Optica Applicata, Vol. LIV, No. 2, 2024
DOI: 10.37190/oa240205

EDFA based adaptive RZ-OOK transmission for FSO communication

PENG-FEI LV, YAN-QING HONG*

School of Information Science and Engineering, Shenyang University of Technology,
Shenyang 110870, China

*Corresponding author: hongy7@sut.edu.cn

This paper proposes an erbium-doped fiber amplifier (EDFA) based adaptive return-to-zero on-off keying (RZ-OOK) transmission for free-space optical (FSO) communication. EDFA has the characteristics of average power limitation. Therefore, the transmitted RZ-OOK duty cycle is varied for accomplishing pulse power variations relying on determined average signal-to-noise ratio of received signal. Thus, the atmospheric turbulent effects can be compensated by this type of adaptive RZ-OOK transmission. The channel models with different turbulence effects are established, and the proposed technique is validated in simulation. The simulation results illustrate that the communication quality of system is considerably enhanced by the proposed technique compared with fixed threshold decision and adaptive threshold decision.

Keywords: free-space optical communication, erbium-doped fiber amplifier, average signal-to-noise ratio, adaptive transmission.

1. Introduction

Free space optical (FSO) communication technique has gained a great deal of research interests in recent years due to the growing requirement for transmission capability in communication networks [1]. FSO communication will play a crucial role in the future wireless networks due to its advantages of low power consumption, spectrum exemption from licensing, good confidentiality, and easy to deployment [2,3]. However, the emitted signal suffers from scintillating effects, which results in power loss, light intensity fluctuations and signal fading [4-7]. Eventually, the result will be a rise to the bit error rate (BER) and a decrease to the performance of communication.

Researchers have proposed various effective methods to suppress the scintillation effect so as to achieve the desired transmission quality. In [8], the authors investigated the diversity technique by deploying multiple transmitters or receivers, and the results showed that this technique can obtain good suppression of scintillation effect and significant diversity gain. But it is difficult to deploy multiple transmitters as well as multiple receivers at the same time in reality. In [9], an aperture averaging method for optimizing the FSO link by analyzing multi-frame images of received intensity scintillation patterns has been proposed. However, the improvement of this method is limited by the size of receiver apertures. In [10], the transmission of orbital angular momentum (OAM) using low density parity check (LDPC) coding was investigated. The OAM beams, nevertheless, are challenging for communicating over long distances. In [11,12], adaptive optics (AO) technique was proposed as a way to rectify phase aberration brought on by the scintillation phenomenon, however, the system design is complicated. Adaptive threshold decision (ATD) is widely adopted [13], which estimates and decides signal bit-by-bit based on channel state information (CSI). But, it is difficult to get perfect CSI [14]. In [15], a scheme of channel fading prediction was studied, but it brings complicity to the FSO communication system.

Many investigators have focused their studies on the adaptive transmission method. It was initially widely studied and applied in radio communication, and then gradually applied to FSO systems [16]. This technique provides a viable solution for improving communication performance under various channel conditions. In [17], a novel adaptive transmitting technique has been proposed to control coding and modulation. The CSI was obtained by estimating the received signal strength. However, the RF based feedback is limited by transmission distance. In [18], the adaptive coding rate technique *f* was studied based on the CSI. In [19,20], authors proposed an adaptive transmission technique which dynamically adjusts the data rates, modulation methods and coding rates in accordance with the CSI. However, CSI estimation process dramatically increases system complexity. Erbium doped fiber amplifier (EDFA) has the characteristics of amplifying optical power and limiting average power [21], thus, we research the scintillation effects alleviation method by using return-to-zero on-off keying (RZ-OOK) modulation and EDFA in this study.

In this paper, we propose an EDFA based adaptive RZ-OOK transmission to enhance the performance of scintillation mitigation in FSO communication. EDFA is used for its physical properties of average power limitation. The RZ-OOK duty cycle is varied according to the calculated average signal-to-noise ratio (SNR). As a result, the RZ-OOK's pulse strength is improved and the robustness of turbulence effects is strengthened. The proposed method is evaluated in simulation, and the channel is accommodated using various turbulence strengths. Besides, the proposed technique is compared with fixed threshold decision (FTD) and ATD. The simulation results illustrated that the capability of the scintillation effect mitigation can be significantly enhanced by the EDFA based adaptive RZ-OOK transmission compared with FTD and ATD.

2. Operation principle

In this section, we deal with the turbulence channels model and explain the principle for proposed EDFA-based adaptive RZ-OOK transmission technique.

2.1. Turbulence channel

Figure 1 illustrates the schematic diagram of the light beam passing through the turbulent channel. A light beam is sensitive to atmospheric turbulences during propa-

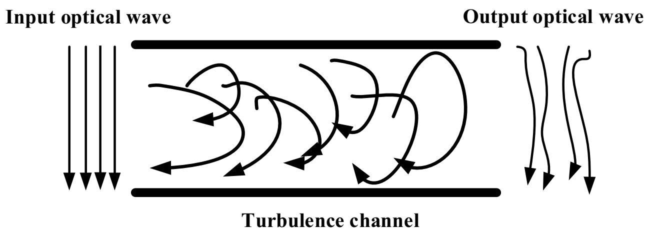

Fig. 1. Schematic diagram of the light beam passing through the turbulent channel.

gation. Atmospheric turbulence effects are created, because the refractive index of the atmosphere is altered because of the irregular variation in pressure and temperature [22-24].

The atmospheric turbulence can cause beam drifting, diffusion, and scintillation effects. And the scintillation effect is one of the key factors causing communication quality and system performance degradation [25-27]. The degree of scintillation effect is usually expressed by the scintillation index σ_I^2, which is given by

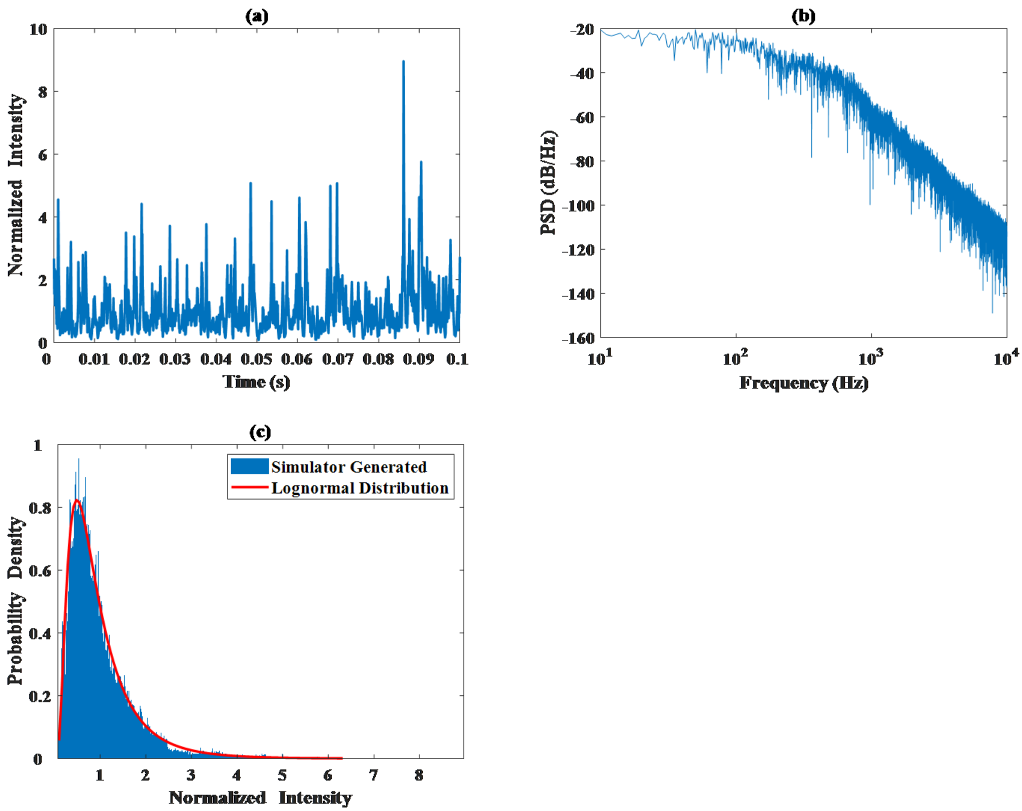

Fig. 2. Simulated scintillation effect with σ_I^2 of 0.5960. (a) Intensity fluctuation in the time domain, (b) power spectral density in the frequency domain, and (c) PDF.

$$\sigma_{\mathrm{I}}^2 = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1 \tag{1}$$

where I is the received signal strength and $\langle \cdot \rangle$ denotes the ensemble average.

Figure 2 illustrates the simulated scintillation effect with σ_{I}^2 of 0.5960. Figure 2(a) shows the time-dependent intensity fluctuations within the turbulent channel. The irregular intensity fluctuation will cause power loss and SNR variation at the receiving end. Figure 2(b) shows the power spectral density in the frequency domain. It is easy to notice that the spectral component appears to decrease gradually as the frequency increases. Figure 2(c) depicts the probability density function from model channel, which is distributed similarly to the lognormal distribution and can be expressed as

$$f(x) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] \tag{2}$$

where μ and σ denote the mean and standard deviation of the lognormal distribution, respectively.

2.2. Proposed EDFA based adaptive RZ-OOK transmission

Figure 3 illustrates the system model of the proposed EDFA based adaptive RZ-OOK transmission technique. Generally, the duty cycle of RZ-OOK is set to a fixed value. In this work, the duty cycle of transmitted RZ-OOK is dynamically adjusted according to the estimated average SNRs of the received signal. Firstly, the average SNR is calculated periodically from the received signal. The average SNR can be expressed as

$$\mathrm{SNR} = 10\log\left(\frac{P_{\mathrm{s}}}{P_{\mathrm{n}}}\right) \tag{3}$$

where P_{s} and P_{n} stand for the signal's and noise's effective powers, respectively. Transmitted RZ-OOK $s(t)$ is modulated into laser diode (LD), and its duty cycle is altered on the basis of the calculated average SNRs, *i.e.* higher SNRs with larger duty cycle

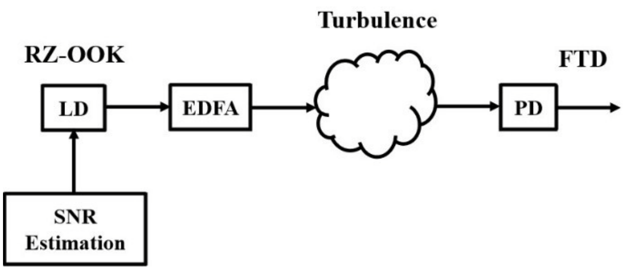

Fig. 3. System model of the proposed EDFA based adaptive RZ-OOK transmission. LD: laser diode, PD: photo diode, FTD: fixed threshold decision, EDFA: Erbium doped fiber amplifier.

and lower SNRs with shorter duty cycle. The correlation between duty cycle and average SNR can be represented by

$$D = D_0 + \beta \cdot \mathrm{SNR} \tag{4}$$

where D represents the adaptive duty cycle, and D_0 represents the fixed duty cycle, and β represents the proportionality coefficient. β is adjusted based on different SNR values. Modulated RZ-OOK signal is amplified by EDFA. EDFA has the average power limitation characteristics, thus, the pulse power of the transmitted signal is changed according to the variation of duty cycle. The average power of the transmitted signal P_a can be expressed as

$$P_a = \frac{T_h \times P_h}{T_t} \tag{5}$$

where T_h is the duration of the pulse, and P_h is the pulse power of transmitted RZ-OOK signal, and T_t is the period of bit '1' or '0'. Since the average power and T_t of the transmitted RZ-OOK signal maintain a constant value, P_h is dynamically altered according to the varying duty cycle DC = T_h/T_t. The RZ-OOK signal after EDFA $c(t)$ is given by

$$c(t) = s(t)I_1^{-1}(t) + n_{\mathrm{ASE}}(t) \tag{6}$$

where $I_1^{-1}(t)$ is the reversed turbulence channel caused by EDFA because of average power limitation, and $n_{\mathrm{ASE}}(t)$ is the amplified spontaneous emission (ASE) noise. The transmitted signal $c(t)$ suffers scintillation effect in the turbulence channel, and it is detected using a photo diode (PD). The RZ-OOK signal after PD $r(t)$ is represented by

$$r(t) = c(t)I(t) + n_{\mathrm{pd}}(t) \tag{7}$$

where $I(t)$ represents the scintillation effect, and $n_{\mathrm{pd}}(t)$ denotes the average noise power constructed from PD and background noises. The scintillation effect is mitigated by this type of adaptive transmission due to high correlation between $I(t)$ and $I_1^{-1}(t)$. Finally, the RZ-OOK signal is decided using FTD.

3. Simulation and results

The proposed method was evaluated in simulation. The BER performance of EDFA -based RZ-OOK transmission was analyzed under fixed and adaptive duty cycles. Simulation was conducted using modeled EDFA and LD with parameters shown in Tables 1 and 2, respectively. Additive white Gaussian noise (AWGN) was accommodated in the PD modeling, and other parameters will be discussed in the further study. The data rate was configured into 100 Mbps, and FTD method was used to distinguish OOK signal.

Figure 4 demonstrates the BER performance of EDFA-based RZ-OOK transmission with fixed duty cycle of 25%, 50%, and 75% under σ_I^2 of 0.1256, 0.3299, 0.4286, and 0.5960. Besides, the performance of EDFA-based RZ-OOK transmission was also

T a b l e 1. Parameters of EDFA.

Parameters	Values
Operation mode	Automatic gain control
Minimum input power	–20 dBm
Optical gain	30 dB
Noise figure	3 dB

T a b l e 2. Parameters of LD.

Parameters	Values
Wavelength	1550 nm
Output power	20 dBm

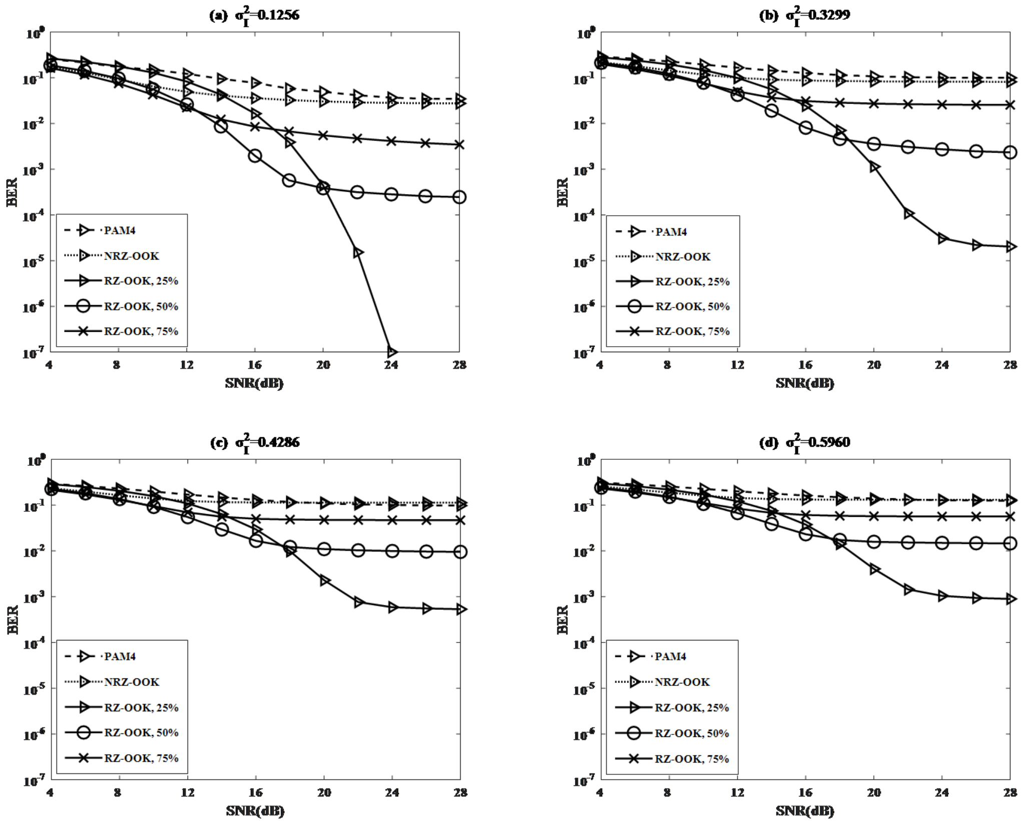

Fig. 4. BER performance of EDFA-based RZ-OOK transmission with fixed duty cycle of 25%, 50%, and 75% under σ_I^2 of (a) 0.1256, (b) 0.3299, (c) 0.4286, and (d) 0.5960.

compared to non-return-to-zero on-off keying (NRZ-OOK) and pulse amplitude modulation 4 (PAM4) transmission. The poor BER performance was obtained under PAM4 transmission due to the multiple amplitude levels of PAM4 signal. A weak BER performance was observed as to the NRZ-OOK transmission, since the pulse power of NRZ-OOK signal is smaller than that of RZ-OOK signal in case of constant average power. The BER performance of EDFA-based RZ-OOK was enhanced alongside a reduction in duty cycle levels, since a larger pulse power was obtained from EDFA at lower duty cycle of RZ-OOK. Besides, the BERs were increased with the increasing of σ_1^2, since stronger scintillation effect requires much shorter duty cycle to compensate the intensity variation. The modulated RZ-OOK signal with shorter duty cycle requires a much larger bandwidth compared to the signal with larger duty cycle, therefore, an adaptive duty cycle of RZ-OOK is needed to improve the bandwidth efficiency of RZ-OOK transmission.

Figure 5 demonstrates the comparison of BER performance for the proposed technique under different period of SNR estimation. The SNRs are estimated periodically from the received signal, and estimated SNRs were used to determine the duty cycle of transmitted RZ-OOK on the basis of the correlation between reception and transmis-

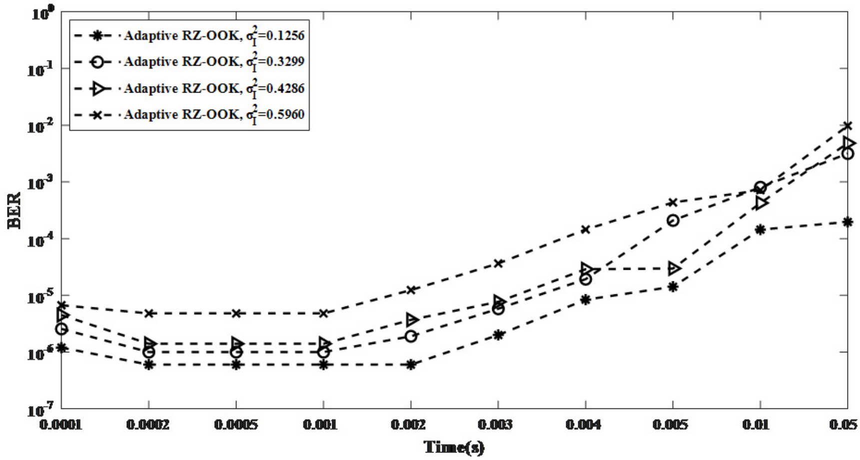

Fig. 5. BER performance for the proposed technique under different period of SNR estimation.

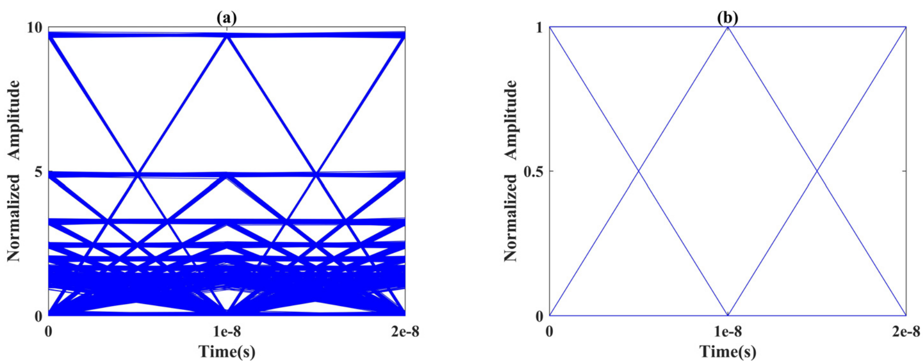

Fig. 6. Eye diagrams of (a) transmitted and (b) received RZ-OOK signal.

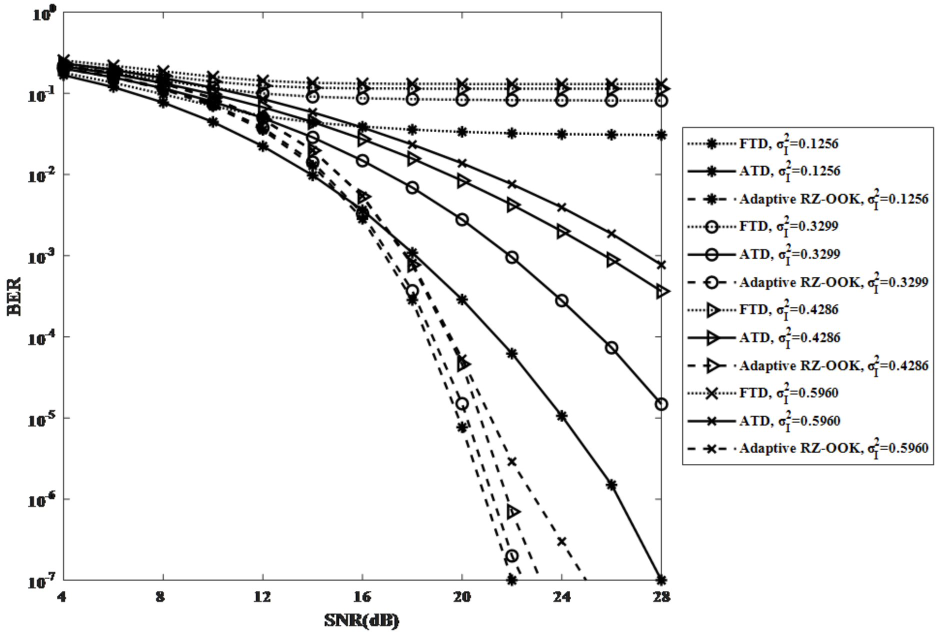

Fig. 7. Comparison of BER performance of the proposed technique with FTD and ATD.

sion channels. Figure 6(a) illustrates the eye diagram of the transmitted RZ-OOK signal with multiples of amplitude. The duty cycle and pulse power of the transmitted RZ-OOK were changed according to the estimated SNR values of the received signal, *i.e.* the shorter duty cycles and larger pulse powers were assigned into the transmitted RZ-OOK signal under the circumstances of the higher estimated SNR values. Thus, the scintillation effect induced fluctuation of the received RZ-OOK signal amplitude was mitigated as shown in Fig. 6(b). A degradation of BERs was observed under the increasing of SNR estimation period due to the decreasing of channel correlation. Besides, when the SNR estimation period is smaller than 0.0002s, the BERs were also decreased due to the inaccurate SNR estimation induced by limited numbers of bits in SNR estimation period.

Figure 7 illustrates the comparison of BER performance of the proposed EDFA based adaptive RZ-OOK transmission technique with FTD and ATD under different atmospheric turbulence channels. The SNR estimation period is set to 0.0002 s according to Fig. 5. A better BER performance was obtained by the proposed technique compared to FTD and ATD under various turbulence channels, owing to an effective scintillation effect compensation by the adaptive duty cycle of RZ-OOK. Besides, at the BER of 1×10^{-3}, the required SNRs were reduced by approximately 2, 4, 7, and 10 dB compared with ATD under σ_I^2 of 0.1256, 0.3299, 0.4286, and 0.5960, respectively. Consequently, the proposed technique can effectively improve the capability for scintillation mitigation of FSO transmission link.

4. Conclusions

In summary, we investigated an EDFA based adaptive RZ-OOK transmission technique to solve the scintillation effect in FSO communication. The duty cycle of RZ-OOK is adjusted according to the average SNRs of the received signal. Besides, the pulse power of RZ-OOK signal was altered by EDFA due to the average power limitation features. Thus, scintillation effect is effectively compensated by this adaptive RZ-OOK transmission. The proposed technique is evaluated in simulation. The simulation results indicated that the BER performance of proposed EDFA based adaptive RZ-OOK transmission technique was significantly improved compared to ATD and FTD. Therefore, we believe that this technique will have a promising development and application in FSO communication.

References

[1] Ferraro M.S., Mahon R., Rabinovich W.S., Coffee A.G., Murphy J.L., Dexter J.L., Freeman W.T., *Adaptive subcarrier intensity modulation for free space optical communication*, Optical Engineering **61**(6), 2022: 066105. https://doi.org/10.1117/1.OE.61.6.066105

[2] Vishwakarma N., Swaminathan R., *On the capacity performance of hybrid FSO/RF system with adaptive combining over generalized distributions*, IEEE Photonics Journal **14**(1), 2022: 7305712. https://doi.org/10.1109/JPHOT.2021.3135115

[3] Hong Y.Q., Shin W.H., Han S.K., *Enhancement of SOA-based scintillation mitigation by PS-OOK transmission in FSO communication*, IEEE Photonics Journal **12**(4), 2020: 7903510. https://doi.org/10.1109/JPHOT.2020.2996600

[4] Samy R., Yang H.-C., Rakia T., Alouini M.-S., *Ergodic capacity analysis of satellite communication systems with SAG-FSO/SH-FSO/RF transmission*, IEEE Photonics Journal **14**(5), 2022: 7347909. https://doi.org/10.1109/JPHOT.2022.3201046

[5] Zhu X., Kahn J.M., *Free-space optical communication through atmospheric turbulence channels*, IEEE Transactions on Communications **50**(8), 2002: 1293-1300. https://doi.org/10.1109/TCOMM.2002.800829

[6] Chen C., Pan S., Ni X., Yang H., Wang T., Liu Z., *Capacity of optical wireless channels in atmospheric turbulence with transmission power adaptation based on fading reciprocity*, [In] *2018 10th International Conference on Advanced Infocomm Technology (ICAIT)*, Stockholm, Sweden, 2018: 72-77. https://doi.org/10.1109/ICAIT.2018.8686625

[7] Liu X., Fang J., Xiao S., Zheng L., Hu W., *Adaptive probabilistic shaping using polar codes for FSO communication*, IEEE Photonics Journal **14**(1), 2022: 7913806. https://doi.org/10.1109/JPHOT.2022.3143112

[8] Tsiftsis T.A., Sandalidis H.G., Karagiannidis G.K., Uysal M., *FSO links with spatial diversity over strong atmospheric turbulence channels*, [In] *2008 IEEE International Conference on Communications*, Beijing, China, 2008: 5379-5384. https://doi.org/10.1109/ICC.2008.1008

[9] Yuksel H., Milner S., Davis C., *Aperture averaging for optimizing receiver design and system performance on free-space optical communication links*, Journal of Optical Networking **4**(8), 2005: 462-475. https://doi.org/10.1364/JON.4.000462

[10] Zhang Y., Wang P., Liu T., Guo L., Li Y., Wang W., *Performance analysis of a LDPC coded OAM-based UCA FSO system exploring linear equalization with channel estimation over atmospheric turbulence*, Optics Express **26**(17), 2018: 22182-22196. https://doi.org/10.1364/OE.26.022182

[11] Li M., Cvijetic M., Takashima Y., Yu Z., *Evaluation of channel capacities of OAM-based FSO link with real-time wavefront correction by adaptive optics*, Optics Express **22**(25), 2014: 31337-31346. https://doi.org/10.1364/OE.22.031337

[12] CHEN M., LIU C., RUI D., XIAN H., *Experimental results of atmospheric coherent optical communications with adaptive optics*, Optics Communications **434**, 2019: 91-96. https://doi.org/10.1016/j.optcom.2018.10.013

[13] CHOI K., CHEUN K., JUNG T., *Adaptive PN code acquisition using instantaneous power-scaled detection threshold under Rayleigh fading and pulsed Gaussian noise jamming*, IEEE Transactions on Communications **50**(8), 2002: 1232-1235. https://doi.org/10.1109/TCOMM.2002.801494

[14] NOURI H., UYSAL M., *Adaptive MIMO FSO communication systems with spatial mode switching*, Journal of Optical Communications and Networking **10**(8), 2018: 686-694. https://doi.org/10.1364/JOCN.10.000686

[15] DUEL-HALLEN A., *Fading channel prediction for mobile radio adaptive transmission systems*, Proceedings of the IEEE **95**(12), 2007: 2299-2313. https://doi.org/10.1109/JPROC.2007.904443

[16] NOURI H., SAIT S.M., UYSAL M., *Adaptive modulation for FSO IM/DD systems with multiple transmitters and receivers*, IEEE Communications Letters **27**(2), 2023: 586-590. https://doi.org/10.1109/LCOMM.2022.3222992

[17] FATIMA K., MUHAMMAD S.S., LEITGEB E., *Adaptive coded modulation for FSO links*, [In] *2012 8th International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP)*, Poznan, Poland, 2012: 1-4. https://doi.org/10.1109/CSNDSP.2012.6292700

[18] SAFI H., SHARIFI A.A., DABIRI M.T., ANSARI I.S., CHENG J., *Adaptive channel coding and power control for practical FSO communication systems under channel estimation error*, IEEE Transactions on Vehicular Technology **68**(8), 2019: 7566-7577. https://doi.org/10.1109/TVT.2019.2916843

[19] JAISWAL A., JAIN V.K., KAR S., *Adaptive coding and modulation (ACM) technique for performance enhancement of FSO link*, [In] *2016 IEEE First International Conference on Control, Measurement and Instrumentation (CMI)*, Kolkata, India, 2016: 53-57. https://doi.org/10.1109/CMI.2016.7413709

[20] NGUYEN T.V., LE H.D., DANG N.T., PHAM A.T., *On the design of rate adaptation for relay-assisted satellite hybrid FSO/RF systems*, IEEE Photonics Journal **14**(1), 2022: 7304211. https://doi.org/10.1109/JPHOT.2021.3130720

[21] TAKAHASHI N., HIRONO T., AKASHI H., TAKAHASHI S., SASAKI T., *An output power stabilized erbium-doped fiber amplifier with automatic gain control*, IEEE Journal of Selected Topics in Quantum Electronics **3**(4), 1997: 1019-1026. https://doi.org/10.1109/2944.649533

[22] KHAN A.N., SAEED S., NAEEM Y., ZUBAIR M., MASSOUD Y., YOUNIS U., *Atmospheric turbulence and fog attenuation effects in controlled environment FSO communication links*, IEEE Photonics Technology Letters **34**(24), 2022: 1341-1344. https://doi.org/10.1109/LPT.2022.3217072

[23] WANG Z., ZHONG W.-D., YU C., *Performance improvement of OOK free-space optical communication systems by coherent detection and dynamic decision threshold in atmospheric turbulence conditions*, IEEE Photonics Technology Letters **24**(22), 2012: 2035-2037. https://doi.org/10.1109/LPT.2012.2218652

[24] CHEN D., LIU Y., GAO Y., CAO Y., *Adaptive transmission based on MIMO mode switching over Malaga turbulence channel with pointing error*, IEEE Photonics Journal **15**(2), 2023: 7301111. https://doi.org/10.1109/JPHOT.2023.3243931

[25] RAKIA T., YANG H.-C., GEBALI F., ALOUINI M.-S., *Power adaptation based on truncated channel inversion for hybrid FSO/RF transmission with adaptive combining*, IEEE Photonics Journal **7**(4), 2015: 7903012. https://doi.org/10.1109/JPHOT.2015.2460118

[26] KAUSHAL H., KADDOUM G., *Optical communication in space: Challenges and mitigation techniques*, IEEE Communications Surveys & Tutorials **19**(1), 2017: 57-96. https://doi.org/10.1109/COMST.2016.2603518

[27] AARTHI G., REDDY G.R., *Average spectral efficiency analysis of FSO links over turbulence channel with adaptive transmissions and aperture averaging*, Optics Communications **410**, 2018: 896-902. https://doi.org/10.1016/j.optcom.2017.11.063

Received September 20, 2023
in revised form January 16, 2024