COMMUNICATIONS SUBSECTION FOR THE CUBESAT 'SPIRIT'

by

Daniel Rea

Rajja Singh

Zhengxing Liu

Jiayang Song

(advisor: Dr. Jayshri Sabarinathan)

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Final Report

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Abstract

This was the first of a three-year program intended to design the Communication Subsystem for a 2U CubeSat. With emphasis on background research and modulation scheme trade-off studies, this team was able build a Link Budget using S band frequencies and select components for future year students. Additionally, practical experience in wireless communication was obtained via preliminary prototyping and testing. This prototype validates aspects of the design of a 2U CubeSat.

Contribution of the Team Members

Zhengxing Liu:

Antenna concept generation

Different types of antennas were proposed, which includes using a single patch antenna or antenna arrays with four dipole antennas.

Antenna models and radiation pattern models in MATLAB

Antenna models were built for each of the proposed antenna concepts. Based on the models, 3D radiation patterns were simulated using Antenna Toolbox in MATLAB.

Concept selection, trade-off study and risk assessment

Radiation patterns, mission objectives and requirements were used to evaluate the antennas. Risk assessment was conducted for the selected patch antenna.

CubeSat antenna and ground station antenna selection

Commercial off-the-shelf models were selected for purchase. The selection process was based on mission requirements including assigned frequency range and desired data rate.

Jiayang Song:

Link budget modelling

Link budget calculation has different components including transmitter side, receiver side, communication channel, antenna effect and modulation scheme.

Data size and data rate evaluation

Based on the data recorded by the camera on CubeSat. A desired data rate was calculated based on a required downloading time duration.

Typical receiver system modelling and system thermal noise calculation

A sample receiver framework was established to evaluate the effect system thermal noise in the entire data link. A general noise temperature was computed and used in the power and data rate calculation.

Selected CubeSat antenna and ground station antenna evaluation

Based on the specifications of selected antenna, the power and antenna gain parameters had been defined. A communication channel was built, and the channel capacity satisfied the time requirements of downloading. An excel table was created to show the entire calculation process dynamically.

Rajja Singh

Problem Statement

Defined the problem statement.

Project Objectives

Defined project objectives and compiled project constraints through discussions with the electrical power and structural teams.

Data Rate Calculation

Found a preliminary data rate to see how much of the data recorded on the CubeSat could be transferred using S Band frequencies during the transfer window.

CubeSat Antenna Selection

Based on project objectives and constraints, an off the shelf transceiver was selected after comparing several transmitters, receivers, and transceivers.

Daniel Rea

Detailed Literature Review

Read up on benefits to S-Band communication, and required components for a CubeSat communication system. Read up on the key considerations of any CubeSat communication subsystem including spectral and power efficiency.

Performed modulation Trade-off Study

read up on performance of low, moderate and high order modulation schemes, and compared their performance in terms of power and spectral efficiency. Analysed Bit error curves to rule out most schemes.

Modeled Basic modulation schemes in MATLABmodulation schemes of BPSK and PAM were coded and bit error curves were plotted to produce results equivalent to theoretical. Gained hands on experience in altering power in a signal to observe its effect on constellation diagram

Transceiver concept generation

Considered multiple transceiver options. Systematically determined best option based on other subsystem limitations, and project objective. Careful consideration on central operating frequency and modulation scheme was taken for link budget calculations.

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1. Introduction/Background

1.1 Problem Statement

The CubeSat project at Western University aims to help Western Engineering students gain valuable experience in the space domain, working alongside experts in the field including personnel from the Canadian Space Agency to develop a CubeSat. The intended purpose of the CubeSat is to send pictures and 360^0 immersive videos to the ground station. The main objective of the Spirit Communication team is to develop a system that uses S-Band frequencies to allow communication between the CubeSat and the ground station.

1.2 Detailed Literature Review

1.2.1 Reasons for Using S-Band

Since 2003, there has been a drastic increase in the popularity of CubeSats, as they provide university students with attainable project experience to enter the space sector. Currently, 2140 picosatellites have been launched, and it is speculated that 3000 more will be launched in the next 6 years [1]. With so many CubeSats in orbit, the amateur radio frequencies (100-500 MHz range) where most of these CubeSats operate is becoming cluttered. A predominant solution to this problem is in using the less cluttered higher frequency bands such as S-Band, C-Band, or K-Band [1]. The size of the ground antenna used to radiate the signal to free space is proportional to its signal wavelength given by equation 1:

$$\lambda = c/f$$

c=speed of light ($3x10^8$ m/s)

f=frequency of transmitted signal.

This means that using higher frequencies also reduces the size of the ground station antenna [2]. Another option for operating frequency would be in the UHF band. UHF uses less power than S-Band and requires less bandwidth, but it also has a slower data rate. Since 'Spirit' CubeSat can handle the S-Band power requirements it will operate in S-Band (2-4Ghz) in order to maximize the data rate.

1.2.2 Required Components for a Successful Communication system

After review of numerous launched CubeSats in [3], it was determined that any successful communication subsystems contain 4 components. These are namely transmitting antenna, receiving antenna, and two transceivers aboard the CubeSat and ground station. Building a transceiver from scratch is ill advised for beginner CubeSat programs since RF board design is difficult and margin for error is great [4]. It is thus recommended that Spirit use commercial off the shelf components for antennas and transceiver [4]. Component selection for an efficient communication system will rely on careful consideration of key restricting factors.

1.2.3 Key Restrictions Overview

When it comes to any wireless communication systems, there are two main restrictions that a designer must prioritize: Power Efficiency and Spectral efficiency [2]. For CubeSat specific design, there are many more secondary restrictions related to other subsystems. Power and Spectral efficiency will be discussed below, while the rest will be presented in Project Objectives.

" Power efficiency relates to the ability to transmit data with a given bit/symbol error probability at a minimum received power level. The received power is usually measured in terms of the Signal to Noise Ratio (SNR), which is ratio of the received energy per bit (Eb) and the noise power spectral density (No). SNR is usually expressed as Eb/N" [5] In a CubeSat, the transceiver is the component that consumes the most DC power [2]. This implies that the power efficiency of the entire CubeSat depends heavily on proper transceiver selection. Basic Energy Efficiency of a transceiver can be defined as its power efficiency over a time period T; given by equation 2:

$$EE = \frac{T * f(SNR)}{T * (\frac{1}{\eta} * P_{OUT} + P_D)}$$

P_{OUT}=output power of power amplifier
P_D=dissipated heat power of transceiver
$\frac{1}{\eta}$=power amplifier efficiency

Energy efficiency can be maximized by either increasing the numerator or decreasing the denominator. Increase of the numerator implies an increase in transmission rate, which involves the entire system including a transceiver, antennas and channel condition [3]. It follows that a proper modulation scheme aboard the transceiver must be selected to optimize SNR and thus transmission rate.

Spectral [or 'Bandwidth] efficiency refers to rate of maximum information being transmitted over a given bandwidth in a specific communication system [2], and is given by equation 3:

$$\eta_s = \frac{R}{B_w}(\text{bit/s/Hz})$$

R=transmission rate (bit/s)

B_w=transmission bandwidth.

Transmission bandwidth (B_w) will be provided by the Canadian Space Agency (CSA). Thus, transmission rate R must be maximized in order to optimize spectral efficiency. Data transfer is directly proportional to power supplied, but on a 2U CubeSat, power is extremely limited. It follows that one of the most appropriate ways for maximizing the data rate of a CubeSat is to use efficient modulation schemes [3].

In conclusion proper modulation and coding contributes heavily to the power efficiency and spectral efficiency of the transceiver. Regardless of whether a designer chooses to value one over the other, it is important to realize that there is always a tradeoff between the two [5]. For example, Error correction coding typically increases power efficiency of transmission at the cost of bandwidth efficiency. a trade-off study of different modulation techniques as well as different antenna configurations to follow in the concept generation and evaluation portion of this report.

1.3 Project Objectives

The objective for the CubeSat project is to design and do preliminary prototyping for a 2U CubeSat operating in the S Band. The CubeSat will store virtual reality images and videos of the Earth. The communication subsystem's main objective is to transmit as much of the data stored onboard the CubeSat to the ground station. To accomplish this goal, we will need to coordinate with the ground station team. We will need to design the antenna and transceiver circuit on the CubeSat that will use a 2-2.4GHz frequency to transmit and receive data from the satellite to the ground station. The modulation scheme and encoding technique that is used for data transmission from the CubeSat will need to be coordinated with the onboard computer and ground station teams to make sure they can receive and read the data that we will transmit from the CubeSat.

With minimal resources and space available on the CubeSat there were several constraints that had to be met. The antenna mass was limited to 100g and the transceiver mass was to be kept below 200g to make sure that the center of gravity was maintained while keeping the total mass of the CubeSat below 3.6kg. The power consumption was limited to 6W for transmission mode and 1W for standby mode.

The CubeSat communication system is composed primarily of the telemetry and command systems, which send and receive data, respectively. Analog and digital data collected by the sensors and payload of the satellite must be relayed to the ground station via the telemetry system, which is composed of a transmitter that acts much like a "modem in a computer". The transmitter then sends the signal to the ground station through the satellite's antenna. A radio operating in the S-band at the ground station will receive the data signal and encode the stream to a form that may be interpreted by software on a laptop.

2. Design Approach

2.1 Concept Generation

2.1.1 Antenna

To generate and select antenna options, a list of requirements is made to highlight the desired features and constraints of the antenna.

1. Antenna must operate in the S-band frequency range of 2.2 - 2.5GHz
2. Antenna shall provide enough gain to achieve a desired data rate of 389 kbps
3. Antenna may be deployable, but it must fit within PPOD for launch
4. Antenna shall avoid obstructing the view from the camera if possible

After reviewing the requirements, the patch antenna and dipole antenna are chosen for further evaluation. These two designs are the most commonly used antennas for satellite communication. They will be evaluated based on their gain, directivity, their mounting mechanism and placement.

Option 1. Patch antenna

The Patch Antenna is a flat sheet of metal that would be mounted on the surface of CubeSat. It is more directional thus it needs to be facing towards the earth for transmission. It requires active pointing mechanism, so it puts more demand on the attitude control subsystem. By sacrificing the beam width coverage, the patch antenna has a higher antenna gain. More power can be transmitted, hence more data can be downloaded. The patch antenna also needs to be mounted on the entire z-plane, which forces the cameras be to be placed on the sides. It results an obstruction in the view of the camera, then the desired 360° view of space is unachievable.

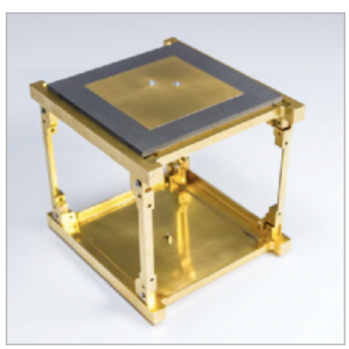


Figure 2.1.1 Patch Antenna Structure

figure 1 Patch Antenna Structure

Option 2. Dipole antenna

The dipole antenna is simply a piece of conducting wire. In this case, there will be four dipole antennas forming an antenna array. Dipole antenna is a simpler antenna, so it would be easier to model and implement. Its radiation pattern is toroidal in shape and omni-directional in the azimuth plane. Due to its broader coverage, only passive attitude control is needed. The CubeSat would be tumbling freely in space, yet the antenna can still transmit to ground station. However, it also means the dipole antenna has less gain, less data can be transmitted. Since the dipole antenna can be mounted on the rails, it makes room for the cameras to be mounted on the z-planes, shooting the full unobstructed 360° view.

Figure 2.1.2 Dipole Antenna Structure

figure 2 Dipole Antenna Structure

2.1.2 Transceiver

When it came to concept generation for transceiver options, the following requirements were considered:

1. Transceiver must send and receive data in the s-band frequency range
2. Transceiver must be less than 200g and consume less than 6 watts in transmitting mode
3. Data rate of board shall be maximized while maintaining all other requirements
4. A proper modulation scheme shall be selected to place even focus on power and spectral efficiency

Since an off the shelf transceiver will be purchased, complete control over which modulation scheme is limited to what scheme the transceiver carries. However, a trade-off study between different modulation techniques will provide the designer with a range of acceptable techniques in a transceiver that would suit project objectives.

2.1.3 Modulation Scheme Trade-Off Study

Different modulation schemes place focus on one of the two key restrictions of power efficiency and spectral efficiency. For example, higher order modulation schemes pack the transmitting signal with more bits per symbol, allowing for higher data rates [7]. However, this implies that more power must be used to send error free data. Alternatively, a spectrally inefficient modulation scheme combined with error correction coding could maintain the same throughout as mentioned before but would require more bandwidth [7]. The figure below shows the bit error rate (BER) performance of different order modulation schemes at varying normalized SNR levels.

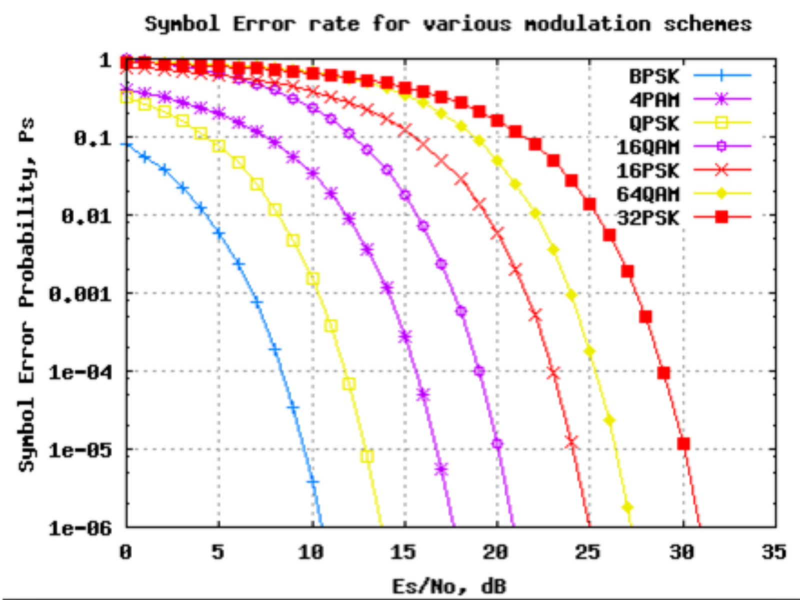


Figure 3: Symbol Error rate for various Modulation Schemes

As expected, 64QAM relative to 16QAM requires more power, but will make efficient use of allotted bandwidth due to more tightly packed symbols. Higher order techniques such as 8-QAM, 16 QAM and 32-QAM provide higher SNR and thus, more throughput. However, these techniques require greater size and more power. Considering that the Electrical Power Subsystem provide a maximum of 6 watts, all modulation orders of 16 or higher are deemed unacceptable due to unattainable power requirements.

As per [8], two previous CubeSats used 2-FSK as their modulation scheme since their mission only required transmitting telemetry data. For Spirits case, a VR camera taking high resolution video will add immensely to required transmitted data on top of the telemetry. For this reason, all binary modulation schemes are deemed unacceptable due to low throughput.

In conclusion, A modulation scheme with a moderate number of constellation points is required. This will ensure that the communication subsystem has a high enough data rate while remaining within the bandwidth and power limitations. Schemes for consideration were OPSK, OQPSK, MSK and GMSK due to their superior performance in terms of BER and relatively equal emphasis on bandwidth and power efficiency.

2.2 Concept Evaluation and Selection

2.2.1 Antenna Evaluation

The antennas are modelled in MATLAB using the antenna toolbox, the follow graphs illustrate the antenna radiation patterns.

Option 1. Patch Antenna

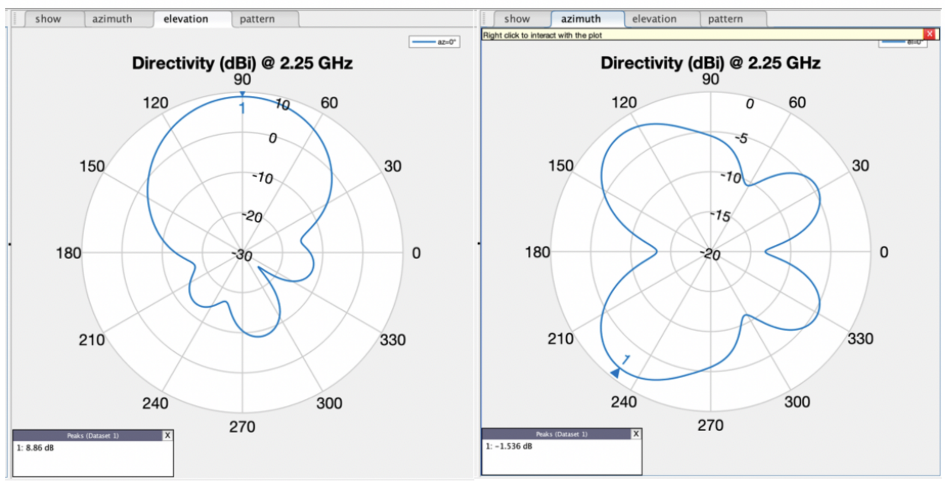


Figure 2.2.1 Patch elevation radiation pattern *Figure 2.2.2 Patch azimuth radiation pattern*

figure 4: Patch Radiation Pattern

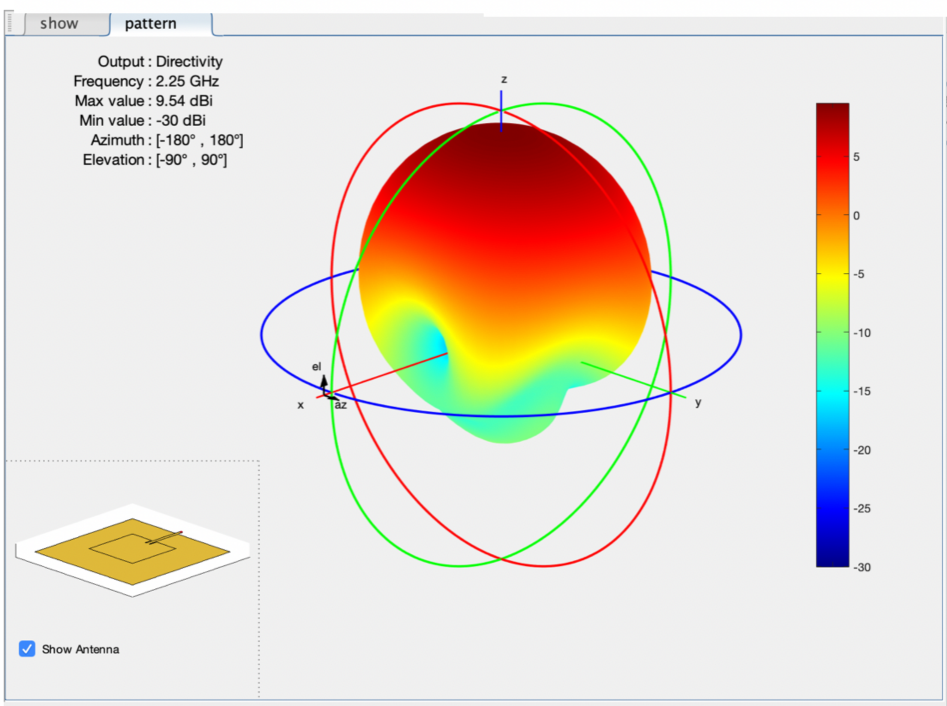


Figure 2.2.3 Patch Radiation Pattern in 3D

figure 5: Patch Radiation Pattern 3D

Option 2. Dipole Antenna

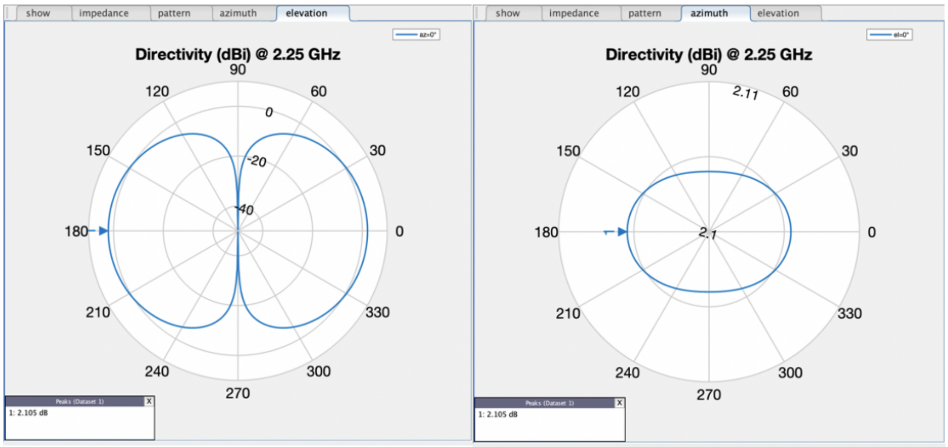


Figure 2.2.4 dipole elevation radiation pattern *Figure 2.2.5 dipole azimuth radiation pattern*

figure 6: Dipole Radiation Patterns

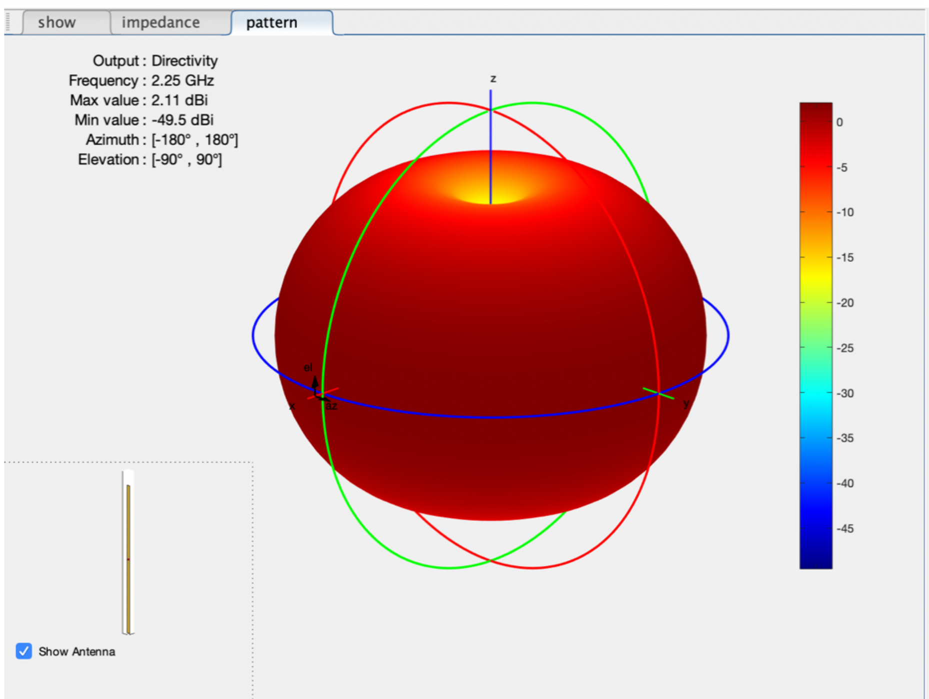


Figure 2.2.6 dipole radiation pattern in 3D

figure 7: Dipole radiation Pattern in 3D

Graphically, the patch antenna is more directive than dipole antenna. In the elevation plane, the radiation pattern of the patch antenna creates a distinct separation between the main lobe and side lobes. The antenna steers upwards towards the z-plane with a beam width of 59˚.

Because it is more directed to one point, the patch antenna can reach a high maximum gain at 9.53dBi.

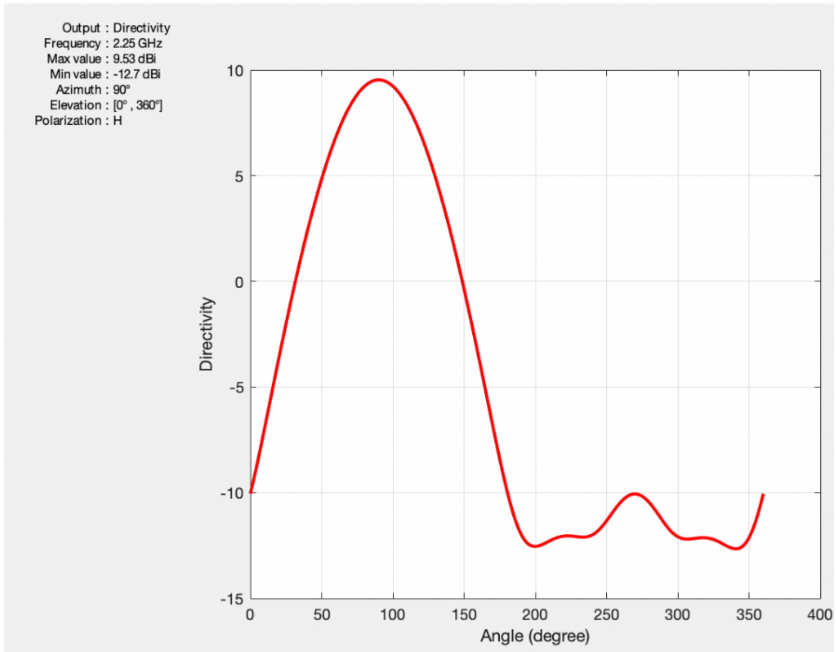


Figure 2.2.7 directivity of patch antenna

figure 8: Directivity of Patch Antenna

For the dipole antenna, the radiation is appearing more like a sphere radiating outwards, it's omni-direction in azimuth plane and toroidal in elevation plane. The beam width of the dipole antenna is 80˚. With less directivity, the maximum gain of dipole antenna can only reach 2.11 dBi.

Since we are designing the transmission link in S-band, the main objective is to achieve a faster data rate at the 2.4GHz frequency rather than the traditional UHF frequency band; therefore, patch antenna is the better option.

2.2.2 Transceiver Evaluation

Given the design choice that minimum number of boards is used for each subsystem, a single transceiver is required to provide both transmitting and receiving abilities. However, many manufacturers only supply transmitters instead of transceivers for S-Band operation. It results very limited options for off-the-self S-Band CubeSat transceiver. The following chart lists the transceiver models that have been viewed for selection.

The preliminary power budget given from the power subsystem is 5 to 7W, with this restricted amount of power, it eliminates options for using high-power high-performance models.

The selected transceiver is the SRS-3 full-duplex low-power s-band transceiver made by Satlab. Although it only supports a maximum transmission rate of 512kpbs, it consumes significantly lower power. It operated in the s-band frequency range 2.2 – 2.32 GHz, and it has integrated transmit and receive filter, low noise amplifier (LNA) and power amplifier.

brand	data rate (kbps)		transmitted power	supply power (V)	power consumption		frequency (GHz)	mass (g)		
	Tx	Tx			Rx	Tx				
Endurosat	20000		2W	5,12	9		2.2-2.29		transmitter	https://www.endurosat.com/products/cubesat-s-band-transmitter/
Nano Avionics	100 - 500	100	20 to 30 dBm	5-40	0.65	6.5 (tx+rx)	2.2-2.30	191	transceiver	https://n-avionics.com/subsystems/s-band-transceiver/
Satlab	128 - 512	128	20 to 30 dBm	5-41	0.65	5	2.2-2.31	190	transceiver	https://www.satlab.com/resources/SLDS-SRS3-1.1.pdf
IQ Wireless	600-40000		27 dBm	7 - 18W	3-4.5	8 - 12 W	2.2-2.32	420	transceiver	http://www.iq-wireless.com/images/pdf/SLINK-Datasheet.pdf
ISIS	3400		27-33 dBm	6-20V	2	9	2.2-2.30	<300	transmitter	https://www.isispace.nl/product/isis-txs-s-band-transmitter/

Figure 1 Satlab SRS-3 transceiver

3. Design Analysis

3.1 Engineering Techniques/Software tools

3.1.1 MATLAB Antenna Toolbox

The antenna toolbox is an add-on module in MATLAB which provides simulations and analysis for designing antennas. It computes properties such as impedance, charge distribution and field properties for antenna design. It also provides 3D visualization for the radiation patterns and antenna geometries.

For the purpose of our CubeSat Design, the antenna toolbox is used to determine the radiation pattern for various types of antennas. Models of the antennas are built in the module to generate the 2D (azimuth and elevation) and 3D figures of the radiation patterns. Visual figures help to analyze the antenna gain, beam width and directivity, which are used to evaluation antenna design options. Detailed analysis created by the antenna toolbox is listed in section 2.2.

3.1.2 Excel

Excel is the main software used for link budget calculation. The data rate calculation is divided into seven sections: data rate, modulation specification, modulation scheme comparison, Noise temperature, receiver antenna, transmitter antenna and beamwidth. Some of the data in the excel are constants or given from the device specifications, and the rest of them are computed by equations. The modulation scheme part shows the difference between various digital modulation schemes and we pick the best out of them. The noise temperature part applies a common model for the receiver system and calculated the theoretical system thermal noise temperature. This parameter is important in the later section to compute the signal noise ratio (SNR). The coefficients in receiver and transmitter sections are derived from datasheets of hardware. Combing the sections above we can get the theoretical data rate which is supported by the antennas and communication channel.

3.2 Complete Analysis/Calculations

3.2.1 Link Budget Design

The goal of this part is to establish a direct telemetry link between the Cube satellite and the ground station. The camera on Cube satellite continuously records data with a constant data rate. The desired communication link is designed to download the data in a specific time duration. The antenna on the satellite is responsible for being able to send recorded videos to the ground station with limited power and a frequency. All parameters related to link establishment will be considered and discussed with calculation and explanation.

A satellite communication network consists of some earth stations interconnected via a satellite. The radio links used for interconnections are designed to deliver messages at the destination with acceptable fidelity. A compromise is exercised between the quality and quantity of delivered messages and practical constraints such as economics and the state of technology. To deliver a large amount of information at a very high quality may require an unacceptably high cost. Factors which need consideration in a link design include operational frequency, propagation effects, acceptable spacecraft/ground terminal complexity (hence cost), effects of noise and regulatory requirements. An appropriate transceiver should be selected which can provide a sufficient data transmission rate in the required frequency. The transceiver should also be able to support serval modulation schemes we need to do a comparing test. Thus, the best modulation scheme can be chosen with enough data rate and good noise immunity. In this project, we are focusing on the downlink and uplink communications from the Cube satellite to the Earth ground station and vice versa.

3.2.2 Design requirements

The link should directly communicate the Earth ground station and the Cube satellite with no relay station. The antenna on the satellite has low power consumption, and the antenna type should be High Gain Antenna (HGA). The antenna on the satellite is directly pointing towards the Earth during this communication, and it is designed to be a patch antenna. The satellite antenna beamwidth can adequately cover the entire earth surface from the CubeSat.

The link frequency should be 2 to 4 GHz which is in S-band. The data recording rata of the camera is 27M bits per picture with a refresh rate of 30 FPS and recorded data can be downloaded once a path with 558 secs duration. The satellite can orbit the earth 16 times per day. To ensure safety and accurate data link the desired bit-error-rate is 10^{-5} which is the common BER requirement for video transmissions.

A proper modulation scheme should be selected and explained. This design should include the specifications and calculations for SNR per bit ($\frac{Eb}{No}$), power transmitted (P_t), Antenna sizes (diameter, aperture areas,), beamwidth (B), gain of antenna on transmitter (Gt), gain of antenna on receiver (Gr) , Thermal Noise (T), frequency (f), Capacity of link (C), SNR and data rates (R).

A 10-20% margin is expected for this design to secure the data transmission. The margin rate can be used for data retransmission. All used design parameters should be followed with justifications or sources. A trade-ff analysis between bandwidth and bit rate should be established and discussed to find the best bit rate with acceptable bandwidth occupation. Continued improvements to the Link Budget tools are needed to increase the accuracy of the calculated Link Margins for downlink and uplink. Currently, there is no detailed receiver system structure from ground station team, thus, a general receiver system is used in this report to provide a commonly-used noise temperature for noise power calculation.

3.2.3 Down link data rate requirements

From the design requirement, the communication link is preferred to download a 30 seconds video recorded by the camera in 7 days.

So, the total data size of this 30 seconds (D_{total}) is:

$$D_{total} = \text{data per picture} * \text{refresh rate} * \text{recording time}$$
$$= 27\text{M bits} * 30 \text{ fps} * 30 \text{ seconds}$$
$$= 24.3\text{G bits}$$

The total downloading time ($T_{download}$):

$$T_{download} = \text{days} * \text{orbits per day} * \text{downloading time per orbit}$$
$$= 7 * 16 * 558 \text{ seconds}$$
$$= 62.496\text{K seconds}$$

Thus, the desired data rate ($R_{desired}$) is:

$$R_{desired} = \frac{D_{total}}{T_{total}} = \frac{24.3G\ bits}{62.496K\ seconds} = 389\text{K bits/second}$$

So, 389K bits/seconds is the minimum data rate needed to download a 30 seconds video within seven days with no error happens. The next step is calculating the maximum data rate that is supported by the selected antenna and transceiver.

With a 10% margin for weather effect and data retransmission, the designed data rate ($R_{designed}$) becomes:

$$R_{designed} = R_{desired} * (1+\text{margin}) = 389\text{K} * (1+0.1)$$
$$= 428\text{K bits/second}$$

3.2.4 Modulation Scheme Selection

There are various digital modulation schemes we can select, but different modulation schemes have different BER/SNR ration and various bandwidth efficiency. The transmitting bandwidth can be calculated from the formula:

$$\text{Bandwidth} = \frac{Bit\ Rate}{Bandwidth\ Efficiency} \qquad (1)$$

Where bit rate is the parameter we want, and Bandwidth efficiency depends on the modulation scheme we choose.

Since Bit-Error-Rate (BER) is directly related with SNR per bit (Eb/No), so we need to find a proper modulation scheme with higher Eb/No to achieve better SNR. From the requirements, the BER is desired to be 10^{-5}. So, from the BER versus Eb/No plot below:

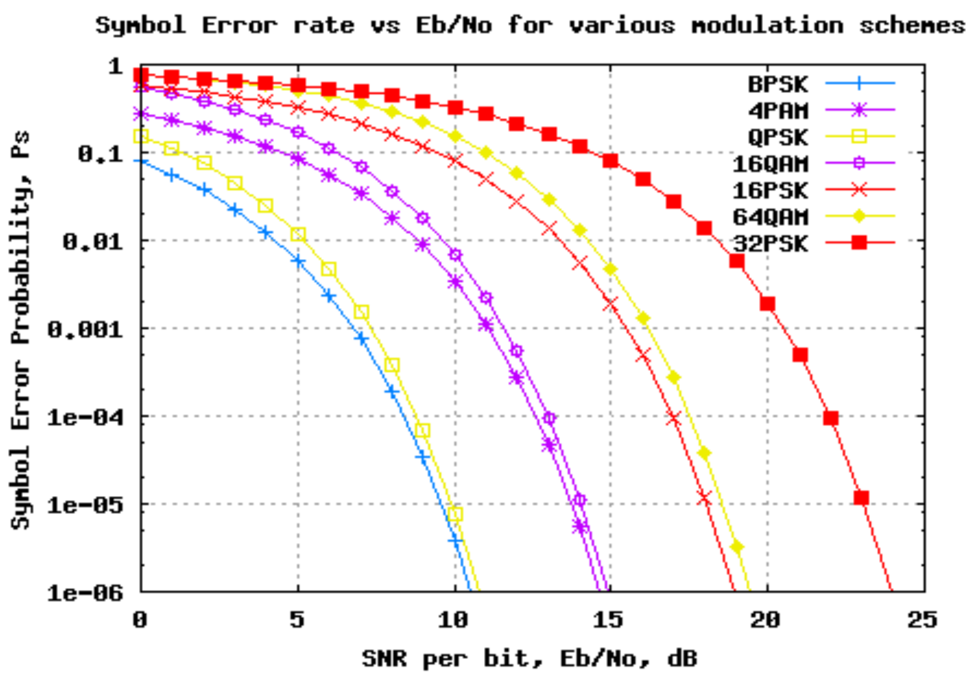


figure 9 BER-Eb/No plot

With fixed BER value, a higher order modulation has higher Eb/No.

Since SNR is not only related to Eb/No, from the formula of SNR:

$$\text{SNR} = \frac{Eb}{No}\frac{R}{B} = \frac{P_{re}}{N_{sys}}$$

Where R is the bit rate, and B is bandwidth. From equation (1) above, we know that bandwidth efficiency:

$$\text{Bandwidth efficiency} = \frac{R}{B}$$

So, equation (2) converts to:

$$\text{SNR} = \frac{Eb}{No} * Bandwidth\ effiency$$

SNR only depends on two parameters: SNR per bit ($\frac{Eb}{No}$) and Bandwidth efficiency.

From the following table:

Table 1: Modulation Schemes

Digital Modulation Scheme	Symbol Time (second)	Bit Rate (bits/s)	Bandwidth (Hz)	Modulation efficiency (bits/second/Hz)	E_b/N_0 (dB) (At BER = 10^{-5})	Eb/N0 (mag) (At BER = 10^{-5})
	T	1/(C*T)	1/T	C	From grath and table	dB to magnitude
BPSK	1.95E-06	5.12E+05	5.12E+05	1	9.5	8.912509381
QPSK	1.95E-06	1.02E+06	5.12E+05	2	9.8	9.54992586
4-QAM	1.95E-06	1.02E+06	5.12E+05	2	9.8	9.54992586
4-PAM	1.95E-06	1.02E+06	5.12E+05	2	13.7	23.44228815
16-QAM	1.95E-06	2.05E+06	5.12E+05	4	14	25.11886432
16-PSK	1.95E-06	2.05E+06	5.12E+05	4	18	63.09573445
32-PSK	1.95E-06	2.56E+06	5.12E+05	5	23.1	204.1737945
64-QAM	1.95E-06	3.07E+06	5.12E+05	6	18.5	70.79457844
GMSK(BT=0.3)	1.95E-06	6.91E+05	5.12E+05	1.35	10	10
GMSK(BT=0.35)	1.95E-06	5.12E+05	5.12E+05	1	10	10

We can find that a higher modulation(bandwidth) efficiency is provided with a higher order modulation scheme, which means we can have a better data rate with the same bandwidth. However, from figure 1, a high order modulation scheme also has a bigger BER with the same SNR per bit ($\frac{Eb}{No}$). So, in general case, we need to consider the error bit probability problem.

In this design, BER is set to be 10^{-5}. So, we are only concerned with the bandwidth efficiency and power consumption.

Since the distance of this communication is exceptionally long. So, all amplitude-based modulation schemes are not workable. Since, after the long-distance transmitting. The amplitude values cannot be guaranteed to be as accurate as the beginning, and the noise in the communication channel can easily distort the amplitude of the signal. So, AM, PAM, QAM are not recommended here.

For the power usage side, 16/32 PSK require more power than BPSK and QPSK, but the rover antenna is a low power consumption antenna. Thus, BPSK and QPSK are the remaining options for us. In the same conditions, GMSK has more modulation efficiency than BPSK and better $\frac{Eb}{No}$ as well. GMSK also has a simple system, and it is commonly used in low speed communication which perfectly fits our requirements.

Table 2 Modulation Scheme GMSK

Modulation Scheme GMSK (BT = 0.35)						
GMSK BT product	BT	N/A	0.35	Hz/s	N/A	From transceiver datasheet
Normalized power spectral density	NPSD	N/A	1	N/A	0	From transceiver datasheet
Bandwidth	B	B = NPSD*R	5.12E+05	Hz	N/A	From modulation table
SNR per bit	E_b/N_0	N/A	10	N/A	10	From modulation table
Calculated SNR	SNR_{sys}	$SNR = P_{re}/N_{sys}$	161.08	N/A	22.07	Calculated
Required SNR	$SNR_{required}$	$SNR = E_b/N_o*R/B$	10.00	N/A	10.00	Required SNR
SNR margin	$Margin_{SNR}$	$SNR_{sys} / SNR_{required}$	16.11	N/A	12.07	Good design, margin>3

3.3.5 Bandwidth Calculation

The selected transceiver is the SRS-3 full-duplex low-power S-band transceiver made by Satlab. Although it only supports a maximum transmission rate of 512kpbs, it consumes significantly lower power. It operated in the S-band frequency range of 2.2 – 2.32 GHz, and it has integrated transmit and receive filter, low noise amplifier (LNA) and power amplimer.

Since GMSK is the only one modulation scheme supported by the transceiver, the bandwidth of GMSK is determined by the bandwidth-Time (BT) product of the gaussian filter. The BT product is the bandwidth-symbol time product where B is the −3 dB(half-power) bandwidth of the pulse/filter and T is the symbol duration. So, the -3 dB bandwidth is calculated by:

$$BT = 0.35,\ T = \frac{1}{Bit\ rate},\ \text{Bit rate} = 512\ \text{kbps}$$

Thus the -3 dB bandwidth is: B_{-3dB} = 0.35*Bit rate = 179 kHz.

However, the bandwidth we calculated above is -3 dB bandwidth, the practical occupied bandwidth normally would be the 99% power interval. To find the 99% power interval, we need the parameter Normalized power spectral density (NPSD).

From the equation:

Occupied bandwidth (B) = NPSD * Bit rate (R)

From the datasheet of the transceiver, the normalized output power spectrum is shown with BT=0.35 Gaussian filter and 3 different output power levels. Measured using a PRBS9 sequence transmitted at 2245 MHz using 512 kbps channel rate.

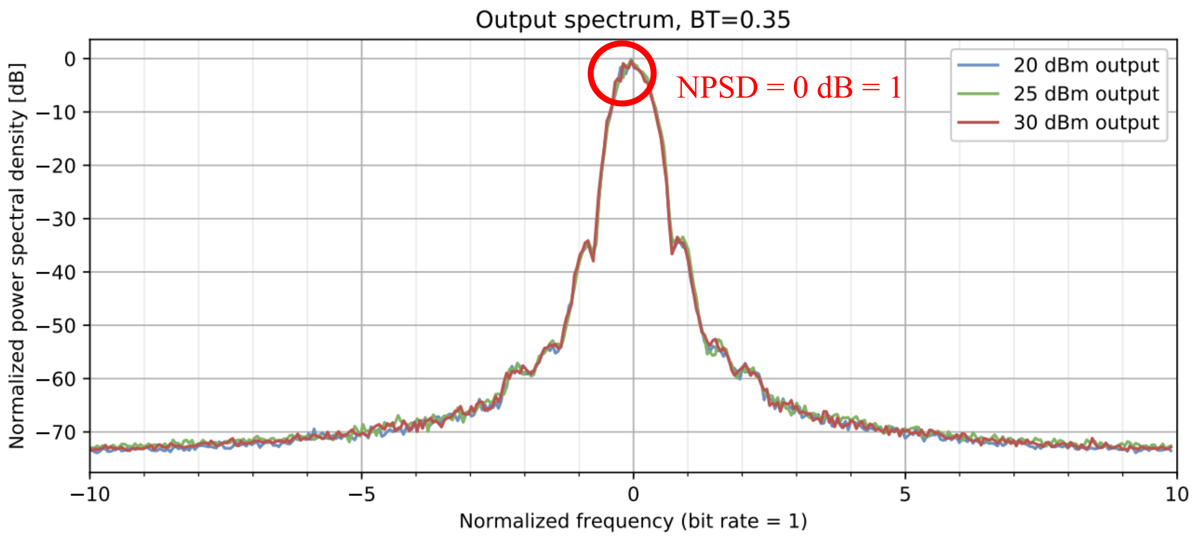


figure 10: Transceiver Output Spectrum

In the figure above, we can see with different power outputs the, the NPSD maintains a same curve. At the normalized frequency, NPSD is 1.

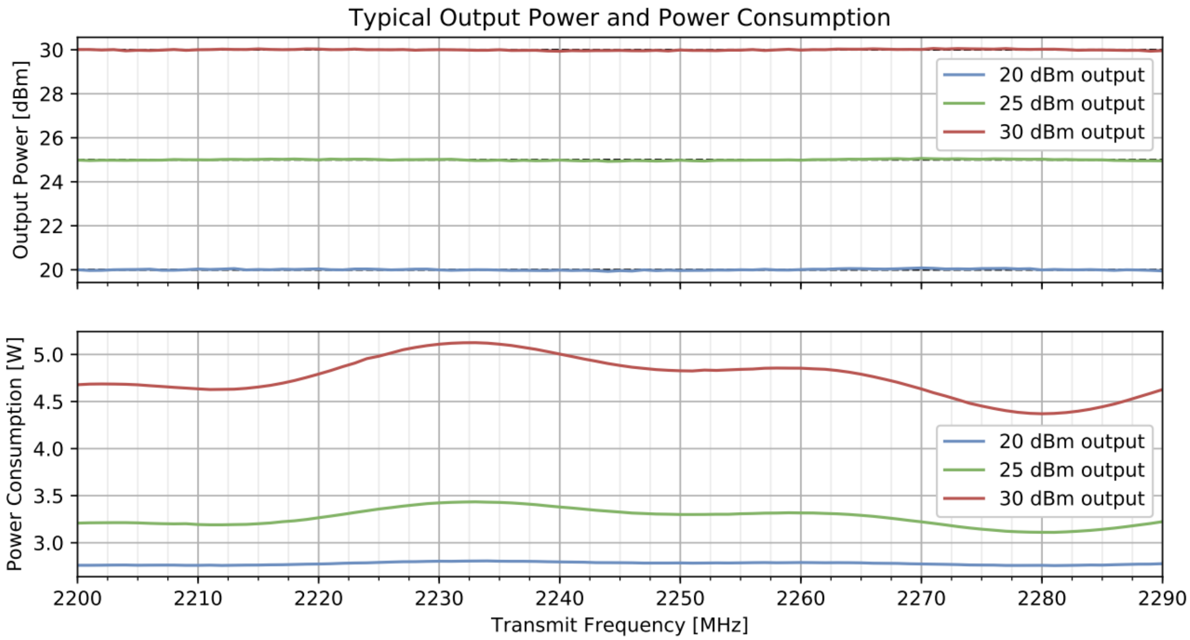


figure 11: Transceiver Output Power and Power Consumption

Since the frequency we are working on is 2.2 GHz, the power output behaves a straight line, so it is independent with a varying operating frequency.

Parameter	**Min**	**Typ**	**Max**	**Unit**
Center frequency	2200	–	2290	MHz
Center frequency resolution	–	20	–	Hz
Bit rate	128	512	512	kbps
GMSK BT product	–	0.35	–	–
Output power	20	–	30	dBm
Output power adjust resolution	–	–	0.1	dB
Occupied bandwidth (99%, normalized freq.)	–	1.0	–	–
SFDR	60	–	–	dBc
Output harmonics	60	–	–	dBc
Adjacent Channel Power (CH BW = 512 kHz, CH Spacing = 750 kHz)	–	-44	–	dB
RF Power sensor directivity	11	18	–	dB
ALC loop resolution (20 to 30 dBm output power)	–	–	0.1	dB
Initial frequency error (20 ℃)	–	–	0.5	ppm
Frequency error (over temperature)	–	1.0	2.5	ppm
Frequency error (aging per year)	–	–	1.0	ppm
Frequency error (20 kRad(Si) board level)	–	1.0	–	ppm
PA protection threshold (reflected power)	–	25	–	dBm

Overall, the occupied bandwidth is computed as:

Occupied bandwidth (B) = NPSD * Bit rate (R) = 1*512k = 512 kHz

Since the bit rate can vary from 128k to 512 kbps, the bandwidth can also change from 128 kHz to 512 kHz. By considering the bandwidth limitation, we can choose the maximum available bandwidth for maximum bit rate. In the previous section, the minimum required bit rate is 428 kbps, thus, the actual bandwidth can no less than 428 kHz. Since the available bandwidth we have is much greater than 512 kHz, so we use 512 kHz as the occupied bandwidth for later calculations.

3.3.6 Bandwidth Verification

Recall the bandwidth bit rate equation we have used above:

$$\text{Bandwidth} = \frac{Bit\ Rate}{Bandwidth\ Efficiency}$$

Table 3:Modulation Schemes

Digital Modulation Scheme	Symbol Time (second)	Bit Rate (bits/s)	Bandwidth (Hz)	Modulation efficiency (bits/second/Hz)	E_b/N_0 (dB) (At BER = 10^{-5})	Eb/N0 (mag) (At BER = 10^{-5})
	T	1/(C*T)	1/T	C	From grath and table	dB to magnitude
BPSK	1.95E-06	5.12E+05	5.12E+05	1	9.5	8.912509381
QPSK	1.95E-06	1.02E+06	5.12E+05	2	9.8	9.54992586
4-QAM	1.95E-06	1.02E+06	5.12E+05	2	9.8	9.54992586
4-PAM	1.95E-06	1.02E+06	5.12E+05	2	13.7	23.44228815
16-QAM	1.95E-06	2.05E+06	5.12E+05	4	14	25.11886432
16-PSK	1.95E-06	2.05E+06	5.12E+05	4	18	63.09573445
32-PSK	1.95E-06	2.56E+06	5.12E+05	5	23.1	204.1737945
64-QAM	1.95E-06	3.07E+06	5.12E+05	6	18.5	70.79457844
GMSK(BT=0.3)	1.95E-06	6.91E+05	5.12E+05	1.35	10	10
GMSK(BT=0.35)	1.95E-06	5.12E+05	5.12E+05	1	10	10

The bandwidth efficiency (C) for GMSK at BT = 0.35 is 1. The occupied bandwidth is:

$$B = \frac{Bit\ Rate}{Bandwidth\ Efficiency} = \frac{512k}{1} = 512\ \text{kHz}$$

The result matched the calculation we made in previous sections, thus the bandwidth is 512 kHz. This is a obvious difference between S-band and UHF, the UHF requires less power consumption and bandwidth which will result in a smaller bit rate. S-band has the ability to transmit data in a higher speed which must be supported by more power and larger bandwidth usage.

3.3.7 Required SNR Calculation

SNR is defined as the ratio of signal power to the noise power, often expressed in decibels. A ratio higher than 1:1 (greater than 0 dB) indicates more signal than noise.

$$\text{SNR} = \frac{Signal\ power}{System\ noise\ power} = \frac{E_b}{N_o} * \text{Modulation Efficiency (C)}$$

$\frac{E_b}{N_o}$: normalized SNR (SNR per bit)

Signal power (P_{re}): power received by the antenna

System noise power (N_{sys}): power of noise generated by the receiver system

There is a relationship between $\frac{E_b}{N_o}$ and BER for each modulation scheme. From the simulation on MATLAB toolbox, the we can find the specific $\frac{E_b}{N_o}$ by a defined BER.

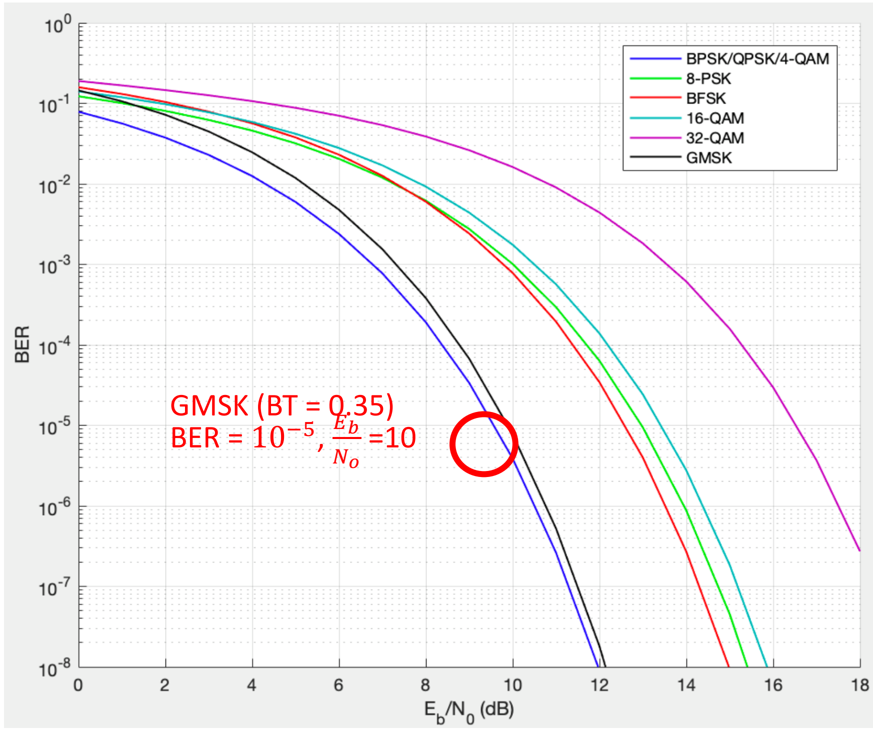


Figure 12: Modulation Schemes BER

By the required BER (10^{-5}), the $\frac{E_b}{N_o}$ is 10 for GMSK modulation scheme. And the required SNR can be determined by:

$$\text{Required SNR} = \frac{E_b}{N_o} * \text{Modulation Efficiency} = 10 \text{ dB}$$

This is the minimum SNR needed to guarantee we can get minimum power received at the ground station and the Bit error rate is less than 10^{-5}. The next step is to calculate the actual SNR value from the parameters of antennas and transceivers. Once the SNR supported by the devices is larger than the required one with a great margin, we can guarantee a stable communication link between the CubeSat and the ground station.

3.3.8 Propagation Losses

In any satellite transmission, there are always losses from various sources. Some of those losses may be constant, others are dependent of statistical data and others vary with the weather conditions, especially with rain.

With the following table, it is intended to provide a clear view of the major impairments this kind of communication may suffer, as well as their origin. A detailed explanation will be given below, in order to determine and justify all the values achieved for the calculations for CubeSat.

<table>
<tr><td rowspan="9">Propagation losses</td><td colspan="3">Free-Space Path Loss</td></tr>
<tr><td rowspan="7">Atmospheric Losses</td><td>Ionospheric Effects</td><td>Faraday rotation
Scintillation effects</td></tr>
<tr><td rowspan="5">Tropospheric effects</td><td>Attenuation</td></tr>
<tr><td>Rain Attenuation</td></tr>
<tr><td>Gas Absorption</td></tr>
<tr><td>Polarizatioin loss</td></tr>
<tr><td>Sky Noise</td></tr>
<tr><td colspan="2">Local Effects</td></tr>
<tr><td colspan="3">Pointing Loss</td></tr>
</table>

Losses in the received signal may have their origin in its propagation from the satellite to the ground station or the opposite, although the uplink will not be calculated with details in this case once CubeSat will only have downlink signal. They also may appear in the ground station itself or in the satellite.

There are three major issues to consider as far as propagation losses concern.

- Free space loss
- Atmospheric losses
- Pointing loss

3.3.8.1 Free-Space Path Loss

In telecommunication, the free-space path loss (FSPL) is the attenuation of radio energy between the feed-points of two antennas that results from the combination of the receiving antenna's capture area plus the obstacle free, line-of-sight (LOS) path through free space. Free space loss is the dominant component in the loss of the strength of the signal. It doesn't refer to attenuation of signal, but to its spreading through space.

From the equation of FSPL:

$$L_f = \frac{\lambda^2}{(4*\pi*d)^2}$$

λ: wave length = 0.136 m

d: distance between the CubeSat and earth = 408 km

Thus, L_f = -151.5 dB

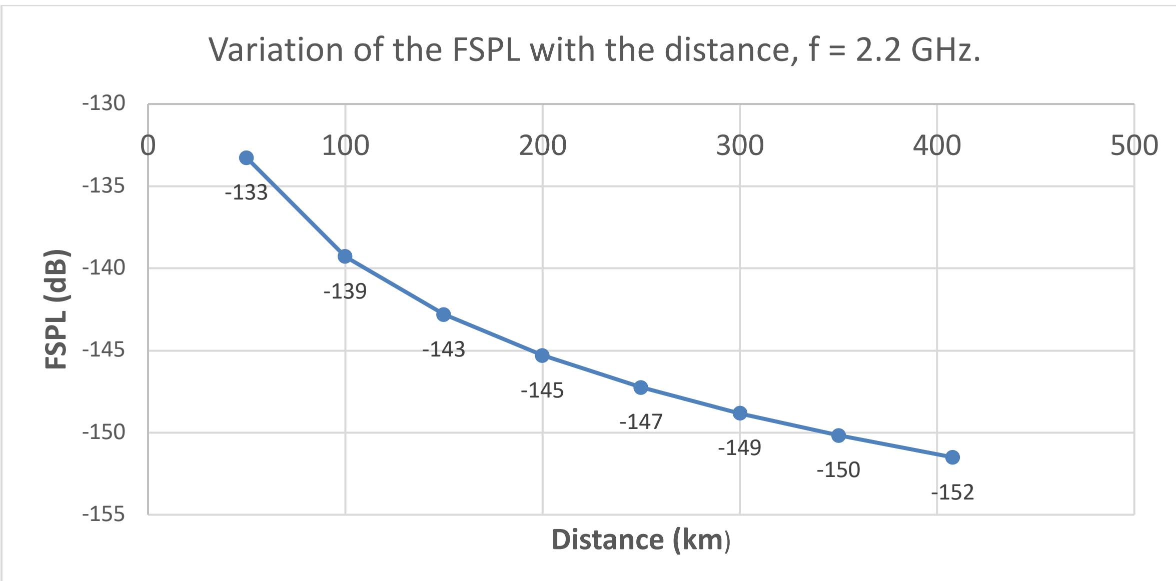


figure 13: Variation of FSPL with distance

3.3.8.2 Atmospheric losses

All radio waves transmitted by satellites to the Earth or vice versa must pass through the ionosphere, the highest layer of the atmosphere, which contains ionized particles, especially due to the action of sun's radiation. Free electrons are distributed in layers and clouds of electrons may be formed, originating what is known as travelling ionospheric disturbances, what provoke signal fluctuations that are only treated as statistical data.

The effects are:

· Polarization rotation;

· Scintillation effects;

· Absorption;

· Variation in the direction of arrival;

· Propagation delay;

· Dispersion;

· Frequency change.

These effects decrease usually with the increase of the square of the frequency and most serious ones in satellite communications are the polarization rotation and the scintillation effects, and those are the ones that will be treated in this dissertation.

Polarization rotation

When a radio wave passes through the ionosphere, it contacts the layers of ionized electrons that move according to the Earth's magnetic field. The direction these electrons move will no longer be parallel to the electric field of the wave and therefore the polarization is shifted, in what is called Faraday rotation. This is not a serious problem in frequencies above 10 GHz. It will not be a problem in the case of CubeSat also because this problem arises only in linear polarization. As said before, CubeSat is being designed for circular polarization, hence the Faraday rotation will only add to the rotation.

Polarization losses for different polarizations in antennas				
Transmit Antenna Polarization	Receive Antenna Polarization	Ratio of Power Received to Maximum Power		
		Theoretical	Practical Horn	Practical Spiral
		Ratio in dB	Ratio in dB	Ratio in dB
Vertical	Vertical	0	0	N/A
Vertical	Slant (45° or 135°)	-3	-3	N/A
Vertical	Horizontal	(-)∞	-20	N/A
Vertical	Circ (RHCP/LHCP)	-3	-3	-3
Horizontal	Horizontal	0	0	N/A
Horizontal	Slant (45° or 135°)	-3	-3	N/A
Horizontal	Circ (RHCP/LHCP)	-3	-3	-3
Circ (RHCP)	Circ (RHCP)	0	0	0
Circ (RHCP)	Circ (LHCP)	(-)∞	-20	-10
Circ (RHCP/LHCP)	Slant (45° or 135°)	-3	-3	-3

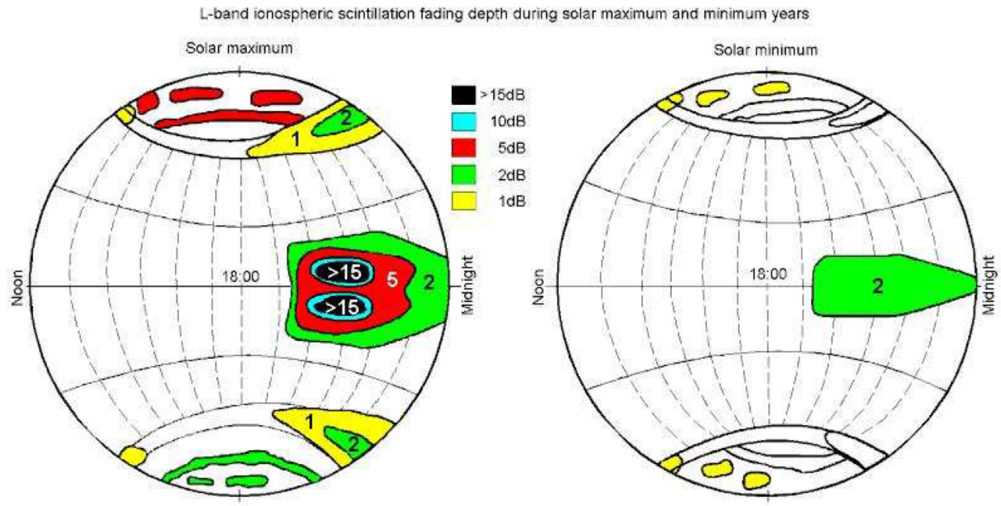
Since we are using the circular polarization for CubeSat, the polarization loss (L_p) would be -3dB for our case.

Scintillation effects

Differences in the atmospheric refractive index may cause scattering and multipath effect, due to the different direction rays may take through the atmosphere. They are detected as variations in amplitude, phase, polarization and angle of arrival of the radio waves.

It is often recommended the introduction of a fade margin so atmospheric scintillation can be a tolerated phenomenon

The graphic below shows how ionospheric scintillation affects signals operating in the L-Band (1 GHz – 2 GHz). It is not exactly the frequency of CubeSat, but it is close. It is possible to observe that Portugal, in its northern mid-latitude, is barely affected and this item may be neglected.



3.3.8.3 Tropospheric effects

Troposphere is composed by a miscellany of molecules of different compounds, such as hail, raindrops or other atmospheric gases. Radio waves that pass by troposphere will suffer their effects and will be scattered, depolarized, absorbed and therefore attenuated.

Attenuation

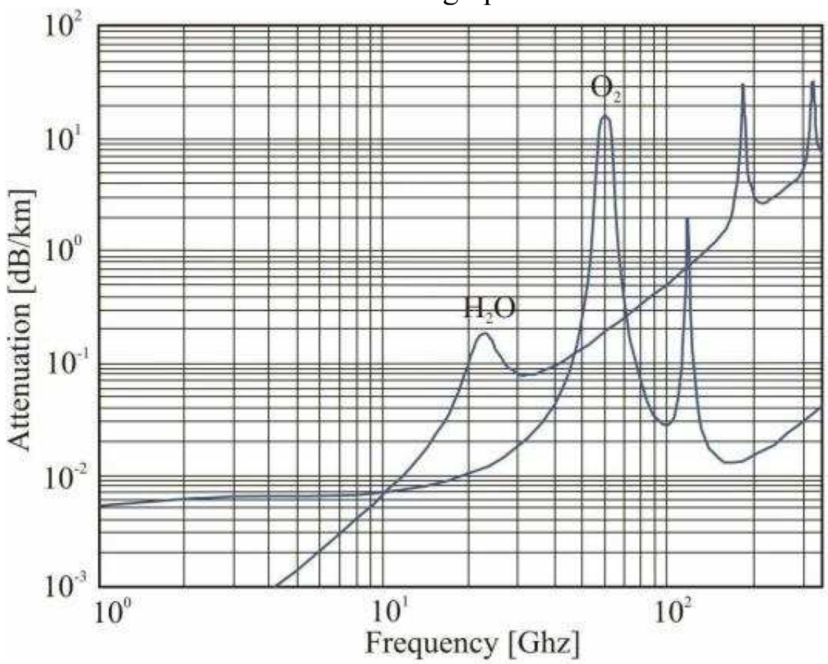
As radio waves cross troposphere, radio frequency energy will be converted into thermal energy and that attenuates signal. They will also be scattered into various directions which means that there is a small percentage that doesn't reach the receiver antenna at the ground station. The main scattered particles in troposphere are hydrometeors like raindrops, hail, ice, fog or clouds, and these particles represent a problem for frequencies higher than 10 GHz. Both this kind of absorption and scattering rise with frequency, hence neither represent a serious problem for CubeSat.

Rain Attenuation

It makes no sense to determine the attenuation caused by rainfall because they will be very punctual events, since rain only causes severe attenuation in situations of heavy rain. Thus, even though one satellite transmission may be strongly affected due to rain, its orbit period of nearly 90 minutes minimizes that loss because the same ground station will have several other opportunities to receive CubeSat signals.

Gas absorption

Under normal conditions, only oxygen and water vapour have a significant contribution in absorption. Other atmospheric gases only become a problem in very dry air conditions above 70 GHz. Thereby, losses caused by atmospheric absorption vary with frequency and the collection of data already received allows the elaboration of the graphic that follows:

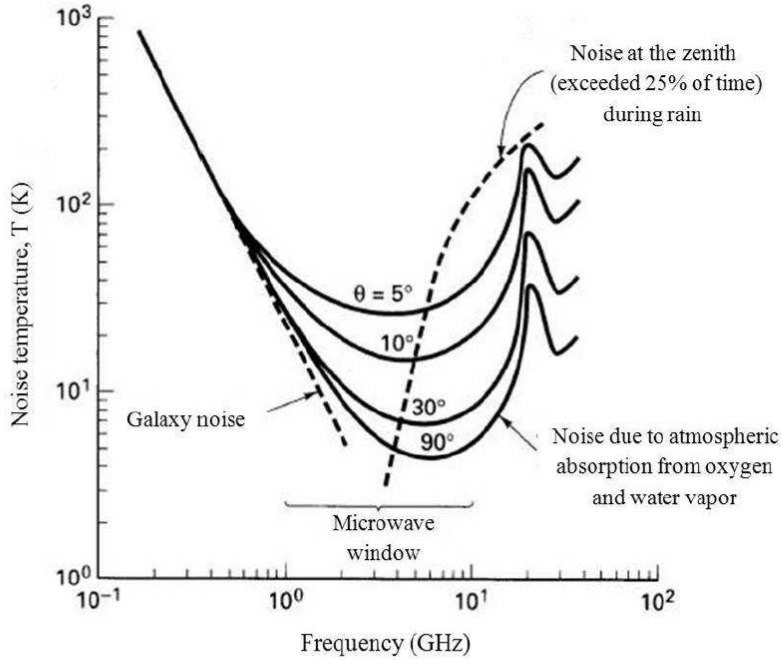


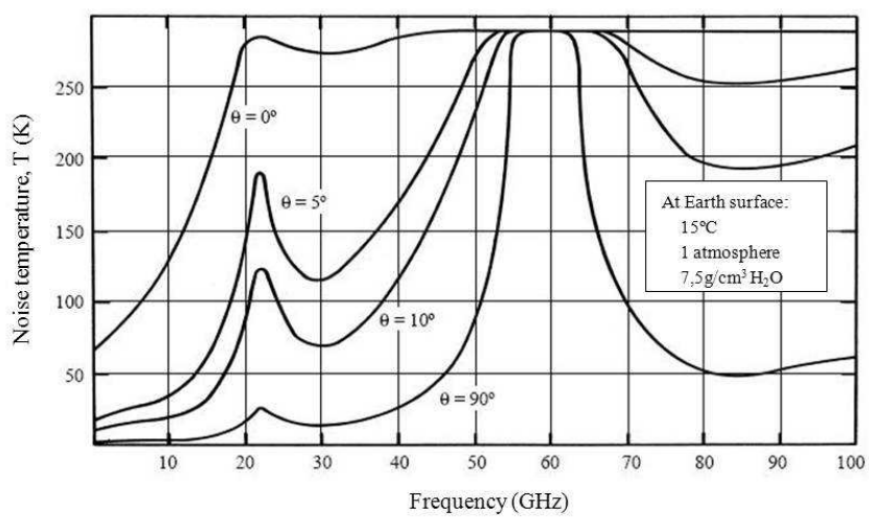
As it is possible to verify, both two peaks are observed at the frequencies 22.3 GHz for water vapor (H2O) and 60 GHz for oxygen (O2), wide far of the frequency of CubeSat signals, at 2.2 GHz. At this frequency, the atmospheric absorption is extremely low, around 0.006 dB/km, depending almost exclusively from oxygen because the water vapor contribution is significantly smaller. So, this kind of attenuation is negligible.

Sky noise

Sky noise is a combination of galactic and atmospheric effects, according as both these factors influence the quality of the signal in the reception. Galactic effects decrease with the increase of frequency. They are due to the addition of the cosmic background radiation and the noise temperature of radio stars, galaxies and nebulae. This value is quite low, and a good approximation is 3 K. Another figure shows also an optimal window between 1 GHz and 10 GHz, rather useful for satellite transmissions due to its low noise temperature. Considering CubeSat operation at 2.2 GHz, the temperature of cold sky can be approximated of 10 K.

Atmospheric effects in satellite transmissions increase with the increase of frequency. As said previously, the effects of the atmosphere in signal attenuation become serious for frequencies above 10 GHz, and the same applies for noise temperature.





For the frequency f = 2.2 GHz, this value is much more reduced.

3.3.8.4 Pointing Loss

Ideal reception implies that the value for misalignment losses would be 0 dB which means maximum gain at the ground station is achieved when both the transmitter and the receiver antennas are 100% aligned. Realistically it is virtually impossible to achieve a perfect alignment between the antennas of the ground station and the satellite, especially in the case of CubeSats, due to their fast movement of nearly 8 000 ms-1.

There are two ways for misalignment:

· Off-axis loss at the satellite;

· Off-axis loss at the GS.

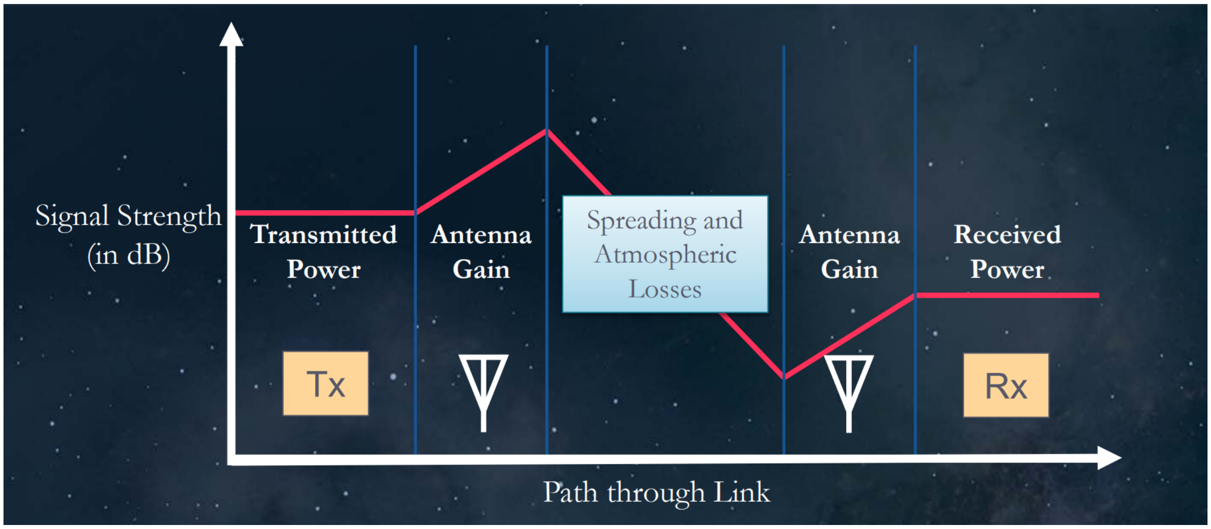
The first one is considered during the design of the satellite. The second type of misalignment is the antenna pointing loss and it is usually quite small, not reaching even 0.5 dB, being this value a good approximation for pointing misalignment loss. Antenna misalignment losses are calculated using statistical data, so these values are an approximation based on real data observed in several GS. Ergo, these values are not calculated, but estimated.

Combine all the losses we calculated and estimated above:

Free Space Path Loss	L_f	L_f = (λ/(4*pi*d))^2	7.07E-16	W	-151.50	Propagation Path Loss
Worst case elevation angle	α	N/A	5	degree	N/A	Used for Slant range
Slant range	S	From equation	1.26E+07	m	N/A	Worst case Slant range
Atm.gaz attenuation	-	N/A	1	W	0	no loss
Rain and clouds attenuation	-	N/A	1	W	0	no loss
Polarization loss	L_p	N/A	5.01E-01	W	-3	From table
Pointing loss	L_a	N/A	8.91E-01	W	-0.5	Misalignment loss
Total loss	L_{total}	Sum of all losses	3.16E-16	W	-155.00	Total propagation losses

The total propagation losses accumulated to -155 dB.

3.3.9 Antenna Received Power



The figure above shows a basic signal path for the CubeSat communication. The power transmitted from the antenna on CubeSat would be gained by the antennas on both transmitter and receiver sides. A great portion of signal power get lost in the propagation process.

The power received by the antenna on the ground station is:

Power received = Power transmitted + Transmitting antenna gain + receiving antenna gain + Total propagation losses

$$P_{re} = P_t + G_t + G_r + L_{total}$$

P_{re}: power received

P_t power transmitted = 30 dBm

G_t: transmitting antenna gain = 8.2 dBi

G_r: receiver antenna gain = 30.8 dBi

L_{total}: total propagation losses = -155dB

Thus, power received = -116 dB

Next step is to calculate the system noise power than find the actual SNR from the communication system.

Receiving Ground Segment Parameters (Ground Station)						
Antenna Received Power	P_{re}	P_{re} = Pt*Gt*Gr/Lf	2.51E-12	W	-116.00	Power received at antenna
Aperture Effiency	e_a	e_a = Ae/Ap	0.8	N/A	N/A	For aperture ea = 1
Receiver Antenna Gain	G_{re}	G_{re} = ξ_r*e_a*(pi*D_{re}/λ)^ 2	1.20E+03	N/A	30.8	Antenna gain at receiver side

Transmitting CubSat Parameters (Satellite)						
Transmitted Power	P_t	Given	1	W	0	20-30 dBm
Transmitter Antenna Gain	G_{tr}	G_{tr} = Ptr/(P_t*G_r*L_f)	6.61E+00	W	8.2	Antenna gain at transmitter side
Transmission line losses	L_{line}	N/A	7.94E-01	W	-1	Cable loss on transmitter
EIRP of Transmitting Antenna	P_{EIRP}	P_{EIRP} = Pre*Gre*L_{line}	5.25E+00	W	7.2	EIRP of rover antenna

3.3.10 Noise Temperature Calculation

Recall the formula of SNR = $\frac{Signal\ Power}{Noise\ Power} = \frac{Antenna\ received\ Power}{Noise\ Power}$

Noise power is equal to the power of Noise in Antenna Receiver System.

$$N_{sys} = KT_{sys}B$$

K: Boltzmann's constant = $1.38*10^{-23}$ J/K

T_{sygs}: Antenna system noise temperature in Kelvin

B: Occupied bandwidth

To find received power, we need to calculate power of noise at first. Constant K is known. We only need to compute system noise temperature T_{sys} on receiver side.

Recall SNR = $\frac{Pre}{N_{sys}} = \frac{Pre}{\text{KTsysB}} = \frac{Eb}{No}\frac{R}{B}$, the parameter of bandwidth is canceled out. So, channel bandwidth B is not necessary in used to find the supported data rate.

We already know that:

$$T_{sys} = T_A * \xi_r + T_{A0}(1 - \xi_r) + T_E$$

T_A: Antenna Noise Temperature

ξ_r: Antenna Radiative Efficiency

T_{A0}: Antenna Physical Temperature

T_E: Effective Internal Noise Temperature

Note from the requirement that the antenna on the satellite can be steered to point to the Earth – so we can assume it is directly pointing towards the earth during this communication.

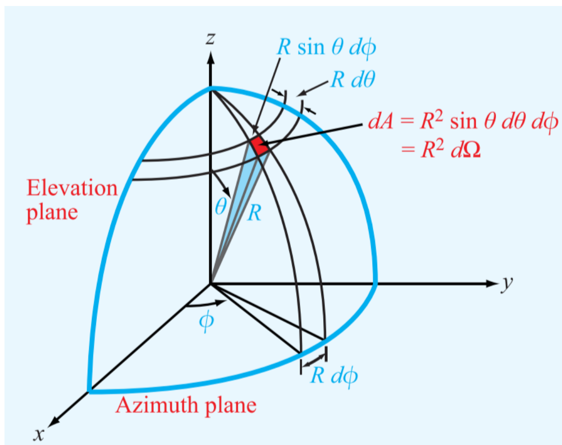


Figure 3.2.4 Radiation Polarization

From figure 3 above, the angle θ should be 90 degrees. The following plot is Antenna Noise Temperature T_A versus signal frequency with angle θ.

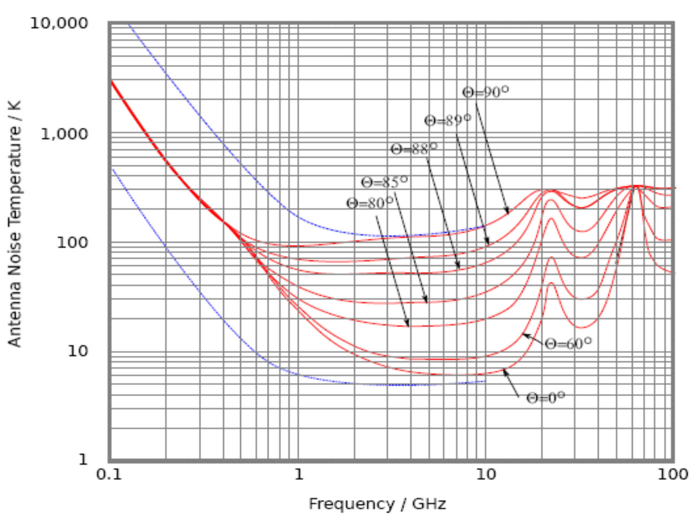


Figure 3.2.5 Antenna Noise Temperature

Based on the conditions we have, θ should be 90 degrees, and the operating frequency is from 2 to 2.4 GHz. So, the antenna noise temperature T_A should be around 103 K.

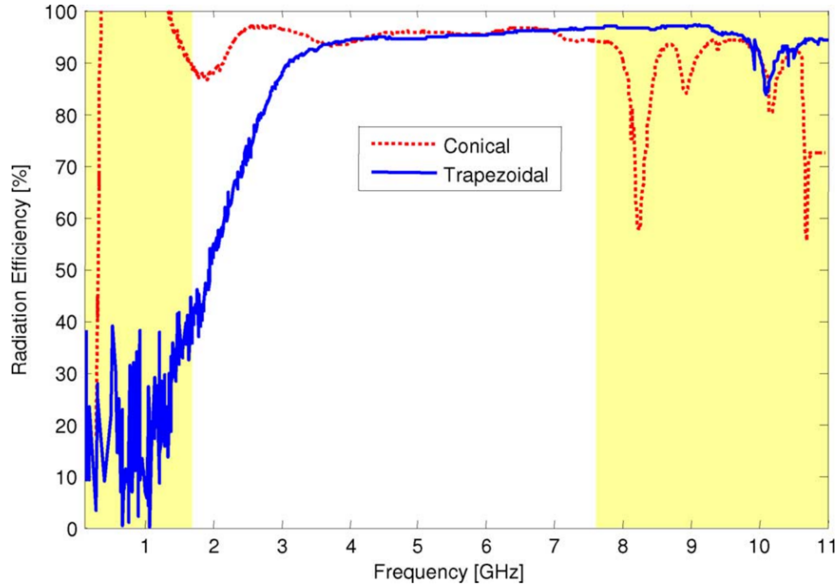


Figure 3.2.6 Radiation efficiency vs frequency

The figure above shows the radiation of types of parabolic antennas relate with various frequency. Here, we pick frequency as 7.4 GHz and Conical type antenna. The Radiation efficiency is about 90%. So,

$$\text{Antenna Radiation Efficiency } \xi_r = 0.9$$

For the antenna physical temperature T_{A0}, the receiver antenna is on the Earth so that we can set the ground temperature T_{A0} as

$$T_{A0} = 290 \text{ K}$$

The last concern is Effective Internal Noise Temperature T_E. This noise parameter is a combination of noise from the entire receiver system.

Figure 3.2.7 Typical antenna receiving system

For a typical cascaded receiver system, the attenuation on previous components will affect the following components as well. There will be some RF, and IF amplifiers in the receiver system, so the gains of these amplifiers must be calculated. Therefore, the total(effective) receiver CKT internal noise temperature:

$$T_E = Tt + (Lt)T_{RF} + (L_t/G_{RF})T_M + (L_t*L_m/G_{RT})T_{IF}$$

Where passive attenuator feedline & mixer:

$$T_t = (L_t\text{-}1)T_0\ ,\ T_m = (L_m\text{-}1)T_0$$

T_0 = physical temperature of receiver components

L_t/L_m: loss(attenuation) factor of feeder line and mixer

G_{RF}: gain of RF amplifier

T_0 is ground temperature 290K, loss factor on feeder line is 1.5 dB, and 6 dB for the mixer. The gain of the RF amplifier is type dependent. So, G_{RF} is commonly 6 dB. So, the total noise temperature T_E is around 2000 K. We use 2000K here to simplify the calculation

Recall the equation for system noise temperature:

$$T_{sys} = T_A*\xi_r + T_{A0}(1\text{-}\ \xi_r) + T_E$$

$$= 102*0.8 + 290(1\text{-}0.8) + 2000 = 2205.3\ K$$

Moreover, the power of noise is:

$$N_{sys} = KT_{sys}B = 1.38*10^{-23} * 2205.3 * 512K$$

$$= \text{-}138.07\ dB$$

System Noise Temperature and Power						
Antenna Noise Temperature	T_A	Main lobe & side lobes 100% effiency	103	K	20.13	From the graph below
Antenna Physical Temperature	T_{Ao}	Ground Temperature	290	K	24.62	Ground Station
Effective Internal Noise Temperature	T_E	Assuem a LNA amplifier	2064.92	K	33.15	Assumption
Antenna Radiative Effiency	ξ_r	Assume 80% effiency	0.8	N/A	N/A	Assumption
System Noise Temperature	T_{sys}	$T_{sys} = T_A*\xi r + (1\text{-}\xi_r)*T_0 + T_E$	2205.32	K	33.43	Toal noise temperature
Antenna Average Noise Power	N_{sys}	$N_{sys} = K*T_{sys}*B$	1.56E-14	W	-138.07	Average Noise power

System Noise Temperature Calculation (Satellite)						
Noise Variable	**Symbol**	**Equation**	**Value**	**Unit**	**Value in db**	**Comment**
Antenna Noise Temperature	T_A	N/A	103	K	20.12837225	From graph above
Physical Temperature	T_{A0}	N/A	2.7	K	4.313637642	Space Temperature
Transmission Line Temperature	T_t	$T_t = (L_t-1)T_0$	1.11385137	K	0.468272435	Noise Temperature in Transmission Line
Transmission Line Attenuation Factor	L_t	N/A	1.41253754	N/A	1.5	Loss factor on transmission line
Gain of RF Amplifier	G_{RF}	N/A	3.98107171	N/A	6	RF amplifier gain
Mixer Attenuation Factor	L_M	N/A	3.98107171	N/A	6	Loss factor on mixer
Mixer Noise Temperature	T_M	$T_M = (L_M-1_)*T_0$	8.0488936	K	9.057361867	Noise Temperature in Mixer
IF Amplifier Noise Temperature	T_{IF}	N/A	870	K	29.39519253	General IF amplifier temperature
Noise Temperature on RF Amplifier	T_{RF}	N/A	290	K	24.62397998	General RF amplifier temperature
Effective Internal Noise Temperature	T_E	$T_E= T_t + (L_t)T_{RF} + (L_T/ G_{RF})T_M + ((L_T L_M)/ G_{RF})*T_{IF}$	1642.51326	K	32.15508884	Effective Internal Noise Temperature
System Noise Temperature	T_{sys}	$T_{sys} = T_A*\xi r + T_{A0}(1-\xi r) + T_E$	1725.45326	K	32.36903199	Total noise temperature

3.3.11 Actual SNR Calculation

From the previous sections, we find the antenna received power and the system noise power. Thus, the actual SNR supported by the antennas and transceivers is:

$$\text{SNR} = \frac{Signal\ Power}{Noise\ Power} = 22.07\ \text{dB}$$

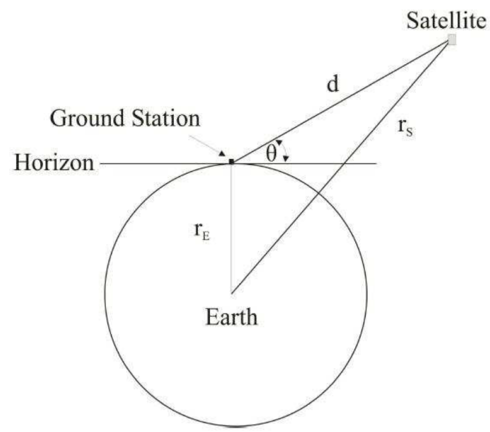
Comparing this value with the minimum required SNR (10dB), we get a great margin between these two, which points we got a good design.

Modulation Scheme GMSK (BT = 0.35)						
GMSK BT product	BT	N/A	0.35	Hz/s	N/A	From transceiver datasheet
Normalized power spectral density	NPSD	N/A	1	N/A	0	From transceiver datasheet
Bandwidth	B	B = NPSD*R	5.12E+05	Hz	N/A	From modulation table
SNR per bit	E_b/N_0	N/A	10	N/A	10	From modulation table
Calculated SNR	SNR_{sys}	$SNR = P_{re}/N_{sys}$	161.08	N/A	22.07	Calculated
Required SNR	$SNR_{required}$	$SNR = E_b/N_o*R/B$	10.00	N/A	10.00	Required SNR
SNR margin	$Margin_{SNR}$	SNR_{sys} / $SNR_{required}$	16.11	N/A	12.07	Good design, margin>3

Date Rate & Propagation wave (Down-link)						
Transceiver Data Rate		R_{design}	5.12E+05	bits/sec	57.09	Maximum data rate that transceiver supports
Calculated Data Rate	$R_{designed}$	R_{design}	5.12E+05	bits/sec	57.09	Calculated data rate based on bandwidth
Channel Capacity	C	$C = B*\log_2(1+SNR)$	3.76E+06	bits/sec	65.75	Shannon Channel Capacity
Bit Error Rate	BER	N/A	1.00E-05	N/A	-50	Pre-defined
Frequency	f	N/A	2.20E+09	Hz	N/A	S-bnad
Satellite Altitude	d	N/A	4.08E+05	m	N/A	Distane from CubSat to Earth
Earth Diameter	d_{earth}	N/A	1.27E+07	m	N/A	Diameter of Earth
Wavelength	λ	λ = c/f	1.36E-01	m	N/A	Wavelength based on frequency

3.3.12 Beamwidth Calculation

From the design requirement, the beamwidth of transmitter antenna should have ability to cover the full Earth surface. Consider the geometric diagram below:

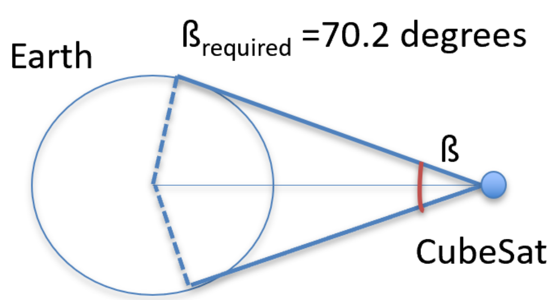


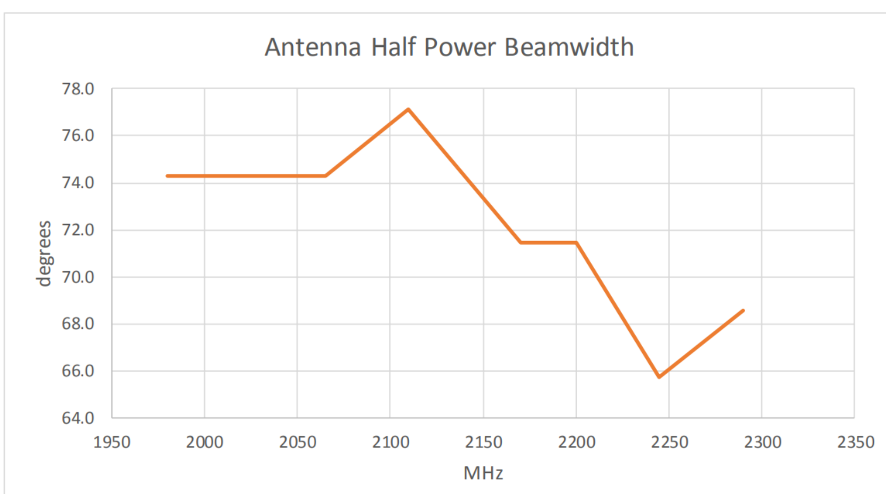
The required beamwidth: $ß_{required}$ is equal to 2sin-1(d_{earth}/(d+d_{earth}))

The diameter of earth: $d_{earth} = 1.27*10^7$ m

The distance from Mars to Earth: $d = 5.46*10^{10}$ m

Thus, $ß_{required} = 70.2$ degrees





The antenna we selected for CubeSat is NanoCom ANT2000. From the datasheet of the antenna, actual Beamwidth = 71.8 degrees at 2.2 GHz frequency.

Comparing the required beamwidth and the value from the antenna we designed, the actual value is much greater than the required one, which has validated that the designed antenna beamwidth can completely cover the entire Earth surface.

Transmitting Antenna Beamwidth & Aperture						
Required Beamwidth	$ß_{required}$	$ß_{required} = \sin^{-1}(d_{earth}/2/(d+d_{earth}/2)$	70.02	Degree	N/A	Beamwidth required to cover the earth suface
Actual Beamwidth	$ß_{actual}$	N/A	71.80	Radian	N/A	From antenna data sheet
Transmitting Antenna Directivity	D_{tr}	$D_{tr} = G_{tr}/ \xi_r$	6.56E+00	N/A	8.17	Directivity of Transmitting Antenna

4. Results and Validation

4.1 Prototype

4.1.1 Prototype Design Background

At the time of this report, the CubeSat Project completed its first-year development out of the three-year proposed timeline. The main focus of first-time development was to propose a preliminary design, so the team had to work on a very limited budget. Since any CubeSat components typically cost thousands of dollars, none of the actual on-board components selected in previous section can be purchased for testing.

In order to still validate our design, a cheap alternative was proposed. We planned to build two transceivers using Arduino that operated in S-Band frequencies and transmit messages between the two devices. Unfortunately, the next problem occurred was that there was no cheap S-band transceiver chip supported to work on Arduino, ultimately the only option available was to select the next closest frequency at 2.4GHz for Wi-Fi and Bluetooth. Since the frequencies were similar, it should have similar characteristics to our target operating frequency at 2.2GHz.

The main function of the prototype was to establish wireless communication between the two transceivers, so message sent from one transceiver can be received at the other transceiver. In addition, hand-shaking mechanism were implemented to enable two-way communication. Character type messages were transmitted using the prototype.

4.1.2 Prototype Components

The selected component was the NRF24L01 transceiver chip operating at 2.4GHz. It requires the Arduino library RF24 to operate. Figure 4.1.1 shows the NRF24L01 chip with its connection pins, and Figure 4.1.2 shows the schematic used to connect the chip to Arduino. Price of the transceiver chip and Arduino are listed in the table below. The Arduino software and the RF24 library are both free to be used.

Prototype Cost List		
Components	**Price**	**Quantity**
NRF24L01 Transceiver Chip	$1.70	2
Arduino Uno	$50	2
Total Prototype Cost	$103.4	

Figure 4.1.1 NRF24L01 Transceiver Chip

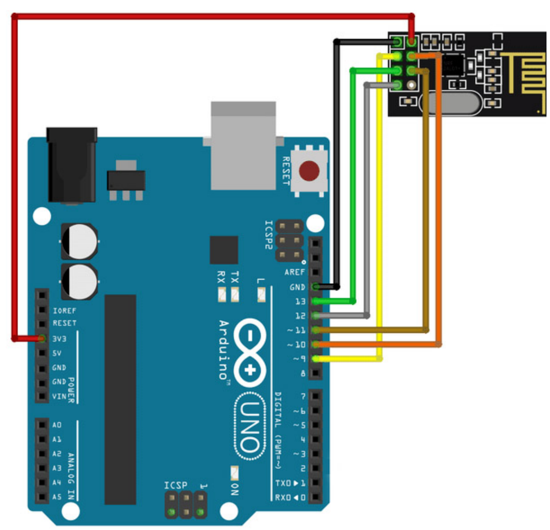


Figure 4.1.2 Arduino Wiring diagram

4.2 Testing Strategy/ Validation Protocols

4.2.1 Establish Communication

Upon obtaining all necessary components to start testing, we took steps to validate our system in a building block manner. The first step was to confirm single way communication from one transceiver to the other. The result is shown in Figure 4.2.1, where the receiver successfully received message from the transmitter.

The next step was to build two-way communication to confirm that two transceivers can communicate to each other through 'hand-shaking' mechanism with acknowledgement messages. One of the transceivers was set up as client to send messages and the other transceiver was set up as server to receive and response. Once a message was received at server, the server would reply back with an acknowledgement to indicate that message was received. This back-and-forth transmission allowed both transceivers to take turn as being transmitter and receiver. Figure 4.2.2 and 4.2.3 illustrated the logic schematic designed for the client and server. It is also important to include a "timed out" function to prevent the client to wait infinitely for response if the acknowledgement was lost. If the client does not receive the acknowledge in 0.2 seconds, it will determine the last message as lost and start sending the next one. Performing these tests between the CubeSat and ground station would ensure a communication link is present.

```
16:30:34.818 -> Hello World
Message arrived!
16:30:35.798 -> Hello World
Message arrived!
16:30:36.803 -> Hello World
```

Figure 4.2.1 output result from single way communication

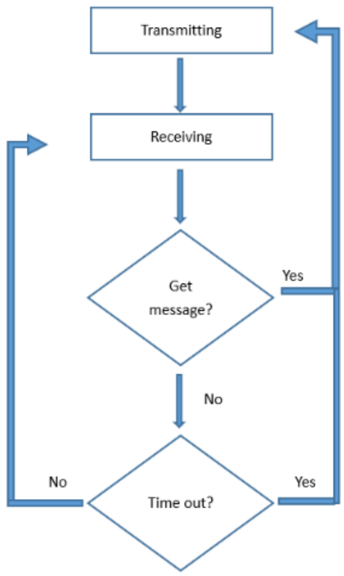


Figure 4.2.2 client schematic

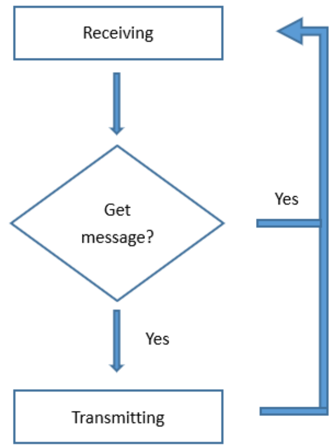


Figure 4.2.3 server schematic

After establishing a basic communication, the next step was to test the quality of the communication link in more advanced approaches. Two scripts were written to test:

1. Packet Loss Rate
2. Bit Error Rate

These tests can evaluate how efficient the CubeSat can send and receive data. It is a significant factor since the CubeSat will be running on limited power and only have limited access time to orbit transmission path.

4.2.2 Packet Loss Rate Test

The RF24 Library used a default built-in CRC encoding. Any packet with error were automatically discarded to guarantee that messages displayed at the receiver were error-free. The packet loss rate test was conducted to see how many packets can be received compared to the number of packets sent.

It used the same acknowledgment approach mentioned in section 4.2.1 with multiple counters. At client, one counter counted the number of messages sent and another counter counted the number of acknowledgements received. Similarly, at server, a counter counted the number of messages received. 20 messages were counted as a transmission period. When the client counter reached 20, it would send an “END” message to the server to indicate completion of current transmission period. Server that received the “END” message would know all 20 messages were sent, so it can calculate the packet loss rate by dividing the number of messages received by the number of messages sent. Refer to Appendix to see complete code.

To compensate for the case where the “END” message was lost in transmission, the 20 messages would accumulate to the next set of messages, then the total number of messages would become 40. This scenario can continue until one “END” message was successfully received at the server. Even though the total number may be changed, the ratio between the sent and received would still be valid for assessment.

4.2.3 Bit Error Rate Test

This section tested the transmission quality in reference to individual bits. The CRC checking was turned off by overriding the software code, so errors were kept in the received messages. All character type messages were converted back to binary bits as raw data in order to test BER.

For convenience, the client only sent a single character ‘0’ repeatedly, which was the 8-bits sequence “00001100” in Arduino code. The received message at the server were checked using this sequence and any unmatched bits would be marked as an error bit. By counting the number of error bits and transmitted bits, we can find the BER rate as a probability. This test needs to be conducted long enough in order to transmit large quantity of bits for accurate result.

4.3 Final Results and Validation

4.3.1 Packet Loss Rate Test

Figure 4.3.1 showed the client output acquired for packet loss rate test. It printed the transmitted messages and received messages along with their counter value. The client switched to listening mode after each transmission and prompted for acknowledgement, then switched back to transmitting mode after acknowledgment was received. Once it received the ‘END’ message from server, it calculated the packet loss rate to be 10% for this trial.

On the other hand, figure 4.3.2 showed the server output. 18 messages of “Hello World” were received followed by the 19th message as “END”, thus indicating 2 messages were lost. The program window offered a concise summary of the success rate to be 18/20 = 90%.

These figures proved and validated the proposed functionality as in section 4.2.2. While the test results might differ in magnitude and delivery from the CubeSats complex system, this set up still allows students to test wireless communication, but on a much smaller, cost effective scale.

```
->
-> Start transmitting --------------------------------
-> Message 17 sent: Hello World
->
-> Start listening +++++++++++++++++++++++++
-> Message 16 received!:acknowledged
->
-> Start transmitting --------------------------------
-> Message 18 sent: Hello World
->
-> Start listening +++++++++++++++++++++++++
-> Message 17 received!:acknowledged
->
-> Start transmitting --------------------------------
-> Message 19 sent: Hello World
->
-> Start listening +++++++++++++++++++++++++
-> Message 18 received!:acknowledged
->
-> Start transmitting --------------------------------
-> Message 20 sent: Hello World
->
-> Start listening +++++++++++++++++++++++++
-> Message 19 received!:END
-> 1
-> Error Rate is: 10.00%
```

Figure 4.3.1 Client output for packet loss test

```
1 Hello World
2 Hello World
3 Hello World
4 Hello World
5 Hello World
6 Hello World
7 Hello World
8 Hello World
9 Hello World
10 Hello World
11 Hello World
12 Hello World
13 Hello World
14 Hello World
15 Hello World
16 Hello World
17 Hello World
18 Hello World
acknowledge END message sent
19 END

---------------------------------
18 out of 20 messages received

90.00% success rate
---------------------------------

1 Hello World
2 Hello World
3 Hello World
4 Hello World
5 Hello World
6 Hello World
```

Figure 4.3.2 Server output for pack loss test

4.3.2 Bit Error Rate Test

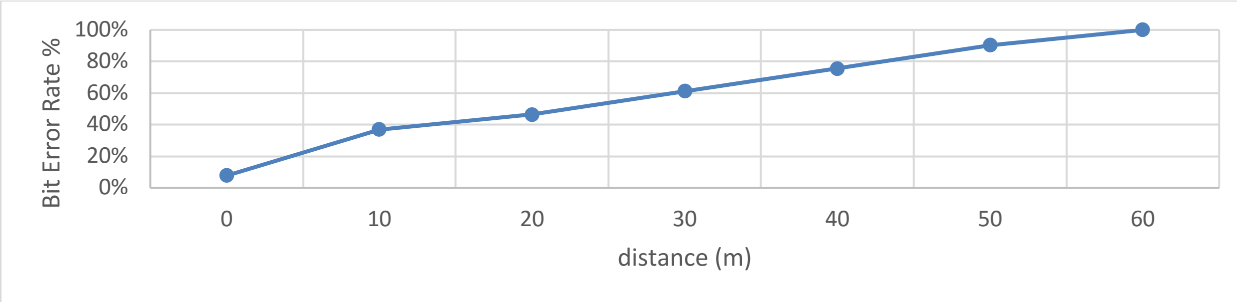
Figure 4.3.3 illustrates the output from BER test. At the server, error bits can only be calculated using the received bits, but many more bits were lost during transmission, therefore the total bit error rate needs to be calculated by adding the lost bits.

Each BER test were conducted for one minute. With the client delay set as 100ms for each transmission, 600 transmissions of 8 bits would occur, so 4800 bits were sent at each test. With this particular trial displayed in figure 4.3.3, only 3128 bits were receiver, which meant 4800-3128 = 1672 bits were lost, the total number of bit error was 1670 lost bits + 100 received error bits = 1770 bits and the BER rate can be calculated as 1770/4800 = 36.88%

```
receiver starts listening
total bit error count:  10 , 248 bits received
total bit error count:  15 , 488 bits received
total bit error count:  25 , 728 bits received
total bit error count:  30 , 968 bits received
total bit error count:  35 , 1208 bits received
total bit error count:  40 , 1448 bits received
total bit error count:  45 , 1688 bits received
total bit error count:  55 , 1928 bits received
total bit error count:  65 , 2168 bits received
total bit error count:  70 , 2408 bits received
total bit error count:  85 , 2648 bits received
total bit error count:  90 , 2888 bits received
total bit error count:  100 , 3128 bits received
```

Figure 4.3.3 Bit error rate output

To further test the prototype, a range test was conducted to see how the prototype performed at various distance. Following graphs were the output obtained from the test. BER rate was at 8% when the transceivers were next to each other. As the distance became further apart, the BER rate increased. Once 60m was reached, the connection was lost as messages can no longer be received. A linear relation between BER and distance can be observed from this test.



distance (m)	bits sent	bits received	bits lost	received bit error	total bit error	bit error rate
0	4800	4568	232	143	375	8%
10	4800	3128	1672	100	1772	37%
20	4800	2648	2152	77	2229	46%
30	4800	1928	2872	66	2938	61%
40	4800	1208	3592	40	3632	76%
50	4800	488	4312	21	4333	90%
60	4800	0	4800	0	4800	100%

This test highly depends on antenna gain and SNR values, with the components used for prototyping, the result is not a direct numerical representation of what is expected for CubeSat. However, the features and overall trend are what we should observe and perceive as we move forward to next phase of the project.

5. Conclusions, Future Work and Recommendations

The first milestone for this capstone project was understanding the key design specifications surrounding satellite communication system design. Students were then able to properly select a transceiver, antennae, and ground station which formed the skeleton of a link budget from datasheet values. Additionally, the knowledge gained from undergrad courses, as well as research into wireless communication enabled this year of students to make a coherent link budget.

The prototype provided small scale replications of tests that future students will perform to validate a CubeSat communication link. Building and modifying the prototype gave students hands on experience in debugging problems related to wireless communication. The key advantage of this prototype is that future students can easily build on it. The option to buy more powerful transceivers and add functionality to the Arduino/transceiver modules can further student's education in wireless communication before committing to final component selection.

Once they have a firm understanding of the link budget and material covered in this report, it is recommended that future students buy selected components and test with them. It is important that next year students seek help from industry professionals before making final purchases. They are also encouraged to maintain good communication with other teams to ensure a unified design approach.

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7. Appendices

Arduino Prototype Client Code

```
#include <SPI.h>
#include <nRF24L01.h>
#include <RF24.h>
RF24 radio(9, 10); // CE, CSN
const byte addresses[][6] = {"00001", "00002"};     //Byte of array representing the address. This
is the address where we will send the data. This should be same on the receiving side.
int time1;
int counter = 0;
int counter2 = 0;
int Error_rate;
int change;
int response;
int total = 20;
void setup() {
radio.begin();                  //Starting the Wireless communication

radio.openWritingPipe(addresses[1]); // 00001
radio.openReadingPipe(1, addresses[0]); // 00002

radio.setPALevel(RF24_PA_MIN);  //You can set it as minimum or maximum depending on the
distance between the transmitter and receiver.

Serial.begin(9600);
Serial.println(F("Start sending------------------------------------------------"));
change = 1;
}

void loop()
{
  radio.stopListening();          // This sets the module as transmitter
  if (change == 1){               // Change = 1, means we are transmitting
   char text1[] = "Hello World";

  if(counter2 == total)
  {char text3[] = "END";
   radio.write(&text3, sizeof(text3));
   counter2 = 0;
  }
  counter2 = counter2 + 1;
  radio.write(&text1, sizeof(text1));                 //Sending the message to receiver
  // time1 = millis();
  Serial.println("Start transmitting ---------------------------------");
```

```
  Serial.println("Message " + String(counter2)+ " sent: " + String(text1));
  Serial.println();
  change = 0;                    // Change = 0, means we are receiving
  }
  // Start listening
  Serial.println(F("Start listening ++++++++++++++++++++++++++++ "));
  radio.startListening();
  unsigned long time2 = micros();

  while(change == 0){
  if(radio.available()){
    counter = counter+1;  // count for # of received message

    Serial.print("Message "+ String(counter)+" received!:");
    char text2[32] = "";                //Saving the incoming data
    radio.read(&text2, sizeof(text2));    //Reading the data
    Serial.println(text2);

    if (String(text2) == String("END")){
      counter = counter - 1;
      int res = counter/total;
      if(counter < 20)
      res = 1;
      float Error_rate = 1 - (float)counter/(total*(res))*100;
      counter = 0;
      Serial.println(res);
      Serial.print("Error Rate is: " + String(Error_rate)+ "%");
    }

    change = 1;
//    response = time2 - time1;
//    Serial.print("Response time:");
//    Serial.print(response);
    Serial.println();
    }
    if (micros() - time2 > 800000 ){            // If waited longer than 0.8 sec, indicate timeout and
exit while loop
      Serial.println("Time out!");
          change = 1;
          break;
      }
 }
delay(300);
}
```

Server Code for Packet Loss Test

```
#include <SPI.h>
#include <nRF24L01.h>
#include <RF24.h>
RF24 radio(9, 10); // CE, CSN
const byte addresses[][6] = {"00001", "00002"};
int count_msg = 0; //received message counter
int count_ack = 0; //ack message counter
int total = 20; //number of messages in one set of messages, used for error rate calculation

void setup() {
pinMode(6, OUTPUT);
Serial.begin(9600);
radio.begin();
radio.openWritingPipe(addresses[0]); // 00001
radio.openReadingPipe(1, addresses[1]); // 00002
radio.setPALevel(RF24_PA_MAX);      // power amplifier level, RF24_PA_MIN,
RF24_PA_LOW, RF24_PA_HIGH and RF24_PA_MAX: -18dBm, -12dBm,-6dBM, and 0dBm
radio.startListening();             //sets the module as receiver
//radio.getPALevel();
//radio.getDataRate();      // RF24_250KBPS for 250kbs, RF24_1MBPS for 1Mbps, or
RF24_2MBPS for 2Mbps

radio.setAutoAck(false);
radio.disableCRC();


Serial.println("receiver starts listening");

}

void loop()
{
if (radio.available())              //receiver looking for data
{

  char text[32];                //save the incoming message
  radio.read(&text, sizeof(text));    //read the message
  count_msg = count_msg + 1;
  Serial.println(String(count_msg) + " " + String(text));

  radio.stopListening();            //send out acknowledge message
  char response[] = "acknowledged";
  radio.write(&response, sizeof(response));
  count_ack = count_ack + 1;
```

```
  if (count_ack == total) {          //notify 20 acknowledges are sent
    char endmsg[] = "END";
    radio.write(&endmsg, sizeof(endmsg));
    count_ack = 0;
    Serial.println("acknowledge END message sent");
  }

  if (String(text) == String("END")) {             //if transmitter has transmitted 20 messages,
calculate the error rate
    Serial.println("\n-----------------------------------");
    count_msg = count_msg-1;
    int res = ceil(float(count_msg/total));    //if the END message is missed, number of received
messages accumulates to next set
    if (count_msg <= 20) res = 0;

    float error = (float)count_msg/(total*(res+1))*100;   //error rate calculation
    Serial.println(String(count_msg) + " out of " + String(total*(res+1)) + " messages
received\n");
    Serial.println(String(float(100 - error)) + "% error rate");
    Serial.println("-----------------------------------\n");
    count_msg = 0;
 }

}
  radio.startListening();

delay(500);
}
```

Server Code for BER Test

```
//NOTE:client code should send a single "0" each message
#include <SPI.h>
#include <nRF24L01.h>
#include <RF24.h>
RF24 radio(9, 10); // CE, CSN
const byte addresses[][6] = {"00001", "00002"};
int totalErrorCount = 0; //counts total amount of received bit errors from the start of the program
int timeCounter = 0; //counter to delay serial print to every 30 loops
int count_msg = 0;

void setup() {
pinMode(6, OUTPUT);
Serial.begin(9600);
radio.begin();
radio.openWritingPipe(addresses[0]); // 00001
radio.openReadingPipe(1, addresses[1]); // 00002
radio.setPALevel(RF24_PA_MAX);      // power amplifier level, RF24_PA_MIN,
RF24_PA_LOW, RF24_PA_HIGH and RF24_PA_MAX: -18dBm, -12dBm,-6dBM, and 0dBm
radio.startListening();             //sets the module as receiver
//radio.getPALevel();
//radio.getDataRate();      // RF24_250KBPS for 250kbs, RF24_1MBPS for 1Mbps, or
RF24_2MBPS for 2Mbps

radio.setAutoAck(false);
radio.disableCRC();


Serial.println("receiver starts listening");

}

void loop()
{
if (radio.available())            //receiver looking for data
{

  char text[32];               //save the incoming message
  radio.read(&text, sizeof(text));    //read the message
  count_msg = count_msg + 1;
  //Serial.println(String(count_msg) + " " + String(text));



  byte check[8];
```

```
  int bitcount = 0;                 //reads the received message into bits
    for (byte i=0; i<8; i++) {
    byte state = bitRead(text[0], i);
    //digitalWrite(pins[i], state);
    //Serial.print(state);
    check[i] = state;
  }


  for (int j=0; j<8; j++) {           //compare the received bits to correct bits
    byte key[8] = {0,0,0,0,1,1,0,0};    //message "O" in bits
    if (check[j] != key[j]) bitcount++; //count number of wrong bits in the single message
    //Serial.print(check[j]);  //print received bits
  }

  totalErrorCount = totalErrorCount + bitcount;

  if (timeCounter >= 5) {        //print out error rate statistics, happens every 30 loops
    Serial.println("total bit error count:  " + String(totalErrorCount) + " , " + String(count_msg*8)
+ " bits received");
    timeCounter = 0;
  }

  timeCounter++;
  radio.startListening();

}

delay(50);
}
```