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Laser Atmospheric Transmission Limitations in Optical Wireless Communication Systems Based on Different Transmission Levels for Short and Local areas Network Applications

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Abstract— This paper has presented optical wireless communication systems performance prediction based on different visibility levels for indoor, local, and wide area network applications s over wide range of the affecting parameters. Optical wireless links provide high bandwidth solution to the last mile access bottleneck. However, an appreciable availability of the link is always a concern. Wireless optical links are highly weather dependent and fog is the major attenuating factor reducing the link availability. Maximum permissible exposure, signal to noise ratio (SNR), atmospheric attenuation limitations, laser intensity fluctuations, and bit error rate (BER) are the major interesting design parameters in the current study.

Keywords: Indoor and local free space systems, Line of sight, Strong channel turbulence, and Weak channel turbulence.

I. INTRODUCTION

Wireless is any communications method that does not depend on wires (metallic or fiber) for the transmission of communications signals. Wireless communications provides "connectivity" between two or more devices (a transmitter and a receiver) enabling them to exchange information [1, 2]. The fundamental difference between wireless communication and other "wired" forms of communications is the medium over which the encoded energy containing information is transferred between the transmitter and receiver. In wireless systems energy transfer occurs through air or through free space without a physical connection between the devices. The energy transfer can be visible optical radiation, invisible infrared, ultraviolet or radio frequency (RF) to name a few. The energy transferred between the two devices can follow a narrow path, essentially a straight line between origin (transmitter) and destination (receiver) line of sight (LOS), and a diverging path or be sent out in all directions (omni directional). The radiated energy behaves in different ways depending on its frequency. Higher frequency signals such as light (optical) tend to be more directional whereas RF signal tend to be transmitted in all directions without the use of specially designed directional antennas. Another characteristic of the energy transmitted is its ability to penetrate solid objects. Optical signals do not penetrate solid objects unless they are transparent to that frequency of radiation, whereas RF signals (at lower frequencies) can flow freely through or around solid objects such as walls. Both optical and RF signals can bounce off various surfaces form walls, water, mirrors and buildings [3-5].

The distance both types of signals can travel and still be capable of being recovered by the receiver depends on the medium the signal travels through and the strength of the signal (amount of energy originally transmitted) and the sensitivity of the receiver. In general the signals become weaker the farther they go. It is clear that each type of signals is affected greatly by the environment that is traversed between the transmitter and the receiver. Optical signals would be confined to a room if there are no transparent walls (windows) or open doors, whereas RF signals would not. Theoretically using optical, the transmission distance is limited only by the output power of the source and the sensitivity of the detector. With a suitably sensitive detector, optical radiations from planets orbiting stars in other solar systems have been detected. Therefore in theory a transceivers could be designed to operate at the proper power level and communicating with a high gain receiver could operate over any desired distance [6, 7]. Optical Wireless communication, also known as free-space optical (FSO), has emerged as a commercially viable alternative to RF and millimeter wave wireless for reliable and rapid deployment of data and voice networks. RF and millimeter wave technologies allow rapid deployment of wireless networks with data rates from tens of Mb/s (point-to-multipoint) up to several hundred Mb/s (point-to-point). However, spectrum licensing issues and interference at unlicensed ISM bands will limit their market penetration. Though emerging license-free bands appear promising, they still have certain bandwidth and range limitations [8]. The main challenge for optical wireless is atmospheric attenuation. Attenuation as high as 300 dB/km in very heavy fog is occasionally observed in some locations around the world [9]. It is impossible to imagine a communication system that would tolerate hundreds of dB attenuation. Thus, either link distance and/or link availability has to be compromised. It is also obvious, that the more link margin could be allotted to the atmospheric attenuation, the better the compromise is. As a result, in the presence of severe atmospheric attenuation, an optical link with narrow beam and tracking has an advantage over a link without tracking.

II. MATHEMATICAL MODELING ANALYSIS

In terrestrial free space optics (FSO), the communication transceivers are typically located in the troposphere. Troposphere is home to all kinds of weather phenomena and plays a very detrimental role for FSO communications in lower visibility range conditions mainly due to rain, snow, fog and clouds. The estimated of fog, snow and rain attenuation effects using empirical models as mentioned in Ref. [10]:

$$\alpha_{fog}(\lambda) = \frac{3.912}{V}\left(\frac{\lambda}{55x10^4}\right)^{-q}, \qquad (1)$$

Where V is visibility range in km, λ is transmission wavelength in μm. $\alpha_{fog}(\lambda)$ is the total extinction coefficient and q is the size distribution coefficient of scattering related to size distribution of the droplets. In case of clear or foggy weather with no rain or snow, Refs. [11, 12] approximations of the q parameter to compute the fog attenuation, that are very accurate for the narrow wavelength range between 0.85 μm–1.55 μm which equal 0.585 $V^{1/3}$ for 0.5 km $\le$ V $\le$ 6.5 km, and equal 0.245 for V $\le$ 0.5 km. Transmitted optical pulses in free space are mainly influenced by two main mechanisms of signal power loss, absorption and scattering. Absorption is mainly due to water vapours and carbon dioxide, and depends on the water vapour content that is dependent on the altitude and humidity. By appropriate selection of optical wavelengths for transmission the losses due to absorption can be minimized. It was found that scattering is the main mechanism of optical power loss as the optical beam looses intensity and distance due to scattering. The beam loss due to scattering can be calculated from the following empirical, visibility range dependent formula [13]:

$$\alpha_{scat}(\lambda) = \frac{17}{V}\left(\frac{550}{\lambda}\right)^{0.195V}, \quad \text{dB/km} \qquad (2)$$

Then the total attenuation of wireless medium communication system can be estimated as:

$$\alpha = \alpha_{fog}(\lambda) + \alpha_{snow} + \alpha_{rain} + \alpha_{scat}(\lambda), \ \text{dB/km} \quad (3)$$

When the optical signal passes through the atmosphere, it is randomly attenuated by fog and rain. Although fog is the main attenuation factor for optical wireless links, the rain attenuation effect cannot be ignored, in particular in environments where rain is more frequent than fog. As the size of water droplets of rain increases, they become large enough to cause reflection and refraction processes. These droplets cause wavelength independent scattering [13]. It was found that the resulting attenuation increases linearly with rainfall rate; furthermore the mean of the raindrops size is in the order of a few millimeters and it increases with the rainfall rate [14]. Let R be the rain rate in mm/h, the specific attenuation of wireless optical link is given by [15]:

$$\alpha_{rain} = 1.076\, R^{0.67} \ \text{dB/km} \qquad (4)$$

If S is the snow rate in mm/h then specific attenuation in dB/km is given by [16] as:

$$\alpha_{snow} = a\, S^{b} \ \text{dB/km} \qquad (5)$$

Where the parameters a and b for dry snow are given as the following:

$$a = 5.42x10^{-4}\lambda + 5.495876, \ b = 1.38 \qquad (6)$$

The maximum transmission distance (MTD) for meeting the good visibility requirements is given by:

$$MTD = 10^{-\alpha/20}, \qquad (7)$$

The main objective of wireless optical link design 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 receive a stronger signal that would result in higher link margin and greater link availability. With indoor wireless communications using infrared beams, eye safety issues must be addressed. The international electro technical commission (IEC) document IEC 825-1 defines the maximum exposure limits. This standard does not distinguish between the laser and LED emission level. The following formulae were established by the american national standards institute as a guideline for the safe use of lasers [17, 18]. The maximum permissible exposure (MPE) values of intrabeam viewing for a nearly point source are [19]:

$$MPE = 1.8\, C_A\, t^{-0.25}\ \ mW/cm^2 \qquad (8)$$

Where t is the irradiation exposure time in sec, which ranges from 1 sec to 1000 sec, and the parameter C_A can be given by the following formula [20-22]:

$$C_A = 10^{0.002\,(ª - 0.7)} \qquad (9)$$

In atmospheric turbulence, an important parameter for characterizing the amount of refractive index fluctuation is the index of refraction structure parameter, C_n^2, introduced by [23]. The value of C_n^2 varies with altitude over ground level, h and a commonly used model to describe it is the mathematical relations given below as:

$$C_n^2(h) = 4.008x10^{-13}\, h^{-1.054}, \quad 20\ m \le h \le 220\ m \qquad (10)$$

$$C_n^2(h) = 6.532x10^{-7}\, h^{-2.966}, \quad 1000\ m \le h \le 6500\ m \qquad (11)$$

On the other hand, when a vertical path is considered, the behavior of C_n^2 is conditioned by temperature changes along the different layers within the Earth's atmosphere, hence, the refractive-index structure parameter becomes a function of the altitude above ground. With taking into account the introduction of the effects of solar radiation and aerosol loading in the atmosphere, as the following expression [24]:

$$C_n^2(T,WS,RH,TCSA,SF) = -3.9x10^{-13} + 1.6x10^{-15}T - 3.7x10^{-15}RH - 3.7x10^{-15}WS$$
$$+ 2.8x10^{-14}SF - 1.8x10^{-14}TCSA \qquad (12)$$

Where T is the effective temperature in K, RH is the relative humidity (%), SF is the solar flux in units of kW/m^2, and TCSA is the total cross sectional area of the aerosol particles and its expression can be found [9]:

$$TCSA = 7.3x10^{-3} + 9.96x10^{-4}\, RH - 1.37x10^{-5}\, SF^4 \qquad (13)$$

Therefore the refractive index structure parameter, C_n^2 can be given by the following formula [25]:

$$C_n^2 = C_n^2(h) + C_n^2\,(T, WS, RH, TCSA, SF) \qquad (14)$$

Another important factor is the rytov approximation which gives relationship between index refraction structure parameter C_n^2 and relative variance of optical intensity fluctuation as the following formula [26-29]:

$$\pm_I = \sqrt{0.5\, C_n^2 \left(\frac{2®}{ª}\right)^{7/6} L^{11/6}} \qquad (15)$$

Where L is the link range (distance between transmitter and receiver). Both signal to noise ratio (SNR) and bit error rate (BER) are used to evaluate the quality of optical communication systems. BER performance depends on the average received power, the scintillation strength, and the receiver noise. With appropriate design of aperture averaging the received optical power could be increased as well as reducing the effect of the scintillation. The SNR with turbulence in terms of the mean signal and noise intensity I_0 and I_n, is given as with taken into account the approximation [30]:

$$SNR\,(dB) = 10\,\log\left(\frac{1}{0.31 C_n^2 \left(\frac{2®}{ª}\right)^{7/6} L^{11/6}}\right) \qquad (16)$$

For optical wireless links with on-off keying (OOK) modulation scheme the BER is considered [31] as:

$$BER = \frac{\exp(-0.5\, SNR)}{\sqrt{2®\, SNR}} \qquad (17)$$

III. SIMULATION RESULTS AND PERFORMANCE ANALYSIS

The model has been investigated to enhance the high signal quality and best performance of wireless optical communication networks for high visibility line of sight between transmitter and receiver to upgrade signal to noise ratio, received power, link margin, transmission bit rate and decreased BER and then to upgrade the transmission bit distance product. 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.

Table 1: List of Simulation parameters for free space optics communication systems [3, 5, 8, 12, 20].

Operating parameter	Value and units
effective temperature, T	$300 \leq T, K \leq 400$
Propagation length indoor applications, L_{Indoor}	$50 \leq L_{Indoor}, m \leq 300$
Propagation length local area applications, L_{Local}	$1000 \leq L_{Local}, m \leq 6500$
Laser wavelength, λ	$0.85 \leq \lambda, \mu m \leq 1.55$
Wind speed, WS	$5 \leq WS, km/h \leq 20$
Solar flux, SF	$0.1\ kW/m^2$
Relative humidity, RH (%)	35 %

Based on the modeling equations analysis and the assumed set of the operating system parameters as shown in Table 1, the following facts are assured as shown in the series of Figs. (1-16):

i) Fig. 1 has indicated that the maximum transmission distance increases with increasing of both operating optical laser signal wavelength and visibility range under the same operating conditions and air weather. It is observed that the increased visibility range this results in the increased maximum transmission distance.

ii) Fig. 2 has indicated that maximum permissible exposure increases with both increasing laser irradiation exposure time and operating laser signal wavelength.

iii)As shown in figs. (3, 4) have assured that refractive index structure turbulence strength increases with increasing altitude above ground level, effective temperature, and wind speed.

iv) As shown in figs. (5-8) have assured that laser intensity fluctuations increases with increasing altitude above ground level, effective temperature, propagation length and wind speed. These figs. (5, 6) have presented the lowest laser intensity fluctuations for the lowest both altitude above ground level and propagation length for indoor area applications. While the series of Figs. (7, 8) have presented the highest laser intensity fluctuations for the highest altitude above ground level and propagation length for local area network applications.

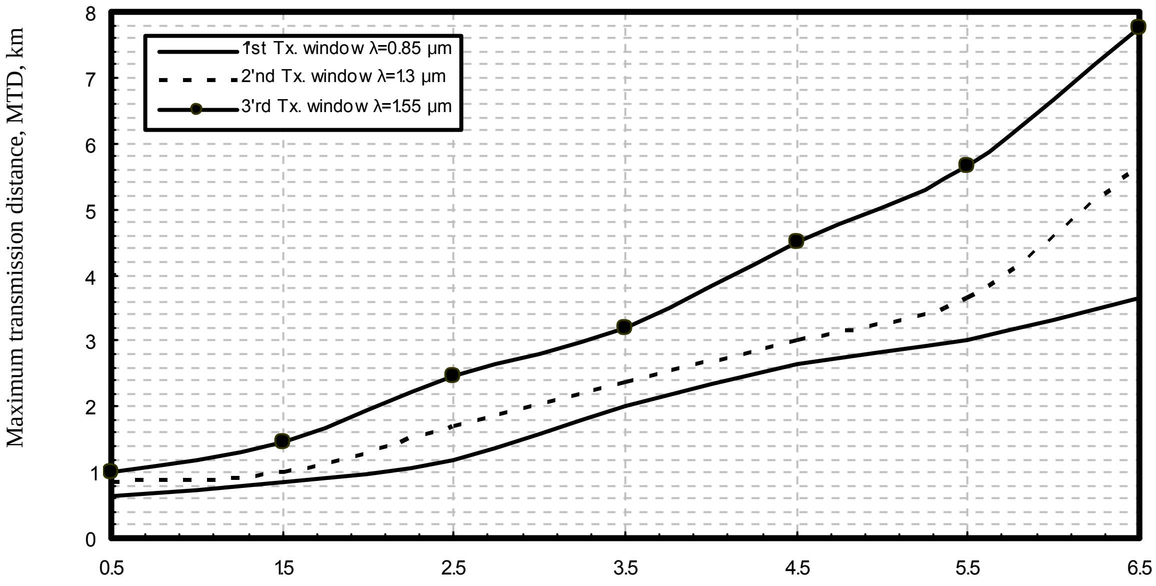

Fig. 1. Maximum transmission distance in relation to medium visibility and operating optical signal wavelength at different transmission windows at the assumed set of the operating parameters.

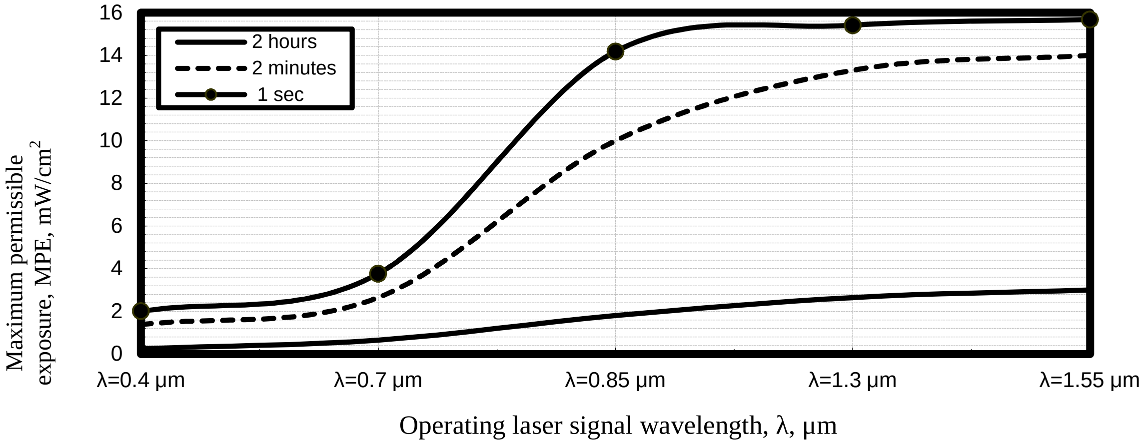

Fig. 2. Maximum permissible exposure in relation to operating laser signal wavelength and laser irradiation exposure time at the assumed set of the operating parameters.

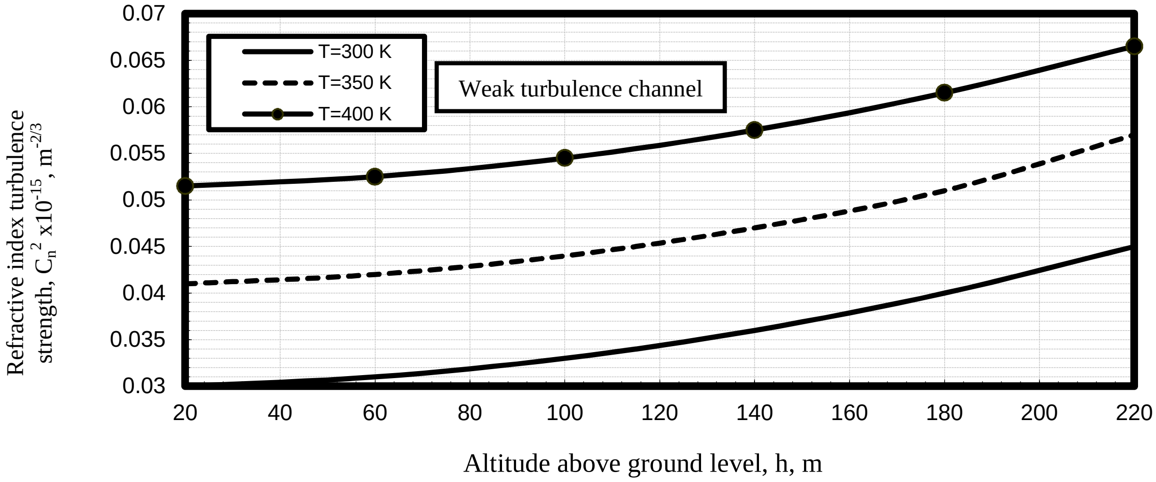

Fig. 3. Refractive index structure turbulence strength against altitude above ground level and effective temperature with wind speed (WS=12.5 km/sec) at the assumed set of the operating parameters.

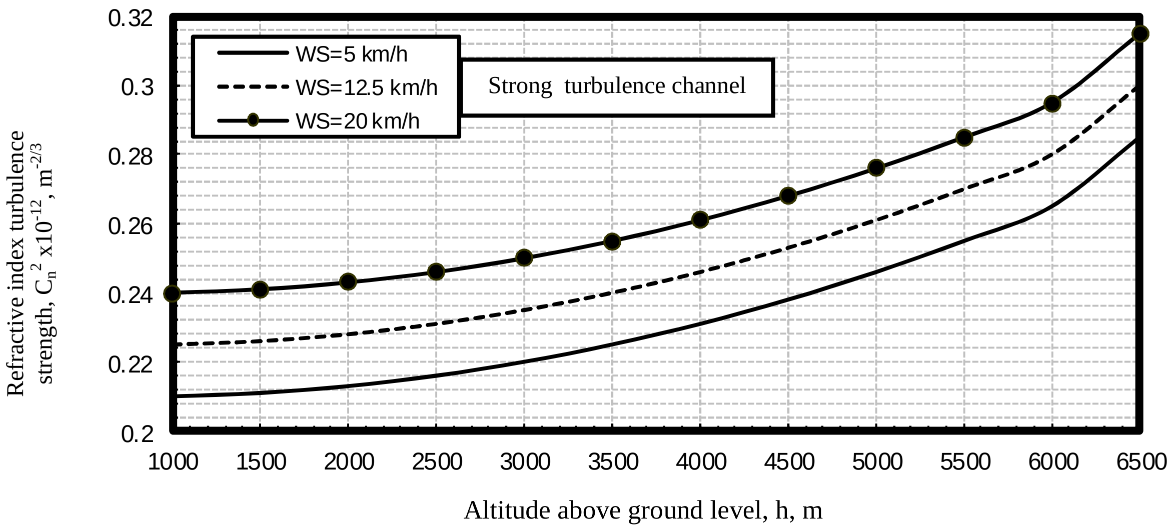

Fig. 4. Refractive index structure turbulence strength against altitude above ground level and wind speed with effective temperature (T=400 K) at the assumed set of the operating parameters.

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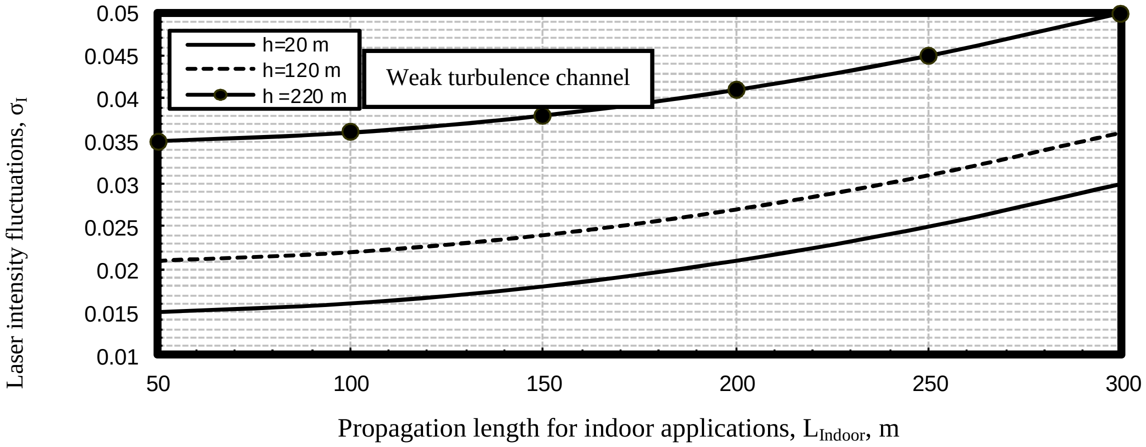

Fig. 5. Laser intensity fluctuations against propagation length for indoor applications and altitude above ground level with average wind speed, third operating laser wavelength (λ=1.55 μm) and effective room temperature (T=300 K).

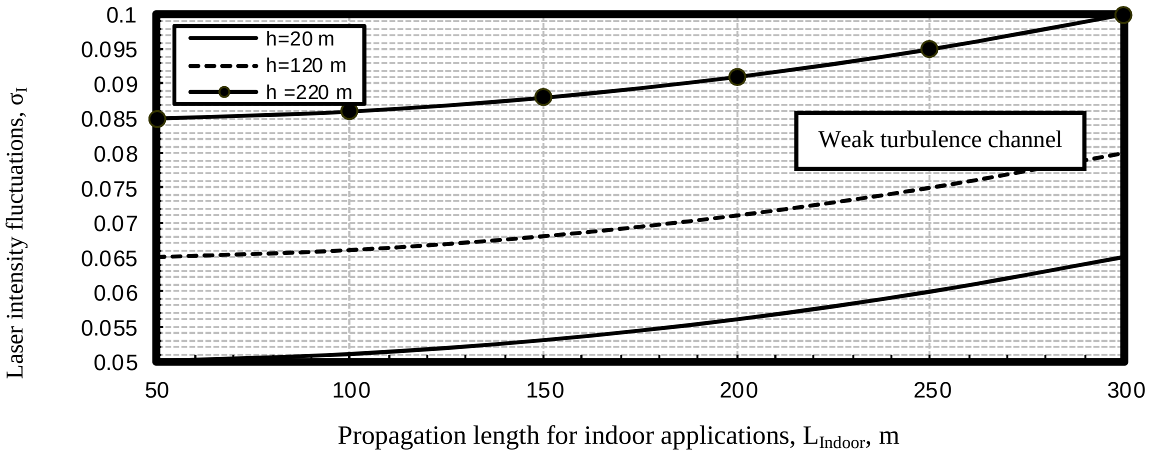

Fig. 6. Laser intensity fluctuations against propagation length for indoor applications and altitude above ground level with average wind speed, third operating laser wavelength (λ=1.55 μm) and effective temperature (T=400 K).

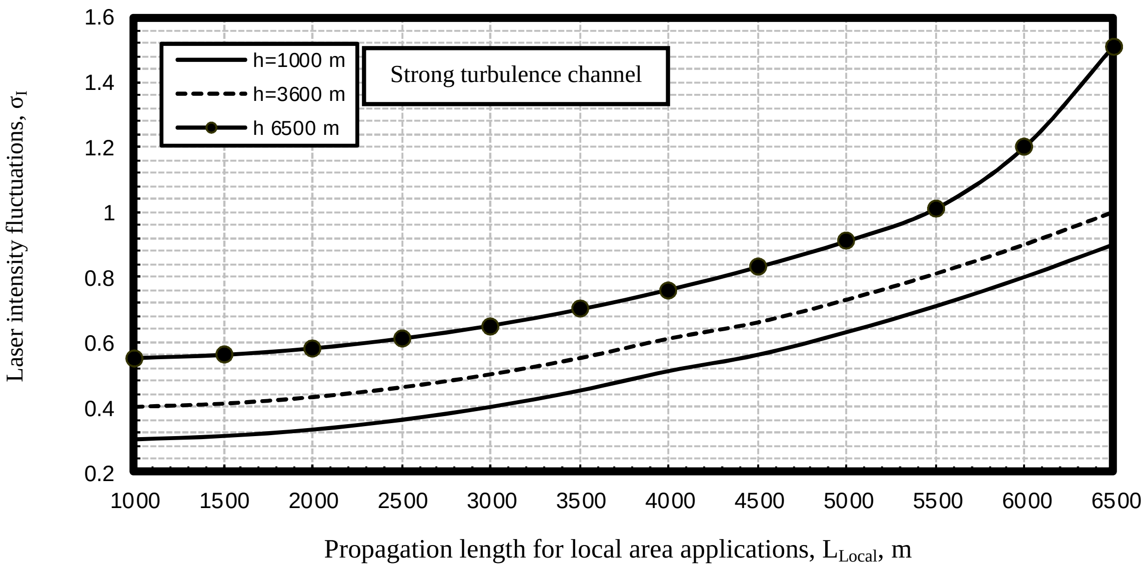

Fig. 7. Laser intensity fluctuations against propagation length for local area network applications and altitude above ground level with average wind speed, third operating laser wavelength (λ=1.55 μm) and effective room temperature (T=300 K).

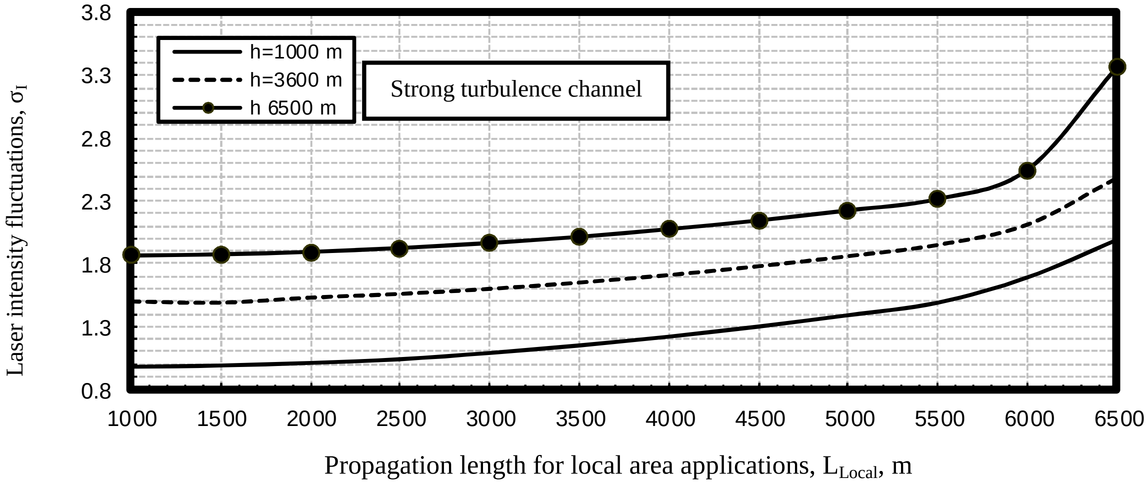

Fig. 8. Laser intensity fluctuations against propagation length for local area network applications and altitude above ground level with average wind speed, third operating laser wavelength (λ=1.55 μm) and effective temperature (T=400 K).

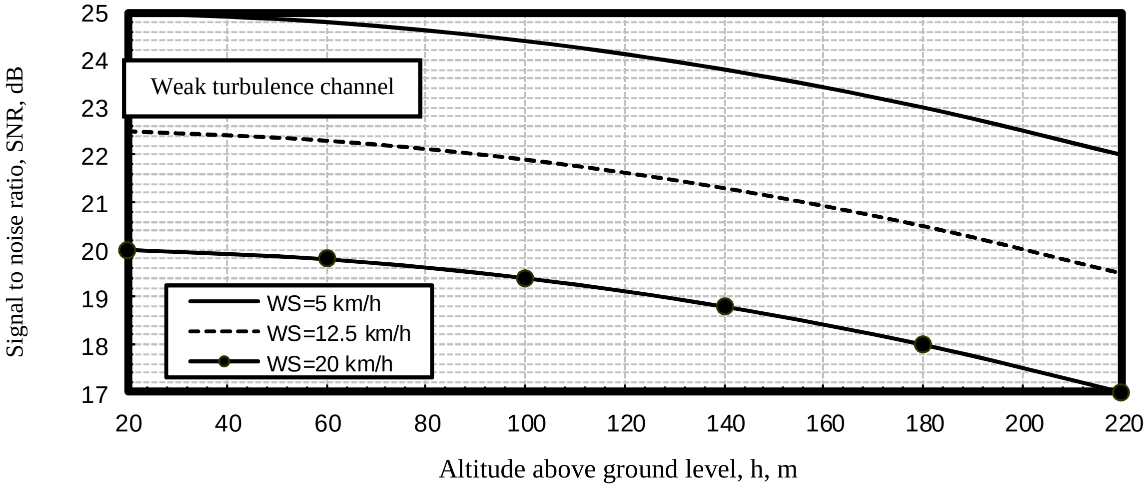

Fig. 9. Signal to noise ratio versus altitude above ground level and wind speed variations for propagation length through indoor applications (L_{Indoor}=50 m), effective room temperature (T=300 K), and third operating laser wavelength (λ=1.55 μm).

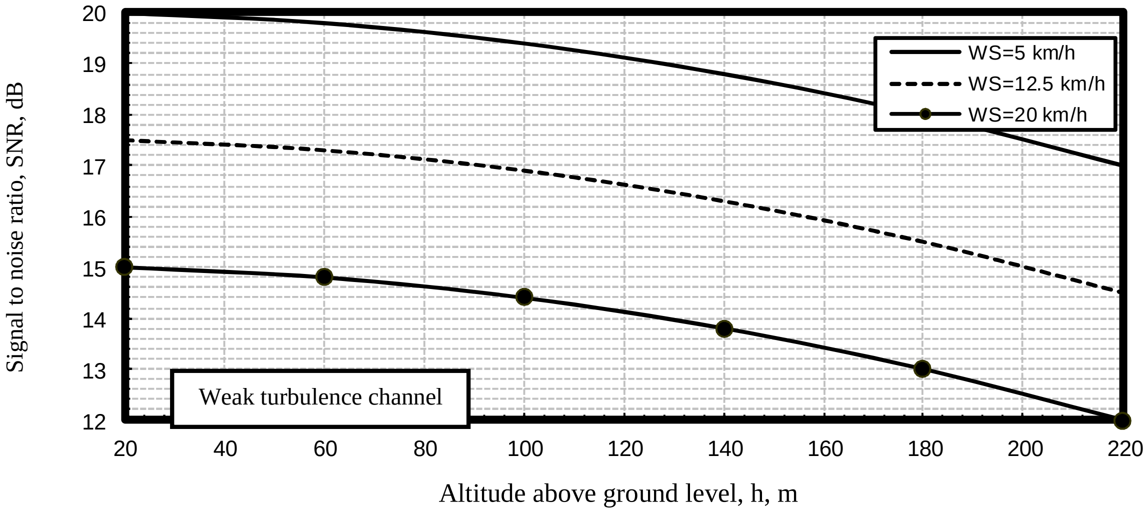

Fig. 10. Signal to noise ratio versus altitude above ground level and wind speed variations for propagation length through indoor applications (L_{Indoor}=300 m), effective room temperature (T=300 K), and third operating laser wavelength (λ=1.55 μm).

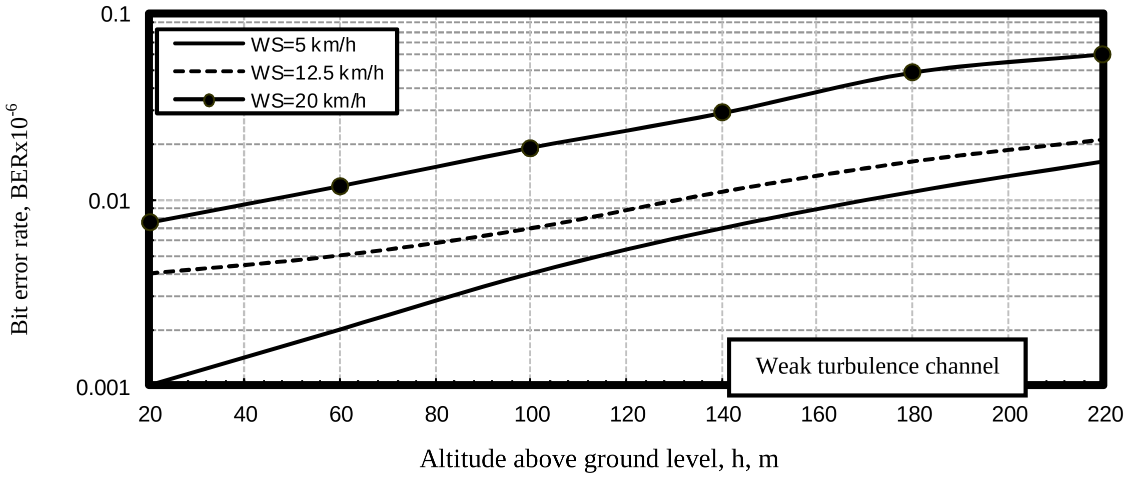

Fig. 11. Bit error rate against altitude above ground level and wind speed variations for propagation length through indoor applications (L_{Indoor}=50 m), effective room temperature (T=300 K), and third operating laser wavelength (λ=1.55 μm).

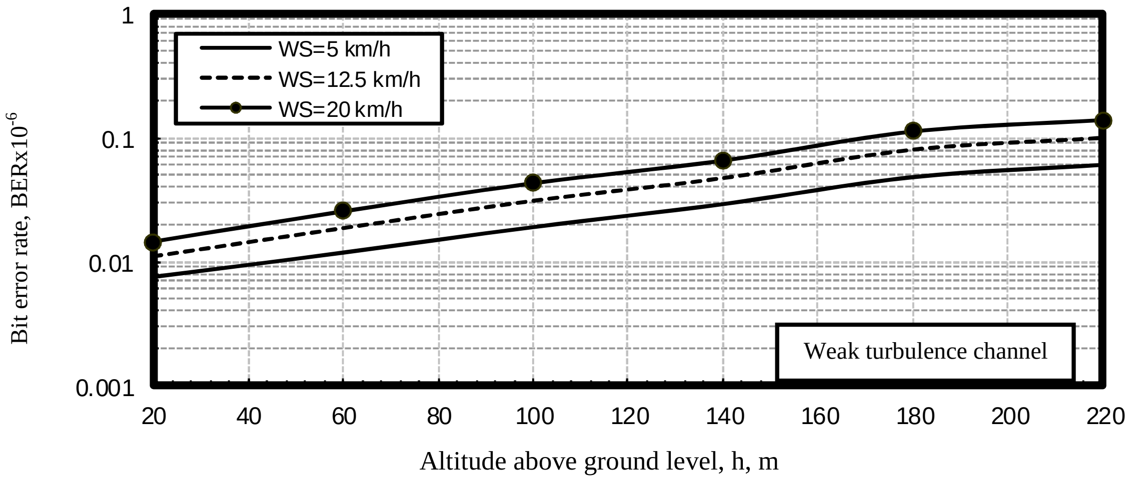

Fig. 12. Bit error rate against altitude above ground level and wind speed variations for propagation length through indoor applications (L_{Indoor}=300 m), effective room temperature (T=300 K), and third operating laser wavelength (λ=1.55 μm).

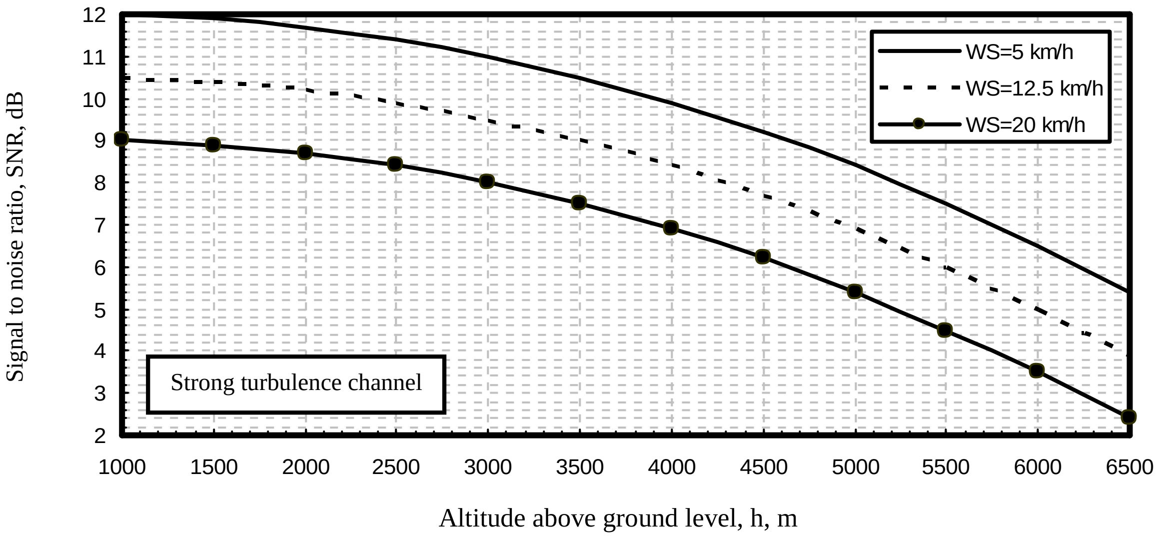

Fig. 13. Signal to noise ratio versus altitude above ground level and wind speed variations for propagation length through local area network applications (L_{Local}=1000 m), effective room temperature (T=300 K), and third operating laser wavelength (λ=1.55 μm).

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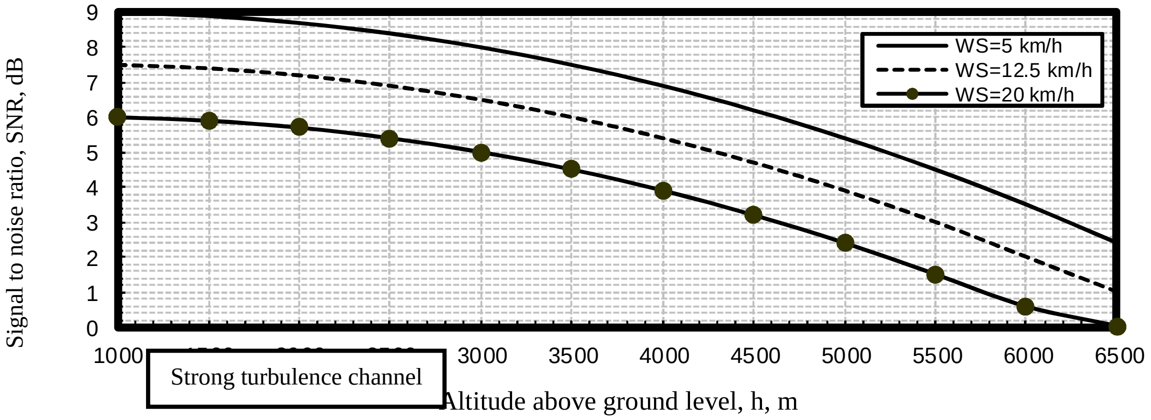

Fig. 14. Signal to noise ratio versus altitude above ground level and wind speed variations for propagation length through local area network applications (L_{Local}=6500 m), effective room temperature (T=300 K), and third operating laser wavelength (λ=1.55 μm).

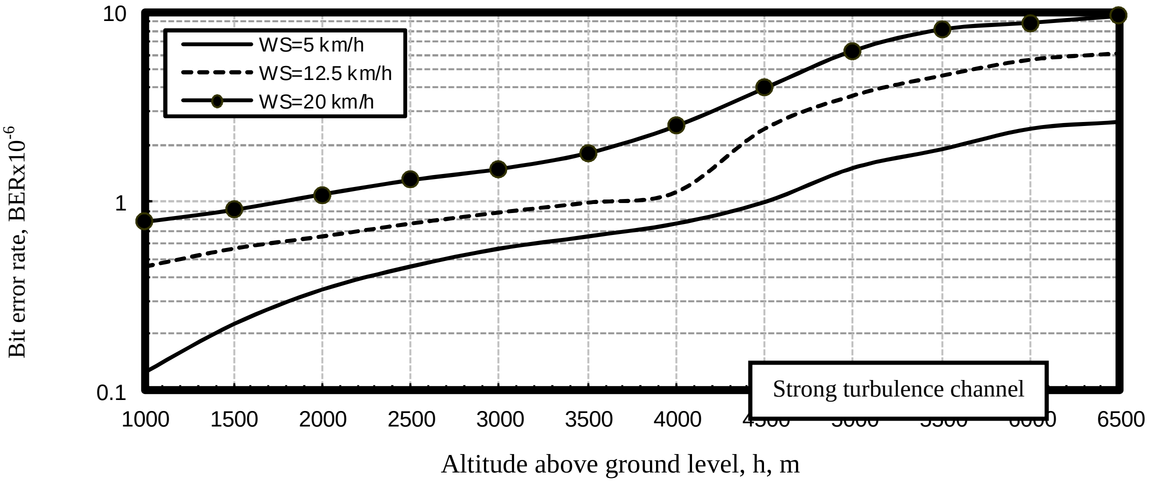

Fig. 15. Bit error rate against altitude above ground level and wind speed variations for propagation length through local area network applications (L_{Local}=1000 m), effective room temperature (T=300 K), and third operating laser wavelength (λ=1.55 μm).

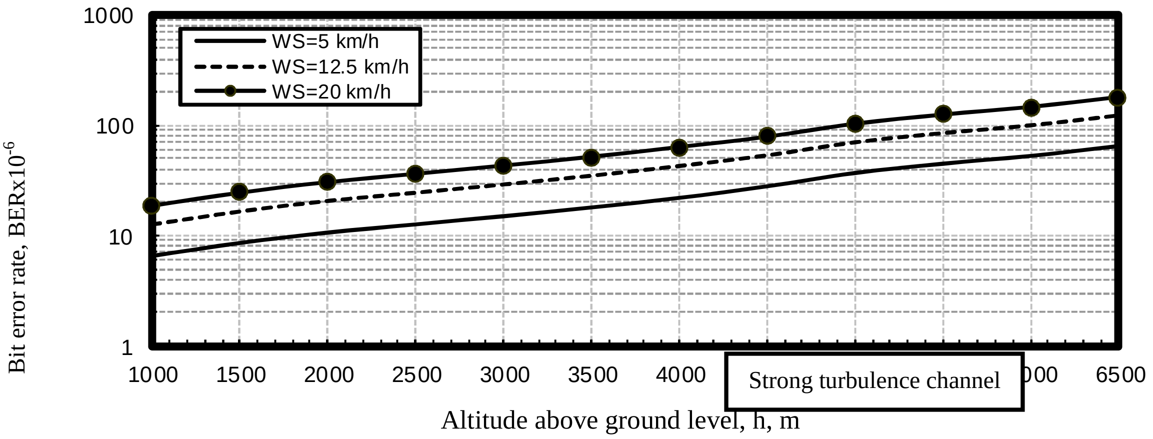

Fig. 16. Bit error rate against altitude above ground level and wind speed variations for propagation length through local area network applications (L_{Local}=6500 m), effective room temperature (T=300 K), and third operating laser wavelength (λ=1.55 μm).

v) Figs. (9-12) have assured that signal to noise ratio decreses but bit error rate increases with increasing wind speed, indoor propagation length and altitude above ground level for indoor area applications. It is observed that with increasing propagation length this results in weak turbulence channel.

vi) As shown in the series of figs. (13-16) have assured that signal to noise ratio decreses but bit error rate increases with increasing wind speed, local area propagation length and altitude above ground level for local area applications. It is indicated that with increasing propagation length this results in strong turbulence channel.

IV. CONCLUSIONS

In a summary, indoor and outdoor optical wireless communication systems in local and wide optical wireless communication network applications have been deeply investigated over wide range of the affecting parameters. It is theoretically found that the increased visibility range, leads to the decreased allowable signal attenuation and so the increased maximum propagation distance. The eye retina is safe up to 560 mW/cm^2 for one second exposure and up to 100 mW/cm^2 for 100 seconds or longer exposure when operating at λ>1.4 μm [19]. This sharp increase of safety threshold is due to water absorption in the cornea preventing laser power from reaching the retina. It is theoretically found that the increased wind speed, effective temperature, propagation length, altitude above ground level, this results in the increased refractive index structure turbulence strength, laser intensity fluctuations, bit error rates, and the decreased signal to noise ratio. It is observed that for local area applications have presented the dramatic effects on channel turbulence, SNR, and BER in compared with indoor area applications. This research has present different visibility ranges to have different propagation distances to be suitable in indoor and local area network (LAN) areas network wireless transmission applications.

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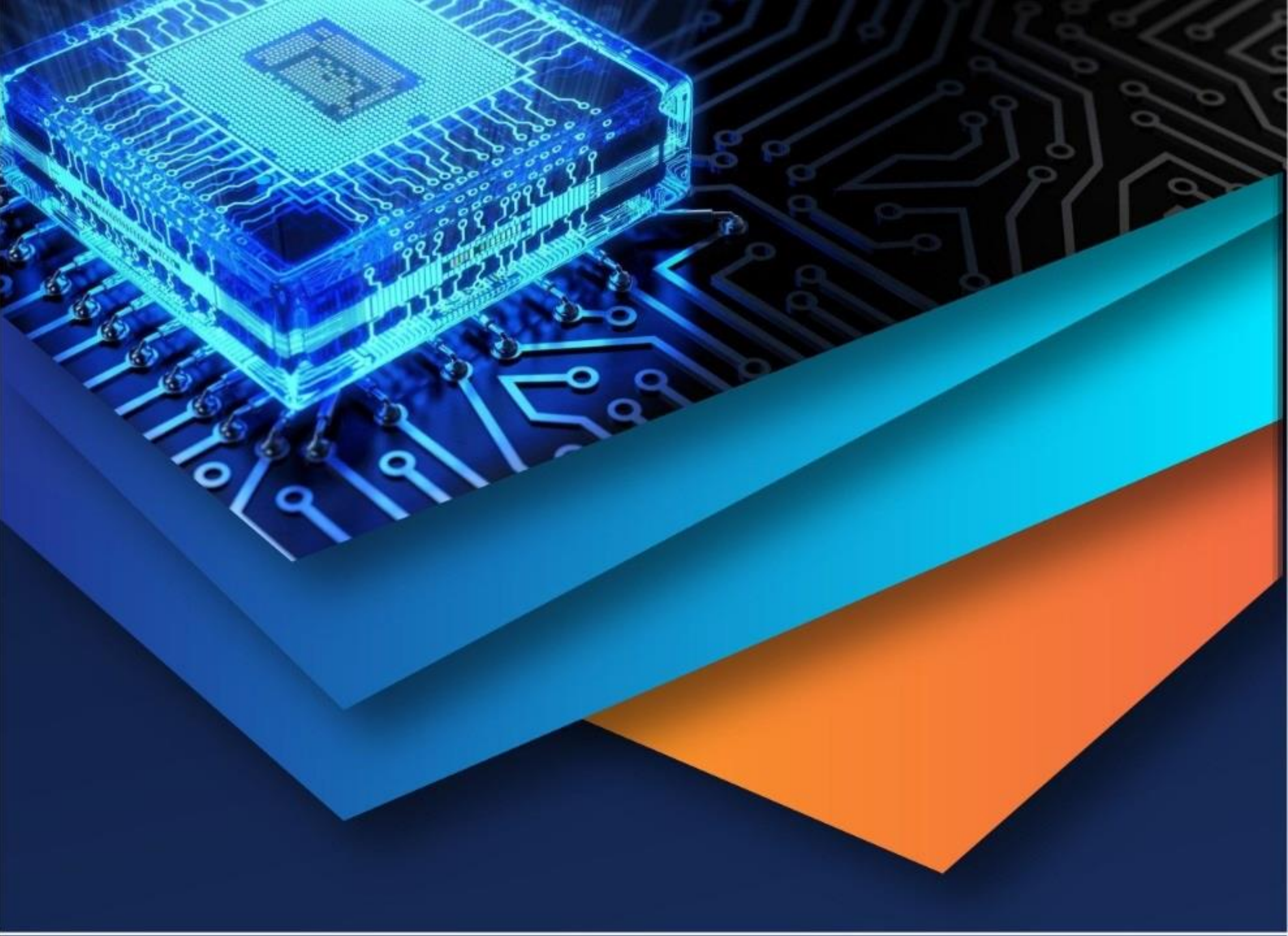

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