Communication Optimization Approach for S-Band LEO CubeSat Link Budget

Mohammed Amine El Moukalafe and Khalid Minaoui

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EL MOUKALAFE Mohammed Amine and MINAOUI Khalid

Faculté des Sciences de Rabat, Université Mohammed V, Rabat, Maroc
elmoukalafe.medamine@gmail.com

Abstract. CubeSats has evolved a lot since their first appearance in 1999. Indeed, we see that small satellites have emerged in several areas that were exclusive to large satellites. However, this miniaturization is costly in term of size and energy which are crucial for high data rate communication systems. Hence, the need to optimize communication link parameters for energy efficiency. Previous works on link budget analysis adjust modulation and coding schemes on worst cases in order to guarantee a robust communication link between CubeSats and Grounds Stations. Thus, penalizing the data rate. In our work we start by establishing a classic link budget on S-band transceivers, then we study the impact of communication conditions improvement on data rate using Variable Coding and Modulation (VCM) approach. Our results have demonstrated a notable performance gain from applying VCM technique to a Low Earth Orbit (LEO) CubeSat link budget.

Keywords: CubeSat, Nano-satellite, Transceivers, Link budget, Data rate, Variable Coding and Modulation

1 Introduction

Nano-satellites, also called CubeSats, are small artificial satellites that are built of multiples of 10 cm^3 cubic units. This technology appeared 20 years ago and mainly attracted researchers interest due to their low cost manufacturing compared to conventional satellites. Nano-satellites were firstly used by California Polytechnic State University and Stanford University in the United States in 1999. Later, space companies also started using them for their advantages [1]. Nano-satellites can be sent with large satellites when launched into orbit, which allows universities around the world to conduct scientific experiment at low cost. Lately nano-satellites are dedicated either to observe and measure terrestrial environment or to test new technologies in space. Nowadays, more than 2500 CubeSats are currently in use or under development [2]. The emergence of such small satellites is due to the miniaturization of embedded systems empowered by Commercial Off-The-Shelf (COTS) products. COTS components present a lot of advantages in space like flight heritage, simplicity in communication with On-Board Computers (using I2C protocol) and the support of AX.25 protocol, widely used by the amateur radio community. Regarding the ascension of Cube-

Sats, scientists are now focusing on improving the quality of on-board components. One of the main challenges is boosting the performance of communication systems, thus to allow the use of high resolution imaging for Earth observation, to put CubeSats in high Earth orbits, and to open up the opportunity for small satellites to participate in deep space missions [3, 4]. Such functionalities were atypical for small satellites few years ago. In order to set the appropriate frequency band for CubeSat's communication sub-system, we must first refer to the International Telecommunication Union (ITU) that is responsible for coordinating the shared global use of the radio spectrum. Fig. 1 shows that the most used frequencies for CubeSats are the Ultra High Frequency (UHF) bands. In the last years, we see particular interest for high frequencies (especially X and Ka bands) as it allows high data rate capabilities. Therefore, using such frequencies increases the global cost of CubeSats missions. One solution is to try to take advantage from lower frequencies using adequate modulation and coding methods. In this paper, UHF band is used for Remote Control (RC) and TeleMetry (TM) link seeing the low need of data rate, while S band is intended for exchanging large data with the CubeSat.

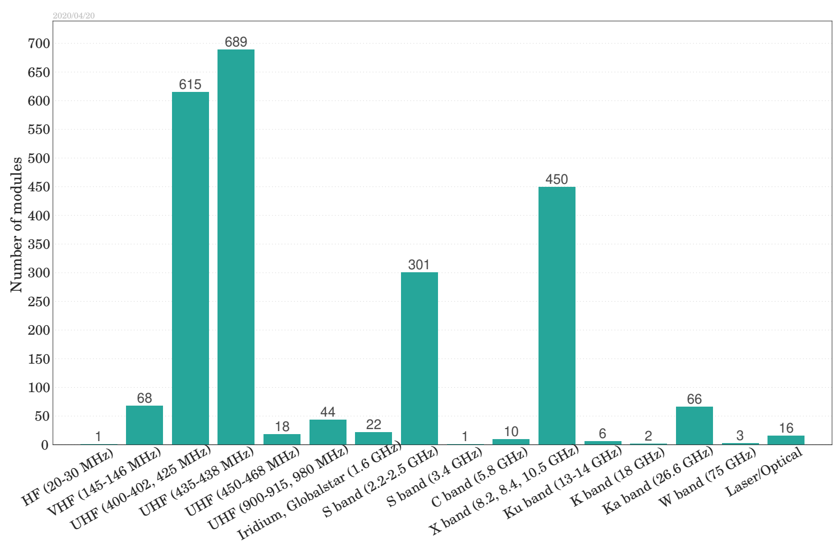

Fig. 1. Frequencies and bands used in CubeSat missions [2]

Previous work on link budget are based on worst case parameters in order to guarantee a reliable communication link [5, 6]. Such approach put safety in first position because it prevents losing communication with the satellite. However, this approach overlooks the favorable cases, thus, penalizing the data rate. In this paper we start by an introduction in Section 1. Section 2 presents the fundamentals of link budget calculation in order to understand the parameters that can be improved. Section 3 presents findings of our paper and the application of Variable Coding and Modulation method to optimize data rate. In Section 4, we present limitations and future work and then we conclude our paper.

2 Methodology

In order to study complex communication systems, we need to build mathematical models of transceivers, antennas and radio wave propagation, especially if we want to focus on key aspects that influence the quality of the link. Also, a radio link simulation will be implemented in AGI STK software for more detailed calculations. We start from geometric background so that distances and angles can be comprehensive to model the motion of the CubeSat. Then, we include different types of communication losses so we can use all these parameters in the link budget. The calculation of the distance between the CubeSat and the Ground Station, also called Slant range s in Fig. 2, is essential in order to establish the first influencing parameter of our radio communication system. Indeed, by increasing the distance between the transmitter and the receiver, we end up with large path losses. We calculate the Slant range s by using the Law of cosines. Therefore, it becomes easier to determine the dependence between the slant range s, the altitude of the CubeSat h and the ground antenna elevation El in eq. 1, where R_E is Earth radius.

$$s = R_E \cdot \left[\sqrt{\left(\frac{R_E + h}{R_E}\right)^2 - \cos(El)^2} - \sin(El) \right] \tag{1}$$

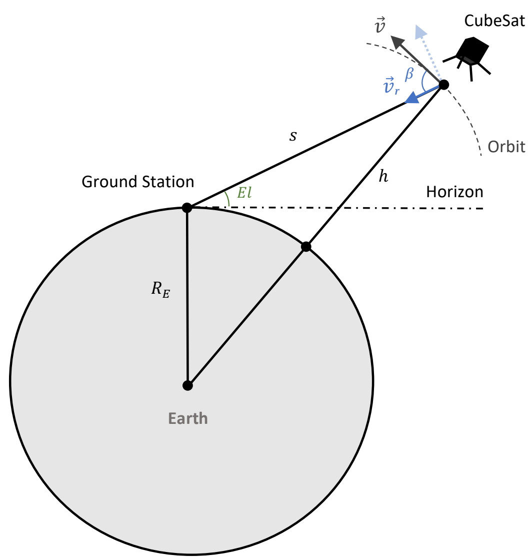

Fig. 2. CubeSat motion and geometry with respect to Earth Ground Station

Also, the high velocity of Low Earth Orbit (LEO) satellites (about 7,58 Km/s in our application) leads to a significant Doppler shift Δf, which is a deviation of the received signal frequency f from the emitted signal frequency f_0 (or carrier frequency). It is estimated at approximatively ± 50 KHz for S-band LEO satellites unsing eq. 2, where v_r is the velocity of the CubeSat transmitter relative to the Ground receiver and c is the light speed.

$$\Delta f = f - f_0 = \frac{v_r}{c} \cdot f_0 \tag{2}$$

We can calculate the radial component v_r using eq. 3, where v is the CubeSat velocity (We assume here that the Earth is a uniform spherical body), μ_E is the Earth standard gravitational parameter and β is the angle between the CubeSat velocity vector and the direction to the ground station.

$$v_r = v \cdot \cos(\beta) = \left(\sqrt{\frac{\mu_E}{R_E + h}}\right) \cdot \left(\frac{R_E}{R_E + h} \cdot \cos(El)\right) \tag{3}$$

Therefore, by setting, in the eq. 4, the CubeSat altitude h at 560 Km (LEO), the carrier frequency f_0 at 2250 MHz (S-Band) and the Ground Station antenna minimum elevation El_{min} at 5 deg (This mask represents the value of the antenna elevation in all azimuth directions, in order to start and to stop CubeSat access in each pass), we end up with a maximum Doppler deviation $|\Delta f_{max}|$ of approximatively 105 KHz. In this study, we use GOMspace tranceivers with Doppler Shift Compensation (DSC) technology adapted to such deviation values [7]. Consequently, we don't include DSC methods in our study.

$$\Delta f = \left(\frac{R_E \cdot (\mu_E)^{1/2} \cdot f_0}{c \cdot (R_E + h)^{3/2}}\right) \cdot \cos(El) \tag{4}$$

Fig. 3 shows a simplified radio communication system where the principal components are illustrated. First, a transmitter uses electrical power to form radio waves, which could include feed losses. These radio waves are communicated to the transmitted antenna that drives energy in different directions according to its gain pattern. The radiated radio waves propagates through space, which includes propagation loss like atmospheric effects. On the other side, a receiver detects the radio waves delivered by its antenna. We include in our study free space loss L_{fs} calculated in eq. 5, atmospheric loss detailed in IUT-R P.676 and IUT-R P.618 recommendations (L_{atm} and L_{rain}), signal polarization loss L_{pol} and pointing losses ($L_{pointingSAT}$ and $L_{pointingGS}$) included in eqs. 6 and 8. In most cases, the choice of a circular polarization is recommended for space systems given the high attenuation of linear polarizations by the atmosphere [8]. It is also important to note that Ground Station antennas must compensate the few energy on board the CubeSats. Thus, by using high gain ground antennas, their beamwidths become very small. Therefore, small pointing errors can lead to large losses. For this reason, we must have an efficient satellite tracking method on the Ground Station using accurate orbit restitution.

$$L_{fs(dB)} = 10 \log_{10} \left(\frac{4\pi s}{\lambda}\right)^2 = 32,45 + 20 \log_{10} s_{km} + 20 \log_{10}(f_{MHz}) \tag{5}$$

$$L_{tot(dB)} = L_{pointingSAT} + L_{pol} + L_{fs} + L_{atm} + L_{rain} \tag{6}$$

In Transmitter side, impedance matching is important in order to maximize the power transfer to the antenna. Indeed, the output impedance of the radio transmitter has to be equal to the antenna input impedance so that signal reflection to the source will be close to zero. If not, impedance mismatch results in standing waves along the transmission line. This is measured by Voltage Standing Wave Ratio (VSWR) where AC voltages irregularities along the transmission line are estimated. In this study we assume that the mismatch loss is equal to 0,12 dB (VSWR equal to 1,4), which is equivalent of saying that 97,2 per cent of the power is effectively transmitted to the antenna [9].

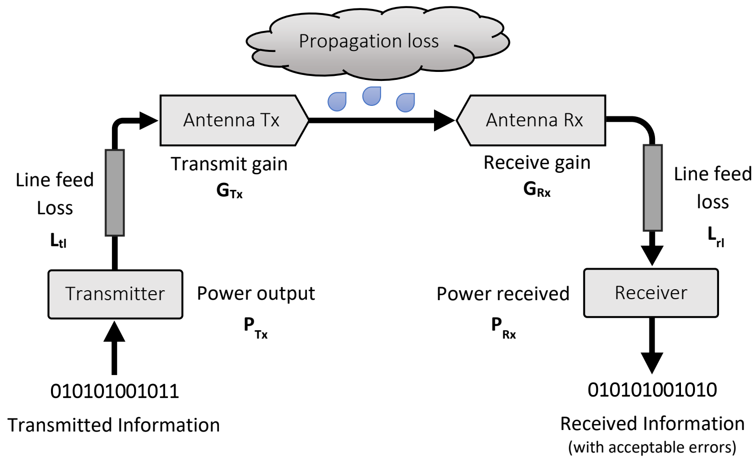

Fig. 3. A block diagram of radio communication system

The overall power output of the transmitter, or the Effective Isotropic Radiated Power (EIRP), is calculated in eq. 7.

$$EIRP_{(dBW)} = P_{Tx} - L_{tl} + G_{Tx} \tag{7}$$

On the other side, the power received at the input of the Low Noise Amplifier (LNA) is calculated in eq. 8.

$$P_{Rx(dBW)} = EIRP + G_{Rx} - L_{Tot} - L_{pointingGS} - L_{rl} \tag{8}$$

It is important to consider the effective Noise temperature of the receiver because it's a limiting factor on the information that can be transmitted over a radio communication link. Noise is often characterized as having a uniform power density, where the noise spectral density No relates to the receiver temperature T via Boltzmann's constant k. We can therefore calculate the Signal-to-Noise Power Density C/No in eq. 9.

$$C/No_{(dBHz)} = P_{Rx} - 10\log_{10}(k \cdot T) \tag{9}$$

Finally, the modulation and Forward Error Correction (FEC) schemes will determine the levels that the system must meet in order to reach the Bit-Error-rate

(BER) performance via $Eb/No_{Threshold}$ in eq. 10, where R is data rate. In this study, we consider a specified BER of 10^{-5}.

$$Margin_{(dB)} = C/No - 10\log_{10}(R) - Eb/No_{Threshold} \quad (10)$$

After examining 5 S-band solutions, we choose, for our high data application, the NanoCom SR2000 CubeSat transceiver with the ANT2000-DUP-215 S-band patch antenna from GOMspace because they can reach high data rates (up to 2 Mbps) in full duplex. On the other hand, we use the NanoCom GS2000 Ground Station transceiver matched with the NanoCom AS2000 parabolic antenna. Also, for RC and TM links, we choose GOMspace UHF transceivers [7].

Table 1. Summarized link budget for S-band CubeSat Downlink

Link Budget (S-band Downlink)	**Nominal**	**Adverse**	**Favorable**
CubeSat			
Transmitter Power Output (dBW)	2,0	2,0	2,0
Antenna Gain (dBi)	8,0	8,0	8,0
Voltage Standing Wave Ratio	1,40	1,40	1,40
Total Transmission Losses (dB)	1,3	1,3	1,3
Effective Isotropic Radiated Power (dBW)	8,8	8,8	8,8
Downlink Path			
Frequency (MHz)	2250,0	2250,0	2250,0
Minimum Elevation (deg)	5,0	5,0	5,0
CubeSat height above surface (Km)	560,0	560,0	560,0
Slant range (Km)	2230,9	2230,9	2230,9
Free Space Loss (dB)	166,5	166,5	166,5
CubeSat antenna pointing bias (deg)	15,0	32,5	0,0
CubeSat Antenna Pointing Loss (dB)	1,0	3,0	0,0
Polarization Losses (dB)	1,0	2,0	0,06
Atmospheric and Rain Losses (dB)	1,5	2,5	1,0
Total link loss (dB)	170,0	174,5	167,5
Ground Station			
Isotropic Signal Level at Ground station (dBW)	-161,2	-165,7	-158,8
Ground Station antenna pointing bias (deg)	2,2	3,8	0,0
Antenna Pointing Loss (dB)	1,0	3,0	0,0
Antenna Gain (dBi)	26,0	26,0	26,0
Total Reception Line Losses (dB)	1,6	1,6	1,6
Effective Noise Temperature (K)	697,0	767,0	628,0
System Link Margin			
Signal-to-Noise Power Density C/No (dBHz)	62,3	55,4	66,2
System Desired Data Rate (Kbps)	500	500	500
Command System Eb/No (dB)	5,3	-1,6	9,2
Demodulation Method Selected		QPSK	
Forward Error Correction Coding Used		Cv(R=1/2,K=7)+RS(255,223)	
System Specified Bit-Error-Rate	10^{-5}	10^{-5}	10^{-5}
Demodulator Implementation Loss (dB)	0,5	1,0	0,0
Eb/No Threshold (dB)	6,5	7,0	6,0
Link Margin (dB)	**-1,2**	**-8,6**	**3,2**

We first established a classic link budget using eqs. 6 to 10 implemented in AMSAT IARU Excel Link Model [9] and AGI STK software. We have also introduced 3 scenarios in order to understand the behavior of the radio link by varying different condition parameters. The main difference between these scenarios is detailed in Table 1 where a color code is assigned to each case. In adverse case (red) we use the worst conditions in order to consider any side effects in our communication link. The main purpose of such approach is to assure an uninterrupted radio communication. However, these conditions are mostly overestimated. For example, we consider here 0,5 dB of rain effects loss and an attenuation of 3 dB on CubeSat and Ground Station antennas pointing (i.e. half of power is effectively radiated) [10] ; In nominal case (blue) we consider moderate conditions, however, overestimating CubeSat and Ground Station pointing antennas errors and atmospheric losses ; In favorable case (green) we take into consideration only atmospheric and free space losses. Such approach is very important to understand the impact of good radio conditions in link margin.

Then, we study the influence of CubeSat altitude h and Ground Station minimum elevation El_{min} in order to increase link margin. Finally, we introduce Variable Coding and Modulation (VCM) method which increases data rate by dynamically changing the modulation scheme and forward error correction. The advantage of VCM method is that high-order modulations are used when link conditions are favorable, in order to maximize the data transfer. While, in poor link conditions, robust modulation and FEC are used to increase the link margin. VCM techniques are efficient when the radio link can be predicted with accurate modeling. This method has proved its efficiency in NASA's experimental link SCaN Testbed on the International Space Station (ISS) [11]. In order to improve the VCM performance, a hysteresis algorithm is implemented to prevent the VCM method from rapid transitions. We have chosen 6 dB for Up Threshold and 3 dB for Down Threshold, hence, the On-board transceiver will wait for additional margin before changing states, keeping link margin around 3 dB to 6 dB, which is recommended for LEO CubeSat's communication systems. In this study, we only focus on varying data rate because the NanoCom SR2000 transceiver uses only Quadrature Phase Shift Keying (QPSK) modulation scheme.

3 Results and discussions

S-band Downlink link margin estimated in STK software (Fig. 4), shows that results are much closer to the favorable case calculated on AMSAT IARU Link Model. This is justified firstly because STK does not take into consideration antennas pointing errors. Secondly, we oversized some losses in Adverse and Nominal link budget in order to be sure that the link is functional. We also notice that link margin on S-band Downlink is tighter than S-band Uplink because the power on board the CubeSat and embedded antenna size remains limited. Therefore, in order to increase the link margin in S-band Downlink, we tried to variate the CubeSat altitude h and the minimum ground antenna elevation El_{min} as we see in Table 2. Firstly, we notice a gain of only 1,9 dB by decreasing

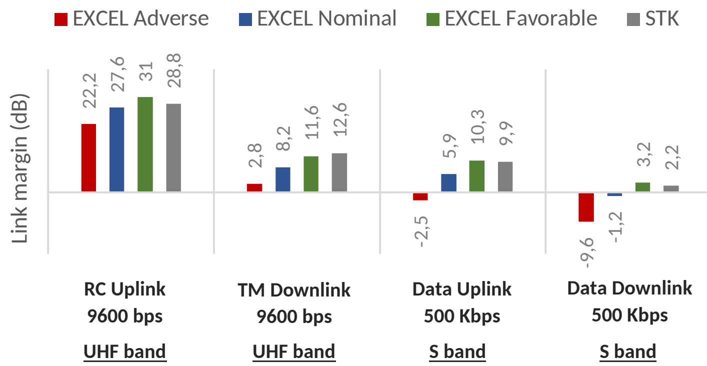

Fig. 4. Comparative link margin results for LEO CubeSat

the CubeSat altitude by 160 Km. This solution is not interesting because the choice of CubeSat's orbit remains on Launch opportunities. Also, decreasing CubeSat altitude leads to less lifespan [12]. Secondly, by increasing the minimum elevation by 15 deg, we notice a gain of almost 4,6 dB. This choice is actually time costly. Indeed, by using 20 deg as minimum elevation, we will only have 2 (or 3 depending on Ground Station location) short CubeSat passes (or visibilities) per day (about 4 mins each pass) instead of 4 longer passes per day (between 7 mins to 10 mins for each pass). In this study, the Ground Station is located in Rabat (Morocco), this limits our CubeSat visibilities to only 2 per day when using 20 deg of minimum elevation. Finally, doubling the communication data rate leads to decrease the overall link margin by 3 dB.

Table 2. Link margin for S-band CubeSat Downlink for different cases

	500 Kbps			1 Mbps		
	Adverse	**Nominal**	**Favorable**	**Adverse**	**Nominal**	**Favorable**
h = 560 Km El_{min} = 5 deg	-9,6 dB	-1,2 dB	3,2 dB	-12,6 dB	-4,2 dB	0,2 dB
h = 400 Km El_{min} = 5 deg	-7,7 dB	0,7 dB	5,1 dB	-10,7 dB	-2,3 dB	2,1 dB
h = 560 Km El_{min} = 20 deg	-5,0 dB	3,4 dB	7,8 dB	-8,0 dB	0,4 dB	4,8 dB
h = 400 Km El_{min} = 20 deg	-2,5 dB	5,9 dB	10,3 dB	-5,5 dB	2,9 dB	7,3 dB

By using the VCM method, we manage to adapt data rate according to the link margin, which is improved for high elevations. We apply it on a 24 hours scenario on STK. We see in Fig. 5 that we manage to reach a speed of 1,5 Mbps instead of 500 Kbps while keeping link margin between approximately 2,5 dB to 6 dB in daily visibilities (data rate step used is 500 Kbps according to the NanoCom GS2000 Ground tranceiver). Therefore, the VCM approach allowed us to get more downloadable data from the CubeSat, keeping a minimum elevation of 5 deg, compared to a conventional link budget. Indeed, by changing dynamically data rate depending on Ground Station elevation, we increase data that can be downloaded from the CubeSat by 116 MB per day (Table 3).

Table 3. Comparative results using VCM method on S-band CubeSat Downlink

	Classic $El_{min} = 20$ deg	Classic $El_{min} = 5$ deg	VCM $El_{min} = 5$ deg
Data rate	1 Mbps	500 Kbps	Variable
Number of passes per day	2	4	4
Total passes duration per day	534 sec	1991 sec	1991 sec
Maximum Data downloaded per day	58 MB	108 MB	224 MB

To do this calculation, we apply a data coding efficiency of 87 % using Viterbi Convolutional code Cv(R=1/2,K=7) and Reed Solomon code R.S(255,223) [7].

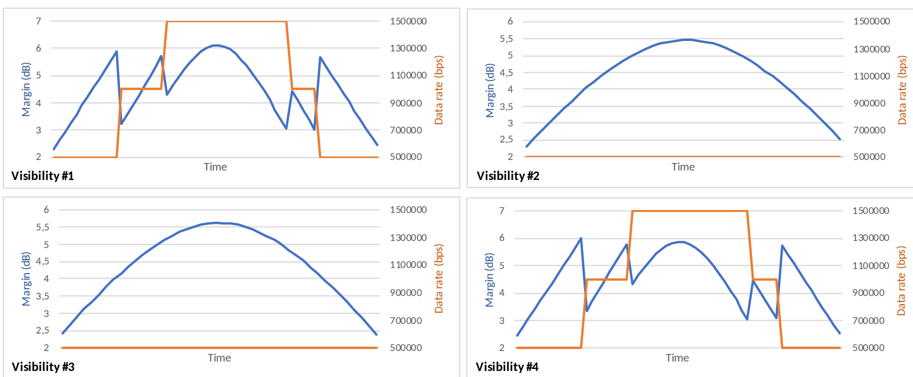

Fig. 5. The impact of VCM method on data rate and link margin

4 Conclusion and Further research

This paper begins by a classic link budget on S-Band downlink between a LEO CubeSat and a Ground Station located in Rabat (Morocco) for 3 different cases in order to apprehend the impact of communication conditions on link margin. Then, we apply VCM technique, which consists of varying data rate depending on the position of the CubeSat in its orbit. Our results have proven the outstanding performance gain on the amount of data that can be downloaded from the CubeSat. Thus improving the communication channel performance for optimized use of bandwidth. There are other more advanced approaches, notably the Adaptive Coding and Modulation (ACM) method [13], which instead of being based on propagation losses prediction, it uses real-time values of the Signal-to-Noise (SNR) measured on the receiver side. This method is more accurate but requires establishing an additional low data rate communication channel, in order to send to the CubeSat the link quality measured on ground. This feedback helps choosing the appropriate communication parameters. However, to examine in depth this approach, we should do the experiment using real space conditions. Next, we will try to apply Neural Network algorithms in order to optimize the choice of modulation and coding by including other parameters instead of focusing only on free space losses variation. We will also try to implement an Automatic Modulation Recognition in the Ground Station to detect the type of modulation chosen by the CubeSat. This approach will allow an automatic synchronization without having to create a dedicated channel.

Acknowledgements

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