Advanced Analysis of FSO Communications considering Direct and Relayed Paths to Improve Satellite-to-Earth Data and Control Links

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***Abstract*— The rapid expansion of satellite constellations and advancements in satellite technology have led to increased demand for high-speed data transmission, posing limitations for traditional RF communication methods. As RF spectrum congestion becomes more prevalent, Free-Space Optics (FSO), is emerging as a promising alternative due to its ability to operate at much higher frequencies, offering greater bandwidth and reduced latency. FSO systems also benefit from compact, lightweight equipment, enhancing satellite integration. But it faces challenges such as alignment accuracy and susceptibility to atmospheric conditions for optimal performance. This paper investigates the role of High-Altitude Platforms (HAPs) in mitigating signal degradation caused by atmospheric disturbances, with simulations comparing direct and multi-hop communication links under varying conditions to evaluate the potential benefits of optical communications in future satellite networks. Simulations are presented to optimise the launch height of the satellite, the modulation used, and the pointing towards the satellite under the conditions of interest.**

***Keywords*—HAP, Free Space Optic, Satellites-to-Earth links, LEO**

I. Introduction

In recent years, the exponential growth in the number of satellites and advancements in on-board measurement technologies have significantly increased data traffic between ground segment and satellites. As a result, conventional radio frequency (RF) communication methods are not always the most suitable option, as they cannot achieve the high transmission speeds offered by optical communications, which has positioned this as a critical area of research for future space missions. Today, a large number of satellites orbit the Earth, performing distinct functions with the most advanced technologies, contributing to technological advancements on our planet, but this has not always been straightforward, as testing new technology in space inherently involves high risks and tight margins for error. Early satellites were designed as passive reflectors, simply bouncing back signals received from the ground and retransmitting them in all directions to be captured globally. Over the years, as functionalities were validated, satellites evolved to become more capable, and now they are able to receive signals at one frequency, process them, and transmit them back to Earth at a different frequency along with additional data.

The advancement of satellite technology, coupled with reduced launch costs due to private sector involvement, has led to a dramatic increase in the number of operational satellites, which has turned into structural risks to future missions, and has resulted in RF spectrum congestion, leading to spectrum scarcity. To address this issue, new technologies and strategies has been developed, such as the use of higher frequencies, smaller and more efficient satellites, advanced modulation and coding techniques to enhance spectrum efficiency, and the exploration of alternative communication technologies like optical communications. By utilizing light beams instead of RF waves, optical communication operates at much higher frequencies, between 200-300 THz, which significantly reduces diffraction losses, and which allows the light beam to be narrower, concentrating the transmitted energy and thereby increasing efficiency. In terms of equipment design, the instrumentation used in optical communication is generally smaller and lighter, and higher frequencies enable faster data transmission, thereby reducing latency. Furthermore, the narrow beamwidth of Free-Space Optics (FSO) signals makes this type of communication more directional and focused than RF communications, reducing the risk of unwanted interference, improving data transmission and reception efficiency, and enhancing security. However, this also presents a challenge, as the system requires extremely precise alignment between the transmitter and receiver to ensure the narrow beam of light reaches its target without deviation, which can be difficult in the dynamic space environment where objects are constantly moving and changing orientation. To validate the performance of this technology, several missions have been launched in recent years with successful or even better-than-expected results. Some of them are illustrated in Fig. 1, and they are summarized in the Section II.

Another limitation of optical communication is its sensitivity to atmospheric conditions when communicating with ground stations. Factors like clouds or rain can attenuate or completely block optical signals. Additionally, unlike RF systems, optical communications cannot penetrate solid objects, meaning the presence of any obstacle that obstructs the line of sight between the transmitter and receiver can entirely disrupt the communication link. This paper presents an analysis of the transmission links between a Ground Station (GS) and the satellite under different weather conditions in line with the recent trend of as relay an aerial High-Altitude Platform (HAP) in order to minimize attenuation and degradation. Simulations will allow a comparison of the direct and multi-hop paths according to the Signal-to-Noise Ratio (SNR) achieved.

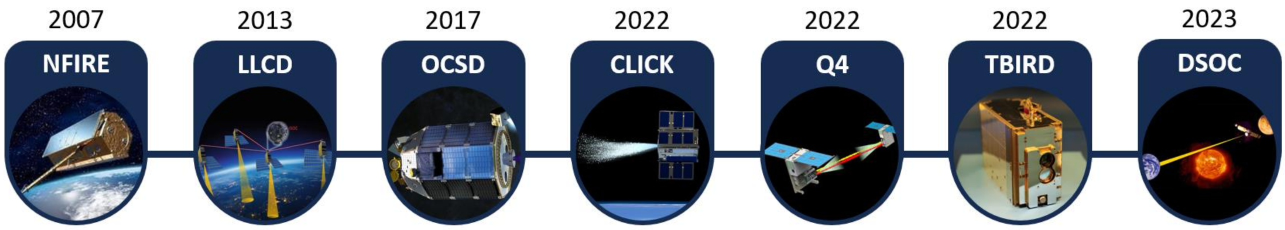


Fig. 1. Optical communication missions

In Section III, an analysis of the system to be studied is performed, modelling the whole architecture and the work carried out prior to the simulations. Section IV contains the description of the use cases to be analysed, the factors to be taken into account, and the simulation results reached. Finally, Section V drives the main conclusions from these results.

II. RELATED WORK

This section shows the progress that has been made in optical communications over the years by the major space agencies, and how the number of missions related to this topic has increased in recent years (see Fig. 1). Main trends in the literature will also be addressed through other relevant works.

Beginning with the NFIRE satellite, that was launched by the U.S. Missile Defense Agency (MDA) to attempt communication with the TerraSAR-X satellite, which was a german radar satellite developed by DLR launched in 2007. Both of these satellites carried an optical communication payload and they stablished more than 950 link sessions achieving distances of over 5,000 km and transmission speeds of 5.6 Gb/s. The next mission is the Lunar Laser Communications Demonstration (LLCD) which was a NASA mission conducted in 2013 to showcase the capabilities of a compact optical system designed to point, acquire, and track an optical signal over a distance of more than 400,000 km. and achieving impressive transmission speeds of up to 622 Mbps from the Moon to Earth.

Focused on investigating two key technologies that could advance future space missions using small satellites, Optical Communications and Sensor Demonstration (OCSD) utilized three 1.5U CubeSats with a weight of about 2.5 Kg, focused on investigating two key technologies that could advance future space missions using small satellites. This mission was disruptive because the laser was integrated into the spacecraft's body, with modulated optical signals received at 100 Mb/s on the ground. The CubeSat Laser Infrared CrosslinK (CLICK) mission was separated in two phases, being the first one used to test a different optical communication systems based on fine steering mirror control; and the second one, which applied this new communication system to demonstrate full-duplex optical communications between two small 3U spacecraft in Low Earth Orbit (LEO). The Q4 mission was launched in 2002 too, and it validated the performance of the Inter-Satellite Optical Communicator (ISOC) for global sky coverage. It involved four 6U satellites at a 400 km altitude in a leader-follower formation and provided full sky coverage.

Next one, TeraByte InfraRed Delivery (TBIRD), is an optical communication system developed by NASA and MIT, designed to demonstrate satellite communications at speeds of up to 200 Gbps. Finally, NASA's Deep Space Optical Communications (DSOC) experiment is the first mission aimed at demonstrating optical communications beyond the Moon, and it involves a laser transceiver on the spacecraft, a ground-based laser transmitter, and a ground-based laser receiver. The critical transceiver is aboard NASA's Psyche spacecraft, which launched in October 2023 on a mission to a metal-rich asteroid of the same name, to establish uplink communication at distances up to one astronomical unit, and maintain operational capabilities for nearly two years with weekly contact. The technology demonstration began shortly after launch and is now entering its second and final phase.

Optical communications, particularly Free-Space Optics (FSO), have shown significant advancements over the past decades, emerging as a promising alternative to traditional RF for inter-satellite links (ISLs) [1]. Compared to RF systems, FSO terminals are more efficient in terms of onboard satellite resources, as they have a smaller form factor and are easier to integrate into satellite platforms. FSO links offer much higher data rates, and they benefit from lower power consumption and reduced interference, making them more energy-efficient and reliable for high-speed data transfer. However, challenges remain, such as the need to reduce setup times and develop efficient systems for crossing orbital planes. Despite these hurdles, FSO's potential to deliver lower latency, positions it as a superior option for long-distance communication in satellite networks, complementing or even surpassing terrestrial fiber optics in specific application.

The interest in using HAPs for optical communications has grown due to their ability to enhance the reliability of FSO links between satellites and ground stations [2]-[3]. HAPs act as relay nodes that shorten the satellite-to-ground optical link distance, significantly reducing atmospheric attenuation and mitigating the impact of tropospheric turbulence. By employing optimization techniques like zenith angle adjustment and flexible networking, HAPs decrease the frequency of link handovers, thereby extending connection stability and improving overall system performance. This approach positions HAP systems as key enablers for next-generation wireless networks, offering superior performance over traditional models.

These systems are becoming so interesting that there are recent studies on the adaptation of HAP systems to enhance the performance of GEO satellite systems by providing high throughput and broad coverage [4]. Leveraging HAPs as relays between GEO satellites and ground stations, combined with non-orthogonal multiple access (NOMA) and two-way relaying, improves spectrum efficiency, and demonstrate the potential of GEO satellite-HAP networks to optimize connectivity in next-generation communications.

FSO communications serve as crucial enablers for applications in Non-Terrestrial Networks (NTN) and the Internet of Things (IoT). Notably, the study in [5] explores multiuser precoding techniques for NTN, highlighting potential advancements. Additionally, satellite-based FSO systems can significantly enhance the range and performance of IoT applications, as demonstrated in [6]-[7]. As well as these, the large number of papers that have been published related to the advantage of these communication systems by using HAPs as relays, has led to large-scale initiatives such as Google's Loon project, in which balloons are used to provide internet coverage in areas of difficult access, with some of its successful tests in areas of Puerto Rico and Kenya. Another organisation born as a consequence of the use of HAPs is the HAPS ALLIANCE, which aims to encourage this type of system, unifying different companies in the space and communications industry to work together in the development of HAPs, allowing interoperability between the different companies, and consequently the implementation of these systems.

III. METHODOLOGY

A. General Overview

The model proposed under this research is based on the study presented in [8], but for those scenarios where FSO are more convenient [8]-[9]. Thus, taking into account only the optical links. The architecture of this kind of systems follows the scheme shown in Fig. 2. In this figure, GS typically connects directly to the satellite, but sometimes a HAP can provide an alternative link, which can offer advantages such as improved performance and reduced signal degradation. A HAP serves as a relay, enhancing communication between the satellite and the ground, and it enables two communication paths for satellite-to-Earth transmissions:

- **SAT-GS FSO:** This system performs a direct communication between the satellite and the ground station by means of lasers and photodetectors. It has the advantage of being able to transmit data at a much faster speed than through RF, but it is more sensitive to different atmospheric conditions, especially when the angle of vision between the station and the satellite is not optimal.

- **SAT-HAP-GS FSO:** This system makes use of a HAP, which is a platform that is positioned between the satellite and the ground station, at an altitude between 17 and 32 km., where weather conditions that could interfere with the optical communication between the HAP and the satellite are greatly reduced. This HAP is placed practically aligned in the zenith of the ground station, as this position is the one that has the best behavior in the face of the meteorological problems that the optical communication between them may encounter.

The choice between the different communication systems described in the paper depends mainly on the atmospheric conditions, and the ability of the system to handle variations in the zenith angle of the satellite. In order to carry out this study effectively, it is essential to precisely define the equations that describe the system and the specific characteristics that compose it, as these relationships are essential to model the behavior of the system under different

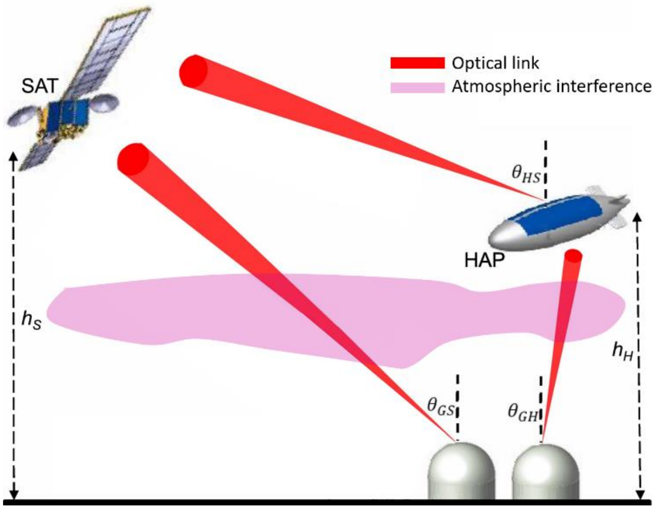


Fig. 2. Optical systems to study

conditions and to evaluate its performance in a rigorous manner. For this, the equations presented in [8] provide a solid mathematical basis for the extended experimental analysis that is carried out and developed throughout the next sections.

B. System model

FSO communications in this work are based on sub-carrier intensity modulation with BPSK, and use direct detection in the optical receiver. The HAP adopts a decode-and-forward scheme to avoid noise forwarding. For channel modelling, the usage of Gamma-Gamma fading model is widely used in the literature for FSO communication systems to describe the variability in signal intensity due to atmospheric turbulence, as it provides an accurate description of the fading by characterizing both small and large fluctuations. Then, a Gamma-Gamma distribution precisely reflects the attenuation pattern of the optical links. In this model, a definition of the average SNR is given by the following formula:

$$\gamma_{ij} = \frac{(\eta_{ij} P_{ij} G_{ij} k_{ij} I_{ij}^{l})^2}{\sigma_{n_{ij}}^2} \quad (1)$$

In which, η_{ij}, indicates the optical-electrical conversion efficiency; P_{ij}, is the transmitted power; G_{ij}, is the communication gain; I^{l}_{ij}, is the attenuation factor; σ_{nij}, represents the background noise; and k_{ij}, is determined by:

$$k_{ij} = \frac{\xi_{ij}^2}{\xi_{ij}^2 + 1} \quad (2)$$

Where the value of ξ_{ij}^2 is assigned based on the pairs of elements involved in the communication. For ground-to-HAP communication $\xi_{GH} = 5.2$; for ground-to-satellite $\xi_{GS} = 5.2$; and for HAP-to-satellite $\xi_{HS} = 13.07$.

It should be considered the free space losses (FSL_{ij}) and the attenuation due to climatic interferences (I_{ij}^{w}), which values are defined by the following equations:

$$FSL_{ij} = \frac{4\pi \, L_{ij}}{\lambda_f} \quad (3)$$

$$I_{ij}^{w} = \exp(-\varphi_f d_w) \quad (4)$$

where L_{ij} represents the distance between the emitter and the receiver, λ_f is the optical wavelength, φ_f is the weatherdependent attenuation coefficient (dB/km), and d_w indicates the distance over which the weather impact takes place. Using (3) and (4), for G_{ij} and I^l_{ij} the values will be determined by the following equations:

$$G_{ij} = \frac{G_f^{tx} G_f^{rx} \lambda_f}{4\pi L_{ij}} \qquad (5)$$

$$I_{ij}^{l} = \frac{\pi D_j^2}{4(\phi_i L_{ij})^2} \exp(-\varphi_f d_w) \qquad (6)$$

Now, substituting these values into the SNR equation, we obtain the expression of the SNR for each link as follows:

$$\begin{aligned} \gamma_{ij} &= \frac{\left(\eta_{ij} P_{ij} G_{ij} k_{ij} I_{ij}^{l}\right)^2}{\sigma_{n_{ij}}^2} \\ &= \frac{\left(\eta_{ij} P_{ij} G_f^{tx} G_f^{rx} \lambda_f k_{ij} \pi D_j^2 \exp(-\varphi_f d_w)\right)^2}{\sigma_{n_{ij}}^2 \left(4\pi L_{ij}\right)^2 \left(4(\phi_i L_{ij})^2\right)^2} \\ &= \left(\frac{\eta_{ij} P_{ij} G_f^{tx} G_f^{rx} \lambda_f k_{ij} D_j^2 \exp(-\varphi_f d_w)}{16\, \sigma_{n_{ij}} L_{ij}^3 \phi_i^2}\right)^2 \end{aligned} \qquad (7)$$

The next step is to assign the corresponding values to the different variables, and leave the equation as a function of the parameters we want to further study, which are the attenuation due to atmospheric interference ($\exp(-\varphi_f d_w)$), the distance between the transmitter and the receiver (L_{ij}^3) and the inclination angle between both of them (ϕ_i). The assigment of the variables can be seen in the following table.

Parameter	Symbol	Value
Optical to electrical efficiency	η_{ij}	0.8
Transmitted power	P_{ij}	5 dBW
Telescope Tx gain	G_f^{tx}	75 dB
Telescope Rx gain	G_f^{rx}	75 dB
Optical wavelength	λ_f	1550 nm
Telescope aperture diameter	D_j	0.2 m
Background noise power	$\sigma_{n_{ij}}^2$	250 µW
$k_{GH} = 0.96434,\ k_{GS} = 0.96434,\ k_{HS} = 0.9942$		

Table 1. Variables assignment

Now, by substituting all these values into equation (7), we can obtain a general expression for the SNR that will be a function of the height of the transmitter and receiver, the inclination angle between them, and the weather conditions of the communication.

$$\begin{aligned} \gamma_{ij} &= \left(\frac{0.8 * 3.16 * 31{,}622{,}776^2 * 1550 * 10^{-9} * 0.2^2 * k_{ij} * \exp(-\varphi_f d_w)}{16 * \sqrt{250 * 10^{-6}} * (15 * 10^{-6})^2 L_{ij}^3}\right)^2 \\ \gamma_{ij} &= 4.1737339 * 10^{36} \left(\frac{k_{ij} * \exp(-\varphi_f d_w)}{L_{ij}^3}\right)^2 \end{aligned} \qquad (8)$$

Based on the components involved in the communication, the SNR of this link will change its value according to k_{ij} as follows.

C. SAT – GS (FSO)

For this type of link, since only the earth station and the satellite are involved, the SNR value will be that of equation (8), assigning the value of $k_{GS} = 0.96434$.

$$\gamma_{GS} = 3.8813707 * 10^{36} \left(\frac{\exp(-\varphi_f d_w)}{L_{GS}^3}\right)^2 \qquad (9)$$

D. SAT – HAP – GS (FSO)

In this system, as it is composed of two different links, the one between the earth station and the HAP, and the one between the HAP and the satellite; the total SNR will be defined by the following equation:

$$\gamma_{TOTAL} = \frac{1}{\frac{1}{\gamma_{GH}} + \frac{1}{\gamma_{HS}}} \qquad (10)$$

Both of them will be computed from the equation (8) with the values of $k_{GH} = 0.96434$ and $k_{HS} = 0.9942$, obtaining the following equations for the SNR at each communication hop (i.e., that is among the GS and HAP, and among the HAP and satellite, respectively):

-
$$\gamma_{GH} = 3.88137069 * 10^{36} \left(\frac{\exp(-\varphi_f d_w)}{L_{GH}^3}\right)^2 \qquad (11)$$

-
$$\gamma_{HS} = 4.125459 * 10^{36} \left(\frac{\exp(-\varphi_f d_w)}{L_{HS}^3}\right)^2 \qquad (12)$$

IV. Simulation results

This section present the main simulation results obtained that serve to evaluate under which conditions a communication could be considered to meet the appropriate requirements to be able to exchange information. The assessment of the SAT-GS and SAT-HAP-GS FSO schemes is performed through extensive simulation analyses.For this purpose, it is taken into account that the SNR value and the probability of error are related by means of the complementary error function (erfc):

$$P(e|\gamma) = \frac{A}{2} * erfc\left(\sqrt{\gamma} * \sin\left(\frac{\pi}{M}\right)\right) \qquad (13)$$

Where *M* is the order of the PSK modulation, and the value of *A* is 1 if *M=2*, or 2 if *M>2*. Initially, as BPSK modulation is the first target modulation under study, M=2 and A=1. So, the equation will be as the following one:

$$P(e|\gamma) = \frac{1}{2} * erfc\left(\sqrt{\gamma} * \sin\left(\frac{\pi}{2}\right)\right) \qquad (14)$$

By subtracting the value of γ from this equation, we can obtain the value of the SNR threshold for a given error probability in BPSK modulation.

$$\gamma = \left(\frac{erfcinv(2 * P(e|\gamma))}{\sin(\pi/2)}\right)^2 \qquad (15)$$

Setting the value of the probability of error as $3*10^{-2}$, the value of the SNR threshold will be 1.76869 (5.7024 dB).
In the following, the definition of the analyses and parameters involved in the simulations is going to be performed. º
For the first analysis, it will be calculated the value of the SNR for each system as a function of satellite inclination angle for different satellite heights and atmospheric conditions (i.e., clear air and light fog conditions). For this analysis the satellite inclination with respect to the ground station will be analysed for the angles between 0º(zenith) and 80º, as after 80º it is considered that the communication will not be possible as it will find so many obstacles on its way. The possible heights of the satellite are 400 km, 600 km, 800 km, 1000km, 5000km and 12000km. For the atmospheric conditions, the values obtained from the document [10] for the φ_f are going to be employed, which will facilitate the calculation of the total atmospheric attenuation.

Atmospheric condition	$\varphi_f \left[\frac{dB}{km}\right]$	d_w[km]	$e^{-2\varphi_f d_w}$
Clear air	0.43	0.1	0.9914
Light fog	3.34	0.5	0.0354

Table 2. Atmospheric attenuation

The results of this first analysis can be seen in Fig. 3 where the graph corresponding to the first system (GS-SAT) are on the left and those corresponding to the second system (GS-HAP-SAT) are on the right. In this figure, the continuous lines represent the clear air weather condition and the hyphened line represents the light fog condition.
In the second analysis, it will be studied for a fixed height of the satellite, in this case 400km, which are the possible modulations that the satellite will be able to operate under. For this purpose, we will first compute the limiting SNR for BPSK, QPSK, 8PSK and 16PSK modulations using equation (13) with the corresponding values of *M* and *A*. After this, we will obtain the range of angles from which communication can be established for clear air and light fog conditions for each modulation.
The third analysis will study for the angles between 0º and 80º what is the maximum satellite height at which it is possible to transmit for each of the modulations seen in the previous analysis and for the previous weather conditions. For this purpose, the limit SNRs calculated in the previous analysis will be used and the value of L_{ij} will be cleared from equation (7), being $L_{ij} = |h_i - h_j|$. Once it has been cleared, the value of the height will be computed using the following equation:

$$h_i = h_j + \left(\sqrt[3]{\left(\frac{\eta_{ij} P_{ij} G_f^{tx} G_f^{rx} \lambda_f k_{ij}\, D_j^2 \exp(-\varphi_f d_w)}{16\, \sigma_{n_{ij}} \phi_i^2}\right)^2 * \frac{1}{\gamma_{ij}}}\right) * \frac{1}{\sec(\theta_{ij})} \qquad (16)$$

The fourth analysis fixes an angle of inclination between the satellite and the ground station or HAP, in our case an angle of 33°, and studies for this angle what is the maximum height of the satellite at which communication can be established for each of the modulations seen in the clear air and light fog cases.

h_{SAT}= 400 km	GS – SAT		GS – HAP – SAT	
Weather condition	Air	Fog	Air	Fog
BPSK	71,424º	14,8º	56,473º	56,473º
QPSK	67,975º		49,44º	49,44º
8PSK	62,602º		37,07º	37,07º
16PSK	54,831º		2,78º	2,78º

Table 3. Tilt limit for a satellite height of 300 km.

θ_{ij}=33º	GS – SAT		GS – HAP – SAT	
Weather condition	Air	Fog	Air	Fog
BPSK	1053,3	347	597,1	597,1
QPSK	894,726	294,821	510,2	510,2
8PSK	729,15	240,32	419,44	419,44
16PSK	582,498	192	339,2	339,2

Table 4. Height limit for a tilt of 33º between emitter and receptor.

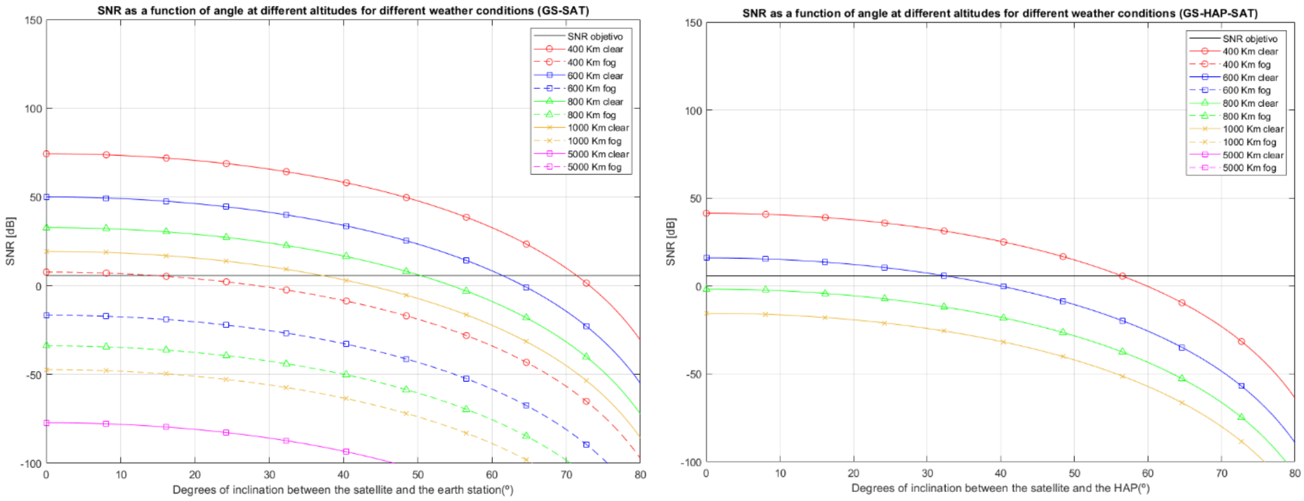
These simulations have been carried out using a minimum of 100 evaluation points. However, when representing them in Fig. 3 and Fig. 4, it has been decided to indicate only one point for each 10 samples in order to facilitate the visualisation and differentiation of the graphs.
In Fig. 3, the SNR as a function of angle at different altitudes for different weather conditions in both systems is evaluated, and as it can be seen, the first system (GS-SAT) works better than the second one (GS-HAP-SAT) under clear air conditions. This changes when fog is set as the weather condition, where the second system works better than the first. With the black horizontal line marking the limit of the SNR that can be considered as appropriate, Fig. 3(a) shows that, for clear air conditions, transmission to satellites at an altitude of 400 km is possible for almost all angles evaluated, a measure that degrades as altitude is increased, with the evaluated limit being 1000 km altitude, which only allows transmission at angles smaller than about 36°. For the next height evaluated (5000 km) the SNR obtained is not enough to stablished communication. This performance is also decreased when weather effects are applied to the communication, where the link capacity is reduced and communication is only possible with satellites at an altitude of 400 km and with inclinations between the ground station and the satellite lower than 20°.
In Fig. 3(b), it can be observed that with the same limit value for SNR, this communication system allows communications with satellites located at an altitude of 400 km with inclinations of up to almost 57º with respect to the zenith of the HAP, and with satellites located at an altitude of 600 km with inclination angles of up to approximately 32º. For the other altitudes evaluated, communication is not possible. The advantage of this system is that, by introducing weather interference, the difference between both SNRs of the link is so low that it is not appreciable visually, therefore, although the capacities are lower than those of the direct connection of the first system, they are more stable as they are independent of weather conditions.
The main idea that can be observed from these two graphs is that while the performance of the first system depends directly on the weather conditions, the second system maintains its characteristics regardless of them. This is because, under the conditions we are modelling, weather interference only affects altitudes of less than 20 km, and since the HAP is located at this altitude, for the second system this interference only affects the link established between the ground station and the HAP. This ground station, as it can

transmit with so much power, and as the distance between it and the HAP is so short, allows the SNR of this link to be very high, which gives a big margin for the weather conditions interferences. After this link, the transmission between the HAP and the satellite is assumed to be under clear air conditions, which means that the characteristics of this link vary very little depending on the weather interference.

On the other hand, results of the analyses shown in Fig. 4 represent the maximum height as a function of the degree of inclination between the satellite and the ground station or the HAP for the aforementioned 4 different modulations and under the meteorological conditions of clear air and light fog. In these graphs, it can be clearly stated that, while the first system sees its capacity degraded depending on weather conditions, the second system maintains its transmission characteristics independently of them. Regarding the type of modulation used, it is noteworthy that the higher the order of the M-PSK modulation, the higher degradation is produced, and the lesser Quality of Service (QoS) can be achieved.

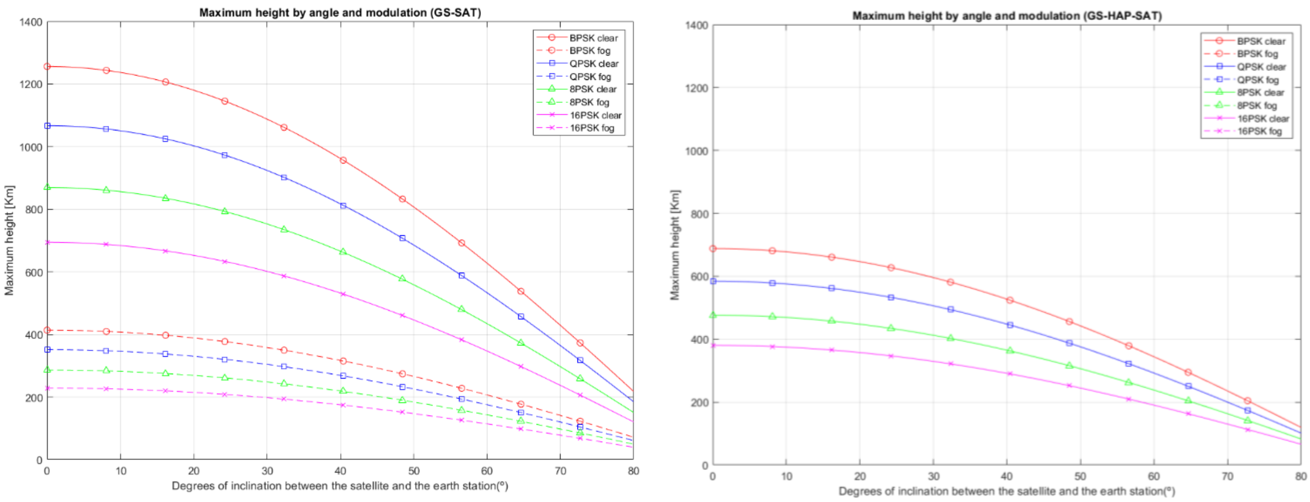
The pointing angle will be another important factor to take into account in order to know at what height it is possible to transmit, since as can be seen, for all modulations, regardless of the weather conditions, it is practically impossible to transmit with a tilt of 80º for altitudes of more than 200 km (except in the case of BPSK for angles of 80º, which can reach an altitude closer to 200 km). Taking into account that the maximum altitude will always be achieved when the satellite and the earth station are aligned at the zenith angle, it can be seen from Fig. 4(a) that the intrusion of light fog weather effects results in a large degradation in link capacity, going from reaching around 1200km for BPSK in clear air to almost 400km for light fog, which represents a degradation of about 66%. This value is repeated for all other modulations when including weather effects and it is useful to appreciate how weather interferes and degrades the resulting system capacity.

In the same way as in the previous analysis, in Fig. 4(b), it is illustrated how the system does not vary in weather conditions such as light fog, and it can be deduced which are



(a) (b)

Fig. 3. SNR as a function of angle at different altitudes for different weather conditions in both systems.



(a) (b)

Fig. 4. Maximum height by angle and modulation for different weather condition in both systems.

the capabilities of this system for each of the types of modulation depending on their angles, with BPSK being the modulation with the best performance, reaching around 700 km of height of the satellite when it is at the zenith angle; and almost 400 km of height for the 16PSK modulation, which is the worst when it is commissioned in the same position.

In addition, Table 3 shows the results and limitations based on the modulation chosen and the weather conditions for a desired fixed altitude. Note that it is required for accurately pointing the antenna under good QoS measures. Ranges of angles producing SNR above the targeted limit are included in the table. For the height of 400km, it can be seen that the first system (GS-SAT) in clear air conditions is able to communicate up to a higher angle than the second system (GS-HAP-SAT), for any of the modulations, but however, when there are light fog conditions, the first system is reduced to being able to communicate using only BPSK and only if it has an inclination with respect to the zenith of less than 14.8º, while the second system maintains its limitations.

Table 4 extends the scope of the simulations to the case of a satellite launch with a fixed target pointing angle. In this case, satellite height is the main value affecting signal strength and probability of error. For the case of the fixed angle at 33º, it can be seen how the above is verified, where the first system is degraded by approximately 66% with the intrusion of the light fog, and however, the second system maintains the working limits at which it operates. This behaviour is fully replicable to other values of the fixed pointing angle.

V. CONCLUSION

The analysis of the optical communication systems SAT-GS FSO and SAT-HAP-GS FSO shows that both offer advantages under different operational conditions. The SAT-GS system is more efficient when the zenith angle is low and atmospheric conditions are favourable, as it maximizes transmission capacity. However, its performance significantly deteriorates under adverse weather conditions. On the other hand, the SAT-HAP-GS system, although more complex and costly, proves to be more robust against atmospheric interference due to the use of a HAP, which helps to mitigate the effects of rain and fog.

When designing an FSO system, it is crucial to consider factors such as the ground station's location, satellite altitude, and local weather conditions, as these directly impact the reliability of the link. Additionally, the choice of modulation is essential, as it affects spectral efficiency and resilience to interference, as certain modulations may not be suitable for all altitudes and inclination angles. Adapting the modulation based on conditions can optimize performance. Finally, the available budget plays a key role, enabling the implementation of advanced technologies and backup systems, such as HAP, which enhance coverage and link stability, especially in adverse weather scenarios.

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