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Effect of different weather conditions on BER performance of single-channel free space optical links

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ABSTRACT

This paper studies and compares the performance of on-off keying (OOK), pulse position modulation (PPM), digital pulse interval modulation (DPIM) and dual-header pulse interval modulation (DH-PIM) schemes in FSO channels in the presence of different weather conditions. The bit error rate (BER) curves for these modulations are simulated. Moreover, a performance comparison between these modulation techniques is provided. Generally, in the absence of turbulence OOK-NRZ (non-return-to-zero) and PPM is found to achieve a better BER performance as compared to DPIM and DHPIM. In the presence of fog, OOK-NRZ and PPM is better than DPIM and DH-PIM by approximately 1 dB at BER 1e-3. While, in case of rain, OOK-NRZ and PPM is better than DPIM and DH-PIM by approximately 1.5 dB at BER 1e-3. Moreover, in case of snow, OOK-NRZ and PPM is better than DPIM and DH-PIM by approximately 1.7 dB at BER 1e-3. Additionally, in the presence of turbulence, in case of weak turbulence, OOK-NRZ and PPM is better than DPIM and DH-PIM by approximately 8 dB and 10 dB, respectively at BER 1e-3. Furthermore, in case of moderate turbulence, OOK-NRZ and PPM is better than DPIM and DH-PIM by approximately 6 dB and 8 dB, respectively at BER 1e-3. Finally, in case of strong turbulence, OOK-NRZ and PPM is better than DPIM and DH-PIM by approximately 3 dB and 4 dB, respectively at BER 1e-3.

1. Introduction

Nowadays, communication networks are the backbone of the world, since all life fields depend on communication networks to carry out life needs such as e-learning, e-shopping, e-business, cable TV, voice over internet protocol (VoIP) calls, etc. [1]. It is widely accepted that, there is an increasing demand for high-speed wireless communication networks to satisfy the needs of the market [2]. In recent years, one of the most important technologies that can provide high-speed (multi-gigabytes per second) wireless communication is FSO communication [1,3]. However, communication capacity can be enhanced significantly by applying multiple access techniques that allow users to share the large bandwidth of the FSO communication link [4,5]. Many researchers confirmed that, the FSO communication technology is the most convenient technology to fill the gap between the end-user and the optical fiber backbone infrastructure [1]. Optical wireless communication (OWC) systems are divided into indoor and outdoor systems [2]. Unlike optical fiber, light travels directly through air between the transmitter and the receiver in an OWC link. So, there are a lot of factors that can affect light during its journey from the transmitter to

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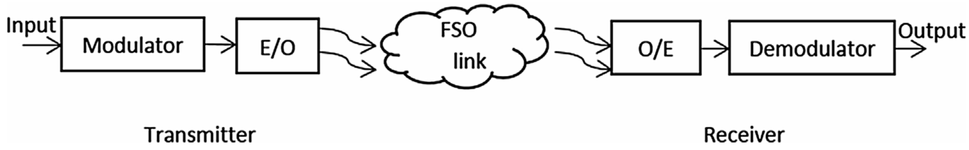

Fig. 1. Typical schematic diagram of an FSO system.

the receiver. These factors can vary according to the type of the OWC system. Outdoor FSO communication system is affected by building sway, which causes misalignment between transmitter and receiver. It occurs because of thermal expansion, wind sway and vibration. However, the performance of any outdoor FSO communication link is fundamentally restricted by environmental factors [2,5].

In prior researches on outdoor FSO communication link, researchers considered the atmospheric effect with gamma–gamma probability density function, pointing error effects, outage capacity optimization with pointing errors and performance of long distance FSO links under beam wander effects. In other researches, scintillation effect was considered as the only atmospheric effect [6–10]. In this paper, a performance comparison between OOK, PPM, DPIM and DH-PIM in the presence of different atmospheric conditions; namely, fog, snow, rain and turbulence is investigated.

The organization of this paper is as follows, Section 2 introduces the system model. Section 3 presents the link budget, and demonstrates the applied attenuation models. Then, Section 4 discusses the used modulation techniques, their waveforms, and their probabilities of error calculation. Section 5 presents the numerical results. Finally, Section 6 provides the paper conclusions.

2. System model

A typical schematic diagram of an FSO transmitter and a single channel receiver is shown in Fig. 1. In the transmitter, the input data is modulated using one of the modulation techniques mentioned in Section 1. The modulator output is then converted from electrical signal to optical signal using the electrical to optical converter (E/O). The optical signal is then transmitted through the FSO link. In the receiver, the optical signal is converted to electrical signal using optical to electrical converter (O/E). The electrical signal is then demodulated to recover the transmitted data.

3. Link design

The performance of any FSO link is basically restricted by the atmospheric factors. The best practice to determine how well the FSO link will perform is to evaluate the link budget equation. This equation is given by [11]:

$$P_r = P_t \cdot \frac{A_{eff}}{(\theta L)^2} \cdot e^{-\gamma L} \tag{1}$$

where, P_r is the received optical power, P_t is the transmitted optical power, A_{eff} is the effective area of the receiver, L is the link length, θ is the beam divergence in rad and γ is the loss due to atmospheric attenuation in dB/km. The total loss coefficient γL is evaluated by [5]:

$$\gamma L = (\gamma_f \cdot L) + (\gamma_s \cdot L) + (\gamma_r \cdot L) \tag{2}$$

where, γ_f is the attenuation due to fog in km^{-1}, γ_s is the attenuation due to snow in km^{-1}, and γ_r is the attenuation due to rain in km^{-1}.

There are a variety of models exist to calculate the attenuation due to fog. The three most widely used models in literature are Kruse, Kim and Al-Naboulsi [12]. Kruse and Kim models give almost the same results as they depend on the same formula to calculate attenuation due to fog. Also, it has been shown that the Kruse model provides a better for fog attenuation predication [13]. In this paper, Kruse model is used, and is given by:

$$\gamma_f = \frac{3.912}{V} \cdot \left(\frac{\lambda}{\lambda_0}\right)^{-q} \tag{3}$$

where, V is the visibility at $\lambda = \lambda_0$ in km^{-1}, λ is the operating wavelength in nm, λ_0 is the reference wavelength in nm, and q is the particle size coefficient given by:

$$q = \begin{cases} 1.6 & V > 50km \\ 1.4 & 6km < V < 50km \\ 0.585V^{1/3} & V < 6km \end{cases} \tag{4}$$

The visibility range considered in this paper is from 0.1 km to 1 km. These values represent the different types of fog. Very light fog (1000m), light fog (770 m), medium fog (500 m), thick fog (200 m) [2].

Attenuation due to snow γ_s can be calculated using the following equation [2]:

$$\gamma_s = a \cdot S^b \tag{5}$$

where, S is the snowfall rate in mm/h, the variables a and b vary according to dry or wet snow. For dry snow, a and b are given by $a = 5.42 \times 10^{-5}\lambda + 5.4958776$ and $b = 1.38$, whereas for wet snow, $a = 1.023 \times 10^{-4}\lambda + 3.7855466$ and $b = 0.72$.

Finally, the attenuation due to rain γ_r can be calculated using the following equation [2]:

$$\gamma_r = 1.076 \cdot R^{2/3} \tag{6}$$

where, R is the rainfall rate in mm/h. The range of rain intensity considered in this paper is from 0.1 mm/h to 100 mm/h; which covers all types of rain. Drizzle (0.25 mm/h), light rain (2.5 mm/h), medium rain (12.5 mm/h), heavy rain (25 mm/h) and storm (100 mm/h) [2].

In the following analysis, atmospheric turbulence effect will also be considered. Atmospheric turbulence can be weak, moderate or strong. The gamma–gamma turbulence model can describe the weak, moderate and strong turbulence [2]. It is based on the assumption that the atmospheric turbulence consists of large scale and small scale cells. Both large and small scale cells are intended to follow the gamma distribution.

The irradiance pdf for the gamma–gamma distribution can be given by [2]:

$$P(I) = \frac{2\left(\alpha\beta\right)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\,\Gamma\left(\beta\right)} \cdot I^{(\alpha+\beta/2)-1} \cdot K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right) \tag{7}$$

where α and β are the effective number of large and small scale cells in the turbulence, $K_n(.)$ is the modified Bessel function of the 2nd kind of order n and $\Gamma(.)$ represents the gamma function. I must be larger than zero.

4. Modulation techniques and error calculation

In this paper, OOK, PPM, DPIM and DH-PIM modulation schemes are considered. OOK is one of the most used modulation techniques in optical communications; because of its simplicity. Both return-to-zero (RZ) and non-return-to-zero (NRZ) can be used. OOK-NRZ is more bandwidth efficient than OOK-RZ. In this analysis, OOK-NRZ is used, which can be represented by [2]:

$$S_{OOK}(t) = \begin{cases} 1 & t \in [0, T_{OOK}] \\ 0 & elsewhere \end{cases} \tag{8}$$

where, T_{OOK} is the bit duration. The BER for OOK-NRZ can be calculated using:

$$P_{OOK} = Q\left(\sqrt{\frac{E_b}{N}}\right) \tag{9}$$

where, E_b/N is the signal-to-noise ratio (SNR) per bit and $Q()$ is Marcum's function. Where $N = N_0 + N_f + N_r + N_s + N_t$ and N_0 is noise due to additive white Gaussian noise (AWGN), N_f is noise due to fog, N_r is noise due to rain and N_t is noise due to turbulence.

PPM can be represented by [2]:

$$S_{PPM}(t) = \begin{cases} 1 & t \in [(m-1)T_{PPM}, mT_{PPM}] \\ 0 & elsewhere \end{cases} \tag{10}$$

where, $m \in \left\{1, 2, \ldots L_{PPM}\right\}$, $L_{PPM} = 2^M$ is the possible time slots within one symbol, M (integer > 0) is the bit resolution and T_{PPM} is the slot duration. The BER for PPM can be obtained using:

$$P_{PPM} = Q\left(\sqrt{\frac{E_b}{N}}\right) \tag{11}$$

DPIM can be represented by [2]:

$$S_{DPIM}(t) = L_{DPIM} P_{avg} \sum_{k=0}^{\infty} c_k p\left(t - kT_{DPIM} - \tau_n\right) \tag{12}$$

Table 1
Summary of simulation parameters.

Parameters	Value
Bit-rate	1 Mbps
Transmitted optical power	−35 dBm
Receiver radius	4 cm
Receiver responsivity	1 A/W
Receiver load resistance	1000 Ω
Beam divergence	1 mrad
Operating wavelength	1550 nm
Reference wavelength	500 nm
Visibility	0.1–1 km

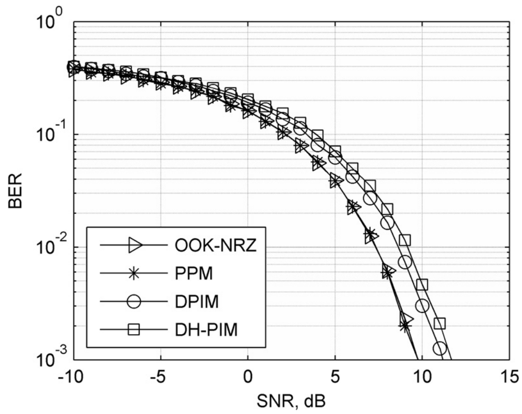

Fig. 2. BER VS SNR for OOK, PPM, DPIM and DH-PIM in the presence of AWGN.

where, L_{DPIM} is the average symbol length, P_{avg} is the average transmitted power, $c_k = 1$ or 0 is a random variable that denotes the existence or non-existence of a pulse in the n^{th} time slot, T_{DPIM} is the slot duration and τ_n is the random jitter within a time slot. The BER for DPIM can be expressed using:

$$P_{DPIM} = Q\left(\sqrt{\frac{E_b}{2N}}\right) \tag{13}$$

DH-PIM can be represented by [2]:

$$S_{DH-PIM}(t) = \frac{4L_{DH-PIM}P_{avg}}{3\delta}\sum_{k=0}^{\infty}\left\{p\left[\frac{2(t-T_k)}{\delta T_{DH-PIM}} - \frac{1}{2}\right] + h_n p\left[\frac{2(t-T_k)}{\delta T_{DH-PIM}} - \frac{3}{2}\right]\right\} \tag{14}$$

where, L_{DH-PIM} is the average symbol length, P_{avg} is the average transmitted power, $\delta > 0$ is an integer, T_{DH-PIM} is the slot duration and $h_n \in \{0, 1\}$ specifies on of the two headers. The BER of DH-PIM can be expressed by:

$$P_{DH-PIM} = \frac{1}{4L_{DH-PIM}}\left[\left(4L_{DH-PIM} - 3\delta\right)Q\left(\sqrt{\frac{2k^2E_b}{N}}\right) + 3\delta Q\left(\sqrt{\frac{2(1-k)^2E_b}{N}}\right)\right] \tag{15}$$

where, $0 < k < 1$ denotes a threshold factor.

5. Numerical results

In the present analysis, different atmospheric conditions are considered. Each modulation technique is analyzed under the effect of fog, rain, snow and atmospheric turbulence. The parameters used in this simulation are summarized in Table 1. Surface leakage current and bulk dark current are taken into consideration.

Monte-Carlo simulations were carried out to evaluate the performance of an FSO communication link using modulation techniques under investigation in the presence of the aforementioned weather conditions based on the parameters summarized in Table 1. Then a performance comparison is illustrated by comparing the BER of the modulation techniques in each case.

Fig. 2 illustrates a performance comparison between the different modulation techniques mentioned earlier in the presence of AWGN and absence of turbulence. At BER value 10^{-3}, the SNR for OOK-NRZ and PPM modulation is 9.7 dB. While

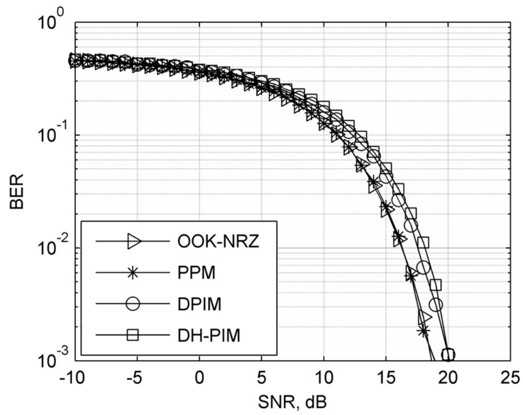

Fig. 3. BER VS SNR for OOK, PPM, DPIM and DH-PIM in the presence of fog.

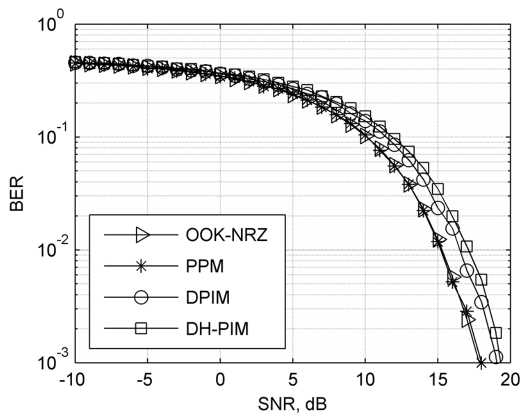

Fig. 4. BER VS SNR for OOK, PPM, DPIM and DH-PIM in the presence of rain.

for DPIM modulation the SNR 11.1 dB and for DH-PIM modulation the SNR 11.6 dB. By examining the results, it is obvious that OOK-NRZ and PPM modulations have the same performance. While DPIM performance is a little better than DH-PIM performance.

Fig. 3 shows the performance comparison between the four modulation techniques in the presence of fog. The BER reaches value of 10^{-3} at SNR approximately 18.5 dB in case of OOK-NRZ and PPM modulations and at SNR 20 dB in case of DPIM and DH-PIM modulations. Therefore, OOK-NRZ and PPM have the best performance.

Fig. 4 demonstrates a performance comparison between the four modulation techniques in the presence of rain. The BER reaches value of 10^{-3} at SNR 18 dB in case of OOK-NRZ and PPM modulations and at SNR 19 dB in case of DPIM and DH-PIM modulations. Consequently, OOK-NRZ and PPM have the best performance while DPIM and DH-PIM have the worst performance.

Fig. 5 displays the performance comparison between the four modulation techniques in the presence of dry snow. The BER reaches value of 10^{-3} at SNR 18 dB in case of OOK-NRZ and PPM modulations and at SNR 19 dB in case of DPIM and DH-PIM modulations. Hence, OOK-NRZ and PPM have the best performance while DPIM and DH-PIM have the worst performance.

Fig. 6 illustrates the performance comparison between the four modulation techniques in the presence of wet snow. The BER reaches value of 10^{-3} at SNR 17.5 dB in case of OOK-NRZ and PPM modulations and at SNR 19.5 dB in case of DPIM and DH-PIM modulations. Hence, OOK-NRZ and PPM have the best performance while DPIM and DH-PIM have the worst performance.

Fig. 7 shows the performance comparison between the four modulation techniques in weak turbulence. The BER reaches value of 10^{-3} at approximately SNR 10 dB in case of OOK-NRZ and PPM modulations, at SNR 18 dB in case of DPIM modulation and at SNR 20 dB in case of DH-PIM modulation. OOK-NRZ and PPM modulations techniques almost have the same performance.

Fig. 8 presents the performance comparison between the four modulation techniques in moderate turbulence. The BER reaches value of 10^{-3} at SNR 32.4 dB in case of OOK-NRZ modulation, at SNR 36.9 dB in case of PPM modulation, at SNR 38.7 dB in case of DPIM modulation and at SNR 40 dB in case of DH-PIM modulation. Therefore, OOK-NRZ has the best performance.

Fig. 9 describes the performance comparison between the four modulation techniques in strong turbulence. The BER reaches value of 10^{-3} at SNR 42.7 dB in case of OOK-NRZ and PPM modulation, at SNR 45.2 dB in case of DPIM modulation

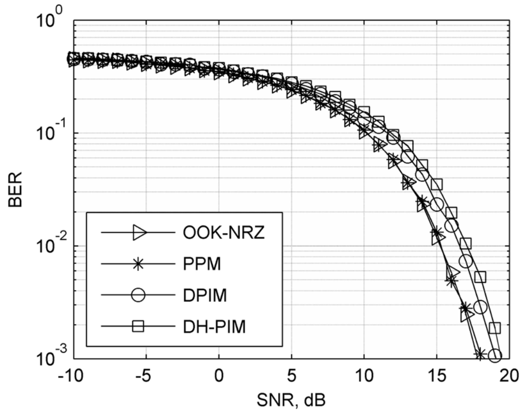

Fig. 5. BER VS SNR for OOK, PPM, DPIM and DH-PIM in the presence of dry snow.

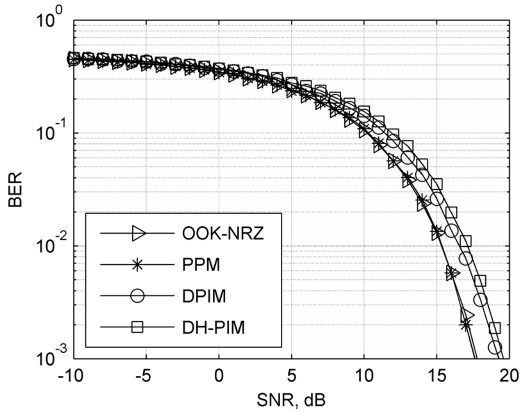

Fig. 6. BER VS SNR for OOK, PPM, DPIM and DH-PIM in the presence of wet snow.

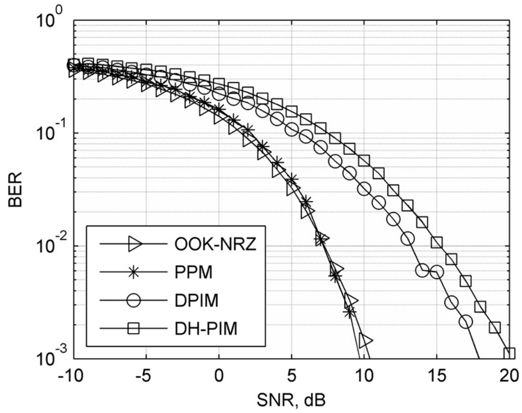

Fig. 7. BER VS SNR for OOK, PPM, DPIM and DH-PIM in the presence of weak turbulence.

and at SNR 46.8 dB in case of DH-PIM modulation. Thus, OOK-NRZ has the best performance while DH-PIM has the worst performance.

6. Conclusion

This paper studied the effect of different weather conditions including fog, rain, snow and atmospheric turbulence on the BER performance of different modulation schemes; namely, OOK-NRZ, PPM, DPIM and DH-PIM. Numerical results showed that OOK-NRZ and PPM achieves the best BER performance among the analyzed modulation techniques under the different

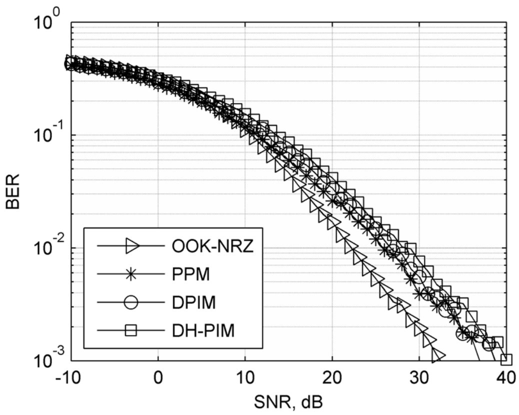

Fig. 8. BER VS SNR for OOK, PPM, DPIM and DH-PIM in the presence of moderate turbulence.

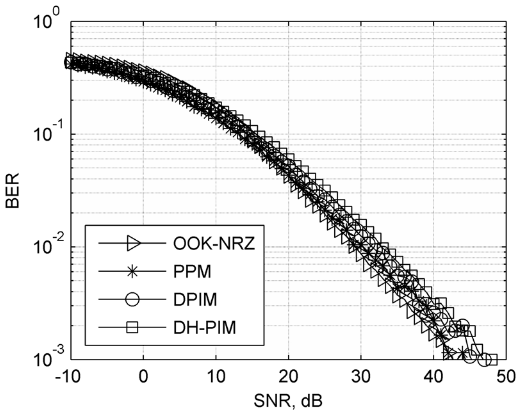

Fig. 9. BER VS SNR for OOK, PPM, DPIM and DH-PIM in the presence of strong turbulence.

weather conditions. In addition, numerical results showed that strong turbulence causes the highest attenuation with SNR 42.7 dB at BER 10^{-3} in case of OO-NRZ modulation technique, while weak turbulence causes the least attenuation with SNR 9.7 at BER 10^{-3} in case of PPM modulation.

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