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Performance Analysis of Multi-hop Parallel Free-Space Optical Systems Over Exponentiated Weibull Fading Channels Optimized By Particle Swarm Optimization

Babita
University College of Engineering
Research Scholar, Punjabi University, Patiala
Punjab, India
babitarana24@gmail.com

Dr. Manjit Singh Bhamrah
University College of Engineering
Punjabi University, Patiala
Punjab, India
manjitsingh_manjit@rediff.com

Abstract— **The performance of multi-hop parallel free-space optical (FSO) communication systems with decode-and-forward (DF) protocol over exponentiated Weibull (EW) fading channels has been investigated. Average bit error rate (ABER) and outage probability (OP) performance are analyzed under different turbulence conditions, receiver aperture size and structure parameters (R, C). The ABER and OP for FSO system is derived based on particle swarm optimization (PSO). The ABER and OP performance of the considered systems are investigated systematically combined with Monte Carlo (MC) simulations. The comparison between existing EW fading model and PSO based EW fading channel demonstrates that performance of the both systems could be enhanced by large aperture sizes for the structure parameters R and C. With the PSO optimization, ABER and OP reduction are achieved. The performance of multi-hop parallel FSO communication system for EW, GG (Gamma-Gamma) and LN (Log-normal) fading channels has been studied analytically and numerically with PSO. The ABER performance under EW fading channels has been compared with that of G-G and LN fading channels and analyzed that the EW fading channel model is regarded as an excellent candidate to accurately predict the probability of fade and the BER performance of laser beam propagating through atmospheric turbulence.**

***Keywords:** multihop parallel relay, free-space optical communication, exponentiated weibull distribution, particle swarm optimization.*

I. INTRODUCTION

Optical wireless communication (OWC) refers to transmission in unguided propagation media with the help of optical carriers, i.e., ultraviolet (UV) visible and infrared (IR), bands which is referred as free space optical communication. In comparison to radiofrequency (RF) transmission, FSO have very high optical bandwidth, high data rates, and excellent security. Main limitation of FSO arises from the atmospheric turbulence channel through which it propagates and degrades its performance with transmission distance longer than 1 kilometer. Inhomogeneities in pressure and temperature of the atmosphere cause variation of the refractive index along the transmission path. Variations in refractive index cause fluctuations in phase and amplitude which increases error probability, called channel fading. To mitigate these effects maximum likehood sequence detection (MLSD), error control coding, spatial diversity, cooperative diversity, and multi-hop transmission have been investigated. Among them, multi-hop transmission is a promising solution to increase coverage and overcome turbulence-induced fading. In multi-hop transmission, the data signal is relayed from the transmitter to the receiver through a series of intermediate terminals called relays. The intermediate relays divide the total transmission distance into smaller inter-relay distances or hops which suffer from less loss and scintillation.

Several mathematical models have been proposed to predict the channel behavior under different atmospheric turbulence conditions. LN distributions are commonly used for weak turbulence regime, K for strong turbulence conditions, GG distributions and EW for weak-to-strong turbulence conditions. The EW fading channel model can be regarded as an excellent model to correctly predict the BER performance and the probability of fade.

In 2005, Jayasri Akella, Murat Yuksel and Shiv Kalyanaraman; proposed Error Analysis of Multi-Hop Free-Space Optical Communication [1]. An error model for a single hop based on visibility, atmospheric attenuation, and geometric spread of the light beam is developed with statistical model Gaussian distribution and DF technique and OOK (On-Off Keying). They investigated that error performance of the multi-hop FSO is better than single hop, mean and variance of error rate is smaller.

In 2010, Christos K. Datsikas, Kostas P. Peppas, Nikos C. Sagias, and George S. Tombras; presented Serial Free-Space Optical Relaying Communications over Gamma-Gamma Atmospheric Turbulence Channels [2]. They studied end-to-end performance of multi-hop free-space optical communication systems over turbulence-induced fading channels, modeled by the gamma-gamma distribution. Analysis is carried out for systems employing amplify-and-forward technique and OP and ABER are also derived.

In 2011**,** Shabnam Kazemlou, Steve Hranilovic, and Shiva Kumar**;** proposed All-Optical Multi-hop Free-Space Optical Communication Systems [3]. All-optical relaying techniques are proposed to improve the error performance and overall distance coverage of free-space optical communication systems, all-optical multi-hop FSO communication systems are developed where at each relay signals are processed in optical domain. In particular, two all-optical relaying techniques, optical amplify-and-forward (OAF) and optical regenerate-and-forward (ORF) are developed and investigated that OAF is simple but limited by noise, ORF removes background noise at the expense of more complex implementation.

In 2011, Sahar Molla Aghajanzadeh, and Murat Uysal; investigated Multi-Hop Coherent Free-Space Optical Communications over Atmospheric Turbulence Channels [4]. They investigated multi-hop relaying as an efficient fading mitigation tool for coherent FSO systems over atmospheric turbulence channels. In comparison to IM/DD systems, coherent FSO systems are relatively more difficult to implement; however, they offer distinct advantages. These systems have much better spatial and frequency selectivity compared to their non-coherent counterpart.

In 2012, Majid Safari, Mohammad M. Rad, and Murat Uysal; studied Multi-Hop relaying over the Atmospheric Poisson Channel: Outage Analysis and Optimization [5]**.** They studied outage behavior of a decode-and-forward multi-hop FSO system over a Poisson channel degraded by atmospheric turbulence. Power control law is used for relay-assisted transmission in the atmospheric Poisson channel which improves the outage probability.

In 2012, Ehsan Bayaki, Diomidis S. Michalopoulos, and Robert Schober; advocate EDFA based All-Optical Relaying in Free-Space Optical Systems [6]. The authors advocate the use of all-optical relays equipped with erbium-doped fiber amplifiers (EDFAs), which, in contrast to conventional FSO relays with electrical amplification, avoid optical-to-electrical and electrical-to-optical conversions. They developed accurate signal and noise models for fixed and variable gain all-optical and electrical relaying which include the effects of all relevant system parameters and types of noise.

In 2013, Mohammadreza A. Kashani and Murat Uysal; investigated Outage Performance and Diversity Gain Analysis of Free-Space Optical Multi-hop Parallel Relaying [7]. In this paper, the outage performance of free-space optical mesh networks is investigated, which build upon the combination of serial (multi-hop) and parallel relaying. They assume log-normal atmospheric turbulence channels and derive outage probability expressions for the multi-hop parallel relaying scheme under consideration. Outage probability analysis demonstrates substantial performance improvements with respect to both standalone serial and parallel relaying schemes.

In 2014, Xuan Tang, Zhaocheng Wang, Zhengyuan Xu, and Zabih Ghassemlooy; proposed Multi-hop Free-Space Optical Communications over Turbulence Channels with Pointing Errors using Heterodyne Detection [8]**.** This paper proposes and analyzes the performance of the multi-hop FSO communication links using a heterodyne differential phase-shift keying modulation scheme operating over a turbulence induced fading channel. Expressions for moment generating function, probability density function, and cumulative density function are derived and then used to derive the fundamental limits of the OP and ASER.

In 2015, Ping Wang, Tian Cao, Lixin Guo, Ranran Wang, Yintang Yang, investigated "Performance Analysis of Multi-hop Parallel Free-Space Optical Systems Over Exponentiated Weibull Fading Channels [9]. The performance of multi-hop FSO cooperative communication system with decode-and-forward protocol under EW fading channels have been investigated. With the max-min criterion as the best path selection, the cumulative distribution function of max-min EW random variable are derived. The ABER and outage probability expressions are obtained.

The literature consulted so far reveals that only multi-hop provides better result to increase the total communication distance of the link while ensuring a reliable high data rate. Multi-hop parallel relaying demonstrates significant performance improvements with respect to both standalone parallel and serial relaying schemes. The EW fading channel model can be regarded as an excellent candidate to accurately predict the BER performance and the probability of fade but only a few work have been reported on the ABER and OP of FSO communication system over EW distributions. In addition, all of them did not consider the multi-hop parallel relaying scheme and only studied the point-to-point scenario. Multi-hop parallel relaying transmission is more realistic in FSO systems for applications. Motivated by the above analysis, a generalized multi-hop parallel DF based FSO communication system with PSO optimization technique over EW fading channel has been studied. The ABER performance of the considered system has been deeply analyzed with different turbulence strengths, receiver aperture sizes and structure parameters. Besides, the ABER performance under EW fading channels has been compared with that over GG and LN fading channels. MC simulation is also provided to confirm the correctness of the ABER expressions.

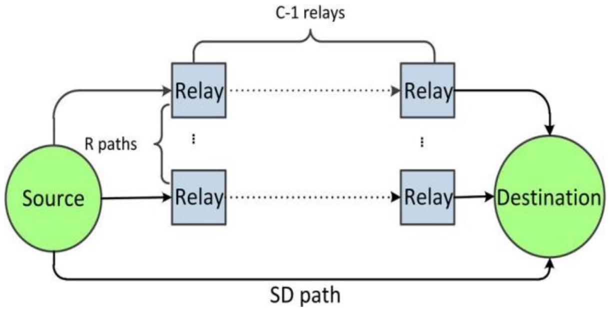

Fig.1. Structure Of multi-hop parallel FSO communication system [9].

Fig. 1 indicates FSO communication system based on the symbol-wise DF with R parallel paths between source and destination nodes. C hops are assumed to be in the cooperative path, that is, there are C-1 relay in each path. R and C are structure parameters. In chosen cooperative path, the relay utilize symbol-wise DF method to demodulate the data transmitted from the previous node and only one relay is allowed to pass the data to the next node at one time without using error correction coding and error detection coding. BPSK modulation is used in each point-to-point link.

Equations for Channel and System Model

ABER and OP performance of multi-hop parallel FSO have been studied in the literature. ABER and outage probability equations have been obtained and optimized using PSO in next section [9].

i) Gamma-Gamma:

$$f_{X_n} = \frac{2\,(K_m)^{\left(\frac{K+m}{2}\right)}}{\Gamma(K)\,\Gamma(\mathrm{m})\overline{X}}\left(\frac{X}{\overline{X}}\right)^{\frac{K+m}{2}-1} \quad (1)$$

$$K_{k-m}\left[2\sqrt{K_m\frac{x}{\overline{X}}}\right] \quad (2)$$

$\overline{X}$ = E{X_n}with E{.} donating exception. Γ(.) is the gamma function.

ii) Lognormal:

For the log normal channel model, the optical irradiance I is given by

$$I = exp(x) \quad (3)$$

x is the Gaussian RV with mean μ and variance σ^2 follows log normal distribution with a PDF I follows log normal distribution with a PDF

$$f_1(I) = \frac{1}{2\prod \sigma I}\exp\left(-\frac{(\ln I-\mu)^2}{2\sigma^2}\right) \quad (4)$$

Normalize the mean i.e. E[I]=1 where E[.] is the expectation operation , the PDF of I can be written as

$$f_1(I) = \frac{1}{\sqrt{2\prod}\sigma I}\exp\left(-\frac{(\ln I-\frac{\sigma^2}{2})^2}{2\sigma^2}\right) \quad (5)$$

σ turbulence level.

iii) EW with Gama -Gama system model:

$$f_{I_{m,n}}(I) = \frac{\alpha_{m,n}\beta_{m,n}}{\eta_{m,n}}\left(\frac{I}{\eta_{m,n}}\right)^{\beta_{m,n}-1}\exp\left[-\left(\frac{I}{\eta_{m,n}}\right)^{\beta_{m,n}}\right]\left\{1-\exp\left[-\left(\frac{I}{\eta_{m,n}}\right)^{\beta_{m,\mu}}\right]\right\}^{\alpha_{m,n}-1} \quad (6)$$

$f_{Im,n}$ is the PDF of the link $\alpha_{m,n}$, $\beta_{m,n}$ are shape parameters and η_{mn} is scale parameter.

From (1) and (6)

The PDF of link is

$$F_{K_{m,n}}(\gamma) = \frac{\alpha_{m,n}\beta_{m,n}\gamma^{\frac{\beta_{m,n}-2}{2}}}{2(\overline{\gamma}\eta_{m,n}^2)^{\frac{\beta_{m,n}}{2}}}\left\{1-\exp\left[-\left(\frac{\gamma}{\overline{\gamma}\eta_{m,n}^2}\right)^{\frac{\beta_{m,n}}{2}}\right]^{\alpha_{m,n}-1}\right\}*\frac{2\,(K_m)^{\frac{k+m}{2}}}{\Gamma(k)\Gamma(m)\overline{X}}\left(\frac{X}{\overline{\overline{X}}}\right)^{\frac{k+m}{2}-1} \quad (7)$$

iv) EW with log –normal

$$F_{K_i,m,n}(I) = \frac{\alpha_{m,n}\beta_{m,n}}{\eta_{m,n}}\left(\frac{I}{\eta_{m,n}}\right)\exp\left[-\left(\frac{I}{\eta_{m,n}}\right)^{\beta_{m,n}}\right]\left\{1-\exp\left[-(\frac{I}{\eta_{m,n}})^{\beta_{m,n}}\right]\right\}*f \quad (8)$$

$$f = \frac{1}{2\prod \sigma I}\exp\left(-\left(\frac{\ln I-\mu}{2\sigma^2}\right)^2\right)$$

These equations give the system and channel model for LN, GG and EW. ABER and OP performance is not analyzed by PSO in the literature. In next section PSO is used to optimize ABER and OP to achieves better error performance.

II. OPTIMIZATION: SNR OPTIMIZED BY PARTICLE SWARM OPTIMIZATION

PSO is a metaheuristic computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard to a given measure of quality. In multi-hop parallel FSO problem SNR is optimized using PSO. It predicts noise in the channel and provides better ABER and OP performance. With the PSO optimize path selection; fast ABER and OP reduction are achieved as compared to other methods presented in literature. A Performance of SNR can be defined by fixed threshold and metaheuristics (PSO).

The optimization problem

$$argminP_e = argmin\left[(1-P_i)\,P_F + P_i P_m\right] \tag{9}$$

ABER gives SNR

$$-(1-P_i)\,f\,(T_{th}|S_0) + P_1 f\,(T_{th}|S_1) = 0 \tag{10}$$

When use PSO in equation 1 and equation 2

$$argminP_{i,\gamma} = \varpi V_{i,\gamma} + \phi_{P_{i,\gamma}} r_{i\gamma}\left(P_{i,\gamma} - X_{i,\gamma}\right) + \phi_{P_{i,\gamma}} r_{\gamma}\left(g_{\gamma} - X_{i,\gamma}\right) \tag{11}$$

The Outage Probability Analysis is given by

$$F_{I_{max}} = \left[1-\left(1-\left\{1-\exp\left[-\left(\frac{1}{\eta}\right)^{\beta}\right]\right\}^{\alpha}\right)^{c}\right]*F \tag{12}$$

$$F = \left\{1-\exp[-\left(\frac{1}{\eta}\right)^{\beta}]\right\}$$

F_{Imax} is the CDF of this system.
The outage probability is defined as the probability that the instantaneous SNR is lower than a specified threshold. According to the PSO criterion, if the outage occurs, RV max must fall below the threshold. Therefore, the outage probability of the system can be expressed as

$$argminP_{i,\gamma} = \varpi V_{i,\gamma} + \phi_{P_{i,\gamma}} r_{\gamma}\left(F_{I_{max}} - X_{i,\gamma}\right) + \phi_{P_{i,\gamma}} r_{\gamma}\left(g_{\gamma} - X_{i,\gamma}\right) \tag{13}$$

III. RESULTS AND DISCUSSION

The analytical results of ABER and outage probability are obtained from (8) and (13), respectively. In computing the generalized PSO, n is chosen to be 30 for ABER. PSO is used in the MC simulation to generate the random fading channels following the EW, G-G and LN distributions. The parameters α, β, η are used in the analytical calculation and MC simulation. Plots obtained for ABER performance of multi-hop FSO system EW with R = 3, C = 3 under weak, moderate and strong turbulence conditions, ABER performance of multi-hop parallel FSO with R = 3, C = 3 under moderate turbulence condition of three different apertures, ABER performance comparison of LN, GG, EW and PSO based EW fading channels under strong turbulence condition with R = 5, C = 3 and outage probability performance comparison of different fading channels in strong turbulence condition with R = 5, C = 3.

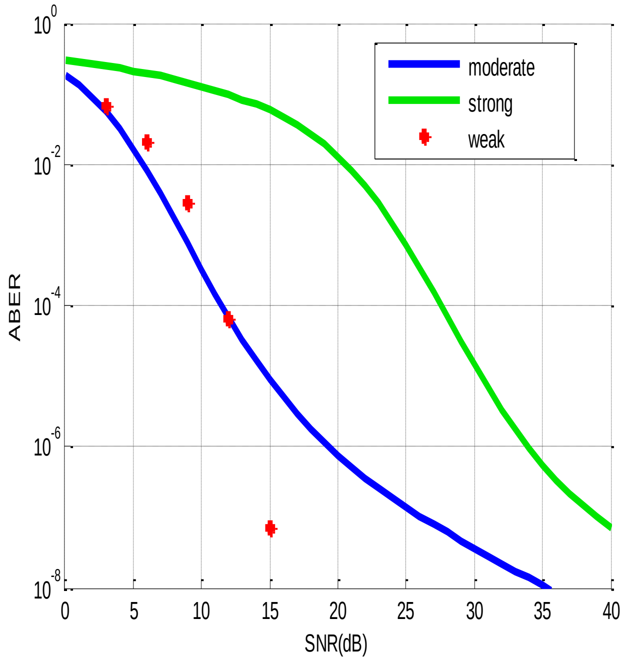

Fig.2. ABER performance of multi-hop FSO system EW with R = 3, C = 3 under weak (0.15), moderate (1.35) and strong turbulence conditions (19.2).

Fig. 2 shows ABER performance of multi-hop parallel FSO system over EW fading channel at different SNRs, which contains three cooperative paths (three hops in each path) i.e. with structure parameters R = 3, C = 3 under weak, moderate and strong turbulence conditions. For weak, moderate and strong turbulence conditions, the corresponding Rytov variance σ^2 equal to 0.15, 1.35 and 19.2 respectively. It can be seen that the ABER of this system increases with the increase of the value of Rytov variance (from weak to strong turbulence). For instance, when SNR value equals to 15 dB, the ABER is about 10^{-1} for strong turbulence, 10^{-5} for medium turbulence and 10^{-7} for weak turbulence conditions. This indicates that the performance of the present system is degraded with the increases of the strength of atmospheric turbulence. So in order to have better error performance and low probability of fade system should withstand the atmospheric turbulence.

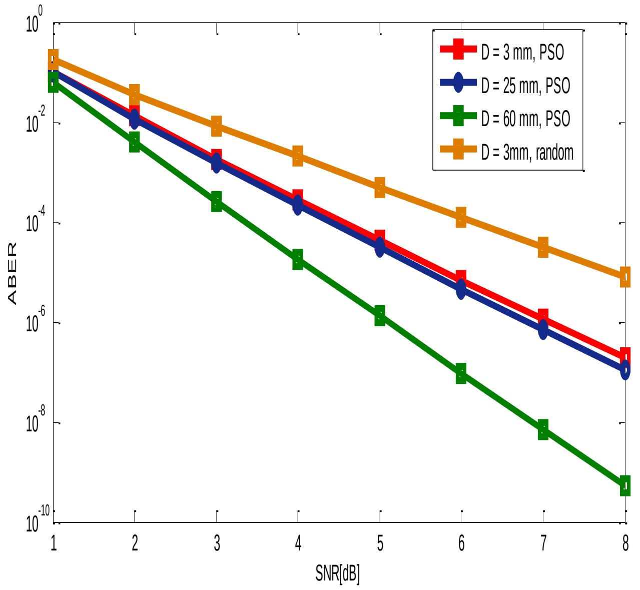

Fig.3. ABER performance of multi-hop parallel FSO with R = 3, C = 3 under moderate turbulence condition of three different apertures.

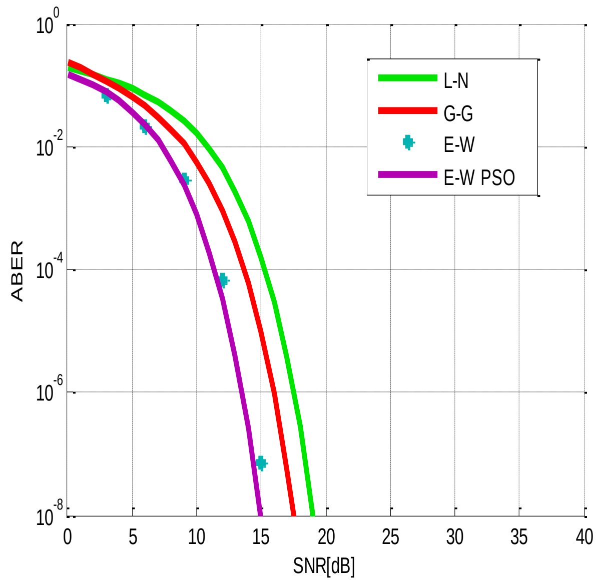

Fig.4. ABER performance comparison of LN, GG, EW and PSO based EW fading channels under strong turbulence condition with R = 5, C = 3.

In fig. 3 the ABER performances at three receiving apertures, D = 3 mm, 25 mm and 60 mm with PSO and D = 3 mm random have been given for comparison. ABER versus SNR performance of random path selection scheme and best path selection scheme under moderate turbulence condition with 3 mm aperture size has been shown. The results of random path selection are obtained by MC simulation. It can be found that the ABER performance of the best path selection scheme is remarkably superior to that of the random path selection scheme over EW fading channels. For instance, when SNR value is 7 dB, the ABER of the random path selection scheme is 10^{-3} while the ABER of best path selection scheme is about 10^{-9} in the moderate turbulence condition. This is because random path selection does not provide any diversity gain compared to best path selection scheme. With PSO path selection, ABER value comes out 10^{-5} for 3 mm aperture size, 10^{-6} for 25 mm and 10^{-9} for 60 mm. It can be seen that the ABER performance of this FSO system has been significantly improved by increasing the aperture size over EW distributions. Thus to have low error large aperture size should be considered for the system.

In fig. 4, the ABER performance comparison of LN, GG, EW and PSO based EW fading channels under strong turbulence condition with structure parameters R = 5, C = 3 has been plotted. The parameters α, β, η are equal to (1.4, 0.95, and 0.65). Each link distance L is equal to 1225 m and the coherence radius ρ_0 equal to 9.27 mm. ABER is plotted against SNR. LN, GG, EW and PSO based EW fading models has been compared for ABER performance. This shows that the EW distribution is more efficient than LN and GG. PSO based EW fading channel achieves low ABER than LN, GG and EW for same link distance.

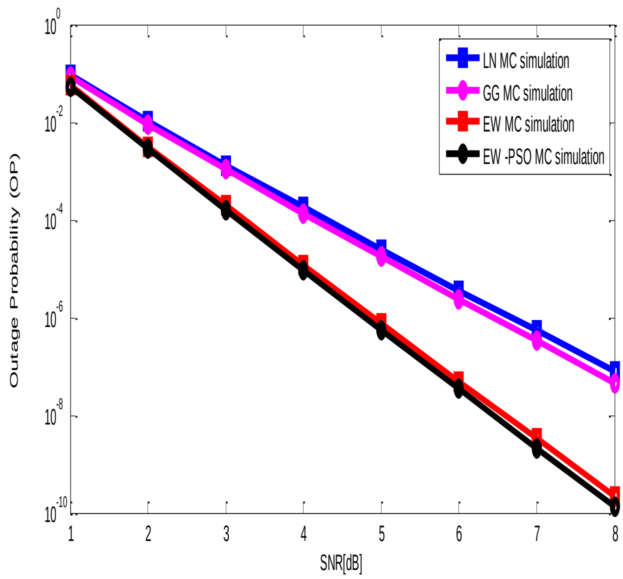

Fig.5. Outage probability performance comparison of different fading channels in strong turbulence condition with R = 5, C = 3.

Fig. 5 shows the outage probability performance of multi-hop parallel FSO for different fading channels. The outage probability is plotted against SNR. It is plotted for LG, GG, EW and EW with PSO fading channels. The comparative analysis of the performances of these four models has been plotted. Fig. 4 is plotted for structure parameters R = 3 and C = 5. When SNR equals to 7 dB OP value for LN fading channel is 10^{-5}, for GG it is 10^{-6}, 10^{-8} for EW and 10^{-9} for EW with PSO. This plot indicates that outage probability performance of EW fading channel optimized by PSO is better than other fading model.

IV. CONCLUSION

The performance of multi-hop parallel DF based FSO communication system for EW, G-G and LN fading channels have been studied analytically and numerically with PSO optimization. The ABER and outage probability performance are analyzed under different turbulence conditions, receiver aperture sizes and structure parameters (R, C). The ABER for FSO system is derived based on PSO. The ABER performance of the considered systems is investigated systematically combined with MC simulations. We investigated that the performance of the present system is degraded with the increases of the strength of atmospheric turbulence. For weak, moderate and strong turbulence conditions, the corresponding Rytov variance σ^2 equal to 0.15, 1.35 and 19.2 respectively. Lowest ABER is achieved for variance σ^2 equal 0.15. So in order to have better error performance and low probability of fade system should withstand the atmospheric turbulence. The ABER performances at three receiving apertures, D = 3 mm, 25 mm and 60 mm with PSO and D = 3 mm random have been given for comparison. It can be seen that the ABER performance of this FSO system has been significantly improved by increasing the aperture size (D = 60 mm) over EW distributions. Thus to have low error large aperture size should be considered for the system. The comparison between existing EW fading model and PSO based EW fading channel demonstrates that performance of the both systems could be enhanced by large aperture sizes for the structure parameters R and C. The ABER and outage probability performance comparison of LN, GG, EW and PSO based EW fading models has been presented which indicates that the EW distribution is more efficient than LN and GG. PSO based EW fading channel achieves low ABER than LN, GG and EW.

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