Fundamental Limitations in High Speed and Low Cost Architecture Free Space Optical (FSO) Networks for Rural Populations

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Abstract. The Free Space Optical (FSO) network system is a technology that uses part of the light spectrum, which is near infrared, to transmit a large amount of information at the speed of light. It offers high bandwidth, low deployment cost, license-free spectrum, and unparalleled security compared to radio communication. The major concern of this technology lies in its transmission channel, which is the atmosphere, because of its many variations in time and space. The objective of this manuscript is to study the limiting factors for high-speed transmission in FSO networks. We offer a complete low-cost FSO network architecture to provide high-speed connections to the rural population. The different blocks of parameters of the architecture of the FSO network are evaluated according to the limiting factor (rain, fog, turbulence, etc.) dominating in the area. In this proposal, we use Optisystem and matlab software to evaluate the maximum range for each factor limiting the FSO channel using the bit error rate and the Q factor indicator.

Keywords: FSO technology · Optisystem · Fog · Rain · Snow · Scintillation

1 Introduction

Nowadays, transmission systems are undergoing a great evolution and affect several sectors of life. In fact, there has been a considerable increase in multimedia services such as the Internet with the arrival of very high-speed television, the increase in the size of digital photos and videos, the need to share and exchange files between Internet users, as well as the arrival of other services such as telemedicine, videoconferencing, video calls, online courses, online shopping, etc. These services promote a great need of high bit rate and high demand for bandwidth. Today, with the decentralization of many activities, the displacement of certain companies to establish themselves in other localities as well as the need to connect the rural population which does not always have access to high-speed services because its geographical position, it is necessary to set up

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long-range networks capable of ensuring connectivity and the implementation of universal services and accessible to everyone. With the increase in population, the number of subscribers is constantly changing. In addition, the need for services in all essential areas of activity, in particular with real-time communication (voice and data), supervision of transactions with video surveillance, the arrival of the Internet of Things (IOT) with the 5th generation of mobile networks, the need for high-capacity infrastructure is in high demand. Thus, to satisfy this strong demand which continues to grow, the Internet Service Provider (ISP) first proposed a wired network based on copper. This technology does not allow to reach a certain flow rate and a certain range because of the nature of the material. Suppliers have migrated to optical transmission systems with the use of optical fiber as the information transmission medium. It is a technology that has allowed today to acquire a certain number of advantages, in particular with very high speed [1] with a link that can reach several kilometers. With the need for communication while on the move, subscriber's have embraced wireless transmission systems with the adoption of microwave beams as the solution to user mobility. Certainly a technology that has solved the problem of mobility but has a limited flow. Thus, to maintain user mobility with comparable speeds, suppliers have opted for fixed/mobile convergence with a core network based on optical fiber. However, the spectrum of conventional RF type radio wireless signals is increasingly crowded to support various IoT applications. Indeed, the saturation of the radio-electric band due to the extension of existing services and the advent of new services such as the Internet of Things, electromagnetic pollution, the cost and difficulties linked to the deployment of optical fiber as well as the quest for broadband are among other reasons that have led to the new wireless optical communication techniques, the FSO (Free Space Optics) systems. The basic principle of FSO transmission is similar to fiber optic communication except that the modulated data is transmitted through an unguided channel instead of an optical fiber. The interception and detection of the laser beam is difficult, which makes FSO communication better for security. FSO systems are therefore better candidates for enabling populations to access broadband at a lower cost in unreached areas. In this work, we focus on a proposal of a low-cost FSO network architecture that can offer high bit rate and allows the connection of the most remote areas such as the rural population. We offer the characteristics of the transmitter modules, the FSO type transmission channel and the receivers to meet these bandwidth and range needs. The parameters of the different blocks of the FSO network architecture will be evaluated according to the limiting factor (rain, fog, turbulence etc.) dominating in the area.

2 Related Work

The data transmission in free space optical networks is a major subject which interests several telecommunications community. Recently, many scientific works have been done to study the communications in FSO networks. Thereby, in [2] H. Singh and D. P. Chechi evaluate the performance of Free Space Optical (FSO) Communication Link. They give the attenuation caused by the rain, the snow and the fog effects in differents lenghts of transmission. The paper in [3] simulates 30 Gbps ground-to-geostationary satellite-FSO communication link under different atmospheric effects like haze and fog; and under different types of cloud-like stratus, cumulus and cumulonimbus; while doing so, the effect of moderate atmospheric turbulence and intensity scintillation is always considered. The work shows that a 2×2 MIMO system having QPSK modulation with coherent detection and digital signal processing gives an extremely low symbol error rate in almost all weather and all cloud conditions. The work published in [4] are accentuated on the study of the environmental parameters effect like rain, fog, haze, snow, and dust on the performance of optical wireless communications using Opti-system program. This work considers the visibility effect as well as operating wavelengths on atmospheric attenuation in different weather conditions for FSO link. The results obtained by Sangeetha A, Nalini Sharma, and Ipsita Deb in [5] are focused on the evaluation of the MIMO Based FSO Links flexibility. Their simulation results show that by implementing Multiple Input Multiple Output (MIMO) techniques for FSO systems, it is possible to reduce the BER for different range and achieve the accurate transmitted data at the receiver side. The performance improvements vis-a-vis, received power levels, bit error rate (BER), Q-factor and link distance range have been demonstrated in the presence of atmospheric turbulence conditions like haze, fog, clear sky etc. In satellite communication systems, R. Samy and al in [6] give an ergodic capacity analysis in SAG-FSO/SH-FSO/RF transmission. The autors used respectively Gamma-Gamma and Rician distributions to characterize FSO and RF links. They uses numerical examples to highlight the significant potential of the SAG-FSO/SH-FSO/RF Integrated Satcom System over existing solutions. They also explain the capacity gain of the integrated Satcom systems with intensity modulation and direct detection in terms of capacity compared to those which integrate heterodyne detection on all the zenith angles of the satellite. fT. N. Khajwal, A. Mushtaq and S. Kaur, in their proposal in [7], focused on the performance analysis of FSO-SISO and FSO-WDM systems under different atmospheric conditions. They conclude that the transmitting optical power above 9 and 15 dB is required in case of FSO-SISO system for transmission of data without error for Moderate and Heavy fog conditions respectively. But, for FSO-WDM system, they suggested power above 16dB in case of Moderate fog conditions for optimal transmission. In summary, we can conclude that several results on FSO transmission systems have been published. But it should be noted that most works consider a typical value equal to 25 dB/km to represent the losses of the FSO signal due to atmospheric conditions. A large number of FSO network architecture proposals have also been provided by the scientific community. However, the proposed networks are very expensive and do not encourage their deployment in rural areas. This work presents a complete low-cost FSO network architecture, capable to provide high bit rate connections to the rural population. The parameters of the different blocks of the FSO network architecture will be evaluated according to the limiting factor (rain, fog, turbulence etc.) dominating in the area.

3 Free Space Optical System Model

In an FSO system, a laser beam is emitted from the source towards the receiver. The intensity of the beam is concentrated in the direction of the receiver in order to ensure safety and the exchange of a large amount of information. Thus, FSO links require direct visibility (LOS: light of sight) between the two entities wishing to communicate. The Free Space Optical communication system 1 is identical to that of fiber optic transmission. But the only difference is at the channel level where the FSO systems use the atmosphere as the medium for transmitting information. It allows the transmission of a large amount of information at speeds equal to that of optical fiber while benefiting from the opportunities of wireless. This information is first received at the modulator block in electrical form. The modulator as its name suggests performs the modulation step by modifying the signal into another form which will be transmittable by the optical source (usually a laser diode or a light emitting diode). Then the signal is transmitted to the receiver via an FSO (free space) channel. At the reception level, the reverse operation of the transmission is carried out, that is to say that the optical signal will be converted into an electrical signal, then demodulated in order to be able to recover the information [9]. The following Fig. 1 illustrates the block diagram of an optical transmission FSO system. An FSO network is a technology that uses the atmosphere as a medium for transmitting information. Since the atmosphere is a complex, turbulent and time-varying medium, the optical signal transmitted through the medium is affected by the physical properties of the environment. This affects transmission efficiency. These factors are simply related to atmospheric and climatic phenomena such as fog, rain, atmospheric scintillation, etc. In this proposal we will study the impact of these factors through an optisystem model.

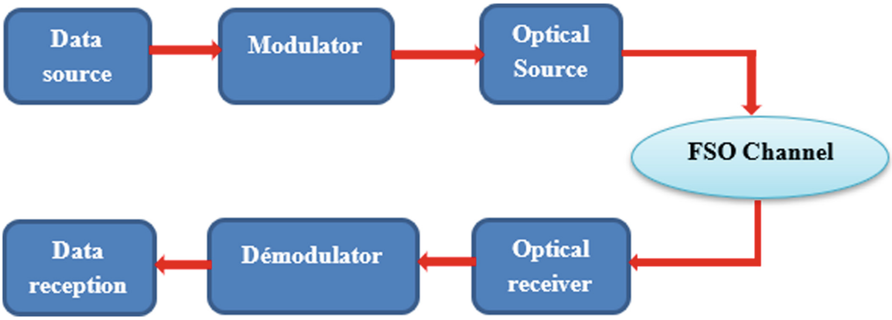

Fig. 1. Transmission schema of an FSO system

4 Free Space Optical Optisystem Model

Our proposal aims to study a low-cost, high-speed architecture for point-to-point communications links in rural areas. We use light to support information through FSO networks. The following Fig. 2 shows our simulation model based on the optisystem software [10]. The transmission block consists of a Pseudo Random Sequence Generator (PRBS) which generates a binary sequence, an NRZ type encoder (Non-Return to Zero) which generates an electrical signal. This electrical signal will modulate the laser with a device external to the source by an external modulation called a Mach Zehnder. A DL(lasser diode) optical source is used to convert the electrical signal into an optical

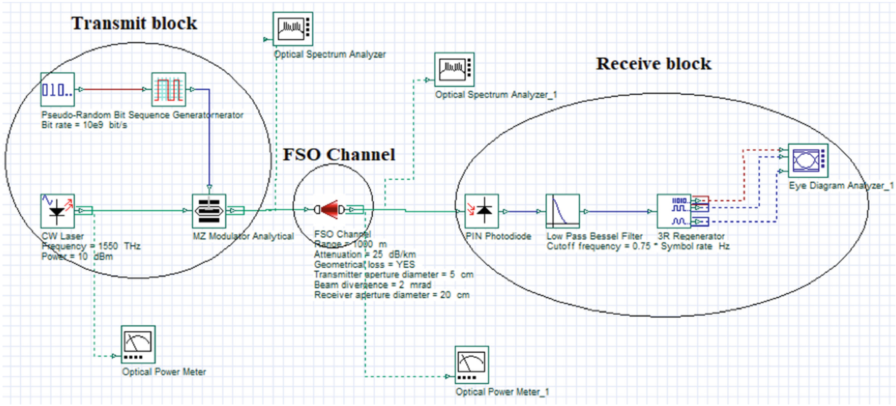

Fig. 2. Transmission schema of an FSO system

signal transmetted to optical channal FSO. The reception bloc is made up of a PIN type photodetector which allows the reverse operation of the optical source. In other words, the photodetector converts the received optical signal to an electrical signal. Low pass filtering is also used to minimize distortion and eliminate some unwanted frequencies. The repeater (3R regenerator) allows reamplification, shaping and resynchronization of the signal in order to compensate for some of the attenuations suffered by the signal during its propagation.

5 Simulation and Results

In this section, we evaluate the fundamental limiting factors in FSO network transmission. These factors are very often related to different atmospheric conditions such as fog, rain, scintillation etc. These different atmospheric conditions are grouped often around a typical value of 25 dB/km by the scientific community. The Table 1 below gives the different simulation parameters used in this proposal. The Fig. 3 above gives the variation of the signal quality obtained on reception as a function of the range of the link.

Table 1. Typical simulation parameters values

similation parameters	Parameters values
Bit rate	10 Gbts
signal pwer	10 dBm
Wavelengh	1550 nm
attetuaton	25 dB/km
Modulation type	External modulation

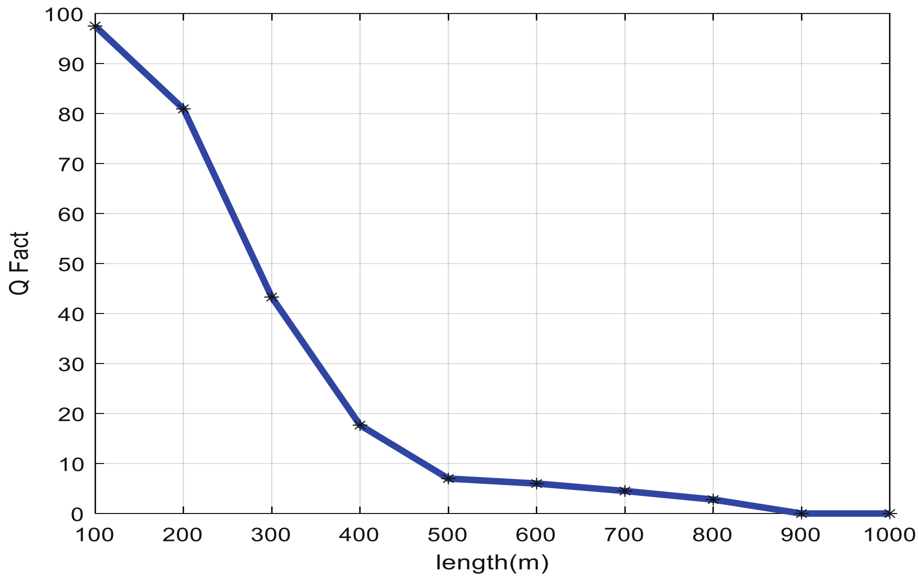

Fig. 3. Performance of FSO links with typical parameter value attenuator (25 dB).

The performance of the link, given by the Fig. 3, is evaluated over a distance ranging from 100 m to 1 km. The results show that, for a range varying from 100 m to 500 m, we observe a very rapid decrease in the quality factor. Beyond 500 m, the variation becomes slow until it reaches its limit value. In addition, the maximum range reached is 520 m with a bit error rate and an acceptable Q-factor (Q-Fact = 6.00028). Beyond this range, the signal obtained is of poor quality with a great Binary Error Rate (BER) and a quality factor less than 6.

In this proposal, a detailed study is carried out on all the limiting propagation factors of the optical signal for a best appreciation of the FSO channel quality impact in an optical transmission in free space link. Indeed, on several articles provided by the experts, the various limiting factors are grouped around a typical value of 25 dB/km. For a best apprication and application of FSO networks in African countries, we have carried out a detailed study on each limiting factor (rain, fog, sparking) to understand its effect on the FSO link. Thus, for each limiting factor, we will use a mathematical model to determine the value of the FSO channel attenuation. Then, we used the Optisystem software to establish the network architecture and perform a series of simulations and visualization of the results. The matlab software is used to determine the evolution of the quality factor, the bit error rate according to the range of the link.

5.1 Rain Limitations in FSO Networks

The rain is one of the factors limiting optical free space transmission. It affects the signal quality in the FSO channel. The losses of the optical signal related to rain are defined by the relation (1) [8]:

$$Att_{rain} = 1{,}076R^{0{,}67} \tag{1}$$

R gives the precipitation rate in (mm/h).

A simulation was carried out for different forms of rain (Drizzle, light, medium and heavy rain). The simulation parameters are grouped in the Table 2 below which gives for each type of rain, the variation of the attenuation according to the rate of precipitation. The Fig. 4 represents the comparison made between the different types of rain on the quality of the FSO link.

Table 2. Attenuation of the different types of rain according to the rate of precipitation

Rain type	R (mm/h)	Attenuation value (dB/km)
Drizzle	0.25	0.42
Light rain	2.5	1.98
Averange rain	12.5	5.84
Heavy rain	25	9.29
storm	100	23.54

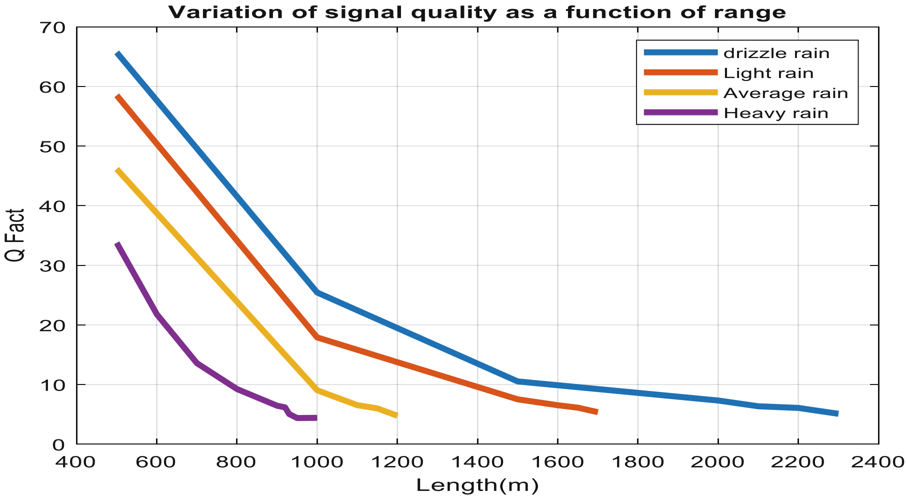

Fig. 4. Comparison of the different forms of rain

For light rain, the connection can be extended up to a range of 2200 m. For light, medium and heavy rain, the maximum range reached is 1650 m, 1150 m and 920 m respectively. For the same range value (for example 500 m), we also observe that, light rain has the greatest performance on reception with a quality factor of 65.699 while heavy rain has the lowest performance compared to the others types of rain. This shows that, for the case of rain, the higher the precipitation rate, the more the link is affected and the more the range is limited.

5.2 The Turbulence Effects in the FSO Network

The scintillation is also one of the factors limiting optical free space transmission. The optical signal losses related to scintillation are defined by the equations (2),(3).

$$Aff_{scin} = 2\sqrt{23,17 \times K^{\frac{7}{6}} \times C_n^2 \times L^{\frac{11}{6}}} \tag{2}$$

where

$$K = \frac{2\pi}{\lambda}, \tag{3}$$

In (2), K gives the wave number, C_n^2 the turbulence intensity and L the distance of the
link between the transmitter and the receiver.

The simulation is done under different conditions, i.e. for the weak, medium and strong scintillation case. The following Table 3 gives for different scintillation strength, the value of the corresponding attenuation.

Table 3. Attenuation of scintillation

Turbulance Intensity	Low Turbulance	Medium Turbulance	High Turbulance
Turbulance value	10^{-16}	10^{-14}	10^{-13}
Attenuation value (1550 nm)	0.39	3.87	12.25

The results obtained are visualized on the following Fig. 5 which represents the variation of the quality of the signal according to the range of the link.

The results in the Fig. 5 show that, for low scintillation, the maximum range reached is 2200 m. For the medium and strong case of scintillation, the connection can be extended up to 1200 m and 800 m respectively. In addition, we also find that the greater the range, the lower the quality of the signal obtained on reception. This shows that the greater the scintillation strength, the more the binding is affected. This is characterized by a decrease in range, a decrease of Q-Factor and an increase in the binary error rate (BER).

5.3 Fog Limitations in FSO Networks

The fog limits also the performance of the free space optical transmission network. In this section we first focus on the tests of the signal FSO quality in clear weather, in light, moderate, thick and then dense fog. The Eqs. (4), (5), (6), (7) explain the optical signal losses due to fog [2]

$$\Gamma_{brouillard} = \frac{3,91}{V} \times (\frac{\lambda}{550})^{-q} \tag{4}$$

$$\beta(\lambda) = \frac{1}{L} * 10log_{10}\frac{P_t}{P_r} = \frac{1}{L} * 10log_{10}(e^{\gamma(\lambda)*L}) \tag{5}$$

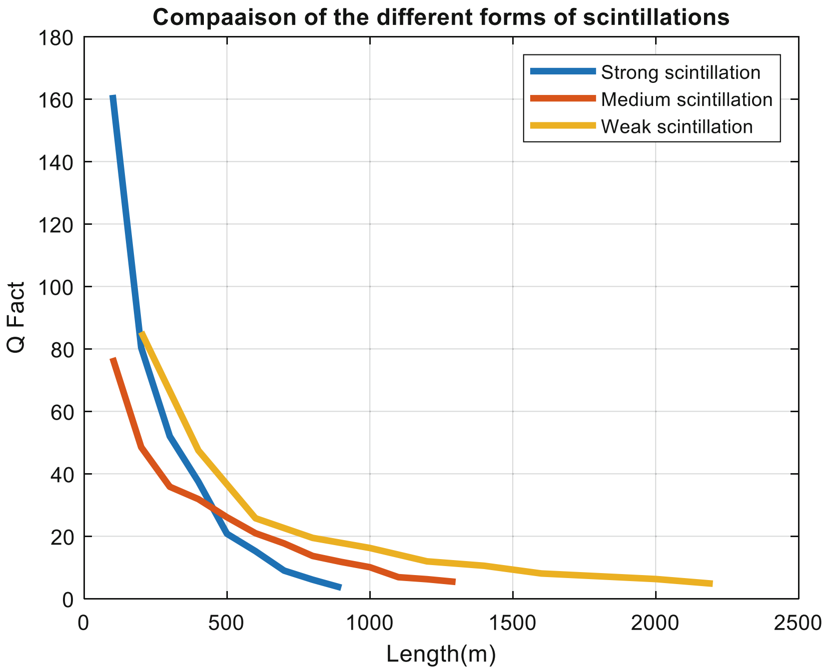

Fig. 5. Comparison of the different forms of scintillation

KRUSE MODEL

$$q = \begin{cases} 11,6 & if \quad V > 50\,km \\ 1,3 & if \quad 6\,km < V < 50\,km \\ 0,585V^{\frac{1}{3}} & if \quad 0\,km < V < 6\,km \end{cases} \tag{6}$$

KIM MODEL

$$q = \begin{cases} 11,6 & if \quad V > 50\,km \\ 1,3 & if \quad 6\,km < V < 50\,km \\ 0,16 * V + 0,34 & if \quad 1\,km < V < 6\,km \\ V - 0,5 & if \quad 0,5\,km < V < 1\,km \\ 0 & V < 0,5\,km \end{cases} \tag{7}$$

V (km) represents the visibility, λ(nm) the wavelength of the radiation, q is the parameter that depend on the particle size.

However, a comparison is made to see the effect of fog on the FSO channel compared to other factors. The following table gives for different types of fog, the corresponding attenuation according to these different parameters given by Table 4 below
.

Table 4. Fog attenuation values

Atmosphetiques conditions	Visibility (meters)	Q visibility parameters	Specific fog loss
clear weather	20.000	1.3	0.01
light fog	770	0.27	3.84
moderate fog	500	0	7.824
thick fog	200	0	19.56
dense fog	50	0	78.24

With parameters values obtained in the Table 4, we obtain an attenuation of 0.22 for clear weather atmospheres conditions, 16.68 for light fog, 33.9792 for moderate fog, 84.948 in thick fog and 339.792 in dense fog atmospheres conditions. The results obtained are displayed in the figure 6 below. It represents the variation in quality of the signal obtained on reception as a function of the range of the link for different types of fog.

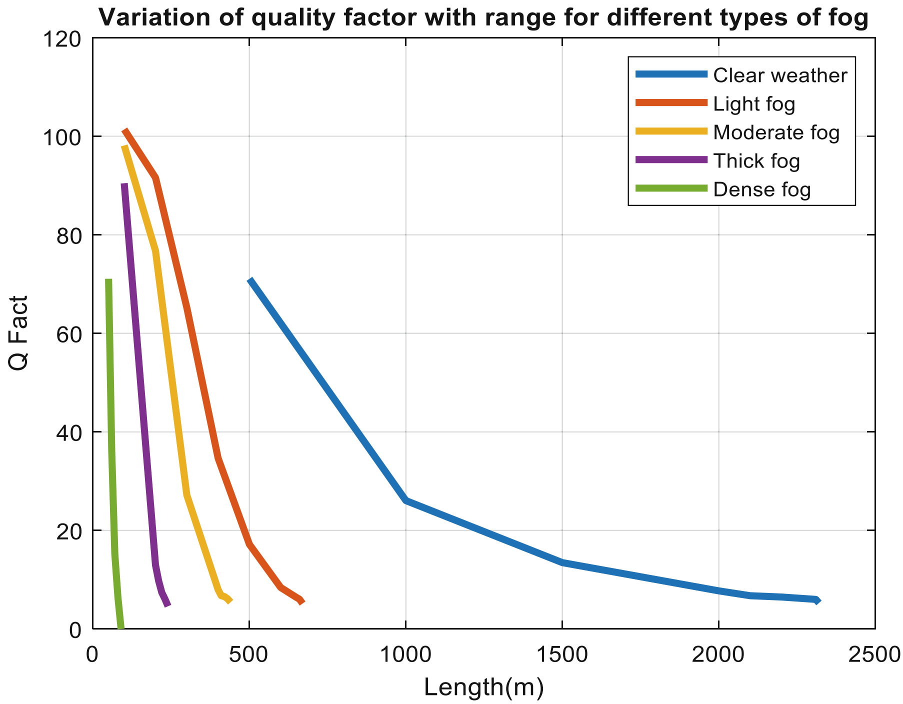

Fig. 6. Comparison of the different forms of fog

The results in the Fig. 6 show that in a clear atmosphere where with no climatic phenomenon (rain, fog, snow, etc.), a FSO link can be extended up to a range of 2310 m.

On the other hand, in the presence of light, moderate, thick or dense fog, the range is limited to 660 m, 430 m, 230 m and 80 m respectively. Which shows that the fog greatly affects the performance of the link. Compared to other factors such as rain, snow, and scintillation, fog gives more degradations in the optical signal. This is justified by the fact that in a situation of heavy rain or strong scintillation, the range is limited to 920 m and 800 m respectively, while in a situation of light fog the maximum range reached is 660 m. This shows that light fog affects the signal more than any other factor present in the atmospheric channel. This means that fog is the main factor limiting optical transmission in free space as confirmed by the simulation results.

6 Conclusion and Futures Works

The main objective of this work is to propose a high-speed point-to-point communications architecture for the most remote areas of operators, such as rural areas. We have proposed a free space optical transmission network based on the FSO. A study of all the factors limiting transmission was carried out with the aim of analyzing and evaluating the performance of the atmospheric channel of the FSO link. The performance of the link is analyzed by evaluating the bit error rate, the quality factor as well as the range of the link in the presence of each phenomenon. However, it should be noted that fog is the major problem of FSO systems among all the limiting factors. Thus, the performance of the link can be improved by considering either MIMO technology, or the implementation of hybrid FSO-RF systems.

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