: Determines the accessibility and readability of the code developed.
- Software Documentation: Considering most of our project is open source and would otherwise have to be developed over the course of years, we opted to employ the availability of open source programs.
- Software limits: Given some of the open source programs available are limited, as to their capabilities, we must employ a software package which is able to complete the tasks required by the project.
- Software Availability: This will manage whether the software is compatible with the systems (Laptop/Rasberry Pi) which will be used throughout the project.

3.2.1 LimeSuiteGUI

Complexity: The LMS 7Suite GUI is a controller for the LimeSDR. It allows for easy control of the reception and transmission of signals by the SDR. It is comprised in three main pieces: GUI control panel, LMS7002M register and UNITE7002board configuration panel, and LOG panel[24]. The GUI can be used to control transmitter and receiver gain and frequency[25]. LimeSuiteGUI is self explanatory using OPEN, SAVE, GUI->Chip, Chip->GUI, and RESET commands[23]. Using these commands and the receiver and transmitter controls, the LimeSDR can be controlled to transmit and receive signals as required by the project.

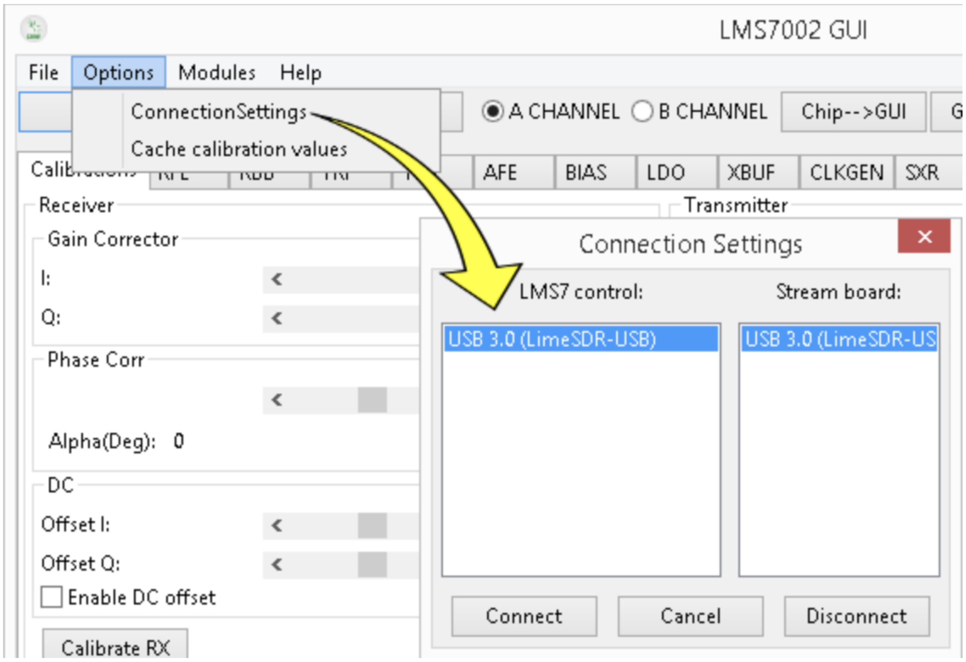

Figure 12: Example of LimeSuiteGUI control panel

Documentation: We have been given previous work in the LimeSuiteGUI by past students, thus we have information on what the setup requires. The GUI has a complete manual describing its usage and integration. It also clearly describes how to install the software and dependencies. However, the dependencies can be difficult to find and documentation beyond the developers manual is limited and does not describe the complexity well[24].

Limits: The LimeSuiteGUI documentation includes how to control and save transmitted and received signals from the SDR. This documentation includes how to transmit .txt files as well as how to save received signals as .txt and .ini files. It also describes how to save these files and transfer them to a computer. The LimeSuiteGUI also allows for the signal to be analyzed in an FFT viewer[25]. Thus, the LimeSuiteGUI should meet all functional requirements for the project[23].

Availability: The LimeSuiteGUI is available on all platforms(Mac OS/Linux), though originally designed for Windows. The necessary dependencies vary between operating systems and the necessary dependencies can be hard to find if not operating on Windows. Thus, running the software in a different operating system may provide difficulties initially[24].

Pros: Available on all platforms including Windows, Linux, and MacOS. Plentiful documentation is available for operation, though description of the software is limited. GUI should allow project to accomplish all tasks including storing data as well as transmitting, receiving, and analyzing signals. The GUI was also developed specifically for the LimeSDR so no plug-ins are required.

Cons: Non-Windows platforms are difficult to install and require difficult to find dependencies. Thus, the setup and groundwork may be more difficult for this software. GUI is less user friendly than alternative. It may be more difficult to perform the simple functionality that this project calls for.

3.2.2 Gqrx

Complexity: GQRX is an open source SDR receiver powered by the Qt graphical toolkit[20]. It follows the flow graph framework developed in association with GNU Radio. The receiver is controlled using a simple Qt GUI. The flow graph framework can be seen in the figure below from the Gqrx documentation[22].

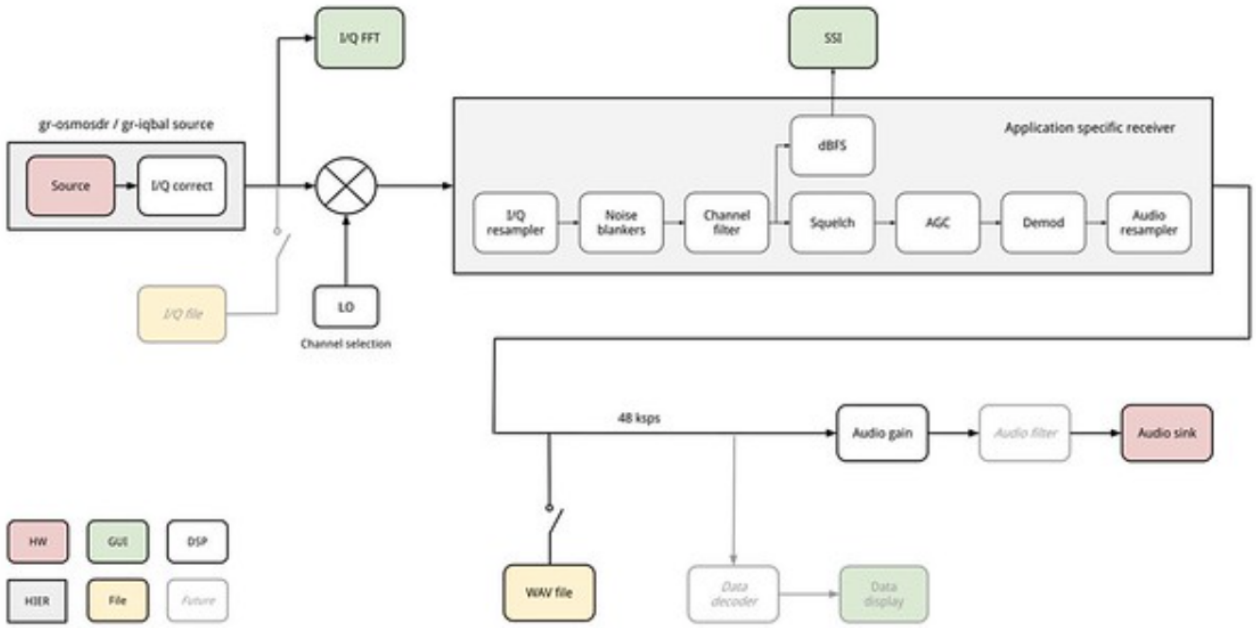

Figure 13: Gqrx Flow Graph Framework

The Gqrx's functionality is shown in the "Application Specific Receiver" block of the framework above. Gqrx resamples the data and translates it into a lower sample rate appropriate for the demodulator. The framework above demonstrates the more complex ability of Gqrx unnecessary for our project.

Similarly, the Qt GUI allows for control of receiver frequency and gain shown below. It also allows files to be saved to the device through the control panel and save settings.

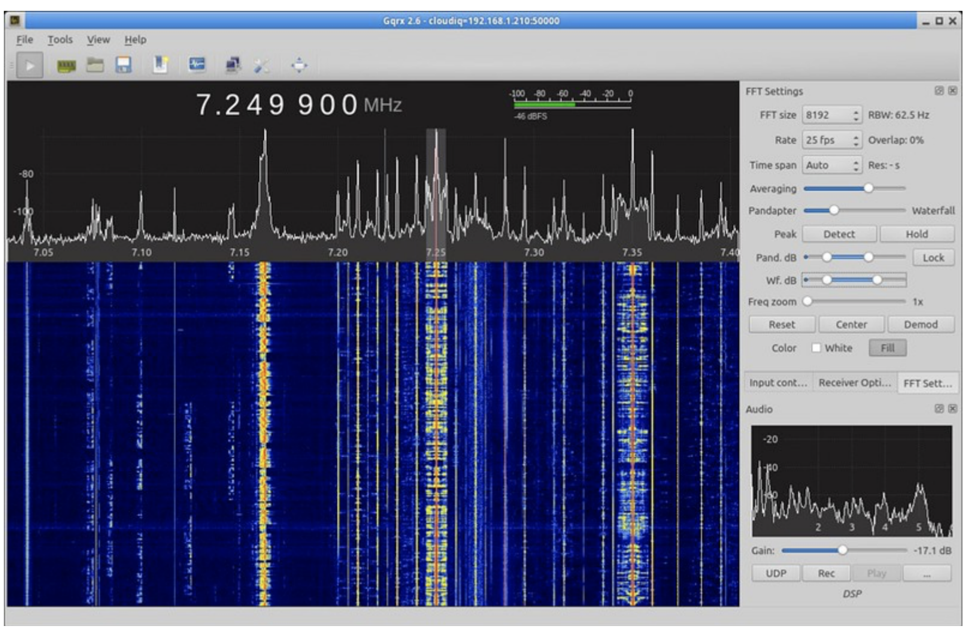

Figure 14: User interface for Gqrx

Documentation: Documentation includes details on install and uses. The documentation describes the software well and defines its development structure. There are also multiple YouTube videos demonstrating its usage. The latest version can easily be downloaded through source code and various binary packages[20]. Descriptive documentation of its usage is also provided through multiple third party sources.

Limits: Gqrx allows for basic control through a TCP connection. It allows for FFT plot and waterfall. The software allows for audio record and playback which may be helpful for level 4 success. It also allows for changes to frequency, gain, and provides signal corrections. Similarly, it can act as a band pass filter[20]. It provides all required demodulation through possible AM, SSB, CW, FM-N and FM-W demodulators. Thus, it should meet all receiver requirements. However, it does not provide transmitting functionality. Therefore, additional software would have to be used to preform the transmission aspect of our project.

Availability: Gqrx supports much of the SDR hardware available, including the LimeSDR using the SoapySDR device string[21]. It runs on Linux and Mac OS, though it is said to be difficult on Mac OS. Documentation states to only provide limited support for Mac OS.

Pros: The UI is incredibly user friendly and graphical. The download is very easy through source code. The software allows for easy control of frequency and gain. The software provides a demodulator that will fulfill all necessary requirements for the receiver. It also allows for simple saving and frequency analysis of the received signal.

Cons: The software runs on Linux and MacOS, but has no support for Windows, which may be the operating system we run on. The LimeSDR is only supported through the SoapySDR device string. It acts only as a receiver and will not help with the transmission element of our project. Some of the best documentation comes from third-party sources instead of the developer.

3.2.3 GNU Radio

Complexity: The GNU radio [7] is a flow graph oriented framework, and therefore is simple to understand and develop in. This flow graph frame work allows the user to see the program flow and therefore the data flow of our radio signal. This complies with the industry standard of representing the stages of signal manipulation through flow charts.

Below we find an example of what the interface will look like:

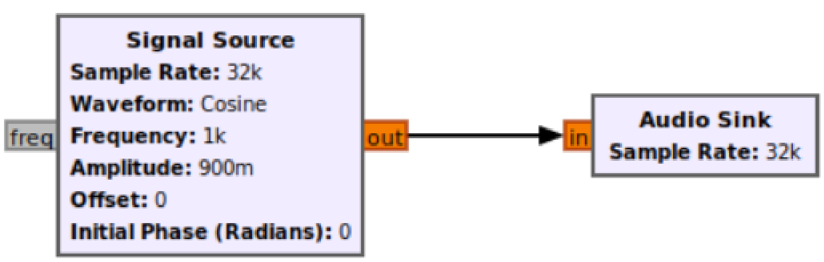

Figure 15: Example Flowgraph Framework Interface [8]

From figure 15, we can pick up on the simplicity of using flow-graphs as coding blocks. We see the input to every operation and the direction of flow for data within the simulation. We can also see the inputs to every function, or in other words, the parameters which will constrict or manipulate the stream of data.

Documentation: We have already received much help from other students which have worked on a similar project and therefore have a head start as to what needs to installed and setup. Thanks to this assistance we have identified the detailed documentation of the GNU Radio software as well as its plug-in. A plug-in is a piece of software which allows accessories to an already existing framework to be added. For example, when the GNU Radio software was developed it might have been intended for use on some specific hardware. However, it was not intended to be used on the LimeSDR board. This is where the Gr-LimeSDR Plugin [10] for GNU Radio software comes in. This plug-in allows for the interface GNU Radio -> Gr-LimeSDR Plugin -> LimeSDR to exist. Detailed documentation of the GNU Radio Software and the Gr-LimeSDR Plugin can be found in the references page below. Specifically items [7], and [10].

Limits: The GNU Radio tutorial page already contains a list of examples and tools which are readily available in the design environment. This includes wave-forms, modulators, instrumentation, math operators, channel models, filters and Fourier analysis. Therefore, the GNU radio's experimental and simulation environment should fulfill all our needs.

The GNU Radio framework supports M-PSK signal encoding or Multi-Phase Shift Keying, this is discussed in detail later (Section 3.3.3). Below is a demonstration that includes an example or sample of what the flow graph style framework is capable of:

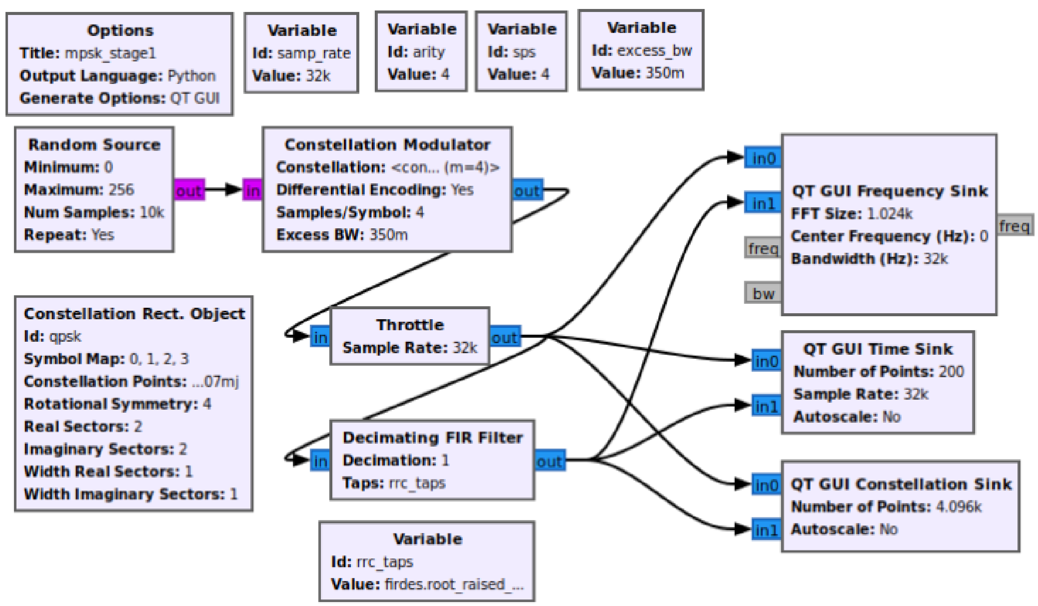

Figure 16: Example flow chart for simulation of M-PSK signal. [9]

Figure 16, above specifically demonstrates the functional blocks required for a simulated QPSK signal. Once compiled, and set to output the simulated data, we get a window similar to figure 17, shown below.

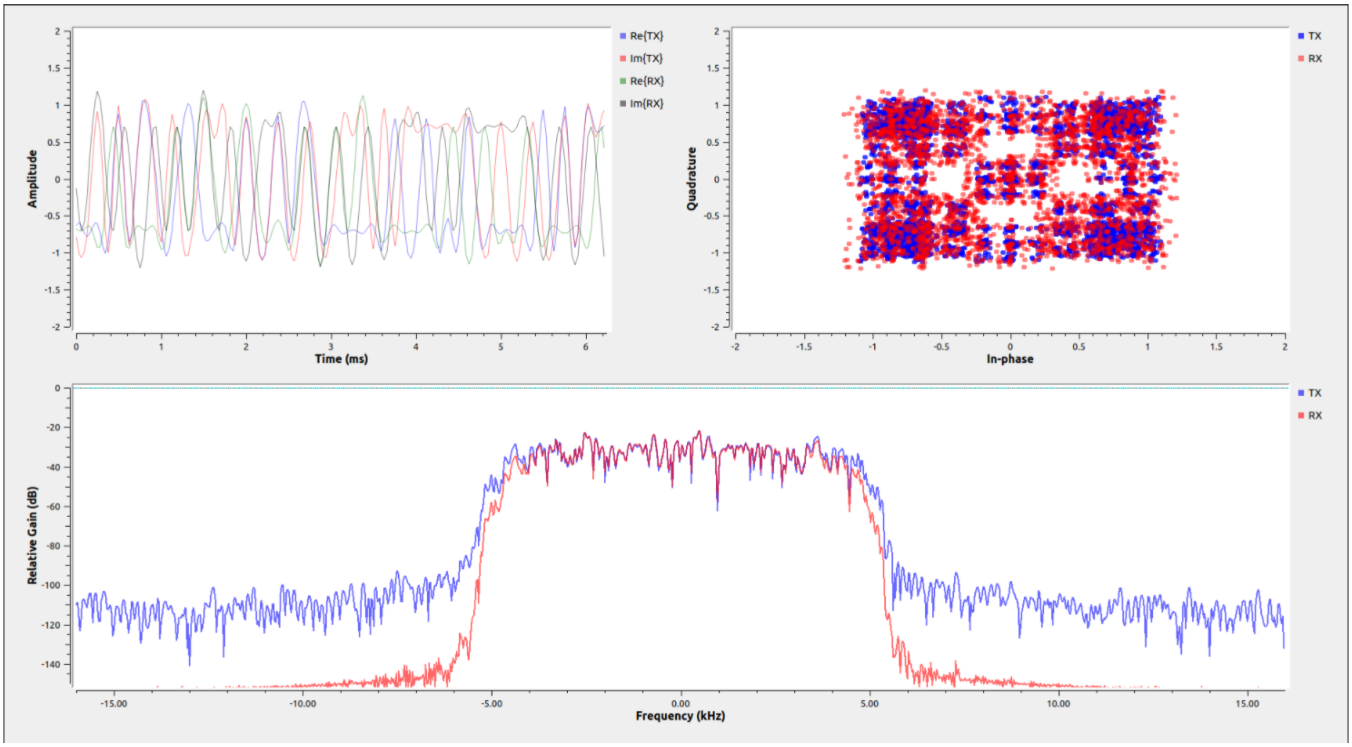

Figure 17: Example simulation data for M-PSK signal. [9]

Availability: The GNU Radio software works well with all platforms that can run Windows, Mac OS, and Linux based systems such as Ubuntu. Thus, considering most of our team-mates have these systems and are familiar with said systems the GNU Radio is well suited for our needs.

Pros: The quantity and quality of the documentation hints at the fact that this software package will be the most helpful in terms of the learning curve that comes with any new language and environment setup. Once the GNU Radio setup is complete, it also seems like the tools which are available will greatly simplify our analysis in the sense that most of the ground up development is already done and therefore the team can focus on the higher level concepts of how each tool works.

Cons: Because the software package is open source, a lot of time and effort will be required to get GNU Radio setup on the LimeSDR and laptop. It can also be said that because much of the component blocks have already been created, much of the low level information and/or circuit setup might be out of reach of the programmer.

3.3 Communication Link Design Parameters

When selecting a communication link, many options must be considered. A good communication link must first and foremost satisfy any International Telecommunications Union (ITU) requirements for what is allowable in the environment we plan to design for (Lunar surface/orbit). Some additional consideration will include how this communication link might have to scale in frequency/power in order to test the functionality of the design. While the team's focus is on the handheld receiver, the team must use a communication link that is compatible with 170 simultaneous lunar surface users and must able to transmit SMS-like signals to satellites (driving transmit power). Also, the communication link must be able to receive signals at an acceptable signal-to-noise ratio (SNR) in order to properly receive the signal and decode it. Additionally, since the receiver must receive navigation messages as well in order to determine range and time, the team must design the link in order to accommodate both the navigation and SMS-like messages while ensuring only the intended user gets their message.

3.3.1 Frequency

The transmit (Tx) and receive (Rx) frequencies of the handheld device is entirely constrained by the customer-defined uplink and downlink frequencies, which are in turn motivated by telecommunications restrictions. The frequencies are then 450 MHz for the receive side, and 400 MHz on the transmit side.

For testing purposes, the team may use any sort of frequencies in a laboratory environment but is constrained by the Federal Communications Commission (FCC) about which frequencies are available for general-purpose use. There are bands at 420-450 MHz, 902-928 MHz, and 1240-1300 MHz available for amateur use [8], and these are the frequency bands within an order of magnitude to the ones required for the lunar environment which provide more than 5 MHz bandwidth for testing.

3.3.2 Bandwidth

Bandwidth is the range of frequencies a signal occupies in space which are greater than half the power of the primary, or center, frequency.

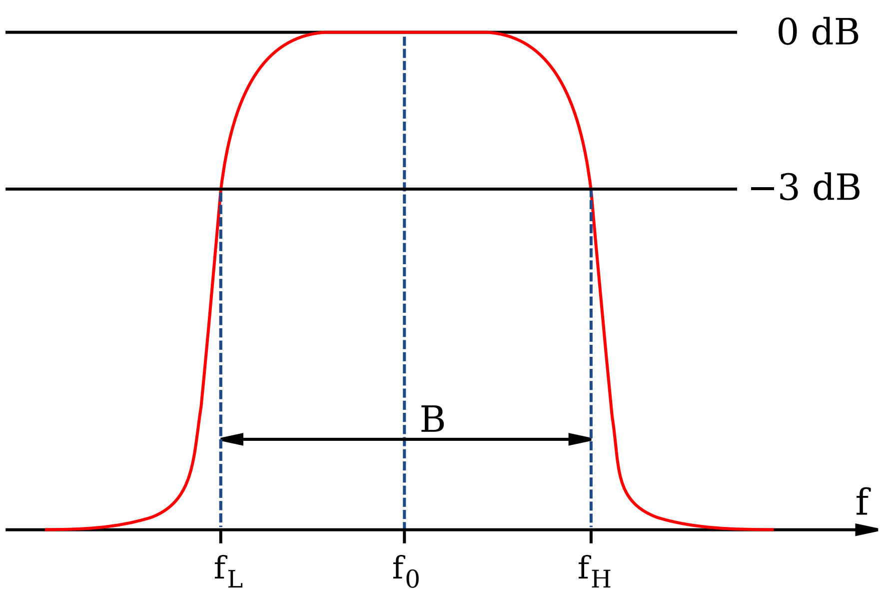

Figure 18: Diagram of Bandwidth B around center frequency f_0

For a communication link, the larger the bandwidth, the larger the number of users as well as the less interference between users. The limitations for bandwidth come from regulation (ITU), which inspire the customer's requirement for maximum bandwidth, 1 MHz.

3.3.3 Modulation Schemes

Modulation is generally the process of converting an analog or digital signal into a carrier signal which is used for transmission. A figure describing two types of analog modulation and one type of digital modulation is shown below:

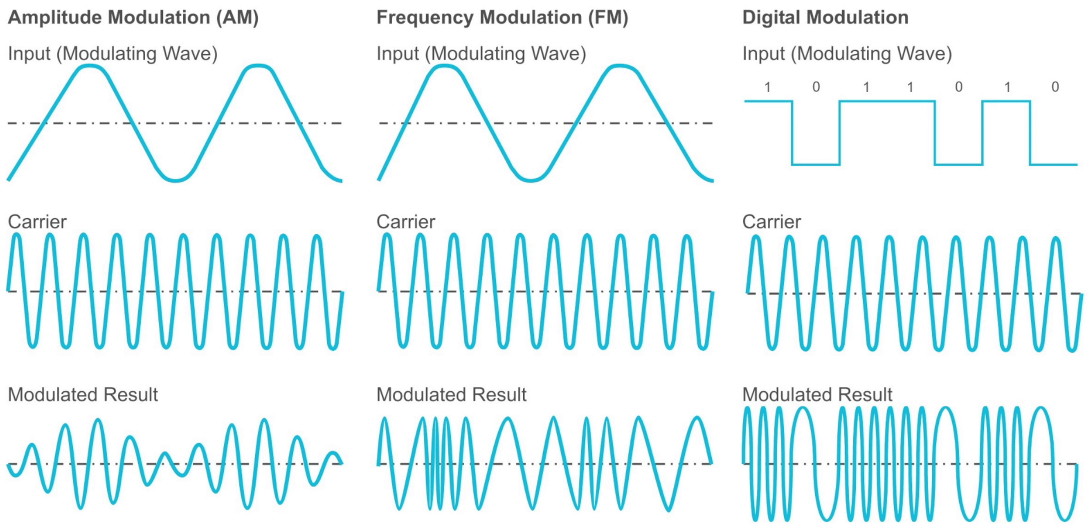

Figure 19: AM, FM, and Digital Frequency Modulation [11]

There are three main groups of digital modulation schemes: amplitude shift keying (ASK), frequency shift keying (FSK), and phase shift keying (PSK) [12]. Within each modulation scheme, there are many possible ways to encode bits (or bits per symbol), which can increase the bit rate at the expense of increasing the bit error rate as signal constellation points get closer together. Additional complexity arises when combining different modulation schemes, such as quadrature amplitude modulation (QAM), amplitude phase shift keying (APSK), frequency phase shift keying (FPSK), etc. Each modulation scheme also reacts differently to different forms of interference, noise, or attenuation such as multipath, path loss, or the presence of other signals. The choice of which modulation scheme to use is also partially driven by a multiplexing scheme (for example, frequency modulation of frequency division multiplexed signals would result in severe inter-signal-interference).

Amplitude Shift Keying

Amplitude shift keying is a type of digital modulation technique where the carrier frequency's amplitude is changed according to which bit or set of bits is meant to be transmitted [12]. A figure detailing the process is shown below:

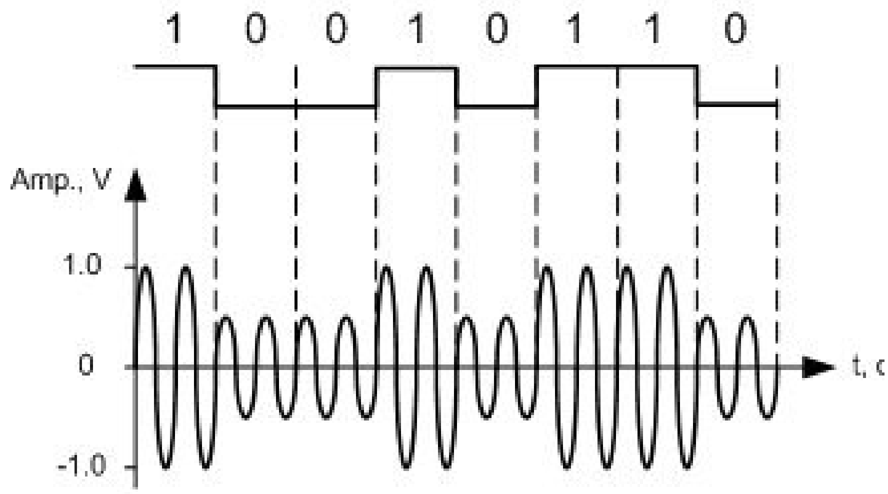

Figure 20: Binary Amplitude Shift Keying [14]

The figure shows a form of ASK called binary amplitude shift keying (BASK), in which two amplitudes are used to represent the digital bit states 0 and 1. This can be depicted in a *constellation diagram*, in which various amplitudes and phases used to modulate the signal are represented as points on the constellation diagram. For example, the constellation diagram for BASK is as follows:

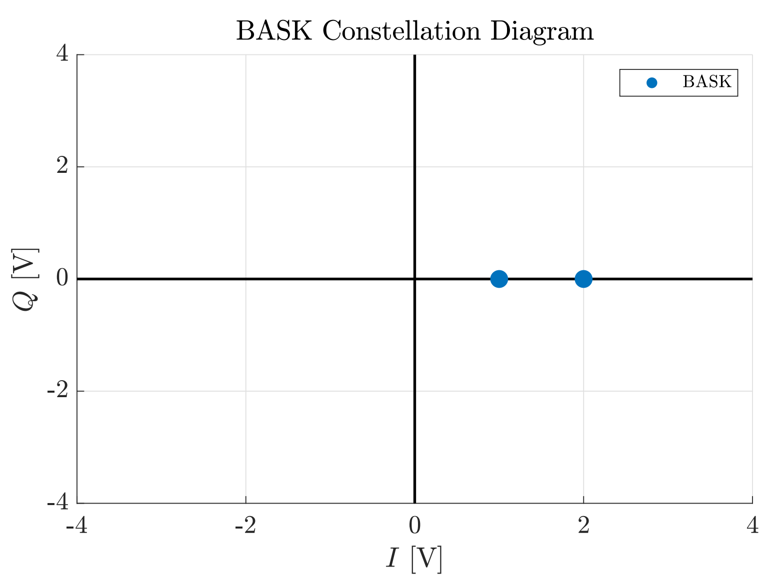

Figure 21: Constellation Diagram for Binary Amplitude Shift Keying

In a constellation diagram, the axes are the *in phase* axis (I) and *quadrature* axis (Q). Their units are volts which represent signal amplitude (so the amplitude of an arbitrary point is its distance away from the origin), and the phase of a constellation point is described by the angle a line drawn between it and the origin makes with the $+I$ axis. A key feature of pure amplitude shift keying is that all the constellation points lie on the same ray from the origin (they all have the same phase). Another example of amplitude shift keying is 4ASK, shown below:

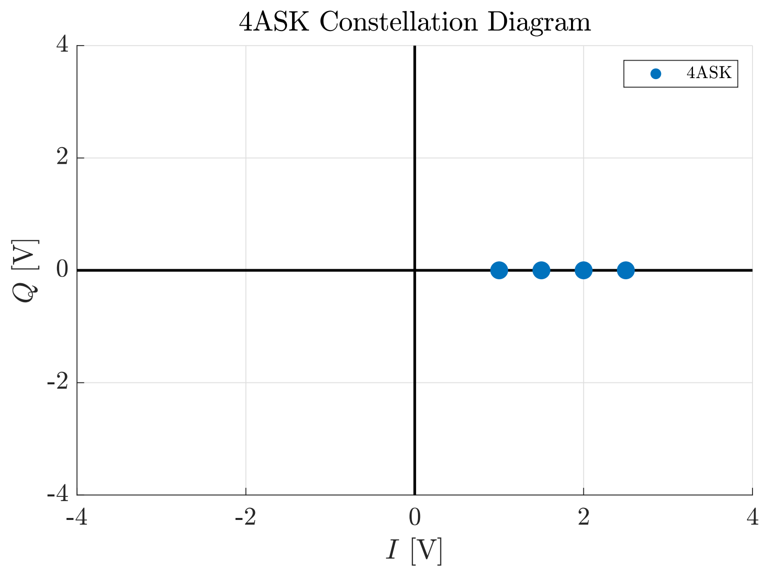

Figure 22: Constellation Diagram of 4ASK Signal

Here, each point in the signal would represent two bits:, either 00, 01, 10, or 11. The mapping of the bit sequences (symbols) to the constellation points is up to the designer of the signal. The benefits of pure ASK are as follows:

- ASK is simple to implement
- Scalable to allow for faster data rates
- ASK can be combined with other modulation schemes to make a more robust hybrid scheme

Some of the drawbacks of ASK are as follows:

- ASK does not utilize the constellation space effectively. The closer constellation points are to each other, the less energy it takes for noise or interference to cause a signal at one constellation point to be interpreted as one from another constellation point, so it is good to maximize the spacing of the constellation points in order to minimize bit error rate [12]
- ASK requires a good amplifier to work properly, or risk increasing bit error rate due to amplifier noise and amplitude/phase shifts due to amplifier nonlinearities (see section on Quadrature Amplitude Modulation) [12]
- ASK can lead to sharp transitions in the carrier signal, so in order to stay within a certain bandwidth, a pulse shaping filter must be applied to the signal to make the transitions smoother [13]

Frequency Shift Keying
Frequency shift keying, as opposed to amplitude shift keying, changes the frequency at which the carrier signal is transmitted in order to convey bits. A figure is shown below:

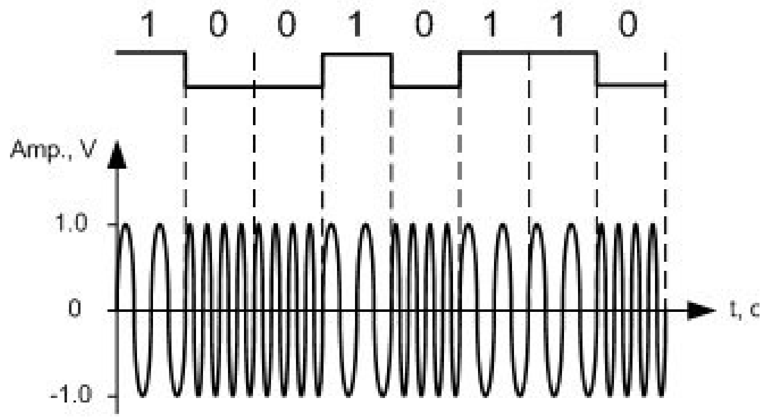

Figure 23: Frequency Shift Keying

Some benefits to FSK are listed below:

- FSK is simple to implement
- Many different frequencies can be utilized to increase data rate by sending multiple bits per symbol
- There aren't sharp transitions in an FSK signal, so there is no need to apply a pulse shaping filter to keep it within bandwidth

Some drawbacks to FSK are listed below:

- FSK must utilize many different frequencies, which removes some bandwidth to be possibly used for multiplexing signals. The data rate is heavily limited by bandwidth.
- The communication link is to be used between users on the surface on the moon and satellites in orbit around the moon. The velocity of the satellites is very large and variable with respect to the lunar surface users, so the Doppler shift on signals could significantly increase the bit error rate of the signals

Phase Shift Keying
Unlike ASK and FSK, phase shift keying uses the phase of a carrier signal to transmit individual bits. A diagram for binary phase shift keying, or BPSK, is shown below:

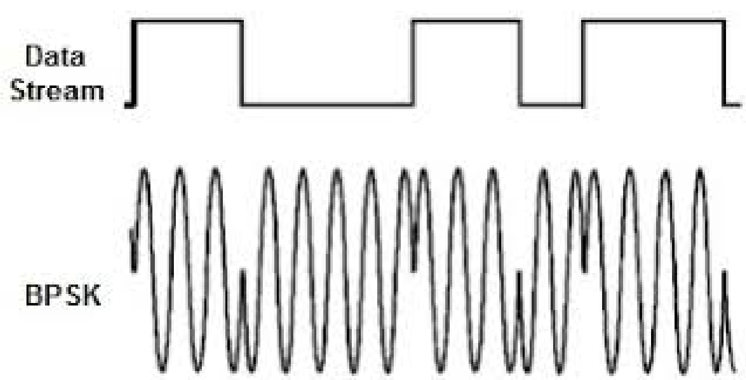

Figure 24: BPSK Modulation onto Carrier Signal [14]

BPSK uses two phases, in phase and exactly out of phase, to represent two states of a digital bit. The figure below shows the constellation diagram of BPSK:

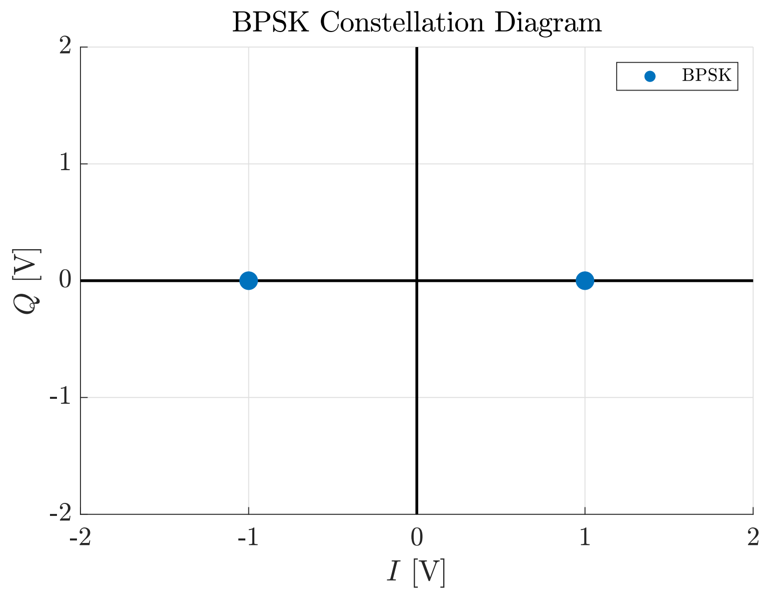

Figure 25: Constellation Diagram of BPSK signal

The constellation diagram above shows two points with the same amplitude, except 180°apart. This can be generalized into higher order PSK, such as quadrature phase shift keying (QPSK). The constellation diagram for QPSK is shown below:

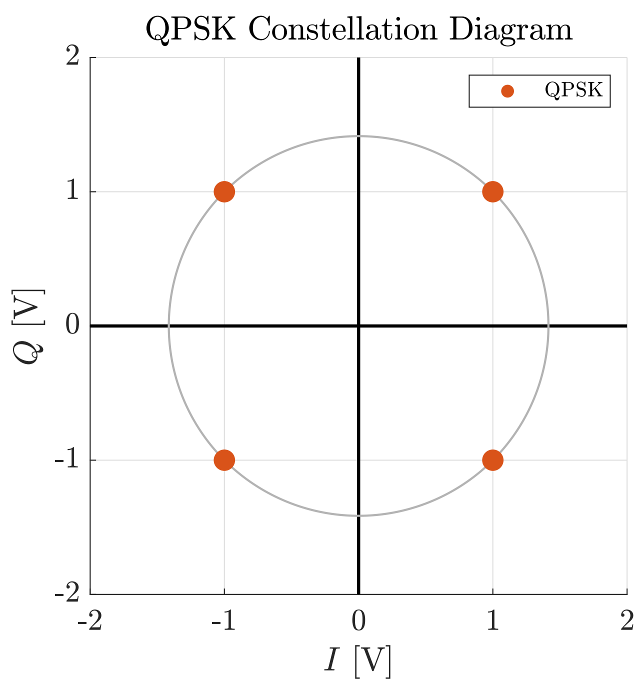

Figure 26: QPSK Constellation Diagram

All the constellation points lie on the same circle centered around the origin, and are separated in phase by 90°. Each constellation point represents a two bit symbol. Like the other main forms of digital modulation, it is possible to include more constellation points on this circle (more phases) to encode more bits per symbol. Here are a list of benefits of phase shift keying:

- A nonlinear amplifier will affect all the points on the constellation of a PSK in similar ways
- There is no bit error rate cost in moving from BPSK to QPSK (but there is bit error rate cost in moving to higher PSK schemes)
- The bit error rate is lower than that of FSK and ASK [15]

Here are some of the drawbacks of pure PSK:

- Constellation spacing could increase if combined with ASK [12]
- It is one frequency, so it is prone to interference at that frequency

Quadrature Amplitude Modulation

Quadrature amplitude modulation is a combination of phase and amplitude shift keying, where the minimum number of constellation points to make improvement over PSK is 16. The constellation diagram for 16QAM is as follows:

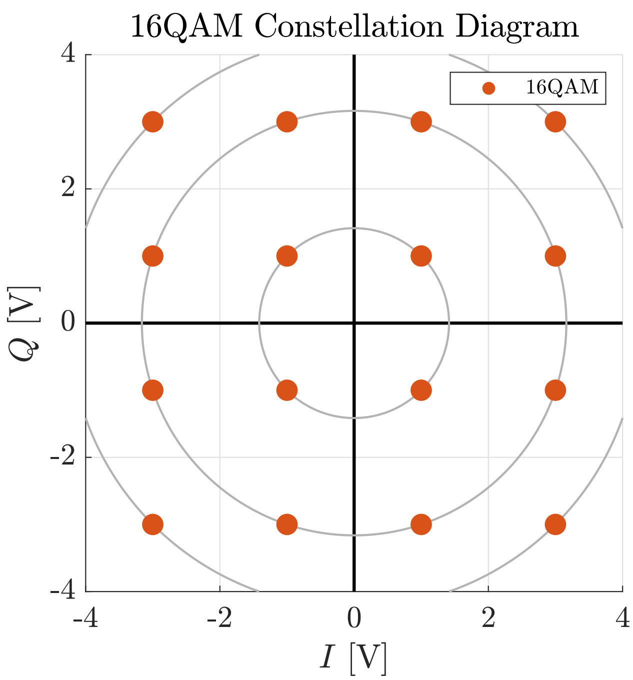

Figure 27: 16QAM Signal Constellation

The constellation diagram shows 16 constellation points spread out fairly evenly across 3 amplitudes and 12 different phases. It's certainly clear that the separation for the number of constellation points is better than what either pure ASK or pure PSK can do by themselves, but the cost of having this many constellation points will still be present in the bit error rate. Additionally, amplitude modulated signals need to use signal amplifiers to boost the signal to different levels for transmission. This amplification process can have nonlinearities which affect both the amplitude and phase of a 64QAM constellation point as a function of its amplitude, as shown in the figure below [12]:

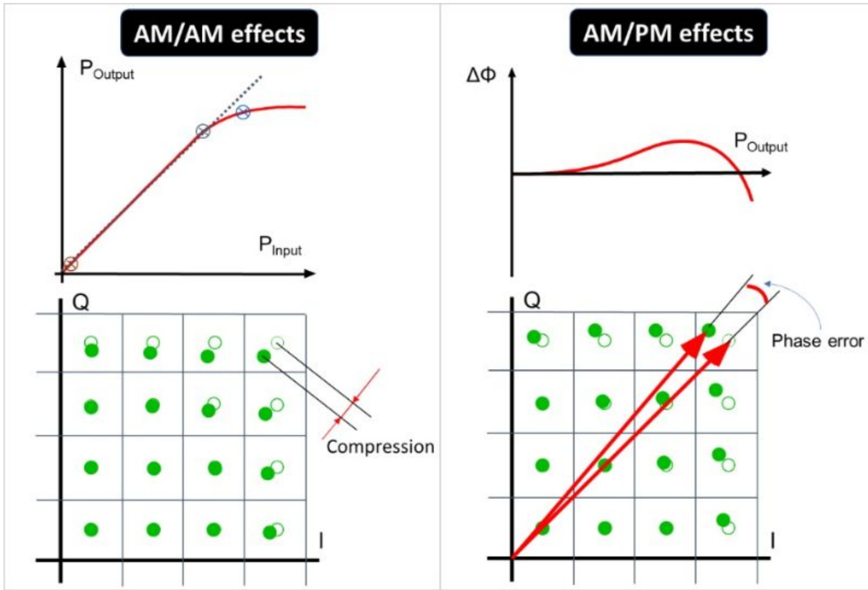

Figure 28: Amplitude and Phase Nonlinearities in 64QAM constellation plot [12]

The figures show the first quadrant of a 64QAM signal, but the compression and phase error is present in any amplitude-modulated signal, not to mention any additional noise caused by the amplifier. It is important to note many ground and space-based systems use QAM for modulation, and its primary benefit which is its sharp increase in data rate comes at the cost of a higher bit error rate.

3.3.4 Multiplexing Schemes

Multiplexing is the process of transmitting multiple signals simultaneously across the same medium. This is useful for this project because there are a number of different satellites communicating to a number of different users across one medium, and it's important to keep signals distinct from one another in order to properly keep track of who sent them. A figure describing the basic principle of multiplexing is shown below:

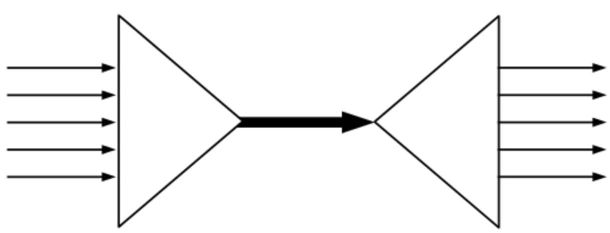

Figure 29: Multiplexing

There are three main groups of digital multiplexing schemes: time division multiplexing/multiple access (TDM/TDMA), frequency division multiplexing (FDM/FDMA), and code division multiplexing (CDM/CDMA). Each employ different strategies in order to send multiple signals across a shared medium, and often times the strategies are used together to further diversify and optimize multiplexing schemes to meet requirements.

Time Division Multiplexing
Time division multiplexing is the simplest of multiplexing techniques, in which different terminals get certain time allocations to send their signals. This means only one signal is being sent through the medium at a time, but this could be optimized to maximize throughput. Some of the pros of time division multiplexing are:

- There aren't any additional multiplexing steps to take other than synchronization between the sender and receiver
- Each signal can make full use of the available bandwidth [16]

Some of the drawbacks include:

- Synchronization between the sender and the receiver to know which signal is transmitting at any given time is hard [16]
- Synchronization between multiple senders (in the case of GPS satellites) would require extremely accurate timing information between satellites and between satellites and the receiver

Frequency Division Multiplexing
Frequency division multiplexing is where many users are assigned their own frequency within the bandwidth of the carrier and then a receiver can use Fourier techniques to split up the joined signal into their frequency components and retrieve the original signal [17]. A variation of FDM, called orthogonal FDM or OFDM, is used widely in many telecommunications applications because of its high spectral efficiency (how well a signal uses its bandwidth) [18]. It achieves this by using several orthogonal closely spaced frequencies which can each carry their own signal. Some benefits of FDM (and its variants) include:

- Potential for very high spectral efficiency if closely spaced frequencies are used [17]
- High data rate and many users [18]
- Can be combined with other single-frequency multiplexing techniques to form a better solution
- Has a wide range of telecommunications heritage (OFDM is the primary multiplexing technology of 4G) [17]

Some of the drawbacks include:

- Closely spaced frequency bands are very sensitive to Doppler shift [18]
- Number of users is limited by number of frequencies available for use within bandwidth

Code Division Multiplexing
Code division multiple access (CDMA) is a technique in which a data signal is combined with a much faster data rate spreading code, which can then be modulated onto a carrier frequency to be received by a receiver with the same spreading code [17]. An image of the spreading process is shown below:

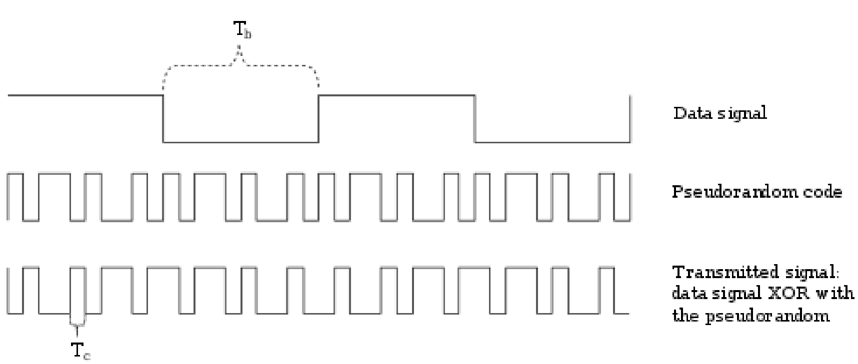

Figure 30: CDMA Spreading

The spreading codes have the property of being mutually orthogonal (or highly orthogonal) - which means their cross-correlations are perfectly (or nearly) zero for all time. This means that a receiver can pick up many different CDMA signals from many different transmitters and they will all look like random noise except the one which matches the code the receiver is using. CDMA is the technology currently in use for GPS because each GPS satellite can transmit using its own unique code, allowing for identification and separation of signals on the receiver end (the receiver can tell which satellite is sending each message). Some of the benefits of a CDMA system include:

- CDMA supports multiple users on the same carrier frequency, which reduces the bandwidth of the transmitted signal (even though the bandwidth of the digital signal prior to modulation increases) [17]
- If the spreading codes are good, CDMA signals have potentially very low inter-signal interference
- CDMA signals have a legacy of being used for navigation and GPS

Some drawbacks of CDMA include:

- The spreading codes only correlate if they are perfectly in phase, which means a receiver has to perform a phase correction in order to correctly demultiplex the signal
- The number of users on a CDMA system is limited by the ratio of the bit rate of the spreading code to data rate, called the spreading factor [17]

Within CDMA, there are multiple options regarding how to generate the spreading code for different bit error rate results. Additional consideration will have to be given to modulation with CDMA to determine if a dataless acquisition signal can be sent in addition to the data to increase the time of signal acquisition.

3.3.5 Ranging Schemes

In order for a satellite-based positioning system to be accurate and remain accurate over time, the satellite and receiver clocks need to have low biases and drifts, but even this is not enough to keep the time accurate on either the satellite or receiver. A timing error of even 1 μs would result in a position error of 300 meters at the speed of light. For this reason, Earth-based GPS uses a widespread array of ground stations whose positions are known precisely. These ground stations have extremely precise clocks on them, and a number of these stations are used to send error (orbit and time) corrections to the satellites so they can broadcast an error correction to a receiver for the receiver to calculate a position with less error. In order for LPS to have longevity, this timing error will have to be corrected by a network of ground stations and both the handheld receivers and the satellites will have to have precise clocks on board.

One way to get around this problem is by using *two-way* ranging as opposed to one-way ranging. In one-way ranging only satellites send navigation messages to receivers in order for the receiver to triangulate its position, which requires both satellite and receiver to have synchronized clocks. In two-way ranging, a receiver will instead send a navigation signal to a satellite, which then sends it back to the user. The time of flight can then be calculated as half the difference between the total time and whatever time the satellite took to reply to the signal (typically a constant) [19]. This technique only relies on the receiver's clock, which is perfectly synchronized with itself. The drawback is that now the receiver must have the ability to transmit adequately strong ranging messages, and the satellite must have a receiver architecture that can receive and process ranging messages from a lunar surface user. Not having to worry about clocks comes at the cost of increased satellite receive and handheld transmit complexity.

4 Trade Study Process and Results

Each trade study is conducted within the appropriate sub-team, who got together and decided which metrics were the most important and assigned weights to them appropriately. The following are the trade study metrics and results.

4.1 Antenna Design

The following table provides more of a general insight of how the antennas shown in section 4 perform, along with other specifications and more description.

Antenna	Type of Antenna	Performance
FairView Microwave- FMAN51160	Large whip antenna categorized as the external mounted antenna	Gain Range from unity to 2dBi, Omnidirectional Frequency range (400 and 450MHz) Fiberglass material
Laird FG4507	Small whip antenna categorized as the attached antenna	Fiberglass Material, heavy duty antenna, Omnidirectional, 7dBi, 2.717 m long. Operates from 450-460 MHz
Molex Patch Antenna	Patch antenna that falls into the embedded category antenna	Operates from 433-455 MHz Compact and has a unity dBi Gain

Table 2: Antenna Performance

Table 2 contains general information of the antennas, from which was provided in the product description and data files.

Antenna	Cost (USD)	Weight (grams)	Compatibility	Cons
FairView Microwave- FMAN51160	201	15	N- Female antenna plug	Doesn't go to a low enough frequency to reach 400 MHz
Laird FG4507	22.64	2721.5 or 2.7 Kg	N- Female antenna plug	Requires an external mount, cannot be integrated with the handheld device, most expensive of all options
Molex Patch Antenna	5.79	1.5	Microaxial	long time for shipping, seems "too cheap", ambiguous frequency data sheet,additional hardware to adapt antenna

Table 3: Antenna Options Specs and Cons

To decide on which antenna appears most adequate for this project, point matrices have been created to give scores to each antenna in the important factor categories discussed previously. Below is the scoring table as well the included scores for each of the three antennas. The antenna with most points was selected as the main candidate fit and will be revised by either the customer or PAB team advisor to verify this choice.

The largest factor in the decision is performance. The mission will not be accomplished and the handheld device will not function properly if the antenna cannot perform correctly. Therefore, the performance category will have a 40% weighting over the trade study on antennas. Weight is another significant factor in antenna selection since the weight of hardware directly correlates to costs of launching that hardware. Minimizing the weight also keeps the handheld device portable. Therefore, the weight category will have a 30% weighting over the antenna trade study. The final 30% will be split up equally between the cost and compatibility. Obviously cheaper hardware will be easier to implement financially since there is a budget for this project and possibly for future projects where this device could be used. Keeping the price of each hardware piece low helps the overall cost of the project remain lower. Also, the compatibility of the antenna with the SDRs, software, and other hardware in this project will also cut down on complexity and potential integration issues. These are both important factors to consider but are not as crucial as weight and performance to the overall design, so each section has 15% weight over the antenna trade study. Table 4 shows the scaling used to evaluate each antenna.

Metric	1	2	3
Cost Effectiveness	Cost is on average more than other antennas (Cost >$200)	Cost is on average: $25 - 200. Reasonable compared to other antennas	Low antenna cost <$25
Weight	Weight is over 500 grams applications	Weight is within the range of 50-500 grams	Antenna weight is very low under 50 grams
Compatibility	Is not compatible with the LimeSDR	NA	Is compatible with LimeSDR
Performance/ Specs	Limited in gain, bandwidth, and frequency. (i.e. does not operate on given transmission and receiving frequency range)	Limited on some aspects of gain, bandwidth, and frequency. (i.e. only meets either the transmission frequency or the receiving frequency requirement.)	Not limited in gain, bandwidth, or frequency with regard to the system

Table 4: Antenna Metric Meaning

		Fairview Antenna	Arcadian Antenna	Molex Antenna
Metric	**Weight**	**Score**	**Score**	**Score**
Cost	0.15	2	1	3
Weight	0.30	3	1	3
Compatibility	0.15	3	3	1
Performance	0.40	3	2	1
Weighted Total		2.75	2.0	1.8

Table 5: Antenna Trade Study Matrix Evaluation

4.2 LimeSDR Software Packages

Metric Rationale: LimeSDR Software Packages

Metric	Weight	Requirement	Description/Rationale
Complexity	**25%**	**3.1.3**	In order for the system to be scaled into a working architectural model, the software used during development must be fast and easy to use. The level of complexity will influence the programmers choice of software and hence, will determine whether the software is used or not.
Documentation	**30%**	**3.1.3**	For the system to be scaled properly into a working architecture, the software must be well documented so that the programmer is able to predict/anticipate any short comings of the software.
Limits	**30%**	**3.2.1** **3.6.1**	In order for the system to demonstrate transmission and reception of data, the software must first be able to provide said capabilities to the hardware. In order for the system to handle 170 users at a time, the software must not be limited in this respect. Hence, a limitation on the number of broadcasted signals is a limitation which will determine whether the software is used or not.
Availability	**15%**	**3.1.3**	So that the system is able to be be scaled up, the underlying hardware and software must be readily available to any developmental set up. This is in regard to the many platforms widely used today.

Table 6: SDR Metric Rationale

Metric Meaning: LimeSDR Software Packages

Metric	1	2	3
Complexity	Software is time inefficient, complex, and not easy to use. Would require an extensive amount of time to get well versed.	Software is time efficient, complex, but easy to use given the amount of time for development.	Software is time efficient, not as complex, and easy to use.
Documentation	Software is not well documented.	Software is documented but lacks specificity.	Software is very well documented.
Limits	Software lacks either transmission or reception capabilities. Software will not support various users. Clearly limited in SDR capabilities.	Software can do signal reception. Software can support various users.	Software package will fulfill all given requirements.
Availability	Software only accessible for Windows based systems.	Software available for Windows and MacOS systems.	Software available for Windows, MacOS, and Linux based systems.

Table 7: SDR Metric Meaning

Final Decision: LimeSDR Software Packages

		LimeSDR GUI	GQRX	GNU Radio
Metric	**Weight**	**Score**	**Score**	**Score**
Complexity	0.25	3	3	3
Documentation	0.30	1	2	2
Limits	0.30	3	1	3
Availability	0.15	1	1	2
Weighted Total		2.1	1.8	2.55

Table 8: Final Software Package Decision

Final Decision Justification: LimeSDR Software Packages

- *GNU Radio Complexity Score: 3*

  The GNU Radio runs on flow-graph type framework and therefore is easy to understand and work with. This sort of framework also works well for scaling up into large architectural problems, in the developmental sense, considering detailed flow-graphs are often used for directional control of information. The complexity of the GNU Radio also allows for quick analysis of complex systems by the grouping of components which allows for a level of abstraction between the programmer and what he want to achieve. Apart from this the GNU Radio offers the ability to characterize parameters for set block, which act as functions, or entire electrical circuits. This helps to test quantities or characteristics in a modular fashion, which again aids in the overall desired scaling of the project.

- *GNU Radio Documentation Score: 2*

  The GNU Radio has a very detailed documentation web page [7]. This again helps in the future scaling of the project. The various 'getting started' pages on the GNU website include ranks such as Beginner, Intermediate, Expert, and Developer pages. Each with its own subset of easy to read examples and 'walk-through's'; these are extremely helpful on the simulation aspect of the GNU Radio software but also in the hardware side considering many of the problems with hardware can be modeled all within the software of the GNU Radio application. With these tools we will be able to provide a good prediction of what the communication between a satellite around the moon and an astronaut with the handheld communications device will experience.

- *GNU Radio Limits Score: 3*

  Reviewing some of the examples in the documentation page of the GNU Radio, it's clear that the GNU Radio is a great tool for the simulation and employment of our project. With the given blocks (Modulation Scheme blocks, Filter blocks, Instrumentation blocks, etc.) already available for use and modification we can build the system needed for an SDR which can transmit and receive in various signal quantities and schemes.

- *GNU Radio Availability Score: 2*

  Given the Gr-limeSDR Plugin for GNU Radio we can see that this requirement is fulfilled in all three desired platforms, Windows, Linux, and MacOS. This is important for the project's architectural scalability and ease of access.

4.3 Communication Link Design Trade Study

4.3.1 Modulation

Metric	Weight	Requirement	Description and Rationale
Complexity	0.1	FR1	Ease of implementation affects how quickly we can get a solution up and running in our time frame
Bit Error Rate	0.35	3.3.1	The bit error rate is closely tied to the SNR of the signal, which affects the position/timing accuracy
Navigation Environment Viability	0.35	3.1	Will the signal actually work with Doppler, multipath, interference, and noise present on the Lunar environment
Data Rate	0.2	FR2	Will the data rate satisfy costumer requirements? Although this requirement will not make or break the project as a whole, if not satisfied, it might greatly limit some of the desired functionalities.

Table 9: Metrics and Weights - Modulation Scheme Selection

Metric	1	2	3
Complexity	Hard to implement. Not much documentation on similar projects/implementations available in online and/or physical sources.	Challenging to implement and some documentation available.	Relatively easy to implement. Documentation for similar projects/implementations readily available in online and/or physical sources.
Bit Error Rate	High bit error rate, with respect to the other modulation schemes.	High bit error rate, with respect to the other modulation schemes.	Low bit error rate, with respect to the other modulation schemes.
Navigation Environment Viability	Very easily affected by environmental effects such as Doppler shift, multipath, signal interference, noise. Or, effects are NOT easily managed and/or corrected for.	Not easily affected by environmental effects such as Doppler shift, multipath, signal interference, noise.	Almost impervious to environmental effects such as Doppler shift, multipath, signal interference, noise. Or, effects are easily managed and/or corrected for.

Table 10: Metric Values - Modulation Scheme Selection

Metrics		**n-ASK**	**n-FSK**	**n-PSK**	**n-QAM**
Metric	**Weight**	**Score**	**Score**	**Score**	**Score**
Complexity	0.1	3	3	2	1
Bit Error Rate	0.35	2	2	3	2
Navigation Environment Viability	0.35	2	1	3	2
Data Rate	0.2	1	1	2	3
Weighted Total	1	1.90	1.55	2.70	2.10

Table 11: Trade Study Results - Modulation Scheme Selection

Justification
The following list describes each modulation scheme with regards to the trade metrics:

- n-ASK
  - *Complexity* - ASK is typically quite easy to implement since all that's needed to modulate the signal is amplification.
  - *BER* - Due to ASK's closer constellation points and being amplitude modulated, noise and interference leads to a higher bit error rate.
  - *NEV* - Amplifier nonlinearities (especially on a handheld device) can cause a shift in constellation points as a function of amplitude, which would degrade the quality of the received signal [12].
  - *Data Rate* - Data rate is a function of the number of constellation points, so n-ASK could theoretically have a comparable data rate to other modulation schemes but it is limited by the constellation points being on one ray from the origin (see section 4.3.3).
- n-FSK
  - *Complexity* - Like ASK, FSK is also quite easy to implement .
  - *BER* - FSK and ASK have comparable bit error rates [15].
  - *NEV* - FSK is heavily degraded by the Doppler shift due to the high relative velocities between moving satellites and lunar surface users.
  - *Data Rate* - The data rate is heavily influenced by how many frequencies are available within a certain bandwidth, and if guard band frequencies will be used to lower the bit error rate the number of available frequencies will be limited [12].
- n-PSK
  - *Complexity* - n-PSK is more complicated to implement because of the phase determination algorithm on the receive side. QPSK is more complicated than BPSK due to there being 4 symbols instead of 2, but both are very widely implemented and well documented.
  - *BER* - BPSK and QPSK have the same incredibly low bit error rates [15] .
  - *NEV* - BPSK and QPSK are currently in use on most Earth-based GPS systems for their robustness in a space environment and good interference/noise characteristics. They are also not as heavily affected by the Doppler shift as FSK.
  - *Data Rate* - QPSK has the double the data rate as BPSK for the same bit error rate [15], and there is no need to increase the data rate beyond that since only SMS-like data rates are desired.
- n-QAM
  - *Complexity* - QAM has the most complexity of the systems due to the combination of amplitude and phase modulation.
  - *BER* - The bit error rate is comparable to that of ASK due to the presence of the amplitude modulation within QAM, and the phase modulation doesn't contribute nearly as much to the bit error rate.
  - *NEV* - Along with ASK, amplifier nonlinearities and poor interference/noise characteristics contribute to the degradation of a QAM signal more than FSK or PSK [12].
  - *Data Rate* - The largest benefit of QAM is its incredibly high data rates — the lowest form of QAM is 16QAM which provides 4 bits per symbol (QPSK provides only 2 bits per symbol). [12]

4.3.2 Multiplexing/Multiple Access Methods

Metric	Weight	Requirement	Description and Rationale
Complexity	0.2	FR1	Ease of implementation affects how quickly we can get a solution up and running in our time frame
Number of Users	0.2	FR6	The multiple access scheme must be able to support the number of users required by the customer
Bit Error Rate	0.3	3.3.1	The BER is closely tied to the SNR of the signal, which affects the position/timing accuracy
Navigation Environment Viability	0.3	3.1	Will the signal actually work with Doppler, multipath, interference, and noise present on the Lunar environment

Table 12: Metrics and Weights - Multiplexing Scheme Selection

Metric	1	2	3
Complexity	Hard to implement. Not much documentation on similar projects/implementations available in online and/or physical sources.	Challenging to implement and some documentation available.	Relatively easy to implement. Documentation for similar projects/implementations readily available in online and/or physical sources.
Number of Users	Does not meet number of user requirement.	Meets number of users requirement.	Meets or exceeds number of user requirement.
Bit Error Rate	High bit error rate, with respect to the other modulation schemes.	Medium bit error rate, with respect to the other modulation schemes.	Low bit error rate, with respect to the other modulation schemes.
Navigation Environment Viability	Very easily affected by environmental effects such as Doppler shift, multipath, signal interference, noise. Or, effects are NOT easily managed and/or corrected for.	Not easily affected by environmental effects such as Doppler shift, multipath, signal interference, noise.	Almost impervious to environmental effects such as Doppler shift, multipath, signal interference, noise. Or, effects are easily managed and/or corrected for.

Table 13: Metric Values - Multiplexing Scheme Selection

Metrics		**CDMA**	**TDMA**	**(O)FDMA**
Metric	**Weight**	**Score**	**Score**	**Score**
Complexity	0.2	2	1	1
Number of Users	0.2	2	1	3
Bit Error Rate	0.3	2	1	3
Navigation Environment Viability	0.3	3	2	1
Weighted Total	1	2.3	1.3	2.0

Table 14: Trade Study Results - Multiplexing Scheme Selection

Justification

- CDMA
  - *Complexity* - the complexity for CDMA lies in decoding the signal — a receiver with the same spreading code has to match the code phase exactly with the receive signal in order to properly decode the signal. Beyond the phase matching there isn't much additional complexity, and CDMA systems for ranging and timing are well documented because of its widespread use in Earth-based GPS systems.
  - *Number of Users* - the number of users of a CDMA signal is bound by the ratio of the spreading code bit rate to the data signal bit rate, called the spreading factor, and there can't be any more users on the system than this upper limit.
  - *BER* - the bit error rate for CDMA largely has to do with which kind of code is used to spread the signal. The best codes for this job are pseudo-random Gold Codes [26].
  - *NEV* - CDMA is widely used in Earth-based GPS systems because of its ability to provide utility in the presence of Doppler shift, multipath interference, and its low inter-signal interference due to CDMA codes typically looking like noise without the right code
- (O)FDMA
  - *Complexity* - Regular FDMA is typically easy to implement, but the bandwidth restriction means some sort of OFDMA must be implemented. The frequency control to get enough bands to make OFDMA viable in a narrow bandwidth increases the complexity significantly [17].
  - *Number of Users* - The number of users in an OFDMA system is quite high barring the complexity barrier, since a high number of closely spaced orthogonal frequencies can fit even in a narrow band, provided the channel environment allows for many closely spaced frequencies
  - *BER* - OFDMA is even more resistant to Gaussian white noise than CDMA [17], which means its bit error rate is quite low provided the channel environment allows for OFDMA to operate well
  - *NEV* - Unfortunately, the presence of a Doppler shift due to the high relative velocity between satellites and lunar surface users means that the tightly spaced frequencies required for OFDMA to work will be distorted
- TDMA
  - *Complexity* - TDMA is simple in concept, but synchronizing the sender and the receiver to the precise interval of the signal transitions requires very precise timing for this technique to be effective [16].
  - *Number of Users* - The number of users is highly limited by the data rate of each user and how precise the timing is between sender and receiver. Often times guard time intervals must be included in the signal to account for imprecise timing, which comes at the cost of the number of users [16].
  - *BER* - As mentioned, guard intervals must be included in the signal to account for any timing imprecision between sender and receiver. This is to account for the large problem of bit errors if the receiver time isn't precisely synchronized with the transmitter time.
  - *NEV* - Other than the precise time synchronization, TDMA signals don't suffer Doppler shift nearly as much as FDMA does.

5 Selection of Baseline Design

5.1 Antenna Design

Based on the scoring scale provided in tables of figure 5 the most adequate antenna for this project would indeed be the Fairview antenna. The antenna itself has high capabilities for performance, low cost, great compatibility and an effective cost when contrasted with the budget allowance. The antenna system will be most likely containing two antennas (two Fairview but one receiving at 400 MHz and another transmitting at 450 MHz) that will be connected to the Lime SDR.But, before a final decision is made, this will be questioned by the PAB Advisor and customer.

5.2 LimeSDR Software Packages

As can be seen in table 6, the software packages were filtered through four qualitative metrics: Complexity, documentation, limits, and availability. The GNU Radio software package met all the design requirements in regard to our project. These mainly included the scalability of the project, the operation of our project in general (i.e. transmitting/receiving signals to 170 users at 400 MHz and 450MHz with SMS-like capabilities), and the overall functionality and of each software package. Our baseline design will then include the laptop-limeSDR-GNU Radio system setup, in which a defined simulation/experimental environment can be used to perform the overall functionality of the design.

5.3 Communication Link

From the functional and design requirements and trade studies, the receive (downlink) signal architecture will be as follows:

- 450 MHz carrier frequency
- QPSK modulation scheme
- Gold Code PRN Asynchronous CDMA multiplexing (1.023 MHz chip rate)
- 1 MHz bandwidth
- 200 bps - 1 kbps data rate

The transmit (uplink) signal architecture will be as follows:

- 400 MHz carrier frequency
- QPSK modulation scheme
- Multiplexing:
  - Gold Code PRN Asynchronous CDMA multiplexing (1.023 MHz chip rate) for two way ranging
  - No multiplexing needed for one way ranging
- 1 MHz bandwidth
- 200bps - 1kbps data rate

As one-way vs. two-way ranging is a major design decision to be made by the customer affecting both handheld receiver and the satellite architecture as a whole, both options are being included in the handheld transmit design until further studies are done to decisively select one.

References

[1] LunaNet: Establishing a Flexible and Extensible Lunar Exploration Communication and Navigation Infrastructure : NASA Goddard Space Flight Center.

[2] D. J. Israel et al., "LunaNet: a Flexible and Extensible Lunar Exploration Communications and Navigation Infrastructure," 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 2020, pp. 1-14. doi: 10.1109/AERO47225.2020.9172509 URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=arnumber=9172509isnumber=9172248

[3] Jerry Colen, "NASA Selects Universities for Collaborative Development of Small Spacecraft Technologies." NASA Ames Features, Published on March 11th, 2020, https://www.nasa.gov/feature/ames/nasa-selects-universities-for-collaborative-development

[4] Brian Dunbar, "Moon's South Pole in NASA's Landing Sites" National Aeronautics and Space Administration, April 19, 2019, https://www.nasa.gov/feature/moon-s-south-pole-in-nasa-s-landing-sites

[5] Richard B. Langley (May 1999). "Dilution of Precision" (PDF). GPS World.

[6] Wolff, Christian. "Radar Accuracy." Radartutorials.eu, Christian Wolff, 2018, www.radartutorial.eu/01.basics/Radars%20Accuracy.en.html.

[7] "Tutorials." Tutorials - GNU Radio, 9 Sept. 2020, wiki.gnuradio.org/index.php/Tutorials.

[8] "Guided Tutorial Introduction." Guided Tutorial Introduction - GNU Radio, 2020, wiki.gnuradio.org/index.php/Guided_Tutorial_Introduction.

[9] "Guided Tutorial PSK Demodulation." Guided Tutorial PSK Demodulation - GNU Radio, 2020, wiki.gnuradio.org/index.php/Guided_Tutorial_PSK_Demodulation.

[10] "Gr-Limesdr Plugin for GNURadio." Myriad, Myriad RF, wiki.myriadrf.org/Gr-limesdr_Plugin_for_GNURadio.

[11] Noordhof, Jan. "How Does Modulation Work?" Tait Radio Academy, Tait Communications, 2020, www.taitradioacademy.com/topic/how-does-modulation-work-1-1/.

[12] Hsu, Eric. "Modulation Schemes for Satellite Communications." Keysight Blogs, Keysight Technologies, 2020, blogs.keysight.com/blogs/tech/rfmw.entry.html/2020/08/24/modulation_schemesf-6MpZ.html.

[13] NI. "Pulse-Shape Filtering in Communications Systems." NI, NI, 2020, www.ni.com/en-us/innovations/white-papers/06/pulse-shape-filtering-in-communications-systems.html.

[14] eValidate. "Binary Phase Shift Keying (BPSK) Modulation." EValidate, EValidate, www.evalidate.in/lab2/pages/BPSK-mod/BPSK/BPSK_I.html.

[15] Bharati, Subrato, et al. "Implementation of ASK, FSK and PSK with BER vs. SNR Comparison over AWGN Channel ." Arxiv.org, Cornell University, 2020, Implementation of ASK, FSK and PSK with BER vs. SNR comparison over AWGN channel .

[16] Editor, Author: Technical. "Advantages and Disadvantages and Applications of Time Division Multiplexing (TDM)." Polytechnic Hub, Polytechnic Hub, 16 Nov. 2017, www.polytechnichub.com/advantages-disadvantages-applications-time-division-multiplexing-tdm/.

[17] "OFDM vs CDMA | Difference between OFDM and CDMA." RF Wireless World, RF Wireless World, 2012, www.rfwireless-world.com/Articles/OFDM-vs-CDMA.html.

[18] Rashed, Ahmed Nabih, and Mohammed Salah Tabbour. "The Trade Off Between Different Modulation Schemes for Maximum Long Reach High Data Transmission Capacity Optical Orthogonal Frequency Division Multiplexing (OOFDM)." Researchgate, Researchgate, May 2018, The Trade Off Between Different Modulation Schemes for Maximum Long Reach High Data Transmission Capacity Optical Orthogonal Frequency Division Multiplexing (OOFDM).

[19] Laaraiedh, Mohamed, et al. “Cramer–Rao Lower Bounds for Nonhybrid and Hybrid Localisation Techniques in Wireless Networks.” Researchgate, EUROPEAN TRANSACTIONS ON TELECOMMUNICATIONS, 2011, www.researchgate.net/publication/235936422_Cramer–Rao_lower_bounds_for_nonhybrid_and_hybrid_localisation_techniques_in_wireless_networks/link/5bfbba00a6fdcc53881ad9

[20] Alexandru Csete OZ9AEC. Welcome to Gqrx, gqrx.dk.

[21] Alexandru Csete OZ9AEC. “Supported Devices.” Qqrx SDR, gqrx.dk/supported-hardware.

[22] Alexandru Csete OZ9AEC. “Gqrx Design.” Gqrx SDR, gqrx.dk/doc/gqrx-design.

[23] MyriadRF. LimeSuiteGUI, wiki.myriadrf.org/LimeSuiteGUI.

[24] MyriadRF. Lime Suite. wiki.myriadrf.org/Lime_Suite.

[25] Myriad. “Getting Started with LimeSDR-USB and LimeSuiteGUI.” Myriad, wiki.myriadrf.org/Getting_Started_with_LimeSDR-USB_and_LimeSuiteGUI.

[26] Carey, Daniel, et al. “STATISTICAL MODELING OF BIT-ERROR-RATES IN ASYNCHRONOUS MULTICARRIER CDMA AND DIRECT-SEQUENCE CDMA SYSTEMS.” Eurasip.org, EURASIP, www.eurasip.org/Proceedings/Eusipco/Eusipco2004/defevent/papers/cr1525.pdf.