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Error Probability and Laser Beam Propagation Analysis in Local Area Optical Wireless Communication Networks Using Pulse Position Modulation Technique under Atmospheric Turbulence Effects

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Abstract*—Free space optics (FSO) is a promising solution for the need to very high data rate point-to point communication. The atmospheric turbulence effect on FSO communications is one of the biggest problems that face FSO systems. This paper has presented the laser beam intensity fluctuations, laser beam spreading with its loss, and receiver arrival angle fluctuations in atmospheric turbulence free space optical communication systems. Our numerical results show that using APD with a proper selection of the average gain could greatly benefit the performance of the free space optics system with pulse position modulation. We have taken into account the impact of link conditions and system parameters on the selection of optimal Si APD gain. Signal to noise ratio (SNR), and bit error rate (BER) are the major interesting parameters in the current research. As well as we have compared our simulation results using silicon APD (Si-APD) receiver with their simulation results using InGaAs APD receiver.

Index Terms*— Laser intensity fluctuations, turbulence channel, Free space optics, Pulse position modulation, and Avalanche photodiode receiver.

I. INTRODUCTION

Optical communication has played a significant although hidden role in our everyday life as the backbone of communication networks. This is a field that seems to appeal to those researchers and engineers with an interest in the physical aspects of optical communications. Thus, optical communication devices are often modelled and designed from physicist's point of view. An initial hurdle faced by early means of wireless communication was the enormous heat generated by pumped laser action. However, in the late 1960's, semiconductor laser was developed and ever since, the possibilities for laser communication have grown [1]. The key element in any optical communication system is the optical source, which can easily be modulated. Such a source should produce energy concentrated in a narrow wavelength band, and should be capable of being modulated at very high rates. The semiconductor laser is one of the primary sources of light in modern optical systems [2]. When transmitted optical signals arrive at the receiver, they are converted to electronic signals by photo detectors. There are many types of photo detectors in existence, but the photodiodes are used almost exclusively in optical communication applications because of their small size, suitable material, high sensitivity, and fast response time [3].

In terrestrial FSO communication, the primary factors that degrade system performance are atmospheric attenuation and turbulence. Atmospheric attenuation, which is caused by absorption and scattering processes, is variable and difficult to predict, and hence significantly limits the coverage of FSO systems. Atmospheric turbulence is a phenomenon occurring when there are variations in the refractive index due to inhomogeneity in temperature and pressure changes [4]. This index inhomogeneity could deteriorate the quality of the received signal and lead to an increase in the bit error rate (BER) of the FSO systems. Conventionally, FSO systems have mainly been implemented by employing on–off keying (OOK) modulation because of the simplicity and low cost. In OOK modulation, the correct selection of adaptive thresholds is critical to the performance. However, due to the fluctuation of the signal intensity, adaptive threshold adjustment is difficult to accomplish. Also, an alternative modulation technique, pulse-position modulation (PPM), has been proposed for FSO communication [5]. It has been found that PPM has superior power efficiency compared to OOK; however, it has poor bandwidth efficiency.

The rest of the paper is organized as in the following sections. Section I has explained the basic principles of the problems with free space optics transmission which is discussed in more details. Section II has explained the laser beam signal propagation through atmospheric turbulent channel. Section III has explained the mathematical model equations. Section IV has presented the simulation results and performance evaluation of laser beam signal propagation and different APD receivers in free space atmospheric turbulence channels. Finally, section V has presented the summary of Si APD receivers transmission performance under study with their InGaAs APD receivers in free space optics communications under the same operating conditions.

II. LASER BEAM PROPAGATION THROUGH TURBULENT CHANNEL

The intensity of a laser beam propagating through the atmosphere is reduced due to phenomena such as scattering and molecular absorption, among other. The changes in the refractive index of the atmosphere due to optical turbulence affect the quality of laser beam through distortion of its phase front and random modulation of its optical power. Also the presence of fog may completely prevent the passage of the optical beam that leads to a no operational communications link [6]. The turbulent atmosphere produces many effects, of which the most noticeable is the random fluctuations of the traveling wave irradiance, phenomenon known as scintillation. Additionally, there are other effects that perturb the traveling wave front such as beam wander, that is a continuous random movement of the beam centroid over the receiving aperture; angle-of-arrival fluctuations, which are associated with the dancing of the focused spot on the photodetector surface; and beam spreading that is the spreading beyond the pure diffraction limit of the beam radius [7].

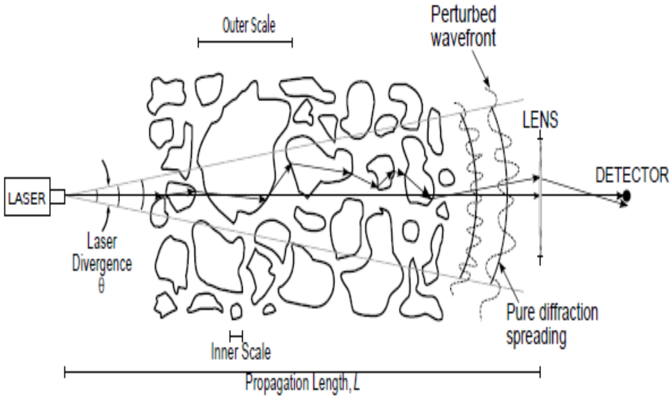

Fig. 1. Laser beam propagation through the turbulent atmosphere.

The rays (solid arrows) leaving the laser source are deflected as they travel through the largest air pockets, whose size defines the turbulence outer scale, arriving off-axis instead of what is expected without turbulence, represented with the straight dashed arrow starting at laser and finishing at the receptor surface in Fig. 1 [8]. Additionally, the turbulent atmosphere induces a spreading of the beam that is the broadening of the beam size beyond of that expected due to pure diffraction, for the case of a laser beam. It is customary to refer as refractive effects to those caused by the outer scale size of turbulence, whereas, the inner scale sizes produces the diffractive effects. As the rays may also be interpreted as the wave vector for the traveling wave front, the variations in the angle respect the optical axis at the receiver represent the concept of angle-of-arrival fluctuations. Furthermore, this bouncing of the optical wave front as it propagates through the atmosphere is also responsible for the beam wander effect as the centroid of the laser beam is displaced randomly at the receiver plane [9].

III. SYSTEM MODEL ANALYSIS

Beam spreading describes the broadening of the beam size at a target beyond the expected limit due to diffraction as the beam propagates in the turbulent atmosphere. Here, we describe the case of beam spreading for a Gaussian beam, at a distance L from the source, when the turbulence is present. Then one can write the irradiance of the beam averaged in time as presented by [10]:

$$I(l, r) = \frac{2P_0}{\pi\,\omega_{eff}^2(l)} \exp\left(\frac{-2\,r^2}{\omega_{eff}^2(l)}\right) \tag{1}$$

Where P_0 is total beam power in W, and r is the radial distance from the beam center. The beam will experience a degradation in quality with a consequence that the average beam waist in time will be $\omega_{eff}(l) > \omega(l)$. To quantify the amount of beam spreading, describes the effective beam waist average as:

$$\omega_{eff}^2(l) = \omega^2(l)\left[1 + T_{beam}\right] \tag{2}$$

Where ω (l) is the beam waist that after propagation distance L is given by [10]:

$$\omega^2(l) = \left[\omega_0^2 + \frac{2\lambda L}{2\pi\,\omega_0}\right] \tag{3}$$

In which ω_0 is the initial beam waist at L=0, T is the additional spreading of the beam caused by the turbulence. As seen in other turbulence figure of merits, T depends on the strength of turbulence and beam path. Particularly, T for horizontal path, one gets [11]:

$$T_{beam} = 1.33\sigma_I^2\,\Gamma^{5/6} \tag{4}$$

While the parameter Γ is given by:

$$\Gamma = \frac{2\lambda L}{2\pi\,\omega^2(l)} \tag{5}$$

The strength of scintillation can be measured in terms of the variance of the beam amplitude or irradiance σ_I given by [12]:

$$\sigma_I^2 = 1.23C_n^2\left(\frac{2\pi}{\lambda}\right)^{7/6} L^{11/6} \tag{6}$$

Evidently, due to the fact that $\omega_{eff}(l) > \omega(l)$. beam will experience a loss that at beam center will be equal:

$$\alpha_{beam}(dB) = 20\log\left(\frac{\omega(l)}{\omega_{eff}(l)}\right) \tag{7}$$

The intensity fluctuation σ_I which would be measured by a receiving aperture with a small diameter. In practice the receiving aperture has a finite diameter and the intensity fluctuations measured will not be σ_I but rather an average of the fluctuations over the whole aperture. When we measure the aperture averaging, the aperture averaging factor A is defined as the ratio of the normalized intensity variance of fluctuating of a receiver with receiver diameter D to that of a point receiver which can be given by [13]:

$$A = \frac{1}{1 + 1.07\left(\frac{2\pi D^2}{\lambda L}\right)^{7/6}} \tag{8}$$

Where D is the receiver diameter, when an optical wave propagated in a random medium, it will have random surface of constant phase. The phase distortion leads to fluctuations in the angle of arrival α. This causes image jitter in the received telescope that has large effect on the FSO system using optical fiber to receive the optical signal [14].

$$\alpha \approx \sqrt{2.92\left(\frac{C_n^2 L}{D^{0.33}}\right)} \tag{9}$$

The log-normal channel is classified as weak turbulence, which is characterized by a scintillation index less than 0.75. In general, the scintillation index is a complicated function of the beam parameters, propagation distance, heights of the transmitter and the receiver, and the fluctuations in the index of refraction. In fact, the main source of scintillation is due to fluctuations (due to temperature variations) in the index of refraction, which is commonly known as optical turbulence. The log-normal model is valid for propagation distances less than 4 km. The BER of pulse position modulation (PPM), without scintillation using APD receiver is given by [15]:

$$BER = Q\sqrt{SNR} = Q\left(\sqrt{\frac{K_s^2}{F\,K_s + K_n}}\right) \tag{10}$$

Where Q(x) is the Gaussian Q-function. F is the excess noise factor, K_s is the number of photons per PPM slot, and K_n is the total noise photons per slot which results from background noise and thermal noise. The scintillation index σ_{Si}^2 as a function of the variance of the log-normal channel σ_I^2 is defined by [16]:

$$\sigma_{Si}^2 = e^{\sigma_I^2} - 1 \tag{11}$$

The total noise photons per slot, K_n which results from background noise and thermal noise, is given by [15]:

$$K_n = \frac{2\,\sigma_n^2\,\sigma_{Si}^2}{\left[E(g)\,q\right]^2} + 2F\,K_b \tag{12}$$

Where K_b is the average background noise photons per slot, E(g) is the average gain of the APD (in the range 100 to 400) and q is the electron charge. As well as the excess noise factor, F, of the APD is defined by [16, 17]:

$$F = 2 + \xi\,E(g) \tag{13}$$

Where ξ is the ionization factor which is a ratio between holes over electronics in the magnification region [16]. The variance, σ_n^2 , of the thermal noise in one slot is defined by [15, 18]:

$$\sigma_n^2 = \frac{2KTT_{slot}}{R_L} \quad (14)$$

where T is the effective absolute temperature of the receiver in K is Boltzmann constant, R_L is the receiver load resistance and T_{slot} is the PPM slot duration which is related to the data rate (R_b), by [19]:

$$T_{slot} = \frac{\log_2(M)}{M R_b} \quad (15)$$

IV. Simulation Results and Performance Analysis

FSO system used the laser beam to transfer data through atmosphere. The bad atmospheric conditions have harmful effects on the transmission performance of FSO. These effects could result in a transmission with insufficient quality and failure in communication. So, the implementation of the FSO requires the study of the local weather conditions patterns. Studying of the local weather conditions patterns help us to determine the atmospheric attenuation effects on FSO communication that occurs to laser beam at this area. we shall discuss the effects of atmospheric attenuation, scattering coefficient during atmospheric turbulence during clear days on the FSO system performance. Finally, we will calculate the atmospheric turbulence with multi level pulse position modulation. we have taken into account the study of laser beam intensity fluctuations, receiver angle arrival fluctuations, signal to noise ratio and bit error rate at the receiver side.

Table 1: List of simulation parameters used in free space optic systems [3, 5, 7, 12, 14].

Operating parameter	Value and unit
Laser wavelength, λ	850 nm≤ λ ≤ 1550 nm
Propagation length, L	0.5 km ≤ L ≤ 4 km
Receiver diameter, D	5 cm ≤ D ≤ 20 cm
Average APD gain, E(g)	100 ≤ E(g) ≤ 400
Effective temperature, T	300 K ≤ T ≤ 500 K
Load resistance, R_L	50 Ω
Quantization levels, M	8 ≤ M ≤ 256
Data rate, R_b	10 Gb/s ≤ R_b ≤ 40 Gb/s
Refractive index turbulence strength, C_n^2	$10^{-17} \le C_n^2 \le 10^{-13}$
Ionization factor, ξ	0.025
Average noise photons per slot, K_b	10
Number of photons per PPM slot, K_s	300

Based on the modeling equations analysis and the assumed set of the operating parameters as shown in Table 1. The following facts are assured as shown in the series of Figs. (2-23):

i) Figs. (2-4) have assured that laser beam spreading increases with increasing both refractive index structure turbulence strength and propagation length while increasing operating laser signal wavelength this results in decreased laser beam spreading.
ii) As shown in Figs. (5-7) have indicated that laser beam spreading increases with increasing turbulence channel media and propagation length. It is observed that strong channel turbulence has presented the highest laser beam spreading in compared with weak and medium turbulence channels under the same operating conditions.
iii) Figs. (8-10) have assured that laser beam loss increases with increasing both refractive index structure turbulence strength and propagation length while increasing operating laser signal wavelength this results in decreased laser beam loss.
iv) Figs. (11-13) have indicated that arrival angle fluctuations at the receiver side increases with increasing both refractive index structure turbulence strength and propagation length while increasing aperture receiver diameter this results in decreased arrival angle fluctuations.
v) As shown in Figs. (14, 15) have assured that signal to noise ratio decreases and bit error rate increases with increasing both refractive index structure turbulence strength and propagation length.
vi) Figs. (16, 17) have assured that signal to noise ratio decreases and bit error rate increases with increasing effective ambient temperature for both avalanche photodiodes under study. It is observed that Si APD in our model has presented higher signal to noise ratio and lower bit error rate in compared with InGaAs APD in their model [19] under the same operating conditions.
vii) As shown in Figs. (18, 19) have indicated that signal to noise ratio increases and bit error rate decreases with increasing average APD receiver gain for both APD receivers under study. It is indicated that Si APD in our model has presented higher signal to noise ratio and lower bit error rate in compared with InGaAs APD in their model [19] under the same operating conditions.
viii) Figs. (20-23) have assured that signal to noise ratio increases and bit error rate decreases with increasing number of quantization position levels while increasing transmission data rates this results in decreased signal to noise ratio and increased bit error rate for both APD receivers under study. It is observed that Si APD in our model has presented higher signal to noise ratio and lower bit error rate in compared with InGaAs APD in their model [19] under the same operating conditions.

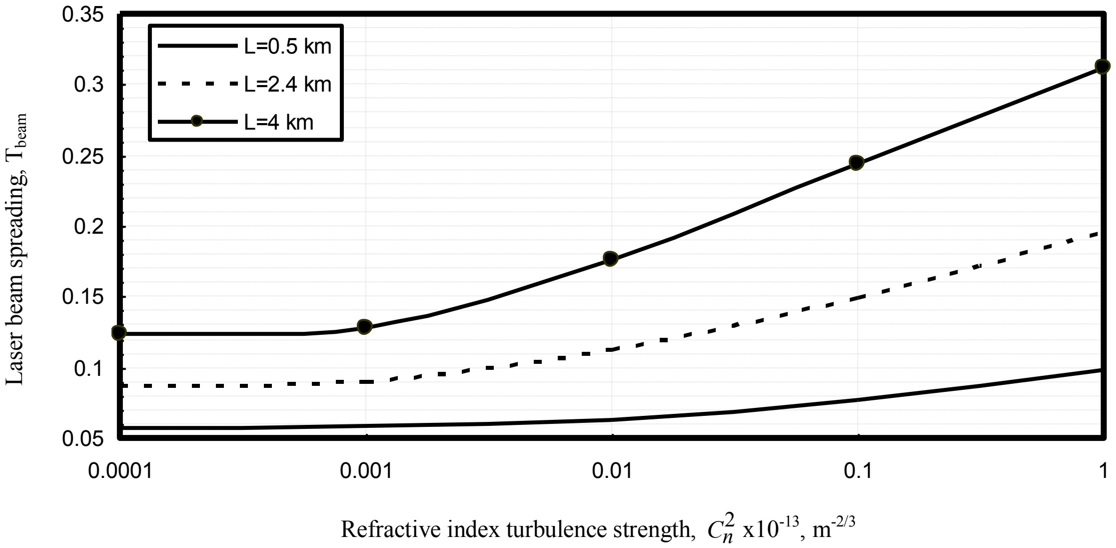

Fig. 2. Laser beam spreading against refractive index structure turbulence strength and propagation length with first laser operating signal wavelength (λ=850 nm) at the assumed set of the operating parameters.

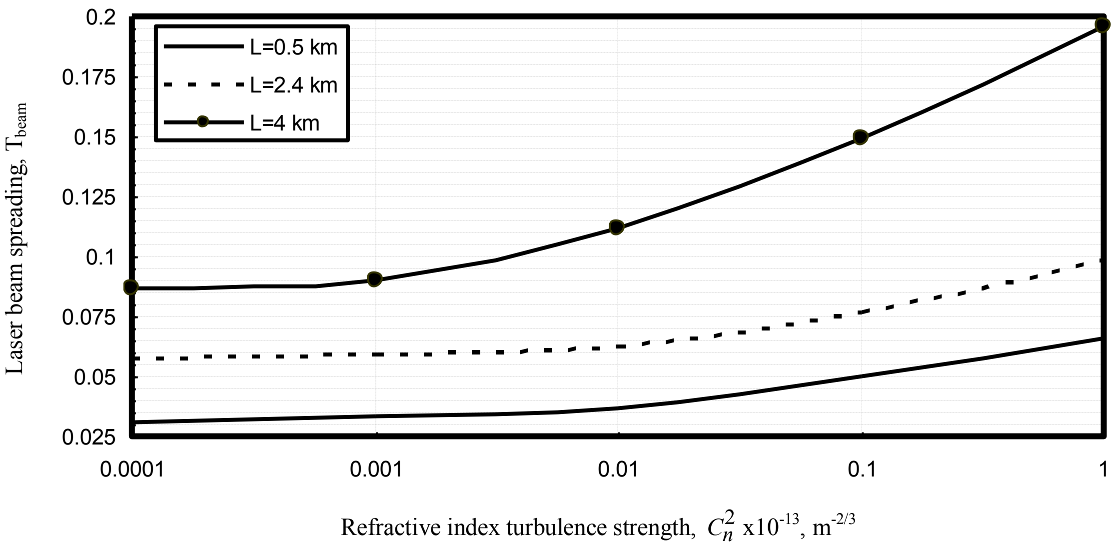

Fig. 3. Laser beam spreading against refractive index structure turbulence strength and propagation length with second laser operating signal wavelength (λ=1300 nm) at the assumed set of the operating parameters.

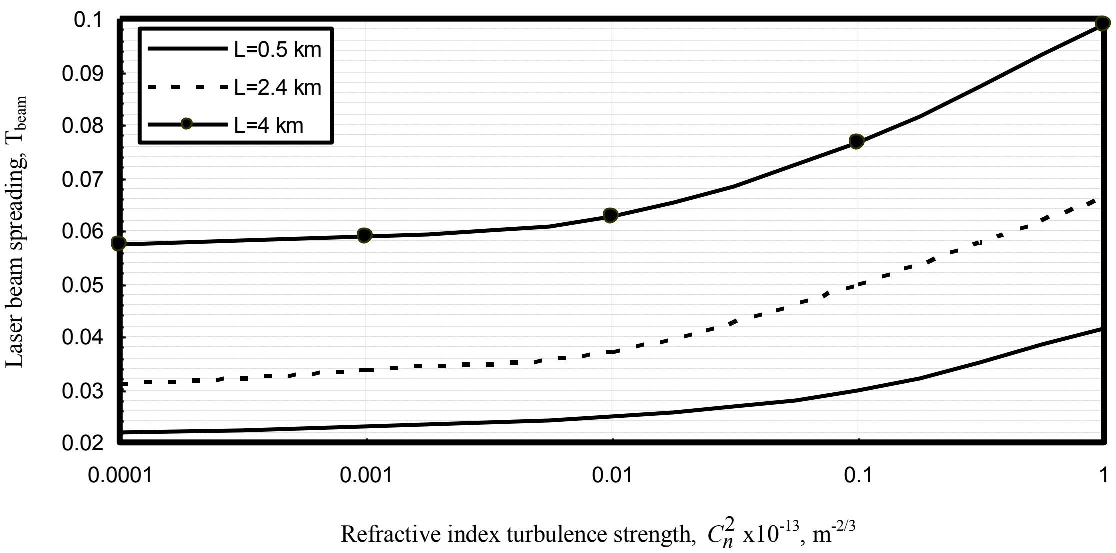

Fig. 4. Laser beam spreading against refractive index structure turbulence strength and propagation length with third laser operating signal wavelength (λ=1550 nm) at the assumed set of the operating parameters.

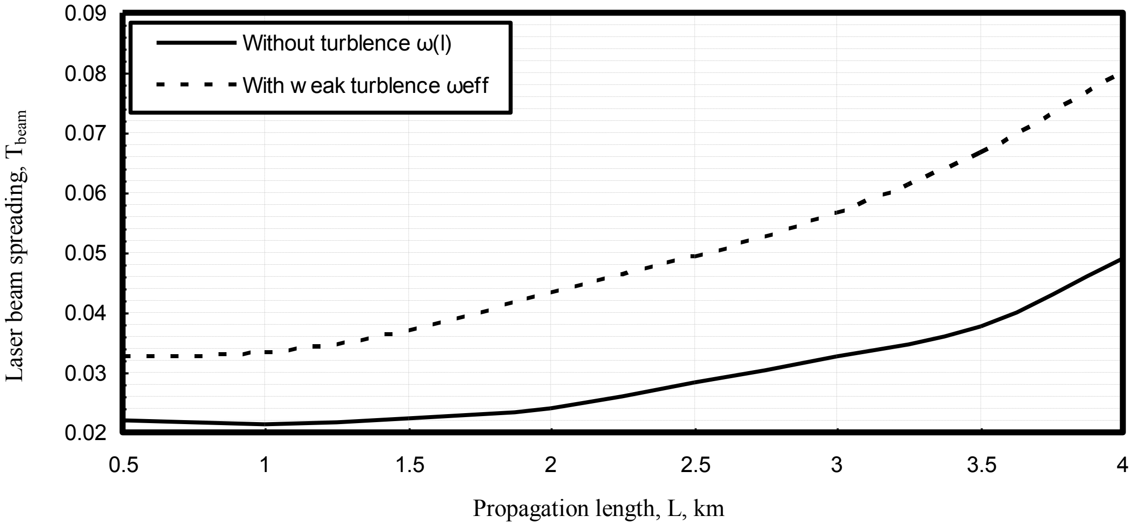

Fig. 5. Laser beam spreading against propagation length with third laser operating signal wavelength (λ=1550 nm) and weak refractive index structure turbulence strength (C_n^2 x10^{-17}, m$^{-2/3}$) at the assumed set of the operating parameters.

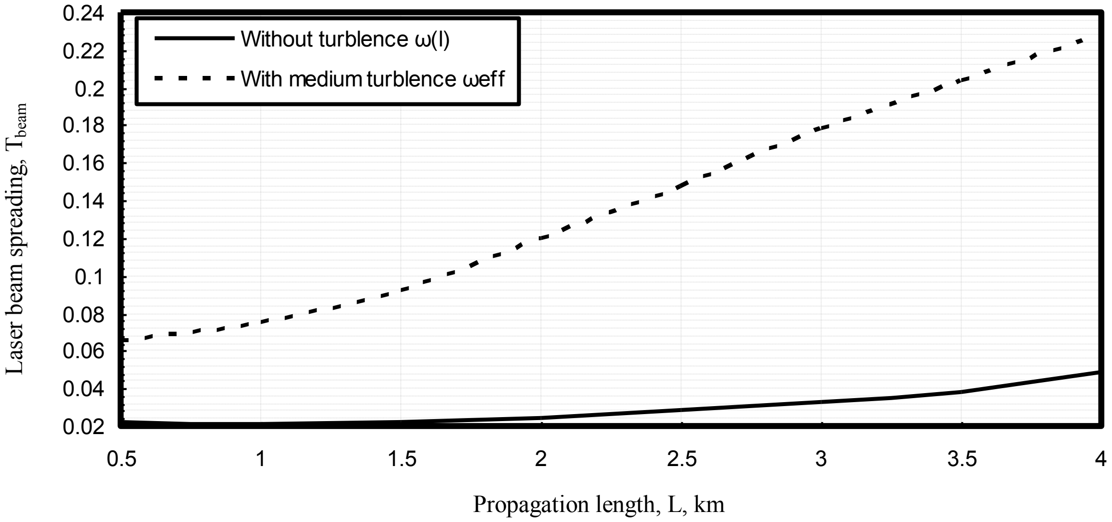

Fig. 6. Laser beam spreading against propagation length with third laser operating signal wavelength (λ=1550 nm) and medium refractive index structure turbulence strength (C_n^2 x10^{-15}, m$^{-2/3}$) at the assumed set of the operating parameters.

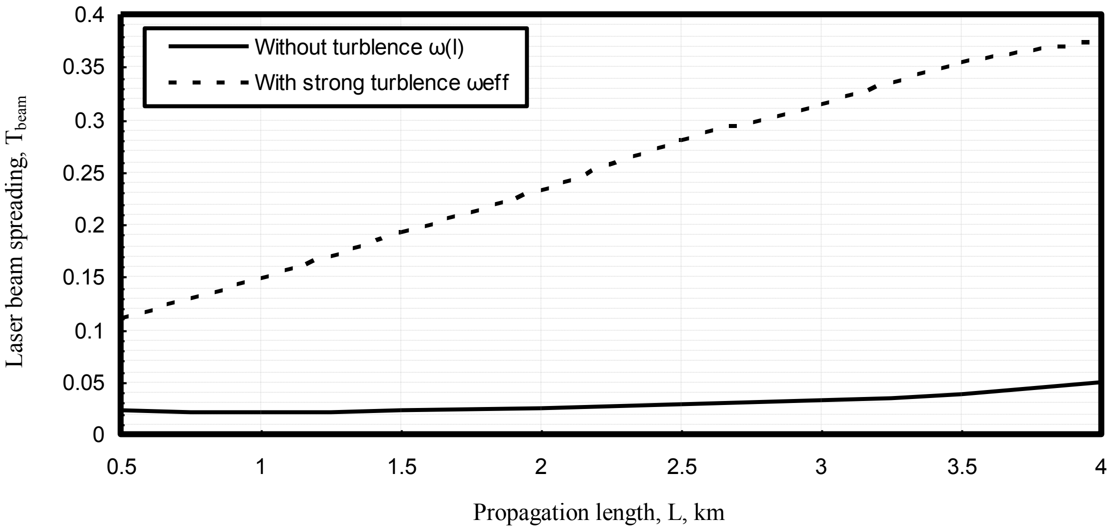

Fig. 7. Laser beam spreading against propagation length with third laser operating signal wavelength (λ=1550 nm) and strong refractive index structure turbulence strength (C_n^2 x10^{-13}, m$^{-2/3}$) at the assumed set of the operating parameters.

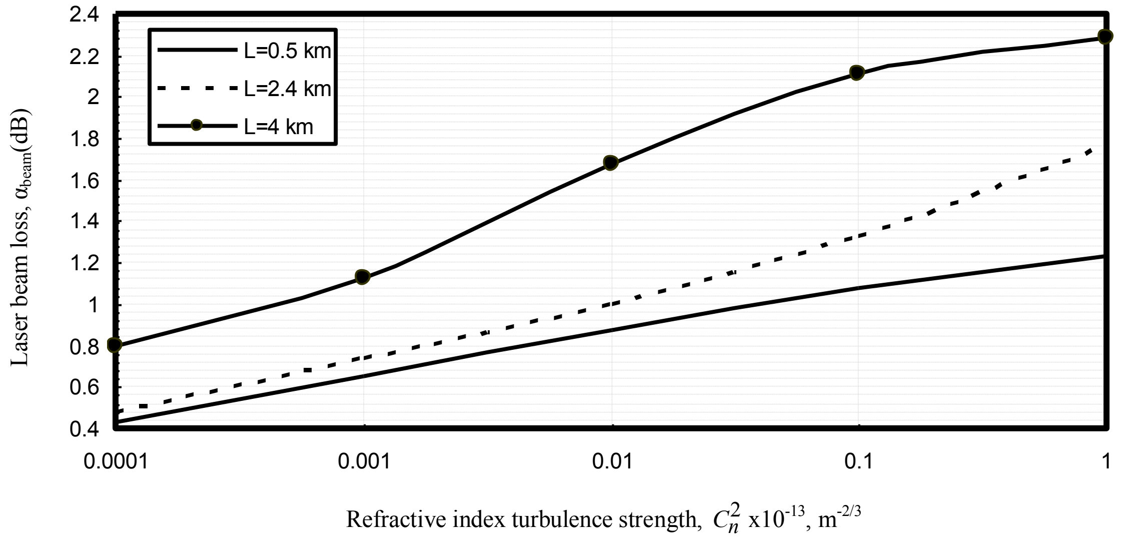

Fig. 8. Laser beam loss against refractive index structure turbulence strength and propagation length with first laser operating signal wavelength (λ=850 nm) at the assumed set of the operating parameters.

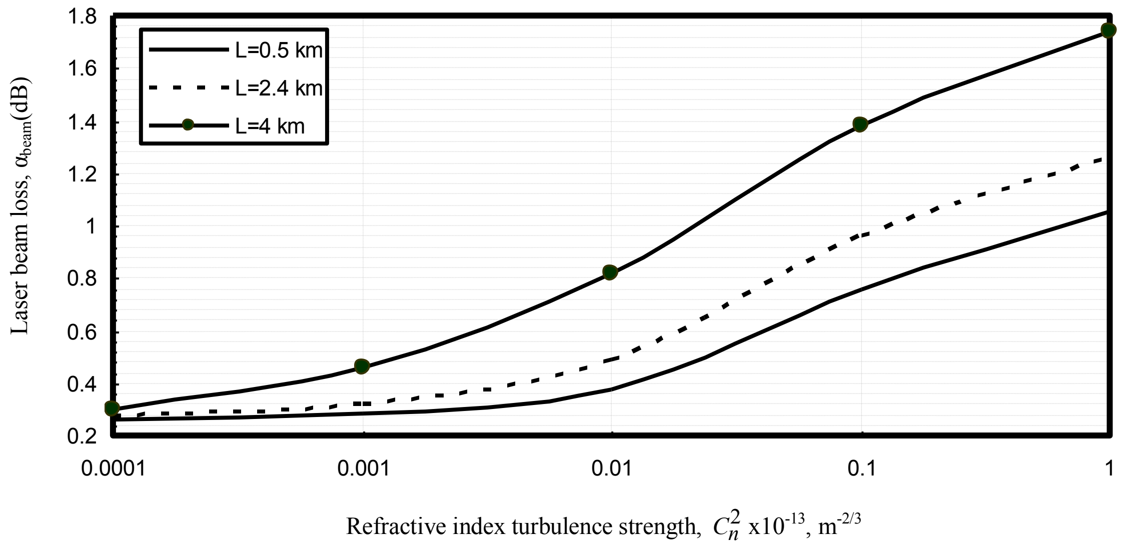

Fig. 9. Laser beam loss against refractive index structure turbulence strength and propagation length with second laser operating signal wavelength (λ=1300 nm) at the assumed set of the operating parameters.

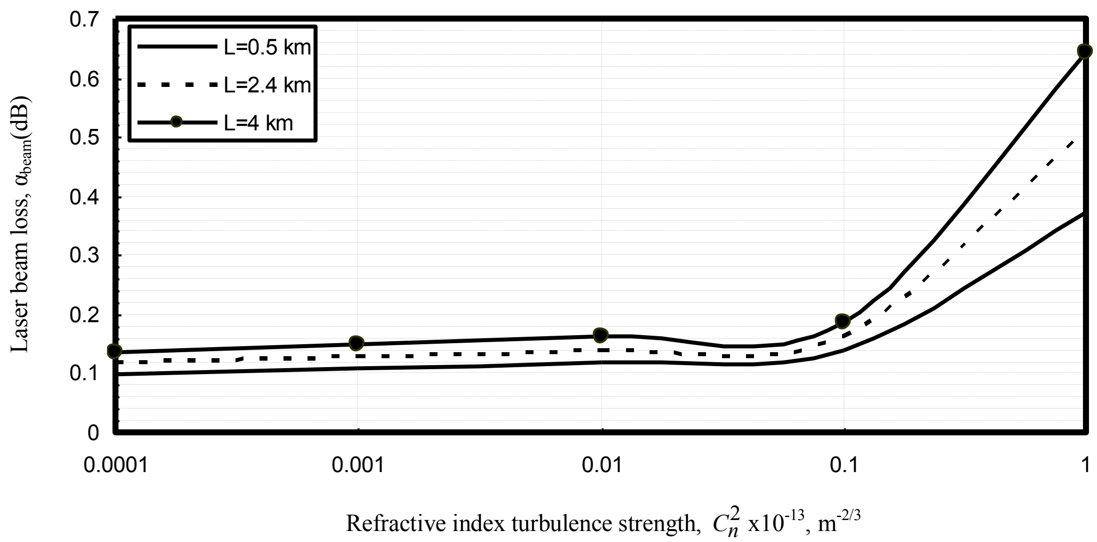

Fig. 10. Laser beam loss against refractive index structure turbulence strength and propagation length with third laser operating signal wavelength (λ=1550 nm) at the assumed set of the operating parameters.

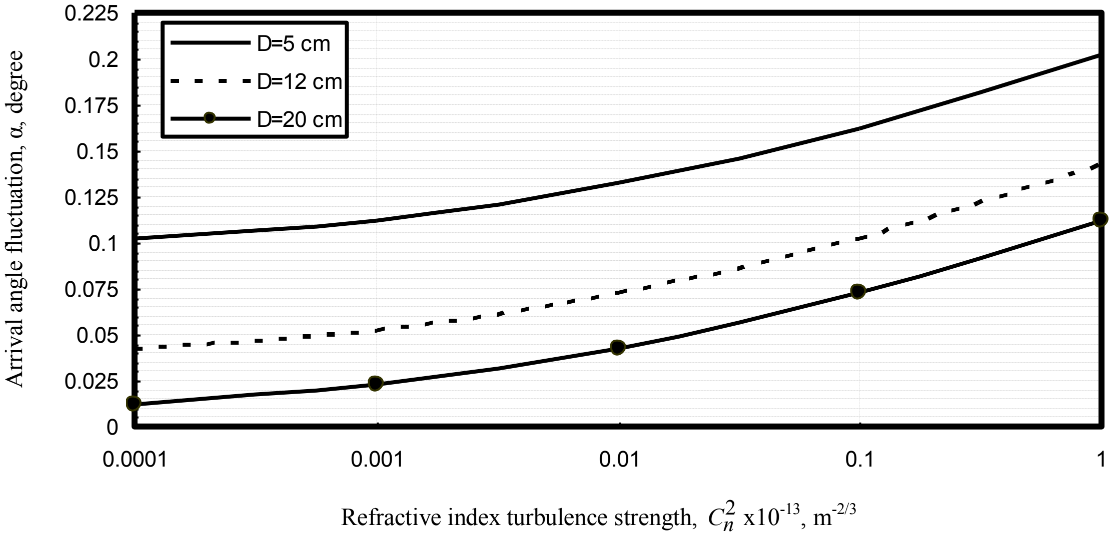

Fig. 11. Receiver arrival angle fluctuations in relation to refractive index turbulence strength and receiver diameter with propagation length L=0.5 km at the assumed set of the operating parameters.

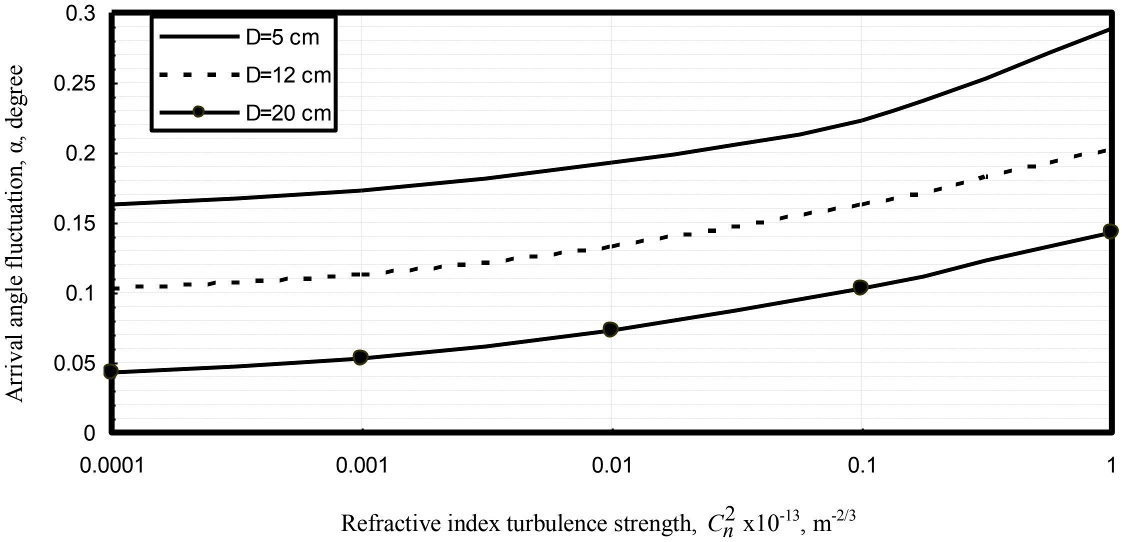

Fig. 12. Receiver arrival angle fluctuations in relation to refractive index turbulence strength and receiver diameter with propagation length L=2.4 km at the assumed set of the operating parameters.

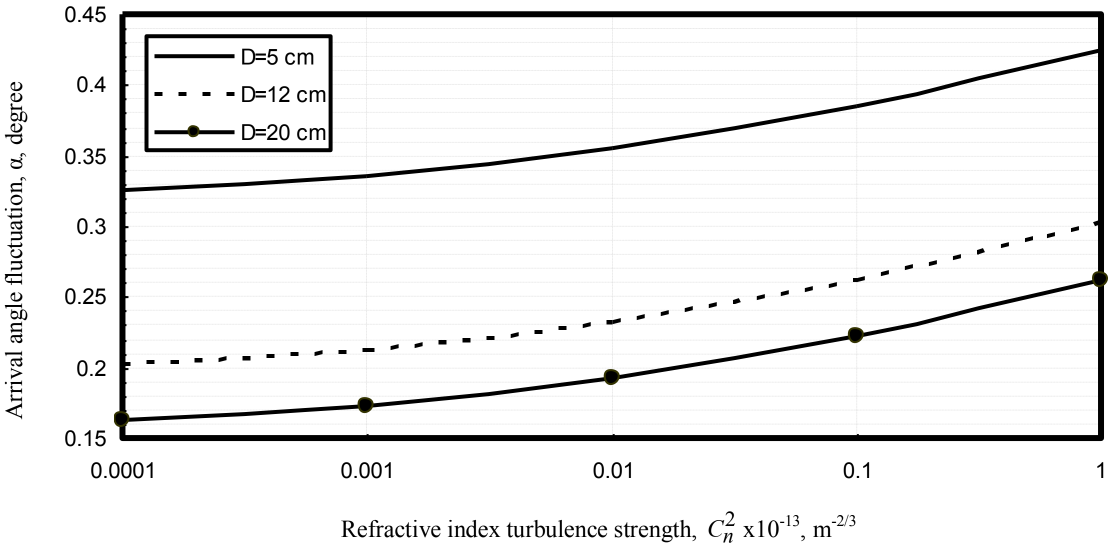

Fig. 13. Receiver arrival angle fluctuations in relation to refractive index turbulence strength and receiver diameter with propagation length L=4 km at the assumed set of the operating parameters.

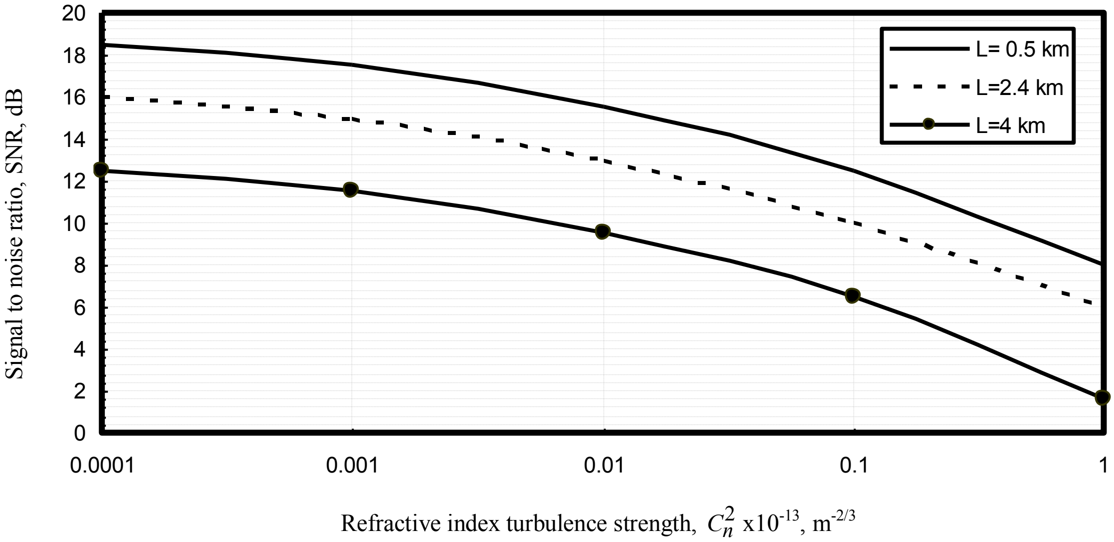

Fig. 14. Signal to noise ratio at receiver side in relation to refractive index turbulence strength and propagation length with third laser wavelength region operation (λ=1550 nm) at the assumed set of the operating parameters.

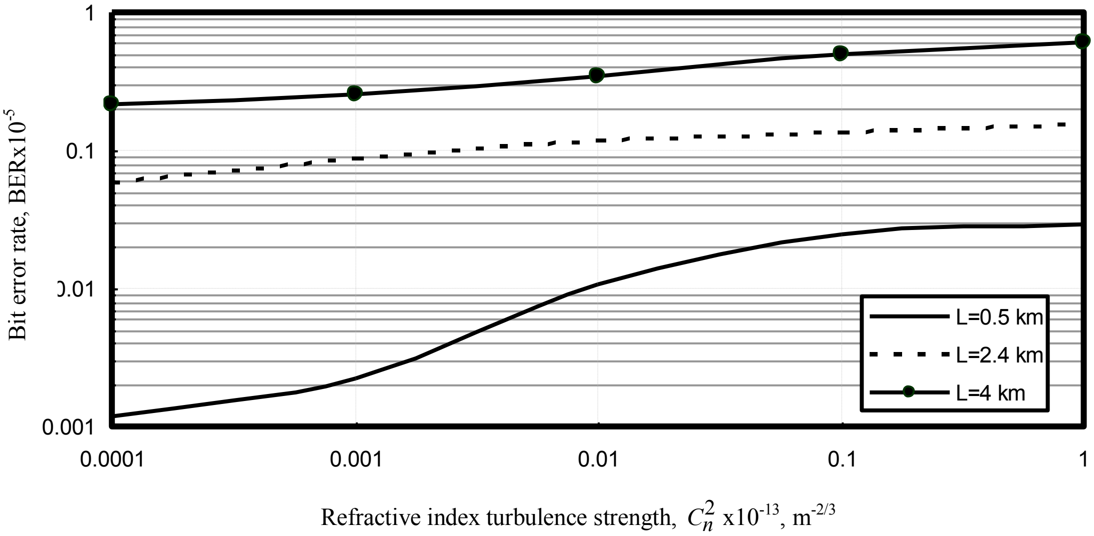

Fig. 15. Bit error rate at the receiver side in relation to refractive index turbulence strength and propagation length with third laser wavelength region operation (λ=1550 nm) at the assumed set of the operating parameters.

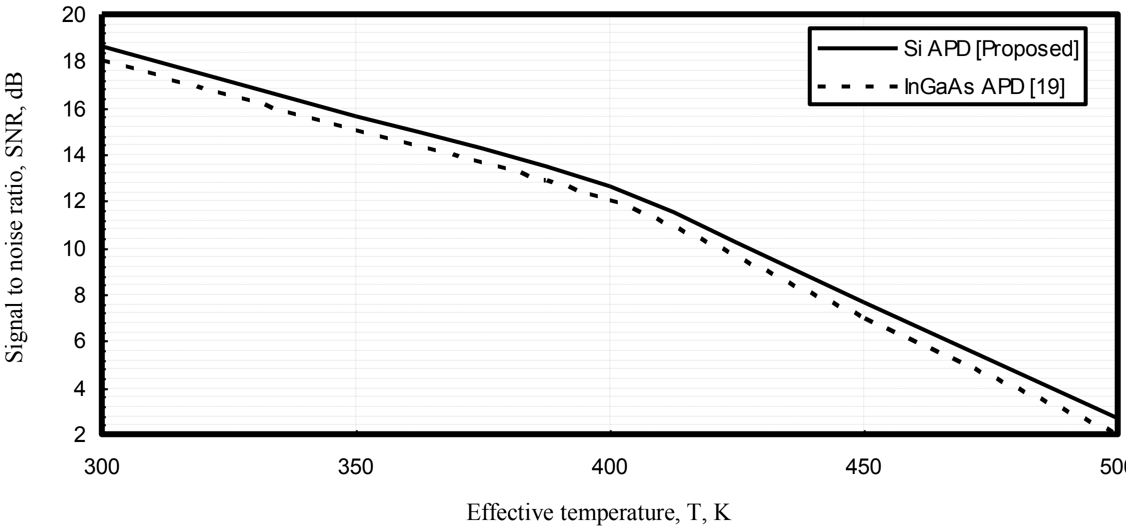

Fig. 16. Signal to noise ratio at the receiver side versus effective temperature for different APD receivers at the assumed set of the operating parameters.

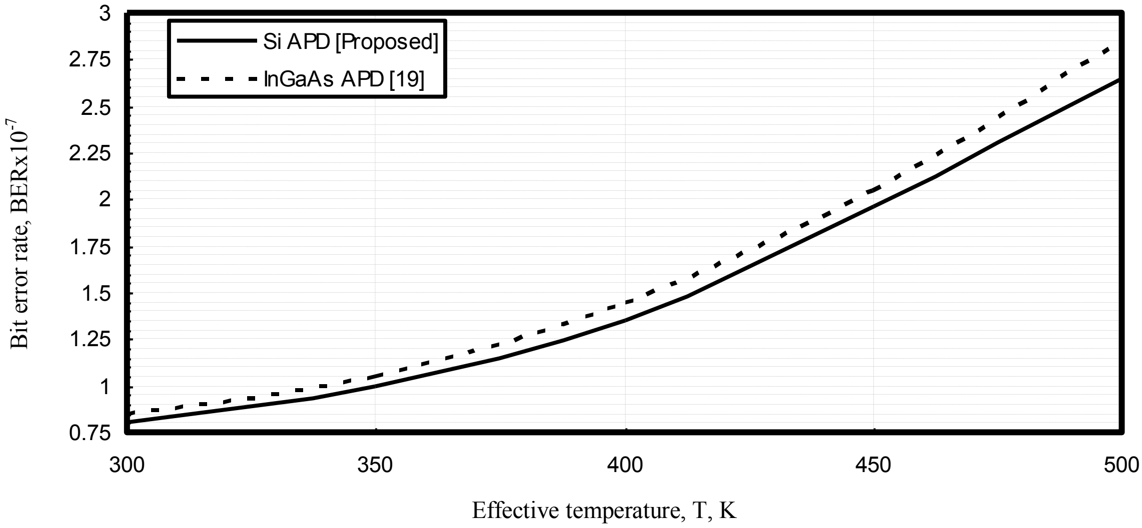

Fig. 17. Bit error rate at the receiver side versus effective temperature for different APD receivers at the assumed set of the operating parameters.

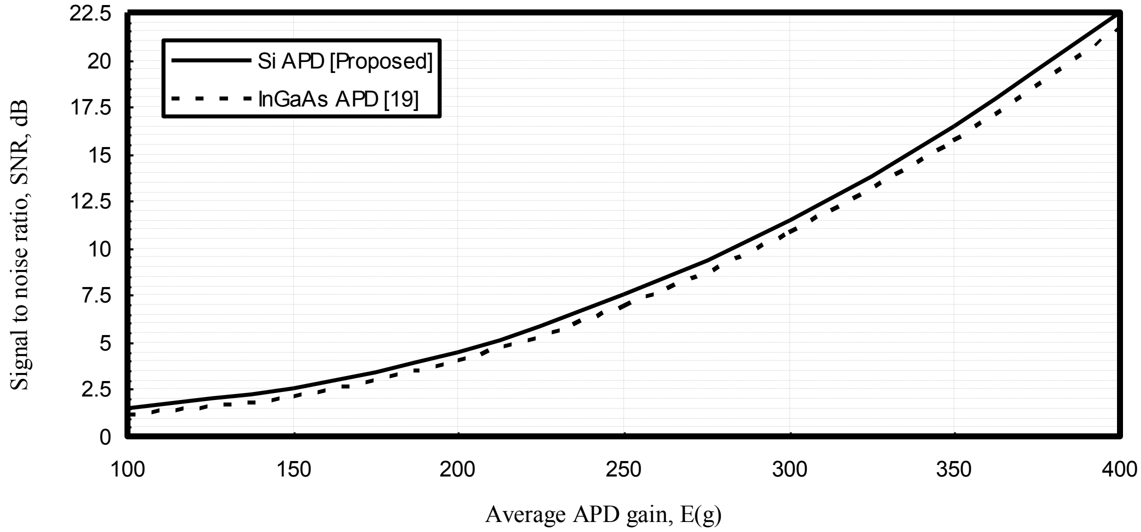

Fig. 18. Signal to noise ratio at the receiver side against average APD gain for different APD receivers at the assumed set of the operating parameters.

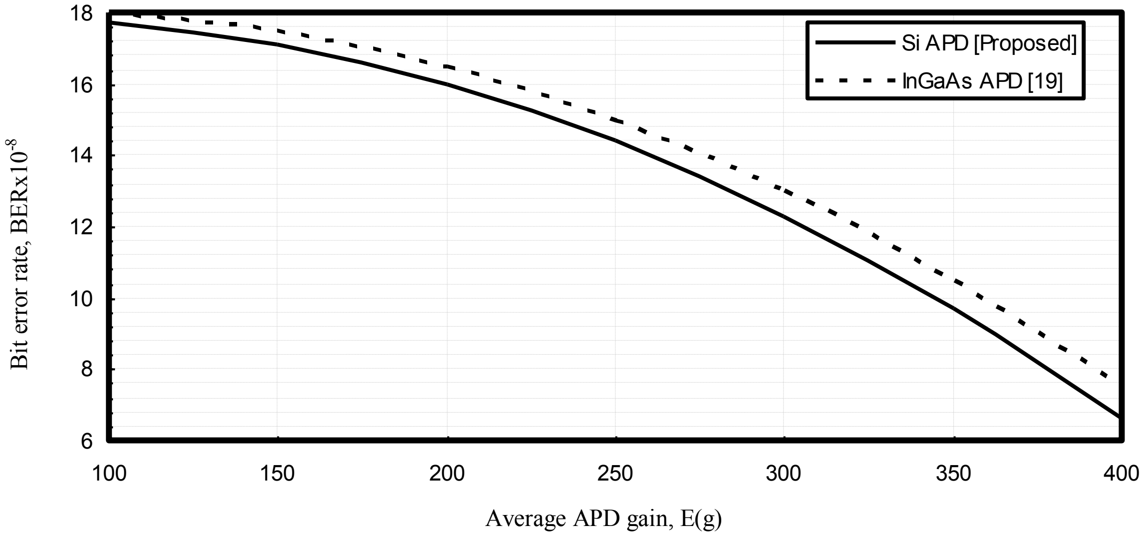

Fig. 19. bit error rate at the receiver side against average APD gain for different APD receivers at the assumed set of the operating parameters.

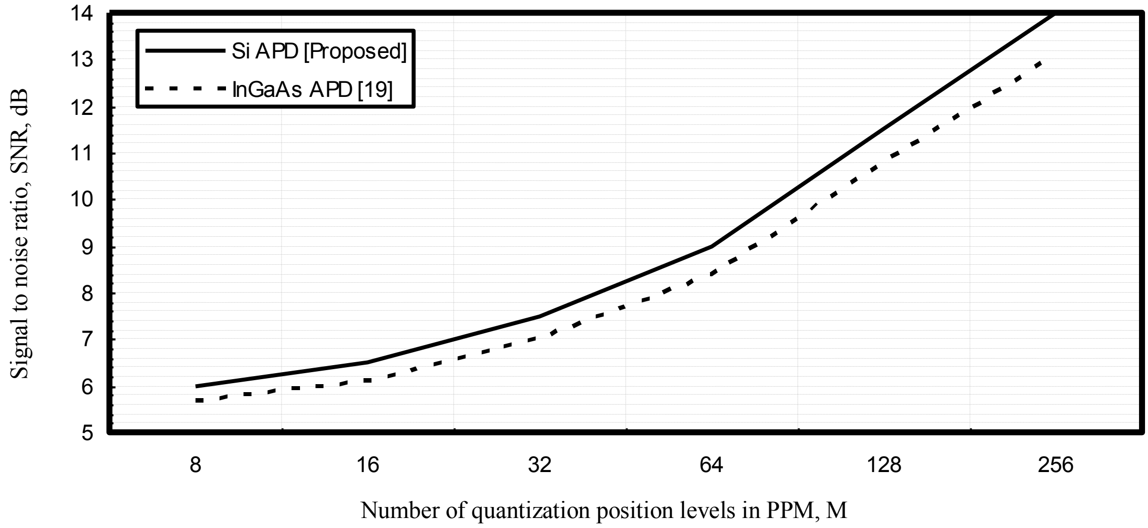

Fig. 20. Signal to noise ratio at the receiver side against Number of quantization position levels in PPM for different APD receivers with transmission data rate (R_b=10 Gbit/sec) at the assumed set of the operating parameters.

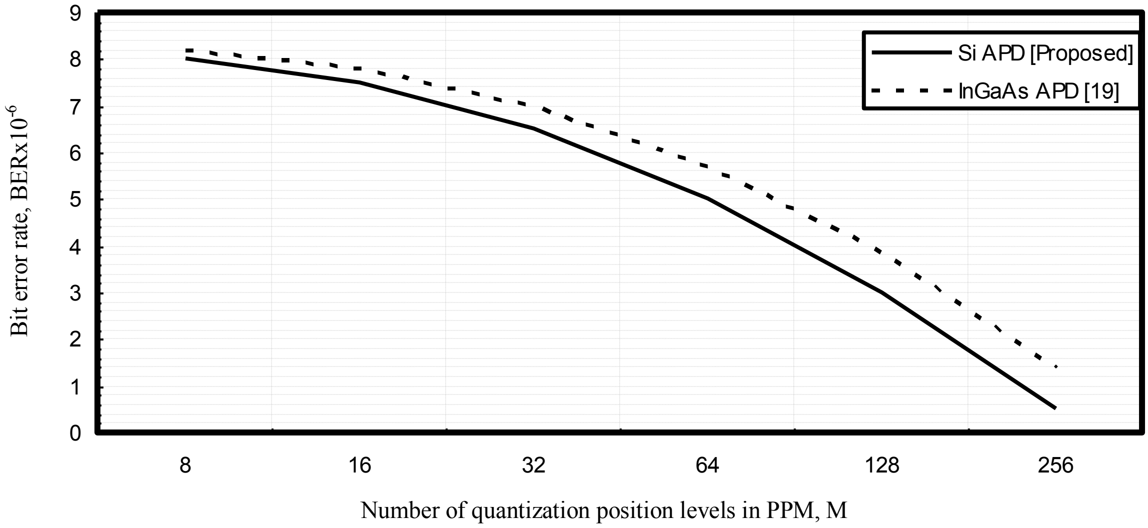

Fig. 21. Bit error rate at the receiver side against Number of quantization position levels in PPM for different APD receivers with transmission data rate (R_b=10 Gbit/sec) at the assumed set of the operating parameters.

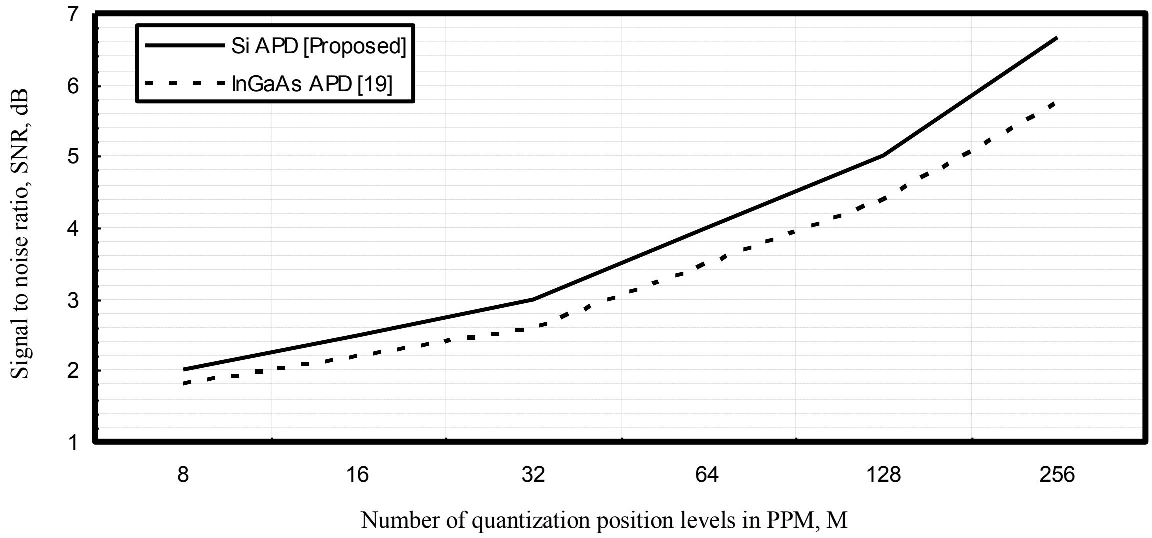

Fig. 22. Signal to noise ratio at the receiver side against Number of quantization position levels in PPM for different APD receivers with transmission data rate (R_b=40 Gbit/sec) at the assumed set of the operating parameters.

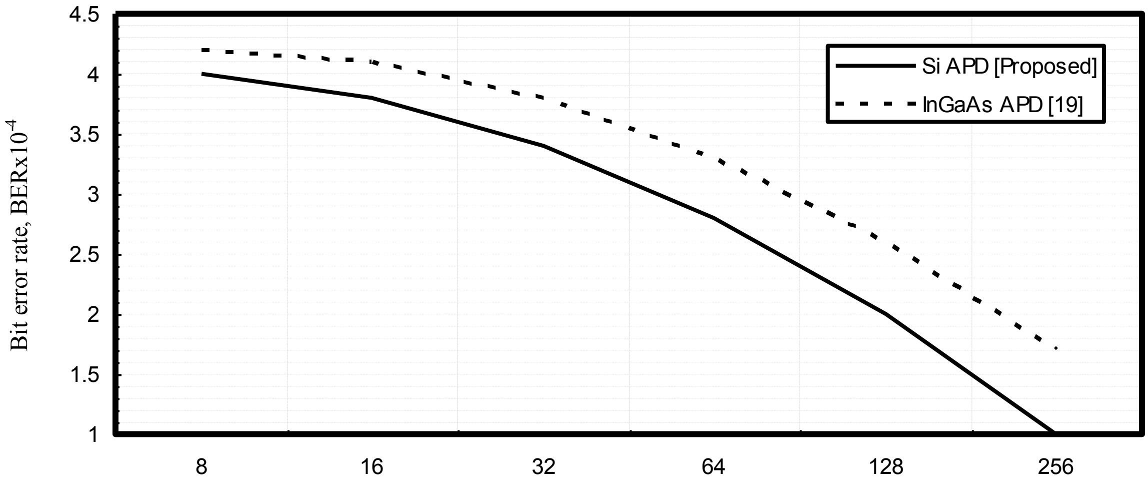

Fig. 23. Bit error rate at the receiver side against Number of quantization position levels in PPM for different APD receivers with transmission data rate (R_b=40 Gbit/sec) at the assumed set of the operating parameters.

V. CONCLUSIONS

We have theoretically analyzed the performance of FSO systems using pulse position modulation and an different APD receiver over atmospheric turbulence channels. It is theoretically found that the lowest propagation length, refractive index structure turbulence strength and the highest operating laser wavelength, this results in the lowest laser beam propagation fluctuations, receiver aperture averaging factor and receiver angle of arrival fluctuations. As well as it is observed that the lowest effective temperature and the highest number of quantization levels in PPM system, APD gain, load resistance, number of photons per PPM slot, this results in the highest signal to noise ratio, and the lowest bit error rates. Moreover it is indicated that the dramatic effects of increasing bit rates on the decreeing signal to noise ratio and the increasing bit error rates. Our simulation results with Si APD receiver has presented the best transmission performance efficiency than their results with using InGaAS APD receiver. It is theoretically found that the dramatic effects of increased propagation length and refractive index structure turbulence strength on the transmitting laser beam loss and its spreading, signal to noise ratio and bit error rate at the receiver side.

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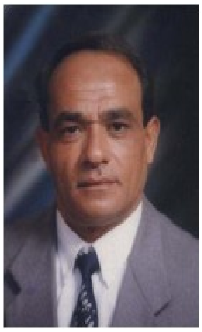

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