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# Design and Development of a Quality-of-Service IHM for Wireless Optical Networks

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*Abstract*- **The prediction of the *Quality of Service* is a vital key in the deployment of Free Space Optical communications networks, it depends on a variety of factors, including equipment reliability, network design and atmospheric parameters such as rain, snow, fog and scintillation. The aim of this paper is to present a quality-of-service software provisioning for wireless optical networks, which allows predicting the availability of a FSO link. Compared to software developed in this area, the proposed software provides instantaneous prediction as well as long-term prediction, and it takes into account the case where the FSO units are implemented behind windows.**

**The FSO software includes different effects (geometric attenuation, atmospheric molecular absorption, fog, rain, snow, sunlight and scintillation), it consists of a Graphic User Interface (GUI) and a calculating kernel.**

*Keywords*- ***FSO, QoS, Software, availability, atmospheric effects, prediction.***

## I. Introduction

With the use of Free-Space Optics (FSO) technology, optical bandwidth connections can send and receive optical data, voice, and video communications over a few kilometers link distances [1,2]. It is a wireless optical technology that uses low power lasers as light sources and the free space, or the atmosphere, as a transmission medium. Based on the connectivity between two FSO communication units, FSO communications can operate over distances of several kilometers, as long as a clear line of sight is available between the communicating units [3,4]. Each FSO unit consists of an optical transmitter/receiver (transceiver) that uses a laser to transmit data and a photo laser for the detection.

The biggest unknown challenge in wireless networks design is the degradation caused by atmospheric attenuation [5]. FSO links availability depends on several factors, such as robustness of the used equipment and network conception, which are fairly quantifiable. Finding the link margin, which provides an estimation of the amount of energy losses the system can withstand, is one of the most important ways to assess how effectively an FSO connection will function.

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In order to quantify the necessary extra power that must be provided under any given set of operating atmospheric conditions we assess the link's reliability and quality of service. Based on [6], [7], and [8], the ultimate goal of this calculation is to determine how far we can place the transmitter and receiver under atmospheric conditions while still maintaining enough margin to allow for a specified minimum link availability.

## II. Link Margin

The assessment of the state of FSO links refers to the calculation of its link margin. As stated in [6], the optical link margin is the power available above the receiver's sensitivity, given by:

$$M_{liaison}\,(\text{dB}) = P_e + |S_r| - Att_{Geo} - Att_{mol} - \sum P_{sys}, \qquad (1)$$

where:

- $P_e$ : is the transmitted optical energy (dBm);
- $S_r$ : is the receiver’s sensitivity (dBm);
- $Att_{Geo}$ is geometrical attenuation of the link (dB);
- $Att_{mol}$ is the link molecular attenuation (dB);
- $P_{sys}$ (dB) are the system losses.

The FSO system's transmission power is the quantity of optical energy it transmits, and the minimum amount of optical energy it must receive is known as the receiver sensitivity. By taking into account the features of FSO systems and the environment where the link is going to be deployed, the link margin evaluates whether an FSO link can transmit sufficient optical power to the other end of the link under unfavorable conditions such as fog, rain, impaired visibility caused by smoke, scintillation, and so on [7].

### A. Geometric losses

Because of the geometric losses a good portion of the transmitted light is not captured by the receiver, this is due to the spreading of the transmitted beam, as illustrates Fig. 1. Less geometric loss is often the consequence of wider receiver aperture or lower divergence angle of the transmitted beam for a given range.

The geometrical loss is equal to: the surface of the wave spot at a distance $l$, on the surface capture at the receiver and it is given by [9]:

$$Att_{Geo} = \frac{S_l}{S_{capture}}, \qquad (2)$$

where:

- $S_l$ : Spot surface at the distance $l$,
- $S_{capture}$ : Receiver capture surface.

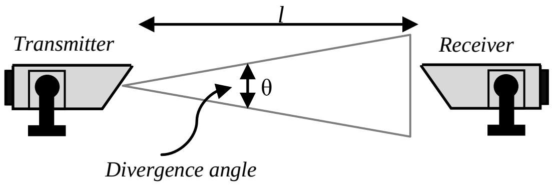


Fig. 1. Link parameters to calculate geometric attenuation

For an FSO link, the geometric path loss is determined by the divergence angle, the distance, and the beam-width of the optical transmitter. The sizes of the transmitter and receiver apertures are measured and are typically provided by the manufacturer. As the angle of beam divergence is very small, typically on the order of a few degrees can considered tan (θ / 2) ≈ θ / 2, so that the surface of the spot at distance *l* is given by:

$$S_l = \frac{\pi}{4}(l\theta)^2 . \quad (3)$$

In dB, Geometric attenuation is given by:

$$Att_{Geo} = \frac{S_l}{S_{capture}} = \frac{\pi / 4(l\theta)^2}{S_{capture}} , \quad (4)$$

where:

- θ : Beam divergence,
- *l* : Transmitter-Receiver distance.

Every FSO connection has this geometric loss, which means that while designing a link, it must always be taken into account. Unlike the loss resulting from rain attenuation, fog, haze, or scintillation, this loss is a fixed value for a particular FSO deployment situation and does not change over time.

### B. Molecular attenuation

Molecular attenuation occurs when gas molecules in the terrestrial atmosphere absorb and scatter infrared light, decreasing the intensity of the transmitted beam. Consequently, it directly impacts the transmission distance and the availability of the communication link. The main molecules responsible for absorption are water, carbon dioxide, and ozone, making molecular absorption a selective process. As a result, the atmosphere has transparent regions, known as atmospheric transmission windows, and opaque regions, known as blocking windows.

Table 1 provides the molecular absorption coefficients for various wavelengths, which have been determined for a clean environment.

TABLE 1
MOLECULAR ABSORPTION AT SOME TYPICAL WAVELENGTHS

| wavelength (nm) | specific molecular Absorption (dB/km) |
|---|---|
| 550 | 0.13 |
| 690 | 0.01 |
| 850 | 0.41 |
| 1550 | 0.01 |

### C. The system losses

The primary cause of loss in a FSO systems arises from the presence of flawed lenses and other optical components, such as couplers. As an example, a lens may allow 96% of the light to pass through, while the other 4% is either reflected or absorbed. The magnitude of this loss is contingent upon the specific attributes of the equipment and the quality of the lenses. The measurement or derivation of this value is required from the manufacturer of the optical components.

## III. ATMOSPHERIC EFFECTS (WEATHER CONDITIONS)

The accessibility and the reliability of FSO links are influenced by the features of the used materials, but also to the atmospheric conditions such as rain, snow, and scintillation [10]. Among these conditions, fog poses the greatest challenge to the deployment of these communication links. For instance, the attenuation caused by thick fog can reach up to 400dB/km [11]. The intensity and length of these impacts will influence the reliability and accessibility of the connection.

### A. Fog effect on FSO links

Fog is the main cause of atmospheric attenuation in FSO systems, as the size of fog particles is similar to the optical wavelengths generally employed for FSO transmission. Al Naboulsi et al. (France Telecom model) have presented equations to forecast fog attenuation by distinguishing between advection and radiation fog [12].

Advection fog occurs when moist and warm air masses flow across colder surfaces, whether they are bodies of water or land. The defining features of this include a liquid water content exceeding 0.20 g/m3 and a particle diameter of around 20 µm [12]. Al Naboulsi presents the advection fog attenuation coefficients as:

$$\sigma_{adv}(\lambda) = \frac{0.11478\lambda + 3.8367}{v} . \quad (5)$$

Radiation fog occurs when the ground cools down due to radiation. It occurs when the air reaches a low enough temperature and gets fully saturated. This fog typically manifests around nocturnal hours and towards the end of the day. The particle size is around 4 µm, whereas the concentration of liquid water ranges from 0.01 to 0.1 g/m3. Al Naboulsi presents the radiation fog attenuation coefficients as:

$$\sigma_{rad}(\lambda) = \frac{0.18126\lambda^2 + 0.13709\lambda + 3.7502}{v} . \quad (6)$$

The specific attenuation in dB/km for both types of fog is given by Al Naboulsi as follows:

$$a_{spec}(dB/km) = \frac{10}{\ln(10)}\sigma(\lambda) . \quad (7)$$

### B. Rain effect on FSO links

Rain has a diminishing effect on FSO systems; however, its effect is considerably smaller compared to that of fog. The reason for this is that the size of raindrops (200–2000 μm) is considerably greater than the wavelength of standard FSO light sources. The attenuation caused by rain, regardless the wavelength, is determined by the precipitation intensity R (mm/h) as stated in [13].

$$Aff_{rain} = 1.076 * R^{0,67} \text{ dB/km.} \quad (8)$$

By utilizing the concept of link margin, we may employ a dichotomous approach to determine the possibility of link interruption by rain.

### C. Snow effect on FSO links

Snowflakes are ice crystals that have diverse shapes and sizes. In terms of size, snowflakes are rather large compared to the operational wavelength, ranging from approximately 2 to 25 mm. This characteristic reduces the likelihood of significant scattering issues for FSO systems. The attenuation caused by snow depends on the wavelength ($\lambda_{nm}$) and precipitation intensity `S` (mm/h) as described by the following equations:

- Wet snow (altitude <500m):

$$Aff_{snow} = (0.0001023\lambda + 3.7855476) \times S^{0,72} \text{ dB/km}, \quad (9)$$

- Dry snow (altitude > or = 500 m)

$$Aff_{snow} = (0.0000542\lambda + 5.4948776) \times S^{1,38} \text{ dB/km}.(10)$$

The snow intensity, denoted as `S`, is the primary measure used to define the snow conditions at a specific location. By utilizing the optical power link margin, we can determine the available extra power. Using a dichotomous approach, we can then calculate the possibility of connection interruption caused by snow.

### D. Scintillations effect on FSO links

The random variation in the refractive index of the atmosphere during clear weather results in significant scintillation losses to the transmitted optical signal. Atmospheric scintillation refers to the fluctuation of light intensities in both time and space at the receiver's location. This phenomenon occurs due to the thermal changes in the air's refractive index, resulting in the formation of random cells of varying sizes (ranging from 10 cm to 1 km) [14]. These cells, illustrated in Fig. 2, cause the atmosphere to behave like a series of small lenses. As a result, portions of the light beam are deflected into and out of the transmission path. The atmospheric structure parameter "$C_n^2$" is often used to measure the scintillation strength. Attenuation due to scintillation is given by:

$$Aff_{\text{scintillation}} = 2\sqrt{23.17 * k^{7/6} * C_n^2 * L^{11/6}}, \quad (11)$$

where: $k$ ($m^{-1}$) is the wave number $2\pi/\lambda$.

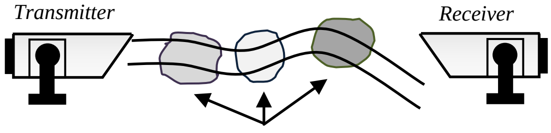


Fig. 2. Schematic sun path with regard to a FSO Link

$C_n^2$ is for low turbulence $10^{-16}$, for moderate turbulence $10^{-14}$, for high turbulence $10^{-13}$ [9]. A typical value is 4 dB for 1km link under moderate atmospheric turbulence [15].

### E. Sunlight Attenuation

A FSO system has a receiver that is extremely sensitive, along with a lens that has a big aperture. Consequently, sunlight has the ability to disrupt the received FSO signals, leading to link outages lasting several minutes when the Sun is within the field of view of the receiver. In some cases, this interference can even result in equipment failure.

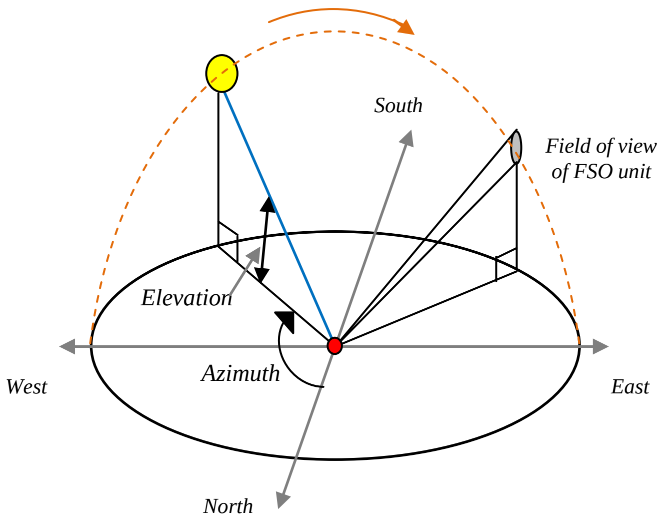


Fig. 3. Schematic sun path with regard to a FSO Link

The power radiated by the sun (Watts/m2) is defined by the following relation

$$Power = 1200 * \cos\left(\frac{\pi}{2} - Elevation\right), \quad (12)$$

where: Elevation is the sun height, in radian.

The power penetrating inside the receiver is given by the following formula:

$$p_{solar} = F_{solar} * Power * Cap.surface * \frac{Width.Band_{reciever}}{100}, \quad (13)$$

- $F_{solar}$ is a wavelength function characterizing the sun spectral power,
- *Cap.surface* is the receiver capture surface,
- *Width.Band* receiver (nm) is the receiver width band.

$$F_{solair} = 8.97162055148876\ 10^{-13}\lambda^5 - 4.649127391289745\ 10^{-9}\lambda^4 + 9.37072684333339\ 10^{-6}\lambda^3 - 9.066632383289905\ 10^{-3}\lambda^2 + 4.05479801934347\lambda - 5.70237282654237\ 10^{+2} \quad (14)$$

According to Fig. 3, the conditions for receiving the sunlight, in the receiver are the following:

$$\begin{cases} E_s \in \left[E_l - \Delta E_l, E_l + \Delta E_l\right] \\ A_s \in \left[A_l - \Delta A_l, A_l + \Delta A_l\right] \end{cases}, \quad (15)$$

or:

$$\begin{cases} E_s \in \left[-E_l - \Delta E_l, -E_l + \Delta E_l\right] \\ A_s \in \left[-A_l - \Delta A_l, -A_l + \Delta A_l\right] \end{cases}, \quad (16)$$

and, $P_{solar}$ > power received from the transmitter.

where $E_s$, $E_l$ are the Elevation angles of the sun and the FSO link, and $A_s$, $A_l$ their Azimuth, and $\Delta E_l = \Delta A_z = 2\theta$ .

## IV. Installation Behind Windows

A major advantage of FSO technology is the possibility of communications through windows. This feature eliminates the need to setup the equipment on a roof space, avoiding complicated cabling, and allows FSO equipment to function in an optimal environment.

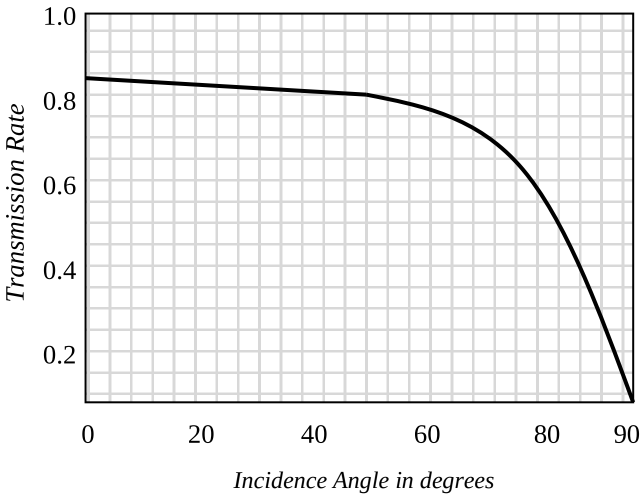


Fig. 4. The transmission rate based on the incidence angle of light beam.

The optimal angle of the beam in relation to the window is crucial. It should be as close to perpendicular as possible, with a small inclination of 5 degrees to minimize the reflection of the beam back to its own receptor. The transmission rate based on the incidence angle is shown in Fig. 4.

Beside the transmission angle, attenuation through glass depends also on the type of glass and the wavelength used. Windows, despite their ability to transmit optical signals, introduce varying degrees of attenuation to the beam, ranging from 0.4 to over 15 dB [16].

In order to ensure good availability of an FSO communication link deployed behind windows, it is crucial to include the attenuation induced by the windows. This will enable correct calculation of the expected performance of the link. The propagation of a laser beam through a window causes attenuation of light transmission, because of the absorption and the reflection. The output ($I_s$) of an incident beam ($I_0$) on a glass thickness ($e$) is given by the Beer-Lambert law [17]:

$$\frac{I_s}{I_0} = (1-R)^2 * e^{-\alpha e}, \quad (17)$$

where:

- $\alpha$: Is the absorption Coefficient of the glass.
- $R$: Reflection Coefficient.

$$R = \frac{1}{2}\left[\frac{tg^2(\theta_r - \theta)}{tg^2(\theta_r + \theta)} + \frac{\sin^2(\theta_r - \theta)}{\sin^2(\theta_r + \theta)}\right]. \quad (18)$$

where: $\theta$ and $\theta_r$ are the incidence and the refraction angle respectively.

## V. Presentation of the Software

The developed software "FSOL.Predi" (Free Space Optical Links Prediction) enables the assessment of the Quality of Service (QoS) of FSO communication link, in terms of the availability of both instantaneous and long-term connections.

Availability, often known as reliability, is the proportion of time that a communication link is operational in a specific year. The decrease in availability is a result of unexpected periods of inactivity, such as those produced by particular weather conditions that vary in location and time. Availability is commonly expressed using the term "nines" as seen in Table 2. For instance, a 99.9% availability, often known as three-nines (3–9's) availability, indicates that the link is likely to be unavailable 0.1% of the time, which averages to approximately 43 minutes each month. Four-nines (4–9's) availability means that there is only four minutes of downtime each month, while five-nines availability averages just 30 seconds of downtime per month [18].

TABLE 2
THE DOWNTIME ALLOWED FOR A PARTICULAR PERCENTAGE OF AVAILABILITY

| Availability % | Downtime per year | Downtime per month | Downtime per week |
|---|---|---|---|
| 99.9% (three nines) | 8.76 hours | 43.2 min | 10.1 min |
| 99.99% (four nines) | 52.6 min | 4.32 min | 1.01 min |
| 99.999% (five nines) | 5.26 min | 25.9 s | 6.05 s |
| 99.9999% (six nines) | 31.5 s | 2.59 s | 0.605 s |

The developed software is made up of a GUI and a kernel of calculation. It consists of two screens: an input data screen for both instantaneous and long-term prediction, and a second screen for presenting the results.

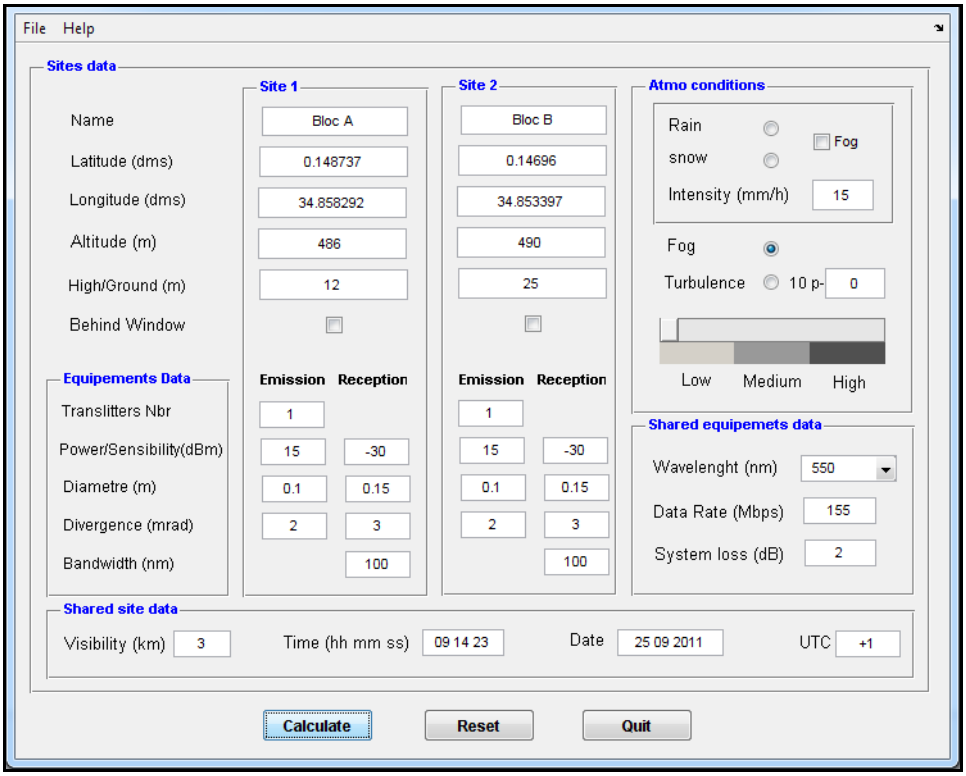


Fig. 5. Input data screen for instantaneous prediction

### A. *Input data screen*

The screen data entry consists of six blocks of information on the different parameters characterizing the atmospheric optical link that will allow us to assess the availability of the connection, as Fig. 5 illustrates.

The Input data screen`s six blocks are:

- Two blocks for the data characterizing the two sites (Names, latitudes, longitudes, altitudes, etc.);
- Data characterizing the used equipment (power, sensitivity, receptor diameter, divergence, etc.);
- Shared sites data (visibility, time…etc.);
- Shared equipment data (data rate, wavelength, system loss);
- Data giving the atmospheric condition accruing at the calculation time (For instantaneous prediction).

Long-term prediction is to be calculated for a given year, records of atmospheric conditions for such place must be available along a given year. When it comes to instantaneous availability calculation the atmospheric condition is to be directly entered to the input fields of the input data screen. From the menu file of the developed software the user can choose the prediction type; instantaneous or long-term, where there are common entrees between the two types, and the different entrees go inactive according to the selected prediction type. For instantaneous prediction all the fields are active, but for long-term prediction the Atmo-conditions block, visibility and time inputs from shared site data block all go inactive.

### B. *Report screen*

The report screen consists of four blocks, common link features, annual link availability, annual climate effects and instantaneous availability. For instantaneous prediction, just the blocks instantaneous availability and common link features are active, as shown in Fig. 6, and for long-term prediction only the block instantaneous availability goes inactive, as Fig. 7 illustrates. Common link features block gives:

- Beam Spot (m),
- path-loss (Geometric losses) (dB)
- Link declination (Deg)
- Molecular losses (dB)
- Link margin (dB) and linear link margin.

Instantaneous availability block gives:

- Climatologic Attenuation (dB)
- Aerosol Attenuation (dB)
- Extra power (dB)

Annual availability block gives

- Availability (%)
- Down time per year

Annual climate effects block gives down time per year, annual value and maximum attenuation value for all the climatologic conditions as well as their combinations.

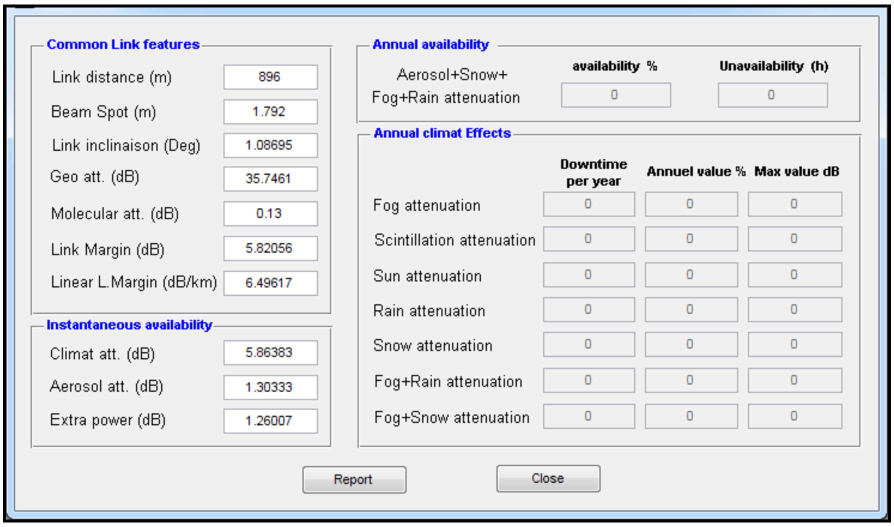


Fig. 6. Report screen for instantaneous prediction

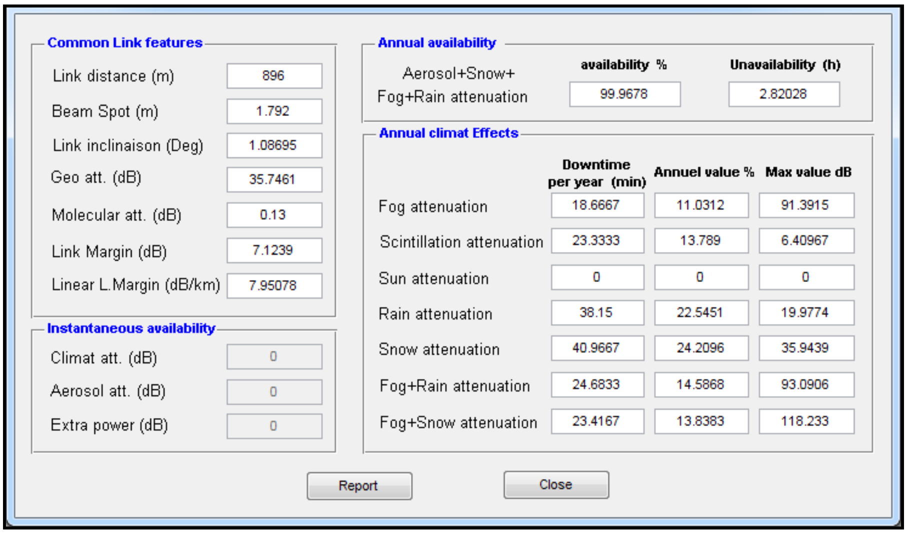


Fig. 7. Report screen for Long-Term prediction

### *C. Input/output files:*

For the long-term prediction an Excel input file of extension (.xls) must be provided, it gives to the kernel of calculation in seven sheets data about (rain, snow, fog, the atmospheric structure parameter, fog + snow, fog + rain and not cloddy days) recorded for one year, in order to give the quality of service of an atmospheric optical link in term of probability of connection under the weather condition during that time. The output file is of extension (.txt), it's kind of report file, can be explored only for long-term prediction, it gathers both input data entered by the user about the site characteristic, the weather conditions, and results data giving the annual availability in addition to statistics about the annual climatologic effects.

## VI. Conclusions

A key issue in the deployment of FSO systems is the reliability and the availability provisioning, which depend on a variety of factors, including equipment reliability, network design and climatic conditions that it will be exposed to, such as rain, snow, fog and scintillation which are function of the geographical and topographical parameters of its location.

In this paper we have introduced a developed software "FSOL.Pred" that allows to evaluate the quality of service and provide an approximate availability estimation of an atmospheric optical link at a given location in term of probability of connection.

We have demonstrated the diverse capabilities of the software that we have developed. It begins by the equipment data, geographical location, and climatic and atmospheric parameters (such as fog, snow, rain, etc.) to calculate the link margin and interruption probabilities for various types of attenuation (including aerosols, scintillation, ambient solar light, rain, snow, etc.). The availability quoted in nines as main results for long term prediction, and extra power for instantaneous prediction. The developed software is an essential tool to the study and to the technical choice of FSO infrastructures and the appropriate optical wavelength for point-to-point very high-speed links on ground-ground short distances, and it may be a useful tool and viable addition in the simulation and modeling field.

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