Proceedings of the 5th WSEAS Int. Conf. on Microelectronics, Nanoelectronics, Optoelectronics, Prague, Czech Republic, March 12-14, 2006 (pp97-104)

Free space optical (FSO) link design under diverse weather conditions

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Abstract: **-** This paper presents the link budget calculations for Free Space Optical (FSO) communication system under diverse weather conditions. It discusses various factors involved in the medium between the transmitter and receiver, which affect link budget calculations. For free space optical communication, atmospheric losses are the dominating factor in the link budget. These losses should be catered in such a way that sufficient power is available at the receiver to retrieve the information. It also describes the limitations of free space optical system under adverse weather conditions.

Keywords: - Link design, Propagation effects, FSO limitations.

1. Introduction

Free space optical technology also called optical wireless (OW) is an optical line of sight broadband communication that transmits information in free space using narrow optical beams. It is used for data, voice and video transmission. It is a point to point link, using laser beam to transmit the data between two transceivers. Laser communication or FSO is accepted world wide because it offers many advantages over other wireless technologies, such as microwave or RF spread spectrum.. These advantages include higher bandwidth, immunity from interference, higher security, smaller size and weight, lower power consumption, lack of regulation and ease of implementation. But its popularity could be hampered if sufficient measures are not taken to cater the atmospheric attenuation under adverse weather conditions, maintaining line of sight link due to sway and vibration in the buildings. This would cause link failure, low throughput or poor link availability. The nutshell is that system performance will be totally deteriorated and degraded under adverse weather conditions. This paper mainly focuses on atmospheric effects on FSO system which is the biggest challenge for its survivability. So either link distance or link availability has to be compromised [1-2].

Sec.2 of this paper explains the link design parameters. In Sec.3, we discuss impact of atmosphere on laser communication under diverse weather conditions. Sec.4 deals with link margin. Sec.5 includes the limitations of FSO system under adverse weather conditions and then different solutions to cater the utter link failure or how to handle the poor link availability. Sec.6 concludes the results and overall findings.

2. Link Design

System design analysis plays a key role in any system implementation. Understanding the requirements is perhaps the most important element in system design. Without a proper understanding of customer needs, the systems cannot cost effectively be designed. Once requirements (data rate, range, bit error rate, power etc) are understood, then we could implement the design successfully. The main objective of FSO link is to get as much light as possible from one end to the other, in order to receive a stronger signal that would result in higher link margin and greater link availability. To evaluate the performance of FSO system, then system parameters can be divided into two parts. That is internal and external parameters of a system. Internal parameters of a system are related to the design of a optical system also called system related parameters. System related parameters include the following list of basic parameters.

- Transmitted Power (P_T)
- Transmit Beam Divergence (θ in rad)
- Receive Aperture Diameter (D_R in m)
- Receiver Sensitivity (S_R)
- Transmitter & Receiver optical losses (η)

These parameters collectively form generalized link margin (GLM) which is direct measure of system ability to overcome the attenuation. For more detail see section 4. Mathematically

$$GLM = \frac{P_T * \eta * A_R}{\left[A_T + (R * \theta)^2\right]} \qquad (1)$$

External parameters of a system (also called link related parameters) deal with the climatical factors which attenuate the signal strength. It includes atmospheric attenuation, range of deployment, visibility, scintillation etc. Sec.3 explains link related parameters in depth. Following table 1 shows the list of parameters used in calculating the link budget for free space optical (FSO) communication [3-4]

Power transmitted (P_T) (two transmitters)	100 mW (each 50 mW)
Wavelength (λ)	1550nm
Transmitter beam divergence	2 mRad
Receiver diameter (D_R)	10cm
Range	2500 m
Data rate	180 Mbps
Receiver sensitivity (S_R)	-33dBm
Transmitter and receiver losses (η)	50%

Table 1. Link design parameters

3. Impact of Atmosphere on FSO

FSO system is extremely weather sensitive. Change in weather conditions cause fluctuations in the received signal. These fluctuations result in increasing the link error probabilities. In other words, FSO link availability and its throughput changes dynamically with the change in weather conditions. This is due to in-homogeneities in pressure and temperature fluctuations in the atmosphere. There are various meteorological factors that affect the transmitted signal. To understand that, media effects are categorized into the following.

- Absorption and scattering
- Turbulent media
- Turbid media

The major distinction between the last two cases is that in turbid medium refractive index variation is large while in turbulent medium it's small. Secondly in turbid media the particles are discrete, give sharp variations in refractive index as compared to a wavelength while in turbulent media, the refractive index are smooth, continuous function of space. Because of these distinctions, in turbid media a single particle gives strong scattering [3-7]

3.1 Absorption and Scattering

Absorption is mainly caused by the water vapor (H_2O) and carbon dioxide (CO_2) present in the air along the transmission path. Gases in the atmosphere have many reservation bands, called *transmission windows*, which allow specific frequencies of light to pass through.

The attenuation coefficient σ has contributions from the absorption and scattering of laser photons by different aerosols and gaseous molecules in the atmosphere. Since the FSO wavelengths (typically 1550nm and 850 nm) fall with in the transmission windows, with in the atmospheric absorption spectra, therefore the contribution of absorption to the total attenuation coefficient is very small. Hence atmospheric and aerosol absorption are negligible [4-5]. It means that absorption contributes very little to the link budget calculations for infrared laser communication. But scattering has a greater effect than absorption [5-9]. The atmospheric scattering of light is a function of its wavelength and the number and size of scattering elements in the air. The optical visibility along the path is directly related to the number and size of these particles. Visibility range is the horizontal distance for which the contrast transmission of the atmosphere in daylight is two percent [4]. It is also defined as the distance that the human eye can just distinguish a one meter square black target against a white background; therefore, it is simply a measure of contrast. The most common scattering elements in the air that affect laser beam transmission are fog, smog, rain and snow.

3.2 Turbulent media effects

When data is traveling through free space, atmospheric turbulence becomes an important factor in fluctuation of a received signal. In-homogeneities in the pressure and temperature lead to change in the refractive index along optical path which results in turbulence. This turbulence produces temporary pockets of air with slightly different temperatures, different densities, and thus different indices of refraction. These air pockets are created continuously and then destroyed as they mix; deteriorates the quality of the signal at the receiver and also changes the phase of the received signal. Hence results in poor link performance. Beam divergence, beam wandering and scintillation are mainly caused by atmospheric turbulence. As laser beam propagates through the earth's atmosphere, tiny changes in refractive index due to non-uniform heating and water vapor, cause relative delays across the beam profile, creating a multi-path effect that result in fluctuations at the optical receiver. This phenomenon is called *scintillation*. Data can be lost due to beam wander and scintillation as the laser beam becomes deformed while propagating through these index of refraction in-homogeneities.

The significance of each effect depends on the size of these turbulence cells with respect to the laser beam diameter. If the size of the turbulence cells is larger than the beam diameter, the laser beam as a whole randomly bends, cause possible signal loss if the beam wanders off the receiver aperture. This phenomenon is called beam wandering. If the size of the turbulence cells is smaller than the laser beam diameter, ray bending and diffraction cause distortions in the laser beam wave front (scintillation). Small variations in the arrival time of various components of the beam wave front produce constructive and destructive interference, and result in temporal fluctuations in the laser beam intensity at the receiver. The constant mixing of the atmosphere produces unpredictable turbulent cells of all sizes, resulting in received signal strength fluctuations that are a combination of beam wander and scintillation. [5-8]. Geometrical losses take place due to beam divergence when beam is transmitted. The reason is that practically laser beam is not collimated.

When it passes through the atmosphere, which has lens like nature results in spreading the beam. In other words, laser beam is just like a cone of light originating as a point at the transmitter and keeps on expanding with the increase in the distance at constant beam divergence rate. At any point on the beam path, the beam will appear as a circle and the power at that point will be inversely proportional to the area of that circle. Moreover as the link length increases, this circle gets larger and the amount of light falling on aperture gets smaller simultaneously as shown in Fig.4. Geometrical loss may be defined in terms of receiver and transmit surface areas as

$$L_{Geo} = \frac{\mathrm{Re}\,ceiver}{transmit}\frac{aperture}{surface}\frac{area}{area}$$

$$L_{Geo} = \frac{A_R}{A_T + (R*\theta)^2} \tag{2}$$

Where L_{Geo} is the geometrical losses, A_R is the receiver aperture area, A_T is the transmit surface area at range R, θ is the beam divergence in radians and R is the range.

Scintillation, geometric losses and beam blocking (e.g. bird) can be handled by using multiple beams transmitted or by increasing the receiver aperture field of view (FOV).

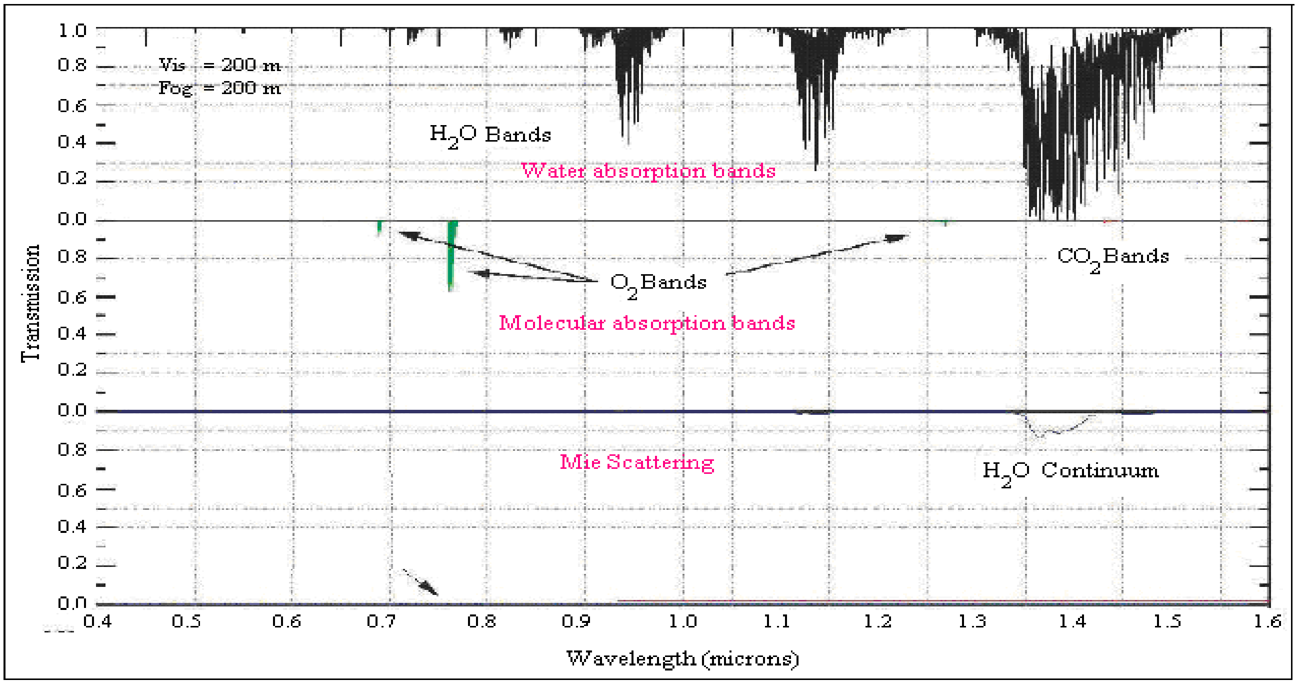

Fig.1: Propagating losses as function of wavelengths [deducted from reference 8]

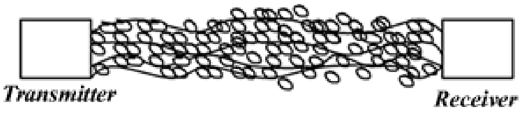

Fig.2: Impact of air pocket on beam intensity at receiver causing scintillation.

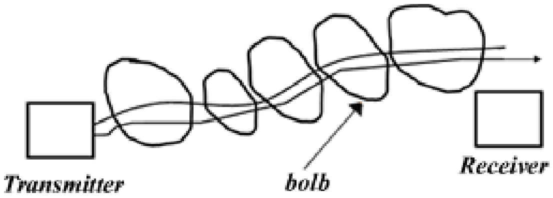

Fig.3: Beam wandering due to air pockets size greater than beam diameter

3.3 Turbid media effects

Propagation through a turbid medium refers to beam Passing through a medium consisting of large number of discrete scatters or aerosol particles (e.g. rain, fog or dust), which give rise to strong scattering effects. Attenuation by fog is significantly greater than attenuation by rain at infra-red (IR) wavelengths. This is because the fog droplet radius is roughly 5 to 15 nm which is of the order of the laser wavelengths, compared to rain droplet size is 200 to 2000 nm [10]. This is not the case for microwave

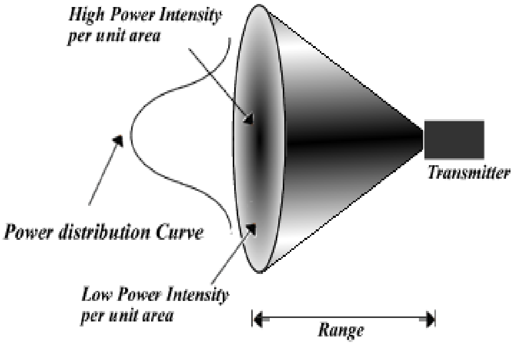

Fig.4: Shows a signal radiated from the transmitter that expands with respect to the increase in the distance. As the area covered increases, the power density (or the amount of power per unit area) decreases.

transmission, where the carrier wavelength is closer to the size of a rain drop. Thus the attenuation of microwaves by rain has a greater effect than attenuation by fog. As the rain rate increases, the effective link range for FSO decreases. However, even in the heaviest rain; the maximum link range is still greater than the heaviest fog, which limits the link range to few meters.

Scattering caused by particles (rain, fog or dust) that are large as compared to the wavelength of the light being transmitted is referred as Mie scattering. Mie scattering coefficient is a complex function of particle size and shape, refractive index, scattering angle, and wavelength. In general, it is described by the following relationship.

$$\sigma = \frac{3.91}{V}\left(\frac{\lambda}{550nm}\right)^{-P} \qquad (3)$$

Where σ is the atmospheric attenuation coefficient, V is the visibility in Km, P is the size distribution of scattering particle and λ is the wavelength in nm.

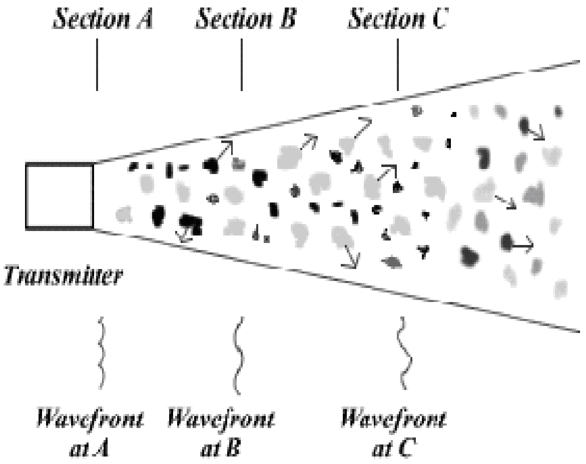

Fig.5: Scattering causes change in the wave front at different sections resulting in fluctuation at the receiver. At section A, all signals are in same phase. At B and C section, phase changes which in turn change the wave front.

P values are assigned corresponding to different visibility categories listed in the table below.

Visibility Category	Visibility Range (Km)	P value
High	V>50	1.6
Average	6 < V < 50	1.3
Haze	1 < V < 6	(0.16V)+ 0.34
Mist	0.5 < V < 1	V – 0.5
Fog	V< 0.5 Km	0

Table 2: Visibility range and categories

According to Exponential Beers-Lambert Law, attenuation of laser power through the atmosphere is given by

$$\tau(R) = \frac{P(R)}{P(S)} = e^{-\sigma R} \qquad (4)$$

Where τ (R) = transmittance at range R, P(R) = laser power at range R, P(S)= laser power at the source, and

σ=attenuation or total extinction coefficient in dB/Km.

4. Link margin

In dealing with atmospheric effects, we have to provide sufficient link margin that result in required link availability in diverse weather condition in a certain region. When a signal radiates from the transmitter, it expands with respect to the increase in the distance. As the area covered increases, the power density (or the amount of power per unit area) decreases. This effectively weakens the laser signal. Eq.3.4 is the link equation for the FSO system which shows that the amount of power received is proportional to the amount of power transmitted and the receiver collecting area. It is inversely proportional to the square of the beam divergence and the square of the link range. It is also inversely proportional to the exponential of the product of the atmospheric attenuation coefficient and link range.

$$P_R = P_T \frac{A_R}{\left[A_T + (\theta * R)^2\right]} e^{(-\sigma R)} \qquad (5)$$

Where P_R is the received power, P_T is the power transmitted, σ is attenuation coefficient, R is the range, θ is the beam divergence and A_R is the receiver aperture area. Clear air link margin is the ratio of the available received power on a clear day (at a given range) to the receiver power sensitivity required to meet the bit error rate specification. It is typically measured in dB. Following are various parameters that contribute to the link margin.

- Transmitted Power (P_T)
- Beam width of transmitter (θ in rad)
- Receiver Aperture Diameter (D_R in m)
- Receiver Sensitivity (S_R)

Mathematically link margin equation is

$$LM = \frac{P_R}{S_R} \qquad (6)$$

From equation (5) and (6)

$$LM = P_T \frac{A_R}{S_R\left[A_T + (\theta * R)^2\ \right]} e^{(-\sigma R)} \qquad (7)$$

Following is the procedure to calculate the link margin.

First we calculated the size of the transmit beam at the range of the link (R). This size equals the divergence of the transmitter (θ) multiplied by the range (R). Next we calculate the fraction of the transmitted beam (in vacuum) intercepted by the receiver using equation (2). Next we calculate an excess power ratio (P_R divided by the receiver sensitivity S) using Eqn. 6 or we can use Eqn. 7. From this, link margin (LM) in dB is calculated. It is to be noted that link margin calculated should be high enough to cater the adverse weather conditions. Other wise, it will cause either link failure, reduce the link throughput or switch to RF system.

5. Limitations

FSO link has poor performance, even link failure under adverse weather conditions. The reason is either some data missing or may be error in data collection. Because the data tabulations do not give information on whether visibility was impaired due to haze, fog, rain or snow. It doesn't show what were lighting conditions and how do they look like. The assumptions being made and the manner in which the data was collected, will affect the amount of attenuation we calculate for a given visibility, and will in turn affect the link budget. In addition, attenuation conditions in a city between buildings may be different from those experienced at the airport or attenuation conditions may be different at the top of building than at the bottom. Moreover, attenuation may not be constant along the whole path of the link due to non-linear behavior of atmosphere.

The main commercial limitation for FSO is that light does not propagate very far in dense fog. If system has small beam divergence then it will have problem with line of sight.

6. Results

Base upon the data available from meteorological department in Islamabad for a specific area, we did the following analysis.

These calculations show that at range of 2.5km with link margin of 7.9dB, the system can still tolerate losses even if it's raining. Let's suppose the rain rate is 10mm/Hr that results in the losses of 2dB/km. It means that still system can survive.

7. Conclusions

The paper presents over all system performance under diverse as well as adverse weather conditions. The FSO system performance can be judged by looking at its link margin. Higher the link margin, more

Rain rate in (mm/Hr)	Attenuation in (dB/km)
35	7
65	13
95	19
140	28
160	32

Table 3. Rain Attenuation data from Met Islamabad.

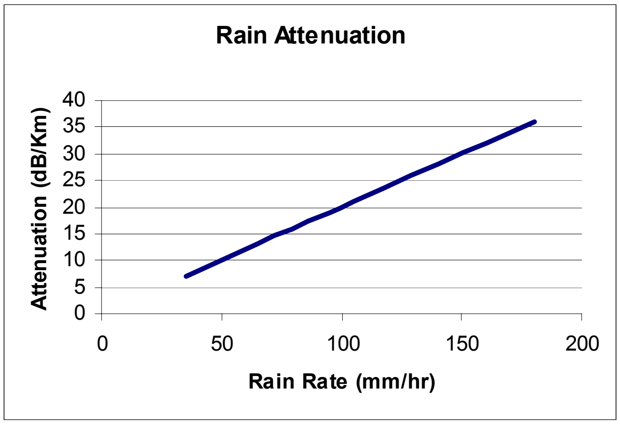

Fig.6: Attenuation vs. different rain rate.

Visibility V(Km)	Atmosp. attenuation co-efficient σ	1550nm Atmosp. attenuation (dB/km)	Weather
0.04	97.75	424.5	Fog
0.08	48.9	212.3	
0.1	39.1	169.8	
0.5	7.82	33.96	
1	2.3	10.11	
1.5	1.14	4	Haze
2	0.986	4.2	
2.5	0	3.14	
3	0.56	2.4	
10	1.3	0.44	Clear
20	1.3	0.22	

Table 4. Visibility and attenuation for different degree of fog

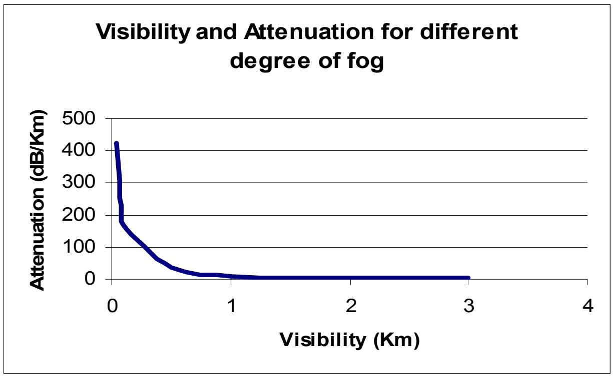

Fig7. Attenuation vs. visibility curve

Power per transmitter in mW	50
No of transmitters	2
Transmitter beam divergence in (milli-rad)	2
Receiver sensitivity for BER of $1*10^{-11}$ in dBm	-33
Range in (km)	2.5
Geometrical losses in dB	-34
Weather losses in dB/km	-3
Losses due to inefficiency in dB	-3
Total losses in dB	-44.5
Actual received power in dBm	-25.1
System dynamic range in dB	53
System link margin in dB	7.9

Table 5. Link budget calculations FSO system.

the system will tolerate the losses. Following are the different techniques used to optimize the system performance under adverse weather conditions.

- By selecting smaller hops (short distance FSO nodes).
- Use hybrid system (FSO switches to RF and vice versa).
- Use adoptive optics.

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