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OPTICAL INTER-SATELLITE LINKS: APPLICATIONS IN DEFENSE

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RESUMO

Nos dias de hoje, o uso de satélites é essencial na vida quotidiana e afeta quase todos os campos de atividade da sociedade. Na Defesa, as comunicações por satélite têm um papel preponderante: a possibilidade de obter informação sobre as atividades do inimigo e sobre o teatro de operações em tempo real, é vital para o sucesso de qualquer missão. A maioria das ligações intersatélites, e entre os satélites e a estação de base, usa a banda de radiofrequência (RF). As comunicações óticas são uma tecnologia emergente que oferece, entre outras vantagens, maior largura de banda, que é necessária para poder transmitir um volume crescente de dados. Este facto representa uma mais-valia significativa para as operações militares. O futuro das comunicações por satélite está pois, dependente dos desenvolvimentos nos sistemas de comunicação óticos. Neste artigo, o diagrama de blocos e as principais características destes sistemas serão apresentadas e analisadas.

Palavras-chave: Comunicações óticas; ligação por satélite; lasers; fotodetetores; radiofrequência.

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ABSTRACT

Nowadays the use of satellites is essential in everyday life affecting many areas of our society. In Defense, satellite communications play a key role. On the military side, the ability to obtain information in time, about the enemy and the theater of operations, is vital to fulfill the missions. Currently, the majority of inter-satellites communications and between the satellite and ground stations uses the radiofrequency (RF) bands. The free space optical communications are emerging as an alternative, providing, among other advantages, a much larger bandwidth, which is necessary to deal with increasingly larger amounts of data. This represents a significant added-value in military operations. The future of satellite communications will then be strongly dependent on developments in optical communication systems. In this paper the block diagram and the main characteristics of these systems will be presented and discussed.

Key-words: Optical communications; satellite links; lasers; photodetectors; radiofrequency.

1. INTRODUÇÃO

Satellite communication systems have evolved significantly over the last decade and currently are a key element in modern communication systems. These systems are in continuous progress, due mainly to the increased use of Internet. Therefore, substantial investments are being made by industry and governments to answer the demand in this area (Misra, 2013).

In Defense, satellite communications play a key role. On the military side, the ability to obtain information in time, about the enemy and the theater of operations, is vital to fulfill the missions. In this kind of activities, the use of satellites allows navigation of the military forces through the analysis of satellite images for the reconnaissance of the territory, as well as meteorological information. It also provides communications, essential to coordination between forces on the battlefield.

The constant increase of traffic on telecommunications networks requires an increase in the used bandwidth, so as to ensure good quality in communications. Thus the development of new optical inter-satellite communication systems, and between a terrestrial base and the satellites, becomes essential to answer the increasing demand of bandwidth (Misra, 2013),(Santos, 2008),(Barbosa, 2008). Compared to radio frequency (RF) links, in use at the present time, optical links offer numerous advantages (Hemmati, 2014), (Zhoou et al, 2008), (Hammado and Zghair, 2014):

- greater bandwidth and the possibility of higher data rates (in the order of Giga bits per second (Gbps));

- smaller terminal size and weight;
- do not require licenses for its implementation (in RF licenses are required due to the request transmission frequencies);
- lower power consumption of the antennas;
- greater security and resistance to interference (due to the smaller beam width and higher directivity), an essential tool for military applications;
- higher power at the receiver.

The analysis of this kind of systems is the objective of this paper.
In Fig. 1 a traditional optical communication system, involving LEO [1] and GEO satellites and a ground station, is shown. The use of LEO and GEO satellites is important because of their functions (Earth observation, communications, scientific and military missions). The link between satellites is established by laser, while the link between GEO satellite and the ground station can be optical or by RF. In this last case it is necessary to determine if the optical link between satellite and Earth is possible, due to attenuation in the atmosphere and the pointing problems between the satellite and the base station. The majority of communication and meteorological satellites use GEO orbits because they are stationary relative to Earth, which facilitates the communication between the satellite and the ground station.

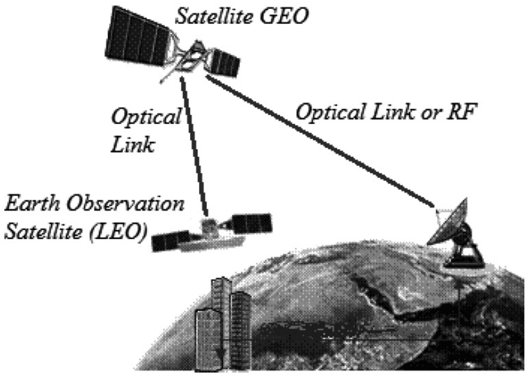

Fig. 1 – Optical communication system representation (Carlo and Roberto, 2006).

The characteristics of the environment involving satellites are influenced by its altitude. An aspect that should be considered is the Earth's atmosphere. The Earth's atmosphere can disrupt the light propagation, therefore its effects must be considered. These effects are shown in particular in Earth-satellite links (or vise versa) because the optical beam travels through the atmosphere. There are three most relevant atmospheric effects that affect the propagation of the

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[2] Types of Orbits: LEO (200-2000 km), MEO (2000-35780 km), GEO (35780 km) and HEO (>35780 km).

optical beam: geometric attenuation, atmospheric attenuation and atmospheric turbulence. The geometric attenuation consists in the increasing divergence of the optical beam, during its propagation, due to diffraction. With this divergence only part of the beam energy is focused and captured in the reception area of the optical antenna. The atmospheric attenuation is caused by the absorption and dispersion of the beam energy due to its interaction with the various particles present in the atmosphere, such as molecules (water vapor, carbon dioxide, ozone, etc), water drops and suspended particles (dusts). Finally, the atmospheric turbulence is due to the changes in the atmospheric refractive index that can be induced, for example, by changes in the temperature profile. These variations cause losses by beam deformation due to random deviations in the beam propagation trajectory.

However, in inter-satellite links, the links are established above 100 km of altitude, so the atmospheric effects are not important, and therefore, it can be considered that the beam propagation channel is free space (Santos, 2008), (Barbosa, 2008). The distance of this links is typically in the order of thousands of kilometers, the most common being around 40000 km. However, there are examples for distances greater than 40000 km. For these distances, only optical links can maintain communications with bitrates around Gbps. Note that with the increase of the distance, the power level required at the transmitter is higher and it is harder to point with precision the optical beam from the transmitter to the receiver.

Then, the implementation of this type of links requires a set of specifications, which are:

- The laser used for the optical source must have a narrow and coherent beam to ensure a lower degradation;
- The transmitted power generally varies from several hundred milliwatts (mW), until 10 W, depending on the needs and characteristics of the link;
- Minimum power at the receiver: receiver requires a minimal power around one nanoWatt (nW). This power is related to the sensitivity of the optical receivers;
- PAT (Pointing, Acquisition and Tracking) systems: allows pointing the laser beam with precision to the receiver, establish communication and follow its trajectory. It is an essential element to the success of these links;
- Reliability of electronic devices in the space environment is mandatory, since there are high levels of radiation and extreme temperature ranges. The electronic devices incorporated in the satellites have to ensure reliability, because maintenance and/or replacement operations are very difficult (if possible) and have high costs. Therefore, there are mainly three ways to make an immune system or, at least, increase its robustness to these adverse conditions: redundant circuits, the use of shields and building electronic circuits with more resistant materials.

2. THE OPTICAL COMMUNICATION SYSTEM

An optical communication system is composed by a transmitter, a receiver, and a signal propagation channel, which depends on the type of link: it can be air or free space. However, in the optical inter-satellite links it is considered that the propagation channel is free space.

Typically, the function of the optical transmitter is to convert an electrical signal (which encodes information to be transmitted) in an optical signal, which will be responsible for transmitting data to the receiver. The receiver converts the information of optical domain to the electrical domain and also has the function of processing correctly the electrical signal in order to recover the transmitted information with minimum error as possible. Fig. 2 presents the standard block diagram of the optical communication system.

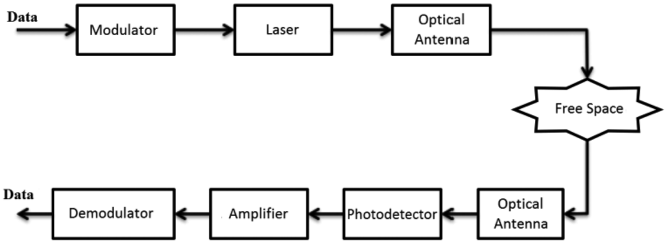

Fig. 2 – Optical communication system block diagram.

2.1 Modulation Techniques

The modulation and demodulation are executed in the electrical domain. The modulator operates in the signal emitted by the laser, converting the transmitted data in an established standardized format (Vilela et al, 2014).

This paper analyzes two modulation techniques: On-Off Keying (OOK) and Pulse Position Modulation (PPM). They are characterized by simple techniques with high reliability and with low implementation costs.

2.1.1 On-Off Keying (OOK)

The OOK modulation may be considered as a special case of amplitude modulation. As can be seen in Fig. 4, it consists in a binary technique where each time slot, , corresponds to one bit. The bit "1" is indicated by the presence of a laser pulse, while the bit "0" is indicated by the absence of signal. The pulses are necessarily unipolar, the NRZ type (Non-Return-to-Zero), that is, the pulse duration has the duration of a bit period, or RZ (Return-to-Zero) in which the pulse duration is a fraction of the bit period. The NRZ pulses are more used than the RZ pulses, because they are simpler and require a smaller bandwidth at the photodetector (Coelho, 2009). For this reason, in this work, we will consider NRZ pulses.

In the demodulation process it is the receiver that checks if at every seconds is reached a signal “0” or “1”(Vilela et al, 2014).

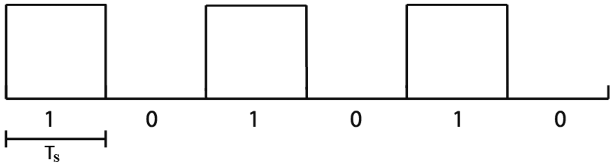

Fig. 3 – OOK signal for NRZ pulses.

The time slot, T_s , can be calculated by the following equation:

$$T_s = 1 / D_b \qquad (1)$$

where D_b is the bitrate (bps).

In Fig. 5 the power levels of the laser signal are defined. Note that the “0” bit power ($P_{\min}$), does not correspond to a null power.

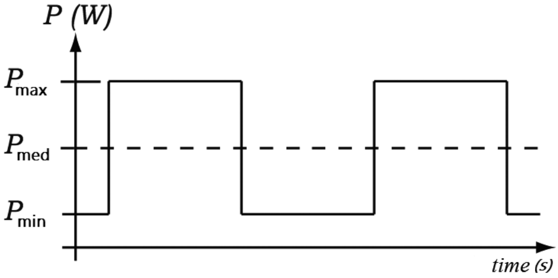

Fig. 4 – Laser signal power levels [2].

The ratio between maximum power, $P_{\max}$, and the minimum power, $P_{\min}$, is called the extinction ratio and is given by (Agrawal, 2002)

$$r = \frac{P_{\min}}{P_{\max}} \qquad (2)$$

where $P_{\min} < P_{\max}$, varying the extinction ratio between $0 < r < 1$.

At the same time, the maximum and minimum power can be also obtained from the average power, P_{med} , and the extinction ratio, r (Cartaxo, 2005):

$$P_{\max} = \frac{2P_{med}}{1+r}; \quad P_{\min} = \frac{2P_{med}}{1+r} \times r \qquad (3)$$

2.1.2 Pulse Position Modulation (PPM)

The PPM modulation consists in dividing the allocated time for the transmission of a symbol in m equal time slots (m is the modulation order). To represent a certain symbol, a pulse is sent only in one the m slots, as shown in Fig. 5.

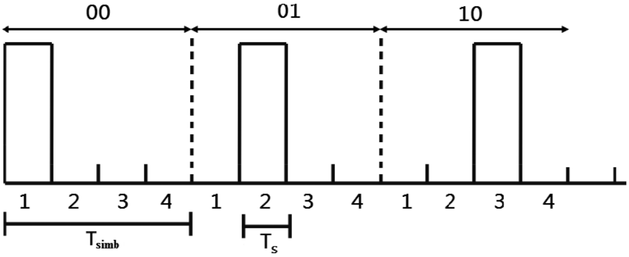

Fig. 5 – 4-PPM Signal.

The number of time slots, m , depends on the number of bits sent per symbol, k :

$$m = 2^k \qquad (4)$$

The symbol duration, T_{simb} , depends on the bit rate D_b , and is given by:

$$T_{simb} = \frac{k}{D_b} \qquad (5)$$

And the duration of the slot, T_s:

$$T_s = \frac{T_{simb}}{m} = \frac{k}{mD_b} \qquad (6)$$

2.2 OPTICAL SOURCE: THE LASER

The main component of the optical transmitter is the optical source which generates the light radiation. There are different types of light sources which can be used for optical communications, such as LED's (Light Emitting Diodes) or lasers. Currently, there are the RCLED (resonant-cavity LEDs), which are based on conventional LED's, but due to some changes in its structure, improvements have been made in emitted light beam, which ensure greater directionality and intensity (Tsai and Xu, 2013).

In the majority of long distance satellite intercommunication systems the laser is used as the light source. These cases are associated with high levels of attenuation, and only lasers have the capacity to establish efficient links, due to its specific characteristics: the emission of monochromatic radiation (wavelength well defined) and narrow and highly directive light beams. These characteristics are essential to ensure a small degradation of the beam, as well as reduce its temporal dispersion, allowing the modulation at higher data rates (Vilela et al, 2014), (Keiser, 1991).

The lasers are classified according the active medium used in them. Currently, solid-state lasers are the most used in optical space communications, which results from their characteristics: smaller dimensions, making possible a more compact design, and greater energy efficiency in converting the electric power supplied into light energy, enabling to establish links at distances greater than 40000 km with light power less than 10W. The most widely used lasers in this kind of links are the semiconductor lasers and the crystal lasers.

The type of laser is chosen according to the characteristics of the link that is implemented, such as distance, altitude, the environmental conditions and the power level required in the receiver. It also depends on the wavelength chosen for the link and on the implemented modulation format. In Table I some examples of solid-state lasers used in optical inter-satellite links are presented.

Table I – Solid-State Lasers Examples Used In Optical Inter-Satellites Links.

Laser	Type	Link	Wavelength (nm)
Aluminium Gallium Arsenide (AlGaAs)	Semiconductor	ARTEMIS – SPOT-4 (2001)	800
Nd:YAG[3]	Crystal	NFIRE – TerraSAR-X (2008)	1064
Nd:YAG	Crystal	Alphasat – Sentinel-2A (2012)	1064

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[3] Nd:YAG (Neodymium-doped Yttrium Aluminium Garnet) is a crystal that is used for solid-state lasers.

2.3 OPTICAL ANTENNAS

In these communication systems, optical antennas are used to transmit and receive the laser beam. These antennas are used to collect and focus light, particularly in visible spectrum.

There are three primary types of antennas: refractors (dioptrics) which use lenses, and reflectors (catoptrics) which use mirrors and combining lens-mirror systems (catadioptrics) which use lenses and mirrors in combination. The last one are most used in optical communication systems.

Typically, an optical antenna has an associated gain. The gain of an optical antenna is given by the following equation (Aviv, 2006):

$$G = \left(\frac{\pi d_a}{\lambda}\right)^2 \times \eta \qquad (7)$$

where d_a is the equivalent aperture of optical antenna, η is the efficiency and λ is the wavelength.

2.4 PHOTODETECTOR

The photodetector is the element of the optical receiver that converts the optical signal in an electrical signal through the photoelectric effect.

Despite the diversity of photodetectors (photomultiplier, pyroelectric detectors, photoconductors, phototransistors and photodiodes), in optical communications the photodiodes are almost always used in these kind of systems. That is because they have the best characteristics, that is, small size, high sensitivity and low cost (Coelho, 2009), (Keiser, 1991)

There are two types of photodiodes used in the optical communication systems: PIN and APD (Avalanche Photodiode) (Keiser, 1991).

2.4.1 PIN photodiode

The PIN photodiode has the structure of a p-n junction, separated by a lightly doped intrinsic region. The photodiode is reverse biased so that in the region with greater resistance, the intrinsic region, there is an intense electric field and there are almost no mobile carriers, electrons and holes (Vilela et al, 82014) (Keiser, 1991).

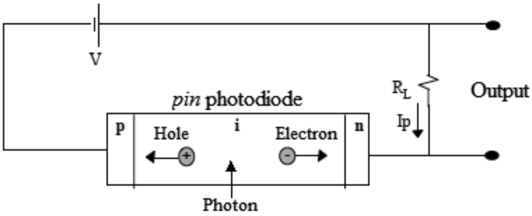

Fig. 6 − Pin photodiode reverse bias representation [3].

As shown in Fig. 6, a photon incident on the depletion region, with an energy higher than the energy gap between the semiconductor bands, will excite an electron from the valence band to the conduction band. As a result, a free electron-hole pair is generated. Due to the intense electric field present in the depletion region, free electrons move to the region "n" and the holes move to the region "p" before their recombination. This charge flow causes the appearance of the current, I_P called the photocurrent.

A photodiode characteristic parameter is the responsivity, which defines the performance of the photodiode. The responsivity is the relationship between the generated current and the optical power incident on the photodiode (Keiser, 1991):

$$R_0 = I_p / P_i \qquad (8)$$

where P_i is the optical power incident on the photodetector.

2.4.2 APD photodetector

The APD photodiode has the capability of amplifying the internal current generated in the photo detection process. It differs from the PIN photodiode because it needs higher bias voltages to achieve the desired operation. As can be seen in Fig. 10, the APD structure includes a very high electric field region, designated by avalanche region. The avalanche region corresponds to the zone where the electric field is greater than the minimum required, E_m , to cause breakdown of the n^+-p junction and to allow signal amplification (Coelho, 2009).

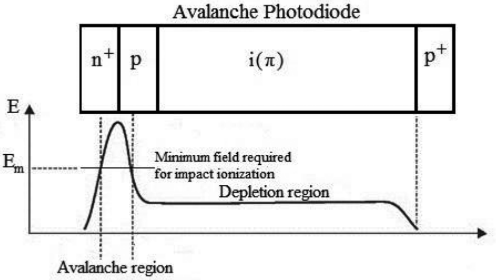

Fig. 7 – An APD together with the eletric-field distribution inside various layers under reverse bias (Keiser, 1991).

Such as the pin photodiode, the APD performance is characterized by its responsivity, R_{APD}, which expresses the relationship between the APD output current and the optical power incident on the avalanche photodiode. The relationship between the APD responsivity and responsivity to the primary current is given by (Keiser, 1991):

$$R_{APD} = MR_0 \qquad (9)$$

where *M* is the avalanche gain.

2.4.3 Photodetection noise

Ideally, the electrical current generated by the photodetector is directly proportional to the incident optical power. However, this current has fluctuations, even when the incident power is constant. These fluctuations are caused by several types of noise. The most relevant are the quantum noise and circuit noise (Keiser, 1991): that will be discussed in the following two sections.

- Quantum noise

An incident optical signal on the photodetector, with a given optical power, corresponds to a certain average number of photons per unit of time. However, the time slot between photons is a random variable and the photocurrent generated by the photodiode is not a continuous process. Besides, the photodetector generates a small current in the absence of any optical signal. This current is called dark current, I_d , and results from thermally generated electron-hole pairs. The contribution of this current can be included in the quantum noise photodiode.

The photodiode quantum noise current variance is defined by:

$$\sigma_q^2 = 2q(R_0P_i + I_d)M^2M^xB_{e,n} \qquad (10)$$

where is the electron charge, *M* is the avalanche gain (in the case of pin photodiode, *M*=1), is a photodiode material parameter, with values between “0” and “1”, and $B_{e,n}$ is the equivalent noise bandwidth from the optical receiver.

- Circuit noise

The circuit noise comes from the resistive and active elements present in the optical receiver. So, its value depends on the remaining electrical elements of the receiver such as the amplifier. For this reason, this type of noise will be discussed in the next section.

2.5 ELECTRICAL AMPLIFIER

Normally, the photodetector output signal is so weak that needs to be amplified before it can be properly processed by other system devices. The electric amplifiers amplify the low levels of transmitted electrical current generated by the photodetectors.

An amplifier must have the following characteristics: low noise, high gain and adequate bandwidth. Since the noise increases with the bandwidth, these two parameters have to be carefully taken into account to optimize the performance of the receiver.(Coelho, 2009).

As mentioned above, the electrical components, which constitute the amplification circuit, also contribute to circuit noise. Besides, the amplifier gain also interferes in the system circuit noise. So, circuit noise current variance, σ^2_c , is given by (Cartaxo, 2005):

$$\sigma_c^2 = \left[\sqrt{S_c(f)}\right]^2 B_{e,n} G_A^2 \qquad (11)$$

where G_A is the amplifier gain, that corresponds to the value of the amplification circuit transfer function for the null frequency, that is, $H_A(f = 0)$ and:

$$\sqrt{S_c(f)} = \sqrt{\frac{4k_B T}{R_L} F_n} \qquad (12)$$

where k_B is the Boltzmann constant, T is the absolute temperature (Kelvin), R_L is the load resistance of the photodetector and F_N is the amplifier noise factor. The square root of the power spectrum density of the circuit noise power, $\sqrt{S_c(f)}$, is measured in units $A/\sqrt{H_z}$. The typical values are in the order of 1 $pA/\sqrt{H_z}$ [4]. So, the total noise current variance, σ^2_n , is obtained from the sum of the different noise variances mentioned above [4]:

$$\sigma_n^2 = \sigma_q^2 + \sigma_c^2 \qquad (13)$$

3. SIGNAL POWER BUDGET AND BIT-ERROR RATE (BER)

3.1 Signal Power Budget

The signal power budget has the objective of estimate the optical received power at the receiver. All the gains and losses involved in the communication process are considered that is, transmitter, receiver and signal propagation channel. Thus, in the optical communication system analysis, the following factors will be considered: optical transmitted power, antenna gains (emission and reception) and attenuation in free space. For simulation purposes it will be considered that the emitted laser beam is perfectly coincident with the receiving surface and therefore the pointing losses will be neglected. The receiver power in dBm is given by (Oscarsson, 2008), (Alluru, 2010):

$$P_{r_{dBm}} = P_{t_{dBm}} + G_{t_{dB}} - L_{s_{dB}} + G_{r_{dB}} \qquad (14)$$

where P_t is the average optical power normalized to 1 mW, G_t and G_r the gains of the transmitting and receiving antennas, respectively, and L_s the free space losses. The free space losses are given by:

$$L_{s_{dB}} = 20\log\left(\frac{4\pi d}{\lambda}\right) \tag{15}$$

where λ is the wavelength and d is the distance between satellites.

3.2 Bit-Error Rate

The optical receiver performance of a digital transmission system is measured by the BER (Bit-Error Rate). This parameter is defined as the ratio between the number of incorrect bits received by the total number of bits transferred in a given time interval. Typically, in this kind of communication systems the BER should be below 10^{-6}, and the typical values are between 10^{-6} e 10^{-9} (Zaki et al, 2014).

3.2.1 BER – OOK Modulation

For OOK modulation, BER can be calculated by the following equation (Agarwal, 2002):

$$BER_{OOK} = \frac{1}{2}erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{16}$$

where Q parameter is given by:

$$Q = \frac{V_1 - V_0}{\sigma_1 + \sigma_0} \tag{17}$$

where V_0 and V_1 are the values of the voltages logic levels “0” and “1” and σ_1 and σ_2 are the squared root of the noise variances to symbols “0” and “1”, respectively, obtained individualizing the expression (13) for the optical power for the symbols “0” and “1”. The *erfc* function is the complementary error function, defined as:

$$erfc(x) = \frac{2}{\sqrt{\pi}}\int_{x}^{+\infty} \exp\left(-y^2\right)dy \tag{18}$$

3.2.2 BER – PPM Modulation

As already mentioned, this modulation technique is more complex than OOK, since several bits are sent in a pulse. A rigorous synchronization is necessary with the start of each symbol by the receiver. Thus, at the receiver, in the decoding process, he correct time interval must be chosen, which in theory, will be the highest intensity of the pulse. However, if the receiver decodes the wrong interval, the number of bit errors will be The average number of wrong bits by decision errors is given by:

$$N_{be} = \frac{m}{2(m-1)} \qquad (19)$$

where *m* is the modulation order.

The receiver probability to choose the correct time interval is represented by the following expression (Oscarsson, 2008):

$$P_{\text{csc}} = \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\sigma_1} e^{-\frac{(x-V_1)^2}{2\sigma_1^2}} \left[\int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}\sigma_0} e^{-\frac{(y-V_0)^2}{2\sigma_0^2}} dy \right]^{m-1} dx \qquad (20)$$

Based on the expressions (19) and (20), the BER for PPM modulation is defined by (Oscarsson, 2008)::

$$BER_{PPM} = N_{be}(1 - P_{\text{csc}}) \qquad (21)$$

4. TESTS AND RESULTS

In this section several practical examples will be analysed, using the simulator developed, with the goal of comparing the system performance in different situations.

4.1 SIMULATION OF INCREASED DISTANCE

This example will be based on data from an optical link held in 2008 between two LEO satellites: NFIRE e TerraSAR-X (Gagnon, 2012).

The data used in the simulator are:

Table II - Parameters Inserted In The Simulator

Parameters	**Values**
P_t (Transmitted Power)	0.7 W
D_b (Bitrate)	5.6 Gbit/s
λ (Optical Wavelength)	1064 nm
r (Extinction Ratio)	0.152
d_{at} e d_{ar} (Aperture Diameter)	12.4 cm
η_t e η_r (Optical Antenna Efficiency)	0.8
Modulation	OOK
Photodiode	APD
R_0 (Responsivity)	0.8 A/W
M (Avalanche Gain)	40
I_d (Dark Current)	5 nA
$B_{e,n}$ (Equivalent Noise Bandwidth)	10 GHz
$\sqrt{S_c(f)}$ (Square root of the PSD of the circuit noise power)	5p $A/\sqrt{Hz}$
G_A (Amplification Gain)	50 dB

With these values, there were several simulations with different distances. The results are presented in Table III.

Table III - Results Obtained in Function of The Distance Variation.

	Results				
d (km)	P_r[dBm]	BER	SNR' [dB]	$\sigma_c^2[V^2]$	$\sigma_q^2[V^2]$
5000	-26.37	$1.84*10^{-28}$	20.09	$2.5*10^{-8}$	$2.87*10^{-6}$
10000	-32.40	$4.04*10^{-8}$	13.91	$2.5*10^{-8}$	$7.22*10^{-7}$
15000	-35.92	$2.81*10^{-4}$	10.16	$2.5*10^{-8}$	$3.25*10^{-7}$
20000	-38.42	$6.75*10^{-3}$	7.36	$2.5*10^{-8}$	$1.86*10^{-7}$
25000	-40.35	0.03	5.06	$2.5*10^{-8}$	$1.22*10^{-7}$
30000	-41.94	0.07	3.07	$2.5*10^{-8}$	$3.25*10^{-7}$
35000	-43.28	0.12	1.29	$2.5*10^{-8}$	$6.6*10^{-8}$
40000	-44.44	0.16	-0.32	$2.5*10^{-8}$	$5.24*10^{-8}$
45000	-45.46	0.20	-1.80	$2.5*10^{-8}$	$4.3*10^{-8}$

With the results obtained in the table, it possible to see that there is a significant increase in the BER with increasing link distance. It should be noted that the BER requirement is largely accomplished for the initial distance (5000 km), but from 15000 km, with these parameters, the link is not viable. The received power and the signal-to-noise ratio follows as expected, the increase of BER. The circuit noise remained constant, because the noise parameters of the electrical elements were not changed. However, quantum noise decreased with increasing distance, since this type of noise depends on the received power. So, if the received power was decreasing, the quantum noise followed this decay.

4.2 Simulation With Different Modulation Types

In this example the data are from an optical link held in 2012 between a LEO satellite and a GEO satellite: AlphaSat and Sentinel 2-A (Gagnon, 2012)
The data used in the simulator were:

Table IV - Parameters Inserted in the Simulator [5].

Parameters	Values
P_t (Transmitted Power)	5 W
D_b (Bitrate)	2.8 Gbit/s
λ (Optical Wavelength)	1064 nm
r (Extinction Ratio)	0.152
d_{at} e d_{ar} (Aperture Diameter)	13.5 cm
η_t e η_r (Optical Antenna Efficiency)	0.8
d (Distance)	45000 km

The receiver parameters remained the same as in the previous example. In Table V the BER results according to the selected modulation format are shown.

Table V - Ber Depending on the Type of Modulation

Modulation Format	BER
OOK	$1.21*10^{-4}$
2-PPM	$8.14*10^{-6}$
4-PPM	$5.24*10^{-6}$
8-PPM	$3.28*10^{-6}$
16-PPM	$1.98*10^{-6}$
32-PPM	$1.16*10^{-6}$
64-PPM	$6.57*10^{-7}$

The objective of this simulation is to compare system performance with the different modulation types. From the results obtained, it is concluded that the OOK modulation has the worst performance. In the other side, it appears that the greater the PPM modulation order, the better is the BER performance. However, the performance improvements are not very significant with increases the modulation order, and the biggest "jump" happens when going from 32 to 64-PPM. Therefore, in most cases, the performance improvement obtained does not compensate the increase of the system complexity. Traditionally, it is for this reason that the modulation order used is 2 (2-PPM). In this case, to have a viable link, the 64-PPM modulation would have exceptionally to be used.

5. CONCLUSIONS

The growing importance of optical communications in the commercial and military areas, in an optical inter-satellite intercommunication system using lasers was presented in this paper. The study has identified the transmitter and receiver subsystems and analyzed the main characteristics associated with these communication systems. A simulator based on Matlab was also developed, which allows the test on the impact that the variation of the parameters has on the performance of the system. The development of this kind of links is a new technological development with very high commercial impact, due to the higher bandwidth requirements caused by the increase of traffic in telecommunications networks and the Internet. Thus, the need of increasingly larger bandwidths, becomes essential to the development of optical communication systems, in ground and space.

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