Emulating the Doppler-Shift for LoRa based Low Earth Orbit Satellite Communication

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List of Acronyms

- ISM - Industrial, Scientific and Medical (Frequency Bands) - Frequencies allocated by the FCC for use in Industrial, Scientific and Medical use.
- LEOSAT - Low Earth Orbit Satellite - A Satellite, or CubeSat, positioned in Low Earth Orbit.
- LoRa - Stands for Long Range communication, a protocol used in Internet-Of-Things devices that allows for power efficient, long range communication.
- BER - Bit Error Rate
- SNR - Signal to Noise Ratio
- VSG - Vector Signal Generator
- ISI - Inter-Symbol Interference

I. Abstract

This project investigates the adverse effects of the Doppler Shift on a LoRa waveform transmitted from a Low Earth Orbit Satellite or LEOSAT. This work is on behalf of Project OWL, who will use these results to justify further investment into developing a LEOSAT for their communication network. Part of the project is to design a test setup to replicate the Doppler Shift in the lab. The Doppler shift replication setup distorts the transmitted waveform, similar to how the signal gets distorted if sent from a LEOSAT. The test setup will comprise both software and hardware control, wherein software, the user provides a center frequency of transmission, LEOSAT orbital altitude, and maximum range of signal transmission. Once given test parameters, the software will calculate the Doppler shift as the satellite travels overhead, then send information to hardware that modulates the output of one of Project OWL's radios to apply the Doppler shift to a transmission. The software will monitor another radio receiver, and determine if communication is theoretically possible from a LEOSAT to one of their radios.

II. Introduction

The project intends to determine if LoRa, the physical layer modulation scheme employed by Project OWL, is susceptible to the Doppler shift when used in satellite communications. Currently, OWL's mesh network is formed by several LoRa radios relaying messages, with one radio acting as a network gateway to the Worldwide Web. As some regions of the world do not readily have internet access, Project OWL wishes to fly their hardware on satellites to provide network access to their radios in these regions. Last year, two Master's students at Cal Poly SLO, Omer Gumus, and Kevin Nottberg conducted research into the maximum range that two of Project OWL's radios could communicate. By attenuating the transmitted signal, they determine that the radios could communicate at ranges up to 850 km.

Our project follows up on the work that Omer and Kevin did by analyzing the adverse effects of the Doppler Shift on system performance. To do this, we are going to create a test bench that utilizes software control to create a frequency versus time profile for the Doppler shift of a LEOSAT. This profile will be applied to a variable frequency source that will modulate the transmitted waveform in order to apply the Doppler shift. Once transmission begins, the software will monitor the receiving radio and determine if the transmission is being demodulated correctly.

The purpose of this project is to prove the reliability of a Long Range (LoRa) wireless communications link between a land-based radio and a Low Earth Orbit Satellite (LEOSAT) and will lay the foundation that it makes sense for Project OWL to invest in designing a CubeSat by furthering the proof that their radios can communicate with spacecraft.

III. Background

1. Project OWL and their Ducks

Project OWL is a company developing a deployable communications network, dubbed ClusterDucks, to deploy in an area where the existing communication infrastructure is compromised. Their network consists of radios, called ducks, that provide WiFi hotspots for phones to message first responders over. Individual ducks can communicate with each other to form large mesh networks, quickly connecting people who may require help. These radios communicate using open-source firmware that controls the higher layers of the communication stack. The firmware is called the ClusterDuck protocol.

There are three main types of radios, DuckLinks, MamaDucks, and PapaDucks. DuckLinks are edge network devices that primarily read sensor data and transmit it to MamaDucks. MamaDucks can interconnect to form mesh networks and provide wireless access points for users to communicate. These radios relay messages to the PapaDucks, which are network gateways for the mesh networks to the world wide web. PapaDucks currently aggregate LoRa data and provide it to Project OWL's Data Management System, or DMS, which relays information to first responders that may be outside of the mesh network. [1]

2. RF Channel

The term RF channel refers to the negative impacts imparted on a signal as it propagates from a transmitter to a receiver. The channel most commonly consists of noise and attenuation, similarly, it includes effects such as Doppler Shift, caused by relative motion between the transmitter and receiver, or Multipath Loss, caused by delayed and attenuated versions of the transmitted signal arriving at the receiver at different times. In the scenario that we are studying, our channel is based on a radio on a LEOSAT communicating with a ground station. This satellite is orbiting at just over 400 km with an orbital velocity of 7.8 km/s, which introduces a maximum Doppler shift of 23 kHz. As the spacecraft flies overhead, the relative angle between the velocity vector of the spacecraft and the ground station increases until it is overhead, then decreases, which varies this shift over time.

3. The Doppler Effect

The Doppler Effect, or Doppler Shift, is the change in frequency of a transmitted signal that is induced by relative motion in the direction of the transmitter and receiver. For non-relativistic speeds, the amount of Doppler Shift $[f_D]$ on an electromagnetic wave can be represented as the product of the center frequency of the transmitted wave $[f_o]$ and the velocity of the receiver [v_{rx}] normalized to the speed of light, and multiplied by the cosine of the angle of elevation [α].

$$f_D = \frac{v_{rx} \cdot f_o}{c} cos(\alpha) \qquad (1) [2]$$

It is worth noting that the magnitude of the Doppler shift is maximized when the angle α is either 0° or 180°. This occurs when the satellite first appears and disappears over the horizon, and is moving at its fastest relative to the ground station.

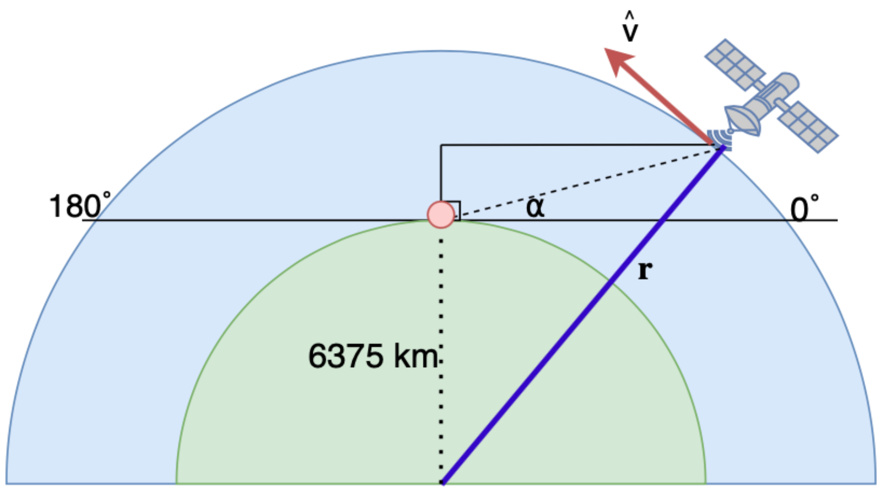

Figure 1: Doppler Shift Angle Consideration Diagram.

In Figure 1, the satellite flies overhead at radius *r*, with velocity vector $\hat{v}$. As the satellite flies overhead, the angle between the velocity vector of the satellite and path between the transmitter and receiver increases, decreasing the amount of Doppler shift over time. Figure 2 shows what the amount of Doppler shift would occur at different angles of elevation as the satellite flies overhead.

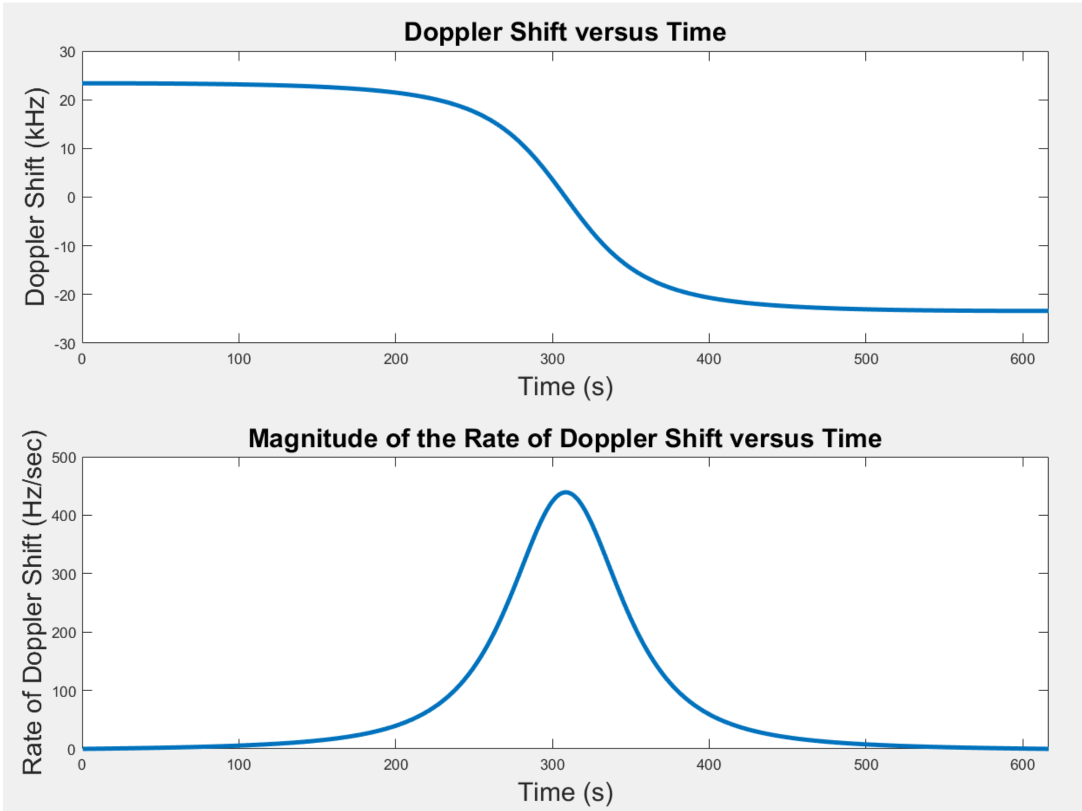

Figure 2: Doppler Shift versus Time.

4. Doppler Spread

In wireless communications, Doppler spread, B_d, is a measure of the spectral broadening due to the changing of the channel [3]. This phenomenon is not replicated by just modulating the center frequency of a spectrum, and must be considered if the difference of Doppler shift at the lowest end of the spectrum and highest end of the spectrum is on the order of the bandwidth of the signal.

For the LoRa waveform implemented by Project OWL, the center frequency is 915 MHz with a bandwidth of 250 kHz, bounded within:

$$f_{low} = 914.875 \text{ MHz}$$

$$f_{high} = 915.125 \text{ MHz}$$

To determine the amount of Doppler spread, the Doppler at the lower and upper ends of the spectrum are computed. In our test, the transmitter is moving at a maximum of 7.8 km/s relative to the receiver, so the respective maximum amount of Doppler shift is:

$$f_{D-low} = \frac{914.875x10^6 * 7.8\ x10^3}{3x10^8} = 23,786\ \text{Hz}$$

$$f_{D-high} = \frac{915.125x10^6 * 7.8\ x10^3}{3x10^8} = 23,793\ \text{Hz}$$

From this calculation, the maximum Doppler spread will be approximately:

$$B_d = 23,793 - 23,786\ Hz = 7\ \text{Hz}$$

As the difference in Doppler at the upper and lower bounds of the spectrum is substantially less than the bandwidth of the waveform, its impact is negligible and its effect can be omitted from our analysis.

5. LoRa - Chirp and Spreading Factor

Lora - “Long Range” is the communication physical layer Project OWL’s radios are using to communicate with Low Earth Orbit Satellites. LoRa involves spread spectrum modulation techniques derived from the chirp spread spectrum (CSS), and is highly resistant to channel noise [4]. A time domain chirp is shown in Figure 3.

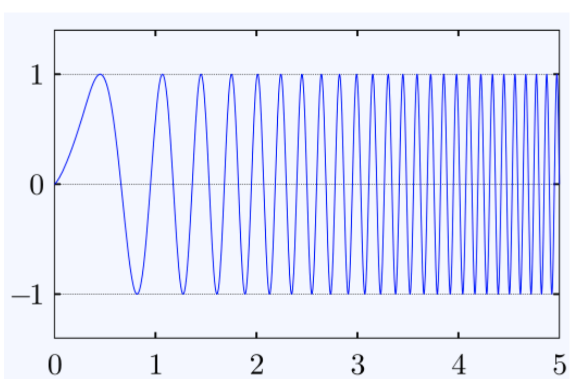

Figure 3: Time Domain Chirp Signal Example [5].

These chirps, or linear increases in frequency, relay information by varying the starting and stopping frequency of each chirp for each symbol, with an example shown in Figure 4. A LoRa chirp has 256 discrete starting frequencies, allowing for 8 bits to be transmitted per symbol.

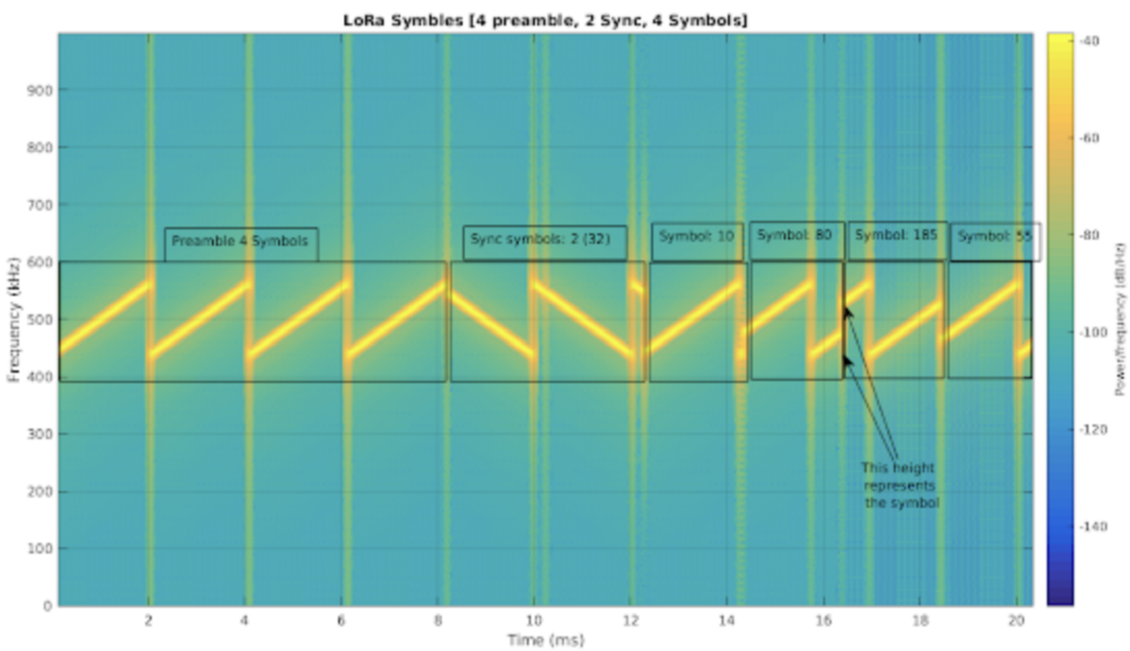

Figure 4: LoRa broken down into symbols [5].

Demodulation begins with the preamble, where some four to eight up chirps are transmitted to signify the beginning of a transmission to the receiver, then two down chirps are sent to synchronize the receivers. Each symbol is then compared to the reference chirp, with some static frequency offset determining the bits that were sent. Figure 5 depicts what this looks like on a spectrogram, with each symbol represented as a static frequency offset.

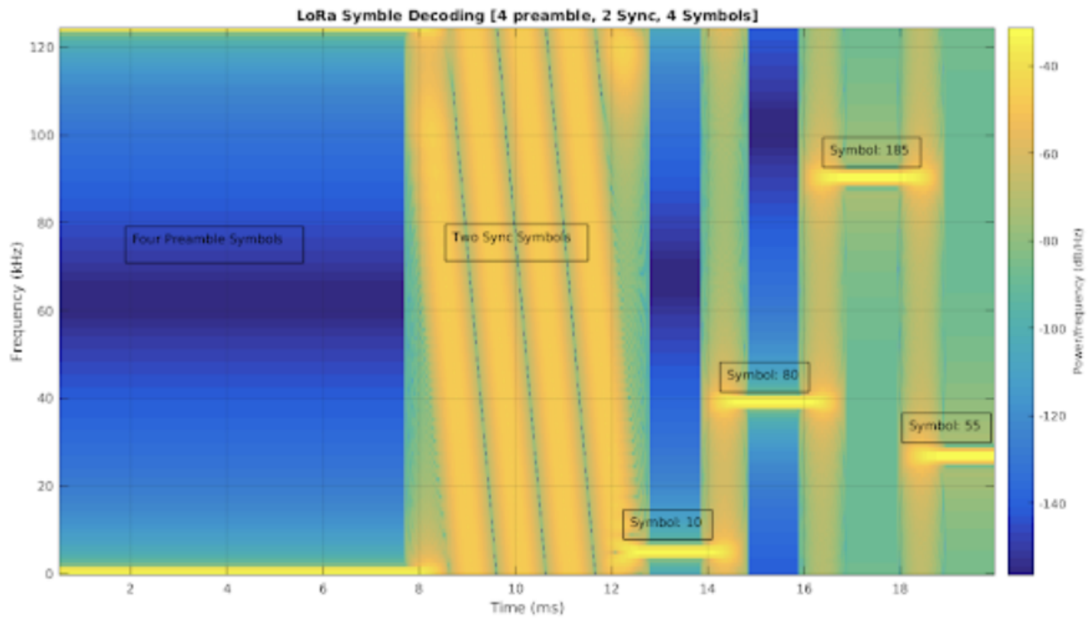

Figure 5: Baseband, decoded LoRa symbols [5].

The instantaneous chirp rate is determined by the spreading factor that is being employed, ranging from 7 to 12. Figure 6 is a spectrogram that shows how the different spreading factors change the chirp rate and symbol rate.

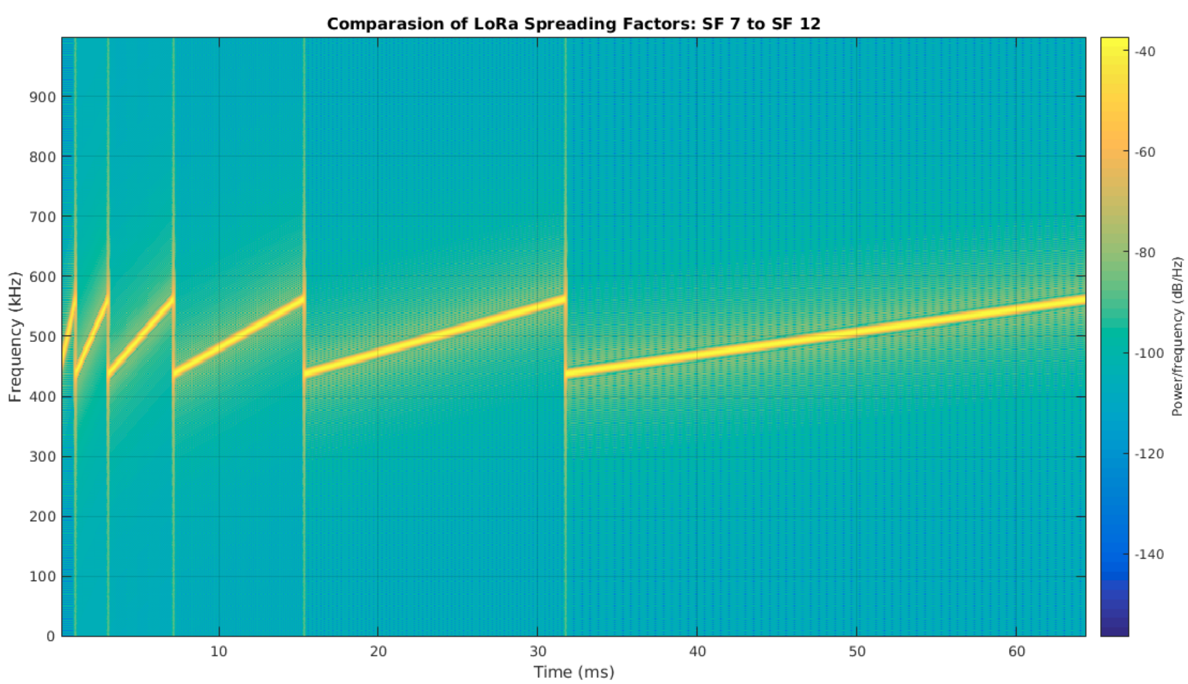

Figure 6: SF7 to SF12 up-chirp of 125kHz bandwidth Spectrogram [5].

Adjusting the spreading factor adjusts the Symbol Rate (Rs), transmission distance, and bandwidth (BW), as shown in (3). For a constant bandwidth, increasing the spreading factor decreases the symbol rate/ increases the symbol time, lowering the sensitivity power. In a communication system, the sensitivity power is referred to as the minimum signal power required in order to demodulate the signal with a fixed, low bit error rate.

$$R_s = \frac{BW}{2^{SF}} \qquad (3)[5]$$

As the spreading factor increases, both the data rate and the sensitivity power decrease, and conversely, decreasing the spreading factor increases the data rate and sensitivity power. LoRaWAN, a medium access controller for LoRa, has the capability to automatically adjust the spreading factor for deployed hardware [6].

6. Previously Completed Work

Last year, Kevin Nottberg and Omer Gumus studied the maximum range that one of the Project OWL's radios can receive a signal. They constructed a test setup that attenuated the transmitted signal to simulate the amount of signal decay that occurs over various ranges. Their work showed that the radios range at 850 km, with the possibility of being able to transmit further as they were not able to break the link with some spreading factors [7]. Our scope will follow up on their work by testing the immunity of LoRa to the next challenge of spacecraft communication, the Doppler shift.

IV. Customer Requirements and Engineering Specifications

TABLE II:
CUSTOMER REQUIREMENTS AND ENGINEERING SPECIFICATIONS

No #	Customer Requirement	Engineering Specifications	Justification
1	Demonstrate ClusterDuck protocol reliability when transmitting from a LEOSAT to Earth	1. Establish a link between two ClusterDuck radios with the transmitter at a fixed offset and stepped frequency.	Prove that the radio can receive a transmission with variable frequency offsets
		2. Establish the fixed offset link with the transmitter carrier frequency adjusted at the same rate as if it was being flown from the ISS.	Show that the radio can compensate for the Doppler shift introduced by transmission from a LEOSAT
		3. Characterize maximum rate of change of the carrier frequency where the link can be maintained.	The maximum rate of change will be a factor used to determine orbital ceiling for a LEOSAT
		4. Provide results for all spreading factors available to the protocol, if there are cases when the link can be maintained for some and lost for others.	If some spreading factors maintain a link longer than others, document any performance differences
2	Create a tool that parametrizes the transmission environment based on carrier frequency, orbital altitude and max TX distance.	1. Parameterize the maximum Doppler shift as a function of orbital altitude and maximum RX range	If a discovery is made that the maximum range is further than 850 km, make the tool easily adaptable for new scenarios
		2. Provide simulations and math that supports our findings and show accuracy of the test bench	Show that the distortion we are inducing is expected for LEOSAT communication
		3. Determine the range of Doppler effect that will be present at a given orbital altitude	Calculate the velocity of the LEOSAT in relation to the receiver, determine what the start and stop shifts will be
		4. Plot Doppler shift versus time for a LEOSAT with ISS orbital parameters that flies directly overhead	Allows us to generate a tunable voltage curve that can be applied to the system using a frequency source to generate the shifted signal
		5. Plot rate of Doppler shift versus time for a LEOSAT with parameterizable orbit that flies overhead	Rate of Doppler shift will be important parameter, frequency source on RX has finite frequency slew rate

		6. Generate a voltage signal that can be applied to a frequency source	Use software to generate an arbitrary waveform that accurately represents the Doppler shift
		7. Determine the minimum and maximum Doppler shifts and rates of Doppler shift that will occur from the orbital altitudes between 400 and 1200 km	With a 1200 km LEO orbital ceiling, we should be able to acquire sufficient data points to determine the maximum orbital altitude
3	Comply with federal, state, and local regulations surrounding radio transmissions when transmitting outside of a Faraday Cage	1. The Transmitter must not have a sustained output power greater than permitted	If transmitting over the air, we have obligations to conduct our testing legally
		2. The Transmitted waveform must not spill over into non ISM bands	If transmitting over the air, we cannot interfere with other people that are communicating
4	Hardware must interface with existing Duckling hardware	1. Test bench must interface with existing duck radios and not require a proprietary transmitter	Should not be too complex of a system where proprietary hardware is required

TABLE III:
ENGINEERING SPECIFICATIONS

Spec #	**Parameter**	**Requirement**	**Target (units)**	**Tolerance**	**Risk* (H, M, L)**	**Compliance** (A, T, S, I)**
1	Resolution of Frequency Source	1.1-3, 3.2	100 Hz	Absolute Maximum	M	A
2	Frequency Source Slew Rate	1.4, 2.6	$\Delta f > 5$ kHz/sec	1 kHz/ sec	L	A, T
3	Simulation Range	2.1,2.7	850 km	Maximum	M	T, I
4	Radiated Power	3.1	$P_{antenna} < 30$ dBm EIRP < 36 dBm	Absolute Maximum	H	T

* Risk Ranges between: High (H), Medium (M), Low (L).
** Compliance: Analysis (A), Test (T), Similarity (S), Inspection (I).

V. Functional Decomposition

1. Level 0 Decomposition

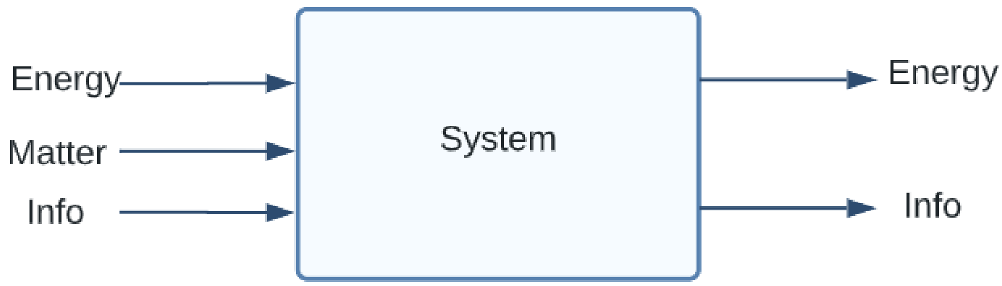

Figure 7: Level 0 Decomposition of our system.

TABLE IV:
SYSTEM INPUTS AND OUTPUTS

System I/O	Input	Output
Energy	Electromagnetic Energy - Hardware will be consuming energy to perform computation of parameters and execution of task Mechanical Energy - User has to input parameters into software with computer interface	Electromagnetic Energy - If over the air communication is done, there will be radiation from our testing Thermal energy - Computer and radios will dissipate heat during testing
Matter	Radios - Test is run on hardware, needs the radios in order to run the test. Computer: Medium to run the software for the test bench Frequency Source - The testing will be performed by modulating the frequency of the transmitted waveform	No material output
Information	LEOSAT Parameters - Each test is based on a provided satellite orbit, software executes test based on these parameters, also specified how many tests to run	Display whether the link is maintained or not

2. Level 1 Decomposition

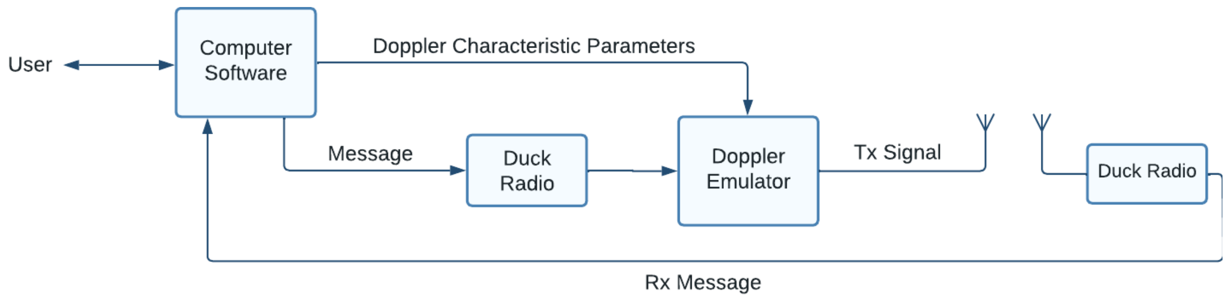

Figure 8: Level 1 Decomposition of our system.

TABLE V:
SOFTWARE INPUTS AND OUTPUTS

	Input	Output
Energy	Electromagnetic Energy - Software will run on a computer that requires electric energy to run	Electromagnetic Energy - If over the air communication is done, there will be radiation from our testing Thermal energy - Computer will dissipate heat while operating
Matter	Computer: Medium to run the software for the test bench	No Material Outputs
Information	User will operate the software and define the parameters for a simulation	Doppler Shift versus time for the Doppler Emulator, relay back to user the results of the test

TABLE VI:
TRANSMITTING RADIO INPUTS AND OUTPUTS

	Input	Output
Energy	Electromagnetic Energy - Both radios will require electric energy to operate	Electromagnetic Energy - The devices will radiate Electromagnetic Energy into the environment to communicate
Information	The radio will take in data from the control software to convert into an Electromagnetic wave	Electromagnetic energy that embodies the data that was sent into the radio

TABLE VII:
RECEIVING RADIO INPUTS AND OUTPUTS

	Input	Output
Energy	Electromagnetic Energy - The radio will require electric energy to operate - The radio will take in information in the form of Electromagnetic waves.	Electromagnetic Energy - The devices will radiate Electromagnetic Energy into the environment to communicate Thermal energy - microcontrollers onboard will generate heat
Information	The radio will receive the Doppler shifted waveform and attempt to decode it	The device will output its best guess at what was sent by the transmitting radio

TABLE VIII:
DOPPLER EMULATOR INPUTS AND OUTPUTS

	Input	Output
Energy	Electromagnetic Energy - The device will take in Electromagnetic energy from the Duck Radio and signals from the software - The device will consume electric energy to operate	Electromagnetic Energy - The device will emit Electromagnetic Radiation Thermal energy - The hardware may dissipate heat as they consume power
Information	The device will take in information from the software about the Doppler shift it has to impart at a given time	A Doppler shifted LoRa waveform that will be received by a Duck Radio.

VI. Budget

TABLE IV:
TOTAL SYSTEM BUDGET

Component	Purpose	Optimistic Cost	Pessimistic Cost	Most Likely Cost	Expected Cost	Quantity	Expected Cost
ClusterDuck Radios	Radios to perform the test on, provided by Project OWL	$0.00	$0.00	$0.00	$0.00	2	$0.00
1.5 GHz Mixers	Perform frequency conversions to add Doppler shift	$35.00	$70.00	$42.00	$45.50	4	$182.00
Band Pass Filters	Remove mixer images from the signal path	$40.00	$70.00	$50.00	$51.67	4	$206.67
FM Transmitters	OTC Frequency Source	$8.00	$40.00	$25.00	$24.67	1	$24.67
Fractional N PLL	Frequency source that allows for fine tuning of output frequency	$250.00	$450.00	$325.00	$333.33	1	$333.33
SDRs	Ettus Research USRPs, provided by Dr. Derickson	$0.00	$0.00	$0.00	$0.00	1	$0.00
Vector Signal Gen	Exploratory frequency source, already in Photonics Lab	$0.00	$0.00	$0.00	$0.00	1	$0.00
Software License	Either MATLAB/Octave or Python. MATLAB Access is provided by Cal Poly, both Octave and Python are free	$0.00	$0.00	$0.00	$0.00	1	$0.00
Engineering Hours	Gantt chart estimates per person hours, engineering hours is for both engineers	$35.00	$45.00	$42.50	$41.67	332	$13,833.33
					Hardware Total		$746.67
					Project Total		$14,580.00

VII. Architectural Design

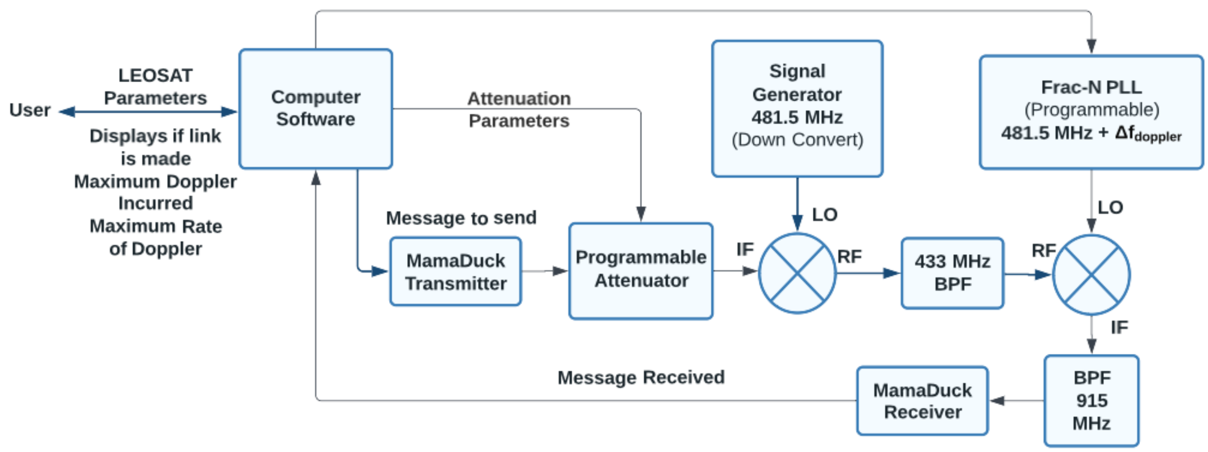

Figure 9: Designed System Architecture.

The proposed system design will consist of computer software to execute the test, a frequency source to introduce the Doppler shift, two mixers and band pass filters, a stable frequency source, and two of Project OWL's MamaDuck radios. To perform the test, the user will input Satellite parameters, and the software will create a frequency versus time profile to match the Doppler shift that would occur in the channel between the transmitter and receiver. This profile will be translated for use with a variable frequency source, such that the output waveform is a sinusoid whose frequency is Doppler shifted, such as in (4).

$$sin(2\pi(f_1 + f_D) * t) \quad (4)$$

To apply the Doppler shift to the LoRa waveform, the output of the MamaDuck transmitter is downconverted with the Doppler shifted waveform, then filtered to remove spurious images introduced by the mixing process. Then, the signal is upconverted by a sinusoid of fixed frequency f_1 and filtered such that the remaining signal is a LoRa chirp that has been Doppler shifted by the amount f_D. This is then broadcast over the air to the MamaDuck receiver, where the transmission is decoded, and sent back to the controlling software. The software then checks the reception against what was sent and determines what errors were made.

Our design is still very open ended to the different frequency sources that we have available, with the most prominent contenders being a Fractional N PLL, Ettus research SDR, an Agilent E4438C Vector Signal Generator. At this moment in time, an FM transmitter is also being considered, however we may have issues finding commercially available band pass filters that support the frequency offset introduced by a commercial FM transmitter.

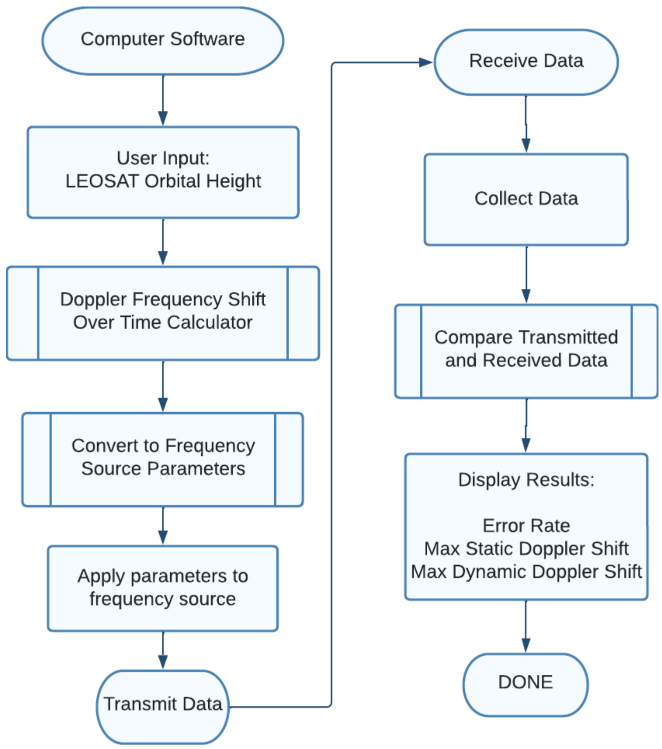

Figure 10: Software Architecture.

Once a user has initiated a test, they will input the orbital altitude of the LEOSAT that they want to test for. The software will calculate the corresponding velocity of the satellite, then generate the Doppler shift versus angle of elevation as the satellite flies overhead. To convert this to Doppler shift versus time, the software will compute the law of cosines twice on Figure 11, which is a repeat of Figure 1.

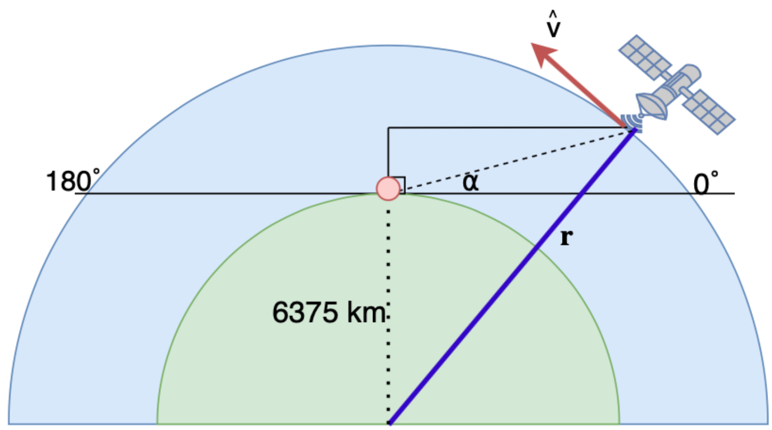

Figure 11: Satellite Orbit Example.

First, the software calculates the distance between the ground station and the satellite. It calculates the distance using the law of cosine property by stepping the angle between the distance from the center of the earth and the ground station, and between the center of the earth and the satellite. The second calculation determines what the angle alpha is for each of these steps. To do this, all 3 side lengths of the triangle will be known, so the law of cosines can be rewritten such that the unknown is the angle containing alpha plus 90 degrees. By assuming that the satellite follows a circular orbit, the radial velocity of the satellite can be approximated as linearly increasing with time, at a rate determined by the orbital velocity and height of the craft. Combining these calculations allows us to parameterize the Doppler shift over time, allowing us to create our frequency profile for the frequency source.

After the profile is created, the software will begin sending a predetermined file to the MamaDuck radio and applying the frequency profile to the frequency source. Once transmission starts, the computer will begin monitoring the MamaDuck receiver radio, and determine if the information being received is the same as what is being sent.

VIII. Implemented Design and Software

The first implementation of our channel emulator consisted of the following components, with the layout shown in Figure 12.

TABLE V:
INITIAL DESIGN COMPONENTS

Specified Component	Acquired Component
ClusterDuck Radios	Project OWL radios
1.5 GHz Mixers	Mini Circuits ZEM-4300 Mixer
Band Pass Filters	Crystek 915 MHz SAW Band Pass Filter
Band Pass Filters	Crystek 433 MHz SAW Band Pass Filter
Step Attenuator	Mini Circuits RUDAT Programmable Attenuator
Fractional-N PLL	Analog Devices ADF4355-2 Fractional-N PLL

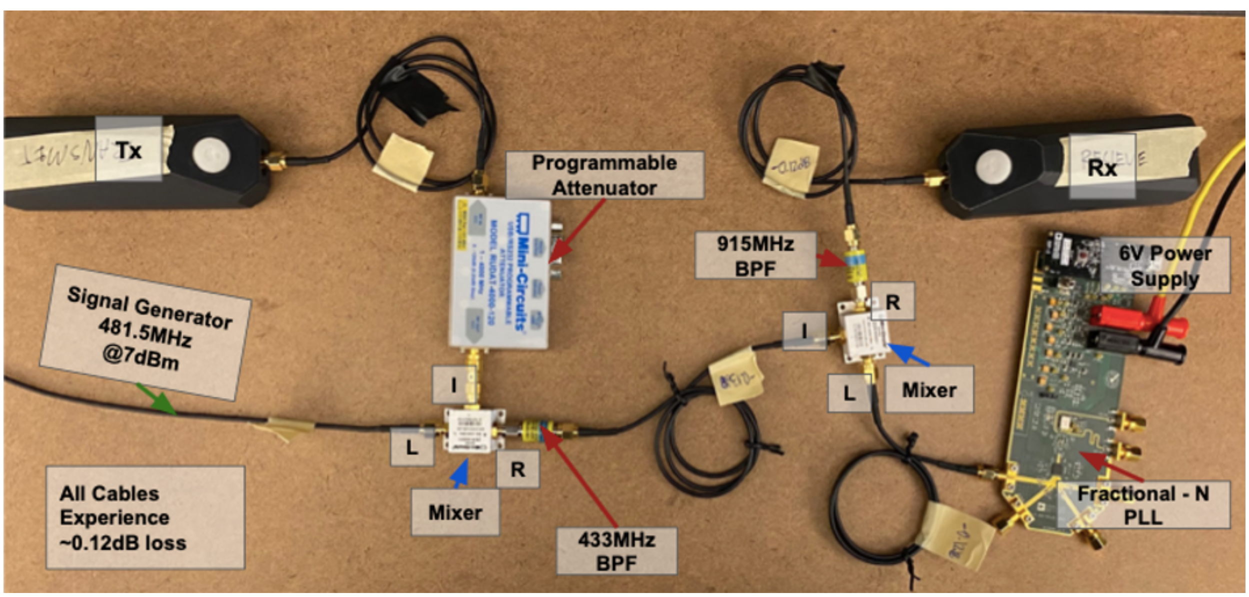

Figure 12: Initial Channel Emulator with labeled components.

IX. Data Collection

In our first round of data collection, we tested how our system behaved with static frequency offsets. Our test parameters were measuring how the Bit Error Rate (BER) and number of dropped packets changed over different frequency offsets. The BER is a direct measurement of the probability of error of a given system, and the number of dropped packets measures if the transmitted message is heard by the receiver. Each test we performed consisted of sending 1 million bits, or 491 packets of 2000 bits, over our channel, and at a Signal to Noise Ratio (SNR) of 3.5 - 4.5 dBs. We conducted our first round of tests with three different frequency offsets: no offset, -23 kHz, and +23 kHz. We selected these specific tests for two reasons: first, the no offset test served as a baseline to measure against in the presence of errors introduced by our channel, and secondly, a magnitude of 23 kHz offset represents the expected amount of Doppler shift caused by a satellite in Low Earth Orbit (See Figure 2). The figures below illustrate the BER and the number of dropped packets as a function of Spreading Factor at coding rates 5 and 8.

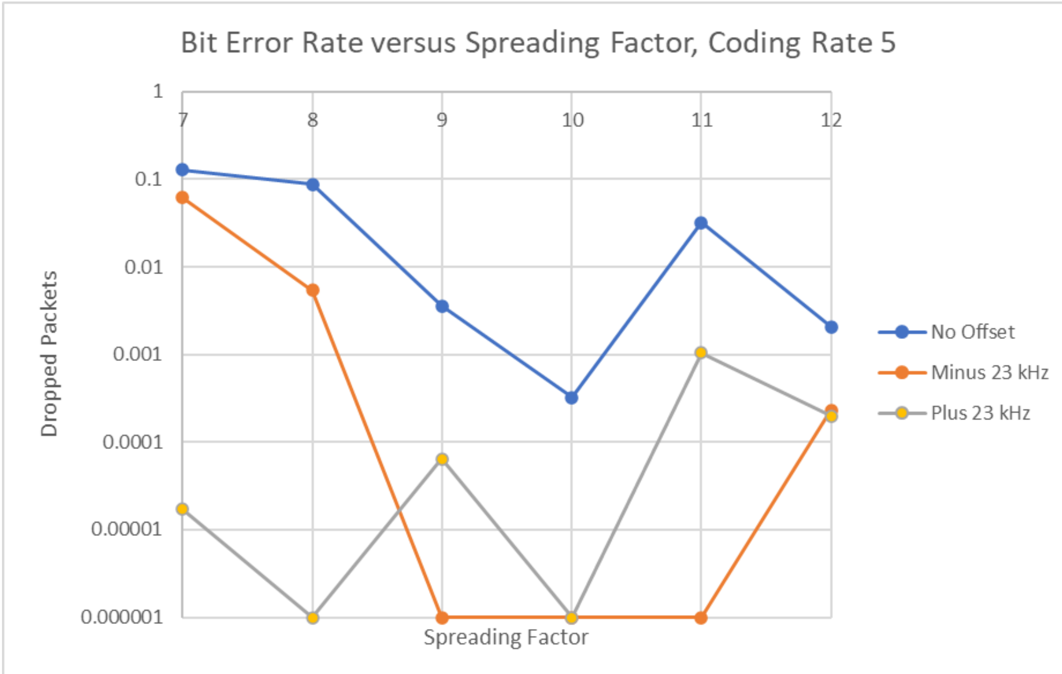

Figure 13: BER versus Spreading Factor, Coding Rate 5.

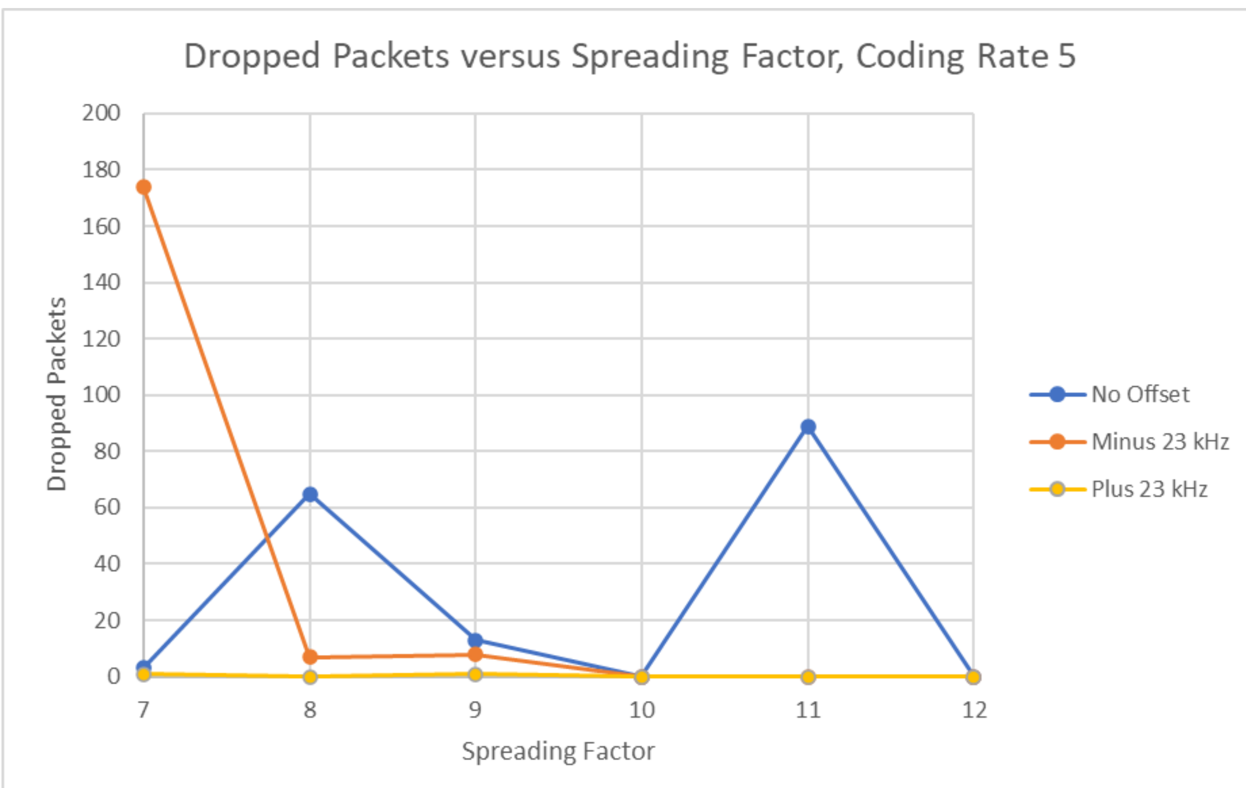

Figure 14: Dropped Packets versus Spreading Factor, Coding Rate 5.

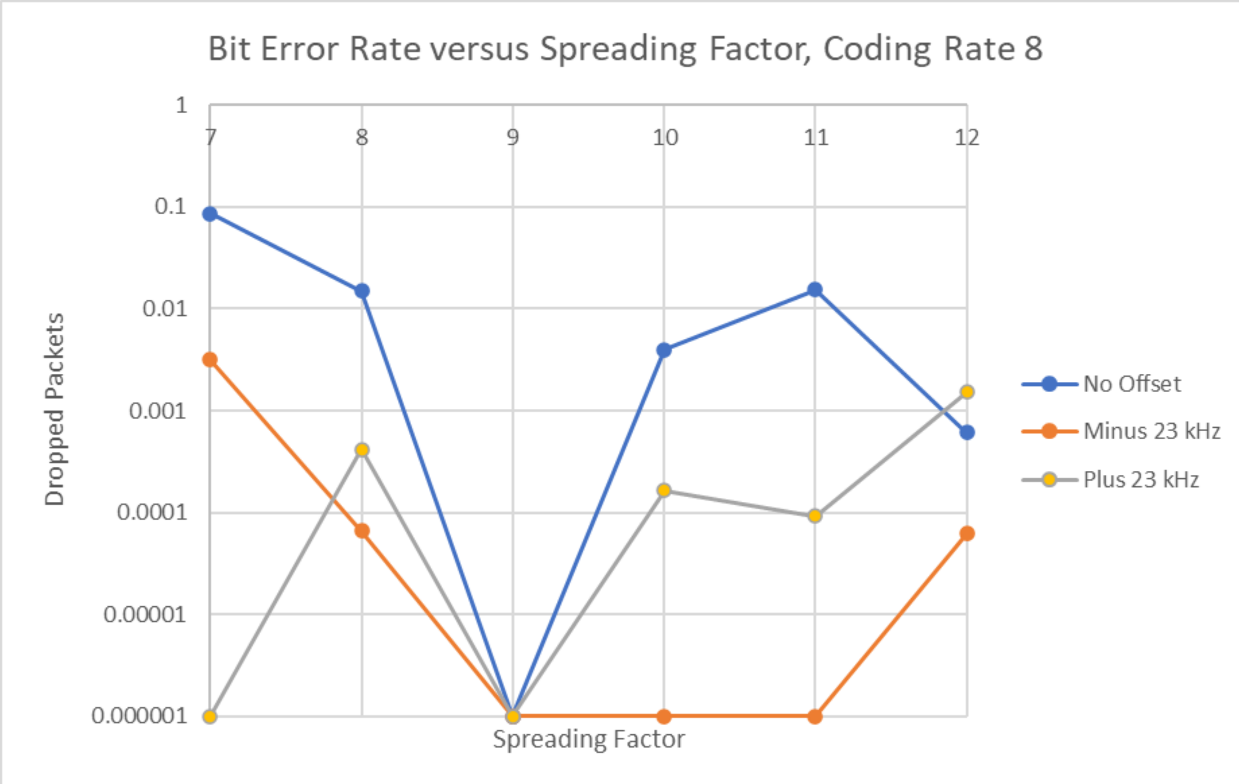

Figure 15: BER versus Spreading Factor, Coding Rate 8.

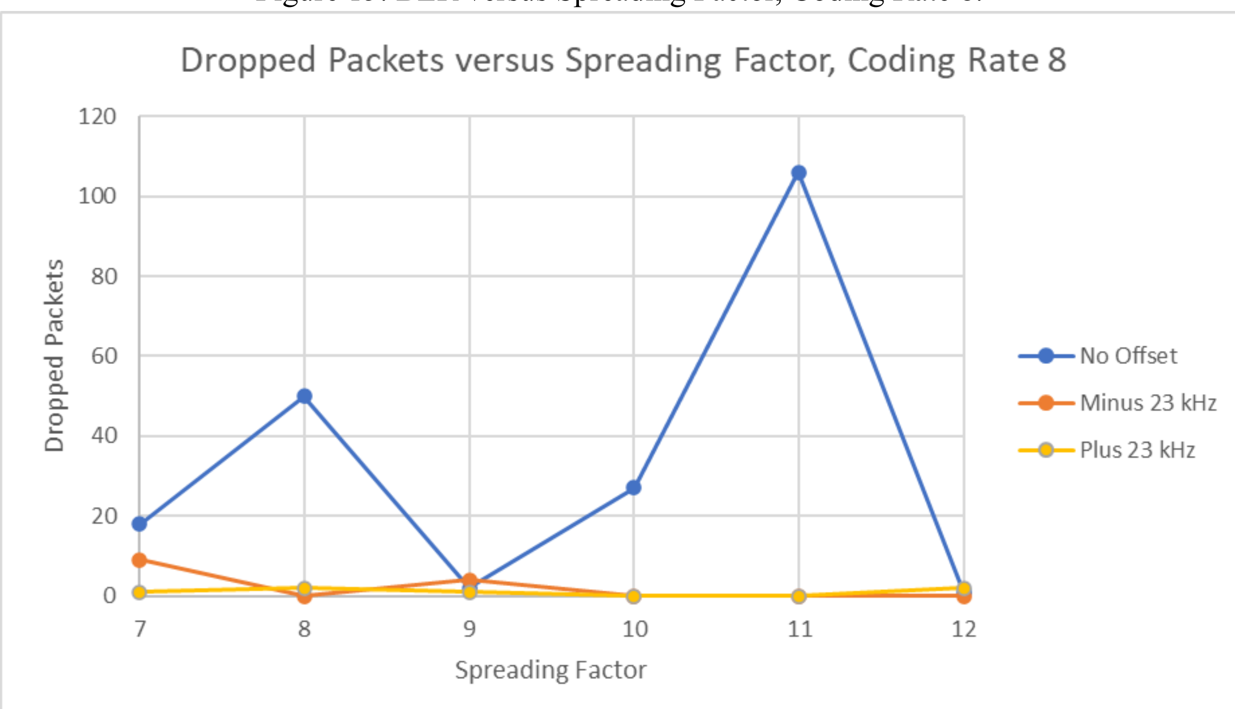

Figure 16: Dropped Packets versus Spreading Factor, Coding Rate 8.

During our initial set of tests, we observed an unusually high Bit Error Rate and number of dropped packets in the test without any frequency offset. However, in almost every other test with different frequency offsets, these values were lower. The decrease in these metrics indicates that there is merit to LoRa being able to handle static offsets, but the presence of errors in our channel indicate that there were unintended errors being introduced by our channel.

X. Architecture Revisions

After conducting numerous testing iterations and collecting inconsistent data, we have come to the realization that the emulated system may not be behaving as expected. As part of our investigation, we disconnected the receiving radio from our channel and performed an additional test to determine the level of coupling that was present in our radios. In this test, we saw that the number of dropped packets and BER was significantly lower, indicating to us that there was severe coupling between the two radios. In other words, communication was still occurring even when the link between the radios was supposed to be broken.

To combat this, we put both of the radios in Faraday Cages to decrease the crosstalk between the radios. A Faraday cage is a structure designed to block external electromagnetic interference and contain electromagnetic fields within it. In the context of wireless communication, a Faraday cage can be used to prevent unwanted electromagnetic coupling or interference from affecting the signal transmission. It acts as a shield by effectively blocking external electromagnetic waves and maintaining a controlled electromagnetic environment within the cage. This helps ensure reliable and undisturbed wireless communication by minimizing the impact of external electromagnetic influences.

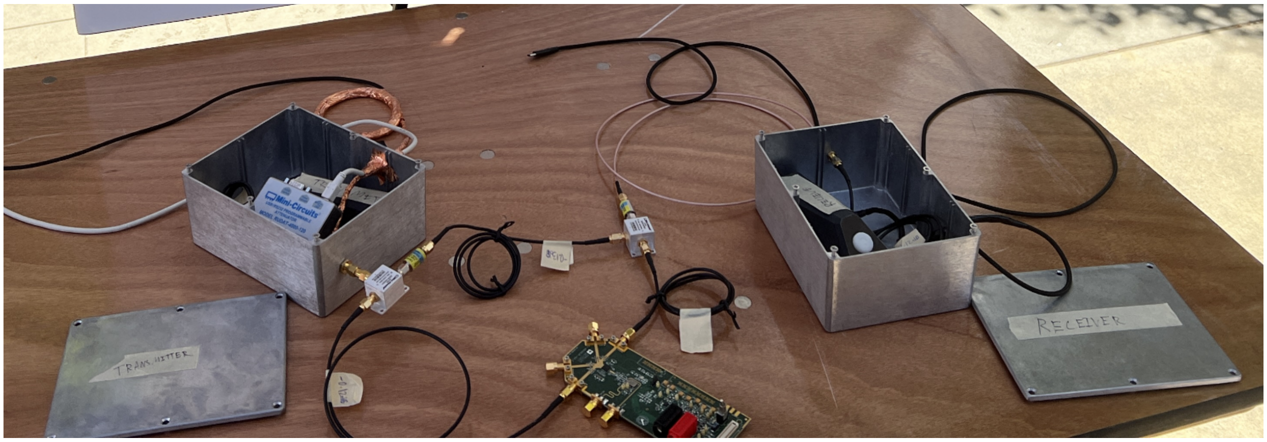

Figure 17: Radios in their respective Faraday cages, representational image.

To measure the amount of coupling present in our system, we employed an RTL-SDR utilized spectrum-analyzing software to detect LoRa transmissions while the radios were communicating. The software would capture the power level of any leakage transmission, which would allow us to quantify the amount of leakage occurring in our system. Before we isolated our radios, we measured leakage of about -25 dBm in the immediate vicinity surrounding the radios, and after isolation, approximately -55 dBm. While our isolation was not perfect and we still detected a minute amount of leakage, assuming that there was an additional 30 dB of shielding on the receiver, the power of the leakage signal would be reduced to -85 dBm, below the noise floor and well below the sensitivity power of the radio.

Figure 18 depicts the amount of leakage signal that we measured using the RTL-SDR.

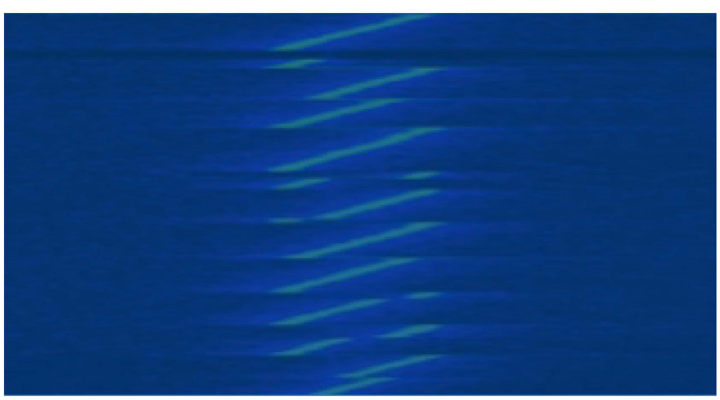

Figure 18: RTL-SDR Capture of LoRa Crosstalk after isolation.

XI. Final Results

After we insulated both radios and confirmed that there was no further crosstalk between the radios, we measured the BER and number of dropped packets at static frequency offsets from minus 50 kHz to positive 50 kHz in 10 kHz increments. It is worth noting that the absolute maximum amount of doppler that can be experienced by a satellite in Earth Orbit is ~25 kHz, we recognize that it would be valuable to know the maximum static frequency offset that LoRa can compensate for. This is valuable because it tells us how much buffer room there is in frequency offset before LoRa fails to compensate. At each frequency offset, we measured the performance at all 7 spreading factors and 4 coding rates. The Signal to Noise Ratio (SNR) for each test is shown in Figure 18, organized by coding rate and graphed by spreading factor, and the results of each test are shown in the subsequent figures.

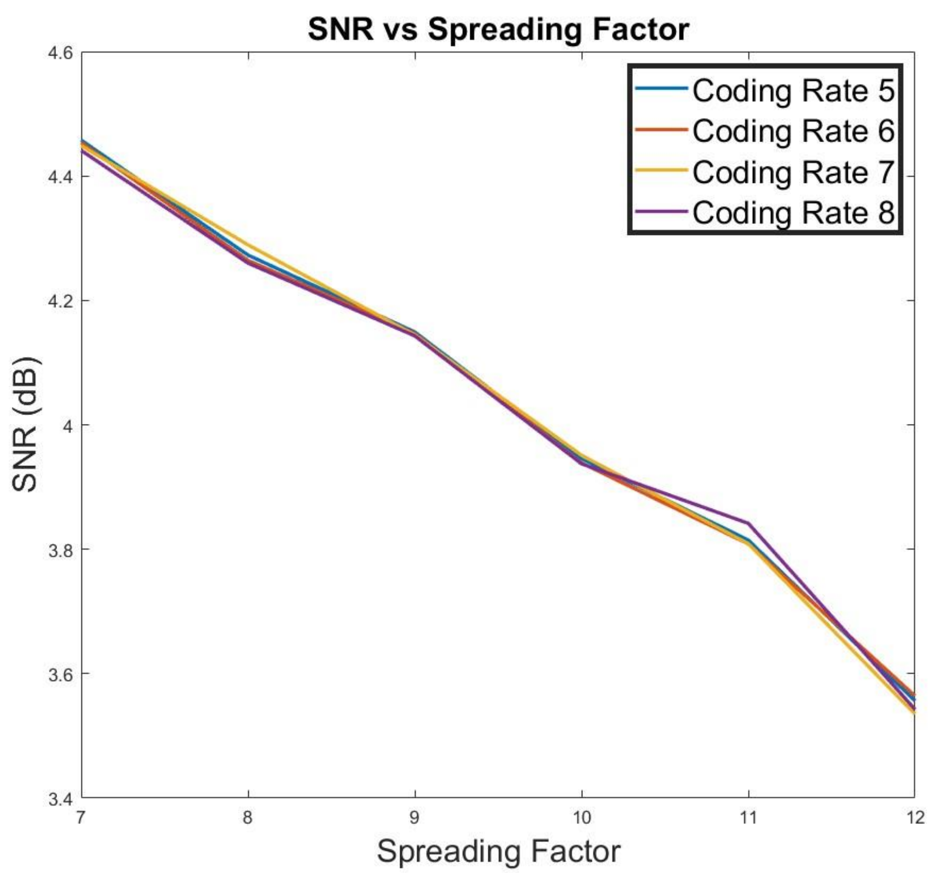

Figure 19: SNR vs Spreading Factor for all covered tests.

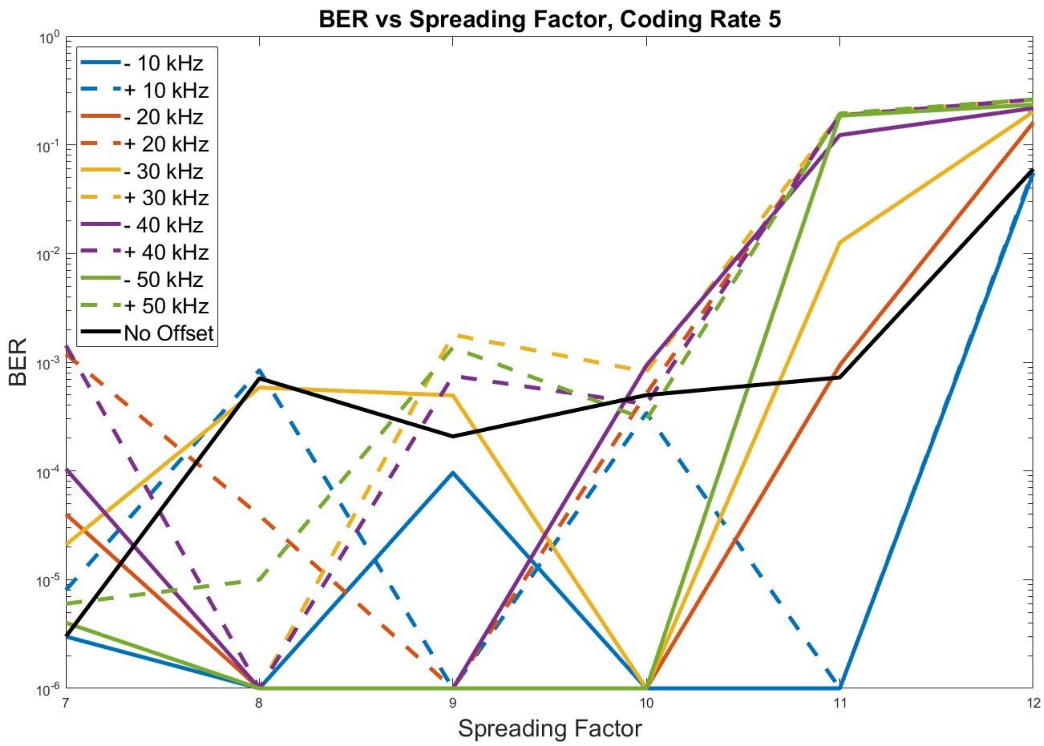

Figure 20: BER vs Spreading Factor, Coding Rate 5.

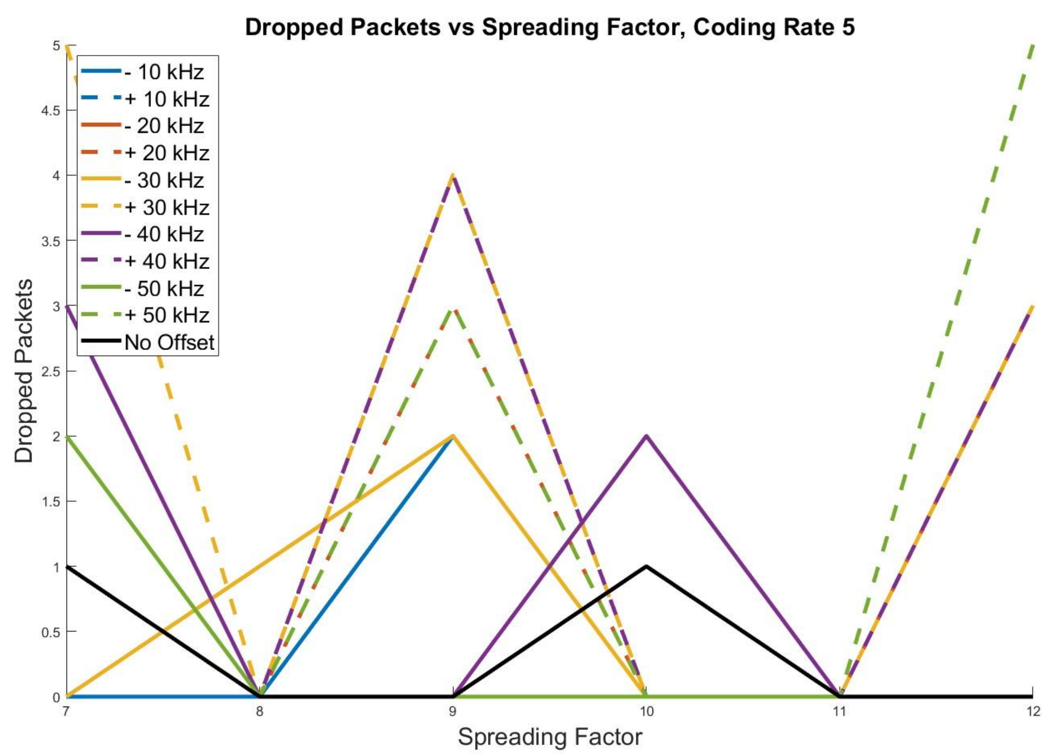

Figure 21: BER vs Spreading Factor, Coding Rate 5.

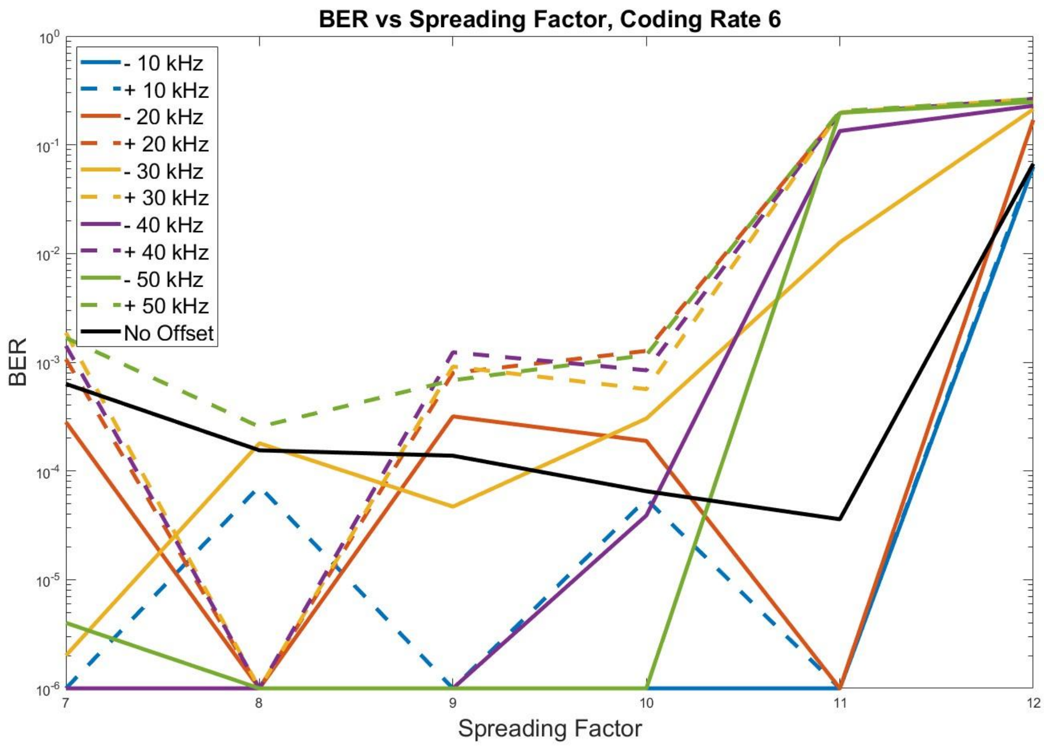

Figure 22: BER vs Spreading Factor, Coding Rate 6.

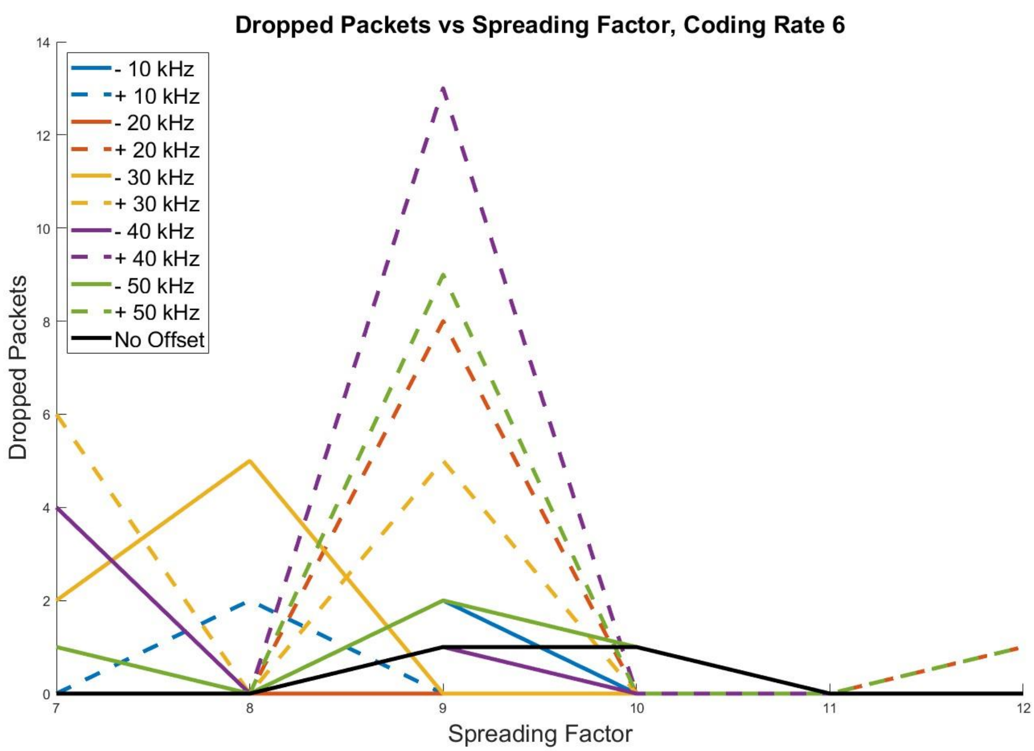

Figure 23: Dropped Packets vs Spreading Factor, Coding Rate 6.

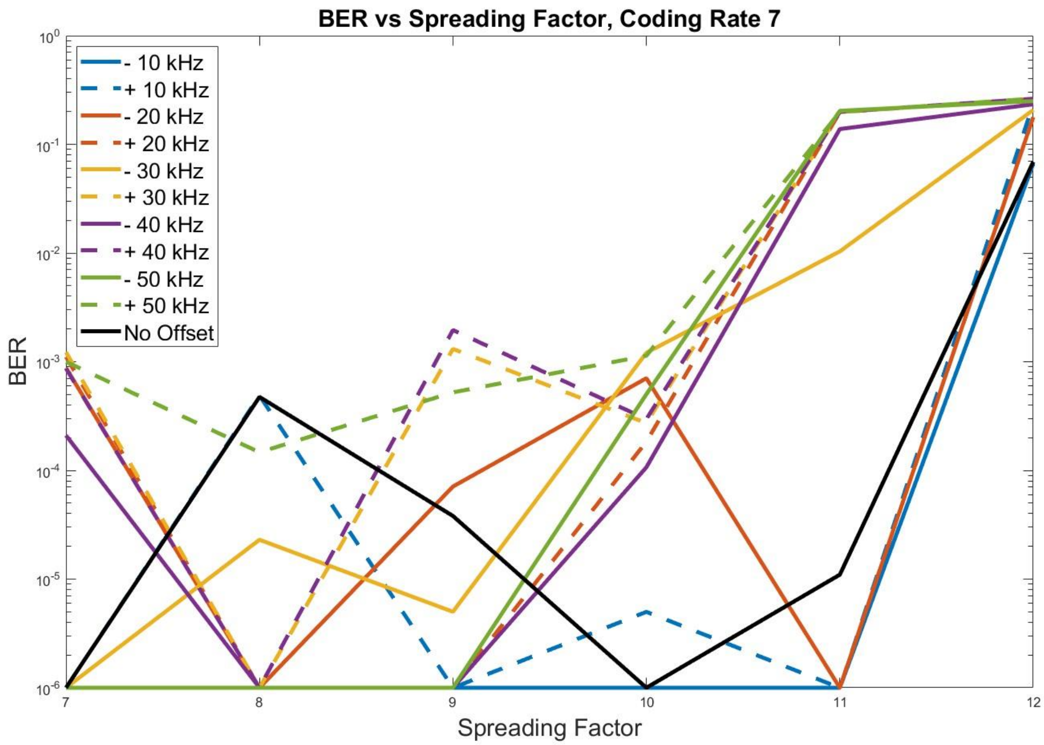

Figure 24: BER vs Spreading Factor, Coding Rate 7.

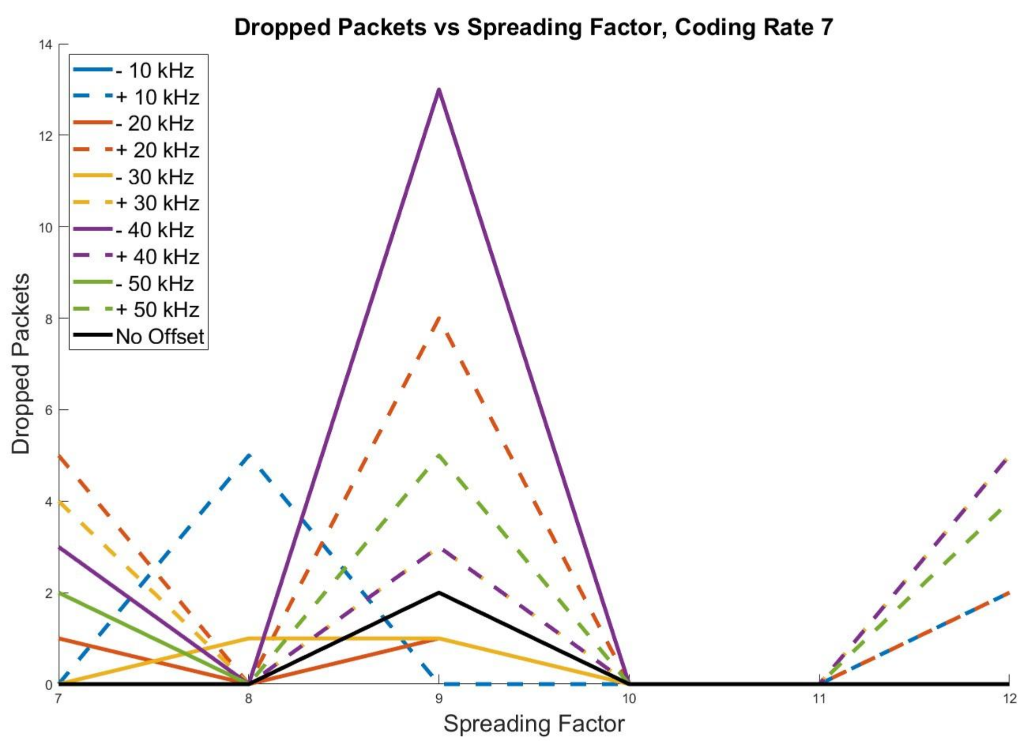

Figure 25: Dropped Packets vs Spreading Factor, Coding Rate 7.

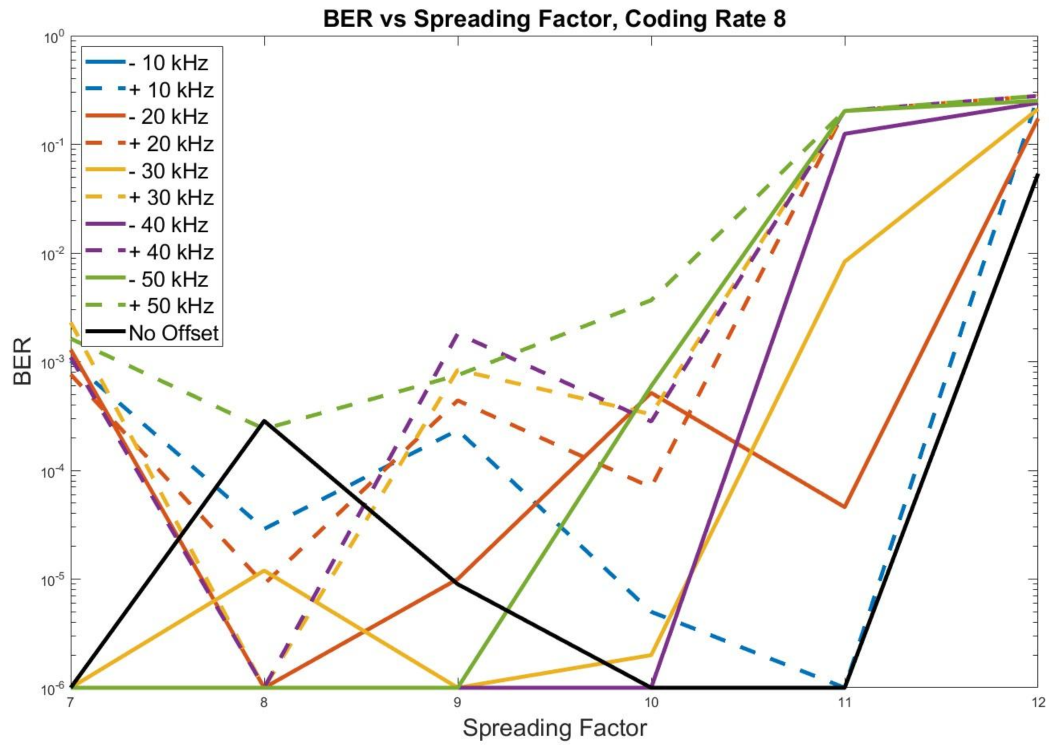

Figure 26: BER vs Spreading Factor, Coding Rate 8.

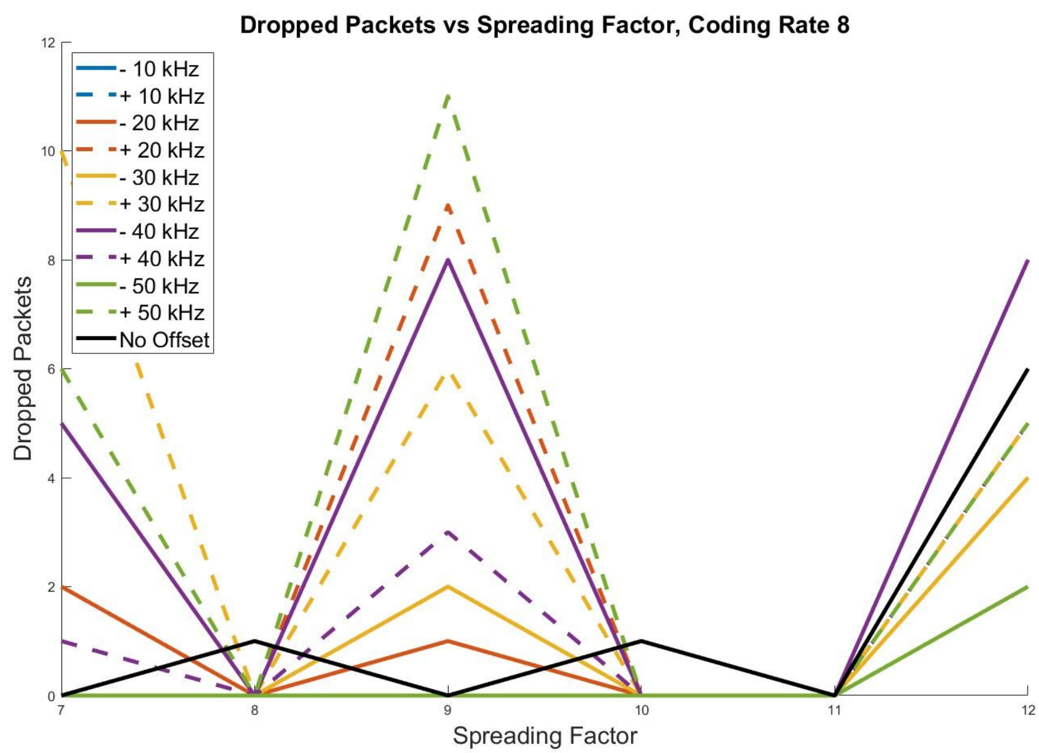

Figure 27: Dropped Packets vs Spreading Factor, Coding Rate 8.

In our tests, we saw that the number of dropped packets had decreased to single digits, indicating that our isolation had removed the erroneous transmissions that were leaking through our channel. In our tests, the low SNR resulted in a non-zero BER in our no offset case, but showed that LoRa could still operate in the presence of a static frequency offset, given a high enough SNR. For spreading factors 7 through 10, we noted that communication with LoRa is still possible, yet not nominal, and for spreading factors 11 and 12, communication is not possible. This is because the SNR has degraded past the point where LoRa can reliably operate, and methods such as directional antennas should be employed to boost the signal if this were to be deployed in the field.

When comparing the performance of the system with and without a static frequency offset, we can conclude that the presence of a frequency offset does introduce some degree of error, however we were not able to generalize how much error was introduced. This is because the variability of error between tests was high, as almost none of the frequency offsets behaved the same from test to test. Furthermore, we noticed that at a spreading factor of 9, there was an inexplicable increase in dropped packets across almost every test that we performed.

XII. Discussion

In reviewing our data, we identified a few potential sources of error that may have corrupted some of the data that we took. In our channel emulator, we used an Agilent E4438C Vector Signal Generator (VSG) to produce a stable 481.5 MHz tone for our first mixer. This VSG was out of calibration, resulting in the output amplitude and frequency to be slightly misaligned with the values that we input. The best that we were able to correct for this was by measuring the output of the VSG with a power meter and spectrum analyzer, but we noted that the amplitude would change by $\pm\ 0.5$ dB over time. The introduction of an unstable LO source resulted in a fluctuating conversion loss in that mixer, impacting our results

Furthermore, the radios used by Project OWL are possibly not 50 Ω terminated, as they are designed to be used with 915 MHz antennas that do not have a characteristic impedance of

50 Ω. With non-matched radios, that would result in excess reflections in the channel, introducing unwanted Inter-Symbol Interference (ISI) and impacting our system's performance.

XIII. Conclusion

In our tests, we found promising results for LoRa to be used in LEOSAT communication in the presence of a static frequency offset. Due to the low SNR, our BER was higher than expected which resulted in less than nominal results, however, this effect can be mitigated with the use of directional antennas, boosting the received signal strength in a realized system where the attenuation cannot be backed off. The next stage of testing the durability of LoRa to the effects of doppler would be to implement an emulation of dynamic doppler. The effect of changing the frequency during packet transmission would introduce symbol collisions, as LoRa symbols are static frequency offsets when decoded, and are spaced by 256 Hz. To test for this, future research groups could introduce a linear chirp instead of a static frequency offset. As of now, we predict that the effects of this can be mitigated in two ways. The first proposal is to shorten the packet duration, which decreases the overall data rate with increased overhead but decreases the amount of accumulated frequency error in packets as the offset is adjusted for more frequently. The second proposal is to introduce a RF front end that compensates for the introduced doppler, as the frequency offset is completely deterministic for a LEOSAT as it flies overhead and can be easily compensated for.

XIV. Works Cited

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XV. Appendix A - ABET Analysis

Project Title: Emulating the Doppler-Shift for LoRa based Low Earth Orbit Satellite Communication

Student's Name: John Gharib, Ariel Freiman

Student's Signature:

Advisor's Name: Dennis Derickson

Advisor's Initials:

Date: June 16, 2023

1. Summary of Functional Requirements

Our project allows us to test the performance of LoRa, a wireless communication waveform, when presented with static doppler offsets. To do this, we take the signal from a radio and introduce a static frequency offset before delivering it to a receiver that attempts to decode the transmitted data.

2. Primary Constraints

In our project, we encountered significant difficulty with isolation between the two radios in our system, which led to significant RF leakage and crosstalk. To combat this, we utilized electrical isolation boxes (Faraday cages) that significantly limited the amount of leakage present in the system. A further complication in our design was the implementation of a microcontroller, as the dependencies to implement dynamic doppler using one was more overhead than we were willing to take on.

3. Economic Impacts

TABLE VI:
Final Bill of Materials

Part Number (Supplier)	Component	Description	Justification	Component Link	Unit Price	Quantity	Total
ZEM-4300+ (Mouser)	RF Mixer	RF Mixer, 300 to 4300 MHz	Required for the frequency conversions	Link	$96.54	4	$386.16
CBPFS-0915	Band Pass Filter	915 MHz CF, 26 MHz BW	Transmit filter	Link	$44.06	2	$88.12
CBPFS-0433	Band Pass Filter	433 MHz CF, 10 MHz BW	Image Reject Filter	Link	$36.82	2	$73.64
CO-174SMAX200-002	SMA Cables	2 foot, 50 Ohm SMA cables	Use for interconnects of our components	Link	$15.16	4	$60.64
EV-ADF4355-2SD1Z	Frac N PLL	Eval board for the ADF4355-2 Frac N PLL	Highly accurate Frequency Source	Link	$346.07	1	$346.07
EVAL-SDP-CS1Z	Control Board	Controller for the ADF4355-2 Eval Board	Required for the PLL	Link	$62.71	1	$62.71
471-SMACONNECTOR	SMA Connector	50 Ohm SMA Connectors	If the selected image reject filter fails, we can replace with our own design	Link	$1.40	4	$5.60
132360	50 Ohm Terminators	SMA 50 Ohm Terminators	Terminate unused ports on the PLL	Link	$4.46	6	$26.76
Bao Boxes	Faraday Cages		Faraday Cage Construction	Link	$26.30	2	$52.60
						Total Cost:	$1102.30

As our project is not a commercial product, it is not being advertised for profit and there is no product release. All of our expenses were generously covered by Project OWL, which we are very thankful for.

Originally, we estimated that we would spend 332 engineering hours on our project, totaling $13,833.33 at an hourly rate of $41.67. In reality, we spent closer to 350 engineering hours on our project, which would have totaled $14,583.33. This is because we spent slightly more hours debugging software and hardware than we anticipated, but was not far off from our initial estimate.

4. **If manufactured on a commercial basis:**

As our device is a one-off channel emulator, it will not be produced on a commercial basis.

5. **Environmental**

Environmental impacts associated with our project are related to the sourcing of Silicon and GaAs components/ crystals. The impacts of sourcing these can be devastating to the environment if not done properly, but on the low scale of our project, will not put a large impact on the already sky-high demand for silicon products.

6. **Manufacturability**

As we built a channel emulator for measurements, it is not a product that will be manufactured and sold on a commercial basis. The components that we sourced are all off the shelf, and do not require any special tooling or set up cost to produce.

7. Sustainability

An upgrade to the design would be the implementation of a microcontroller to allow for dynamic shifts in frequency, which we were unable to accomplish in this timeframe. To implement this, students would have to interface with the PLL using a serial connection, with further documentation described in it's datasheet

8. Ethical

The most prominent ethical concerns with our project is unsustainable production of silicon/ metal products that were used in our system, as the production of items such as cast aluminum takes a lot of energy, with little to no return on the embodied energy in the products.

9. Health and Safety

Because our project operates in the Radio Frequency band, precautions must be taken to follow the guidelines set by the FCC for RF exposure. The FCC limit for public exposure of nonionizing radiation is 1.6 W / kg. As our project operates at less than 100 mW, we are well within this limit

10. Social and Political

Our project's primary stakeholder and beneficiary is Project OWL, who will be using our data to inform their decision to fly their radios in space, and other users of LoRa that seek to implement their radios on spacecraft. Each shareholder benefits equally, as they get access to the data that we took for their own benefit.

11. Development

Over the course of our project, we learned a lot about electromagnetic coupling, Faraday cages, the basics of implemented radios and metrics such as sensitivity powers, and a lot about what is expected in the channel between a ground station and a LEOSAT.