THE HASHEMITE UNIVERSITY
FACULTY OF ENGINEERING
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EVALUATION OF STARLINKS SATELLITES GLOBAL INTERET SERVICE

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1. Abstract

Starlink is a satellite internet constellation that provides satellite internet access to several countries on earth. It is yet to achieve its primary objective of providing satellite internet access to most of the earth because the number of currently orbiting satellites is only a fraction of what is needed for such task. In this report, Starlink's global internet service will be evaluated by gathering a small sample of ten satellites residing on the same orbital plane using the satellite map tracking tool[i] and investigating the communication link between the satellites and a user terminal placed in Irbid. Since this is only a proof-of-concept design that utilizes a very small sample of the actual satellites, this report is quite simple and is consisted of only the methodology.

2. Methodology

To completely investigate such system, it is divided into three sections. Firstly, the overall system is Implemented in STK simulation environment. Then, a communication link compromised of the transmitters, receivers and interference is defined. Finally, the problem of interference is investigated with various mitigating solutions.

2.1. The Overall System

The overall system is a set of parts that are based on producing a method of communication between the transmitter and the receiver. To make such that communication in satellite communication, those parts must be integrated into two parts, one is the ground station which represent the transmitter side, the other one is the satellite which represent the receiver side.
Firstly, the transmitter side (ground station) must have:

- a transmitter so we can transmit our signal
- a receiver so we can receive the signal from the satellite
- an antenna that the transmitter and the receiver will be linked to it

these parts specification will be scheduled as follows:

1. transmitter:

Frequency (GHz)	Power (dBW)	Data rate Mb/sec	Antenna Type
14.5[ii]	3.8739[iii]	150	Linked

2. Receiver:

Frequency (GHz)	Antenna Type
Tracked	Linked

3. Antenna:

Antenna Type	Frequency (GHz)	Diameter (m)	Efficiency (%)
Parabolic	14.5	0.589[iv]	73

Secondly, the receiver side (Satellite) must have:

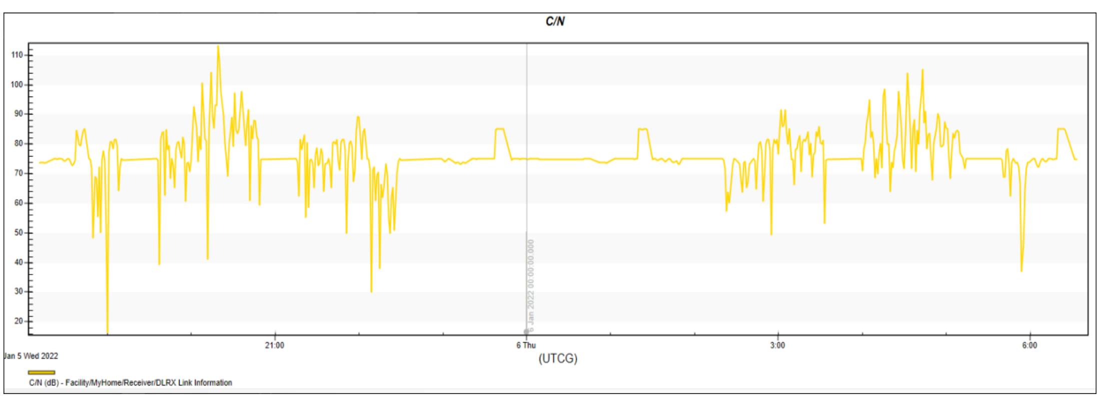
1. Two Sensors:

	IN (sensor)	Tracker (sensor)
Cone Half Angle (degree)	5	5
Pointing Type	Targeted	Targeted
Target	Neighboring facility	Ground facility

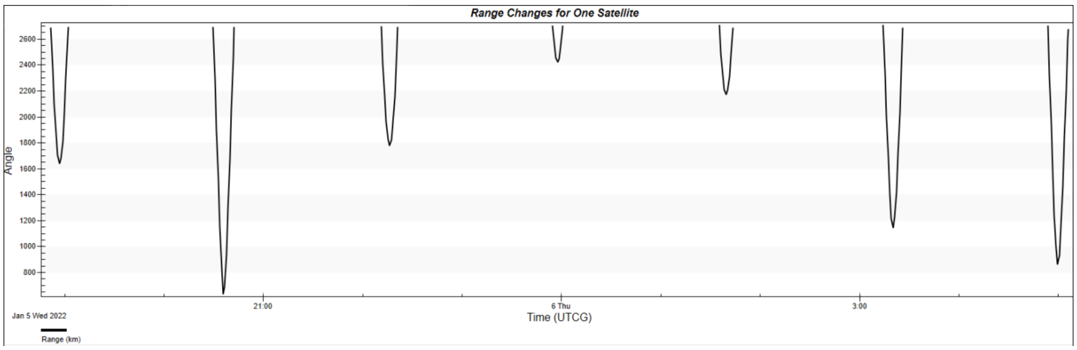
2. Two Transmitters:

	TX(Transmitter)	IN(Transmitter)
Frequency (GHz)	12	12
Power (dBW)	80	80
Data Rate (Mb/sec)	150	150
Antenna Specification	Linked	embedded with the same specifications as TX

This power has been chosen to achieve a practical and good-enough carrier to noise ratio, this figure shows that this power achieved the desired objective:



- These variations seen in the preceding graph occur because the range varies between the TX and RX, the below figure shows the range variation:



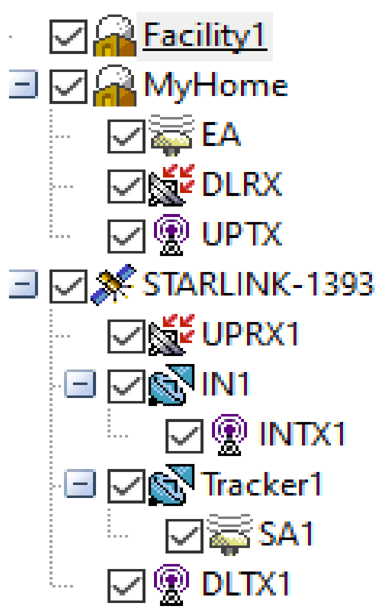
3. Antenna:

Antenna Type	Frequency (GHz)	Diameter (m)	Efficiency (%)
Parabolic	12	4	73

4. Receiver:

Frequency	Antenna Type
Tracked	Linked

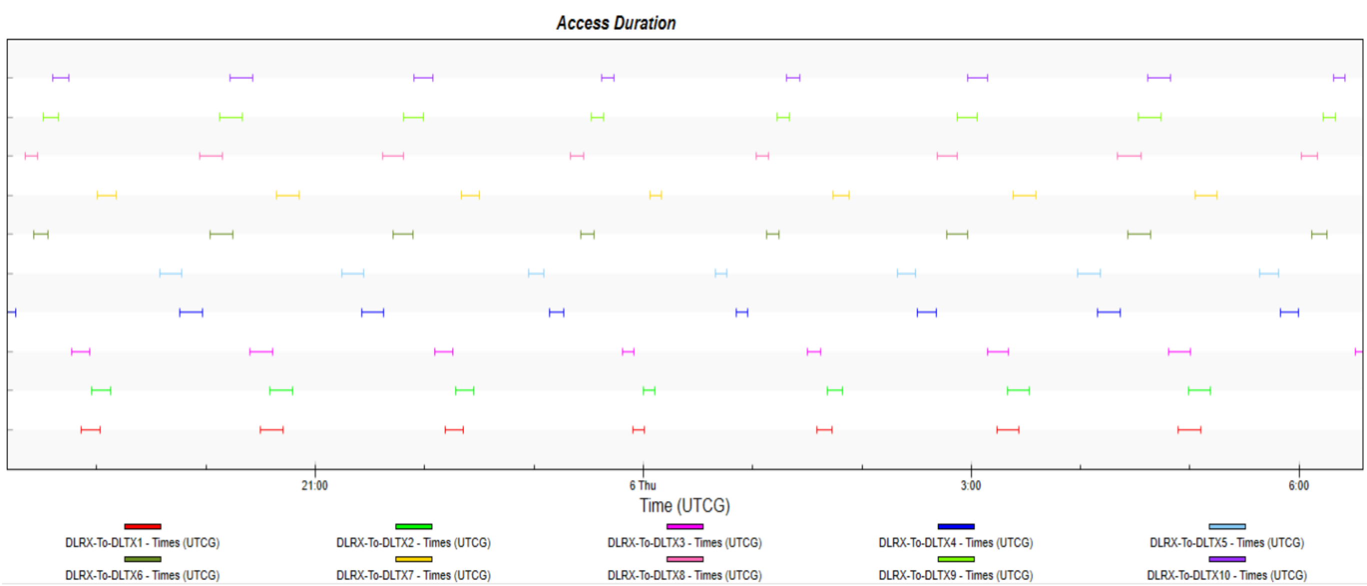
Finally, the following picture represents the aforementioned objects:



- The table below represent the time of each satellite to rotate one turn around the earth and how many times does the satellite have an access at the Ground Facility per day.

Satellite Name	Access Frequency (Access/day)	Min Duration (min)	Max Duration (min)	Mean Duration (min)	Total Duration (min)
Starlink-1393	7	6.118	12.625	10.183	71.278
Starlink-1394	7	6.013	12.581	10.212	71.483
Starlink-1399	8	3.675	12.654	9.332	74.657
Starlink-1402	8	4.848	12.671	9.446	75.564
Starlink-1404	7	6.091	12.617	10.190	71.333
Starlink-1413	8	6.902	12.639	9.614	76.914
Starlink-1414	7	6.085	12.586	10.282	71.975
Starlink-1417	8	6.700	12.666	9.594	76.749
Starlink-1419	8	6.750	12.659	9.603	76.825
Starlink-1422	8	6.293	12.672	9.558	76.467

- The figure shown describes the access of each satellite on the Ground Facility and how many satellites will access at the same time on that facility.



In order to achieve a better understanding of the underlying orbital and physical conditions that the satellites are in, the following table shows tabulated value of the orbital speed and period and the access duration of each satellite to the ground facility. All the equations were taken from[v].

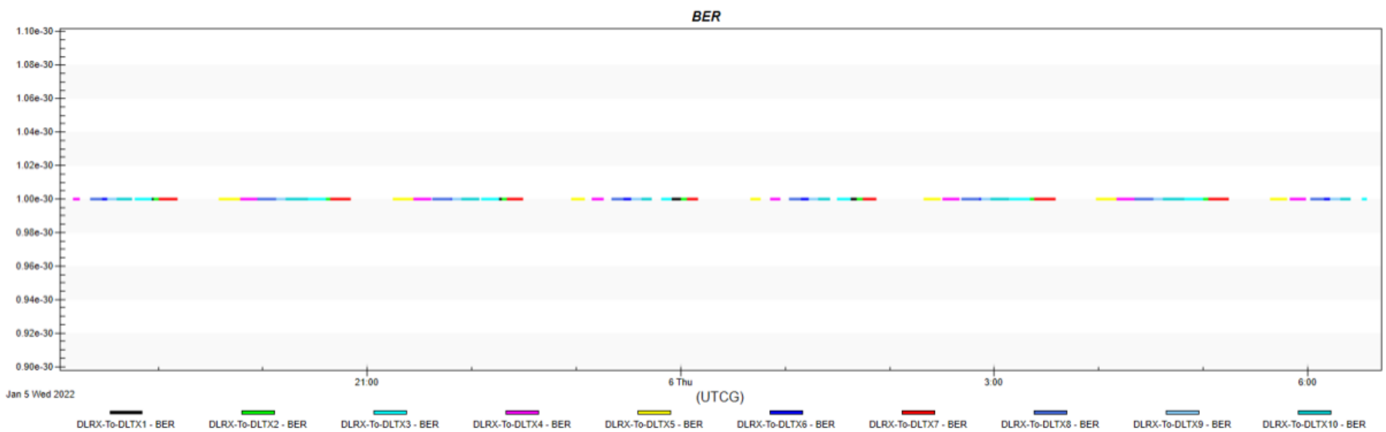
Satellite Name	Altitude (Km)	Radius (Km)	Orbiting Period (min)	Orbiting Velocity (Km/s)
STARLINK-1404	550.3	6920.3	95.43	7.59
STARLINK-1402	546.8	6916.8	95.36	7.59
STARLINK-1417	552.8	6922.8	95.48	7.59
STARLINK-1413	558.6	6928.6	95.61	7.59
STARLINK-1419	563.5	6933.5	95.71	7.59
STARLINK-1422	566.4	6936.4	95.77	7.58
STARLINK-1399	563.6	6933.6	95.71	7.59
STARLINK-1393	558.3	6928.3	95.6	7.59
STARLINK-1394	552.7	6922.7	95.48	7.59
STARLINK-1414	552.8	6922.8	95.48	7.59
Formula	*Given*	$R = R_{earth} + Altitude$	$T = \sqrt{\frac{4\,\pi^2 R^3}{G \times M_{earth}}}$	$V = \sqrt{\frac{G \times M_{earth}}{R}}$
CONSTANTS	$M_{earth} = 5.98 \times 10^{24}$ kg			
	$R_{earth} = 6.37 \times 10^{6}$ m			
	$G = 6.673 \times 10^{-11}$ N m^2/kg^2			

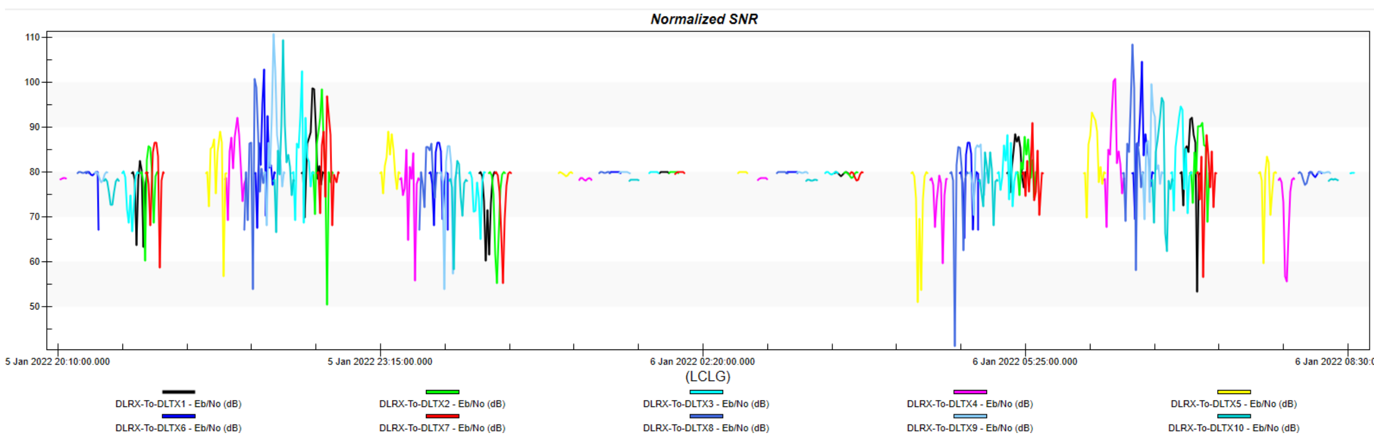
2.2. The Communication System

As in any typical communication system, the transmitter, receiver, and interference must be defined. Therefore, a communication scenario object is inserted into the STK simulation environment with three constellation objects. A transmitter is defined as the transmitter utilized in the sensor that tracks the ground facility defined in section (2.1). The receiver is defined as the receiver at the ground facility. Finally, the interference is defined as the transmitter defined in the sensor that tracks a neighboring facility.

- Note that the transmitter and the interference are assigned to ten different objects to fully represent the ten satellites.

Now that the communication system is built, its performance shall be evaluated, and to evaluate any digital communication link in general, its normalized SNR and BER are considered as the two key metrics. The lower the BER, the less error there is and the better is the communication system. For the normalized SNR, the higher it is, the better because it represents the signal to noise ratio per bit. Concerning the communication system at hand, here is its performance:

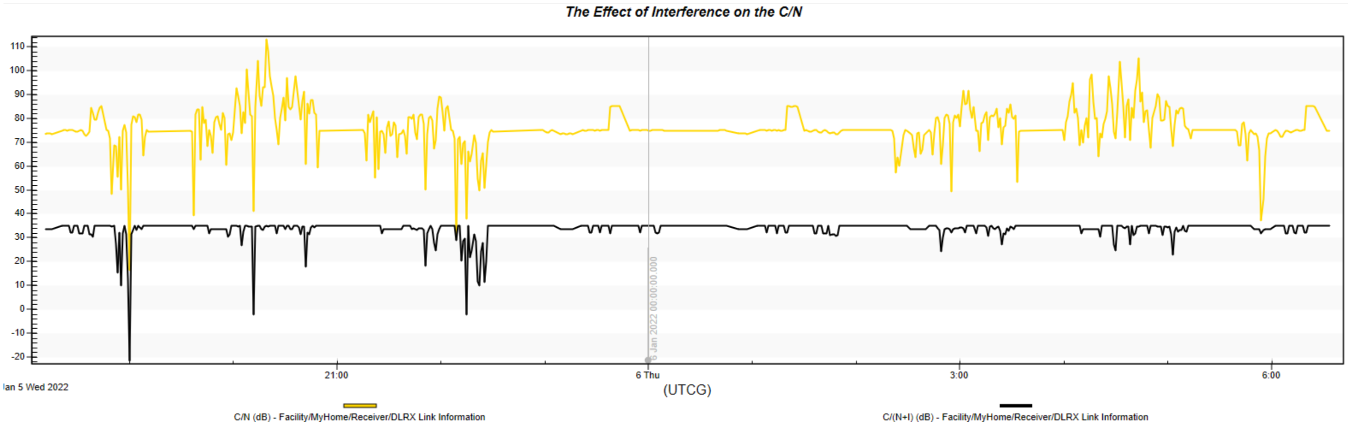




Although it is evident that this system has a descent performance once there is an access to the ground station from the satellites, the interference effect is yet to be considered, which is the very topic discussed in the following section.

2.3. Interference

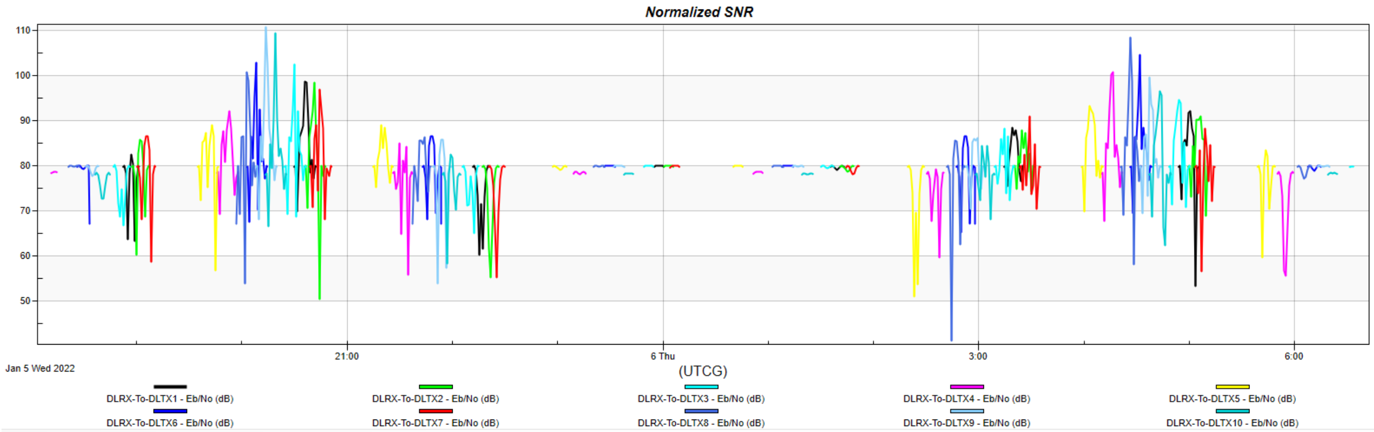
Interference is the presence of any unwanted signals at the receiver's input, which is the case in the defined scenario, a signal source with the same frequency is transmitting to a ground station that is within a great proximity to ours. In order to grasp the effect of the interference, the carrier to noise ratio (C/N) is graphed below with and without the presence of the interfering signal.



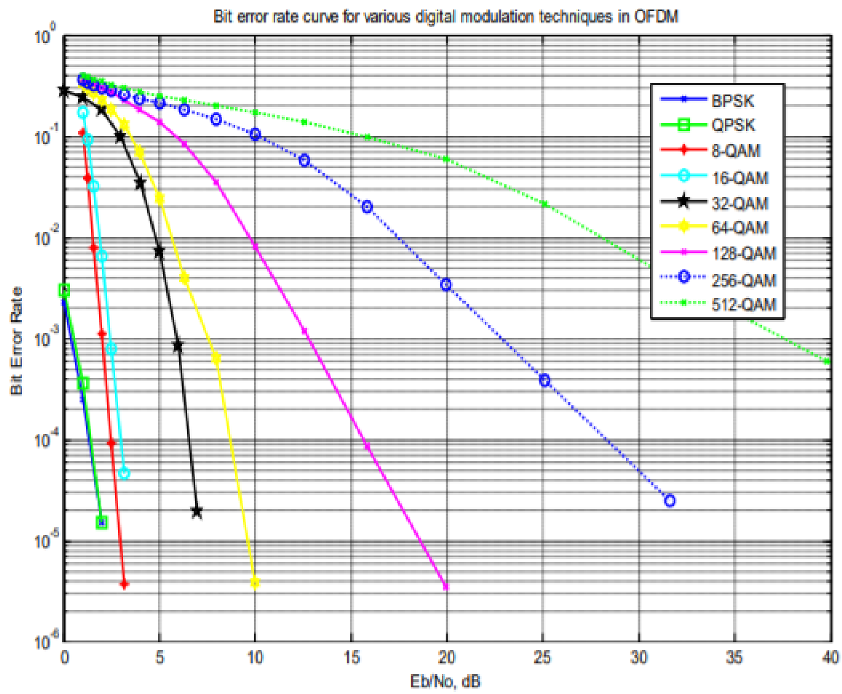
It is very clear that the fraction of desired power received at the receiver's input decreases significantly from its original value without interference due to an increase of the unwanted power coming from the interference.

Various techniques are then implemented to help decrease the effect of the interference. Firstly, the goal shall be defined more concretely. This problem can be looked at from different perspectives, one of them is the spectral efficiency, it is desired to facilitate the greatest amount of transmitted power to overlap with the bandwidth of the receiver. To do so, one can modulate the signal, making its significant spectra is thinner, demanding less bandwidth from the receiver. To do so, one can modulate the signal, making its significant spectra (PSD) thinner, demanding less bandwidth from the receiver. One can also auto track the bandwidth of the transmitted signal at the receiver forcing the bandwidth overlap ratio to always be (1) which means that the bandwidth of the transmitted signal is identical to the bandwidth of the receiver. Note that in order to make the auto-tracking of the bandwidth an effective method, the modulator must ensure that the center carrier remains at the center of the bandwidth, otherwise, non-significant PSD will be considered forcing the receiver to accept more noise without a comparable increase on the PSD.

The transmitter's modulator is mentioned only vaguely in the preceding paragraph, it is only right to speak about it in more detail now. Different modulators affect the PSD differently. Therefore, the choice of the modulator type is an important one. Firstly, the channel conditions are estimated and the required BER is designated, if the channel performance is poor, one can get better BER with a modulation technique such as the QPSK rather than the QAM-256 per say. On the other hand, if the channel performance is good enough, which translates to a high enough normalized SNR, one can get more spectra efficiency with the QAM-256 than the QPSK[vi]. Therefore, our channel performance is estimated with the normalized SNR as the metric, which is the signal-to-noise per bit and then the modulation type is determined. Below is the normalized SNR graph:



The average normalized SNR is calculated by converting the report generated from the STK simulations into a .CSV file and then calculating the average using excel. The normalized SNR was found to be 80.39. With the help of the following graph, the modulation type was chosen as the QAM 1024, which is a more complex modulator, but gives more spectral efficiency, which is the more concrete goal we defined earlier.



Below is a summary of the various experiments made to choose the best condition:

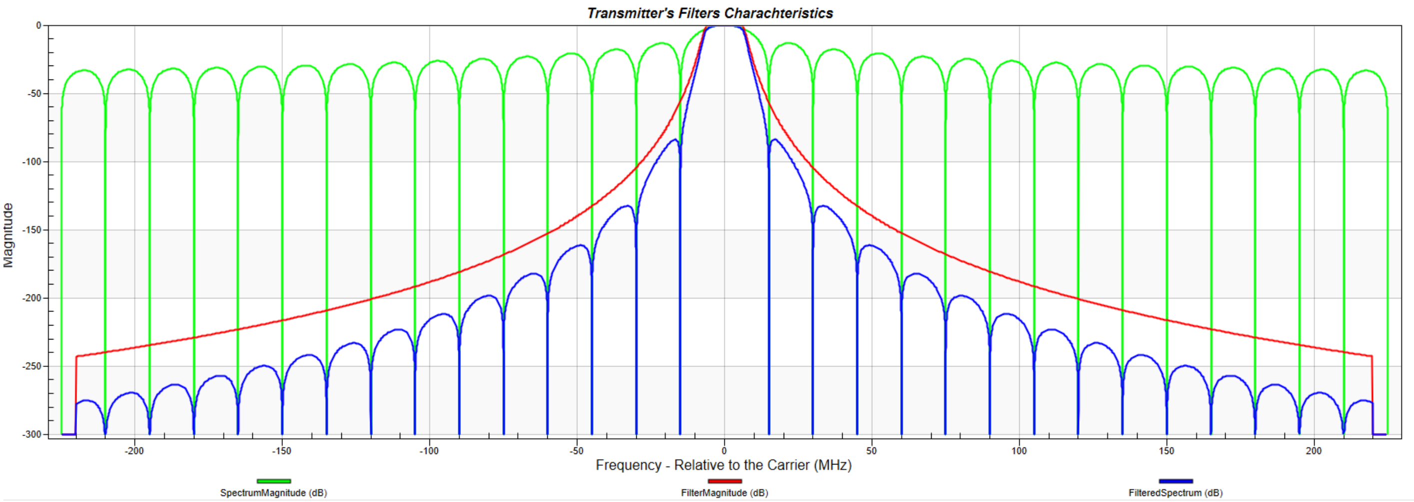
Status	BER	BER + I	C/N (dB)	C/N + I (dB)	E_b/N_o	$\frac{E_b}{N_o + I}$	Bandwidth Overlap
Default	1×10^{-30}	0.17	83.40	-1.46	80.39	-4.47	1
Halving the receiver's bandwidth	1×10^{-30}	0.19	83.40	-1.46	77.38	-7.48	0.5
Modelling the signal's PSD	1×10^{-30}	0.19	85.33	-1.46	79.31	-7.48	0.78
QPSK Modulator at the transmitter	1×10^{-30}	0.31	83.14	-3.65	77.12	-9.67	0.47
QAM-1024 modulator at the transmitter	1×10^{-30}	0.09	86.03	-0.67	80.01	-6.78	0.92
QAM-1024 with auto-scaled receiver bandwidth	1×10^{-30}	0.09	75.62	-1.42	80.39	3.35	1

After all these experiments, a QAM-1024 with auto-scaled receiver bandwidth is chosen because this case has it all, perfect bandwidth overlap, small BER and high Normalized SNR and C/N.

- Note that the values tabulated above are average values calculated using excel after converting the reports generated in the STK environment to a .CSV format.
- Note that many more experiments were made in the STK environment, but here we put the extremes and some interesting cases only.

Now after having the best case to use chosen, one major solution is to be implemented, which is *filtering*.

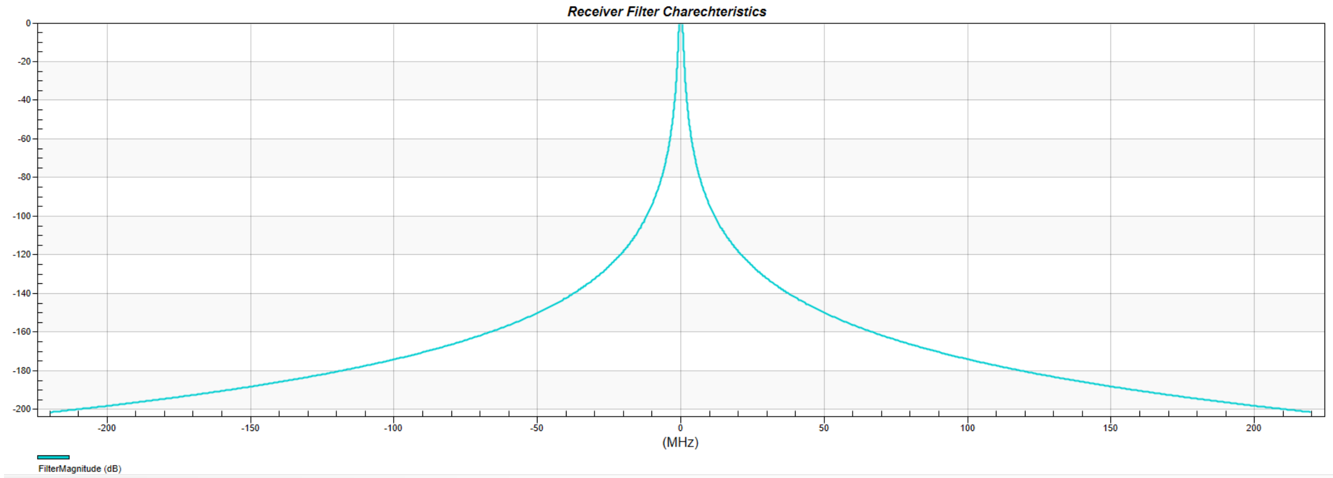
Two filters can be implemented, one at the transmitter and another one at the receiver. It is desired to use filters at the transmitter. That is odd, one might say. It turned out that filtering the signal before transmitting it allows altering its PSD to a specific shape and value that fit our desires best. In order to better get the idea, below is a graph of the spectrum of original signal to be transmitted along with the filter spectrum and the filtered spectrum:



It is clearly seen that the PSD of the filtered signal differs from the PSD of the original one. To design an appropriate filter, three key parameters must be designated: the filter type, the filter order, and the cutoff frequency. The cutoff frequency is calculated by mapping the 3dB power to its frequency, which is the low pass 3dB bandwidth. The filter type is chosen by comparing the Butterworth and the Chebyshev filters by their corresponding resulting BER, Chebyshev gives a faster roll-off but with more ripple, the Butterworth filter is smoother but has a slower roll-off. Increasing the order of the filter gives a faster roll-off. This procedure facilitates transmitting a signal with its significant spectrum captured, which makes the job of the receiver to differentiate between the transmitted signal and the interfered signal much easier.

This brings us to our next topic, *the receiver's filter*.

After having the received signal easily differentiated from the interference, a filter at the receiver is mandatory. Similar procedure as the transmitter's receiver is made to determine the parameters of the filter. A Chebyshev filter is used at the receiver with a ripple, cutoff frequency, and order suitable to differentiate the transmitted signal from the received signal. Below is the Chebyshev filter:



)	Bandwidth (MHz)	Bandwidth Overlap (units)	Pol. Rel. Angle (deg)	Polarization Effic (dB)	C/N (dB)	C/(N+I) (dB)	Eb/No (dB)	Eb/(No+Io) (dB)	BER	BER+I	C/I (dB)
1	400.0000	1.0000	0.000	0.0000	74.7142	-0.6155	78.9739	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	74.9690	-0.6155	79.2287	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	75.0352	-0.6155	79.2949	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	74.9953	-0.6155	79.2550	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	74.8060	-0.6155	79.0657	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	74.8369	-0.6155	79.0966	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	75.1070	-0.6155	79.3667	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	75.0166	-0.6155	79.2763	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	74.8848	-0.6155	79.1445	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	74.9669	-0.6155	79.2265	3.6442	1.0000e-30	9.4693e-02	-0.6155
9	400.0000	1.0000	0.000	0.0000	75.0840	-3.4987	79.3437	0.7610	1.0000e-30	9.6941e-02	-3.4987
6	400.0000	1.0000	0.000	0.0000	75.1132	-3.5170	79.3729	0.7427	1.0000e-30	9.6952e-02	-3.5170
1	400.0000	1.0000	0.000	0.0000	74.8221	-0.6155	79.0818	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	74.3123	-0.6155	78.5720	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	74.2664	-0.6155	78.5261	3.6442	1.0000e-30	9.4693e-02	-0.6155
5	400.0000	1.0000	0.000	0.0000	74.7417	-3.6261	79.0014	0.6336	1.0000e-30	9.7013e-02	-3.6261
4	400.0000	1.0000	0.000	0.0000	75.0730	-3.6482	79.3327	0.6115	1.0000e-30	9.7025e-02	-3.6482
0	400.0000	1.0000	0.000	0.0000	74.6432	-3.7276	78.9029	0.5321	1.0000e-30	9.7069e-02	-3.7276
1	400.0000	1.0000	0.000	0.0000	73.4315	-0.6155	77.6912	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	72.6263	-0.6155	76.8860	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	73.3235	-0.6155	77.5831	3.6442	1.0000e-30	9.4693e-02	-0.6155
2	400.0000	1.0000	0.000	0.0000	74.5432	-3.9224	78.8029	0.3373	1.0000e-30	9.7173e-02	-3.9224
5	400.0000	1.0000	0.000	0.0000	74.5614	-3.8891	78.8210	0.3706	1.0000e-30	9.7156e-02	-3.8891
3	400.0000	1.0000	0.000	0.0000	72.4128	-4.9463	76.6725	-0.6866	1.0000e-30	9.7658e-02	-4.9463
1	400.0000	1.0000	0.000	0.0000	69.4441	-0.6155	73.7038	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	69.3862	-0.6155	73.6459	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	72.3202	-0.6155	76.5798	3.6442	1.0000e-30	9.4693e-02	-0.6155
1	400.0000	1.0000	0.000	0.0000	74.4922	-0.6155	78.7519	3.6441	1.0000e-30	9.4693e-02	-0.6155

After implementing the two filters, it is time to make a small comparison between the communication system performance with and without interference.

Above is the system report without the two filters, note that the BER+I is very poor.

Now after applying the two filters, here is the system report:

nits)	Pol. Rel. Angle (deg)	Polarization Effic (dB)	C/N (dB)	C/(N+I) (dB)	Eb/No (dB)	Eb/(No+Io) (dB)	BER	BER+I	C/I (dB)
..0000	0.000	0.0000	73.5873	33.6597	78.2609	38.3333	1.0000e-30	1.0000e-30	33.6601
..0000	0.000	0.0000	73.8422	33.6597	78.5158	38.3333	1.0000e-30	1.0000e-30	33.6601
..0000	0.000	0.0000	73.9083	33.6597	78.5820	38.3333	1.0000e-30	1.0000e-30	33.6601
..0000	0.000	0.0000	73.8685	33.6597	78.5421	38.3333	1.0000e-30	1.0000e-30	33.6601
..0000	0.000	0.0000	73.6791	33.6597	78.3528	38.3333	1.0000e-30	1.0000e-30	33.6601
..0000	0.000	0.0000	74.9971	35.0441	79.7683	39.8153	1.0000e-30	1.0000e-30	35.0445
..0000	0.000	0.0000	75.2671	35.0441	80.0384	39.8153	1.0000e-30	1.0000e-30	35.0445
..0000	0.000	0.0000	75.1768	35.0441	79.9480	39.8153	1.0000e-30	1.0000e-30	35.0445
..0000	0.000	0.0000	75.0449	35.0441	79.8161	39.8153	1.0000e-30	1.0000e-30	35.0445
..0000	0.000	0.0000	75.1270	35.0441	79.8982	39.8153	1.0000e-30	1.0000e-30	35.0445
..0000	0.000	0.0000	75.2441	32.1610	80.0153	36.9323	1.0000e-30	1.0000e-30	32.1613
..0000	0.000	0.0000	75.2734	32.1427	80.0446	36.9140	1.0000e-30	1.0000e-30	32.1429
..0000	0.000	0.0000	74.9822	35.0441	79.7534	39.8153	1.0000e-30	1.0000e-30	35.0445
..0000	0.000	0.0000	74.4724	35.0440	79.2436	39.8152	1.0000e-30	1.0000e-30	35.0445
..0000	0.000	0.0000	74.4265	35.0440	79.1977	39.8152	1.0000e-30	1.0000e-30	35.0445
..0000	0.000	0.0000	74.9018	32.0337	79.6730	36.8049	1.0000e-30	1.0000e-30	32.0339
..0000	0.000	0.0000	75.2331	32.0116	80.0044	36.7828	1.0000e-30	1.0000e-30	32.0118
..0000	0.000	0.0000	74.8033	31.9321	79.5745	36.7033	1.0000e-30	1.0000e-30	31.9324
..0000	0.000	0.0000	73.5916	35.0439	78.3628	39.8151	1.0000e-30	1.0000e-30	35.0445
..0000	0.000	0.0000	72.7864	35.0438	77.5577	39.8150	1.0000e-30	1.0000e-30	35.0445
..0000	0.000	0.0000	73.4836	35.0439	78.2548	39.8151	1.0000e-30	1.0000e-30	35.0445

- *Note that the BER+I is greatly minimized.*

- **Please note that section 2.2 is just a quick summary of what was done in this project because we presented the needed information yesterday.**

3. References

Each footnote in the report brings you here were you can find its corresponding URL.

- Any information that is not directly referenced can be found in one of the references defined throughout this report.

[i] https://satellitemap.space/

[ii] https://imgur.com/gallery/3ztiS

[iii] https://wccftech.com/brand-new-starlink-dish-to-reduce-power-yet-improve-range-efficiency/?fbclid=IwAR2NeYUmTXwMizBYxTanOF7rcammoenfCF2yzNMtmRX5dZifdf6fDpLPPoI

[iv] https://www.theverge.com/2021/11/11/22776563/spacex-starlink-rectangular-dish-router-mounting-internet-satellites

[v] https://www.physicsclassroom.com/class/circles/Lesson-4/Mathematics-of-Satellite-Motion

[vi] http://ijarece.org/wp-content/uploads/2016/04/IJARECE-VOL-5-ISSUE-4-835-842.pdf