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Ucuk Darusalam, Purnomo Sidi Priambodo, Harry Sudibyo, Eko Tjipto Rahardjo

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Keywords: free-space optical communication (FSOC) system, scintillation, turbulence media, , ,

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Abstract

We report an experimental of free-space optical communication (FSOC) system that use tube propagation simulator (TPS) as the turbulence medium. The FSOC system use wavelength of 1550 nm at the rate transmission of 1000 Mbps and amplified with EDFA at the output of +23 dBm. Index structure of 10^{-15}–10^{-13} as the representation of atmosphere index turbulences are used for simulation of intensity distribution model or scintillation. The simulation use gamma-gamma and K model as well. The beam wave propagation models used in simulation are plane wave, spherical wave and Gaussian wave. Spherical wave achieves highest performance via gamma-gamma in strong turbulence. While Gaussian wave achieves highest performance also via K model. We also found, characteristical FSOC system performance is calculated more accurately with gamma-gamma method for strong turbulence than K model. The performances from gamma-gamma for strong turbulence are $\langle SNR \rangle$ at 22.55 dB, $\langle Prfade \rangle$ at 5.33×10^{-4}, and $\langle BER \rangle$ at 9.41×10^{-6}.

Abstrak

Performansi Sistem Komunikasi Optik Media Atmosfir (*Free-Space Optical Communication*) dalam Kondisi Turbulensi Kuat. Kami melaporkan eksperimen sistem komunikasi optik media atmosfir (FSOC) menggunakan *tube propagation simulator* (TPS) sebagai kanal media turbulen. Sistem FSOC menggunakan panjang gelombang 1550 nm pada tingkat transmisi 1000 Mbps dan penguatan sinyal dengan EDFA pada luaran +23 dBm. Struktur indeks atmosfir pada kisaran 10^{-15}-10^{-13} digunakan sebagai parameter skala turbulensi untuk menghitung distribusi model intensitas atau sintilasi. Simulasi perhitungan menggunakan model statitistik gamma-gamma dan K. Model propagasi gelombang yang digunakan dalam simulasi adalah gelombang datar (*plane wave*), gelombang sirkular (*spherical wave*), gelombang Gaussian (*Gaussian wave*). Gelombang sirkular menghasilkan performansi tertinggi menggunakan model gamma-gamma pada turbulensi kuat. Sedangkan gelombang Gaussian menghasilkan performansi tertinggi menggunakan model K. Kami juga menemukan bahwa karakteristik performansi sistem FSOC dapat terukur lebih akurat menggunakan metode gamma-gamma untuk turbulensi kuat daripada model K. Hal tersebut mengacu pada hasil simulasi dan eksperimen. Hasil tersebut adalah dalam kondisi turbulensi kuat performansi $\langle SNR \rangle$ berada pada rentang 22,55 dB, $\langle Prfade \rangle$ dalam rentang $5{,}33\times10^{-4}$, dan $\langle BER \rangle$ pada rentang $9{,}41\times10^{-6}$.

Keywords: free-space optical communication (FSOC) system, scintillation, turbulence media, $\langle SNR \rangle$, $\langle BER \rangle$, $\langle Prfade \rangle$

1. Introduction

Atmospherical turbulence is the major problem for implementation of free-space optical communication (FSOC) system as terrestrial platform. It caused the media propapagation of beam wave behaves random distribution of refraction index spatially and temporally. This is caused by fluctuation of wind speed, temperature and medium density in randomly fashion. It leads beam wave propagation deterioration such as diffraction, scattering, and attenuation that behaves randomly as well. Those leads to random beam irradiance into the receiver lens. Hence it cause the scintillation phenomena to receiver. By all means the characteristical performance of FSOC system is decreasing [1-3].

Scintillation is fluctuation of signal intensity which is received by photodetector. It also exhibits noise. It is

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represented as intensity distribution of received beam wave that is induced by atmospherical turbulence. Higher degree of scintillation represents the scale of turbulence. The intensity distribution has a charactheristics for each turbulence scale. This cause *SNR* no longer constant but also has the mean value for each turbulence scale. The mean value of *SNR* contributes major parameter to characteristical performance of FSOC system. The mean value of *SNR* determines the rate of probability of fade (*Prfade*) of beam waves in atmospherical turbulence. Higher rate value of probability of fade means lower possibility of photodetector to detect beam wave intensities. It also contributes major factor for mean value of *BER*. The ideal charactheristical performance of FSOC system is the lowest of *Prfade*, lowest mean value of *BER* and higher mean value of *SNR*.

In order to mitigate the deteriorating beam waves by the presence of atmospherical turbulence many methods have been reported successfully overcoming those problem. Multiple beam waves transmission and multiple beam receiver or MIMO has been reported could enhanced the performance FSOC system at signifficant value [3]. Saturated EDFA at transmitter beacon has been reported successfully overcoming high turbulence [4]. In order to shrink wide distribution of scintillation, the spatial diversity has been reported to mitigate high scale of turbulence successfully [5-6]. In order to overcoming beam wander effect, the wide angle of lens receiver in array configuration has been reported in simulation to elevate the FSOC system performance as well [7]. CMOS imaging receiver has been reported in mitigation the induced atmospherical turbulence in order to detect the lowest of signal intensity.

The accuration and precission is also being studied widely in representing the distribution of irradiance or scintillation, in order to improve the characteristical performance. Common statistical methods are gamma-gamma, K, and lognormal [8-9]. Markov chain model in maximum-likelihood has been reported reach improve significant results [10]. Radiative transfer theory also been reported successfully in minimizing *BER* [11]. Wavelet signal processing also being used as optimation method on the receiver unit in reduction *BER* [12].

On this preliminary research we have designed the FSOC system over turbulence media (TPS/tube propagation simulator). TPS is designed to induced beam wave propagation in the scale of weak to strong turbulence. The goal of research is investigation the effect of strong turbulence medium in order to seek the high characteristical performance of FSOC system when it already to be implemented in real atmosphere environment or turbulence. The characteristical performance of system is analyzed with gamma-gamma and K model. Beam wave propagation models are used plane wave, spherical wave and Gaussian wave for simulation.

We compare the results of simulation with analytical measurement of experiment. We also make an analysis comparison with previous work of others that implement gamma-gamma and K model distribution. We have great intention to develop FSOC system that have robust characteristical performance in real atmospherical turbulence.

2. Experiment

Model of FSOC System. Atmospherical turbulence affects the signal intensity which received by photodetector. Signal intensity which propagates from transmitter and reach the receiver lens behaves fluctuation randomly, as can be seen in Eq. 1 [13]:

$$I^0(r, L+L_f) = \frac{W_0^2}{W^2\left(1+\frac{\Omega_G}{\Lambda_1}\right)} exp\left(-\frac{2r^2}{W^2}\right)$$

$$I(0, L+L_f) = \frac{W_G^2}{W_0^2}\frac{I^0(0,L)}{SR} exp\left(-\frac{2r^2}{W^2 SR}\right) \quad (1)$$

W is focus spot behind single finite lens. r is radius of focus spot. $\Omega_G = \frac{2L}{kW_G^2}$ W_G is radius of receiver lens. W_0 is the radius of transmitted beam wave from the sources or TX. $I^0(0,L)$ is the signal intensity in the absence of atmospherical turbulence. SR is the Sthrel ratio of $1+1{,}63\sigma_R^{\frac{12}{5}}\Lambda_1$ which is the function of Rytov factor $D_1G, \Lambda_1 1 \gg \Omega_1 G)$

$$I^0(r, L+L_f) \cong \frac{W_G^2}{W^2} I^0(0,L) exp\left(-\frac{2r^2}{W^2}\right).$$

The signal power is in Eq. 2. $I^0(0,L) = \frac{W_G^2}{W^2} I(0O,L)$ is the instaneous irradiance.

$$P_s \cong \int_0^{2\pi}\int_0^{\infty} I(r, L+L_f)\, r\, dr\, d\theta \;\cong\; \frac{1}{8}\pi D_G^2 I(0,L). \quad (2)$$

The output current of photodetector is the mean value as stated in Eq. 3,

$$\langle I_s \rangle = \frac{\eta e\langle P_s \rangle}{hv}. \quad (3)$$

Integrating Eq. 2, the mean of signal power is given in Eq. 4,

$$P_s\langle P_s \rangle = \frac{1}{8}\pi D_G^2 I(0,L) \cong \frac{\pi D_G^2 I^0(0,L)}{8\left(1+1{,}63\sigma_R^{\frac{12}{5}}\Lambda_1\right)}. \quad (4)$$

The variance of signal noise shall behave,

$$\sigma_{SN}^2 = \langle I_S^2 \rangle - \langle I_s \rangle^2 + \langle I_N^2 \rangle = \left(\frac{\eta e}{hv}\right)^2 \langle \Delta P_S^2 \rangle + \frac{\eta e^2 B \langle P \rangle_S}{hv} \quad (5)$$

$\langle \Delta P_S^2 \rangle = \langle P_S^2 \rangle - \langle P \rangle_S^2$ is the fluctuation of input signal power that contributes to signal noise at photodetector. If $\langle I_s \rangle$ and σ_{SN}^2 is larger then the mean of SNR is given in Eq. 6 [13],

$$< SNR > SNR = \frac{\langle I_s \rangle}{\sigma_{SN}^2} = \frac{\langle P_S \rangle}{\sqrt{\langle \Delta P_S^2 \rangle + \frac{2hvB\langle P_S \rangle}{\eta}}} \quad (6)$$

$< SNR >$ in Eq. 6 can be simplified as stated in Eq. 7,

$$< SNR > = \frac{SNR_0}{\sqrt{\left(\frac{P_{S0}}{\langle P_S \rangle}\right) + \sigma_I^2(D_G) SNR_0^2}} \quad (7)$$

SNR_0 is value of SNR when the turbulence does not induce beam wave propagation. Hence P_{S0} represents the output signal power from photodetector at the absence of turbulence. $\sigma_I^2(D_G)$ is scintillation index within range value of 0-1 [13]. The ratio of output power by the induced of turbulence is $\frac{P_{S0}}{\langle P_S \rangle} \cong 1 + 1{,}63\sigma_R^{\frac{12}{5}} \Lambda_1$. Those ratio is deterioration effect of atmospherical turbulence. $\frac{P_{S0}}{\langle P_S \rangle}$ is the Strehl ratio, which is the characteristical of imaging system. It can be approximated as given in Eq. 8,

$$\frac{P_{S0}}{\langle P_S \rangle} = \cong 1 \quad (8)$$

Hence the <SNR> is the function of SNR_0 and σ_I^2 as can be seen in Eq. 9,

$$< SNR > = \frac{SNR_0}{\sqrt{1 + \sigma_I^2(D_G) SNR_0^2}} \quad (9)$$

Rate detection related with $< SNR >$ is given in Eq. 11,

$$Pr_d = \int_0^\infty \int_{i_T}^\infty p_i(s) p_{i+n}(i|s)\, di\, ds = \frac{1}{2}\int_0^\infty p_i(s)\, erfc\left(\frac{i_T - s}{\sqrt{2}\sigma_N}\right) ds \quad (10)$$

or

$$Pr_d = \frac{1}{2}\int_0^\infty p_I(U)\, erfc\left(\frac{TNR - \langle SNR \rangle u}{\sqrt{2}}\right) du \quad (11)$$

Rate detection is <SNR> when the Ps which represented as $p_I I\ (U)\ p_I I)$ achieves threshold level of photodetector (TNR/threshold to noise ratio). By all means the probability of false alarm rate also exhibits on the photodetector as can be seen in Eq. 12,

$$Pr_{fade} = \frac{1}{2} erfc\left(\frac{TNR}{\sqrt{2}}\right). \quad (12)$$

Also FAR (false alarm rate) has relation with the probability of false alarm rate as stated in Eq. 13,

$$FAR = \frac{B}{2\sqrt{3}} exp\left(-\frac{TNR^2}{\sqrt{2}}\right). \quad (13)$$

In order to evaluate Pr_{fade} in Eq. 12 as function of $<SNR>$ it can be acquired by assummption that the Probability Density Function of irradiance is gamma-gamma as can be seen in Eq. 14,

$$p_i(u) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} u^{\frac{(\alpha+\beta)}{2}-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta u}\right), \quad u > 0. \quad (14)$$

While for K model is,

$$p_i(u) = \frac{2\alpha}{\Gamma(\alpha)} (\alpha u)^{\frac{\alpha-1}{2}} K_{\alpha-1}(2\sqrt{\alpha u}), \qquad u > 0. \quad (15)$$

If the beam wave propagation is modelled as spherical wave, the paramaters of scintillation index of α_{sw} dan β_{sw} in Eq. 16-17, are [13],

$$\alpha_{sw} = \frac{1}{exp\left[\frac{0{,}49\beta_0^2}{\left(1 + 0{,}18d^2 + 0{,}56\beta_0^{\frac{12}{5}}\right)^{\frac{7}{6}}}\right] exp\left[\frac{0{,}49\beta_0^2}{\left(1 + 0{,}18d^2 + 0{,}56\beta_0^{\frac{12}{5}}\right)^{\frac{7}{6}}}\right] - 1} \quad (16)$$

$$\beta_{sw} = \frac{1}{exp\left[\frac{0{,}51\beta_0^2\left(1 + 0{,}69\beta_0^{\frac{12}{5}}\right)^{-\frac{5}{6}}}{\left(1 + 0{,}9d^2 + 0{,}62d^2\beta_0^{\frac{12}{5}}\right)^{\frac{7}{6}}}\right] - 1} \quad (17)$$

$\beta_0^2 = 0{,}5C_n^2 k^{7/6} L^{11/6}$ is Rytov variances of beam wave which propagates through distance L meter. $d = \sqrt{\frac{kD^2}{4L}}$ For the case of plane wave, the index scintillation (α_{pw} dan $\beta_1 pw$) of Eq.18-19 are [13],

$$\alpha_{pw} = \frac{1}{exp\left[\frac{0{,}49\beta_0^2}{\left(1 + 0{,}65d^2 + 1{,}11\beta_0^{\frac{12}{5}}\right)^{\frac{7}{6}}}\right] - 1} \quad (18)$$

$$\beta_{pw} = \frac{1}{exp\left[\frac{0{,}51\beta_0^2\left(1 + 0{,}69\beta_0^{\frac{12}{5}}\right)^{-\frac{5}{6}}}{\left(1 + 0{,}9d^2 + 0{,}62d^2\beta_0^{\frac{12}{5}}\right)^{\frac{7}{6}}}\right] - 1}. \quad (19)$$

Also for the case of Gaussian wave model is given in Eq. 20-21 [13],

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$$\alpha_{gw} = \frac{1}{exp\left[\frac{0{,}49\left(\frac{\Omega_G-\Lambda_1}{\Omega_G+\Lambda_1}\right)^2\beta_0^2}{\left(1+0{,}\frac{4\left(2-\overline{\Theta_l}\right)\left(\frac{\beta_0^2}{\beta_B^2}\right)}{\left(\Omega_G+\Lambda_1\right)\left(\frac{1}{3}-\frac{1}{2}\overline{\Theta_l}+\overline{\Theta_l^2}\right)^{\frac{6}{7}}}+0{,}56(1+\Theta_1)\beta_0^{\frac{12}{5}}\right)^{\frac{7}{6}}}\right]-1} \quad (20)$$

$$\beta_{gw} = \frac{1}{exp\left[\frac{0{,}51\beta_0^2\left(\frac{\square}{1+0{,}69\beta_0^{\frac{12}{5}}}\right)^{-\frac{5}{6}}}{\left(1+\frac{\left[1{,}2\left(\frac{\beta_0^2}{\beta_B^2}\right)^{\frac{12}{5}}+0{,}83\beta_0^{\frac{12}{5}}\right]}{\Omega_G}+\Lambda_1\right)^{\frac{7}{6}}}\right]-1} \quad (21)$$

.

The Rytov variance $(\beta_{\downarrow}B^{\uparrow}2)$ of Eq. 20-21, for Gaussian wave is given in Eq. 22 [13],

$$\beta_B^2 \cong 3{,}86\beta_0^2\left\{0{,}4[(1+2\Theta_1)^2+4\Lambda_1^2]^{\frac{5}{12}}\times cos\left[\frac{5}{6}tan^{-1}\left(\frac{1+2\Theta_1}{2\Lambda_1}\right)\right]-\frac{11}{16}\Lambda_1^{\frac{5}{6}}\right\} \quad (22)$$

.

Finally $\langle BER\rangle$ is given in Eq. 23 [13],

$$\langle BER\rangle = \frac{1}{2}\int_0^{\infty} p_I(U)\, erfc\left(\frac{\langle SNR\rangle u}{2\sqrt{2}}\right) du \quad (23)$$

Proposed experiment. As shown on the Fig. 2-3, FSOC system is fiber detection. Optical modem of full-duplex TX/RX at λ of 1550 nm and rate transmission of 1000 Mbps. For each unit of TX and RX is connected to UTP of PC's in order to perform point-to-point connection. On TX, output of laser transceiver of -2.4 dBm is amplified by EDFA at the output of +23 dBm. The output from EDFA is collimated by beam collimator and transmitted into TPS. Beam wave propagates through turbulence medium of TPS. TPS is designed with various scale of turbulence. It reaches lens focuser (RX). The focus spot is coupled into MMF and detected by Optical Power Meter.

TPS diagram is shown in Fig. 3. It is composed of main tube of 3.5 inch diameter with the length of 2.2 m. The tube is designed to be locallized turbulence medium

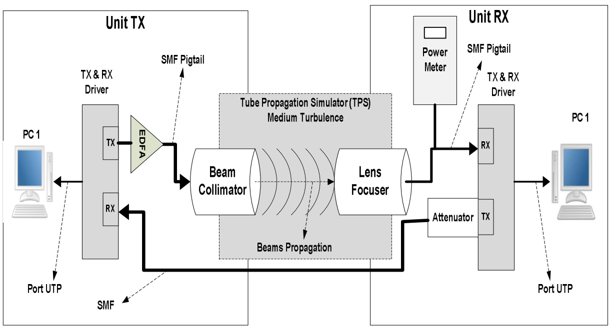


Figure 2. Experiment Diagram of FSOC Fiber Detection Method

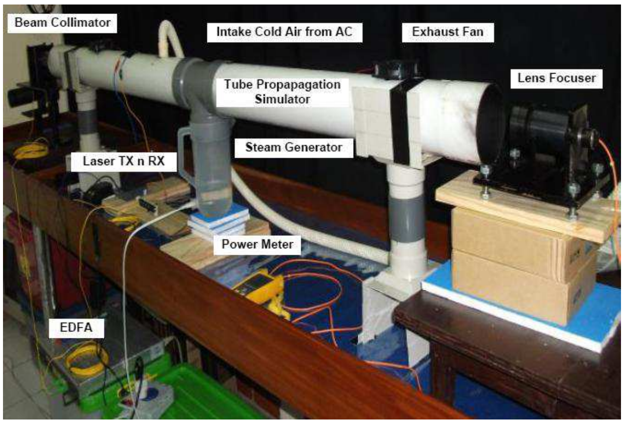


Figure 3. Set-up Diagram of Turbulence Medium as the Optical Beam Wave Propagation (Tube Propagation Simulator/TPS)

which are performed by configuration of exhaust fan, steam generator (SG) and intake cold air (air conditioner, AC). Hence turbulence medium induces beam wave propagation optimally. The scale of turbulence is determined by configurations of those main equipment. Strong turbulence is designed extremely by the collition of cold air from AC (T_{AC} = 16 °C) and steam (T_{SG} > 50 °C) then air is expansioned rapidly by exhaust fan. Through those, the index refraction distribution on TPS is the same conditions as real atmospherical turbulence.

Fig. 2-3 are the proposed experiment set-up for FSOC system that implement full-duplex communication scheme with different wavelength for TX-forward and -backward. In this work we use experiment set-up of Fig. 3 to perform analytical measurement. The analytical measurement is calculated <*SNR*> from data of transmitted and received of signal power. Hence we can compare the characteristical performance of FSOC system between results of simulation and analytical measurement. We equipped Fig. 3 with OSA (Optical Spectrum Analyzer) and BER-T (BER tester) in order to measure *SNR*, *BER*, and spectral analysis.

3. Results and Discussion

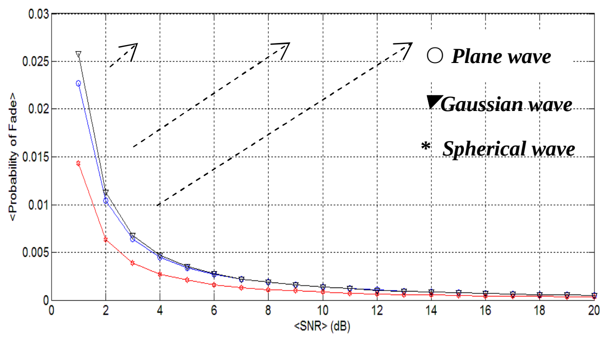
The results of simulation for gamma-gamma model (Eq.14) with the means of probability of fade <*Prfade*> and means of bit error rate <*BER*> as functioned of means of *SNR* (<*SNR*>) are shown in Fig 4.a-b. The models of beam wave propagation are using plane wave, spherical wave, and gaussian wave for strong turbulence and the wavelength is 1550 nm. The index of structure for gamma-gamma and K models is using 10^{-13} for strong turbulence [13]. While the distance of propagation is 1000 m. <*SNR*> is in the range of 0-20 dB. The scintillation index parameter use Eq. 16-21 for each beam waves propagation model.

The results of simulation using K model for <*Prfade*> and <*BER*> are shown in Fig 5.a-b. The index scintillation or decompositon of α and β (gamma-gamma parameters) for each beam waves is resulted from Eq. 16-21.

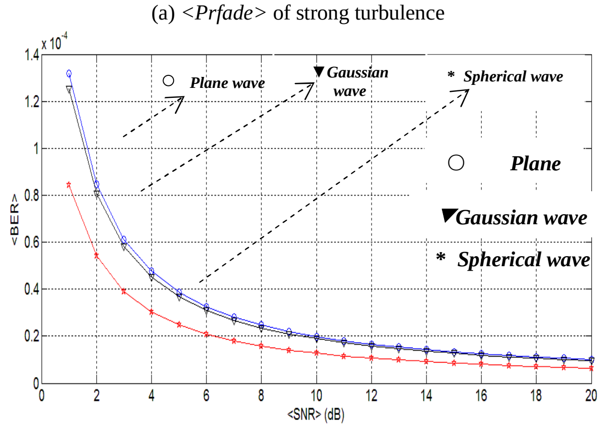
From gamma-gamma and K distribution model for plane wave, spherical wave, and Gaussian wave, it can be seen that (Fig. 4 and Fig. 5): (a) In strong turbulence, spherical wave achieve highest performance, <*Prfade*> is in range value of 0.001–0.015 and <*BER*> is in range order of 0.09×10^{-4}–0.82×10^{-4}. (b) Gaussian wave also achieves highest performance, <*Prfade*> is in range value of 0.01–0.02 and <BER> is in range order of 0.2×10^{-4}–1.5×10^{-4}.

FSOC system performances measurement using gamma-gamma and K distribution for <*Prfade*> and <*BER*> are shown in Fig 6-7. <*SNR*> is the actual values resulted from analytical measurement by comparing signal power at the absence and the present of turbulence on TPS.

From Fig. 6 and Fig. 7, it is shown that gamma-gamma and K measurement method for various scale of turbulence are: (a) In strong turbulence <*SNR*> is

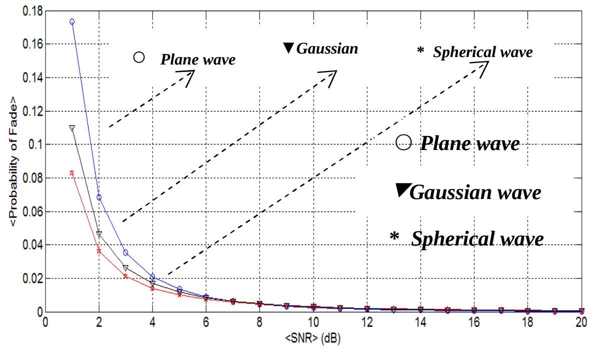


(a) <*Prfade*> of strong turbulence

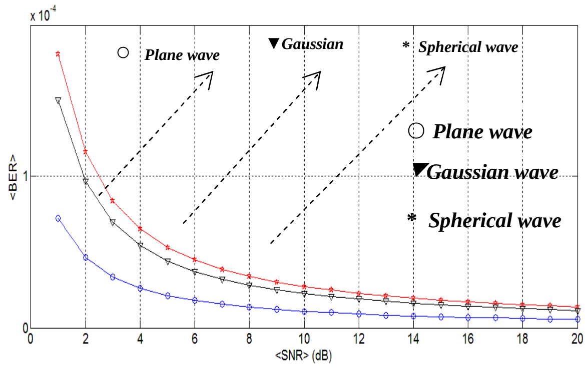


(b) <*BER*> of strong turbulence

Figure 4(a-b). Simulation of Means of Probability of Fade (<*Prfade*>) and Means of *BER* (<*BER*>) Over Strong Turbulence Using Gamma-Gamma Distribution

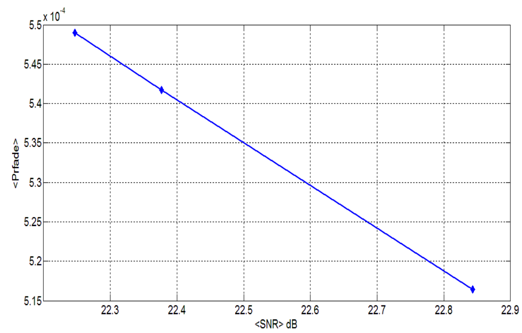


(a) <*Prfade*> of strong turbulence

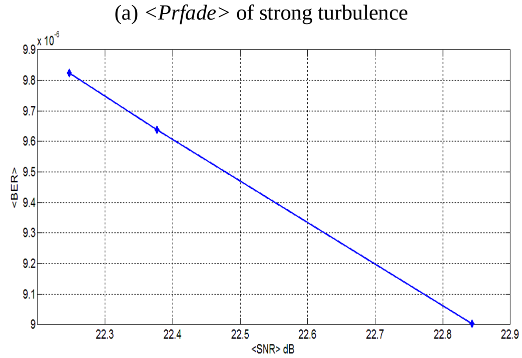


(b) <*BER*> of strong turbulence

Figure 5(a-b). Simulation of Means of Probability of Fade (<*Prfade*>) and Means of *BER* (<*BER*>) Over Strong Turbulence Using K Distribution Model



(a) <*Prfade*> of strong turbulence



(b) <*BER*> of strong turbulence

Figure 6(a-b). Measurements of <*Prfade*> and <*BER*> Over Strong Turbulence Using Gamma-Gamma Distribution Model

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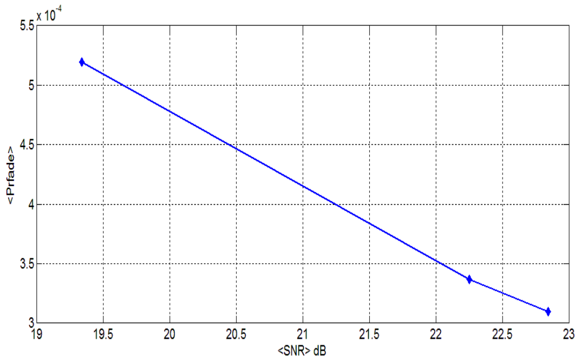
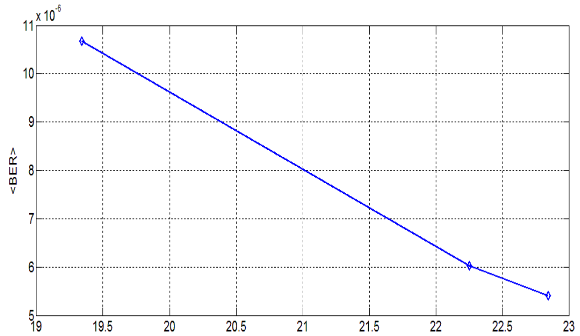


(a) <*Prfade*> of strong turbulence



(b) <*BER*> of strong turbulence

Figure 7(a)-(b). Measurements of <*Prfade*> and <*BER*> Over Strong Turbulence Using K Distribution Model

22.25–22.85 dB, <*Prfade*> is 5.17×10^{-4}–5.49 x10^{-4}, while <*BER*> is 9.0×10^{-6}–9.83×10^{-6}. (b) <*SNR*> is 19.3–22.75 dB, <*Prfade*> is 3.15×10^{-4}–5.25×10^{-4}, and <*BER*> is 5.4×10^{-4}–10.75×10^{-4}.

From the simulation via gamma-gamma and K model, it can be seen that <*Prfade*> and <*BER*> get lower order as <*SNR*> increase from 0-20 dB. Higher <*SNR*> in strong turbulence has great impact to increasing those parameter. For gamma-gamma spherical wave achieves high characteristical performance for all scale of turbulence. This is caused by characteristical beam wave propagation which the divergence from the transmitter is minimum to be induced by turbulence media, compared to plane wave and Gaussian wave that have constant beam dimension from beam collimator to lens receiver. The characteristical of spherical wave can be said has lower probability to be induced by turbulence medium. From gamma-gamma model the index scintillation is decomposed into two parameter which are α and β. For the constant beam wave dimension along propagation distance, it shall contributes to accumulation of wider distribution of scintillation. For that reason plane wave and Gaussian have great probabilities to be induced by turbulence relatively. However the results via gamma-gamma show the same trend as the results from the work of reff. [8].

The results analytical measurement of characteristical FSOC system performance also show that <*BER*> gamma-gamma approximates the simulation results in strong turbulence. This results also has been shown by W. Gapmair et al. [14], gamma-gamma is appropriate in measurement of heavy turbulence. Jaedon Park et al. [14], also have achieved results that gamma-gamma was suitable in measuring the moderate-strong turbulence. J. Perez [16] also have reported that in controled medium turbulence the results of strong turbulence at 10^{-6}. Ehsan Bayaki et al. [17], also had reported that in strong turbulence which were 10^{-2}–10^{-3} for the range <*SNR*> of 20–25 dB.

From K model simulation it also has trend as the gamma-gamma simulation for <*Prfade*> and <*BER*> increase as <*SNR*> goes higher. But using K model, Gaussian wave is more robust from turbulent inducement. In K model the index scintillation does not being decomposed into α and β. the index scintillation is join value of α and β parameters. It means that in K model does not measure the distribution of scintillation in inner scale and outer scale of turbulence medium parameters. Hence for measuring the performance in strong turbulence, K model is not representative to acquisition the real condition of turbulence medium. Also by comparing the masurement and comparing to other research works using K also, It was stated that K is precise method for weak turbulence. Samimi et al. [18] have reported that K model is appropriate for weak turbulence condition. Mingbo Niu et al. [19], also have reported that with $\alpha < 2$ and the range <*SNR*> of 10–30 dB, <*BER*> sebesar 10^{-2}–10^{-7}. Kamran Kiasaleh [20] have had strong justification that the <*BER*> via K model never achieved order at 10^{-9}.

4. Conclusions

From the simulation via gamma-gamma, spherical wave model achieves highest characteristical performance than other beam wave model. For K model, Gaussian wave achieves high characteristical performance than other ones. The comparison from simulation and analytical measurement results show that gamma-gamma model is more accurate and precise than K model. The accuration and precission are caused by the averaged values of α and β from all beam waves model approximates at real condition of scintillation distribution for strong turbulence on TPS.

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