Space Communication System for Education

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Abstract

This article describes EnduroSat's Space Educational modules which are used to physically simulate radio wave communication in space applications for small satellite missions. The educational modules generate physical ultra high frequency radio waves and recreate the conditions of the environment. They can also simulate the effects of S-band and X-band frequencies by changing the losses accordingly while the physical simulation remains at ultra high frequencies. They are intended for practical hands-on exercises of students in the space communications sector. The modules utilize the same equipment currently used in space and are used to experimentally analyze the link budget, noises and error rate of signal. Simulating a given configuration of a satellite and ground station's parameters with them exposes the system's vulnerabilities and its reliability when transmitting signals. The system consists of two identical transceiver modules that can emit and receive information in the form of radio waves, and a free space propagation simulator module. Each of the modules connects via Universal Serial Bus to a host computer with the simulation software. In this paper we present the modules and some of their uses for education.

Keywords
Budget, Communication, Link, Satellite, Simulation

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Nomenclature

P_r	Power received
P_t	Power transmitted
G_t	Gain of the transmitter
G_r	Gain of the receiver
λ	Wavelength
r	Distance
π	Mathematical constant
E_b/N_0	Energy per bit per unit spectral noise density
L_s	Free space propagation loss
L_a	Additional signal losses
k_B	Boltzman's constant
T_s	Effective system temperature
R	Data transmission rate

Acronyms/Abbreviations

UHF	Ultra High Frequencies
PER	Packet Error Rate
BER	Bit Error Rate
GFSK	Gaussian Frequency-shift Keying
FSPS	Free Space Propagation Simulation
USB	Universal Serial Bus
CRC	Cyclic Redundancy Check

1. Introduction

The subject of this paper is EnduroSat's Space Communication System for Education modules, which are a part of the European InnoSpaceComm project. EnduroSat's Education modules work physically with ultra-high frequencies (UHF), S-band and X-band frequencies and simulate the conditions of space environment. They can be used to analyze the reliability of a space communication system with given parameters. The Education modules are developed with the intent to expand the space communications industry and academic fields. Simulating communication with a satellite can serve as a testing method to check the functionality of developing ground station and amateur satellite equipment. 50 of the modules were donated to universities to facilitate hands-on educational activities as part of the InnoSpaceComm project.

We have provided an example of how the modules can be used for education and how through a practical experiment students can acquire intuitive understanding of link budget, interference, Doppler shift. They will also be able to compare the empirical results with theoretically based expectations.

2. Equipment Description

As shown in Figure 1. the system consists of three modules. Two are identical transceiver modules that can emit and receive information in the form of radio waves. The third is a free space propagation simulator module that imitates the signal strength losses. Losses are caused due to the electromagnetic waves traveling in free space and the atmosphere, polarization mismatch and interference with external noises. The transceivers represent modern communication modules, used in CubeSat missions. They are additionally modified to be used for simulations on ground with standard interface connectors and adjusted for the purposes of education.

Figure 1. EnduroSat's Educational Communication System [1]

2.1. Capabilities

The transceiver modules can be set to different Gaussian Frequency-shift Keying (GFSK) modulation schemes ranging from 1200 to 19200 bits per second. The simulation parameters can be adjusted for transmission power between 27dBm, 28dBm and 31dBm. The actual power used is between -3dBm and 1dBm with the intent of minimizing radiation emission outside the modules for safety reasons. Except for the rate and power, the transmitter and receiver gain, carrier wave frequency, feeder loss and Doppler effect compensation can be configured. The modules' capabilities are in the UHF range between 430MHz and 450MHz with a tuning step of 10kHz. The modules generate radio waves via analog hardware – they are equipped with a micro controller unit that communicates the data send by the host computer to a radio frequency modulator chip and modulates it onto the carrier frequency, generated by the local oscillator. S-band and X-band frequencies are also hardware-simulated but are outside of the frequency range of the internal oscillator. The workaround method is the original signal being reprocessed with help from the software. This enables simulation in the 2GHz and 8GHz range link budget parameters while the actual RF signals remain in the UHF range.

Both transceiver modules are equipped with hardware for automatic frequency shift compensation. Frequency shifts in the simulations are caused by the simulated velocity between the transmitter and the receiver.

The free space propagation simulation (FSPS) module simulates the decay in radio signal strength throughout its propagation from a satellite transmitter to a ground station receiver. It substitutes the signal strength attenuation caused by free space path loss and the influence of the atmosphere, dependent on the signal wavelength. Those effects are achieved using hardware attenuators. Apart from electromagnetic propagation, losses caused by polarization mismatch and pointing inaccuracy on the receiver, Doppler shift, monochromatic wave interference, or a 20dB increase of background noise floor that can be simulated. This module is equipped with an additional coaxial port for connecting to external noise/interference generators for more realistic noise profiles in cases of jamming.

3. Working with the equipment

Each of the modules connects via Universal Serial Bus (USB) at a symbol rate of 115200 bits per second to a host computer with the simulation software, developed for the modules, installed. The modules are connected to each-other by coaxial cable. The modules simulate information transmission using radio waves from a satellite to a ground station on different frequencies and different parameters for power of transmission and receiver antenna gain. One of the transceiver modules is used with typical parameters to mimic a CubeSat in orbit, sending its data to a ground station. The second transceiver module is used as the receiver antenna and demodulator on the ground station. The third, FSPS module, is used to substitute the losses in signal strength that occur when the carrier wave travels the distance between a satellite in orbit and the station on ground. It represents the attenuation caused by atmospheric conditions but also the effects of Doppler shift, difference in polarization of the transmitter and receiver as well as noises and interference from external sources. Using the software, the user can adjust the system parameters separately for each module. A spectrogram can be used to visually display the shape of the signal in any stage of message transmission. It enables students to monitor the free space propagation losses, the effect of noise and external signal interference, which is especially useful in telecommunications and communication technologies studies.

4. Use for education

4.1. Link budget [2]

As the name suggests, this is simply a ”budget” which lets you know how much power is available versus how much power is needed with respect to a given noise - it is one of the most important quantities to consider. Link budget is performed iteratively in order to determine what antennas should be used and gives restrictions on frequencies, power, modulation scheme and signal readability. The procedure we are going to introduce will also allow us to evaluate the BER (Bit Error Rate) for the system under consideration and determine how to improve it if necessary.

Link Budget is calculated during the design phase of a communication system to determine the received signal to noise ratio from a given transmitted “budget”, after accounting all gains and losses. A high enough budget ensures the probability of errors in the received information is within some margin. The primary quantity in the link budget is the amount of power that is received with respect to the system noise (usually per unit bandwidth). Determining the link budget of a system will indicate what limitations it has, regarding the type of the antenna, frequency used, transmission power, modulation scheme and error checking method.

4.2. Antenna gain

To understand antennas, one needs to understand directivity [3]. It is determined by the radiation pattern of an antenna’s type and design parameters. Directivity is a property that describes the distribution of power radiated by an antenna in space. It represents the ratio of the amount of power radiated by an antenna in its direction of strongest emission to the power radiated by an isotropic antenna (which has an ideal spherical radiation pattern) with the same transmission power. The directivity is straightly proportional to an antenna’s gain, which is a key value in Link Budget. The gain describes how well antennas turn radio waves into electrical power or electrical signals to radio waves in a specific direction. Gain increases the amount of received or transmitted power. It is one of the most important parameters to consider in a communication system both on the receiver and transmitter antennas.

4.3. Why decibels

Knowing the output power and the gains of the antennas and taking into account all losses, we can estimate the amount of power that would be received on the other end of the system. This is done using Friis' equation of propagation [4].

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi r)^2} \quad (1)$$

Because the terms Friis' equation vary a lot in orders of magnitude, usually in telecommunication systems, the budget is expressed in decibels. This allows to substitute multiplication with very large and small values with addition and subtraction of smaller numbers in logarithmic scale. For this reason, equation (1) is frequently used in its decibel notation:

$$P_r(dBWs) = P_t + G_t + G_r - 10log_{10}\left(\frac{4\pi r}{\lambda}\right)^2 \quad (2)$$

The last term in equation (2) is referred to as the free space propagation loss. This is the reduction in power carried by the electromagnetic wave due to the distance it has traveled from its origin and depending on its wavelength. The received power returned by Friis' equation is the absolute power that is turned into electricity by the receiver antenna. Since a physical system is never perfect, it always has noise. Because of this, the reliability of the communication system is determined by the ratio of the received power to the noise power.

4.4. Powers and noises

To compare the signal strength to the strength of noises, the noise is mathematically substituted with an equivalent amount of thermal noise, also known as Nyquist-Johnson noise [5][6]. The thermal spectral density of that noise is constant per unit bandwidth and is equal to the product of Boltzmann's constant and some effective temperature in Kelvin. Knowing the absolute received power and the spectral noise density, we can compare them to estimate the error rate of the communication channel. This is the carrier-to-noise ratio of the system [7]. The carrier-to-noise ratio is expressed by the total power received, given by the Friis' equation (2), divided by the noise spectral density and the bandwidth of that channel, where high ratios correspond to low error rates. The error rate of each one bit in a message is directly connected the energy per bit per unit spectral density (E_b/N_0), as represented by the following equation:

$$\frac{E_b}{N_0} = \frac{P_t G_t G_r \lambda^2}{(4\pi r)^2 L_a k_B T_s R} \quad (3)$$

As described in section 4.3, equation (3) is converted into decibel notation:

$$\frac{E_b}{N_0} = G_t + P_t + \frac{G_r}{T_s} - L_s - L_a + 10log_{10}k_B - 10log_{10}R, \quad (4)$$

where the less energy a bit carries, the higher its probability of error. The type of modulation and error checking method determines the impact the signal to noise ratio that any one bit has on the error rate of a whole transmitted message.

4.5. Margins

Typically, a telecommunication system has some requirement on the bit error rate, depending on its application, which defines a required E_b/N_0 ratio. In terms of decibels, positive values indicate the bit error rate is lower than the required amount and negative values denote that the system needs improvement in order to fit the required link margin. In this case, the parameters of the antennas, transmitter, receiver, modulation, etc. must be adjusted to guarantee the required link reliability.

5. Results

5.1. Experiment results compared to expectations from theory

Link budget is an important concept that is dependent on various parameters. Because of that, it can pose a difficulty in the introduction to communication technologies. Simulations done using the Space Educational Modules can ease this process by revealing the impact of different parameters on link budget in real time. They also contribute the opportunity for comparing theoretical expectations with empirical observations of real ground station to satellite communication systems.

5.2. Effects of Doppler shift

The Doppler shift depends on the relative speed between the satellite and the ground station, which changes over time and also with the type of orbit. At higher frequencies such as UHF, the effect of Doppler shift can alter the carrier frequency and offset it outside of the receiver's range and this has to be compensated. Simulations done using the modules demonstrate how the shift of frequency affects the PER both with and without automatic frequency compensation. Figure 2. displays how frequency compensation automatically adjusts the receiver's frequency and reliably locks on to signals with a maximum deviation of 11.7kHz at 4800Hz frequency deviation, which is comparable to the signal bandwidth. Signals immediately outside of that range are lost. Such high frequency shifts occur at low elevation angles during satellite passes from low Earth orbit, since small altitudes correlate to higher amounts of Doppler shift.

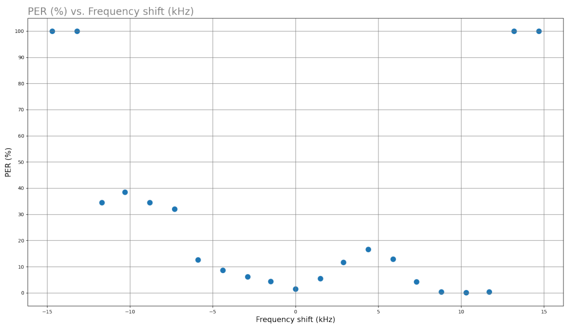

Figure 2. Doppler shift with frequency compensation

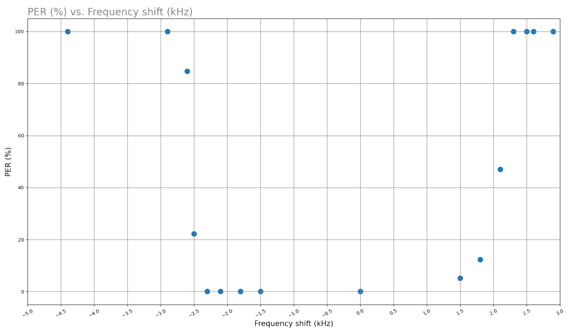

Figure 3. Doppler shift without frequency compensation

Figure 3. shows a setup without automatic frequency compensation, where the receiver is only at the base frequency. In the second setup, the receiver starts reading signals with a deviation of up to 2.9kHz with high PER. The reliability increases when the received frequency approaches the base frequency. When the shift is lower than half the frequency deviation of the modulation scheme (in this case ½*4800Hz), the losses due to Doppler effect are negligible.

5.3. Effects of external noise and sensitivity to interference

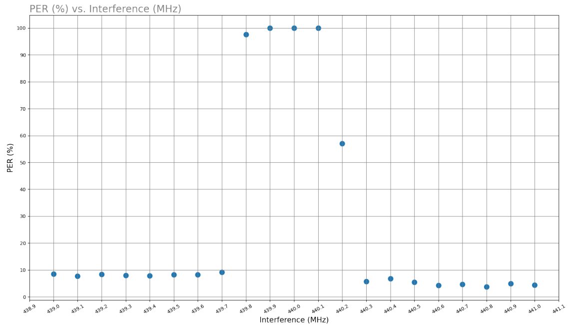

Figure 4. Packet loss to interference

External noise can directly increase the BER of a signal since it means a higher noise spectral density. Interference with the same intensity can cause from increase of error rate to complete signal loss, depending on the frequency. The closer the interference frequency is to the carrier frequency, the more of the channel's bandwidth is overlapped by the interference wave and its information is lost. The graph demonstrates that when the difference between the interference frequency and the carrier frequency is close to the frequency deviation of the modulation scheme (between 439.8MHz and 440.2MHz), almost all of the information is lost.

5.4. Receiver and transmitter gain

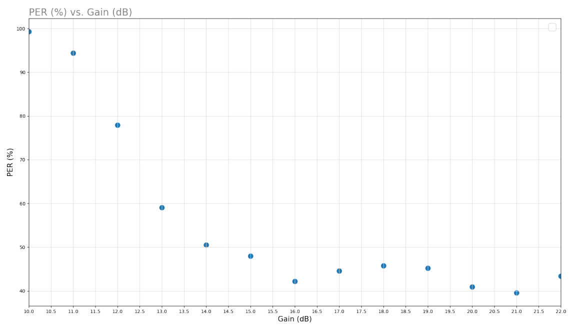

Figure 5. Packet loss and gain

Higher gain is directly proportional to the amount of power that is radiated in the proper direction by the transmitter or the amount of power that the receiver turns an electromagnetic wave into. Therefore, the received power is proportional to the gain. Higher power correlates to a higher signal-to-noise ratio. Consequently, a link with higher gains will transfer information with lower error rate, and this is exactly what is observed in measurements done using the modules.

5.5. Results

The software performs a simulation with the specified parameters. The transmitter module streams a sequence of a given number of packets with information (random bits), after which the simulation is over. The software keeps track of the number of received packets and the count of bit errors, caused by the signal being altered in the FSPS module. The bit error rate (BER) is tracked by the program and is directly reflected on the PER displayed value where corrupted bits cannot be corrected by the packet's cyclic redundancy check (CRC).

6. Discussion

With the introduction of space practice to the education programs, the access to space will increase significantly. This will speed up development in the space industry, allowing mankind to progress towards its goal of space exploration. Producing communication systems for space often involves problems without pure analytical solutions, where simulations solve this issue. Simulating the system's performance in the target environment is a utile tool for determining the system's vulnerabilities and its reliability by monitoring the PER in given scenarios. The Space Communication System for Education modules closely represent the equipment already used in standard CubeSat missions and precisely imitate their use conditions. They serve as a suitable method to study communication systems in the classroom and in the lab.

7. Conclusions

The education modules serve as a tool for simulating a satellite and ground station system. Their use is a method for strengthening student's knowledge of link budget through actual measurement and comparison between theory and reality. This is an exceptionally useful tool for enthusiasts who are looking to build their own ground station in order to analyze their system requirements as well as for universities aiming to launch CubeSats for education purposes.

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