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Design of a free space optical link for the communication between nearby nanosatellites

Pablo Ángel Gómez de Zamora Lara

UC3M · Universidad Carlos III de Madrid

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ABSTRACT

The specific purpose of this final degree project is the connection of nanosatellites by a free-space optical communication system. The development and training of these nanosatellites is supported by the collaborative platform Nanostar. The analysis, modelling and simulation of the FSO system will has been carried out along with the study of their components and the electronic circuit.

FSO communication has been described, analyzing its advantages and disadvantages compared to other technologies. Moreover, the different modulations and the reason for the selected one has been explained. Simulink has been used to complete the simulating.

The electronic circuit has been designed to be in charge of the transmission and reception stage, with the components that match on this project. The function of each component has been briefly explained.

Finally, a simulation of the FSO system has been obtained and a PCB has been obtained from the final circuit. Unfortunately, this project has been adaptated to show a theoretical study instead of a practical one.

Keywords: Optical transmitters, Antennas, Optical propagation, Propagation losses, Frequency modulation, Circuits, Transceivers, Telecommunication control, Demodulation, Modulation, Diode lasers .

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TABLE OF CONTENTS

Project funded by the Interreg Sudoe Programme through the European Regional Development Fund (ERDF)

LIST OF FIGURES

REFERENCES

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INTRODUCTION AND MOTIVATION

Unguided communications were already used in prehistoric times with smoke signals to transmit information at a distance. But until the 1860s when Maxwell postulated the basic laws of electromagnetism there were no significant improvements. Heimrich Hertz proved its existence 20 years later. Nikola Tesla demonstrated the transmission and reception of electromagnetic energy without wires in 1893 and soon after, Marconi made the first transatlantic communication with radio waves. From this moment on, radio technology evolved allowing communications over long distances.

In 1957, the first artificial satellite was launched with which satellite communications begin. Since that time the most sophisticated satellites have succeeded one another, in 1968 a fully operational global satellite communications system called Intelsat became effective.

Optical communications, with different variations, have been used for hundreds of years. In 1880 Alexander Graham Bell created the photophone. The device allowed the transmission of sound on a beam of light. On June 3, 1880, Bell made the first wireless telephone transmission between two nearby buildings.

The invention of the laser in the 1960s revolutionized optical communications in free space. Military organizations were particularly interested and their development was encouraged. However, the technology lost momentum in the market when the installation of fiber optic networks for civil use was at its peak.

Free space optics are also used to enable spacecraft communications. Optical links can be implemented using infrared light lasers, although also to send data at low speeds, and for short distances LEDs are used. The quality of the link is highly dependent on atmospheric factors such as rain, fog, dust and heat. In outer space, the range of free-space optical communications today is on the order of several thousand kilometers, but it has the potential to reach interplanetary distances of millions of kilometers, using optical telescopes as beam expanders.

Currently, many of the satellites have FSO systems on board for communication with ground stations or also for communication between satellites. [1] Communications by means of FSO in the field of space exploration have been used by space probes, high-speed links have been achieved even at interplanetary distances due, in large part, to the fact that in space the link is not disturbed by atmospheric effects that degrade the optical signal. [two]

The growing interest that nanosatellites have aroused to carry out increasingly complex missions has led to the creation of nanosatellites clusters, which is a group of nanosatellites that operate together and perform tasks collaboratively, sharing the information collected by the instruments on board each of the nanosatellites that make up the cluster and that, therefore, require a communication link that allows the exchange of information between them. In the present work, a first FSO-based approach is proposed that allows two-way point-to-point communication between two nearby nanosatellites. [3]

STATE-OF-THE-ART

One of the most important projects developed in recent years is NASA's LLCD. This project aims to encode data in the light of a laser beam and if it works, use it as a new means of communication in space. They will use highly reliable infrared lasers capable of transferring information at a speed of 622 Mbps. It will transfer data from lunar orbit aboard LADEE. NASA has considered the use of FSO communications due to the large amount of data they transmit in their missions and they want to transmit even more, it will also allow them to work in a less crowded range. The wavelength of the laser is shorter which allows to have a narrower beam, they are safer and offer the same amount of power, in short, they are more efficient and profitable for NASA. To prove it, NASA will send millions of tiny pulses with the LLST aboard LADEE. The telescope on the spacecraft is 4 inches in diameter and allows it to be pointed at Earth in a variety of orientations. The LADEE is also mounted on the modem, which has the highly sensitive receiver that decodes the light pulses. At the ground terminal, MIT has developed the LLGT, which is made up of eight transceiver and receiver telescopes. This terminal is transportable near MIT for calibration.

The engineers hope that this project will be beneficial for the next space missions, this technology will allow to transport more data and will take advantage of its lower manufacturing costs. [eleven]

With the satellite in lunar orbit, LLCD demonstrated an error-free download speed and upload speed of 20 Mbps. The laser was transmitted from 384633.216 km from the primary ground station and consumed 25 percent less energy. The LLCD broadcast demo was successful, it was able to communicate with multiple locations. It also made it possible to observe how accurate it was to less than half an inch. In the next tests they assured that the sending of data would be tested but during the day and in different positions. [12]

The design presented in this work presents different contributions with respect to the different projects that have been discussed previously. It is proposed to work with a wide beam divergence, this would save energy by not having to control the laser pointing so precisely. Thus other systems that would have to control targeting would use less energy. In the same way, in the nanosatellite the VCSEL laser would be used for different tasks, in our case to perform the link and in another task, for temperature measurement. This allows us to save space on the device, which is one of the main problems in the nanosatellite.

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ESTIMATION OF THE BIT ERROR RATE (BER)

To estimate the BER, the use of Matlab has been evaluated, which allows simulating and analyzing the BER curve from different influence parameters. By not having the possibility of going to the laboratory, other ways to visualize the project have been studied. With Matlab the value of the theoretical BER can be obtained, in this way it can be seen in figure (1).

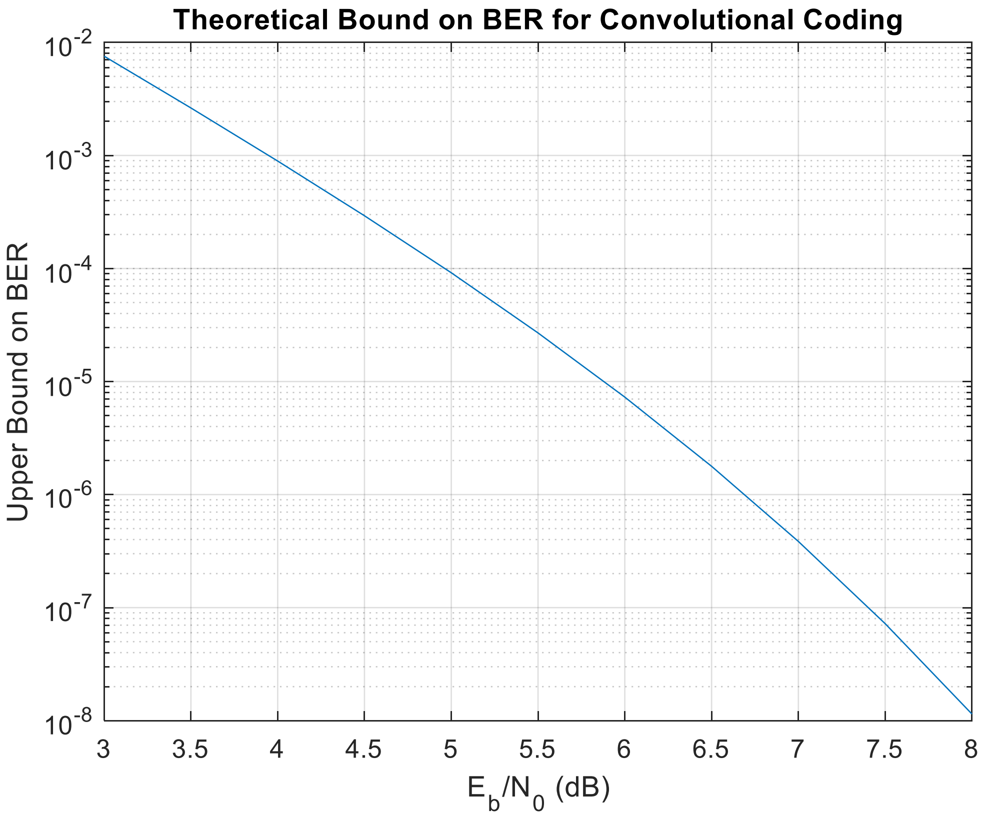

Fig. 1. Comparison of the BER as a function of the ratio of energy per bit to noise power spectral density (Eb / No).

Figure (1) shows the calculation of the bit error rates for convolutional coding with a flexible decoder, to be able to observe this example the vertical coding function has been used.

- **Link with FSK modulation**

Simulink is a tool that is part of Matlab, which will allow us to work with a block diagram that simulates modulation and demodulation. It is considered a good tool to apply the theory in communication systems. In order to obtain a good result, the simulation time, the number of samples and each block must be configured correctly.

The Simulink Communications Systems Toolbox library includes the main functions and blocks that we will use to generate the project simulation. This library also has a wide range of blocks for many

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other digital simulations based on communication systems. It also allows you to control the calculation rate from the block it executes and to create discrete time systems. The set of blocks that allow us to complete the system are the following:

- Random Integer Generator: this block is a random generator of information with a certain sampling time, in this case it generates integers. The block generates integers in intervals of 1 / 0.002 seconds. A starting seed 37 is used which will generate random numbers.
- Modulator and demodulator: the modulation block generates the baseband signal and the demodulation block will convert the data into bits. At the input of the modulator bits pass and modulated symbols come out, oversampled by 17 which is the value of samples per symbols.
- AWGN: this block adds the Gaussian white noise to the signal, it does not change the input signal, it simply adds this noise. In the block you can select one method among several to calculate the variance of the white noise. Choose “Signal to noise ratio (Eb / No)”, it is the relationship between bit energy (Eb) and noise spectral density (No). For theoretical results it is the best method of comparison. The sampling time in this block will be the same as in the bit generator. The Eb / No values will be modified to be able to observe the different BER results.
- Spectrum diagram: measures the magnitude of the input signal with respect to the frequency and represents it in a graph in which it gives you the possibility of measuring values in the signal.
- Error rate calculation: the next block will be in charge of comparing the transmission and reception signals, that is why the Rx and Tx signals will be connected, after demodulation and the other, before modulation. After the comparison we will obtain three vectors, the number of detected errors, the total number of bits and the error rate. In this block a maximum number of errors and bits transmitted will be marked, which will be what marks the end of the simulation.
- Error rate display: you can see in this block the values of the error that the system has, the BER, which will be the first value that is observed. The second value is the number of errors made in all the transmitted bits and the third the total number of transmitted bits.
- Scope: represents the oscilloscope and the waves are observed.

Next, after the explanation of all the blocks used in the simulation of the proposed system for FSK modulation, we can see the final system in figure (2).

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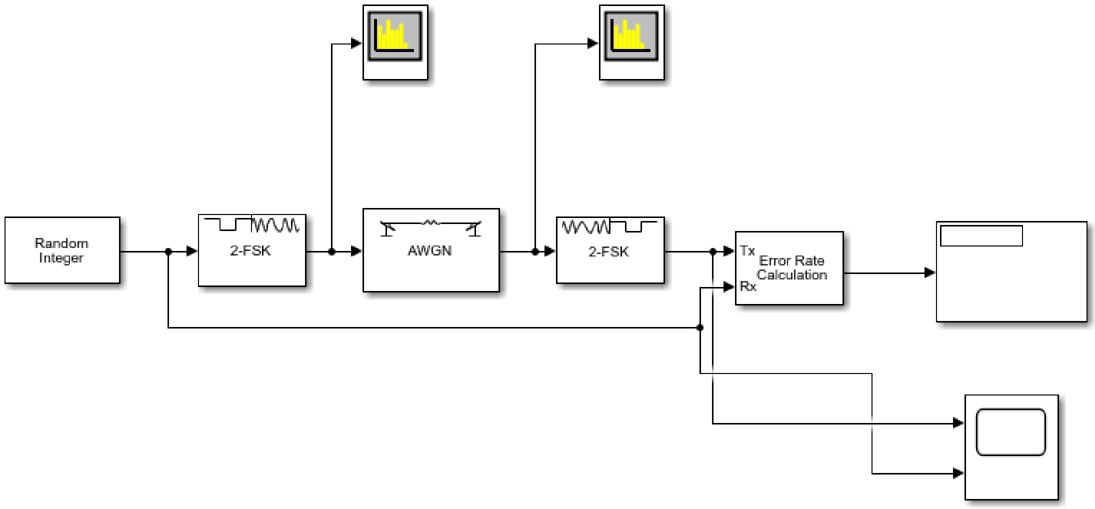

Fig. 2. Simulink FSK system scheme.

An AWGN channel is a basic model and its applications can be seen in spatial communication models with directional antennas [16].

The system's spectrum analyzer will measure the magnitude of an input signal versus its frequency, allowing us to measure the power of the signal's spectrum. In figure (3) we see how the data is between 4 and 2 Hz. The noise drops to below -20dBm.

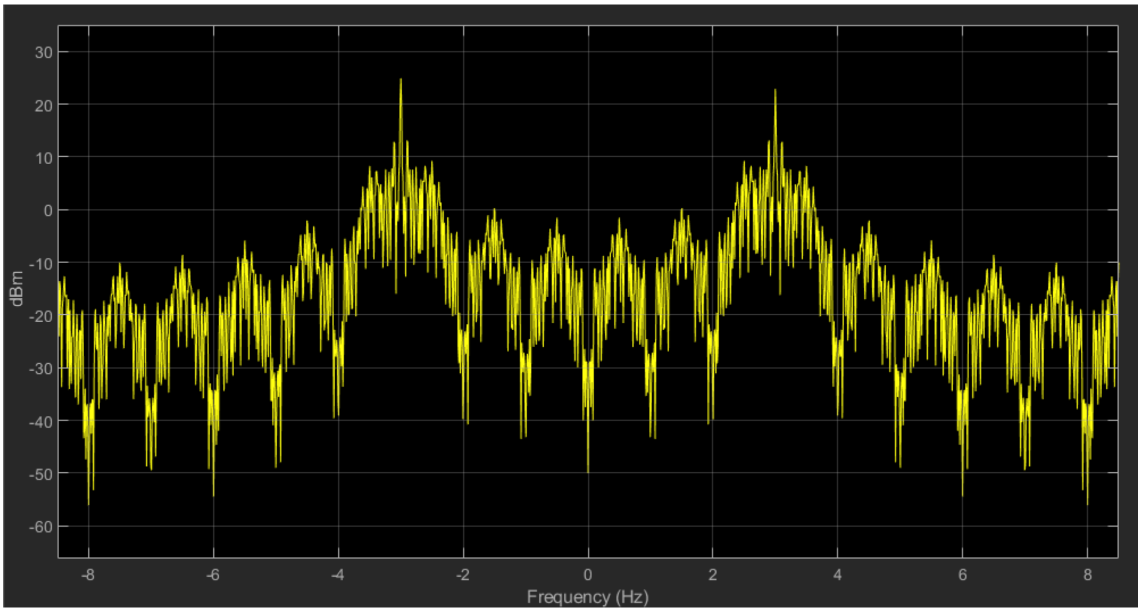

Fig. 3. Spectrum diagram before AWGN.

When passing through the AWGN channel the noise rises considerably to near to 0dB and the maximum remains similar at 25dB, as seen in figure (4). This result is carried out after passing through the noise channel with an Eb / No ratio of 1 dB in this example, the difference is clearly appreciated.

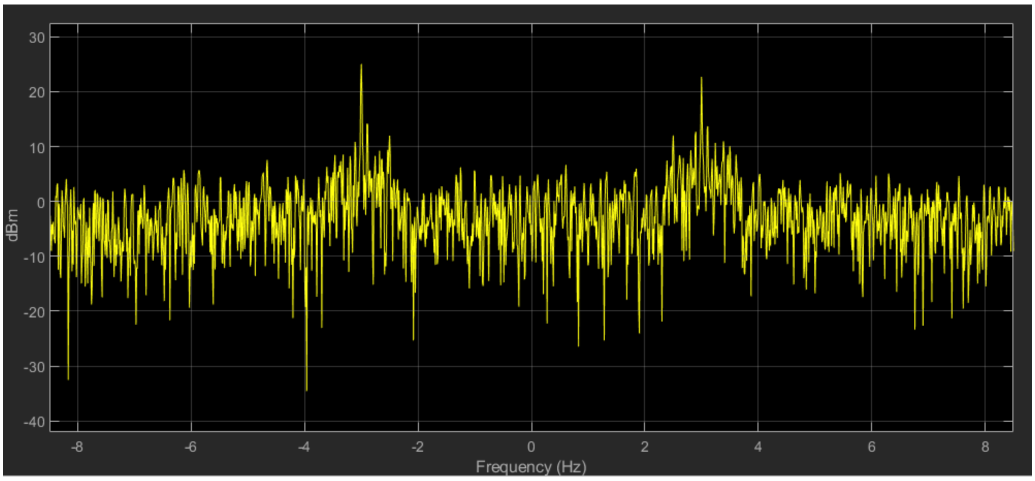

Fig. 4. Spectrum diagram after AWGN.

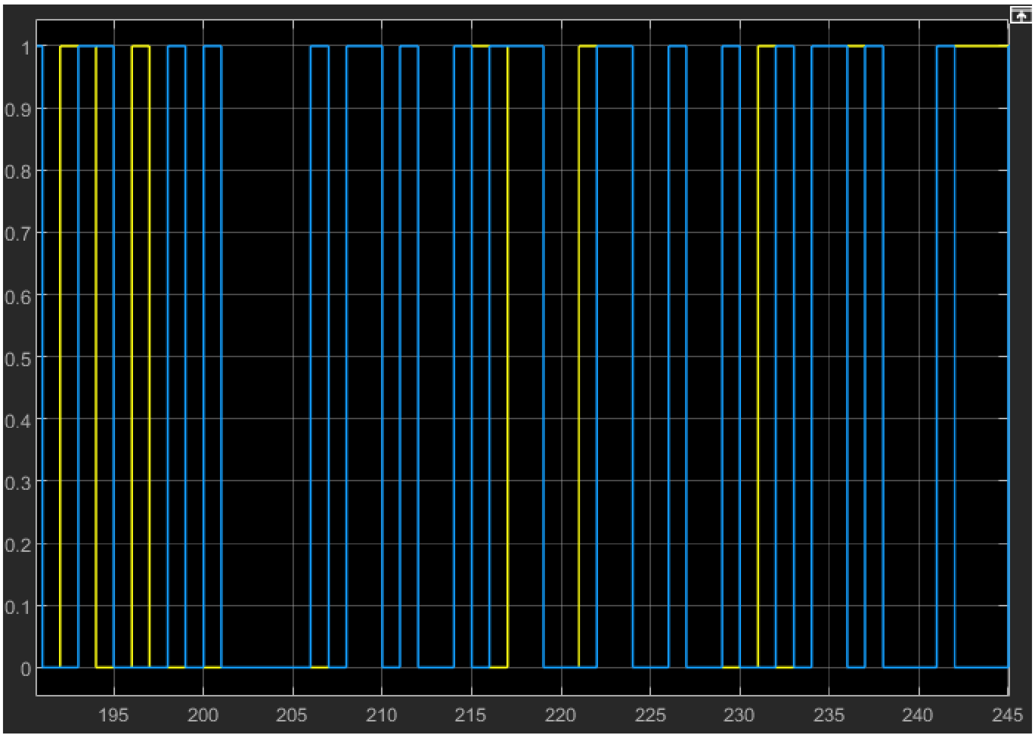

Fig. 5. Representation of the outputs on the oscilloscope for an Eb/No = 1 dB.

In figure (5) we can see the final result of the output obtained from the complete system with a value of the Eb / No ratio of 1 dB. Two waves can be observed, the blue one represents the information sent by the transmitter without going through the modulation and demodulation process. The yellow wave represents some of the errors in this section of the graph and that, as you can see, the transmitted signal is not the same as the received signal.

In figure (6) with an Eb / No ratio of 14 dB a wave is obtained only in blue color, because there are no faults between the transmission and reception and the two waves overlap one on top of the other. The system works perfectly as you can see.

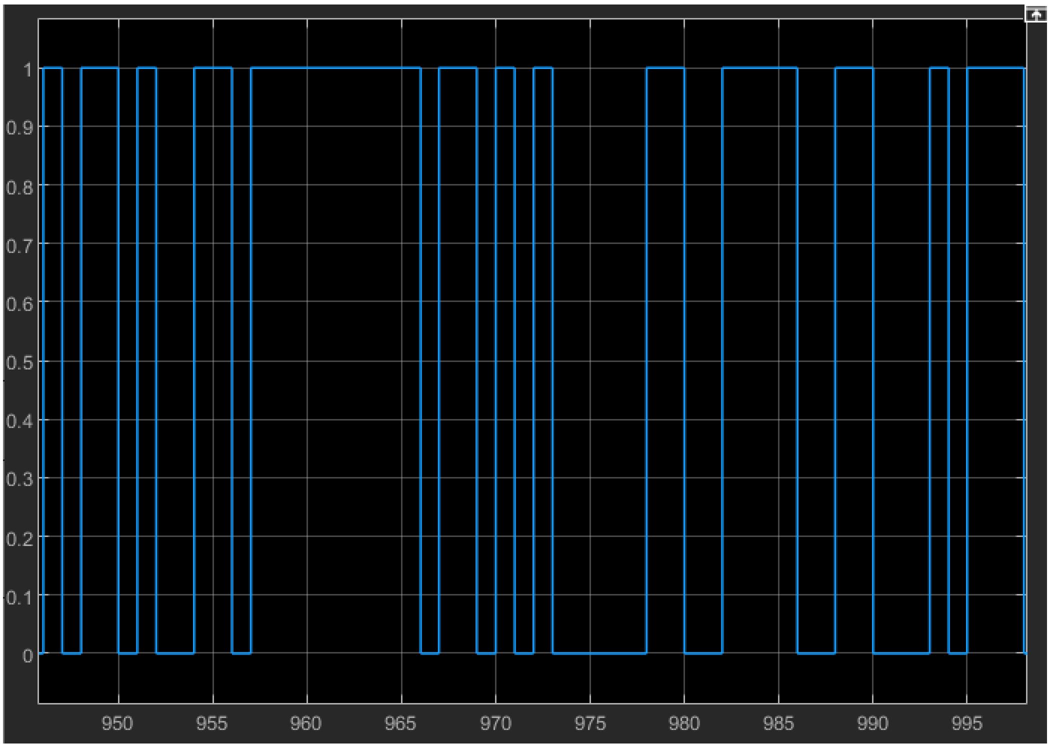

Fig. 6. Representation of the outputs on the oscilloscope Eb/No = 14 dB.

With the BER data, a graph has been created in Excel. Comparing it with the graph of the theoretical BER that has been previously analyzed, they will be compared. The data obtained by modifying the Eb / No ratio can be observed in table 1.

Tabla 1. SIMULATION RESULTS OF THE BER FOR DIFERENT Eb/No

Eb/No	BER
0	0,3041
2	0,2273
4	0,1383
6	0,06453
8	0,0194
10	0,002533
12	0,0002

With these data, figure (7) is generated, looking at this graph it can be seen that it is similar to the graph of the theoretical BER. This curve is similar because the system created in Simulink has no interferences and only has noise caused by the AWGN block, which makes it look like the theoretical one.

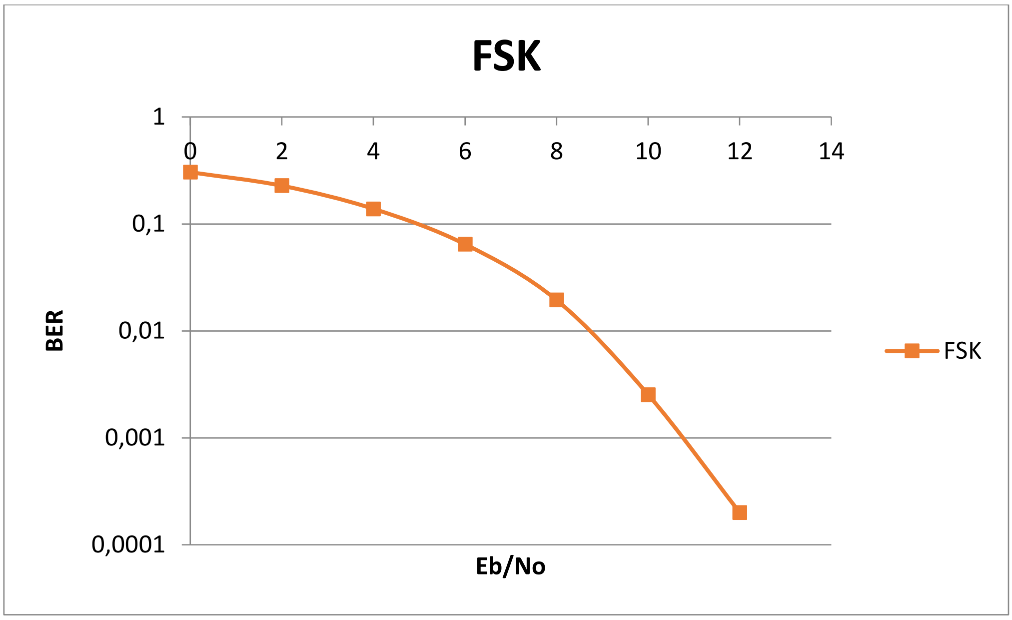

Fig. 7. BER vs. Eb / No curve with FSK modulation.

With the BER data it will be observed, at the maximum speed allowed by the transceiver, the value of the BER that will be obtained. With this data and analyzing the magnitude of the BER, the option of slowing down will be evaluated in order to obtain a data with which the amount of erroneous data decreases. The maximum speed allowed by the 2.4 kbps transceiver and from that data it will start decreasing it until an efficient link is achieved.

CONCLUSIONS AND FUTURE WORK

In this project, the performance and efficiency of the system has been valued above all else. It has been observed that FSO technology is a viable option for the future of communications and in particular of space communications. Ground links present many more complications due to interferences that can be caused by elements that are in the middle of the link or by climatic causes and interferences. The problems that can arise in nanosatellites can be caused mainly by the misalignment between both satellites, which has been studied in the present work and a solution has been proposed by introducing a divergence in the beam that forms the optical carrier. In this way, losses caused by geometric attenuation are assumed in exchange for obtaining a more robust link against misalignment. The losses introduced by the geometric attenuation are compensated to some extent in the receiver by including an APD type photodetector, which intrinsically introduces a gain of 10 dB (re 1A / W), and also by means of a transimpedance amplifier with a high gain and low noise. Likewise, using low power consumption electronics in the design, it was estimated that the link power consumption is around 180 mW.

Due to the world pandemic COVID-19 and the lockdown derived from it, the current work has had to be adapted to the special circumstances that have prevented the realization of laboratory works and the implementation of a prototype, which was one of the main goals, limiting the objectives to mostly a theoretical work. Therefore, as a future work, it is proposed is the implementation of a prototype of the optical link and compare the results of the simulation with the obtained in a characterization of the implemented system. In addition to this, environmental tests and other measurements focused on the evaluation of the system performance in a real vacuum environment are also proposed to be done in the vacuum chamber available in the facilities of the UC3M Aerospace engineering department, which is one of the shared resources of the NANOSTAR consortium.

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