Performance Evaluation of Free Space Optics Laser Communications for 5G and Beyond Secure Network Connections

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Abstract: Free Space Optics (FSO) represent a promising technology for secure communications in several types of architectures: from Quantum Key Distribution Networks (QKDNs) to satellite communications. In this paper, in particular, we take into account terrestrial point-to-point laser communications and evaluate the performance in terms of Signal-to-Noise Ratio (SNR) and Bit Error Rate (BER), taking into account different scenarios, that can reflect real situations in which long distances can be reached in a secure way, guaranteeing an acceptable level of BER. So, after a huge campaign of simulations, we would like to let the scientific community know which are the theoretical limits that such kind of communications can reach. We take into account standard telescopes parameters (available today in the market), while configuring several real situations, in function of, for example, bit-rate, visibility, link distance, etc. A brief survey of the existing works is given, then a clearer performance evaluation of terrestrial FSO links is proposed.

1 INTRODUCTION

Nowadays, the classical cybersecurity algorithms have been affected by the progress in quantum computing, giving to machines the possibility to execute computational operations which were unpredictable several decades ago. So, classical security protocols and algorithms are becoming inadequate to protect data, given the huge power of quantum computers (Adhikari et al., 2021). The secret keys exchange has become critical, with the needing of a complete innovation, in terms of robustness to external attacks (Rosch-Grace and Straub, 2021).

Free Space Optics (FSO) represent a promising technology that can be used also in satellite environment for future advanced telecommunications where algorithms of call admission (De Rango et al., 2008) and opportune scheduling schemes (Tropea et al., 2021) are important techniques to be taken into account.

For the reasons above, the Quantum Key Distribution (QKD) paradigm has become really promising, given its theoretical impossibility to be broken by external attacks (Zhou et al., 2022), (Mehic et al., 2019). There are several works proposed in literature about QKD Networks (QKDNs), but most of them take into account what happens from the 3^{rd} OSI layer and above. In this paper, instead, we want to give to the scientific community the possibility to know what happens at the PHY layer, by deeply analysing which performance, in terms of photons detection accuracy, can be reached by considering several parameters that are useful and suitable to describe real scenarios.

In particular, we are focusing on terrestrial point-to-point communications, although the idea can be easily extended to satellite QKD communications (Vu et al., 2022), (Ai et al., 2020), (Elser et al., 2015). The core of this paper consists in the proposal of a theoretical channel model for photons detection, from a generic source and a generic destination, and a con-

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sequent performance analysis of what happens to the PHY optical channel, under several and different conditions. This paper wants to be a starting point for a more complex stochastic modeling, which can be easily implemented in several simulators, such as (Campanile et al., 2020), (Chen et al., 2022), (Mehic et al., 2020).

The main contribution of this paper, in addition to the numerical performance evaluation, is represented by accounting for several physical parameters, which have been neglected or disregarded in other works (e.g. device diameters, pointing error, scintillation, scope efficiency, etc.), or not considered together.

As regards the structure of the paper, the next section gives a detailed overview of the main scientific works existing in literature, Section 3 introduces the proposed theoretical model, with the specification of several terms and parameters, directly related to the considered devices. Section 4 provide details about the main obtained results, in terms of SNR and BER, and, at the end, Section 5 concludes the paper, underlining the main reached results and future developments.

2 RELATED WORK ON QKD AND FSO CHANNEL MODELING

The channel modeling issues is a key topic due to the fundamental importance of the channel in every communication network. Many studies have been proposed by researchers about the modeling of the channel in the different networks such as satellite platforms (Tropea and De Rango, 2022), acoustic communications (De Rango et al., 2012), vehicular networks (Fazio et al., 2015). In this section, several literature contributions will be overviewed. Over the last ten years, free space optical (FSO) communication has grown more fascinating and in the literature a lot of works have been proposed by scientific community. This type of communication covers both indoor and outdoor environments and it is important to consider the effects of the weather on the signal propagation. Some works try to review the proposed channel models able to taking into account the weather and channel condition such as scattering, absorption, fog, rain, haze, snow (Jarangal and Dhawan, 2018).

The different effects introduced by atmosphere in the FSO channel are described in (Kaushal et al., 2017). The atmospheric turbulent channel models have been discussed based on various empirical scintillation data of the atmosphere. Different statistical models to describe the irradiance statistics of the received signal due to randomly varying turbulent atmospheric channel, lognormal, negative exponential, gamma-gamma, etc. have been discussed and different techniques to mitigate these phenomena in the channel are shown.

In (Esmail et al., 2016) the effects of fog impairment is analysed by authors in order to propose a channel model for characterizing the FSO communication able to provide improvement in the system performance. They propose a model based on a closed formulation and evaluate the overall performance both theoretically and numerically, in terms of average signal-to-noise ratio (SNR) and outage probability. Their results have showed that under light and moderate fog, the FSO system performance is acceptable for short link length in hundreds of meters.

This type of technology is also used in satellite, high altitude platforms (HAPs) and unmanned aerial vehicles (UAVs), so many contributions are related to these neworks such as (Ivanov et al., 2021), (Guo et al., 2022).

In (Najafi et al., 2020) the authors investigate the channel between a central unit and a swarm of UAVs that communicate also in critical conditions that do not permit to correctly align the lens and so the laser results in a non-orthogonal beam due also to the random fluctuations of the position and orientation of the UAV. They try to derive corresponding statistical models for different weather condition and UAV position proved by simulations that have validated the accuracy of the presented analysis and provide important insights for system design.

In (Ivanov et al., 2022) a testebed emulator for satellite channel has been proposed able to take into account the effect of atmospheric including scintillations and clouds.

A simplified approach for modeling the received power dynamics of the atmospheric FSO channel developed based on the statistics of received power measurements from a maritime-mobile link, a land- mobile link, and a satellite downlink is presented in (Epple, 2010). The proposed approach is easy to develop without requiring deep knowledge of the physical channel.

The performance evaluation of different type of channel models is reported in (Barua et al., 2011). This evaluation is based on different simulation parameters such as detector threshold level, probability of detection, mean fade time, number of fades, BER, and SNR The paper tries to investigate the most efficient PDF model. It compares channel model such as Rayleigh, Log-normal, Rician and Nakagami-m distribution showing that these are valid in atmosphere turbulence but the Gamma–gamma model performs better for all regimes from weak to strong turbulence region. So, their suggestion is to prefer gamma-gamma model in this type of atmosphere conditions in FSO propagation.

On the basis of these works proposed in literature our intent in this paper is to provide a FSO channel model proposal deriving a closed expression able to take into account error probability related to the photon transmission in a FSO channel.

3 OUR PROPOSED FSO CHANNEL MODEL

In this section, we will derive a closed expression to evaluate the error probability of a photon transmission between a source and a destination in Free Space Optics (FSO) channels. The relation between SNR and BER is very important, because it gives to the researchers the possibility to collect some important statistics about PHY channel degradation during time (as shown in the next section).

First of all, let us consider a couple of nodes, one transmitting (n_S) a photon and the other one receiving it (n_D) on a FSO link.

Figure 1 shows the typical considered scenario.

As in (Zhao and Alouini, 2019), we indicate the pointing error angle as θ, assuming that it follows a Beckmann distribution (Simon and Alouini, 2001). From the proposals in (Rahman et al., 2021), (Kupferman and Arnon, 2018), we can write that the received power, due to path loss, on the n_D side is:

$$P(n_D, \theta) = K \cdot G(n_D) \cdot L(\theta), \tag{1}$$

where:

$$K = \eta(q) \cdot \eta(n_S) \cdot \eta(n_D) \cdot P(n_S) \cdot G(n_S) \cdot \cdot \frac{Loss(dist)}{dist^2} \cdot \left(\frac{\lambda}{4\pi}\right)^2, \tag{2}$$

$G(n_D)$ is the telescope gain of n_D, $L(\theta) = e^{-G(n_D)\cdot\theta^2}$ is the pointing loss factor and K is a constant value, given that it is evaluated by fixed terms, as the quantum efficiency ($\eta(q)$, with q the elementary charge), the efficiencies at the sender and receiver sides respectively ($\eta(n_S)$, $\eta(n_D)$), transmission power ($P(n_S)$), source telescope gain ($G(n_S)$), the atmospheric loss in function of distance $dist$ ($Loss(dist)$) and the wavelength λ. Knowing the particular shape of the involved telescopes (mainly the diameter), we can obtain specific values for $G(n_S)$ and $G(n_D)$ (Kamal et al., 2022):

$$G(n_S) = G(n_D) = \left(\frac{\pi \cdot T_{diam}}{\lambda}\right)^2, \tag{3}$$

where T_{diam} is the telescope diameter: in our work we consider the same diameter for each optical device, typically 35cm for the main mirror (Saito et al., 2021).

From (Jia et al., 2006), (Wainright et al., 2005), it is also known that the function $Loss(d)$, which depends on scattering (the light traveling in free space impacts on the particles suspended in the air) and absorption (effect related to the molecular makeup of the atmosphere), can be expressed by the Beer's law:

$$Loss(d) = e^{-(\alpha+\beta)\cdot\frac{d}{10^3}}, \tag{4}$$

where α is the scattering coefficient and β is the absorption coefficient. The second one can be neglected, due to the fact that manufacturers of FSO devices set them to use wavelengths that fall in the ranges where the absorption from H_2O and CO_2 are minimal. So, in conclusion, β is equal to 0 and the α term can be expressed by the Kruse formula (Jia et al., 2006):

$$\alpha = \frac{3.91}{V} \cdot \left(\frac{\lambda}{550}\right)^{-\overline{q}}, \tag{5}$$

where V is the visibility (expressed in km), λ is expressed in $[nm]$, $\overline{q}$ can assume the values $0.585(V)^{1/3}$ if $V < 6$km, 1.3 if $6km < V < 50km$ and 1.6 if $V >$50km.

The expression of the received power by n_D is now explicitly derived and, in order to obtain the Bit Error Rate (BER, our final goal in this subsection), we need to make an assumption regarding the noise power in the FSO channel, so the Signal to Noise Ratio (SNR) can be firstly derived. Equation (2) represents only the path loss component of the signal while, especially in FSO, the noise plays also a key role.

In particular, in FSO environments, there are several types of noise (N^2 will indicate the noise power: it is the variance but we assume that it is a 0-mean process, so the variance is equivalent to the related power) impacting on the overall performance of the channel (Xu et al., 2021), (Moosavi and Saghafifar, 2018); the formal terms referred to them are background, thermal and quantum noises (Ghassemlooy et al., 2019):

$$N^2_{back} = \frac{2 \cdot q \cdot I_{back} \cdot R_b}{R \cdot I_0^2}, N^2_T = \frac{4 \cdot k_1 \cdot T \cdot R_b}{R \cdot R_L \cdot I_0^2}, N^2_Q = \frac{2 \cdot q \cdot R_b}{R \cdot I_0}, \tag{6}$$

where, for the N^2_{back} background noise, q is the elementary charge, I_{back} is the background irradiance, R_b is the symbol rate, R is the responsivity of the photodetector, I_0 is the average received irradiance. For the N^2_T thermal noise, k_1 is the Boltzmann's constant, T is the ambient temperature, R_L is the load resistance

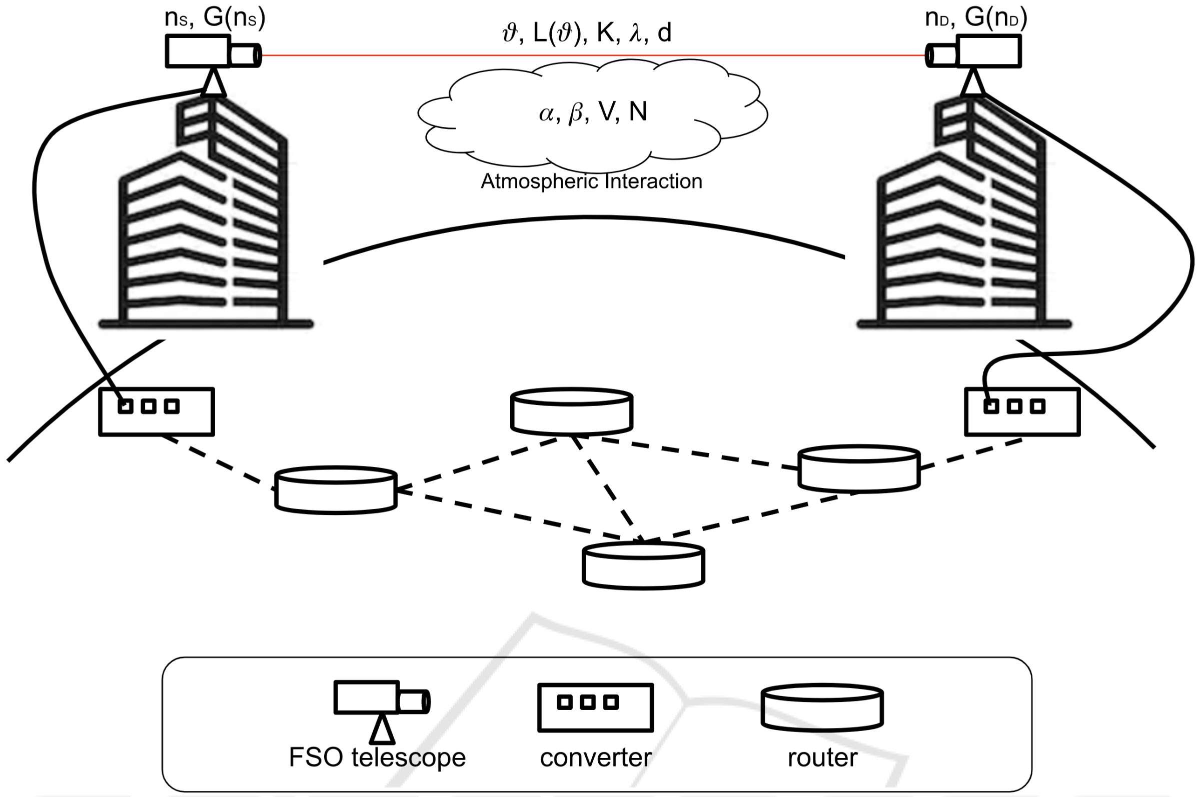

Figure 1: The typical scenario of FSO p2p communications.

of the receiver circuit. So we can consider the total noise as $N^2 = N_{back}^2 + N_T^2 + N_Q^2$.

So, the given SNR for the transmission of a photon between n_S and n_D will be:

$$SNR(n_D, \theta, dist) = \frac{P(n_D, \theta)}{N^2}. \quad (7)$$

Clearly, there are several parameters from which the expression of the SNR in equation (7) will depend, and we indicated the most important, such as n_D, θ and *dist*.

The last step to have a closed expression for the BER, then, will be the relationship between SNR and BER, which depends on the adopted modulation (Stallings, 2007): in our work we consider several types of modulations, typically used to transmit information bits over laser (Basudewa et al., 2020).

In the case of the On-Off Keying (OOK) with No Return to Zero (No-NRZ) signaling and we can write that:

$$BER_{OOK-NRZ}(n_D, \theta, dist) = \frac{1}{2} \cdot \cdot erfc\left(\frac{1}{2 \cdot \sqrt{2}} \cdot \sqrt{SNR(n_D, \theta, dist)}\right). \quad (8)$$

In the case of the OOK with Return to Zero (RZ), the equation is:

$$BER_{OOK-RZ}(n_D, \theta, dist) = \frac{1}{2} \cdot \cdot erfc\left(\frac{1}{2} \cdot \sqrt{SNR(n_D, \theta, dist)}\right). \quad (9)$$

For the Pulse Position Modulation (PPM, referred to the transmission of one data bit), the expression is:

$$BER_{PPM}(n_D, \theta, dist) = \frac{1}{2} \cdot \cdot erfc\left(\frac{log(4)}{2 \cdot \sqrt{2}} \cdot \sqrt{SNR(n_D, \theta, dist)}\right). \quad (10)$$

At the end, for the N Pulse Amplitude Modulation (PAM-N) (Sakib and Liboiron-Ladouceur, 2013), where $N > 1$ is the number of amplitude levels, we have:

$$BER_{PAM-N}(n_D, \theta, dist) = \frac{1}{2} \cdot \cdot erfc\left(\frac{\sqrt{log2N \cdot SNR(n_D, \theta, dist)}}{2 \cdot \sqrt{2} \cdot (N-1)}\right). \quad (11)$$

At this point, we have the elements to relate the BER to several system and environmental parameters.

4 SIMULATION RESULTS

Based on the model introduced in section 3, we carried out several simulation campaigns, in order to obtain some important statistics on the effective theoretical SNR and BER. Table 1 summarises the main parameters of the considered point-to-point system.

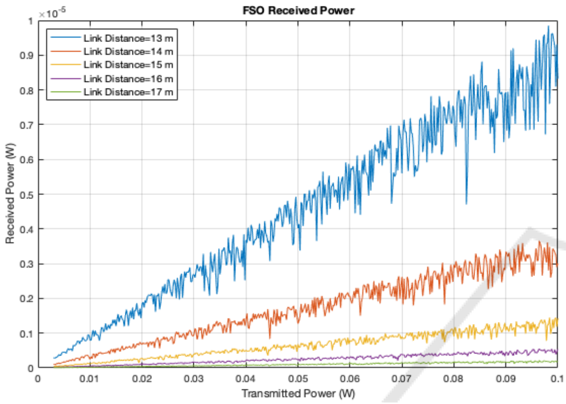

Figure 2: The power on the receiver side, with a visibility of 10 km and for different TX and distance values.

Figure 2 shows the trend of the instantaneous received (RX) power, in function of the transmitted (TX) one, for an average visibility of 10km and a path distance of $\{13,\ldots,17\}$km. It can be seen how the received signal strength decreases for higher distances and increases of higher transmission power (from 3mW to 100mW) and there is a huge path-loss (for a maximum TX power of 100mW, the maximum received power is about 9mW).

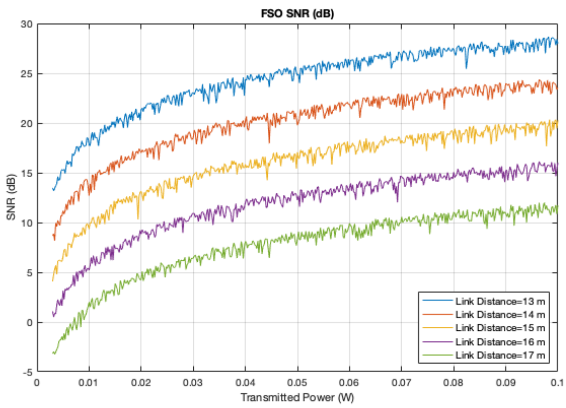

Figure 3: SNR at the receiver side, with a visibility of 10 km and for different TX and distance values.

Figure 3 shows also the trend of the instantaneous SNR at the RX side: as expected, the trend is the same of the previous case, although the derivative positive trend decreases for higher TX power values.

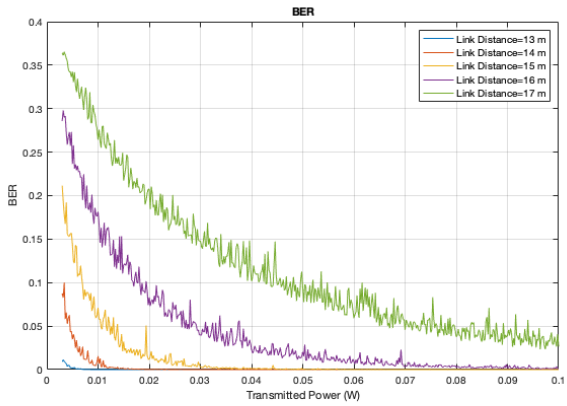

Figure 4: (Q)BER at the receiver side, with a visibility of 10 km and for different TX and distance values.

Figure 4 shows the trend of the BER (or Quantum BER, QBER, if we refer to a photon). It can be seen that increasing TX power may lead to a negligible BER, but if the distance is too high, BER tends to be higher, because of the involved physical effects.

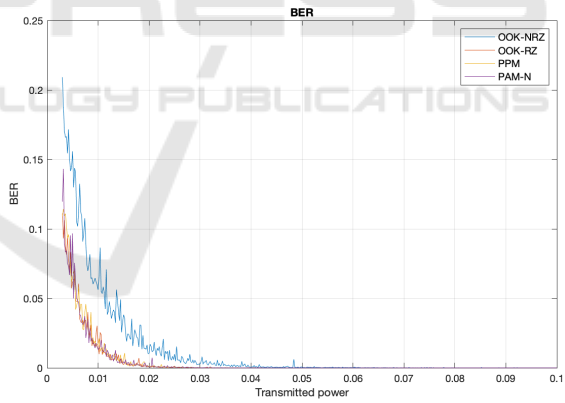

Figure 5: (Q)BER at the receiver side, with visibility of 10 km and distance of 15 km for different modulation schemes.

Figure 5 considers different modulation schemes used in FSO communications: the OOK with NRZ presents the worst trend (highest BER), while there is no noticeable differences among the other schemes (OOK-RZ, PPM, and PAM-N).

Figure 6 shows the trend of the (Q)BER at the receiver side for a fixed scenario and different values of equivalent load impedance (resistance); the typical value is R_L=50Ω, but it can be seen that an increasing R_L offers to the system a better performance in terms of (Q)BER.

Table 1: Simulation parameters.

Parameter	Description	Value
η_q	Quantum efficiency	0.1
λ	Wavelenght	976e-9 (m)
T_d	Telescopes diameter	0.35 (m)
η_S	Optical efficiency (source side)	0.9
η_D	Optical efficiency (destination side)	0.9
$\theta_{p,e}$	Pointing error angle - elevation	Gaussian (μ_v=1e-7, σ_v=1.44e-14)
$\theta_{p,a}$	Pointing error angle - azimuth	Gaussian (μ_h=3e-7, σ_h=1.44e-14)
q	Elementary charge (Coulomb)	1.602e-19
I_0	Average received irradiance	0.001
R	Photodetector responsivity	1
I_{back}	Background irradiance	$4\cdot\pi\cdot0.62\cdot(1e\text{-}6)+(5.5e\text{-}5)$
R_b	Transmission bitrate (B/s)	10e6, variable
k_1	Boltzmann constant	1.380649e-19
T	Temperature in °K	300
R_L	Load resistance at n_D (Ω)	50, variable

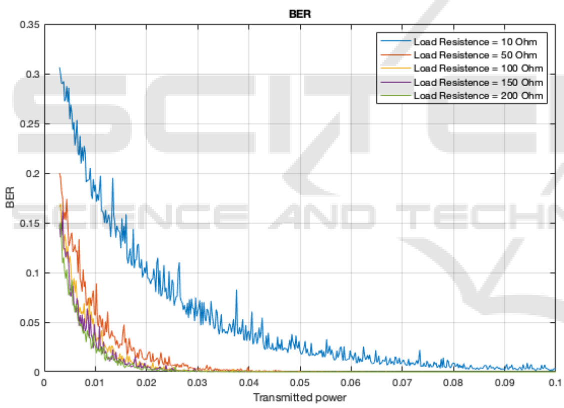

Figure 6: (Q)BER at the receiver side, with visibility of 10 km and distance of 15 km for different R_L values.

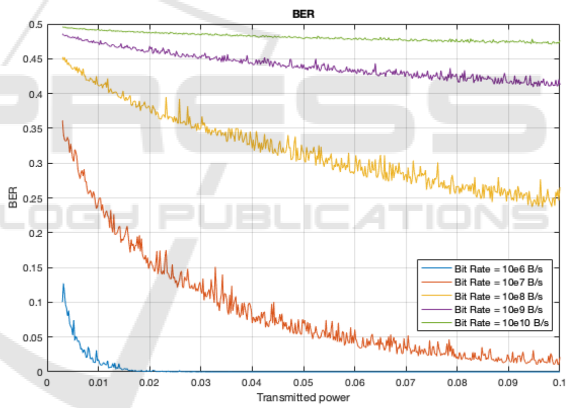

Figure 7: (Q)BER at the receiver side, with visibility of 10 km and distance of 15 km for different R_b values.

The last figure (7) illustrates how the transmission speed influences the overall (Q)BER: it can be seen that higher TX speeds result in higher errors; those trends are very important because they give the possibility to know, in advance, the expected channel performance (knowing the main scenario parameters). So, it is possible to perform a kind of link-budget if new devices should be installed in several strategic positions. Clearly, for Gbps speeds, from the figure the (Q)BER seems to be too high, but we would like to underlined that those performances are reachable for a visibility of 10km and a covered link distance of 15km (a very critical scenario for FSO communications).

5 CONCLUSIONS AND FUTURE WORKS

In this paper we proposed a simple FSO Laser channel modeling, taking into account the main phenomena that impact on those communication scenarios. This work is just a demonstration (performance evaluation) of what kind of performance can be reached, in function of distance, visibility and other kind of physical parameters (modulation, transmission rate, background noise level). From our point of view, this contribution represents the starting point for real topology link budgets, especially with the advent of quantum communications in FSO scenario, able to secure traditional Internet traffic. We demonstrated, by setting a typical scenario, which limits can be reached by the considered FSO technology.

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