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A Literature Survey on Performance of Free Space Optical Communication Links under Strong Turbulence

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Abstract: *Free space optical communication is widely used for long range of distance operating under weak to strong turbulence conditions. In the existing method, many ideas have been proposed to analyze the performance of FSO links. To mitigate the effect of turbulence, error control codes and spatial diversity are used. This literature survey deals with the BER performance and turbulence effects on FSO links in the existing method.*
Keywords: *Atmospheric turbulence, bit error rate, coherent detection, free space optical communication, spatial diversity*

I. Introduction

Free space optical communication has widespread use because of its advantages such as high modulation bandwidth, enhanced security and low power. In free space optical communication, laser beam signals are transmitted through air[1]. Due to atmospheric turbulence, signals are affected. This atmospheric turbulence leads to fading of the channel. The variations in the temperature and pressure of the atmosphere cause variations in the refractive index. The beam distortions have been analyzed using various models. Particularly K-distributed models have been widely used for km-scale FSO links[2]. In order to mitigate the effect of turbulence, error control codes and spatial diversity schemes are used. Atmospheric turbulence causes fluctuations in the intensity (scintillation) and phase of the received laser beam signal. If the propagation distance is small, then the number of scatterers will be finite and random in nature. Due to this unpredictable temperature and wind velocity, there will be fluctuations in the intensity of the signal which occurs in random. The optical signals are subjected to different turbulence conditions. With IM/DD, phase information of the signal is not considered. Intensity modulation with direct detection is analyzed only for weak turbulence conditions. Since phase is an important character to be considered, coherent homodyne/heterodyne detection is used [3]. Coherent detection is implemented using the heterodyne or homodyne down conversion by a LO laser and balanced optical receivers. Heterodyne detection is easily implemented since it requires a balanced optical receivers to have the bandwidth of the order of the symbol rate R. These coherent detection provides good background noise rejection, high sensitivity and improved spectral efficiency [4]. In [5] Kiasaleh introduced an exact BER of uncoded DPSK with coherent detection. Here, optical beam is subjected to K-distributed turbulence. In [7] Zhu and Kahn introduced two approaches to mitigate the effect of turbulence. In these approaches Ml symbol by symbol detection and ML sequence detection are used. Here, On-Off keying using intensity modulation with direct detection is performed. In [8] error control codes are used to mitigate the effect of turbulence. An upper bound for probability of error for various coding schemes such as block codes, turbo codes and convolutional codes. In free space optical communication, phase noise is an important attribute to be considered. In coherent FSO, phase of the signal should be recovered at the receiver. In [11] Belmonte derived an exact bit error rate of MPSK with lognormal turbulence. For phase noise, active modal compensation technique is utilized. In [16] Letzepis investigated the mitigation of scintillation for multiple input multiple output channels. Outage probability for MIMO channels is studied using PPM and EGC at the receiver. A unified approach is introduced to calculate SER of linearly modulated signals over fading channels [17]. In [20] Mingbo Niu analyzed the exact bit error rate of M-ary PSK and M-ary QAM using moment generating function of intensity.

II. Literature Review

2.1.*Uncoded DPSK system*

In [3] K.Kiasaleh introduced an exact bit error rate of uncoded differentially phase shift keying with coherent detection. Here, optical beam is subjected to K-distributed turbulence. Since the propagation distance is long, the random fluctuations of the intensity are characterized by K-distributed turbulence. The drawback of this paper is that the impact of phase noise is not considered though coherent detection is used. Moreover, the conditions stated here are not suitable for differentially encoded PSK. For DEPSK, the channel should be constant atleast for two consecutive bit intervals. The condition of the atmosphere may be considered as frozen.

But coded DPSK cannot achieve an error rate of 10^{-9} in frozen atmospheric condition also. This uncoded DPSK only achieves an bit error rate of 10^{-3}.

Table I

Average SNR VS BER with channel parameter α=1.2, α=1.4, α=1.6, α=1.8

Parameter (α)	Average SNR (γ)dB	Bit Error rate P_b
1.2	27	$2.3x10^{-3}$
1.4	27	$1.8x10^{-3}$
1.6	27	$1.4x10^{-3}$
1.8	27	$1.1x10^{-3}$

From table1 it is shown that the bit error rate reduces when the channel parameter α increases. Here, channel parameter varies from 1.2 to 1.8.The average SNR is given in the range of 20dB to 27dB. Also the average received power is given in the range of -47.9dBm to -40.9dBm. At average SNR 27dB, the bit error rate of uncoded DPSK is given in the table. Hnece in this paper error floor is formed at $P_e = 10^{-3}$.

2. 2 *Temporal and Spatial domain approach*.

In [7] Zhu and Kahn introduced temporal and spatial domain approaches to mitigate effect of turbulence. In temporal method, single receiver that knows the distribution of fading is used. ML symbol by symbol detection is used. If the receiver also knows the joint temporal fading distribution, Maximum Likelihood Sequence detection is used. In spatial domain method, two receivers are used which are placed separately at a particular distance..

Only then the fading will be uncorrelated. But this is not possible for practical applications. Hence, spatial correlation between the receivers is considered and optimal ML detection scheme is derived for correlated spatial diversity reception. ML detection scheme is used to reduce the correlation among multiple receivers. Here, On-Off keying with Intensity modulation/Direct detection is used. This paper concludes that Maximum Likelihood detection has better performance than conventional EGC method. The bit error probability of OOK can be calculated as

$$P_b = P(off).P(bit\ error \mid off) + P(on).\ P(bit\ error \mid on) \qquad (1)$$

The drawback of this paper is that the intensity modulation with direct detection is analyzed only under weak turbulence conditions. If the correlation among receivers is increased, then this will degrade the performance of the system. Moreover, the space between two receivers must be greater than the fading correlation length which is difficult to achieve.

2.3.*Error Control Codes*

In [8] Zhu and Kahn introduced an error control codes for the mitigation of turbulence and to improve the performance of the system. Here, an approximation upper bound for pairwise error probability is found. Then this approximation upper bound is applied to find the upper bound for many codings schemes such as block codes, turbo codes and convolutional codes. An expression of upper bound for codeword error probability P_{block} is given by,

$$P_{block} \leq \sum_{j,Cj \in sc} P(C_j) \left[\sum_{k,Ck \in Sc} P(C_j,C_k) \right] \qquad (2)$$

Here also, OOK is analyzed in the system. An error bound is derived for coded OOK system. The random fluctuations in the intensity is characterized by lognormal distribution under weak turbulence. The pairwise error probability (PEP) is unvalid under strong turbulence conditions since OOK with intensity modulation/direct detection is used. IM/DD is analyzed only for short range of distance 1km or longer. This is the drawback of this paper.

2.4. *Spatial diversity*

In [9] Navidpour used spatial diversity scheme to mitigate the effect of turbulence. 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 is 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 photodetectors. If the receiver knows only the channel State information (CSI), then bit error rate of 10^{-5} is achieved.

2.5. *Modal Compensation Technique*

In [11] Belmonte derived an exact bit error rate of M-ary Phase Shift Keying. Phase of the signal should be recovered at the receiver. Phase noise is the fluctuations in the phase of the waveform. For phase noise, active modal compensation technique is utilized. Phase wavefront distortion has great impact on system performance. Two different regimes of turbulence depends on the receiver aperture diameter is considered. The amplitude fluctuations is characterized by lognormal distribution and phase fluctuations is characterized by Gaussian distribution. This paper particularly deals with QPSK using synchronous homodyne/heterodyne detection. This paper describes the number of modes needed for compensation at the receiver. The drawback is, that the impact of phase noise will be small if the normalized aperture diameter is small. In this case, fluctuations in the intensity dominates and greatly affect system performance. If the normalized receiver aperture diameter is large, then the phase noise will be dominated. Hence, higher order modes for compensation is needed.

2.6. *Pairwise Error Probability*

In [10] Uysal and Navidpour used error control coding schemes to mitigate turbulence induced fading. Here an upper bound on the Pairwise Error Probability(PEP) is derived. Then this PEP is used in conjuction with union-bound technique to obtain BER. K-distributed model is used under strong turbulence regime. In K-channel model, intensity of the beam is the product of two independent random variables I=yz where,

$$f(y) = \exp(-y), \quad y > 0 \qquad (3)$$

$$f(z) = \frac{\alpha^{\alpha} z^{\alpha-1} \exp(-\alpha z)}{\Gamma(\alpha)}, \quad z > 0 \qquad (4)$$

FSO systems with IM/DD using OOK is considered. To derive an upper bound on the PEP, convolutional code which has code rate of 1/3 and minimum hamming distance of 6 is used. The drawback of the paper is that simulation results are shown upto 10^{-7} which is not the target BER.

2.7. *General Parameterization Quantifying Performance*

In [18] Zhengdao Wang analyzed the performance of wireless communication systems over random Nagakami fading channel. Here average error probability and outage probability are calculated using the probability density function of SNR. With this PDF of SNR, moment generating function is calculated. The two parameters such as average BER and outage probability are characterized by diversity gain and coding gain. These gains are based on PDF of SNR's. For diversity combining, Maximal ratio combiner is used. The exact outage probability is found using

$$P_{out} = P(\gamma \le \gamma_{th}) \qquad (5)$$

The drawback is that these two parameters using instantaneous SNR's PDF are found only at high SNR values not for low SNR values.

2.8. *Outage probability*

In [16] Letzepis found an outage probability for MIMO Gaussian channel. Here Pulse Position Modulation scheme is used. Equal gain combiner is employed for spatial diversity. The effect of scintillation is mitigated through the use of multiple lasers and multiple apertures. The scintillation index is given by

$$\sigma_I^2 \triangleq \frac{Var\,(H)}{(E[H])^2} \qquad (6)$$

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 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.

2.9. *Optical communication systems with diversity reception*:

In [20] Mingbo Niu, Julian Cheng and Jonathan studied the exact error rate of coherent free space optical communication under weak turbulence conditions. Equal gain combiner is employed in the optical communication systems. An exact error rate of BPSK is found. An outage probability for the system is also found. Here, both EGC and selection diversity are analyzed for long range of optical communication. The received optical signal is characterized by K- distributions. But for selection diversity scheme, asynchronous Differential Phase Shift Keying(DPSK) and Frequency Shift Keying(FSK) modulations schemes are used. For selection diversity there is no need for co-phasing of the received optical signal. Hence it reduces the receiver complexity. The performance of EGC is compared with the Maximal ratio combiner (MRC). At SNR of 1dB less is required to achieve the performance of MRC. Here, to reduce the system complexity, the selection diversity is used. The drawback of this paper is that selection diversity scheme is used only for asynchronous detection of the optical signal. Since phase of the signal is an important attribute to be considered, the phase of the signal should be recovered at the receiver. Because phase of the laser beam is affected when it is transmitted through atmosphere. The turbulence-induced fading and effect of scintillation affects the phase of the laser beam signals. Hence co-phasing of the signal is important. The phase of the signal is very much affected due to atmospheric turbulence-induced fading and scintillation effect. Hence it is very much important to recover the phase of the signal at the receiver.

2.10. *Statistical model:*

In [21] Nestor, Harilos, George and Michail proved that the inverse Gaussian distribution is less complex than the lognormal distribution under weak turbulence conditions. Two typical FSO systems are considered here. One is IM/DD FSO systems with MPPM and the second is Heterodyne FSO systems with DPSK. Then this two models are compared by using KS- goodness of fits. This paper concluded that Inverse Gaussian distribution is less complex than the lognormal distribution. The drawback is that this inverse Gaussian is also analyzed for weak turbulence conditions. And this Inverse Gaussian method is analyzed only for short range of distances. For long range of distance, this Inverse Gaussian method is not applicable since turbulence is very strong.

2.11. *Coherent M-ary under K-distributed Turbulence*

In [22] Mingbo Niu analyzed the exact bit error rate for M-ary PSK and M-ary QAM using closed form moment generating function of intensity I_s. Due to atmospheric turbulence, the intensity and phase of the received laser beam signals are changed. So here, intensity and phase of the optical signal are taken as a random variable. The nth moment of Is is shown as [13]

$$E\,[I_s^n] = (\alpha)_n\, \eta^{2n}\, \Gamma(n+1) / \alpha^n \qquad (7)$$

Where E(.) denotes the expectation and $(\alpha)_n$ is the Pochhammer symbol given as $(\alpha)_n = \alpha\,(\alpha+1)\ldots(\alpha+n-1)$ [14]. From scintillation index $\sigma_{si}^2 \triangleq E[I_s^2]/(E[I_s])^2 - 1$ [15], α is shown as $\alpha = 2/(\sigma_{si}^2 - 1)$. And the variance of the shot noise [12] is given as

$$\sigma^2 = 2qRP_{LO}\Delta f \qquad (8)$$

Intensity I_s is characterized by K-distributed turbulence. For this random variable, PDF is given using this K distributions. With this PDF, moment generating function is calculated. An exact bit error rate for BPSK is calculated using MGF with channel parameter α varies from 1.2 to 1.8 and scintillation index (2,3). For diversity combining, Maximal ratio combiner is used. The BER of BPSK operating on L-branch K-distributed turbulence channels for α =1.8 is given in the below table. By using L-branch, bit error rate reduces. Hence spatial diversity schemes are used to improve the performance on FSO links.

Table II

Average SNR vs BER with channel parameter α=1.8 over L-branch.

Parameter (α)	L-branch	Average SNR(γ)dB	BER P_b=
1.8	L=1	50	10^{-4}
1.8	L=2	50	10^{-9}
1.8	L=3	50	10^{-14}
1.8	L=4	50	10^{-19}

In table 2, BER of BPSK operating on L-branch K-distributed channels for α = 1.8 is shown . Asymptotic BER of BPSK and 4QAM is also found. An exact bit error rate of BPSK with phase compensation error is also found by keeping the standard deviation below 20degrees.

Table III

Average SNR vs BER of BPSK with the standard deviation of phase compensation error $\sigma = 0^0, 20^0, 30^0, 40^0, 60^0$

Standard deviation of phase compensation error($\sigma_{\Delta\varphi}$)	Average SNR (γ)dB	Bit Error Rate P_b
0^0	40	10^{-4}
20^0	40	10^{-4}
30^0	40	10^{-3}
40^0	40	10^{-2}
60^0	40	10^{-1}

In the above table, the bit error rate of bpsk with phase compensation error is given. Hence, the drawback of this paper is that phase noise effect will be small if the standard deviation of phase compensation error is below 20degrees. If the phase compensation error exceeds 20degrees then it will degrade the system performance severely.

III. CONCLUSION

In this paper, a brief literature survey on performance of free space optical communication links is discussed. From this study it is concluded that all the digital modulation schemes with coherent detection achieves better bit error rate than with non-coherent detection.

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