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Single Logarithmic Amplification and Deep Learning-based Fixed-threshold On-off Keying Detection for Free-space Optical Communication

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This paper proposes single logarithmic amplification (single-LA) and deep learning (DL)-based fixed-threshold on-off keying (OOK) detection for free-space optical (FSO) communication. Multilevel LAs (MLAs) can be used to mitigate intensity fluctuations in the received OOK signal by their nonlinear gain characteristics; however, it is ineffective in the case of high scintillation, owing to degradation of the OOK signal's extinction ratio. Therefore, a DL technique is applied to realize effective scintillation compensation in single-LA applications. Fully connected (FC) networks and fully connected neural networks (FCNN), which have nonlinear modeling characteristics, are deployed in this work. The performance of the proposed method is evaluated through simulations under various scintillation effects. Simulation results show that the proposed method outperforms the conventional adaptive-threshold-decision, single-LA-based, MLA-based, FC-based, and FCNN-based OOK detection techniques.

Keywords : Deep learning, Free-space optical communication, Single logarithmic amplification
OCIS codes : (010.1330) Atmospheric turbulence; (060.2605) Free-space optical communication; (060.4510) Optical communications

I. INTRODUCTION

Free-space optical (FSO) communication is widely used in terrestrial, satellite, and deep-space links because of its wide bandwidth, lack of license requirement, high spectral efficiency, high data rate, ease of deployment, and low power consumption [1]. However, the atmospheric-turbulence-induced scintillation effect poses a significant challenge to an on-off keying (OOK)-FSO communication system; That is, the received OOK signal's intensity variation causes difficulty in decision-threshold estimation [2].

Hence, research on mitigating the scintillation effect is crucial for enhancing the reliability and performance of FSO communication systems. Various techniques such as adaptive optics, adaptive-threshold decision (ATD), channel coding, and aperture averaging, have been studied to mitigate the scintillation effect [1, 3]. Adaptive-optics systems with wavefront sensing can detect and correct wavefront distortions in real time [4]. However, the drawback lies in the wavefront-correction capability under strong turbulence. ATD can mitigate the scintillation effect by estimating the bit-by-bit decision threshold using instantaneous channel-state information (CSI) [5]. Nevertheless, a large number of computations are required to obtain the instantaneous CSI and calculate the decision thresholds. The aperture-averaging technique employs a large-aperture receiver to reduce the scintillation effect; however, the deployment of a large aperture is a significant challenge in practice [6]. A generalized likelihood-ratio test (GLRT) receiver was used to detect the OOK sequence using the Viterbi algorithm [7]. However, pilot symbols are required for the beginning of data transmission. Polarization-shift OOK modulation has

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been studied using a linear polarizer and logarithmic amplifier (LA) to achieve a fixed-threshold decision (FTD) [8]. Nevertheless, polarization shifting and polarization-coordinate alignment are difficult to implement in OOK signals.

Recently, deep learning (DL) has emerged as a promising technique for optical communication systems. In [9], a universal artificial neural network (ANN) was proposed to classify both analog and digital modulation types using nine key features. However, reliance on training data and susceptibility to local optima limit its performance and applicability. A convolutional neural network (CNN) has been used to solve the phase-compensation problem caused by atmospheric turbulence in free-space orbital-angular-momentum-encoded quantum key distribution [10], but the training of DL models requires a large amount of data and numerous iterations. In [11], a receiver architecture based on a fully connected deep neural network (FC-DNN) was introduced and validated in underwater optical wireless communication to fulfill the received-signal synchronization and recovery data. Deep neural networks (DNNs) may be used to detect the received signals under incomplete CSI [12], but different model weights are required for various turbulence channels. In our previous work, multilevel LAs (MLAs) were utilized to suppress scintillation using nonlinear gains; However, the level of the MLA needs to be dynamically controlled under various scintillation effects to avoid degradation of the extinction ratio (ER), and noise from the PD and background was ignored [13]. Therefore, it is preferable to have single-LA-based OOK detection with the assistance of the DL technique.

In this study we propose a fixed-threshold OOK detection technique based on a single LA and DL. First, a single LA is deployed to reduce the scintillation effect of the received OOK signal by leveraging nonlinear gain characteristics. Then the DL model is applied to further compensate for scintillation by the training and recovery processes. Two DL models, fully connected (FC) networks and fully connected neural networks (FCNNs), are introduced, owing to the nonlinear modeling characteristics. Finally, FTD is realized by combining the single LA and DL. The efficiency of the proposed OOK transmission scheme is validated through simulations using various turbulent channels. The simulation results show that the bit-error-rate (BER) performance of this technique outperforms FTD, ATD, single-LA, MLA, and DL-based OOK detection under various turbulence channels.

II. OPERATION PRINCIPLE

A block diagram of the proposed single LA and DL-based OOK detection is shown in Fig. 1. A 1550-nm laser diode (LD) is directly modulated by an OOK signal $s(t)$. The modulated laser beam propagates through the FSO links and experiences a turbulence-induced scintillation effect [1]. This effect is evaluated using the scintillation index σ_I^2. The received OOK signal $r(t)$ is denoted as

$$r(t) = I(t)s(t) + N_{\mathrm{PD}}(t), \tag{1}$$

where $I(t)$ represents the intensity fluctuation and $N_{\mathrm{PD}}(t)$ denotes the combination of background and PD noise [14]. $r(t)$ is converted into a digital signal $r[k]$ by analog to-digital conversion (ADC). A single LA is deployed to decrease the scintillation-caused signal-intensity variation by means of nonlinear gain features, *i.e.* larger gain assigned to lower input-signal power and lower gain assigned to higher input-signal power. Besides, the reduction of signal-intensity variation improves the capability for feature representation and reduces the computational complexity of DL models. The LA-amplified signal $r_{\mathrm{SLA}}[k]$ is given by

$$r_{\mathrm{SLA}}[k] = \log_a^{\{r[k]+b\}} = \log_a^{(I[k]s[k]+N_{PD}[k]+b)} + N_{\mathrm{LA}}[k], \tag{2}$$

where a and b are constants and N_{LA}[k] denotes LA noise. The nonlinearity of the LA can be altered by the a and b values, and determines the degree of reduction of intensity variation. Besides, N_{LA}[k] reduces the ER of the amplified signal. Two types of DL models, FC network and FCNN, are used after the single LA to compensate for the residual scintillation effect, using their nonlinear modeling capabilities. The output signal of the LA is used to train the DL models. In addition, early stopping and dropout are employed to prevent the DL models from overfitting.

Figure 2 shows the proposed DL-based detector using an FC network. The FC layer extracts and learns the feature input signal and maps the learned features into the convo-

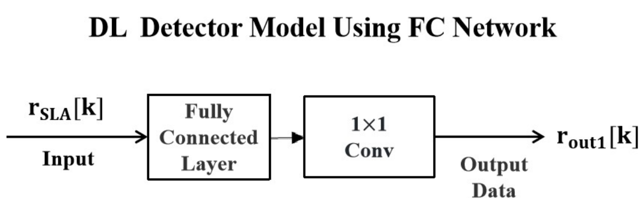

FIG. 2. Proposed deep learning (DL)-based detector using Fully connected (FC) network.

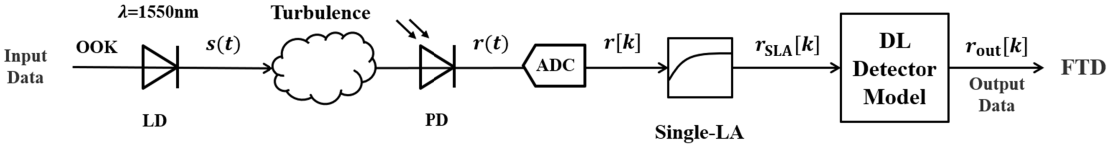

FIG. 1. Block diagram of the proposed technique.

lution layer. Taking $r_{\mathrm{SLA}}[k]$ as the input, the output of this layer H_{FC} can be expressed as [15]

$$H_{\mathrm{FC}} = \sigma(W_{\mathrm{FC}} r_{\mathrm{SLA}} + n_{\mathrm{FC}}), \tag{3}$$

where W_{FC} is the weight matrix, n is the bias vector, and σ denotes the rectified-linear-unit (ReLU) activation function. The ReLU replaces a negative input value with 0 and retains an original positive input value. Then a 1D convolutional layer is introduced to compensate for the signal variation by constructing a nonlinear model using the extracted features, which is given by [16]

$$r_{\mathrm{out}_1} = W_{\mathrm{conv}} * H_{\mathrm{FC}} + n_{\mathrm{conv}}, \tag{4}$$

where W_{conv} is the convolution kernel and $*$ denotes the convolution operation. The features learned in the convolutional layer can help the neural network to model the turbulence phenomenon effectively and nonlinearly, and thus perform turbulence compensation. Finally, the mean value of output r_{out_1} is used as a fixed threshold to achieve FTD.

Figure 3 illustrates the DL-based detector using an FCNN [17]. The detector consists of two hidden layers $\in R^5$ and one output layer $\in R^1$. A hidden layer is used to extract and learn the feature input signal $y_{\mathrm{SLA}}[k]$. The output layer is applied to compensate for the turbulence effect by constructing a nonlinear model using the extracted features. The process for each layer is represented by

$$\begin{aligned} H_{\mathrm{FCNN}_1} &= \sigma\left(W_1 r_{\mathrm{SLA}} + n_1\right) \\ H_{\mathrm{FCNN}_2} &= \sigma\left(W_2 H_{\mathrm{FCNN}_1} + n_2\right) \\ r_{\mathrm{out}_2} &= \sigma\left(W_3 H_{\mathrm{FCNN}_2} + n_3\right), \end{aligned} \tag{5}$$

where H_{FCNN_i} represents the output of the hidden layer, and r_{out_2} represents the output of the output layer. The mean value of the output r_{out_2} is also used as a fixed threshold for the FTD. Consequently, the proposed single LA and DL-based OOK detection methods can effectively compensate the scintillation effect.

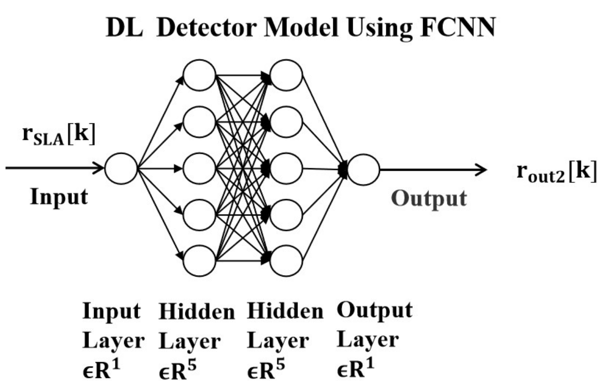

FIG. 3. Proposed deep learning (DL)-based detector using a fully connected neural networks (FCNN).

III. SIMULATIONS AND RESULTS

We conduct a simulation to verify the proposed OOK transmission method. The proposed method is compared with ATD, single-LA, MLA-based, FC-based, and FCNN-based OOK detection techniques. LA with a larger base number has a high degree of gain nonlinearity, and the stronger level of turbulence effect causes a larger degree of received-signal-intensity variation. Thus the ER of the signal is degraded by LA more seriously with increasing base number of LA. Therefore, the base number of logarithmic amplification is set to 2, for the sake of reducing the signal's ER distortion from LA under a stronger degree of turbulence effect.

In this work the lognormal distribution is used to model the scintillation effect, which is the major issue of a turbulence channel [18]. The model is derived from the temporal spectrum of log-amplitude fluctuations, and is given by

$$\begin{aligned} W_A(f) = 0.528\pi^2 k^2 \int_0^L C_n^2(h) \int_{\frac{2\pi f}{v(h)}}^{\infty} [(\kappa v(h))^2 - (2\pi f)^2]^{\frac{-1}{2}} \kappa^{\frac{-8}{3}} \\ \sin^2\left(\frac{\kappa^2 \gamma h}{2k}\right) F(\gamma\kappa)\, d\kappa\, dh, \end{aligned} \tag{6}$$

where A is the log-amplitude, L is the link distance, h is the altitude, C_n^2 is the refractive-index structure parameter, V is the wind speed, κ is the optical wave number, λ is the wavelength, k is the spatial wave number, and F is the aperture filter function [19]. Then the phase modulation, inverse Fourier transform, and first-order Rytov approximation are applied to realize channel modeling [20]. Figure 4 shows the modeled turbulence channel at $\sigma_I^2 = 0.0596$. The modeled channel has the features of time-varying intensity and low-frequency dominance, and its PDF follows the lognormal distribution. Therefore, this modeled channel is included in the simulation to emulate the scintillation effect. Figure 5 illustrates the BER performance of single-LA-based fixed OOK detection for various turbulent channels. The value of b is optimized for various σ_I^2 values of 0.0596, 0.1256, 0.2080, and 0.4286. The b values of LA are optimized to 1.2 and 1.5 under these turbulence channels, and larger b values are required for stronger σ_I^2 due to the higher degree of the received signal's fluctuation. The BER increases with increasing b value of the single LA. However, the BER is reduced owing to the signal distortion from the serious nonlinear gains induced by the ER reduction.

Figure 6 depicts the BER performance of the MLA-based OOK detection for the optimized b value. For $\sigma_I^2 = 0.0596$, the BER of single-LA-based OOK detection is poorer than that of ATD, because of ineffective scintillation compensation and amplified noise, and it surpasses FTD because of the intensity variation caused by variation in the signal-to-noise ratio (SNR). In addition, the BER of MLA-based OOK detection increases with the addition of LA levels, owing to serious ER degradation. With the increase in scintillation effects, that is σ_I^2 increase, the performance of

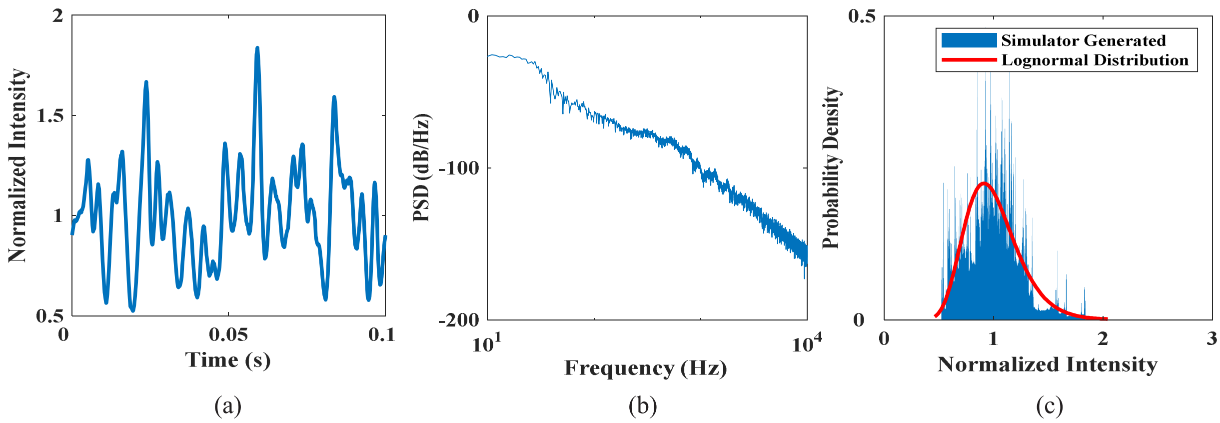

FIG. 4. Modeled turbulence channel for $\sigma_I^2 = 0.0596$: (a) Time domain, (b) frequency domain, and (c) probability density function (PDF).

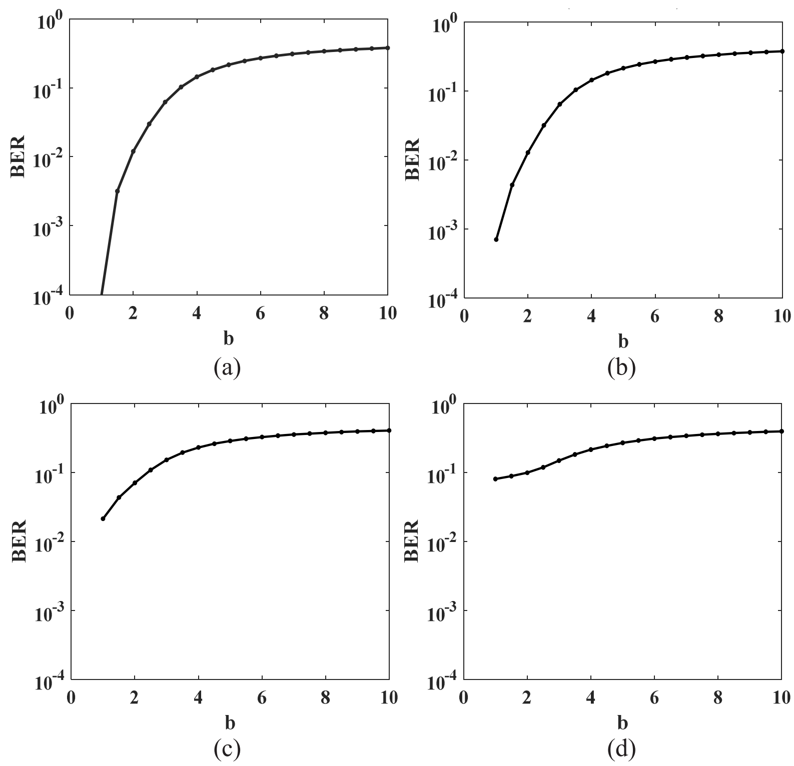

FIG. 5. Bit-error-rate (BER) performance of single-logarithmic amplification (LA)-based fixed on-off keying (OOK) detection, under different b values of LA: (a) $\sigma_I^2 = 0.0596$, (b) $\sigma_I^2 = 0.1256$, (c) $\sigma_I^2 = 0.2080$, and (d) $\sigma_I^2 = 0.4286$.

MLA-based OOK detection dramatically declines because of significant ER degradation induced by nonlinear gains. Therefore, the DL technique is introduced to realize scintillation mitigation under a single LA.

Figure 7 depicts the BER performance of the proposed single LA and DL-based OOK detection for the optimized b value. DL models of FC networks and FCNN are applied to improve the single-LA-based scintillation mitigation. The performance of the proposed single LA and FC network-based OOK detection is similar to that of the proposed single LA and FCNN-based fixed-threshold OOK detection techniques. In addition, both proposed methods outperform ATD, FC networks, and FCNN-based OOK signal detection, because the capability of FC networks and FCNN are enhanced by the reduction of signal-intensity variation using nonlinear LA. However, it is difficult to dynamically change the b value. Therefore, the proposed technique is evaluated with fixed a and b values. Figure 8 depicts BER performance of the proposed single LA and DL-based OOK detection for a fixed b value of the single LA. The b value of the single LA is fixed at 1.2, according to Fig. 5. The proposed technique with a fixed b value is close to ATD in

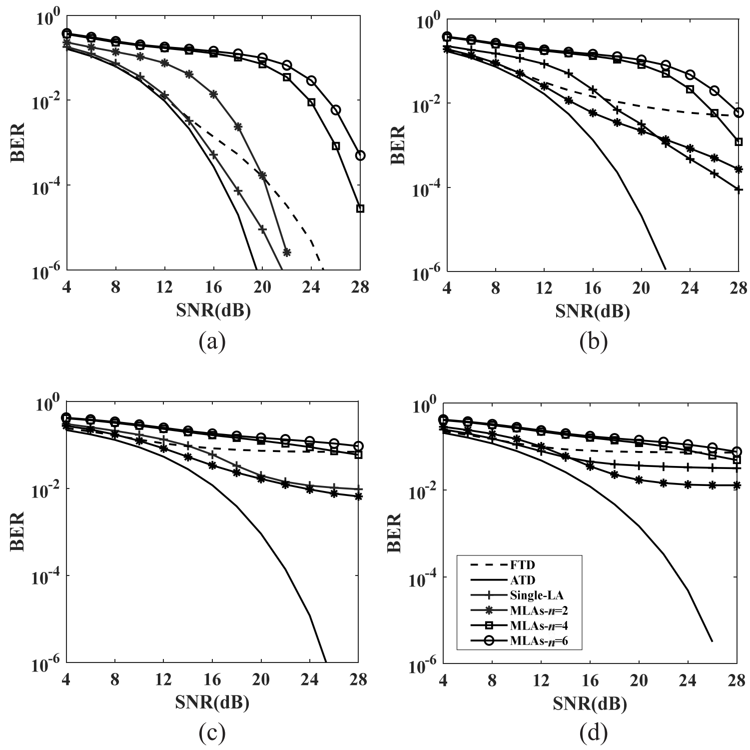

FIG. 6. Bit-error-rate (BER) performance of multilevel logarithmic amplification (MLA)-based on-off keying (OOK) detection, under optimized *b* value: (a) $\sigma_I^2 = 0.0596$, (b) $\sigma_I^2 = 0.1256$, (c) $\sigma_I^2 = 0.2080$, and (d) $\sigma_I^2 = 0.4286$. LA-n = 1, single-LA; MLAs-n = 2, 2-level of MLAs; MLAs-n = 4, 4-level of MLAs; MLAs-n = 6, 6-level of MLAs.

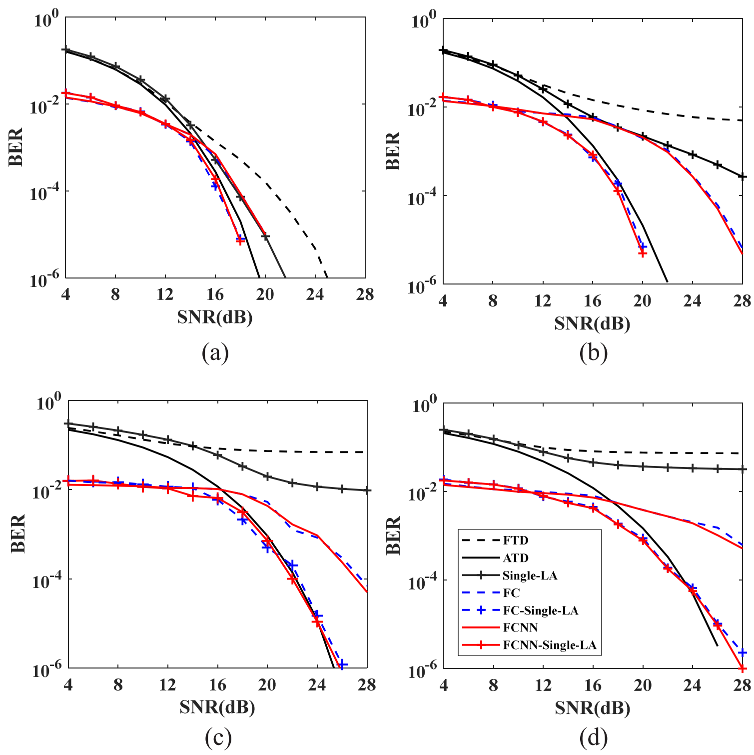

FIG. 7. Bit-error-rate (BER) performance of the proposed single logarithmic amplification (LA) and deep learning (DL)-based on-off keying (OOK) detection for optimized *b* value: (a) $\sigma_I^2 = 0.0596$, (b) $\sigma_I^2 = 0.1256$, (c) $\sigma_I^2 = 0.2080$, and (d) $\sigma_I^2 = 0.4286$.

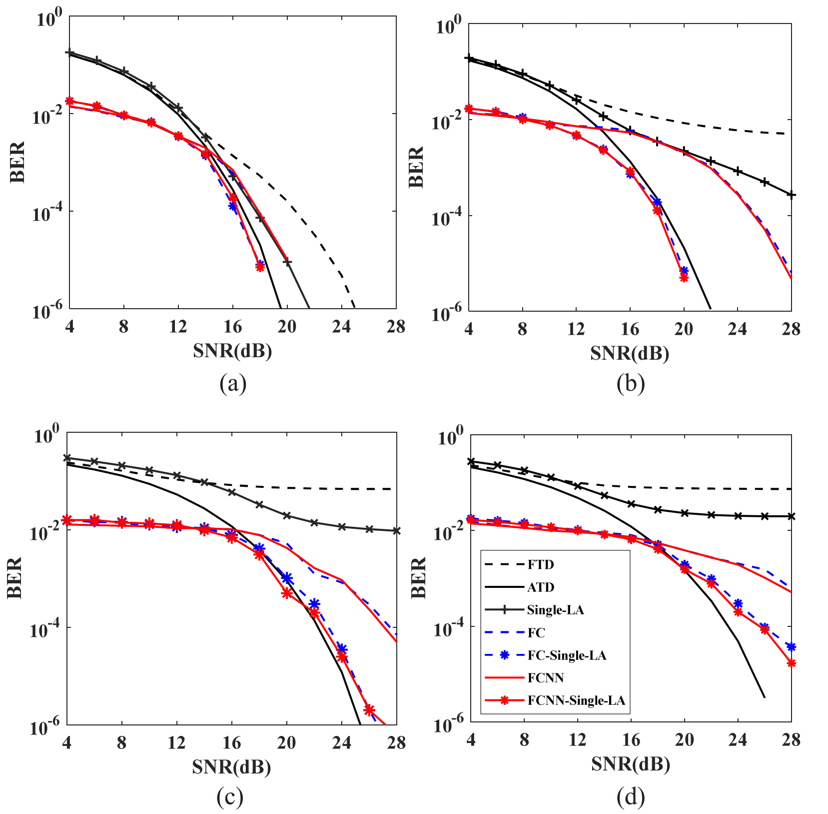

FIG. 8. Bit-error-rate (BER) performance of the proposed single logarithmic amplification (LA) and deep learning (DL)-based on-off keying (OOK) detection for fixed *b* value: (a) $\sigma_I^2 = 0.0596$, (b) $\sigma_I^2 = 0.1256$, (c) $\sigma_I^2 = 0.2080$, and (d) $\sigma_I^2 = 0.4286$.

performance. Therefore, the turbulence effect is effectively compensated using the proposed technique, with and without the optimization process. Consequently the proposed technique is effective for various turbulence channels. In this work, the proposed technique is discussed for LA with ideal characteristics; The bandwidth limitation of LA will be studied in our further work.

IV. CONCLUSION

In conclusion, we have proposed single LA and DL-based fixed-threshold OOK detection techniques for FSO communication systems. FC networks and FCNN models were applied to realize single-LA-based scintillation compensation. The proposed OOK detection method was compared to FTD, ATD, single-LA, MLA, and DL-based OOK detection methods in simulations, under various turbulence effects. Simulation results illustrated that the proposed single LA and DL-based OOK detection techniques were effective for various turbulence channels. Therefore, it provides a promising solution to compensate for turbulence issues in FSO communication systems. Research on DL-based simultaneous LA optimization and scintillation-effect compensation will be conducted in our further work.

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DISCLOSURES

The authors declare no conflicts of interest.

DATA AVAILABILITY

Data underlying the results presented in this paper are not publicly available at this time, but may be obtained from the authors upon reasonable request.

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