Design of a Two Wavelenght Optical Downlink for LEO Spacecrafts

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Optical fiber brought high data transmission for terrestrial communication systems, consequently the community had the ambition of establishing similar data rates for free-space optical links. This work presents a system architecture and a design method for optical downlink for spacecrafts in Low-Earth orbit - LEO - and aims to achieve easy integration as well as simplicity for assembly. A statistical model for laser propagation in atmosphere is employed in order to obtain a theoretical model for description of the system.

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1. INTRODUCTION

The advent of fiber-based optical communications has benefited terrestrial data transmission with higher data rates compared to RF communication. This ambition is also present in the scope of aerospace communications. First experimental results were obtained by Galileo mission, operated by NASA in 1992. In 2001 the first laser data connection in space was achieved by the satellite Artemis, developed by the European Space Agency. Most recently, NASA's OPALS experiment achieved a 400Mbit/s optical link in 2014.

This work presents a proposal for an optical communication downlink with two channels based in On-Off Keying - OOK - and it's designed to attend dimensional specifications for cubesats. The system also strives for simplicity and aims to be possible to build with commercial devices in a laboratory environment. The downlink is designed to operate in LEO, as Earth observation and communication satellites are in this orbit, including the International Space Station. Here are described the OOK modulator circuit, telescope design, system architecture and theoretical model for atmospheric laser propagation.

2. SYSTEM ARCHITECTURE

In order to increase the transmission rate, a system with two operating lasers is proposed. The wavelengths initially used are 1310 and 1550nm, chosen because they suffer less scattering, commercial viability and easy integration with other optical components because they are in the spectrum of fiber communications. By means of a beam combiner, the two wavelengths unite into a single beam, which is collimated by the telescope and sent into free space.

To implement OOK (On-Off Keying) modulation, a MOSFET switching circuit can be designed to control the laser diode. Such circuits don't require great energy resources and can easily be powered in a Cubesat environment. The Figure 1 shows a suggestion of a OOK modulator circuit. In this system, two of these modulator circuit cells will be needed.

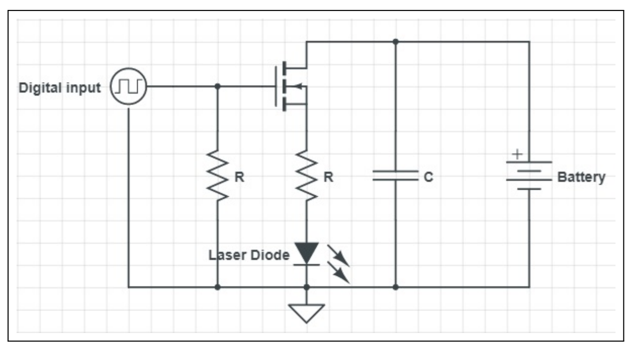

Fig. 1. Basic cell of the OOK modulator.

In order to avoid dispersive elements in the emitting telescope, two alternatives arise, Newtonian and Cassegrain configuration. Considering the simplicity of the Newtonian telescope, we opt for this configuration. The project has the following specifications: 2.5cm opening; Image size 0.1cm and focal length 10cm. Such numbers lead to a diagonal size of 0.34cm for the secondary mirror. Specifications are chosen to achieve significant beam collimation and to meet satellite dimensional requirements.

The maximum baud rate is related to the lasers rise time and varies with the commercial devices being used.

A commercial beam combiner has, typically, a loss of approximately 0.4dB, which will be considered negligible in this work.

The Figure 1 shows the final architecture of the proposed system.

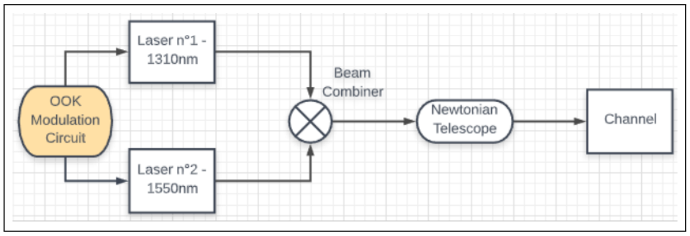

Fig. 2. System architecture for two wavelength optical link.

3. ATMOSPHERIC PROPAGATION AND LINK BUDGET EQUATION

Equating the optical link requires a model for atmospheric losses in beam propagation. Rytov's theory is used for propagation in turbulent media and therefore a statistical model based on the power received in the photodetector is developed. As previously derived by Giggenbach et al[1] and Rytov[2] , we have:

$$\sigma_R^2 = 2.25 \cdot k^{7/6} \int_0^L C_n^2 \cdot (L-z)^{5/6} dz \qquad (1)$$

$$= 1.23 C_n^2 k^{7/6} L^{11/6}, k = \frac{2\pi}{\lambda} \qquad (2)$$

With C_n^2 being the Rytov constant,

$$\sigma_{P,sph}^2(D_{Rx}) = exp\{\frac{0.2\sigma_R^2}{[1+0.18d^2+0.2(\sigma_R^2)^{6/5}]^{7/6}} + \frac{0.21\sigma_R^2[1+0.24(\sigma_R^2)^{6/5}]^{-5/6}}{1+0.9d^2+0.21d^2(\sigma_R^2)^{6/5}}\} - 1 \qquad (3)$$

for $d = D(\pi/2\lambda L)^{1/2}$.

$$\frac{P_{min}(p_{thr})}{P_o} = \frac{exp\{erf^{-1}(2p_{thr}-1) \cdot [2Ln(\sigma_P^2+1)]^{1/2}}{(\sigma_P^2+1)^{1/2}} \qquad (4)$$

Equations (1) and (2) bring the Rytov variance, equation (3) shows the relation between the Rytov variance and power scintillation variance. Equation (3) brings the power scintillation variance. Both equations (2) and (3) culminates in the dimensionless term found in (4). This term needs to be included in the optical link analysis for representing the atmospheric loss, and has p_{thr} as an experimental parameter, which is the probability of receiving a signal below of the minimum power for detection.

With the results offered by the analysis of atmospheric propagation, we can equate the optical link. As developed in chapter 3 of the reference [3] and with the introduction of the equation (4), we can obtain one single equation to calculate gain and losses in the optical link, the so called Link Budget equation, which is shown as (5).

$$P_r = P_t \cdot \frac{4\pi A}{\lambda^2} \cdot e^{\theta/\theta_d} \cdot \frac{exp(erf^{-1}(2p_{thr}-1) \cdot \sqrt{2Ln(\sigma_P^2+1)}}{\sqrt{\sigma_P^2+1}} \cdot (\frac{\pi D}{\lambda})^2 \qquad (5)$$

With $A =$, θ_d being the divergence angle of the laser device, θ the misalignment angle between the spacecraft and the reception point on the ground and D the receiving telescope aperture.

To observe its behaviour in dB, the link budget equation can be rewritten as (7).

$$P_r(dB) = P_t(dB) + Gains(dB) - Losses(dB) \qquad (6)$$

$$P_r(dB) = P_t(dB) + 10[log_{10}(\frac{4\pi A}{\lambda} \cdot (\frac{\pi D}{\lambda})^2) - log_{10}(e^{\theta/\theta_d} \cdot \frac{exp(erf^{-1}(2p_{thr}-1) \cdot \sqrt{2Ln(\sigma_P^2+1)}}{\sqrt{\sigma_P^2+1}})] \qquad (7)$$

4. RESULTS AND DISCUSSION

Based in equation (7), it's possible to investigate the received power behaviour for both channels. Considering an aperture of 20cm of the receiver telescope, $p_{thr} = 10^{-6}$, and an index-of-refraction structure constant $C_n^2 = 10^{-17} m^{-2/3}$, as can be observed in higher altitudes (more than 2km above ground), the link budget equation is evaluated separately for each channel. Curves for two different values of misalignment angle are also shown in the figures. Observing equation (5), it's useful to present the misalignment in terms of the divergence angle, which is a parameter of the commercial laser device being employed. The goal is to calculate the maximum possible deviation of the angle between the spacecraft and the receiving telescope through the effect it has on the received power. This analysis is useful for obtaining the maximum tolerated misalignment angle for the required SNR, and it can be a parameter for spacecraft control system design. Figure 2 shows the received power behaviour for channel 1, while Figure 3 shows curves for channel 2.

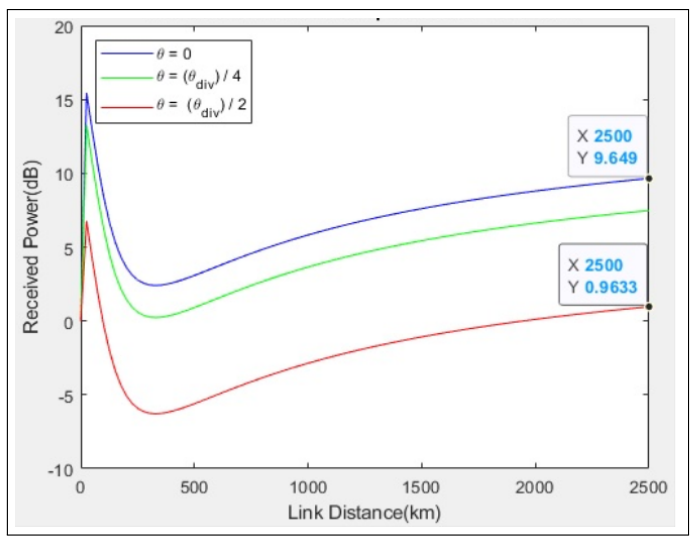

Fig. 3. Received power for the 1310nm link.

As the graph shows, the mathematical model that results in equation (7) is able to predict the power received on the ground and the influence of misalignment between the satellite and the receiving telescope. For the 1310 nm wavelength, in this system architecture, it would be possible to obtain a signal of about 9.6 dB with ideal alignment. Increasing the angle of

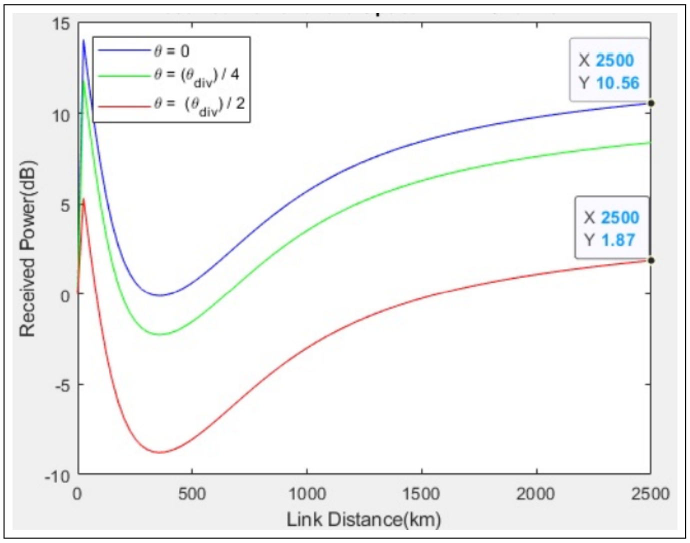

Fig. 4. Received power for the 1550nm link.

misalignment causes a drop in signal power, which is expected, even if intuitively. For $\theta = \theta_d/2$, a theoretical value of about 1 dB is obtained for the signal received on the ground.

For the 1550 nm wavelength, we have a curve with similar behavior but with slightly higher received power values. This is expected since the farther in the infrared spectrum, smaller the power scintillation due to the effects of atmospheric turbulence. For ideal alignment, a 10.56 dB signal is obtained, while for misalignment angle equal to half the divergence angle, a 1.87 dB signal is obtained.

The signal received on the ground could be read with the use of a dichroic mirror and two different photodetectors, one for each wavelength.

It is necessary to note that this system is susceptible to synchronization problems. So when a considerable amount of information packages is lost, it must be detected and the sending must be restarted. This situation could occur when the laser beam passes through a thick cloud, for example. The ground detection of lost packages should be made as fast as possible, once the passing of time increases the misalignment between spacecraft and ground telescope.

5. CONCLUSIONS

Considering the main objective of the work, which is designing a two channel optical downlink for LEO spacecrafts, a basic cell for a OOK modulator circuit is discussed as well as the design of a Newtonian telescope, culminating in the final system architecture. To obtain design parameters of the downlink, statistical models are applied for turbulent media wave propagation, transmission and reception are included in the link budget equation, which is also used to observe the received power behaviour on the ground. This paper presents a simple design which offer easy integration, while the mathematical formalism can be used to model similar systems varying in number of channels, employing different telescope configurations or alternative wavelengths, as well as different laser devices.

The problems that this design should face are also discussed and possible subsequent problems are cited.

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