

Effect Of Smoke/Fog On Point To Point Free Space Optical Communication Links

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Abstract

The use of copper technology has decreased drastically in recent years due its bandwidth limitation and connectivity problem across networks. Fiber optic cables on the other hand have the advantage of better reliability, higher bandwidth and longer distances but are greatly limited by energy and power supply problems. Although power emitters can be used to boost the power supply problem of optic fiber cables, overhead cost makes them extremely uneconomical. Since energy and power optimization solutions have taken center stage in today's technological advancement, Free Space Optics (FSO) proves to be the best alternative for communication. FSO has advantages of high bandwidth and no spectrum license making them faster and more economical than fiber optic cables. In this study analysis on different parameters of system design to minimize these losses due to fog and smoke was carried out. Presentation of the analysis of internal design parameters such as diameter of receiver aperture, diameter of transmitter aperture, link distance was done. Finally was to propose optimized suitable parameters for system design. Optimization of the FSO link at data rate of 2Gbps and link length of 800 meters was achieved using On-Off keying (OOK) modulation.

Keywords: Free space optics; On-Off keying modulation

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1. Introduction

Free Space Optics (FSO) communication provides point-to-point transmission of communication information through the atmosphere using the Optical signals as the carrier frequencies. It has drawn attention in telecommunication industry, due to its cost effectiveness, easy installation, and quick establishment of communication link especially in the disaster management scenario, high bandwidth provisioning and wide range of applications. The range of frequencies where it operates makes FSO communication free from licensing. With FSO communication, maximum data transfer rates up to 2.5 Gbps is possible, unlike the maximum data transfer rates of 622Mbps offered by radio frequency (RF) communication systems. FSO involves the optical transmission of voice, video, and data using air as the medium of transmission. Transmission using FSO technology is relatively simple. It involves two systems each consisting of an optical transceiver which consists of a laser transmitter and a receiver to provide full duplex (bi-directional) capability. Each FSO system uses a high-power optical source (e.g., laser) plus a telescope that transmits light through the atmosphere to another telescope that receives the information. At that point, the receiving telescope connects to a high-sensitivity receiver through an optical fiber.

A Free Space Optical transmission system is a wireless form of connection designed for the interconnection of two points which have a direct line of sight. The system operates by taking a standard data or telecommunication signal, converting it into a digital format and transmitting it through free space. The carrier used for the transmission of this signal is Infrared and is generated by either high power light emitting diode (LED) or laser diode. The basic principles for the transmission of a signal along a fiber are the same as for transmission through free space.

2. Review of relevant literature

Preet, K (2017) on the performance optimization of free space optical links. This study optimized the FSO link at data rate of 1.25Gbps using the NRZ modulation format. Results obtained showed that for a 1550nm laser wavelength at 1km, the link range yielded a Q factor range between 17 and 19.8 with loss going up to 11.3dB.

Navidpour and Li (2014) used spatial diversity scheme to mitigate the effect of turbulence on FSO communication links. The turbulence induced fading severely degrades the performance of the system. To improve the error rate performance, multiple transmitters/receivers are used over FSO links. Here, OOK modulation was assumed. Hence, the bit error rate optical communication links with spatial diversity over lognormal atmospheric turbulence channels is investigated. BER expression is derived with multiple transmitters/receivers considering both spatially independent and correlated channels. Here, the performance of Equal Gain Combiner and Optical communication receivers are compared. The drawback of this paper is that loss of the received signal will be severe if the correlation among transmitters/receivers increases. This method is analyzed only under weak turbulence conditions. The bit error rate of 10^{-7} is achieved. Moreover aperture averaging is introduced to reduce the effect of turbulence. But it is impossible to maintain large aperture by just employing more number of photo detectors. If the receiver knows only the channel State information (CSI), then bit error rate of 10^{-5} is achieved.

(Letzepis, 2008) In this paper, two types of Channel State Knowledge (CSI) is assumed. First, receiver only knows the CSI and the transmitter knows only the channel statistics. Second, CSI is known to transmitter also. Here, various types of distributions are studied. For weak turbulence conditions, lognormal distribution for strong turbulence, gamma-gamma- distribution and for moderate turbulence, lognormal rice distribution is analyzed. The gamma-gamma distribution is the product of two gamma random variables having probability density function. Though the closed loop for expressions of single input single output channel is not given in closed form expressions, the SNR exponent is proportional to the number of lasers and apertures. Hence this technical report had given the results of outage probability and power allocation for multiple input multiple output channel.

The main attraction of FSO systems is their less cost and time to setup. They also have the advantage of a free spectrum which doesn't require licensing. Although they are limited by attenuation caused by the air medium especially attenuation due to smoke and fog, they are today's hot technology. WDM FSO however seems to be the future of FSO technologies. FSO has many benefits besides its massive bandwidth. These include:

1. Operation in a completely unregulated frequency spectrum (range of THz). Because there is little or no traffic currently in this range, the Federal Communications Commission (FCC) has not required licenses above 600 GHz. This means FSO is not likely to interfere with other transmissions.

2. Cost is a major advantage. Significantly lower cost on average than the construction of a new fiber optical solution,

or leased lines. With FSO, there is also no capital overhang. It can be deployed in days to weeks versus months to years (no excavation of sidewalks, building permits).

3. Bandwidth can easily be scaled with virtually unlimited headroom (10 Mbps to 1.25 Gbps) per link.

4. An FSO network architecture need not be changed when other nodes (buildings) are added and customer capacity can be easily increased by changing the node numbers and configurations.

5. The technology is easily upgradeable, and its open interfaces support equipment from a variety of vendors, which helps carriers protect the investment in their embedded infrastructures. One would think that security is problematic with wireless, but FSO is fairly difficult to intercept. Because its beams are invisible, narrow, and very directional (aimed at a particular antenna), it is hard to find a particular traffic link in the air, let alone crack the code. In addition, links from customer to hub are typically encrypted. Like any new technology, FSO does have its potential drawbacks, which will be discussed later. In spite of these drawbacks, however, FSO is poised to become a major player in the local broadband access market, particularly among small and medium-size businesses, which typically lack fiber connections.

3. Materials and methods

The methodology used involves the studying of the basic characteristics and components of the FSO link and representing them by suitable equations and integrated systems with their respective attributes. Engineering modeling is becoming more popular due to the high cost of implementing experiments. The robustness of MATLAB aided as an effective tool of the results based on different performance measures.

2.1 Simulation model

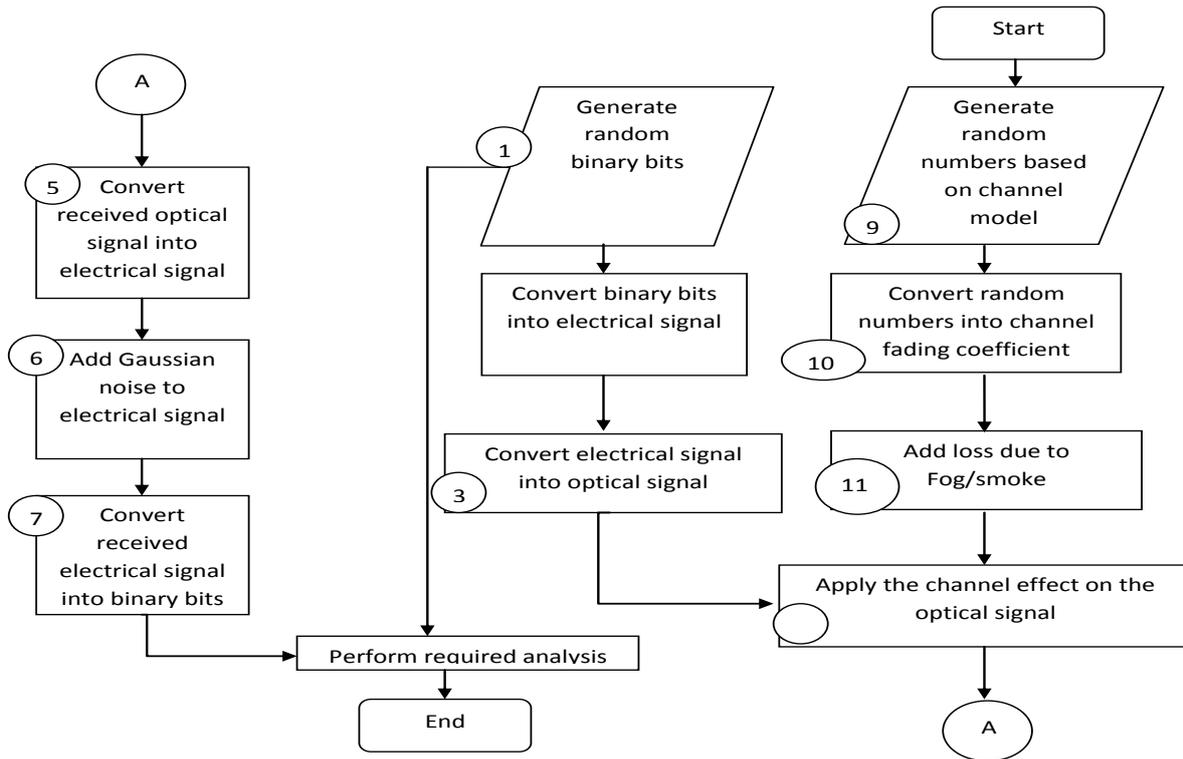


Figure 1: An Integrated Model showing setup of the FSO communication link

In order to ensure the quantity & quality of data analyzed, accuracy of model, the steps shown in figure 1 are necessary.

2.1.1 System Design

The FSO link consists of a transmitter, FSO channel, and receiver. Simulation is based on a semiconductor laser lasing at wavelength 700-2550nm. The Laser is directly modulated with OOK modulation technique. The receivers features detectors based on APD. Transmitter consists of PRBS generator and data rate of 2 Gbps, with a directly modulated LED at 780, 1550, and 2550 nm. Optical power out of transmitter is 1.3 dBm. FSO link has maximum range set at 13km with background light power of 0.01e-3. The environmental additional attenuation is specified by additional atmospheric losses with a value of 1.5 dB.

FSO transmitter consists of PRBS generator that basically produces random bit codes that is the basic input signal code required for driving the circuit which means the information to be transmitted. The signal is OOK modulated to be provided to the LED to be processed and to be converted to light signal that is being presented to the FSO link which is a wireless point to point communication in which the points have clear line of sight between them. This line of sight technology currently enables full duplex optical transmissions at gigabits per second speeds over metropolitan distances of a few city blocks to a few kilo-meters. This is more than enough to support data, voice and video traffic, in addition providing for connectivity without deploying fiber optic cable or securing spectrum licenses.

The link parameters utilized for the system are:

1. Bit rate
2. Transmitter power
3. Link distance
4. Laser wavelength
5. Laser internal modulation efficiency
6. Add Attenuation (Misc loss)
7. Background light power
8. Reference wavelength
9. Receiver aperture diameter
10. Fog/smoke visibility

2.1.2 Method

1. Generating random binary bits

The random binary bits or pseudorandom binary sequence (PRBS) represents any random input data for the FSO system. These bits are generated using a uniform random number generator engine.

MATLAB function: *randi*.

2. Bit to electrical signal conversion

The generated bits *PRBS* are resampled so that each bit is represented by *NoS* sample.

MATLAB function: *rectpulse*.

The value of *NoS* depends on the available memory and the time window over which the train is assumed stationary. For high data rates or slow trains, larger number of samples could be generated. If the train moves with the speed of v over the distance of Δl then it takes

$T_{travel} = \frac{\Delta l}{v}$ to finish the travelling.

If the baud rate is $BR = \frac{1}{T_s}$ where T_s is the symbol duration, then:

$$NOS \leq \frac{T_{travel}}{T_s} = \frac{\Delta l \times BR}{v} \quad (1)$$

3. Electrical to optical signal conversion

Knowing the average output power p_{avg} and extinction ratio e . The following equations are used to calculate the high and low powers corresponding to bits 1 and 0 when implementing OOK modulation:

$$P_1 = \frac{2P_{avg}}{1 + \frac{1}{e}} \quad (2)$$

$$P_0 = \frac{2P_{avg}}{1 + \frac{1}{e}} \quad (3)$$

$$\Delta P = P_1 - P_0 \quad (4)$$

By multiplying the generated electrical signal S_{elec} from step 2 by ΔP and adding the required optical power offset to accommodate the optical power average value, the optical signal at the transmitter side is generated

$$\Delta P \times S_{elec} + P_{avg} \quad (5)$$

4. Applying the channel effects

Once calculating the channel coefficients, the optical power generated from step 3 is multiplied by the coefficients. The outcome is the optical received power at the receiver side. Depending on the simulation purpose, the coefficient h may be applied to varying optical signal P_{sig} or average optical power P_{avg} part. If calculating BER is the target of the simulation, the received signal is $h \times \Delta p \times S_{elec}$

However, if simulating a real system is desired the received signal would be $h \times (\Delta p \times S_{elec} + P_{avg})$

5. Optical to electrical signal conversion

To convert the received optical power to electrical signal, the responsivity of the photodiode as well as the TIA gain are used.

6. Adding white Gaussian noise

If the SNR is given, by measuring the power of transmit signal in step 3, the required noise power P_n is calculated. To generate the additive noise, random numbers are generated based on random normal distribution $\mathcal{N}(0, \sqrt{P_n})$. MATLAB function: *randn*.

7. Bit extraction

A threshold level is set based on the average value of the received electrical signal. By comparing the midpoint of each received bit with the threshold, the received bit is determined to be 0 or 1. To perform adaptive thresholding, the length of averaging is changed from the whole received signal to smaller sections.

8. Analysis

To perform the analysis, original transmit bits are compared to received bits, which leads to *BER* value. MATLAB function: *biterr*.

Another parameter extracted from the received signal is the Q-factor. Having the electrical signal level for bits 0 and 1, Q- factor can be calculated as:

$$Q - factor = \frac{|V_1 - V_0|}{\sigma_0 + \sigma_1} \quad (6)$$

Where v_1 and v_0 are the mean values of received electrical signal corresponding to bits 1 and 0, respectively. While σ_0 and σ_1 are the standard deviation values of received electrical signal corresponding to bits 1 and 0, respectively.

The electrical SNR value is also calculated based on the signal power and existing noise power. The optical signal power is Δp and at the receiver it results in voltage V_{sig} defined as:

$$V_{sig} = G \times \eta \times \Delta p \quad (7)$$

Where G and η are transimpedance (TIA) gain, and responsivity, respectively. Knowing the load impedance R_{load} the electrical signal power will be:

$$P_{sig} = \frac{(G \times \eta \times \Delta p)^2}{R_{load}} \quad (8)$$

If noise equivalent power (NEP) of the receiver is given and the signal bandwidth BW is known, the detector noise power is obtained as:

$$P_{det} = NEP \sqrt{BW} \quad (9)$$

To take into account the background light and shot noise we have:

$$i_n^2 = 2 \times q \times l \times BW \quad (10)$$

Where q is the electron charge and l is the induced current due to the noise. For background noise $I_{bg} = \eta P_{bg}$, where P_{bg} is the background illumination power. In case of shot noise, if the received average optical power is p_r then $I_{sn} = \eta P_r$. Finally the noise power at the output of TIA will be:

$$P_n = \frac{2q\eta G^2 BW}{R_{load}} (P_{bg} + P_r) \quad (11)$$

Then the total noise power will be:

$$P_{noise} = NEP\sqrt{BW} + \frac{2q\eta G^2 BW}{R_{load}}(P_{bg} + P_r) \quad (12)$$

9. Generating random numbers for channel fading

Based on the fading type, different kinds of random numbers are generated. Different models are used to generate channel coefficient for each.

A. Turbulence, Log-Normal model: $X = \mathfrak{N}(\mu_{x,turb}, \sigma_{x,turb})$ (13)

$$h_t - LN = \exp(2X) \quad (14)$$

MATLAB function: *randn*

B. Turbulence, Gamma-Gamma model: $X = \Gamma(\alpha, 1)$ (15)

$$Y = \Gamma(\beta, 1)$$

$$h_{t-GG} = \frac{1}{\alpha\beta} XY$$

MATLAB function: *gamma*

10. Fog/Smoke loss

Based on the visibility *Vis* and by using Kim model, *q* parameter is defined:

$$q = \begin{cases} 1.6, & \text{Vis} > 50 \\ 1.3, & 6 < \text{Vis} < 50 \\ 1.6 \times \text{Vis} + 0.34, & 1 < \text{Vis} < 6 \\ \text{Vis} - 0.5, & 0.5 < \text{Vis} < 0.1 \\ 0, & \text{Vis} < 0.1 \end{cases} \quad (16)$$

Having the laser wavelength λ (*nm*), the parameter β_λ in *1/km* is defined as:

$$\beta_\lambda = -\frac{\ln 0.02}{vis} \left(\frac{\lambda}{550}\right)^{-q} \quad (17)$$

Using Beer's lambert law, the fog/smoke loss will be:

$$h_{FS} = \exp(-\beta_\lambda L) \quad (18)$$

Where *L* is the link distance in *km*.

4. Results

Performance of the modeled optical communication link is gauged on the basis of Receiver aperture diameter, smoke/fog visibility and link length. The output has been obtained on the sample basis that illustrates that higher the attenuation, worse is the performance. The results have been obtained in order to ensure the optimal functioning of the system over entire wavelength range.

Table 1: Loss over the 8km Gaussian propagation model for 2550e9 wavelength value

System Parameter	Value
Data rate	2e9
Transmitter power	1.3
Link length	8 km
Modulation efficiency	0.5
Added attenuation	1.5dB
Background light power	$0.01e-3$
Reference wavelength	550e9
Receiver aperture diameter	0.5
Fog/smoke visibility	2.25
Contrast threshold	2%
Laser wavelength	2550e-9
Loss	3.551dB

Table 2: Loss over the 8km Gaussian propagation model for 1550e9 wavelength value

System Parameter	Value
Data rate	2e9
Transmitter power	1.3
Link length	8 km
Modulation efficiency	0.5
Added attenuation	1.5dB
Background light power	$0.01e-3$
Reference wavelength	550e9
Receiver aperture diameter	0.5
Fog/smoke visibility	2.25

Contrast threshold	2%
Laser wavelength	1550e-9
Loss	8.908dB

Table 3: Loss over the 8km Gaussian propagation model for 780e9 wavelength value

System Parameter	Value
Data rate	2e9
Transmitter power	1.3
Link length	8 km
Modulation efficiency	0.5
Added attenuation	1.5dB
Background light power	0.01e-3
Reference wavelength	550e9
Receiver aperture diameter	0.5
Fog/smoke visibility	2.25
Contrast threshold	2%
Laser wavelength	780e-9
Loss	31.679dB

Table 4: Loss over the 10.5 km Gaussian propagation model for 2550e9 wavelength value

System Parameter	Value
Data rate	2e9
Transmitter power	1.3
Link length	10.5km
Modulation efficiency	0.5
Added attenuation	1.5dB
Background light power	0.01e-3
Reference wavelength	550e9
Receiver aperture diameter	0.5
Fog/smoke visibility	2.25
Contrast threshold	2%

Laser wavelength	2550e-9
Loss	4.660dB

Table 5: Loss over the 10.5 km Gaussian propagation model for 1550e9 wavelength value

System Parameter	Value
Data rate	2e9
Transmitter power	1.3
Link length	10.5km
Modulation efficiency	0.5
Added attenuation	1.5dB
Background light power	<i>0.01e-3</i>
Reference wavelength	550e9
Receiver aperture diameter	0.5
Fog/smoke visibility	2.25
Contrast threshold	2%
Laser wavelength	1550e-9
Loss	11.692dB

Table 6: Loss over the 10.5 km Gaussian propagation model for 780e9 wavelength value

System Parameter	Value
Data rate	2e9
Transmitter power	1.3
Link length	10.5km
Modulation efficiency	0.5
Added attenuation	1.5dB
Background light power	<i>0.01e-3</i>
Reference wavelength	550e9
Receiver aperture diameter	0.5
Fog/smoke visibility	2.25

Contrast threshold	2%
Laser wavelength	780e-9
Loss	41.578dB

Table 7: Loss over the 13 km Gaussian propagation model for 2550e9 wavelength value

System Parameter	Value
Data rate	2e9
Transmitter power	1.3
Link length	13km
Modulation efficiency	0.5
Added attenuation	1.5dB
Background light power	0.01e-3
Reference wavelength	550e9
Receiver aperture diameter	0.5
Fog/smoke visibility	2.25
Contrast threshold	2%
Laser wavelength	2550e-9
Loss	5.7dB

5. Discussion

Table 1 show that the quality of the system is good with additional attenuation of about 1.5 dB. That means the system can respond well and can handle the additional attenuation of this much value without degrading its quality with constant threshold set at 2%. But after this value, the quality of the system begins to degrade.

From Table 1-7 it can be seen that additional attenuation should be less than 1.5 dB to satisfy the optimization requirements. Total FSO channel loss is a sum of geometrical and additional attenuations. Hence, the link can tolerate up to 1.5dB losses in order to achieve optimum performance.

The performance evaluation of the OOK modulation format has been analyzed in terms of bit error rate (BER), and eye diagrams against additional attenuation. The Optimization parameters that are taken into consideration in this case are Distance (distance) and Additional Attenuation.

Simulation results show that quality of the system responds almost perfectly well up to the distance of 800 meters. But it reduces after that i.e. the quality of the system gradually degrades at 850meters of distance. So the distance of 800 meters is an optimized distance and the system can work well up to this distance with even a large amount of additional attenuation. Since this study is focused on longer distances, the value isn't considered as an optimized value.

At a distance of 8km, the total losses (dB) ranges between 3.55 and 4.78 while keeping the additional attenuation to be 1.5dB and the beam divergence to be 2.5×10^{-3} and at the same values of the distance, attenuation and beam divergence, the BER value ranges from 10^{-12} to 10^{-23} which is acceptable. With an additional attenuation of -3.01dB, the quality of the system still remains good and the system responds well under these conditions.

6. Conclusion

In this study, the system parameters for FOS optimization were discussed and implemented. By using the differential OOK modulation method, the FSO system was protected against the background illumination and attenuation due to smoke/fog. It was also seen that receiver aperture has an impact on the performance of the FSO link under the moderate to strong turbulence regime. Under fog conditions the FSO link was dynamically adjusted to suit the atmospheric conditions and provide link loss margins. Both the link availability and the average data rate were assessed using the recorded channel condition. Link assessment were performed to investigate the effect of FSO data rate on the link availability. Another assessment where the distance was varied showed that as expected the longer link distances led to less availability and lower hybrid data rates. Finally, the maximum data rate and a guaranteed availability for a given distance was obtained.

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