Study of BER performances of various atmospheric channel models for free space optical communication

Dhaval Gami
Electronics and Comm. Dept.
Nirma University
gamidhaval2009@gmail.com

Dhaval Gujarati
Electronics and Comm. Dept.
Nirma University
dhavalgujarati31@gmail.com

Prof. Dhaval Shah
Electronics and Comm. Dept.
Nirma University
dhaval.shah@nirmauni.ac.in

***Abstract*—In this paper, various atmospheric channel models like lognormal, gamma-gamma, K,I-K are discussed. These channel models are used to describe atmospheric channel condition in mathematical form. BER performances of every channel model are shown according to turbulence scenario based on BER equations available. Advantages and limitations of each model is also described.**

Keywords-lognormal,gamma-gamma,k,i-k,scintillation index,turbulence

INTRODUCTION

Recently, the use of free space optics is growing rapidly compared to other transmission media like fiber, co-axial cable etc. Free-Space Optics (FSO) is a line-of-sight technology that uses lasers to provide optical bandwidth connections. Currently, FSO is capable of up to 2.5 Gbps of data [1], voice and video communications through the air, allowing optical connectivity without requiring fiber-optic cable or securing spectrum licenses. FSO requires light, which can be focused by using either light emitting diodes (LEDs) or lasers (light amplification by stimulated emission of radiation). The use of lasers is a simple concept similar to optical transmissions using fiber-optic cables; the only difference is the medium. Light travels through air faster than it does through glass, so it is fair to classify FSO as optical communications at the speed of light.

FSO technology is relatively simple. It's based on connectivity between FSO units, each consisting of an optical transceiver with a laser transmitter and a receiver to provide full duplex (bi-directional) capability. Each FSO unit uses a high-power optical source (i.e. laser), plus a lens that transmits light through the atmosphere to another lens receiving the information. The receiving lens connects to a high-sensitivity receiver via optical fiber. FSO technology does not require spectrum licensing. FSO is easily upgradeable, and its open interfaces support equipment from a variety of vendors, which helps service providers protect their investment in embedded telecommunications infrastructures [2].

FEATURES OF FSO

Working principle

Free Space Optics (FSO) transmits invisible, eye-safe light beams from one "telescope" to another using low power infrared laser in the teraHertz spectrum. The beams of light in FSO systems are transmitted by laser light focused on highly sensitive photon detector receivers. These receivers are telescopic lenses able to collect the photon stream and transmit digital data containing a mix of Internet messages, video images, radio signals or computer files .Commercially available systems offer capacities in the range of 100 Mbps to 2.5 Gbps[2], and demonstration systems report data rates as high as 160 Gbps[1]. FSO systems can function over distances of several kilometers. As long as there is a clear line of sight between the source and the destination, and enough transmitter power, FSO communication is possible.

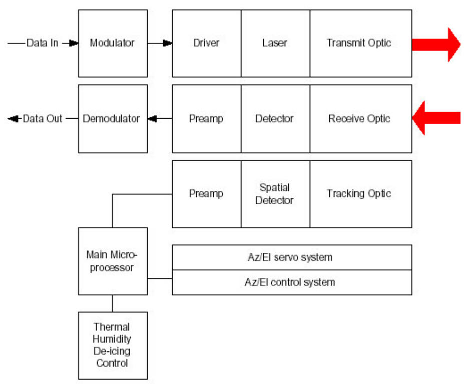

Fig.1.general block diagram of FSO major subsystem

Advantages

FSO systems offer a flexible networking solution that delivers on the promise of broadband. Only FSO provides the essential combination of qualities required to bring the traffic to the optical fiber backbone virtually unlimited bandwidth, low cost, ease and speed of deployment.

- High bit rate (10 Mbps to 2.5 Gbps)
- No licensing required
- Installation cost is very low as compared to laying Fiber
- Easy to install
- Narrow light beam
- Highly secure transmission possible
- The lasers used are eye safe, so even a butterfly can fly unscathed through a beam

Security is an important element of data transmission, irrespective of the network topology. It is especially important for military and corporate applications. Building a network on the SONAbeam platform is one of the best ways to ensure that data transmission between any two points is completely secure. Its focused transmission beam foils jammers and eavesdroppers and enhances security. Moreover, SONA systems can use any signal-scrambling technology that optical fiber can use. The common perception of wireless is that it offers less security than wireline connections. In fact, FSO is far more secure than RF or other wireless-based transmission technologies for several reasons: FSO laser beams cannot be detected with spectrum analyzers or RF meters. The laser beams generated by FSO systems are narrow and invisible, making them harder to find and even harder to intercept and crack Data can be transmitted over an encrypted connection adding to the degree of security available in FSO network transmissions

Safety risks

As with any laser, eye safety is a concern. There are two wavelengths of light, 800nm and 1550nm. The 1550nm units are, generally, safe due to the fact that the human eye (aqueous lens) absorbs the light energy and no damage will be sustained to the retina.

The 800nm wavelength can cause damage to the retina. The person will not be aware of the damage since the retina has no pain receptors and invisible light does not cause a blink reflex. Therefore 800nm lasers need to be installed carefully and ensure that human eyes will receive the signal. This is easily done by mounting the lasers on a wall.

TERRESTRIAL FSO COMMUNICATIONS CHALLENGES

Fog

Fog substantially attenuates visible radiation, and it has a similar affect on the near-infrared wavelengths that are employed in laser communications. Similar to the case of rain attenuation with RF wireless, fog attenuation is not a show-stopper for optical wireless, because the optical link can be engineered such that, for a large fraction of the time, an acceptable power will be received even in the presence of heavy fog.

Laser communication systems can be enhanced to yield even greater availabilities by combining them with RF systems.

Physical Obstructions

Laser communications systems that employ multiple, spatially diverse transmitters and large receive optics will eliminate interference concerns from objects such as birds.

Pointing Stability

Pointing stability in commercial laser communications systems is achieved by one of two methods. The simpler, less costly method is to widen the beam divergence so that if either end of the link moves the receiver will still be within the beam. The second method is to employ a beam tracking system. While more costly, such systems allow for a tighter beam to be transmitted allowing for higher security and longer distance transmissions.

Scintillation

Performance of many laser communications systems is adversely affected by scintillation on bright sunny days. Through a large aperture receiver, widely spaced transmitters, finely tuned receive filtering, and automatic gain control, downtime due to scintillation can be avoided[3].

Sunlight on Receiver

Direct sunlight on the receiver face may swamp in the input. Units should not get direct sunlight on the receiver. This is why all the units have a little "roof" that shade them. Water or rain on the lens is not a issue but the roof helps too.

Building movement

One concern with mounting lasers on the top of very tall buildings is that they move quite a bit. A twenty storey building will typically move 30 centimetres in either direction in windy conditions and more for taller buildings.

Surprisingly, this doesn't seem to be a problem. The Laser signal does have some dispersal and can "fan out" so that the receiver can get enough signal to function.

Some of the newer devices are able to autonomously recalibrate themselves up to 3.4 degrees, which means even if the building or the mountings move a bit, the system keeps working.

Thermal expansion

A common concern is that the thermal expansion of buildings or mounts will cause problems.The laser fan out seems to be sufficient.

CHANNEL MODELS

We studied an FSO communication system using intensity modulation/direct detection (IM/DD). The laser beams propagate along a horizontal path through a turbulence channel with AWGN. The channel is assumed to be memory less, stationary, with independent, identically distributed (i.i.d.) intensity slow fading statistics. The statistical channel model is :

$$y = sx + n = \eta Ix + n \quad (1)$$

where y is the signal at the receiver, $s = \eta I$ is the instantaneous intensity gain, η is the effective photo-current conversion ratio of the receiver, I is the normalized irradiance,x is the modulated signal (and takes values "0" or "1"), and n is the AWGN with zero mean and variance N0/2[4].

Lognormal channel model

Lognormal channel model is widely used for weak turbulence scenario due to its simple mathematical expression for BER performance [5].

Here, perfect channel state information is assumed during the derivation of mathematical equations. It means that the receiver has the information about the instantaneous value of fading coefficient for each symbol. Thus ,the receiver does not require the estimation of the channel to mitigate the effect of fading on signal. Here, an on-off keying modulation format at the transmitter and direct detection at the receiver side.

Two approaches can be applied to derive closed-form expression for BER in this model[6]. One is the power series approach which provides an exact expression while the second is based on the help of Gauss–Hermite quadrature which provides approximate error. According to power series approach , BER can be calculated by

$P_{e,L}(\Upsilon_g,\sigma_x)=$ (2)

Where Pe,L is bit error rate probability which is a function of ϒg (signal to noise ration) and σx (fading intensity).SNR can be calculated by .Where, R is responsivity of receiver, P is transmitted power and σ1 and σ0 are standard deviation of noise currents for symbols ‘1’ and ‘0’.

Assuming that the channel coefficients h at different times are independent, than according to moment-generating function (MFG) the variance of h can be calculated as

$\sigma_I^2=$

$=M_x(4)-(M_x(2))^2$ (3)

Where, μ and σ are mean and standard deviation of random variable x at transmitter. In scintillation fading with scintillation index S.I., we cangenerate average power loss due to atmospheric fading unity, such that the fading does not, on average, attenuate or amplify the optical power. We have choosen

$\mu_I=1$ (4)

So, $\mu=-\sigma^2$.The varience will be equal to

$\sigma_I^2=$ (5)

This parameter is called scintillation index, S.I. [6,9-11]. For weak turbulence, SI falls in the range of [0, 0.75][3].

By mathematical simulation of equation (2), fig(1) shows the graph of the bit error rate probability Pe,L , versus the signal to noise ratio ϒg for the different values of fading intensity, σx. For weak turbulence, the simulation results can easily be related to the experimental results.

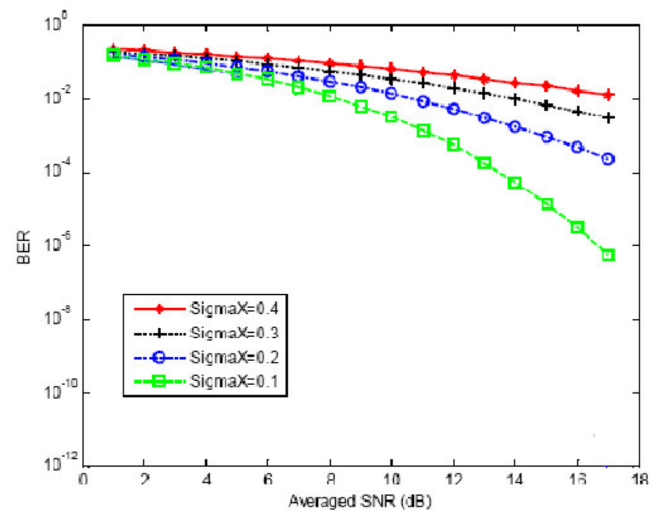

Fig .2. BER $P_{e,L}$, versus SNR Υ_g for the different values of fading intensity, σ_x

Gamma-gamma channel model

Gamma-gamma channel model is used for weak to strong turbulence. Andrew et.al[7] introduced the modified Rytov theory and proposed gamma-gamma pdf as a tractable mathematical model for atmospheric turbulence.It is a two-parameter distribution which is based on a doubly stochastic theory of scintillation and assumes that small-scale irradiance fluctuations are modulated by large-scale irradiance fluctuations of the propagating wave. Both fluctuations are governed by independent gamma distributions. The gamma-gamma pdf can be directly related to atmospheric conditions and provides a good fit to experimental results.

Lognormal channel model is only applicable to weak turbulence conditions. As the strength of turbulence increases, multiple scattering effects must be taken into account, lognormal statistics exhibit large deviations compared to experimental data. Furthermore, it has been observed that lognormal pdf underestimates the behavior in the tails as compared with measurement results. Since detection and fade probabilities are primarily based on the tails of the pdf, underestimating this region significantly affects the accuracy of performance analysis.

For an FSO communication system operating at λ = 1550nm and Cn2 = 1.7×10−4 , a typical value of refraction index for FSO links near the ground during daytime. Here also perfect CSI is assumed at the receiver. Uysal et.al[8] investigated that BER can be calculated by,

Pb= (6)

Where D(θ) is given by

$D(\theta)=K_{\alpha-\beta}$ (7)

Where c1= (8)

c2= (9)

and $K_{\alpha-\beta}$ is Bessel function of second kind having order α-β ,τ is signal to noise ratio , α and β are the effective number of small scale and large scale eddies of the scattering environment and can be calculated by according to [3],

(10)

(11)

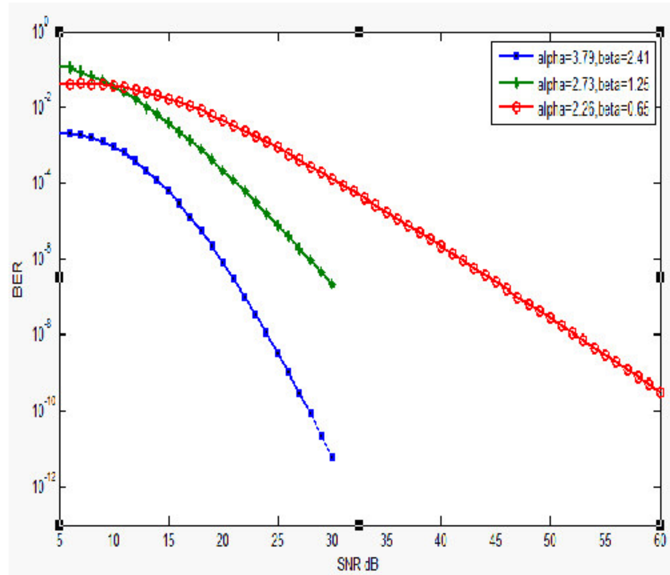

Fig .3, BER performance of gamma-gamma channel for different values of α and β

Here, BER is calculated for three different distances L=2600m, L=3000m, L=3400m, and channel parameters results into (α ,β)=(3.79,2.42) , (α ,β)=(2.73,1.25), (α ,β)=(2.26,0.65) respectively. The BER performance is calculated based on equation (6) and it provides very good approximation due to use of constants c1 and c2, which are used in the derived pairwise error probability. The simulation results match with experimental results for weak to strong turbulence scenario[8]. The computation complexity is higher during the simulation of the equation.

K channel model

This cannel model is used in strong turbulence condition. Here ,SI is nearly 1 and the value of log intensity variance is between 3 and 4 .

This channel model can be considered as a product of two independent models-Exponential and Gamma[12]. This model provides Excellent agreement between theoretical and experimental values[12] .

Pdf for the instantaneous electrical SNR, γ, at the receiver can be given by[14],

$P_\gamma(\gamma)$ = (12)

Where β is related to the effective number of discrete scatterers., while Γ(.) is the Gamma function. Kν(.) is the modified Bessel function of the second kind of order ν. ξ is average electrical SNR at the receiver. Which is given by ξ= .

Here one Bessel function is used which is denoted by K. Therefore this channel model is known as K channel model.

Based on (12), following result can be obtained in form of BER vs. SNR for different values of β.

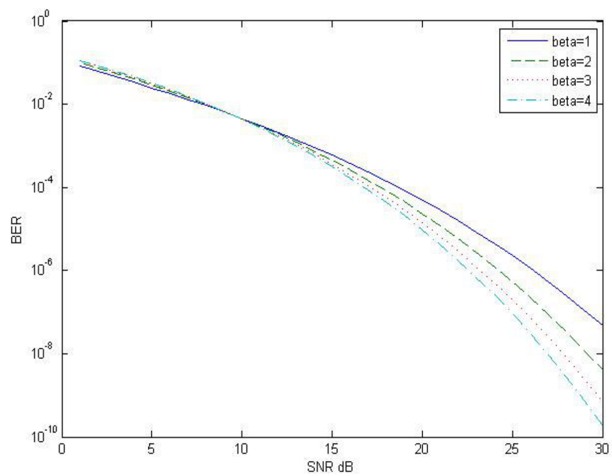

Fig .4, BER performance of K channel for different values of β

K distribution lacked the numerical computation in closed form. Also, it could not easily relate the mathematical parameters with atmospheric turbulence and therefore it had limited application and utilization.

I-K channel model

This channel model can be used in both scenarios , weak turbulence and strong turbulence. Moreover it has less complexity than gamma-gamma channel model. So ,this channel model is generally used.

Pdf for the instantaneous electrical SNR, γ, at the receiver can be given by[15],[16],

$$P_\gamma(\gamma) = \quad (13)$$

Where Iν (.) is the modified Bessel function of the first kind of order ν, while α and ρ are the distribution's parameters and represent the effective number of scatters and a coherence parameter, respectively [17-19].

Here, it has been assumed that our channel is fast fading[20-22]. When the fluctuations of the signal intensity are supposed to be very rapid, and thus there is a difference from one symbol to another, the channel can be characterized as fast fading, while these fluctuations are very slow compared to the bit rate of the link, as slow. For the cases of high bit rate transmission, the channel can be characterized as slow fading. Therefore channel can be considered as quasi-static[20].

Here, it has also been assumed that, the field of the optical wave is modeled as the sum of a coherent (deterministic) component and a random component.

Here, the important parameter is ρ. The parameter ρ is a measure of the power ratio of mean intensities of the coherent and random components of the field. For extremely weak scattering, ρ is relatively large since the field is dominated by the coherent component. The power ratio decreases as the strength of turbulence increases. By properly selecting values of α and ρ, both the weak-scattering regime and the strong-scattering regime can be obtained.

Two kinds of Bessel functions are used symmetrically here, which are indicated by I and K. There this channel model is referred to as I-K.

By using (13), following numerical results can be obtained. The result can be obtained for different values of α and ρ.

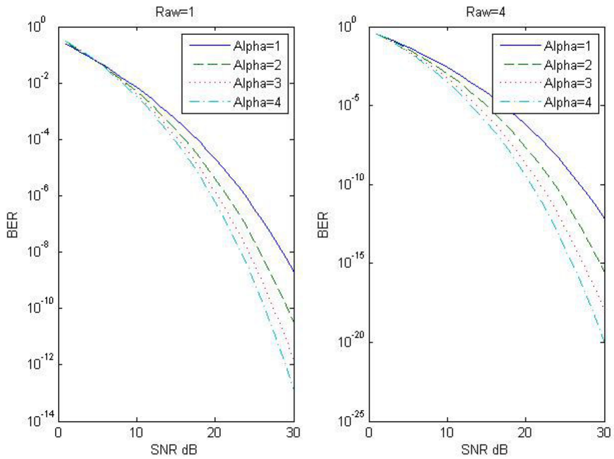

Fig .5, BER performance of I-K channel model for different values of α and ρ

TABLE I
COMPARISON OF DIFFERENT MODELS

Model	**Turbulence scenario**	**Key factors**	**Limitation**
Lognormal	Weak	Sigmax	Strong turbulence
Gamma-gamma	Weak to strong	Alpha, Beta	Computation complexity
K	Strong	Beta	Weak turbulence
I-K	Weak to strong	Raw	-

Conclusion

In nearby future, FSO will become important medium of information exchange due to its advantages. In this type of communication environment condition plays an important role in transmission setup. Proper distribution model must be used while designing the channel model. For weak turbulence scenario lognormal distribution is used, for strong turbulence scenario K distribution must be used while I-K distribution model is used for weak to strong turbulence scenario and it has less complexity than gamma-gamma channel model. Above all models are discussed based on assumption of perfect CSI at receiver. These models can also be expanded for imperfect CSI at receiver side.

References

J. Li and M. Uysal, "*Optical wireless communications: system model, capacity and coding*", IEEE 58th Vehicular Technology Conference (VTC) 2003-Fall, vol. 1, pp. 168-172, 2003.

H. Henninger and O. Wilfert, "*An introduction to free-space optical communication*", Radio Engineering, Vol. 19, No. 2, June 2010..

L. C. Andrews, R. L. Phillips, and C. Y. Hopen, "*Laser beam scintillation with applications*", SPIE Press, 2001.

Gagliardi, R. M., and Karp, S., *Optical Communications*, 2nd edition, John Wiley & Sons, Inc., 1995..

Kamran Kiasaleh, "*Performance of APD-Based, PPM free-space optical communication systems in atmospheric turbulence*". IEEE Transactions on Communications, vol. 53, pp.1455-1461, 2005.

H. Moradi, M. Flahpour, H. H. Refai, P.G. LoPresti, M. Atiquzzaman, "*BER Analysis of Optical Wireless Signals through Lognormal Fading Channels with Perfect CSI*".IEEE Transection on Communication,2009.

L.C.Andrews, R.L. Philips, C.Y. Hopen, "*Aperture averaging of optical scintillations: power fluctuations and the temporal spectrum*", Waves Random Media, Vol.10, pp. 53-70, 2000.

M. Uysal and J. Li, "*Error rate performance analysis of coded free-space optical links over gamma-gamma atmospheric turbulence channels*", IEEE Transactions on Wireless Communication, Vol. 5, No. 6, June 2006.

L. C. Andrews, R. L. Phillips, C. Y. Hopen and M. A. Al-Habash, "Theory of optical scintillation", *Journal of Optical Society America A*,vol. 16, no.6, p. 1417-1429, June 1999.

L. C. Andrews, R. L. Phillips and C. Y. Hopen, "Aperture averaging of optical scintillations: Power fluctuations and the temporal spectrum", *Waves Random Media*, vol. 10, p. 53-70, 2000.

M. A. Al-Habash, L. C. Andrews and R. L. Phillips, "Mathematical model for the irradiance probability density function of a laser beam propagating through turbulent media", *Optical Engineering*, vol. 40, no. 8, p. 1554-1562, August 2001

O. Bouchet et.al, "Free Space Optics: Propagation and Communication", Wiley, 2006.

E. Jakeman and P.N.Pusey, "*A model for non-Rayleigh sea echo*", IEEE Trans. Antennas Propagation., Vol.24, pp. 806-814, Nov. 1976.

SANDALIDIS, H. G., TSIFTSIS, T. A. Outage probability and ergodic capacity of free-space optical links over strong turbulence.*Electronics Lett*ers, 2008, vol. 44, no. 1, p. 46 - 47.

ANDREWS, L. C., PHILIPS, R. L. I-K distribution as a universal propagation model of laser beams in atmospheric turbulence. *Journal of the Optical Society of America A*, 1985, vol. 2, no. 2, p. 160 – 163.

ANDREWS, L. C., PHILIPS, R. L. Mathematical genesis of the IK distribution for random optical fields. *Journal of the Optical Society of America A*, 1986, vol. 3, no. 11, p. 1912 - 1919.

ANDREWS, L. C., PHILIPS, R. L. I-K distribution as a universal propagation model of laser beams in atmospheric turbulence. *Journal of the Optical Society of America A*, 1985, vol. 2, no. 2, p. 160 - 163.

ANDREWS, L. C., PHILIPS, R. L. Mathematical genesis of the IK distribution for random optical fields. *Journal of the Optical Society of America A*, 1986, vol. 3, no. 11, p. 1912 - 1919.

LETZEPIS, N., FABREGAS, A. G. Outage probability of the freespace optical channel with doubly stochastic scintillation. *IEEE Transactions on Communications*, 2009, vol. 57, no. 10.

SIMON, M. K., ALOUINI, M. S. *Digital Communications over Fading Channels*. Wiley Interscience, 2000.

NISTAZAKIS, H. E., TOMBRAS, G. S., TSIGOPOULOS, A. D., KARAGIANNI, E. A., FAFALIOS, M. E. Capacity estimation of optical wireless communication systems over moderate to strong turbulence channels. *Journal of Communications and Networks*, 2009, vol. 11, no. 4, p. 387 - 392.

BELMONTE, A., KAHN, J. M. Capacity of coherent free space optical links using atmospheric compensation techniques. *Optics Express*, 2009, vol. 17, no. 4, p. 2763 - 2773.