Experimental Investigation of the Performance of Different Modulation Techniques under Controlled FSO Turbulence Channel

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***Abstract*— This paper experimentally investigates and compares the performance of the free space optics system employing three different modulation schemes, on-off keying (OOK) with non-return-to-zero (NRZ) and return-to-zero (RZ) and the binary phase shift keying (BPSK) operating under the turbulent atmosphere. The received average signal is measured and used to characterize the strength of the turbulence. The experiment is performed with a temperature gradient of 4 degrees at a wind velocity of 4 m/s. The temperature gradient within the controlled channel results in turbulence of a log irradiance variance of 0.002, which is classified as a very weak turbulence. The received signal eye diagram and power histograms are presented and analyzed for performance evaluation of the selected modulation schemes in the weak turbulence model.**

***Index Terms*— FSO, atmospheric turbulence, Refractive Index**

I. INTRODUCTION

Free space optics (FSO) communications offers an enormous unregulated bandwidth where a data rate in excess of 100 Gbit/s is achievable over a distance of 1-4 km [1]. The local area network (LAN) based FSO system has the potential to solve the “last-mile” problem for the foreseeable future as a bandwidth in excess of 2 THz is readily available in optical wavelengths. Besides a high data transfer, a direct line-of-sight FSO link offer numerous advantages compared to the conventional wired and radio frequency (RF) wireless communications [2]. FSO links consume a relatively low power, offer a high security due to beam confinement within a very narrow area and are less sensitive to the electromagnetic interference [3].

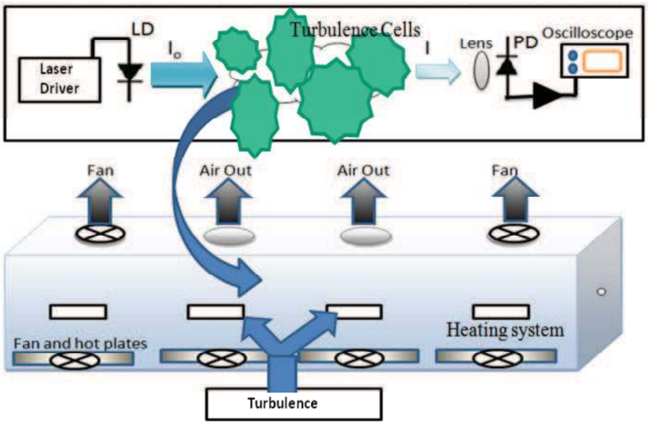
The fog, smoke and turbulence have a detrimental impact on FSO links performance. The severe attenuation of optical intensity is primarily caused by the absorption, the scattering and the refraction of optical waves by gas molecules, smoke, snow, rain and fog [4]. Fog has the largest impact on FSO links, limiting link range to a few hundred meters under heavy fog conditions [5]. However, when the link length exceeds several hundred meters, irradiance fluctuations of the received optical signal due to the turbulence present a severe problem [6]. The turbulence induced by the random fluctuation of temperature and pressure [7-10] results in random variation of the atmospheric refractive index. The variations in the refractive index along the optical path cause random fluctuations to the received optical irradiance, which can lead to severe system performance degradation.

A number of methods can be used to combat the effect of turbulence such as the multiple input multiple output (MIMO) system, and the temporal and spatial diversity and aperture averaging. However, selecting a modulation format that is most immune to scintillation effect is also important. OOK-NRZ and OOK-RZ modulation schemes are widely used in commercial FSO communication systems because of their ease of implementation, bandwidth efficiency and cost effectiveness [11]. From the view point of the receivers’ sensitivity, RZ offers improved performance over NRZ [12, 13]. In the turbulent-induced atmosphere, data recovery using a fixed threshold level is not the optimum option when using OOK. Though the adaptive threshold detector can significantly improve the performance, the system is not practically feasible as it requires adaptive optical components as well as continuous monitoring of the atmospheric conditions. Alternatively, modulation techniques like the subcarrier intensity modulation (SIM) and the polarization shift keying (PoLSK), which are more immune to turbulence induced amplitude fluctuation, could be employed. The SIM binary phase-shift keying (SIM-BPSK), which does not requires an adaptive threshold, also benefits from a matured RF technology and a simple and low cost direct detection receiver design compared to the PoLSK. However, SIM-BPSK requires a higher average transmitted power than OOK due to the DC bias requirement and the likelihood of signal distortion and the signal clipping [14].

In this paper, we report the practical implementation of OOK-NRZ, OOK-RZ and BPSK based FSO link operated over a laboratory controlled turbulence channel. The aim of the experiment is to optimize the link performance for weak turbulence by increasing the transmission power of OOK-NRZ, OOK-RZ and BPSK systems and comparing their performance. The paper is organized as follows: Experimental description is discussed in Section 2. In Section 3 measurement of the turbulence is explained. Experiment results and analysis are discussed in Section 4. The conclusion and future work is presented in the final Section.

II. EXPERIMENTAL DESCRIPTION

A typical FSO link consists of a transmitter and a receiver separated by the atmospheric channel. The experimental set-up for the controlled study of the scintillation effect on the FSO link for different modulation schemes is shown in Fig. 1. The transmitter uses a laser source with a maximum optical output power of 10 mW and a wavelength of 830 nm.



(a)

(b)

Figure 1. (a) Block diagram of the experimental set-up and (b) FSO setup in the laboratory.

The intensity of the output of a laser varied according to the modulating data format. To ensure system linearity, the laser is accurately biased and the peak-to-peak voltage of the input signal is kept within the specified values. The receiver front-end consists of an optical telescope (or lens) and a photo-detector. The electrical signal at the output of the PIN-photo-detector is amplified using a trans-impedance amplifier. The complete set of parameters used in the experiment is given in Table I.

Using a number of heaters and fans, we are able to generate and control temperature induced turbulence within the chamber. A pseudorandom binary sequence (PRBS) of 1000-bit length generated is applied to all three modulation schemes prior to being transmitted along the chamber. For like-to-like comparisons, the wind velocity and the temperature within the chamber is kept almost identical. The parameters used in the controlled turbulence environment are given in Table II.

Table I. MAIN PARAMETERS OF FSO USED IN THE EXPERIMENT

Parameter		Value
Data source	Modulation schemes used	NRZ / RZ / BPSK
Laser diode	Laser type	Class IIIb
	Peak wavelength	830 nm
	Max. optical power	10mW
	Beam divergence	10 mrad
	Beam size at aperture	5mm × 2 mm
	Modulation bandwidth	75 MHz
Photodetector	Active area	1 mm^2
	Full angle field of view	150 Deg
	Spectral range	750 - 1100 nm
	Max. wavelength sensitivity	900 nm
	Spectral sensitivity	0.59 A/W
	Rise and fall time	5 ns
	Reversed bias voltage	50 V
Lens	Diameter	34 mm
	Focal length	200 mm
Receiver	Transamplifier (IC)	AD8015

Experiments were carried out for a range of signal amplitudes and temperatures were measured at the transmitter side, the centre of chamber and the receiver side, see Table III.

Table II. MAIN PARAMETERS OF EXPERIMENTAL SET UP IN THE TURBULENCE CHAMBER

Parameters	Value
Dimension	550×30×30 cm^3
Temperature range	20 - 80 °C
Wind speed	4 - 5 m/s

The emphasis of the experiment is on the effect of the scintillation, and hence less focus is given to data rates, though higher data rates can be achieved with the present experimental set-up. To achieve the same average optical power for all modulation schemes, the amplitude of OOK-RZ is made twice that of OOK-NRZ.

Table III. SYSTEM PARAMETERS FOR DIFFERENT MODULATIONS

Modulation Technique	Modulation Amplitude (mV)	Temperature (degree Celsius)	Data Rate
OOK-NRZ	50, 150	45, 50, 55	5Mbps
OOK-RZ	100, 300	46, 51, 55	5Mbps
BPSK	50, 150	44, 49, 54	50Kbps

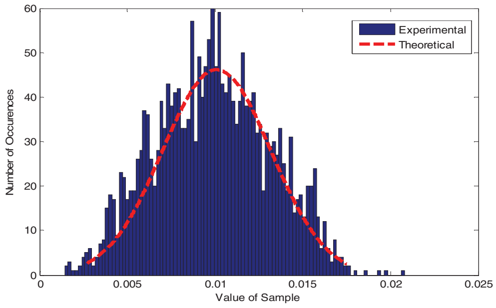
III. MEASUREMENT OF THE TURBULENCE

The most commonly reported model for describing the atmospheric turbulence in the weak range is the log-normal model, and is given by: [14-16].

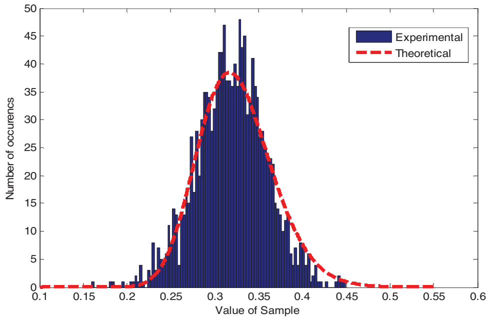
$$y(I) = \frac{1}{I\sigma\sqrt{2\pi}} \exp\left[-\frac{\left(\ln\frac{I}{I_0}+\frac{\sigma^2}{2}\right)^2}{2\sigma^2}\right]; \quad (1)$$

where y(I) is the power density function (pdf), I_0 and I are the average optical irradiance without and with turbulence respectively. σ^2 is the log irradiance variance and it is considered as a Rytov parameter. Note, the value of $\sigma^2 < 0.3$ for weak turbulence case [17].

In order to characterize the strength of turbulence generated within the chamber, we have measured the average received signal with and without the cold/hot air combination. From the data, we plot in Fig. 2(a) and (b) the signal distribution without and with scintillation, and fit them respectively to the Gaussian and log normal distributions using (1). From the theoretical analysis, we have observed that the log intensity variance of the generated turbulence is 0.002, while without the turbulence the irradiance variance is 10^{-5}. Hence the strength of the generated turbulence is very weak.



(a)



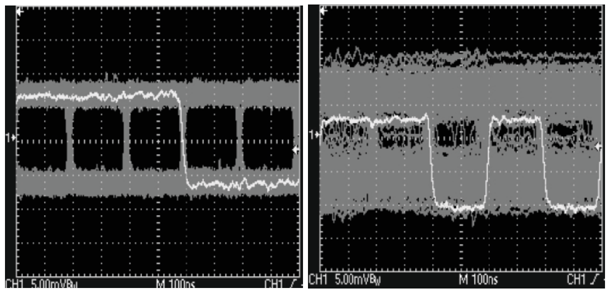
(b)

Figure 2. The received average signal; (a) without scintillation, and (b) with scintillation

IV. EXPERIMENTAL RESULTS

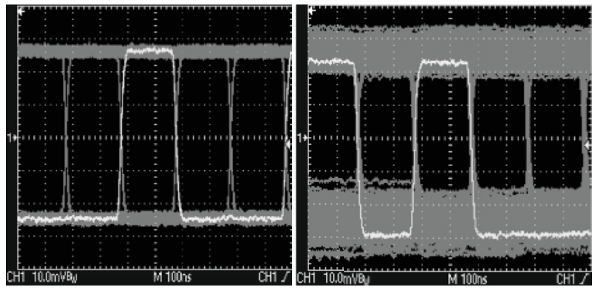
Experimental data for different modulation schemes has been recorded under a controlled weak turbulence environment and are analyzed using the eye diagram and the received signal distributions. The eye-diagram gives an indication of the quality of the received optical signal before and after the turbulence. Fig. 3 shows the eye-diagram for the OOK-NRZ modulation scheme for peak-to-peak modulating signal amplitude of 50 mV with and without the turbulence. The adverse effect of the turbulence on the performance of OOK-NRZ is clearly demonstrated by a wide opening and almost closure of the eye-opening with and without the turbulence, respectively. The random fluctuation of received optical signal causes closure of the eye-opening and hence requires for adaptive optics and special diversity to improve the performance [15, 16]. However, increasing the transmitted optical power can enhance the overall performance as demonstrated by the clear eye-opening (Fig. 4) in the presence of turbulence when transmitted power is doubled. However, increasing the transmitted optical power is not the recommended solution due to the eye-safety and high power consumption.

To further demonstrate the turbulence effect on the received signal, we also plotted the signal distribution histogram for bits '1' and '0' without and with the turbulence



(a) (b)

Figure 3. Eye diagram representations of OOK-NRZ for a 50 mV p-p input signal; Received voltage is 5mV/div: (a) without turbulence, and (b) with turbulence



(a) (b)

Figure 4. Eye diagram representations of OOK-NRZ for a 150 mV p-p input signal; Received voltage is 10mV/div: (a) without turbulence, and (b) with turbulence

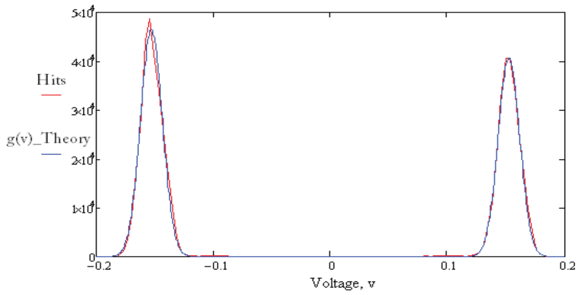
in Fig. A1 and A2, respectively (see appendix A) for the OOK-NRZ scheme. The histogram shows that the there is an optimum threshold level between signal distribution before the induced irradiance fluctuations. While with the induced irradiance fluctuations due to weak turbulence, the threshold level is perturbed as the variance of the distribution is increased.

Considering that the distribution of the received signal is Gaussian as the turbulence strength is very weak, we have estimated the average variance for the NRZ using a curve fitting method, see Fig. 5. The average estimated variances are 9.20×10^{-3} and 0.070 without and with the turbulence, respectively. The complete set of average variances estimated by the curve fitting with and without the turbulence for modulation schemes are given in Table IV. The increase in the noise variance due to the turbulence for the NRZ data format increases the error probability and may results in the link failure.

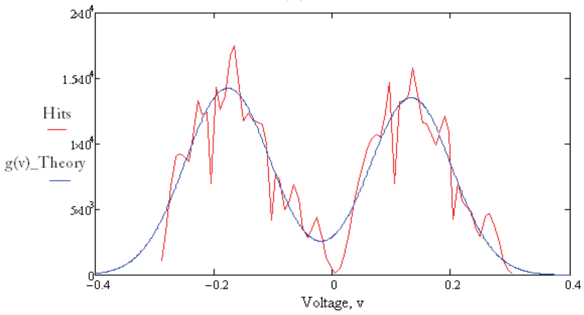
Table IV. THE VALUES OF NOISE VARIANCE BEFORE AND AFTER THE TURBULENCE FOR NRZ, RZ AND BPSK

Modulation	Without turbulence (σ_{wot})		With turbulence (σ_{Wt})	
	50 mV	150 mV	50 mV	150 mV
OOK-NRZ	9.20×10^{-3}	6.58×10^{-3}	0.070	0.030
OOK-RZ	5.58×10^{-3}	3.39×10^{-3}	9.12×10^{-3}	7.15×10^{-3}
BPSK	5.09×10^{-5}	8.28×10^{-4}	5.38×10^{-4}	7.38×10^{-4}

This study shows that OOK-RZ outperforms OOK-NRZ for the channel with turbulence induced fluctuations. This can be verified by analyzing the eye-diagram of OOK-RZ as in Fig. 6. The higher peak power adopted in OOK-RZ reduces the effect of turbulence, which can be noticed by a wider eye opening in Fig. 7. In fact, OOK-RZ shows significantly improved performance compared to the OOK-NRZ at a higher turbulence level. The advantage of the OOK-RZ schemes is at the cost of bandwidth efficiency. The received signal distribution under the same turbulence level for the RZ is depicted in Fig. A3 and A4, respectively. The distributions of bits ‘1’ and ‘0’ are well apart with a well defined threshold level, unlike the NRZ, in the presence of weak turbulence. This reduces the error probability and improves the performance of the FSO in the weak turbulence environment.

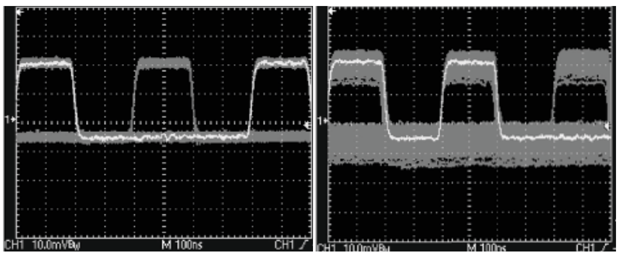


(a)



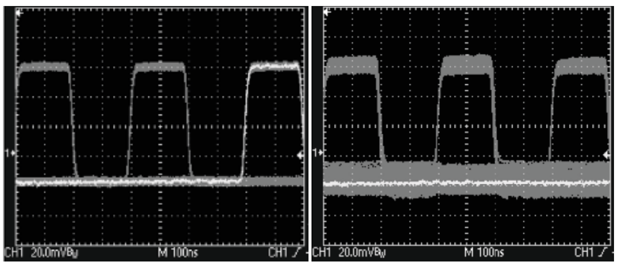
(b)

Figure 5. Received signal distributions of OOK-NRZ for 50 mV p-p signal: (a) without scintillation, and (b) with scintillation (Red line: experimental data; Blue lines: Theoretical fit)



(a) (b)

Figure 6. Eye diagram representations of OOK-RZ for a 100 mV p-p input signal; Received voltage is 10mV/div: (a) without turbulence, and (b) with turbulence

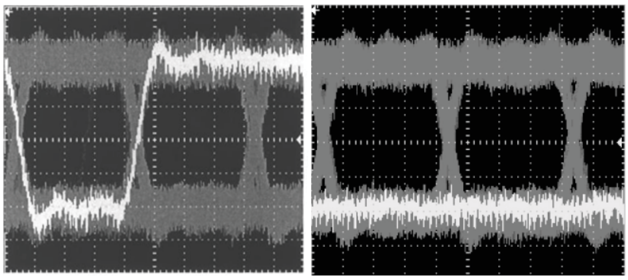


(a) (b)

Figure 7. Eye diagram representations of OOK-RZ for a 300 mV p-p input signal; Received voltage is 20mV/div: (a) without turbulence, and (b) with turbulence

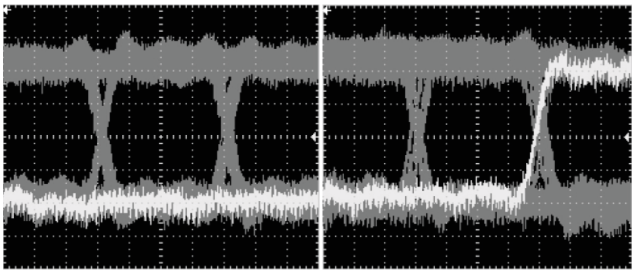
A carrier signal of 1 Mbps is used to modulate a 50 kbps data signal using a random data of 1000-bit length for the BPSK modulation scheme. The output from the BPSK modulator is used to drive the laser. At the receiver side, a BPSK demodulation with a low pass filter of a cut-off frequency of 128 KHz is used to remove the carrier from the received signal. The output of the low pass filter is used to examine the effect of the turbulence. The performance of the SIM-BPSK modulation format is investigated in the weak turbulence channel using the same amplitude levels as the NRZ.

The eye-diagrams of BPSK schemes with and without the turbulence for a 50 mV peak-to-peak input signal are illustrated in Fig. 8. The eye-diagram clearly demonstrates the superiority of BPSK compared to OOK, as the height of eye-opening are almost identical with and without the turbulence. This is because the information in BPSK schemes is encoded in the phase of the signal rather than the amplitude as in OOK. Thus BPSK requires no adaptive threshold level, so showing superior performance compared to the NRZ albeit a lower data rate due to the present experimental setup. The turbulence effect induces severe fluctuations in the intensity of the signal, as in NRZ, rather than the phase. The advantage of the BPSK scheme is at the cost of the power and bandwidth efficiencies.



(a) (b)

Figure 8. Eye diagram representations of BPSK for a 50 mV p-p input signal; received voltage is 5mV/div: (a) without turbulence, and (b) with turbulence



(a) (b)

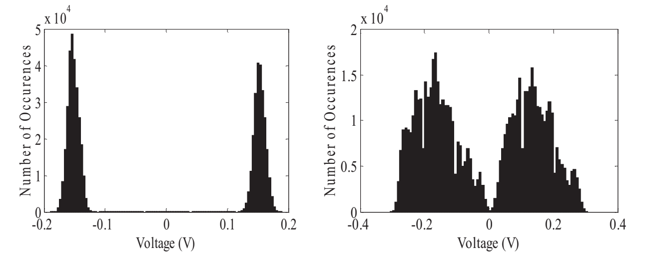
Figure 9. Eye diagram representations of BPSK for a 150 mV p-p input signal; Received voltage is 10mV/div: (a) without turbulence, and (b) with turbulence

The eye-diagrams in Fig. 9 for higher power levels also confirm the superior performance of the SIM-BPSK. The received signal distribution for the BPSK modulation for 50 mV and 100 mV input peak signals under the same turbulence strength is shown in Fig. A5 and A6, respectively. The distributions of bits ‘1’ and ‘0’ show the same shape with and without the turbulence. The profile of the received signal distribution after the turbulence is Gaussian rather than the log normal. The result shows that the BPSK scheme is less sensitive to the irradiance induced fluctuation under the weak turbulence condition. The noise variances before and after the turbulence is also measured showing a close figure with and without the turbulence see Table IV.

V. CONCLUSION

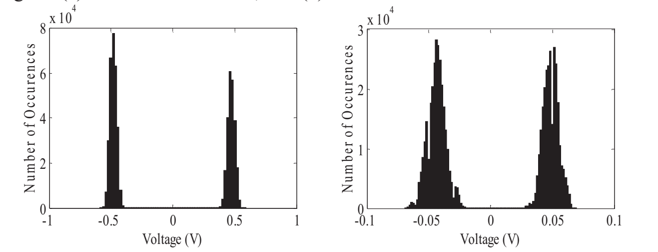
The motivation of the experiment was to fully understand the turbulence effect on the optical signal and also to demonstrate the performance of different modulation schemes for FSO links. The experimental results showed that the performance of the BPSK is far better than the OOK-NRZ and OOK-RZ albeit at the expense of bandwidth and power efficiencies. Therefore a suitable modulation scheme should be appropriately selected to adapt with the weather condition. This helps to maintain the link connectivity in very high turbulence conditions.

APPENDIX A



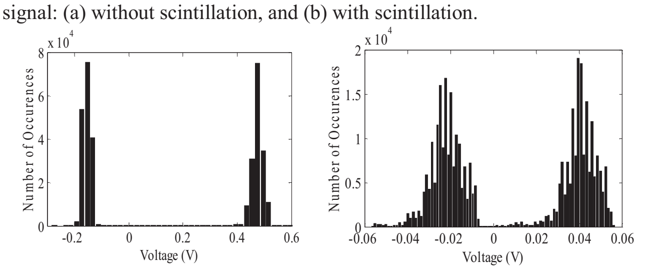
(a) (b)

Figure A1. Received signal distribution for OOK-NRZ for a 50 mV p-p input signal: (a) without scintillation, and (b) with scintillation.



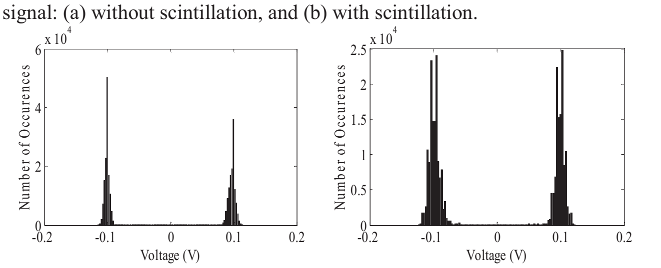
(a) (b)

Figure A2. Received signal distribution for OOK-NRZ for a 150 mV p-p input signal: (a) without scintillation, and (b) with scintillation.



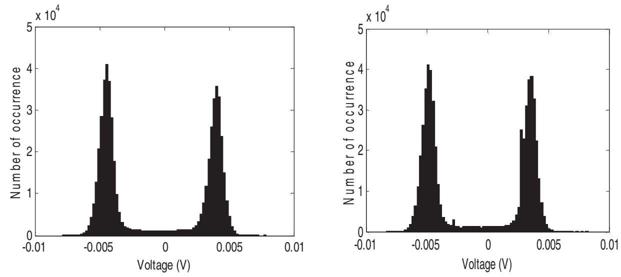
(a) (b)

Figure A3. Received signal distribution for OOK-RZ for a 100 mV p-p input signal: (a) without scintillation, and (b) with scintillation.



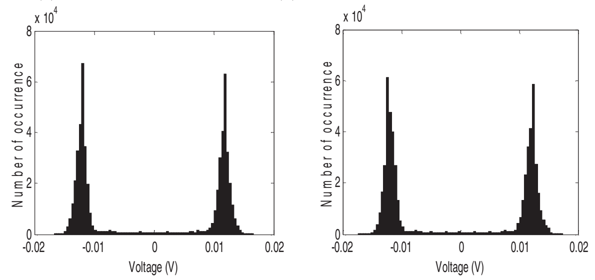
(a) (b)

Figure A4. Received signal distribution for OOK-RZ for a 300 mV p-p input signal: (a) without scintillation, and (b) with scintillation.



(a) (b)

Figure A5. Received signal distribution for BPSK for a 50 mV p-p input signal: (a) without scintillation, and (b) with scintillation.



(a) (b)

Figure A6. Received signal distribution for BPSK for a 150 mV p-p input signal: (a) without scintillation, and (b) with scintillation.

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