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Manchester Return-to-Zero On–Off Keying Modulation for Free-Space Optical Communication

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Abstract: This paper proposes a Manchester return-to-zero on–off keying (M-RZ-OOK) modulation for free-space optical (FSO) communication. M-RZ-OOK modulation is achieved by introducing Manchester coding into the RZ-OOK format. M-RZ-OOK has the features of phase-flipped impulse series in the spectrum. Therefore, normal and inversed channel state information (CSI) can be extracted by applying a local oscillator (LO) with the frequencies of impulses, respectively. These extracted CSIs can be applied to realize adaptive threshold decision (ATD) and adaptive power transmission (APT) in the forward and backward links simultaneously. The proposed M-RZ-OOK modulation was verified in simulations using various turbulence channels. The simulation results demonstrated that ATD and APT were effectively accomplished in the forward and backward links with the estimated normal and inversed CSIs.

Keywords: adaptive power transmission; adaptive threshold decision; channel state information; free-space optical communications; Manchester return-to-zero on–off keying



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1. Introduction

Free-space optical (FSO) communication systems have the remarkable features of high bandwidth, low latency, high security, ease of deployment, strong resistance to electromagnetic interference, and low cost [1]. Despite these spectacular advantages, similar to other techniques, it suffers from serious signal distortion from atmospheric turbulence caused by the varying temperature and pressure of the atmosphere [2]. Thus, it is essential to resolve this turbulence effect to improve FSO systems' performance.

Many studies have been conducted by researchers in order to cope with the turbulence effect. The aperture-averaging technique has been found to decrease the turbulence effect through the adoption of a larger receiver aperture [3]. Nonetheless, the efficiency of reductions in the turbulence effect is restricted by limitations on aperture size. The diversity technique has been found to reduce the turbulence effect by establishing different propagation links [4]. However, it introduces huge complexity into the FSO system. The adaptive threshold decision (ATD) with instantaneous channel state information (CSI) has been applied to compensate for the turbulence effect through a symbol-by-symbol threshold calculation and decision [5]. However, this method requires the estimation of instantaneous CSI knowledge from a communication link. The adaptive power transmission technique (APT) has been found to mitigate the turbulence effect by altering the transmitted optical power according to the channel state [6]. Nonetheless, instantaneous CSI knowledge is required for this pre-distortion method as well. In [7], turbulence-tolerant Manchester-OOK (M-OOK) transmission was employed to mitigate scintillation effects using low-pass filter (LPF)-based ATD and high-pass filter (HPF)-based fixed-threshold decision (FTD). However, the performance was dependent on the optimized cutoff frequency of the filter. Return-to-zero on–off keying (RZ-OOK) modulation has the features of impulse series in

the spectrum; thus, it is preferable to investigate compensation for the turbulence effect using this spectrum characteristic [8].

In this paper, we propose M-RZ-OOK modulation for FSO communication. The M-RZ-OOK signal is modulated by introducing Manchester coding into the RZ-OOK format. The phase difference of π is obtained for the impulse series in the spectrum of M-RZ-OOK through Manchester coding. At the receiver end, the local oscillator (LO) with the frequencies of impulses series of M-RZ-OOK is deployed to extract the CSI signals. CSI signals with normal and inversed channel information can be obtained by LO from different impulses simultaneously, and extracted CSI knowledge can be used to accomplish ATD and APT. The proposed M-RZ-OOK modulation method is validated in simulations using various turbulent channels. Simulation results indicate that ATD and APT can be effectively realized using these estimated normal and inversed CSIs.

2. Operation Principle

Figure 1 represents the block diagram of the proposed M-RZ-OOK transmission technology. At the transmission end, the M-RZ-OOK signal is directly modulated into the laser diode (LD) with a wavelength of 1550 nm. The modulated M-RZ-OOK signal $s[k]$ is expressed as [9]

$$s[k] = A[0.5(1 + \text{sign}(m(k))) * \text{rect}((k - nT)/T)], \quad (1)$$

where A denotes the amplitude of modulated M-RZ-OOK signal, $\text{sign}(x)$ is the sign function, $\text{rect}(x)$ is a rectangular function, and T is the duration of a bit. The M-RZ-OOK signal has a similar waveform to the M-OOK signal, with a shorter pulse width, as shown in Figure 2. Therefore, the M-RZ-OOK signal requires a much larger spectrum compared to non-return-to-zero OOK (NRZ-OOK), RZ-OOK, and M-OOK signals, as illustrated in Figure 3. Moreover, it features impulse series in the spectrum, as does RZ-OOK. The phase of impulse series $\varphi(f)$ is given by [10].

$$\begin{aligned} \varphi(f) = & \arg[A] + \arg[M(f)] + \theta(f) \\ & + \pi/2[\text{sign}(f - f_i) + \text{sign}(f + f_i)], \end{aligned} \quad (2)$$

where f is the frequency of impulse series. The phase of first impulse $\varphi_1(f_1)$ and second impulse $\varphi_2(f_2)$ is calculated by

$$\begin{aligned} \varphi_1(f_1) &= \arg[A] + \arg[M(f_1)] + \theta(f_1), \\ \varphi_2(f_2) &= \arg[A] + \arg[M(f_2)] + \theta(f_2) - \pi, \end{aligned} \quad (3)$$

where $2f_1 = f_2$. The phase difference between impulses of RZ-OOK varies under different pulse duration; however, a constant value of π is obtained for M-RZ-OOK due to the Manchester coding as shown in Figure 4. Therefore, the impulse series of M-RZ-OOK undergo a phase flipping phenomenon. The modulated M-RZ-OOK signal suffers from the turbulence effect due to variations in atmospheric temperature and pressure, and the scintillation effect is a major consequence of the turbulence effect. It is measured by the scintillation index σ_I^2 , and it is given by [11].

$$\sigma_I^2 = \langle I^2 \rangle / \langle I \rangle^2 - 1, \quad (4)$$

where I denotes the optical intensity variation, and $\langle \cdot \rangle$ is the ensemble average. At the receiver, the optical signal is transformed into an electrical signal $r(t)$ through photodiode (PD). Then, the analog signal $r(t)$ is converted into a digital signal $r[k]$ via an analog-to-digital converter (ADC), and it is expressed as [1]

$$r[k] = I[k]s[k] + n[k], \quad (5)$$

where $n[k]$ represents the additive white Gaussian noise (AWGN). $r[k]$ is divided into two branches. The upper one is used to extract M-RZ-OOK, and the lower one is applied to estimate CSI knowledge. A delay is added to match synchronization. The LO with the frequency of impulse series of M-RZ-OOK is introduced to extract CSI signal $r'[k]$ from $r[k]$, and it is given by

$$r'[k] = r[k] \cdot \cos(2\pi f_i t), \quad (6)$$

where frequency f_i is the frequency of LO. LPF is applied after LO, and the normal CSI signal $c_1[k]$ and inversed CSI signal $c_2[k]$ are obtained via this low-pass filtering due to the low frequency characteristics of the atmospheric turbulence effect. A weight factor is assigned into $c_1[k]$, and it is used as the decision threshold to distinguish the M-RZ-OOK signal in the forward link. Moreover, $c_2[k]$ is used to determine the dynamic transmission power of the backward link to realize APT. Finally, ATD and APT techniques are achieved by utilizing the estimated normal and inversed CSIs from the proposed M-RZ-OOK modulation.

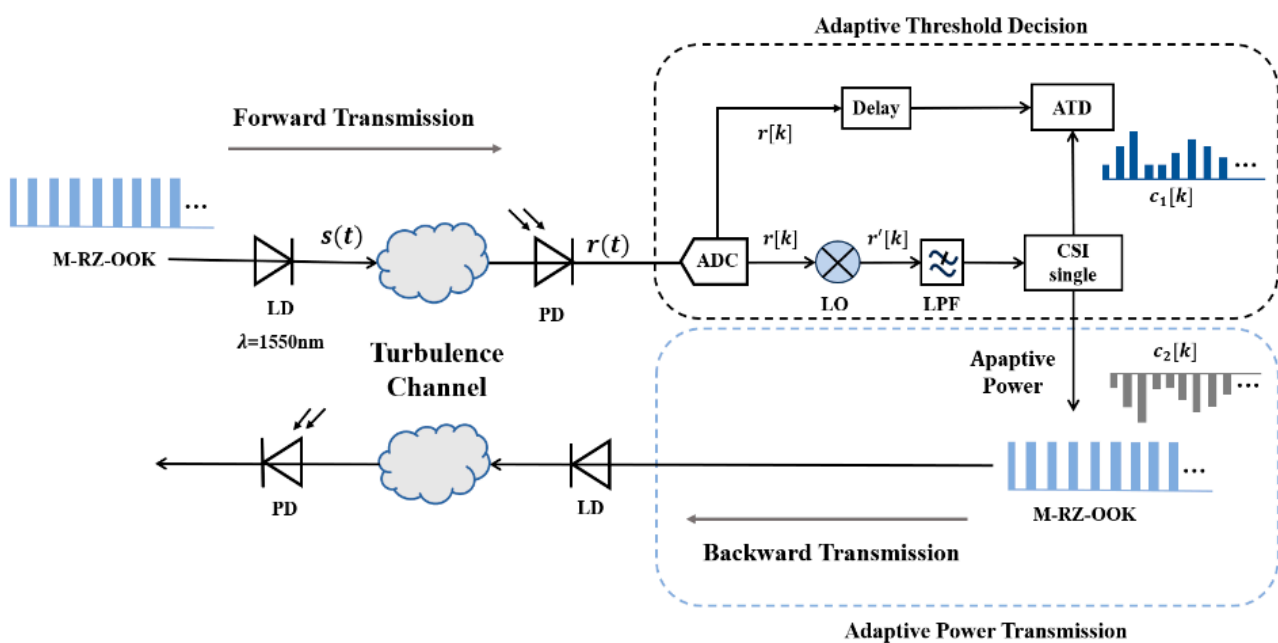


Figure 1. Block diagram of the proposed M-RZ-OOK transmission technique.

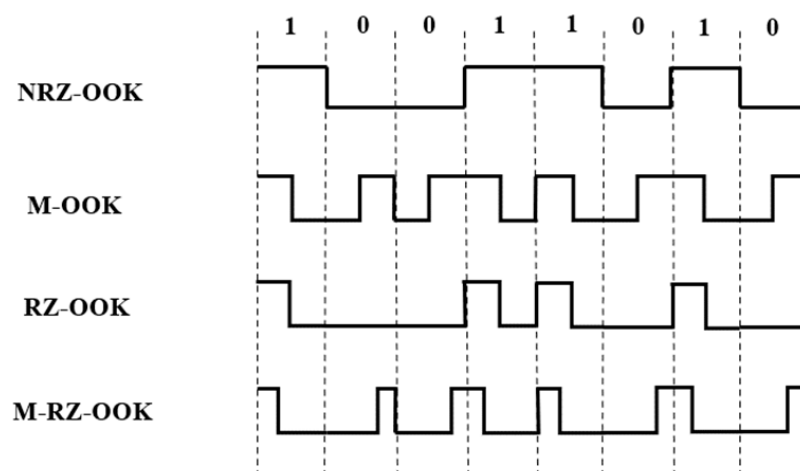


Figure 2. Waveform of NRZ-OOK, M-OOK, RZ-OOK, and M-RZ-OOK.

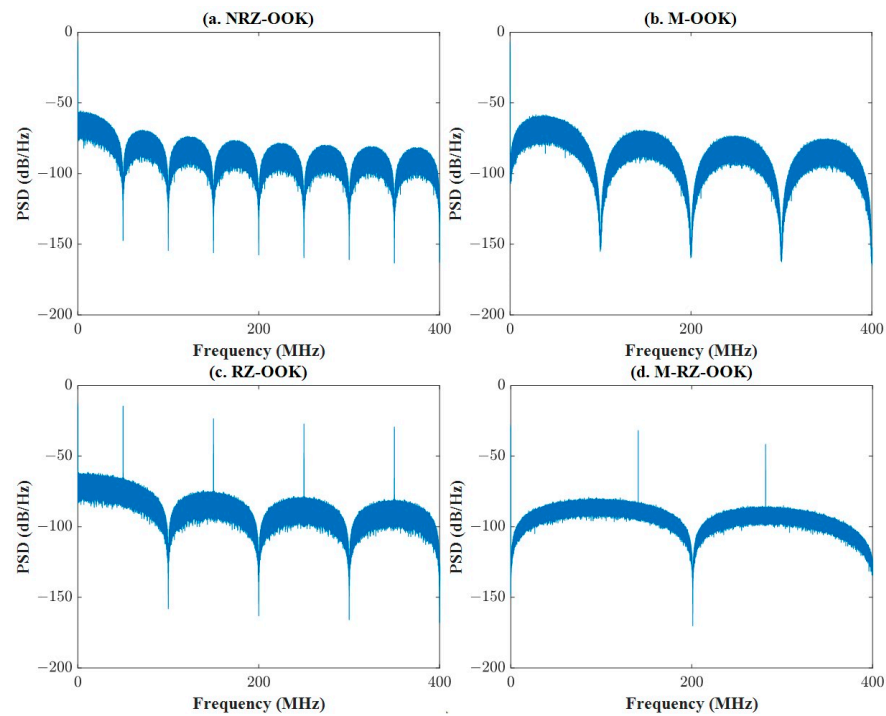


Figure 3. Spectrum of (a) NRZ-OOK, (b) M-OOK, (c) RZ-OOK, and (d) M-RZ-OOK.

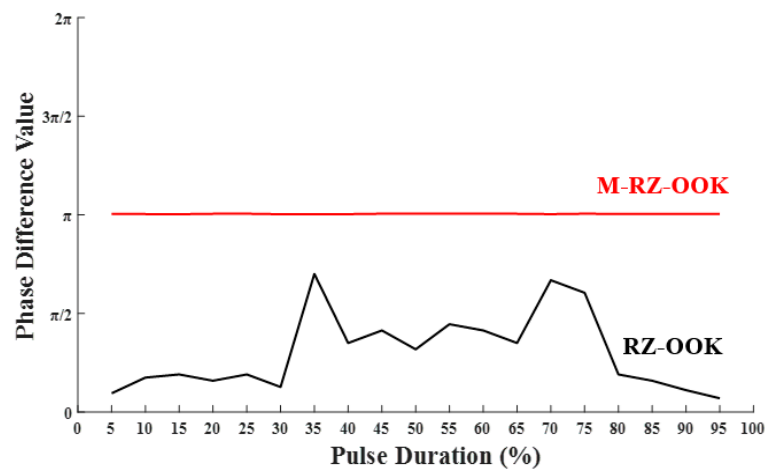


Figure 4. Phase difference between impulse series for RZ-OOK and M-RZ-OOK with different pulse durations.

3. Turbulence Channel Analysis

The atmospheric scintillation effect is caused by the random variation of temperature and pressure in the atmospheric channel, which contributes to the dramatic fluctuation of received optical irradiation [8]. In this study, the lognormal distribution is selected to model time-varying fluctuations in the intensity of the weak turbulence channel due to its simplicity. The probability density function (PDF) of the lognormal distribution is expressed as follows [12]:

$$f(I) = \frac{1}{\sqrt{2\pi\sigma_I^2}} \exp\left[-\frac{(\ln(I) - \mu)^2}{2\sigma_I^2}\right], \quad (7)$$

where I represents the intensity of received signal, and μ is the mean of $\ln(I)$. The turbulence channel is modeled by the process of phase modulation, inverse Fourier transform,

and the first-order Rytov approximation. The turbulence channel is modeled using the parameters in Table 1. Figure 5a depicts the features of time-dependent variation in the intensity of the turbulence channel, and Figure 5b demonstrates the spectrum characteristics of low frequencies' domination. Figure 5c shows the PDF of the modeled turbulence channel, which is close to the lognormal distribution. Thus, this modeled turbulence channel is applied to accommodate the scintillation effect in this study. Turbulence channels modeled with gamma–gamma distribution, Weibull distribution, K distribution, and negative exponential distribution will be discussed in the further works.

Table 1. Parameters of the turbulence channel.

Parameters	Values
Link distance	10 km
Wavelength	1550 nm
Aperture diameter	10 cm
Wind velocity	5 m/s
C_n^2	1.5×10^{-11}
Divergence angle	10 urad
Visibility	30 km

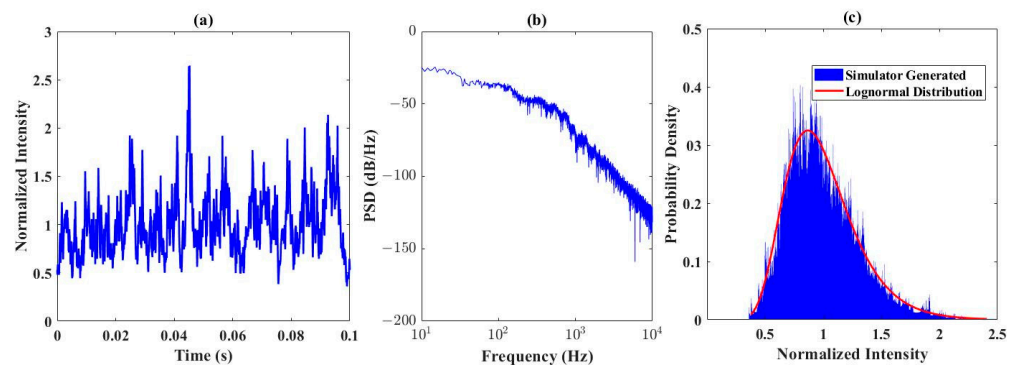


Figure 5. Turbulence channel model at $\sigma_I^2 = 0.1$. (a) intensity variation, (b) frequency, and (c) probability density function.

4. Simulations and Results

The proposed M-RZ-OOK modulation was evaluated in simulations with various turbulence effects at σ_I^2 of 0.1 and 0.5. M-RZ-OOK signals with 30% and 60% pulse durations. The estimated CSI-based ATD and APT were compared to the FTD and ATD with precise CSI.

Figure 6 illustrates the extraction of CSI signals using different LO frequencies of 25 MHz and 50 MHz using a turbulence channel with σ_I^2 of 0.1. The pulse duration of M-RZ-OOK was set to 60%. LPF with a cutoff frequency of 100 kHz was employed to filter sufficient CSI components. Figure 6a demonstrates the precise CSI knowledge of the turbulence channel with σ_I^2 of 0.1, which has the features of time-varying intensity. Figure 6b shows the CSI signal estimated from the first impulse tone of the M-RZ-OOK spectrum using the LO with a 25 MHz frequency. This first tone's extracted signal has normal CSI features, and it has a high correlation coefficient of 0.9725 compared with the precise CSI signal. Thus, it can be used as decision threshold in the ATD process in the forward link. Figure 6c describes the CSI signal estimated from the second impulse tone of the M-RZ-OOK spectrum employing the LO with a 50 MHz frequency. This second tone's extracted signal has inverse CSI features, and it also has a high correlation coefficient of 0.9820 compared with the precise CSI signal. Therefore, it can be used for the APT process in the backward link.

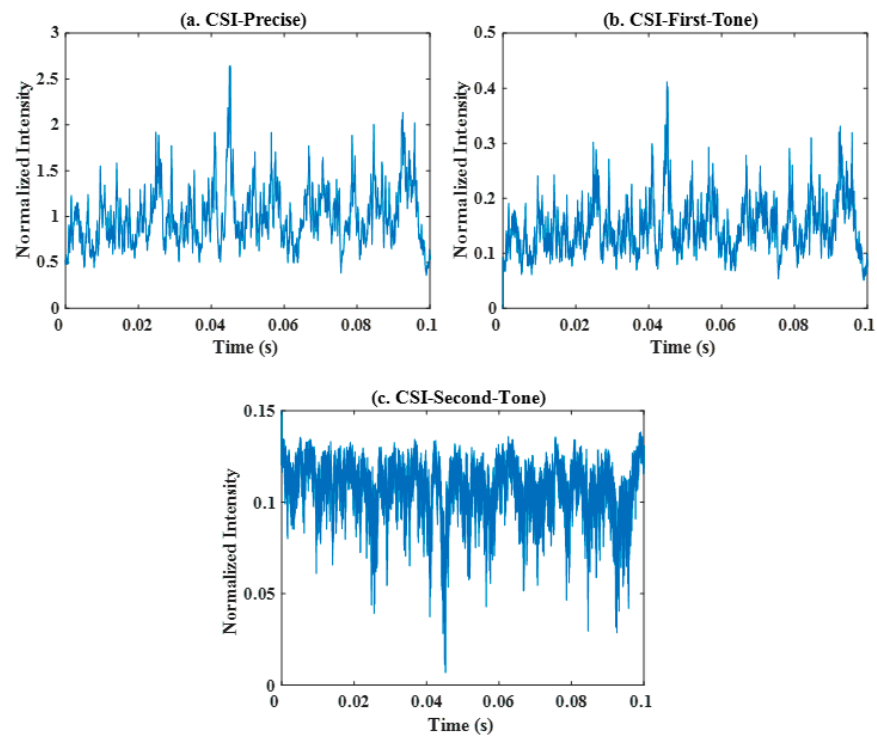


Figure 6. Extracted CSI signal with a pulse duration of 60% and σ_I^2 of 0.1. (a) Precise CSI, (b) first impulse extracted using an LO frequency of 25 MHz, and (c) second impulse extracted using an LO frequency of 50 MHz.

Figure 7 shows the extracted CSI signal with a pulse duration of 30% using the turbulence channel with σ_I^2 of 0.1. The frequencies of LO were configured to 50 MHz and 100 MHz due to the expansion of the signal spectrum. Figure 8 indicates the phase of the received M-RZ-OOK signal in the first tone and second tone. The phase difference between the first and second tones was π , indicating phase flip. Thus, the normal and inverse CSI signals were extracted from the first and second tones, respectively. In addition, the correlation coefficient between the estimated CSI signal and the precise CSI signal remains high.

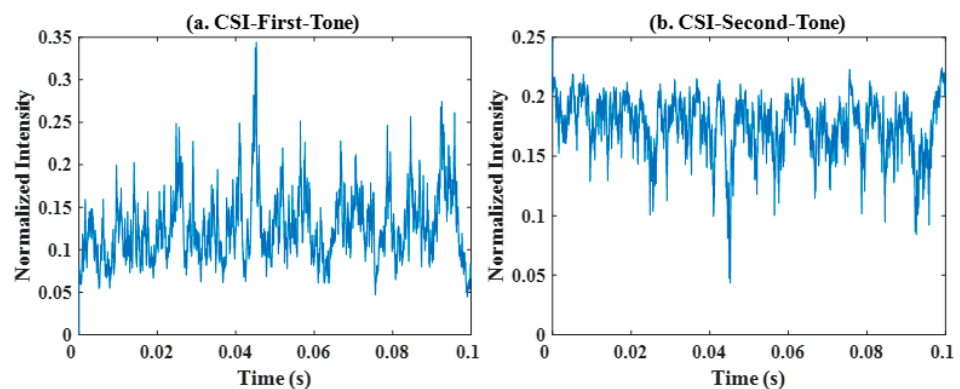


Figure 7. Extracted CSI signal with a pulse duration of 30% and σ_I^2 of 0.1. (a) First impulse extracted using LO frequency of 50 MHz and (b) second impulse extracted using an LO frequency of 100 MHz.

Figure 9 illustrates the bit error rate (BER) performance of ATD using the first tone's estimated CSI using the turbulence channel with σ_I^2 values of 0.1 and 0.5. M-RZ-OOK signals with a pulse duration of 30% and 60% were analyzed using fixed average power. The proposed ATD was studied using the estimated CSI signal with and without weight factor assignment, and it was compared to the conventional FTD and conventional ATD

with precise CSI knowledge. As for the conventional FTD, poor BER performance was achieved due to the serious variation in the intensity of the received signal, and M-RZ-OOK signal with pulse duration of 30% showed better BER performance compared to a pulse duration of 60%; this is because the reduction in pulse duration caused pulse power enhancement. As for the ATD with the first tone's estimated CSI without weight factor, poorer BER performance was observed compared to the conventional ATD with precise CSI due to the small signal intensity of the extracted CSI signal. Similar BER performance was realized by assigning an optimized weighing factor to the extracted CSI signal. Therefore, it is evident that the ATD can be realized by using the CSI signal estimated from the spectrum of the proposed M-RZ-OOK modulation using various turbulence channels and pulse durations.

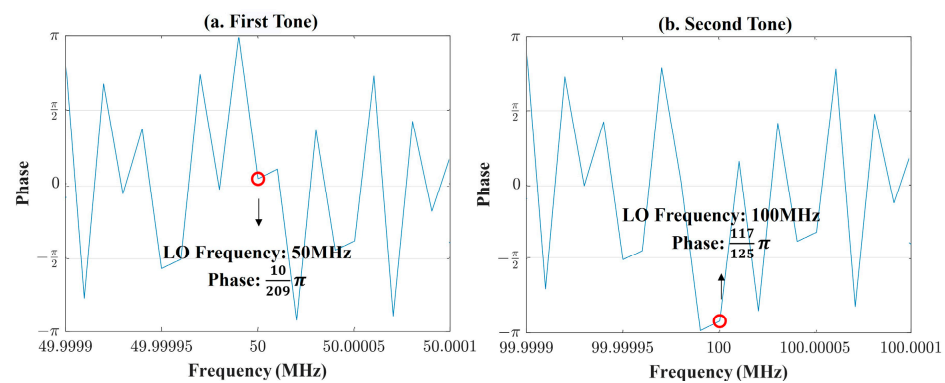


Figure 8. Phase of the received M-RZ-OOK signal in the (a) first tone and (b) second tone.

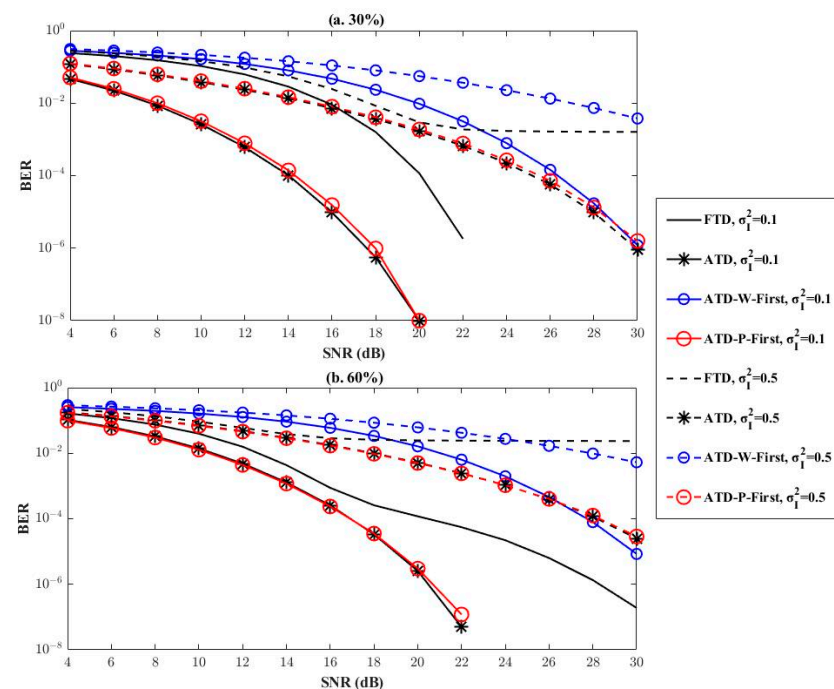


Figure 9. BER performance of ATD using the first tone's estimated CSI and the M-RZ-OOK signal with a pulse duration of (a) 30% and (b) 60%. ATD-W-First: ATD with the first tone's estimated CSI without weight factor; ATD-P-First: ATD with the first tone's estimated CSI with optimized weight factor.

Figure 10 illustrates the BER performance of APT using the second tone's estimated CSI and the turbulence channel with σ_I^2 values of 0.1 and 0.5. APT backward linking was accomplished using the CSI estimated from the forward link, and high channel reciprocity

was assumed in this work. Improved BER performance was achieved by the APT compared to the ATD with precise CSI, considering various turbulence effects and pulse durations. Figure 11 shows the BER performance of ATD using the first tone's estimated CSI and APT using the second tone's estimated CSI under the M-RZ-OOK signal with a pulse duration of 60% alongside various transmission rates. The transmission rates were discussed from 10 to 1000 Mbps. The SNRs were configured to 10 dB and 20 dB. High BER performance was achieved by both ATD and APT using the estimated CSI alongside various transmission rates. Concerning the SNR value of 10 dB, BER performance decreased in quality due to noise-induced CSI degradation. Consequently, ATD and APT were effectively realized in the forward and backward links, respectively, using estimated CSI knowledge and various turbulence channels.

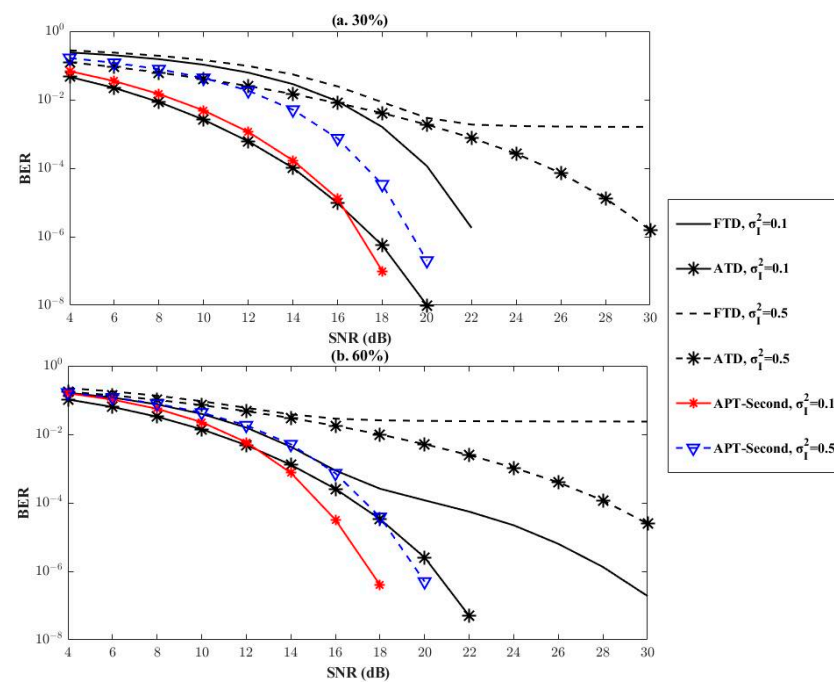


Figure 10. BER performance of APT using the second tone's estimated CSI under M-RZ-OOK signal with pulse durations of (a) 30% and (b) 60%. APT-Second: APT with the second tone's estimated CSI.

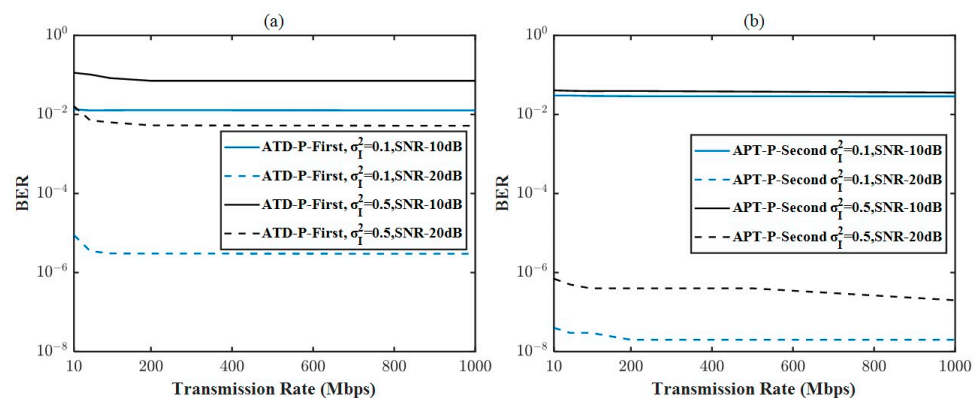


Figure 11. BER performance of (a) ATD using the first tone's estimated CSI and (b) APT using the second tone's estimated CSI and the M-RZ-OOK signal with a pulse duration of 60% and various transmission rates.

5. Conclusions

In summary, we have proposed M-RZ-OOK modulation for FSO communication links. M-RZ-OOK modulation with the feature of phase-flipped impulse series in the

spectrum was achieved by introducing Manchester coding into the RZ-OOK signal. The normal and inversed CSI signals were estimated using LO from the impulses of the M-RZ-OOK spectrum simultaneously, and these CSI signals were applied to realize ATD and APT in the forward and backward links, respectively. The proposed M-RZ-OOK modulation was evaluated in simulations using various turbulent effects. The simulation results demonstrated that ATD and APT were effectively accomplished in the forward and backward links by utilizing estimated CSI knowledge. Therefore, this is an efficient and viable technique for FSO links.

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