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The Investigation of SNR for Free Space Optical Communication Under Turbulence

Türbülans Altında Serbest Alan Optik Haberleşmede SNR Araştırması

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Abstract

Atmospheric turbulence is a significant attenuation effect in free-space optical communication systems. The turbulence varies according to the vertical distance, temperature, pressure and wind speed. In this study, SNR values with three different wavelengths and turbulence strength were analyzed up to 10 km altitude. As a result of the analysis, the SNR values were compared according to height and turbulence values.

Keywords: Free space optic, Turbulence, Signal to noise ratio

Öz

Atmosferik türbülans, serbest alan optik iletişim sistemlerinde önemli bir zayıflatma etkisidir. Türbülans, dikey mesafe, sıcaklık, basınç ve rüzgar hızına göre değişmektedir.

Bu çalışmada üç farklı dalga boyunda (1064nm, 976nm ve 850nm) ve türbülans altında SNR değerleri 10 km yüksekliğe kadar analiz edilmiştir. Analiz sonucunda yükseklik ve türbülans değerlerine göre SNR değerleri karşılaştırılmıştır.

Anahtar Kelimeler: Serbest uzay optik, Türbülans, Sinyal gürültü oranı

1. Introduction

Free Space Optical (FSO) communication systems have much more advantages over Radio Frequency (RF) based systems. These are, point to point architecture offers higher bandwidth, mesh architecture offers redundancy and higher reliability, point-to-multipoint architecture offers cheaper connections and facilitates node addition. Free-space optical transmission can also provide high-speed links for a variety of applications (Mahdieh ve Pournoury 2010).

Free space optics communications were used for satellite-to-satellite crosslinks, up-and-down links between space platforms and aircraft, ships, other ground platforms, among mobile and stationary terminals within the atmosphere. Recent successes of laboratory, in atmosphere and space demonstrations of free-space optical communications (Li et al. 2015, Tóth et al. 2015, Cao et al. 2017, Parenti et al. 2012, Singhand and Singh 2014) indicate that the technology is ready for experimental set ups.

While these experiments have shown that there are no laws of physics against the realization of such systems, currently, their estimated system costs are still much too high for serious considerations in commercial systems (Chan 2006).

Besides being expensive, laser beam is affected by various atmospheric phenomena as it propagates in free space. These effects are to be weaken the laser beam. But next to them is a great importance for effective communication.

Atmospheric events, including absorption, scintillation, scattering and turbulence effects, can be listed in several ways for attenuation. Attenuation varies with day and night, clear and foggy weather (condition), wind, pressure and temperature variations.

Aerosol scattering caused by rain, snow, and fog results in performance degradations in FSO systems (Yüksel 2005).

The atmospheric turbulence, which is the most important effect, is expressed by the turbulence power. Atmospheric

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turbulence, small-scale, irregular air motions characterized by winds that vary in speed and direction. Turbulence is important because it mixes and churns the atmosphere and causes water vapor, smoke, and other substances, as well as energy, to become distributed both vertically and horizontally (Talay 2006). Atmospheric turbulence affects SNR value of communication channel. In communication systems, signal to noise ratio (SNR) are used for analyze channel quality. The quality of the channel is important for finding out how accurate and ineffective the communication is.

In this study, atmospheric turbulence strength and SNR were investigated depending on the wavelength. The three different wavelengths and turbulence strengths determined and were compared with each other. It is aimed to see the effects of wavelength and turbulence on SNR.

2. Atmospheric Turbulence

The local density of atmosphere is constantly fluctuating because of temperature and pressure fluctuations. In this case it's called atmospheric turbulence (Navidpour et al. 2007). Atmospheric turbulence expressed as turbulence strength refractive index structure parameter $C_n^2(m^{-2/3})$ (Mahdieh 2008). Refractive index parameter expressed by (1),

$$C_n^2 = \left[79x10^{-6}\frac{P}{T^2}\right]C_T(m^{-2/3}) \quad (1)$$

In here *P* atmospheric pressure in mbar, *T* is temperature in Kelvin and $C_T(K^2m^{-2/3})$ is temperature structure parameter. $C_T(K^2m^{-2/3})$ is expressed by (2) difference between two separated point temperatures along *L(m)* distance.

$$C_T = [(T_2 - T_1)^2]L^{\frac{2}{3}})(K^2m^{-2/3}) \quad (2)$$

Turbulence limitations are strong at near ground level because of the heat transfer between ground and air. The temperature drops as the turbulence rises towards the troposphere (Navidpour et al. 2007).

Atmospheric turbulence varies at vertical distances, especially up to 1000 m from Earth, at higher levels it is most effective than the ground level. However, above 1000 m, refractive index structure is independent from ground level $(C_n^2(0))$. Therefore another expression of $C_n^2(m^{-2/3})$, depends on height, altitude, wind speed expressed by (3),

$$C_n^2(h) = A\exp\left(-\frac{h}{100}\right) + 5.94x10^{-53}\left(\frac{v}{27}\right)^2 h^{10}\left(-\frac{h}{1000}\right) + 2.7x10^{-16}\exp\left(-\frac{h}{1500}\right)(m^{-2/3}) \quad (3)$$

In here *h(m)* is height, v is wind speed(m/s), $A(m^{-2/3})$ is nominal value of C_n^2 at the ground level (Cherian et al. 2015). Turbulence is a state of the flow of a fluid in which apparently random irregularities occur in the instantaneous velocities, often producing major deformations of the flow (Saha 2011).

Atmospheric turbulence is classified as weak and strong values which $10^{-17}m^{-2/3}$ or less is weak turbulences, $10^{-12}m^{-2/3}$ or more is strong turbulences (Majumdar ve Ricklin 2008).

In Figure 1 one can see $C_n^2(m^{-2/3})$ values and temperature changing with geometric altitude (Bufton et al. 1972).

Another phenomena is scintillation, consist of signal fluctuations due to atmospheric turbulence. In long distance communications, scintillation limits the data rate and system performance.

Particles such as gases, water vapor and dust in the atmosphere, which creates scattering and absorption effects in the laser beam. Scattering effect is more effective on laser beam than absorption.

These particulates matter decrease the optical signal besides turbulence degrade the quality of signal carrying laser beam. Accordingly laser signal intensity fades at receiver (Majumdar 2015).

Rayleigh, Mie, and geometrical types of scattering classifies by particle sizes (Mohammed and Aly 2016). On Off Keying (OOK) conventional modulation using to mitigate the fading effect comes from atmospheric turbulence. This basic modulation gives low cost and simple application (Odeyemi et al. 2017).

Shown in figure 2 due to atmospheric turbulence unwanted sign as noise added in the laser signal in FSO communication.

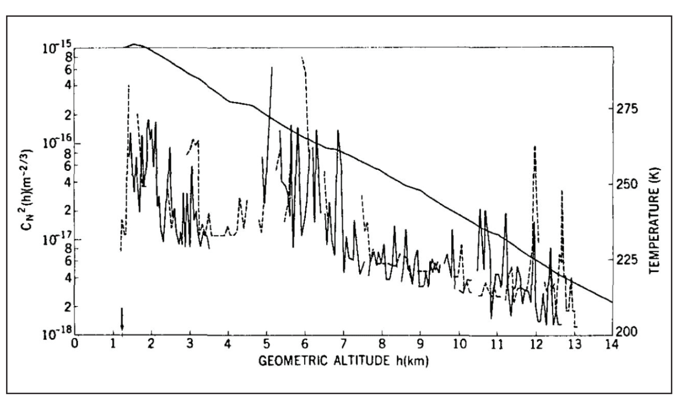

Figure 1. Refractive-index-structure coefficient and temperature vs altitude. (Diagonal line is the corresponding temperature profile. Arrow indicates altitude of launch site.)

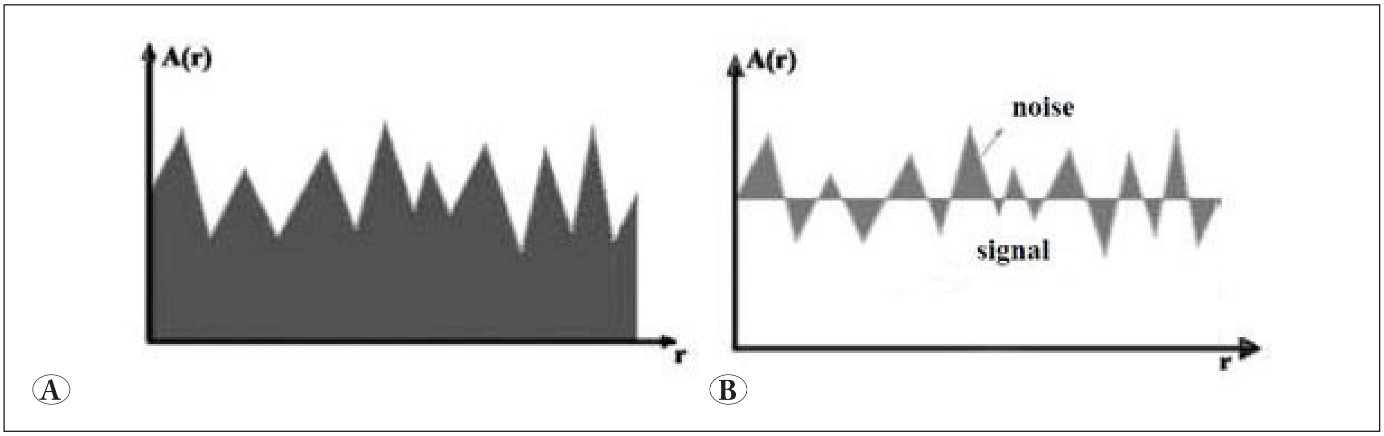

Figure 2. A) Received by receiver, **B)** Simulated signals and noises.

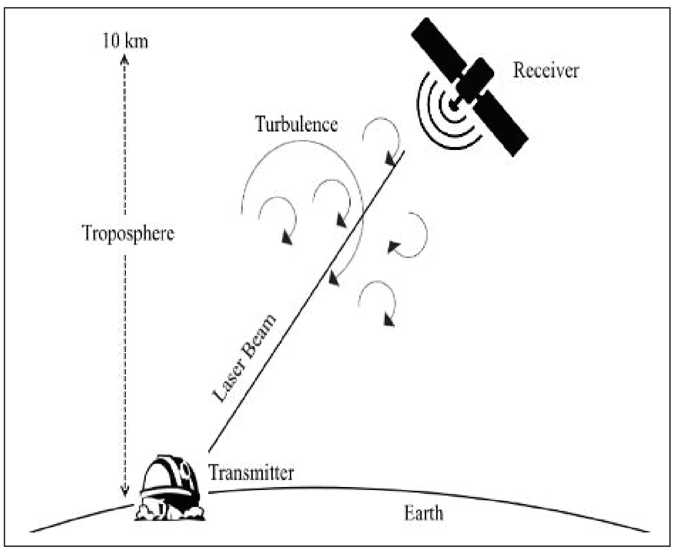

Figure 3. Atmospheric turbulence.

The noise level may be determined with SNR in order to improve the performance of the system. (Guoliang et al. 2004).

In propagation at communication channel, Rytov theory explains that plane wave is (4), (Motlagh et al. 2008)

$$E_0(\vec{r})\exp\left(i\varphi_0(\vec{r})\right)\ E(\vec{r}) = A(\vec{r})\exp\left(i\varphi(\vec{r})\right) = E_0(\vec{r})\exp(\phi) \tag{4}$$

$A_0(\vec{r})$ is amplitude of the laser beam in the atmosphere without turbulence φ and $E_0(\vec{r})$ the phase and laser beam profile. In Equation (4), *A(r)* is laser beam amplitude at turbulence conditions. Ø is exponential factor when given turbulence as (5),

$$\phi = Ln\left(\frac{A(\vec{r})}{A_0(\vec{r})}\right) + i\left(\varphi(\vec{r}) - \varphi_0(\vec{r})\right) = \chi + iS \tag{5}$$

In here (5), χ is ripple of the amplitude, *S* is phase fluctuations. Rytov suggested variance as (6)

$$\sigma^2_{\ln IR} =< (\ln I - < \ln I > ^2) >= 1.23 C_n^2 k^{7/6} L^{11/6} \tag{6}$$

In here (6), *I(W/sr)* light intensity, *k(rad/m)* wave number, *L(m)* propagation length is distance between receiver and transmitter.

We can arrange for FSO system for irradiance variance as (7),

$$< \chi^2 >= 0.31 C_n^2 k^{7/6} L^{11/6} \quad \chi = In\left(\frac{A(r)}{A_0(r)}\right) = In(1+\varepsilon) \approx \varepsilon \tag{7}$$

$$\varepsilon = \frac{A_n(r)}{A_0(r)} \tag{8}$$

SNR with signal and noise intensity defined by (9)

$$SNR = \frac{I_0}{I_n} = \frac{A_0^2(r)}{A_n^2(r)} = [\varepsilon^2]^{-1} \tag{9}$$

Here, $I_0\left(\frac{W}{sr}\right)$ is signal intensity, $I_n\left(\frac{W}{sr}\right)$ is noise intensity. *An*(*r*) is the amplitude of noise FSO communication is also often used with OOK switching that easy modulation and defined with SNR (Motlagh et al. 2008),

$$SNR = [\langle x^2 \rangle]^{-1} = (0.31 C_n^2 k^{7/6} L^{11/6})^{-1} \tag{10}$$

Atmospheric turbulence as it shown in the Figure 3, through vertical path propagation, temperature gradient is different at different altitude.

Turbulence is strong at near ground level but as the distance increases upwards turbulence is weak. As seen in Figure 4. clean air atmospheric transmission windows and wavelength. Atmosphere's index of refraction varies depending on place and time due to non-stationary and inhomogeneous situations.

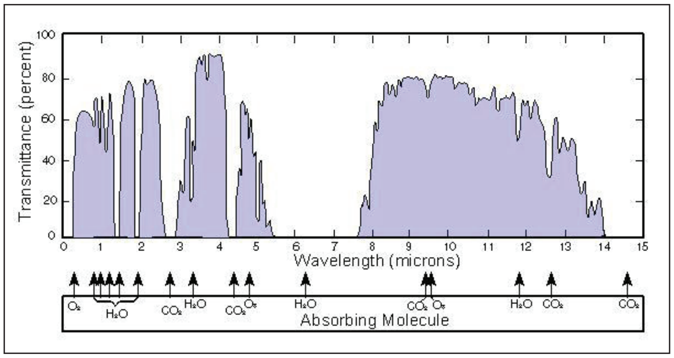

Figure 4. Clear air atmospheric transmission windows.

In the air the areas with different temperatures and pressures create zones with different refraction indices. Various inhomogeneities in the atmosphere affect the beam distortion. It is possible to evaluate the turbulence extent with the help of the structural parameter of the index of refraction. The relative optical variance is,

$$\sigma_{I,rel}^{2} = KC_{n}^{2}\left(\frac{2\pi}{\lambda}\right)^{7/6} L_{12}^{11/6} \tag{11}$$

where K is the constant, 1.23 for the plane wave and 0.5 for the spherical wave. It is possible to use an approximate formula for a weakly turbulent atmosphere to estimate the attenuation α_{turb}, which is caused just by the turbulence,

$$\alpha_{turb} \approx \left| 10\log\left(1-\sqrt{\sigma_{I,rel}^{2}}\right)\right| \tag{12}$$

Attenuation α_{turb} caused by weak turbulence is summarized in Table 1 the characteristic time period of the turbulence effect is of about several milliseconds.

Table 1. Attenuation caused by turbulence, L_{12}=850m

C_n^2	αturb	Turbulence
10^{-14}	3.2	Weak
10^{-15}	0.82	Very Weak
10^{-16}	0.25	Calm

This phenomenon can be regarded as changing relatively fast. The links operating in suburban localities with areas of green vegetation have problems with the presence of birds that can disturb the beam. (Kvíčala et al. 2007).

2.1 Atmospheric content and models

The atmosphere of Earth is composed of several gases which it contain 78.09% nitrogen, 20.95% oxygen, 0.93% argon, 0.04% carbon dioxide and small amounts of other gases and water vapor. Also has small and large particulates which are solid or liquid matters. The optical attenuation caused by the particles is very important for the SNR values.

The parameter establishing the degree of particle dispersion is the Stokes number St which is the ratio between the particle response time to the flow time scale,

$$St = \frac{\tau_p}{\tau_g} \tag{13}$$

Particles with St << 1 respond instantaneously even to the smallest eddies of the flow and as a result the turbulent particle diffusion is the same as for the fluid. For St >> 1 particles are not affected by the turbulence they will retain the memory of their previous velocity and their turbulent diffusion is thus approximately zero. Particles with St ~ 1 will filter high frequency turbulence fluctuations and will be centrifuged to the peripheries of the turbulent structures. In this regime the turbulent particle diffusion will be larger than the turbulent diffusion of the fluid because particles have smaller velocity fluctuations but larger autocorrelation time than the flow.

Particles with St ~ 1 tend to have a convective drift in non-homogeneous turbulent flows as they move from regions with high gas turbulence intensity to regions with low gas turbulence intensity.

This is because particles are “thrown” out from regions of high turbulence intensity to regions of lower turbulence intensity where there are no eddies with enough energy to disperse the particles back. This leads to a mean migration of particles counter to the fluctuating velocity gradient, which is often referred to as the effect of turbophoresis. Turbophoresis is the tendency for particles to migrate in the direction of decreasing turbulence level (Strömgren 2008).

Scattering and absorption effects along the transmission line vary with wavelength. According to atmospheric transmission windows, 3 µm to 4 µm wavelengths are absorbed by H2O. 8 µm to 14 µm wavelengths are absorbed by CO2, O3, H20. Absorption degrades photon energy and laser beam power density at receiver (Plank et al. 2012).

While atmospheric turbulence is modeled, channel models are proposed for the turbulence force. These models are Lognormal, Negative Exponential, Gamma-Gamma, K channel and I-K channel modelling. The lognormal turbulence model shown in Figure 5 is valid only for weak turbulence conditions and for travel distances of 100 m lower.

σ_I is the standard deviation of ln(*O*), the pdf of the received optical field *O* is given as *f (O)*. For negative exponential model, during communication, growth of the scattering may lead Rayleigh distribution that became negative exponential statistic for the signal intensity shown in Figure 6.

Large scale and small scale turbulent eddies and each of them follows gamma distribution. This gives the gamma-gamma turbulence model. K channel model is a model that is a perfect fit between theoretical and experimental and is used in strong turbulence. The I-K model is obtained by adding the weak turbulence to the K channel model. I-K can be used both weak and strong turbulence (Shah et al 2014).

3. Materials and Method

In this section, relations between SNR and distance are calculated with equation (10). Three different wavelength in transmission windows that 0 to 1 μm was selected. Wavelengths are taken as 1064 nm, 976 nm and 850 nm.

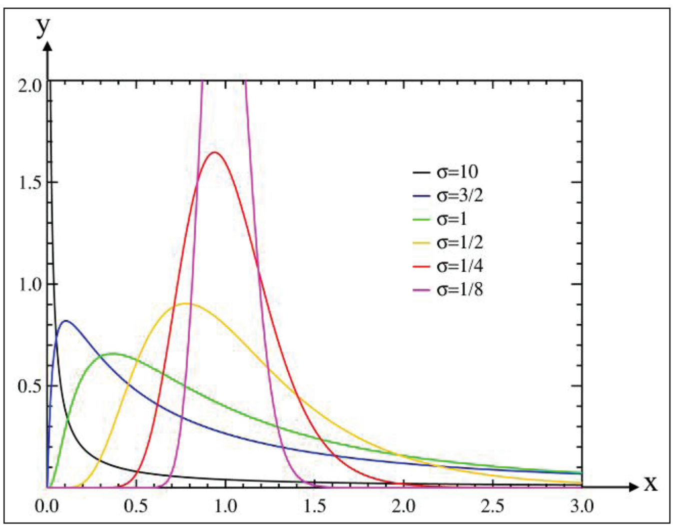

Figure 5. Lognormal distribution.

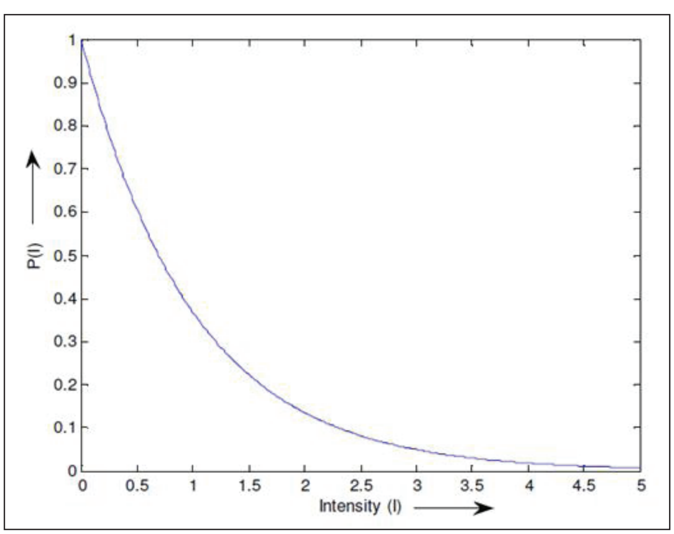

Figure 6. Negative distribution.

Three different turbulence strength were selected to see different conditions.

Turbulence and distance values were changed for selected wavelength and SNR values were found. The turbulence values have been changed from weak to strong. Equation 10 shows that there is a linear correlation between the SNR and the wavelength of 1.6 times.

Reason for choosing 1064nm, since the 1064 nm wavelength can be obtained with various methods of 850 nm and 976nm wavelength. On the other hand 850 nm and 976 nm wavelengths that can be produced by the semiconductor diodes. Semiconductor diodes are small and powerful for using experimental set ups. These three wavelengths are also located near infrared region in electromagnetic spectrum. The aim here is the analysis of the use of the near infrared region in the free space optical field. In Table 2, 3 and 4 calculated SNR values and distance shown.

Figure 7, Figure 8 and Figure 9 respectively 850nm, 976nm and 1064nm wavelength calculated as $C_n^2 = 10^{-17}(m^{-2/3})$ is weak, $C_n^2 = 10^{-12}(m^{-2/3})$ is strong and is very strong $C_n^2 = 117.10^{-9}(m^{-2/3})$ turbulence strength. Strong to weak turbulence conditions and as altitude increases, SNR value decrease. As predicted, the best conditions occur under weak turbulence. The relationship between SNR and distance is the inverse ratio of 1.83, as seen in equation (10).

Table 2. Calculated SNR Values for 850 nm

L(m)	SNR		
	$C_n^2 = 10^{-17}$	$C_n^2 = 10^{-12}$	$C_n^2 = 117^{-9}$
1000	1.38x10^{5}	1.383	1.18x10^{-5}
5000	7.24x10^{3}	0.072	6.19x10^{-7}
10000	2.03x10^{3}	0.020	1.74x10^{-7}

Table 3. Calculated SNR Values for 976 nm

L(m)	SNR		
	$C_n^2 = 10^{-17}$	$C_n^2 = 10^{-12}$	$C_n^2 = 117^{-9}$
1000	1.59x10^{5}	1.588	1.36x10^{-5}
5000	8.31x10^{3}	0.083	7.10x10^{-7}
10000	2.33x10^{3}	0.023	1.99x10^{-7}

Table 4. Calculated SNR Values for 1064 nm

L(m)	SNR		
	$C_n^2 = 10^{-17}$	$C_n^2 = 10^{-12}$	$C_n^2 = 117^{-9}$
1000	1.59x10^{5}	1.588	1.36x10^{-5}
5000	8.31x10^{3}	0.083	7.10x10^{-7}
10000	2.33x10^{3}	0.023	1.99x10^{-7}

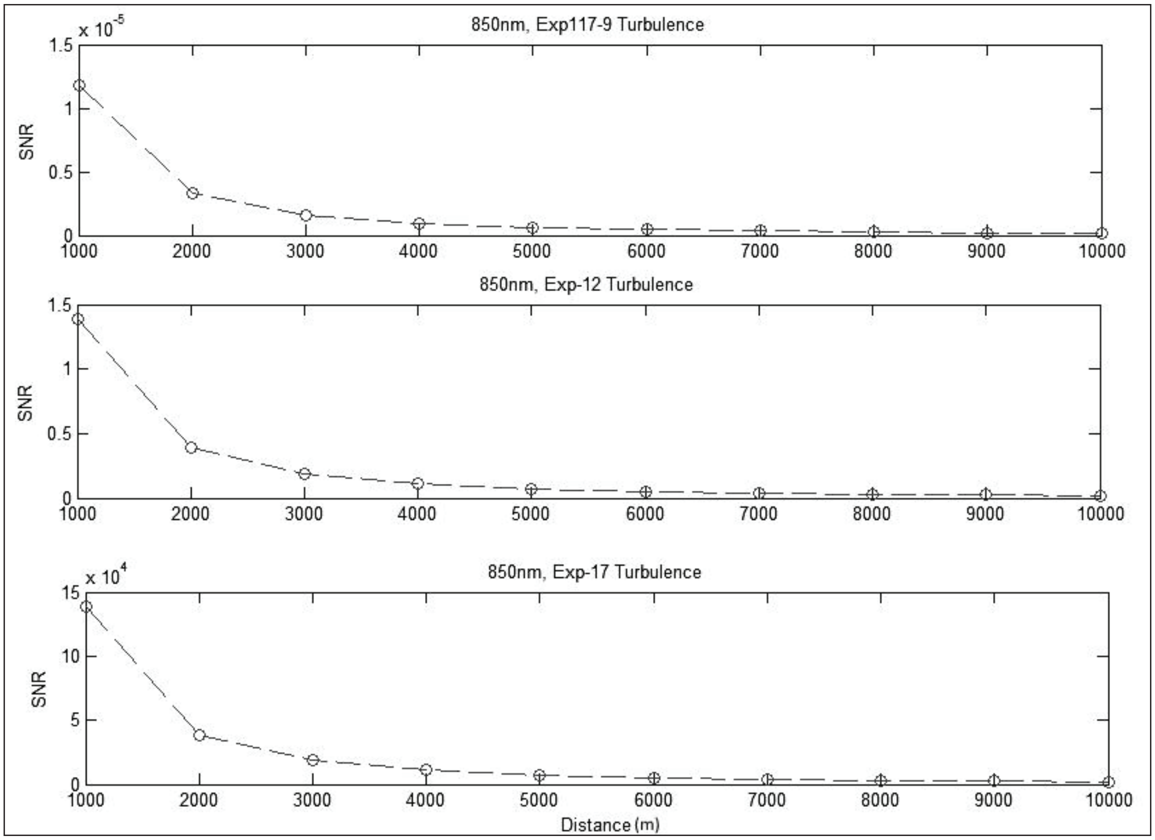

Figure 7. 850 nm wavelength turbulence conditions and SNR.

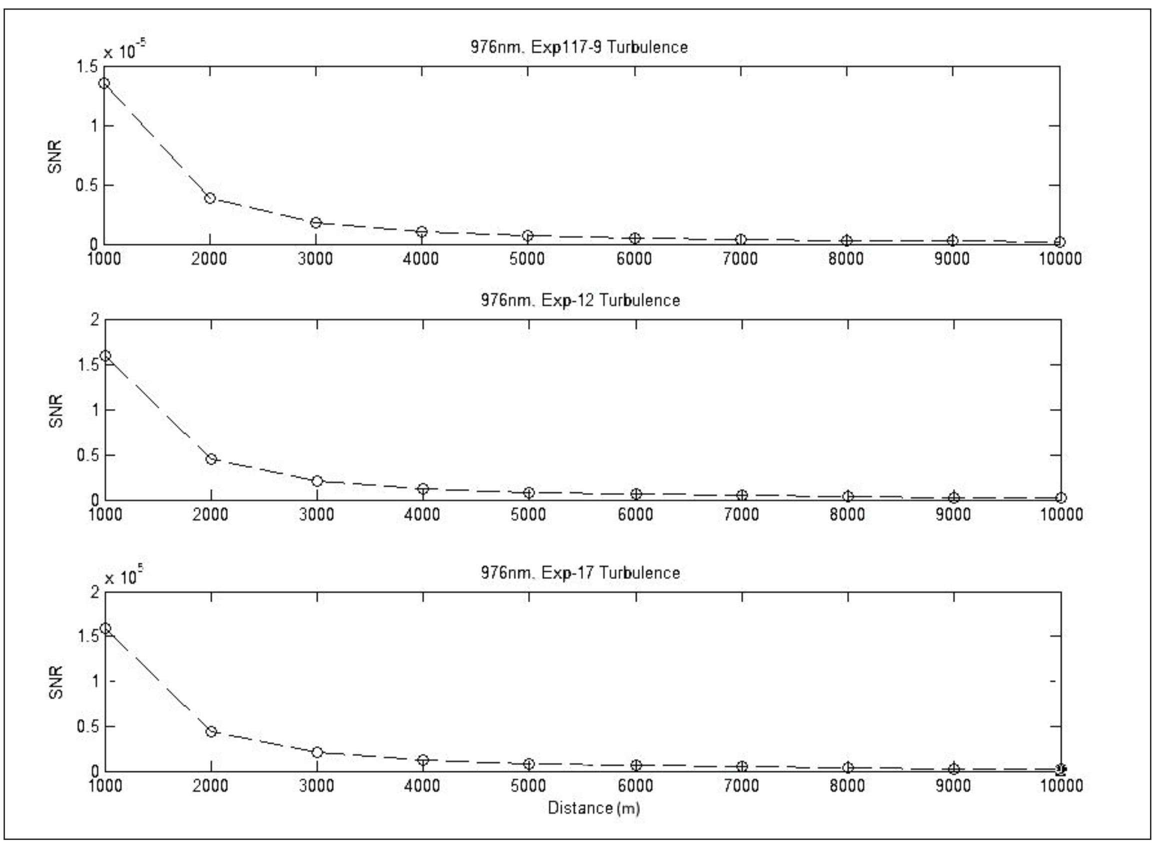

Figure 8. 976 nm wavelength turbulence conditions and SNR.

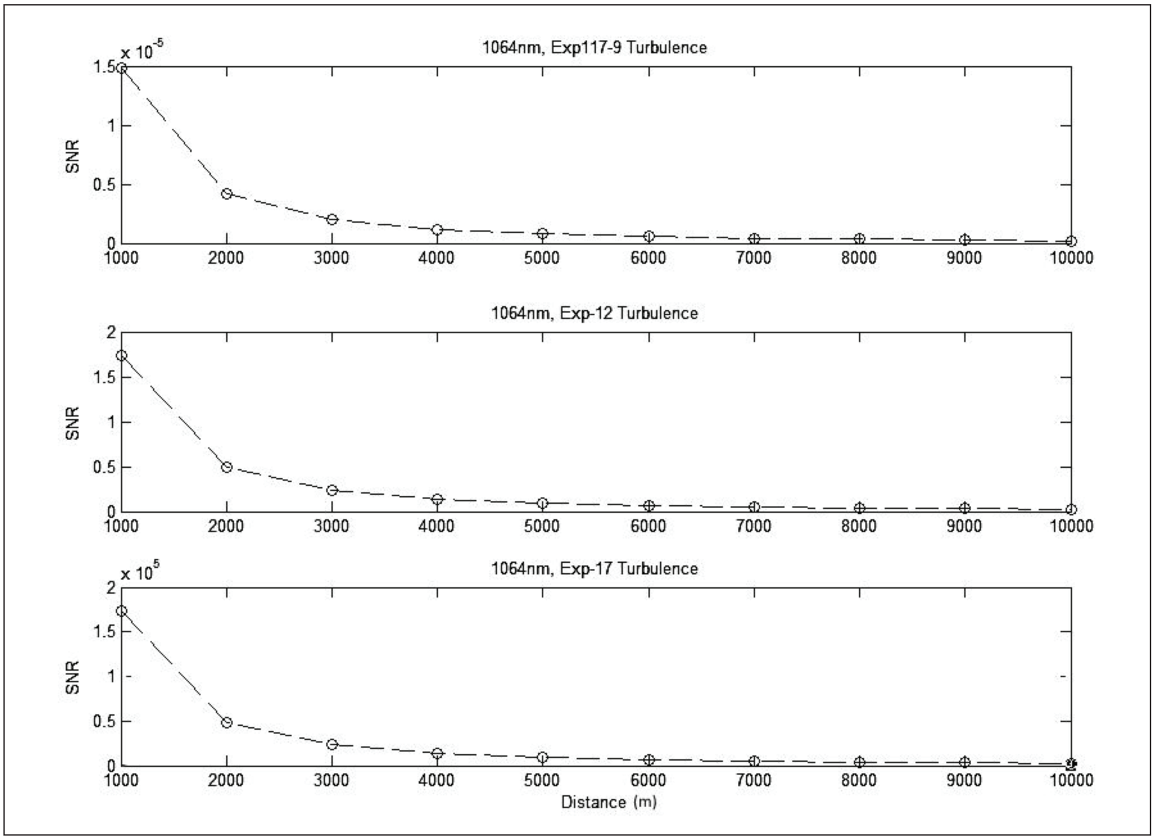

Figure 9. 1064 nm wavelength turbulence conditions and SNR.

4. Results and Suggestions

As the distance increases, the SNR value decreases which the signal quality is reduced.

In three turbulence types, 1064 nm is better than the others at 1000 m to 2000 m altitude. In up to 1000 m, using 1064 nm wavelength laser transmitter is useful for detecting signal to noise ratio for effective communications.

It is observed that reduction in signal properties depends on turbulence strength, distance and wavelength. Since the intensity of the turbulence cannot be controlled, the communication quality can be improved by selecting the appropriate wavelength.

In this paper atmospheric turbulence is considered as a significant parameter the performance of FSO communications. Under weak, strong and very strong turbulence regimes analysis on SNR was performed. It's shown that using 1064 nm wavelength is best performance in strong turbulence and lower altitude for effective communication. This study provides useful information for selecting wavelength in near infrared region.

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