

# Performance Analysis of Modulation Techniques over a Smart City Optical Communication Channel Under Weak Atmospheric Turbulence



Sazid Hasan, Md Musfiqul Islam, Firoz Ahmed, S. M. Mustahsin Saabit, Nazmus Shaker Nafi, Mohammad Kamrul Hasan, Shayla Islam, and Imran Memon

## 1 Introduction

Free space optical (FSO) communication is a technology which is line of sight (LOS) that utilizes light-emitting diodes (LED) or lasers to propagate a light signal through free space, which acts as a communication channel between transceivers. FSO links providing 2.5 Gbps [1] of video, voice, and data transmission have been implemented. FSO is generally implemented using transmission wavelengths between 780 nm and 1600 nm. FSO systems have the following characteristics:

---

S. Hasan · M. M. Islam · F. Ahmed  
Military Institute of Science and Technology, Dhaka, Bangladesh

S. M. M. Saabit  
Swinburne University of Technology, Melbourne, Australia

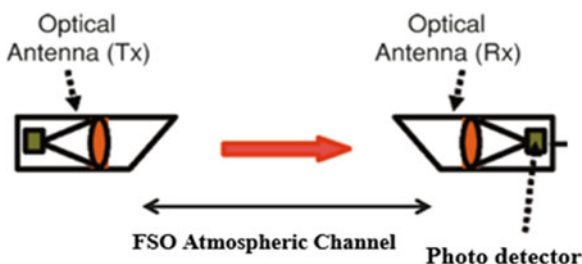
N. S. Nafi  
Melbourne Institute of Technology, Melbourne, Australia  
e-mail: [nnafi@mit.edu.au](mailto:nnafi@mit.edu.au)

M. K. Hasan (✉)  
Center for Cyber Security, Faculty of Information Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Selangor, Malaysia  
e-mail: [mkhasan@ukm.edu.my](mailto:mkhasan@ukm.edu.my)

S. Islam  
Department of Computer Science, UCSI University Malaysia, Kuala Lumpur, Malaysia  
e-mail: [shayla@ucsiuniversity.edu.my](mailto:shayla@ucsiuniversity.edu.my)

I. Memon  
Department of Computer Science, Bahria University, Karachi, Sindh, Pakistan  
e-mail: [Imranmemon.bukc@bahria.edu.pk](mailto:Imranmemon.bukc@bahria.edu.pk)

**Fig. 1** Simple FSO communication model



- Capable of operating at very higher power levels
- High-speed data modulation
- Low power consumption
- Minimal performance degradation with varying temperatures

The elements of FSO are typically described in three stages. By following the Beer-Lambert law [2], the transmitter converts digital information into optical radiation that is transmitted across the free space, where turbulent eddies exist that include smoke, gas, fog, cloud, or rain. The signal at the receiver is processed to return the digital information.

In Fig. 1 an electrical message signal is converted into light using a media converter before the light is modulated and transmitted using an optical transmitter. The antenna of receiver gets the signal which is optical and demodulates it before conversion to an electrical message signal. However, signal distortion can occur when the transmission of signal occurs through freeways due to turbulence.

One of the major challenges for FSO is atmospheric turbulence, which creates signal distortion and possible signal loss. Light waves can be attenuated, distorted, or deflected by atmospheric turbulence. The light signal at the receiver can be detrimentally affected by the attenuation that occurs in free space due to absorption and scattering. Gaining an understanding of the FSO communication's performance under weak nature of conditions of turbulence is important and will help in the design of systems that minimize bit error rates (BER).

In central business district (CBD), making connection via cable is very complex and costly. FSO is the future concept for communication in short distance. To establish FSO ground-to-ground connection, some factors that obstruct the LOS needs to be improved. Ground-to-ground FSO communication is the focus of this paper. An analysis is presented of the BER performance of selected modulation techniques when weak turbulence conditions are experienced. Also, the power penalty has been derived for selected modulation techniques and for various link distances. The analysis provides the optimum FSO system parameters.

The organization of this paper is as follows. Methodology is elaborated in Sect. 2. Results and analysis are presented in Sect. 3. Section 4 concludes the paper and highlights future research.

## 2 Methodology

FSO transmits optical wave of data like voice, video, etc., using air as the medium of transmission. FSO transmission technology is relatively simpler than optical fiber technology. It includes two structures. One is a transceiver of optical nature that comprises a transmitter which has laser, and another one is a receiver to offer capability of being full-duplex (bidirectional). There is a telescope in the receiver end which collects the information. The telescope at the receiving end links to a receiver having a high sensitivity that is connected by optical fiber. Unlike frequencies of radio, this technology needs not require licenses of spectrum. Its interfaces which are open support tools from various vendors and are easily upgradeable.

In the field of FSO, extensive research is ongoing. There are different types of modulation techniques for FSO transmission. ASK, FM, OOK, PSK, PWM, OFDM, and PPM are some modulation techniques that are considered for FSO transmission in a different research project. This paper focused on PSK and considered the optimum link distance to transmit with less error.

In this paper, a weak atmospheric turbulent channel is considered to simulate the weak atmospheric turbulence; additive white Gaussian noise model, atmospheric turbulence model, log normal model, gamma PDF model, and atmospheric turbulence channel with pointing errors are used. Using these models in the probability of bit error for M-PSK (BPSK, Q-PSK, 8-PSK, and 16-PSK) modulation is simulated over 500 m, 1000 m, 1500 m, and 2000 m length respectively in MATLAB simulation. In the simulation the probability of BER for M-PSK is calculated and plotted against SNR for the lengths 500 m, 1000 m, 1500 m, and 2000 m. After modulating the optical signal with M-PSK modulation and transmitted through media containing weak atmospheric turbulence particles, the modulated optical signal at the receiver ends with the errors which are calculated with standard Gaussian approximation. Then, power penalty over link distances is plotted which denotes the optimum modulation technique and performance of the optical communication.

### 2.1 Error Rate Performance on M-PSK Modulation

After modulation, what we get is the signal with the errors. So to get the exact signal performance, it is needed to measure the rate of bit error. The mean rate of error of a subcarrier system over channels of turbulence can be shown as

$$P_e = \int_0^{\infty} P_e(I) f_I(I) dI \quad (1)$$

where  $p_x$  presents the probability of conditional error and  $f_I(I)$  presents the channel gain's PDF.

## 2.2 Bit Error Rate (BER)

The rate of error of bit that represents the digital link's quality is measured from the error bits number obtained divided by the quantity of transmitted bits

$$BER = (\text{bits in error}) / (\text{number of bits obtained in total})$$

BER can also be known as per the probability of error (POE) [3] and shown by Eq.

$$POE = \frac{1}{2} (1 - \text{erf}) \sqrt{\frac{E_b}{N_0}} \quad (2)$$

Here, erf = error function,  $E_b$  = energy in one bit, and  $N_0$  = noise power spectral. For links of FSO with a modulation scheme of an on-off keying, BER can be written as

$$BER = \frac{\exp(-SNR/2)}{(2\pi SNR)^{0.5}} \quad (3)$$

## 2.3 Signal-to-Noise Ratio (SNR)

SNR is the total obtained signal power's ratio over the strength of noise in the range of frequency of an operation. Noise strength includes the environment's noise and other signals which are unwanted. BER is in reverse to SNR. The relation between BER and SNR is very difficult to be determined in the environment of multi-channel. Signal-to-noise ratio (SNR) is being calculated in decibels and shown by Eq. (4)

$$SNR = 10 \log_{10} \left( \frac{\text{signal power}}{\text{noise power}} \right) \quad (4)$$

Both BER and SNR are utilized for evaluating the excellence of communication systems. In presence of turbulence, the SNR is represented as follows [4]:

$$SNR = \left( 0.31 C_n^2 k^{7/6} l^{11/6} \right)^{-1} \quad (5)$$

The photo detector’s total surface area is large enough so that the effective SNR comprises the effect of the spreading of the beam. The effective SNR is stated as [5–7]

$$SNR_{eff} = \frac{SNR}{1 + 1.33\sigma_i^2 \left[ \frac{2l}{k\omega(l)^2} \right]^{5/6}} \tag{6}$$

### 2.4 BER and SNR on M-PSK Modulation

The mean value of BER for modulation of BPSK can be estimated by a finite series as [8]

$$P_2 \approx \frac{\Delta(\alpha, \beta, \varphi)}{2\sqrt{\pi}} \sum_{p=0}^K \left[ \frac{\Gamma\left(\frac{p+\beta+1}{2}\right) a_p(\alpha, \beta, \varphi, A_0)}{(p+\beta)(\varphi^2 - p - \beta)} \gamma^{-\frac{p+\beta}{2}} - \frac{\Gamma\left(\frac{p+\alpha+1}{2}\right) a_p(\beta, \alpha, \varphi, A_0)}{(p+\beta)(\varphi^2 - p - \alpha)} \gamma^{-\frac{p+\alpha}{2}} \right] \tag{7}$$

where  $K = \lfloor \varphi^2 - \alpha \rfloor > 0$  and  $\lfloor \cdot \rfloor$  is the floor function. The BER for the modulation of BPSK in high regimes of SNR can be estimated by [9]

$$P_2^\infty = \frac{\Delta(\alpha, \beta, \varphi) \left(\frac{\alpha\beta}{A_0}\right)^\beta \Gamma\left(\frac{\beta+1}{2}\right)}{2\sqrt{\pi} \Gamma(\beta + 1 - \alpha) (\varphi^2 - \beta) \beta} \gamma^{-\frac{\beta}{2}} \tag{8}$$

where  $\alpha < \varphi^2$ . Since  $\alpha > \beta$ , the inequality  $\varphi^2 > \alpha$  also implies  $\varphi^2 > \beta$ , which will ensure the rate of error as positive.

### 2.5 Probability of Bit Error for M-PSK Modulation

For a modulation of M-PSK, the bits amount in each symbol of constellation is

$$k = \log_2(M) \tag{9}$$

Since each symbol consists of bits of k number, the symbol-to-noise ratio  $E_s/N_o$  is K times the ratio of bit to noise  $E_b/N_o$ , i.e.,

$$\frac{E_s}{N_o} = K \frac{E_b}{N_o} \tag{10}$$

The bit error probability for a general M-PSK modulation is [10],

$$P_b = \frac{1}{k} \left[ \sqrt{\frac{kE_b}{N_o} \text{Sin} \left( \frac{\pi}{M} \right)} \right] \quad (11)$$

## 2.6 Binary Phase-Shift Keying (BPSK)

BPSK is a digital system of modulation that carries data by modulating or changing a reference signal phase. It practices two phases, which are opposite by 180°. The BER equation of modulation of BPSK is as given below [11, 17–19]:

The signal of BPSK can be represented as

$$S_n(t) = \sqrt{\frac{2E_b}{T_b}} \cos \left( 2\pi f_c t + \pi (1 - n) \right) \quad (12)$$

The transmitted power of BPSK signal is  $P_t = (E_b/T_b)$ . Received signal power of BPSK signal is  $S = P_r(d) = P_t \cdot e^{\alpha d}$ , where  $\alpha$  is the attenuation constant and  $d$  the distance between receiver and transmitter. The signal-to-noise ratio is

$$SNR = \frac{s^2}{\sigma_{th}^2 + \sigma_{shot}^2} \quad (13)$$

The conditional BER is given by

$$BER = \frac{1}{2} \text{erfc} \left( \sqrt{SNR} \right) \quad (14)$$

The mean value of BER of the BPSK system over weak turbulence due to pointing errors and path loss can be expressed from Eq. (1) by [12]

$$P_{BPSK} = \int_{-\infty}^{+\infty} P_e(I) f_I(I) dI \quad (15)$$

## 2.7 *M-Phase Shift Keying (M-PSK)*

In M-PSK ( $M = 4, 8, 16$ ), the signal equation is like BPSK. The only difference is the phase shifts. With increasing M value, the phase is changing more. The signal of M-PSK can be represented as

$$S_n(t) = \sqrt{\frac{2E_b}{T_b}} \cos\left(2\pi f_c t + (2n - 1) \frac{\pi}{M}\right) \quad (16)$$

The transmitted power of M-PSK signal is  $P_t = E_b/T_b$ . Received signal power of M-PSK signal is  $S = P_r(d) = P_t e^{-\alpha d}$ , where  $\alpha$  is the attenuation constant and  $d$  the distance between receiver and transmitter. The signal-to-noise ratio is

$$SNR = \frac{s^2}{\sigma_{ih}^2 + \sigma_{shot}^2} \quad (17)$$

The equation of rate of bit error of M-PSK modulation is given below:

$$BER = \frac{M}{4} \operatorname{erfc}\left(\sqrt{SNR}\right) \quad (18)$$

The mean value of BER of the M-PSK system over weak turbulence due to pointing errors and path loss can be expressed from Eq. (1)

$$P_{M-PSK} = \int_{-\infty}^{+\infty} P_e(I) f_I(I) dI \quad (19)$$

## 3 Results and Discussions

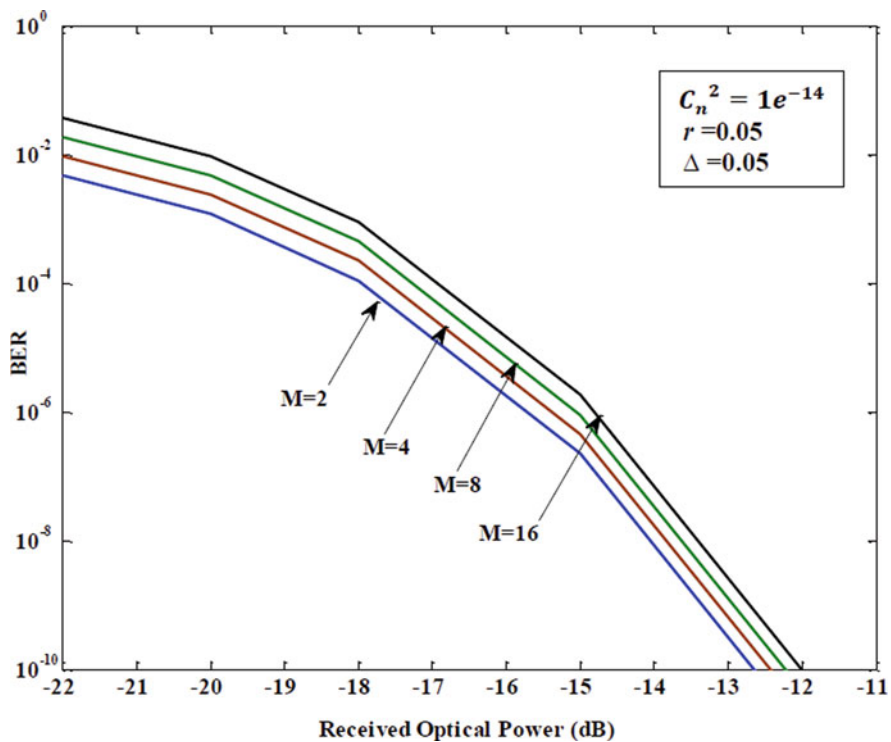
Following the analytical approach, the free space optical communication's performance with different techniques of modulation over different lengths is evaluated. The standard Gaussian approximation (SGA) evaluates the SNR and BER performance in different modulations (Table 1).

### 3.1 *Performance Analysis of Different PSK Modulations*

Plots of BER vs SNR for BPSK, QPSK, 8-PSK, and 16-PSK modulation considering link distance of 500 m are shown in Fig. 2. In Fig. 2, it is clear that increasing the symbol bits for modulation SNR increases irrespective with BER. The result showed

**Table 1** System parameters [11–19]

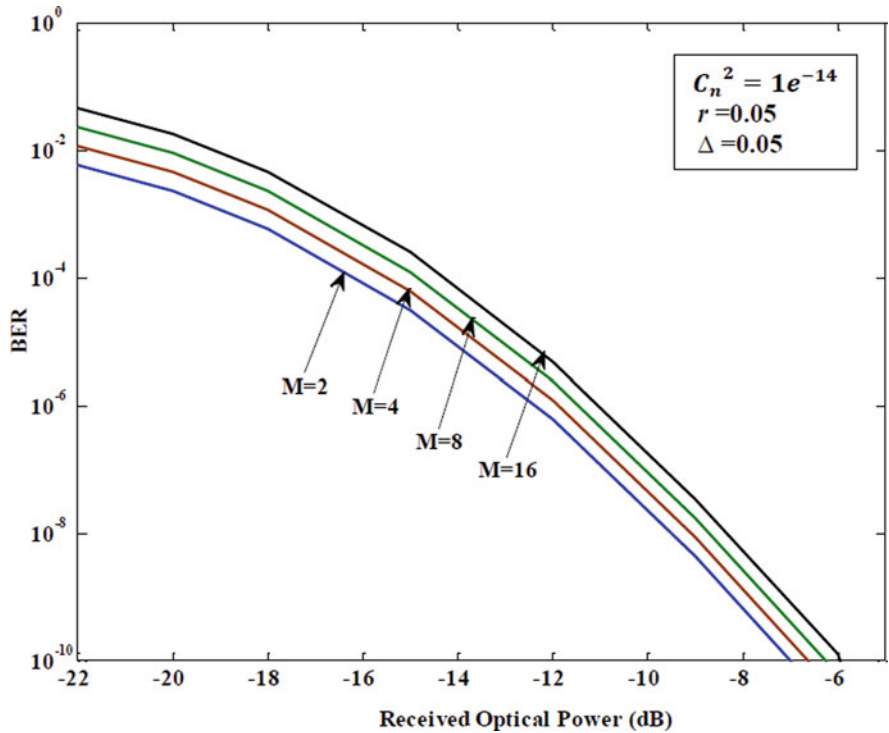
Parameter	Symbol	Value
Link distance	$L$	$500 \text{ m} < L < 2500 \text{ m}$
Boresight	$A_0$	0.20 m
Wavelength	$\lambda$	1550 m
Large-scale distribution	$\alpha$	$2.04 < \alpha < 4.03$
Small-scale distribution	$\beta$	$1.1 < \beta < 3.45$
Effective radius of beam at the transmitter	$W_0$	0.2 m
Receiver radius of beam at the receiver	$W$	0.5 m
Distance from the mean beam center on the transverse plane	$r$	0.05 m
Optical wave number	$K$	2–16
Strength of atmospheric turbulence	$c_n^2$	$10^{-14}$



**Fig. 2** BER vs SNR of BPSK, QPSK, 8-PSK, and 16-PSK modulation, where distance of link  $L = 500 \text{ m}$ , and taking the parameters  $C_n^2 = 1e^{-14}$ ,  $r = 0.05$ ,  $\Delta = 0.05$

that 16-PSk has many bit symbols, which indicates better performance than others. Taking a specific SNR, we can evaluate that 16 PSK has less BER than others, 2 PSK has higher BER, and 4, 8 PSK have BER in between 2 and 16 PSK.





**Fig. 3** BER vs SNR of BPSK, QPSK, 8-PSK, and 16-PSK modulation, where link distance  $L = 1000$  m

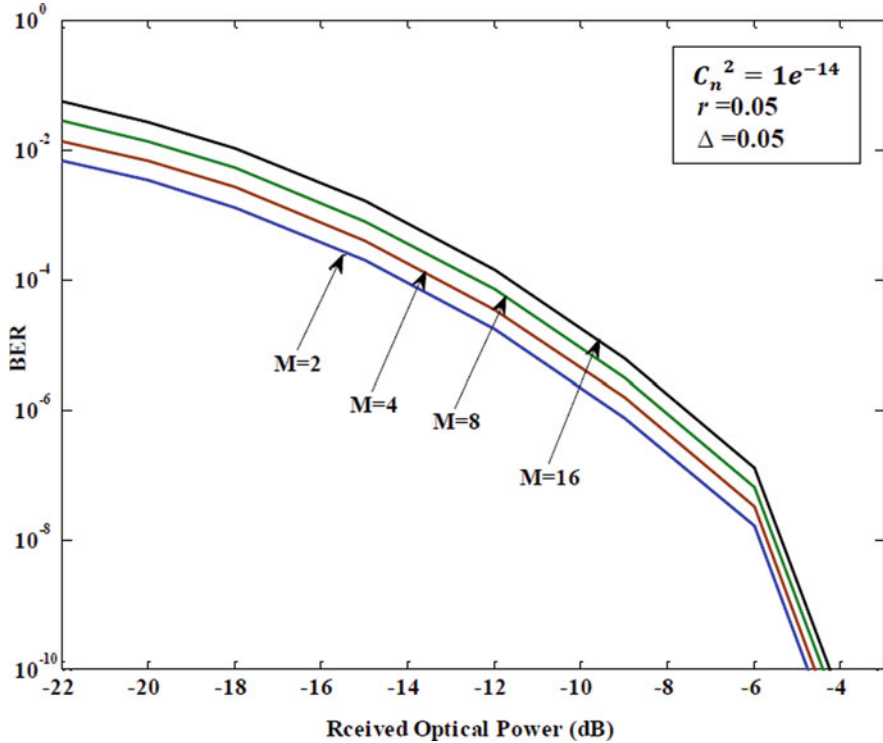
Plots BER vs SNR of BPSK, QPSK, 8-PSK, and 16-PSK modulation for length of 1000 m are shown in Fig. 3. In Fig. 3, we can see that increasing the symbol bits for modulation SNR increases irrespective with BER. Similarly, with increasing modulation array, the BER performance is much more better.

Plots BER vs. SNR of BPSK, QPSK, 8-PSK, and 16-PSK modulation for the length of 1500 m are shown in Fig. 4. It can be noticed from Fig. 4 that the symbol bits for modulation SNR increases irrespective of BER. Similarly, 16- PSK has better performance.

Plots BER vs SNR of BPSK, QPSK, 8-PSK, and 16-PSK modulation for length of 2000 m are depicted in Fig. 5. Figure 5 depicts that the symbol bits for modulation SNR increases irrespective with BER.

Plots BER vs SNR of BPSK, QPSK, 8-PSK, and 16-PSK modulation for length of 2500 m are shown in Fig. 6.

From the above figures (Figs. 2 until 6), it is cleared that with the increase in distance from the transmitter to the receiver, BER increases, and consecutively SNR decreases.

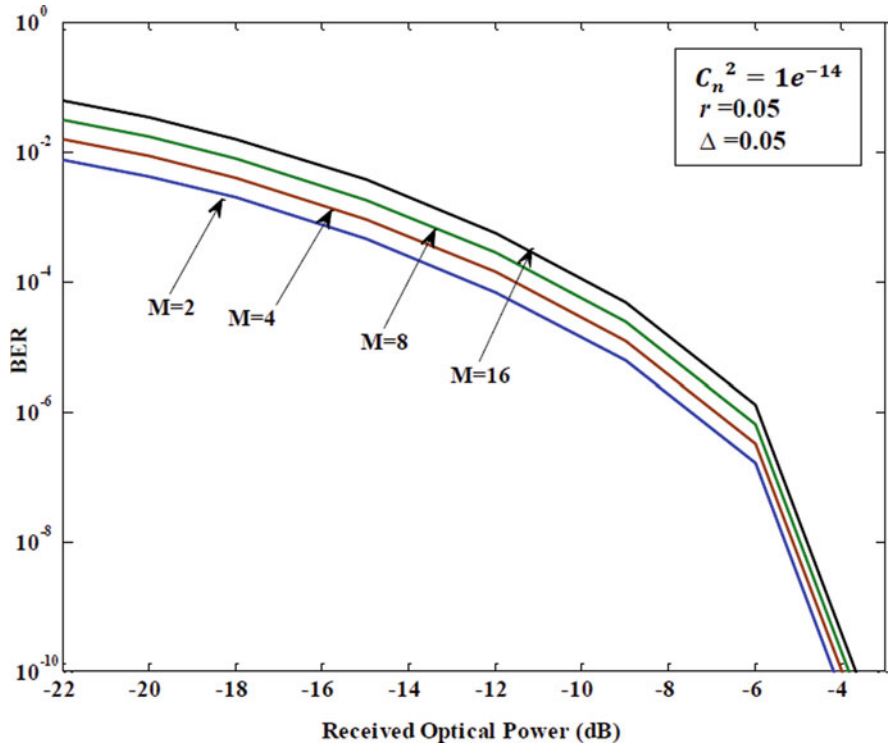


**Fig. 4** BER vs. SNR of BPSK, QPSK, 8-PSK, and 16-PSK modulation, where link distance  $L = 1500$  m

Figure 7 shows that for each M-PSK, the power penalty curve is increased over increasing link distance. Increasing link distance, power penalty curve behaves differently.  $L = 1500$  m shows less power variation for all types of modulation as it is less steeper. Hence, considering each M-PSK (BPSK, QPSK, 8-PSK, 16-PSK) at 1500 m link distance, power penalty is more acceptable than other link distances.

### 3.2 Analysis of Different Modulations for Constant Link Distance

In Fig. 8, the result of simulation depicts the BPSK modulation’s performance using different link distances. By increasing the link distance, BER also increases. The figure shows that at distance of link  $L = 500$  m, the SNR is approximately  $-13.5$ , and at distance of link  $L = 2500$  m, the SNR is approximately  $-4.50$ . Taking 500 m length as a reference, with increased length from 500 m to 1000 m required power to be increased by 5.3 dB approximately, for 1500m to 500m increased amount



**Fig. 5** BER vs SNR of BPSK, QPSK, 8-PSK, and 16-PSK modulation, where link distance  $L = 2000$  m

of power is around 8.1 dB. With an increasing length from 500 m to 2000 m, required power is increased by 8.7 dB, and from 500 m to 2500 m, required power is increased by 9 dB. So with the enhance in length, the required power also gets enhanced. Again at  $-13.5$  dBm received power (as reference) for 500 m length, BER is  $10^{-9}$ ; for 1000 m length, BER is  $10^{-6}$ . Accordingly, for 1500 m, 2000 m, and 2500 m,  $BER > 10^{-6}$ . So it is noticed that for 1500 m, 2000 m, and 2500 m, bit error rate is higher.

In Fig. 9, QPSK modulation is done using different link distances. Increasing the link distance, BER increases. At distance of link  $L = 500$  m, the SNR is approximately  $-13.1$  dB, distance of link  $L = 2500$  m where the SNR is approximately  $-4.2$ . Taking 500 m length as a reference, with an increase in length from 500 m to 1000 m, the required power is increased by 5.2 dB accordingly; from 500 m to 1500 m, it is 8.6 dB; and for 2000 m the required power is 9.3dB. With an increasing length from 500 m to 2500 m, the required power is increased by 9.5 dB. Hence, with the enhance in length, the required power also gets enhanced.

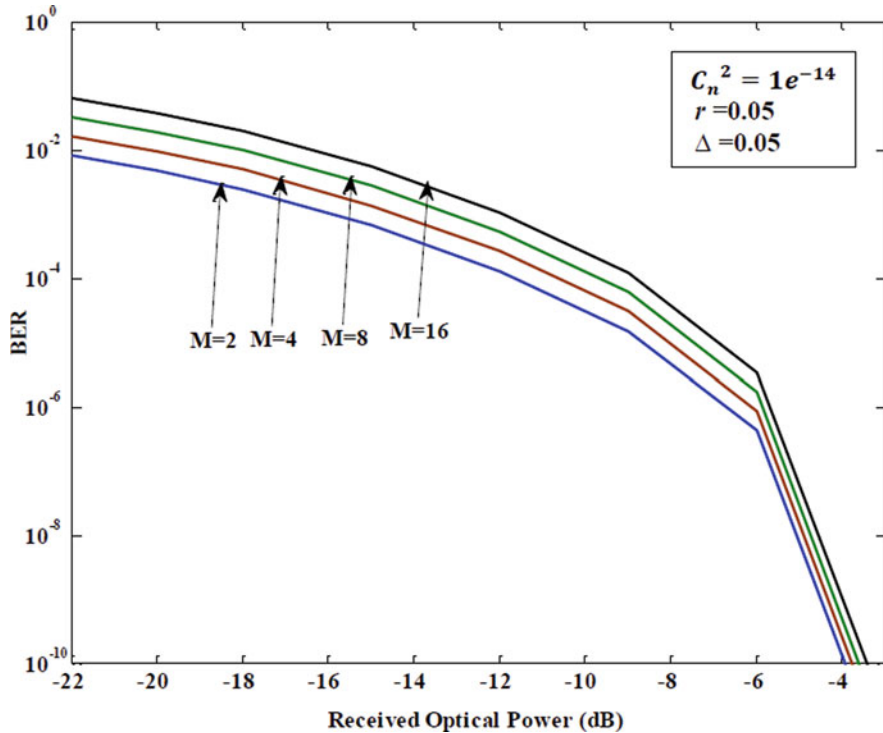


Fig. 6 BER vs SNR of BPSK, QPSK, 8-PSK, and 16-PSK modulation, where link distance  $L = 2500$  m

In Fig. 10, evaluation is done for the performance of 8-PSK modulation using different link distances. Figure 10 shows that at link distance  $L = 500$  m, SNR is around  $-13$  dB, and at link distance  $L = 2500$  m, SNR is around  $-4.1$  dB.

Taking 500 m length as a reference, with an increase in length from 500 m to 1000 m, the required power is enhanced by 6.5 dB; for length from 500 m to 1500 m, the required power is enhanced by 9 dB. Similarly, for link distance from 500 m to 2000 m, the required power is increased by 9.5 dB; for length from 500 m to 2500 m, the required power is increased by 9.7 dB. Hence, with the enhance in length, the required power is also enhanced. Again at  $-13$  dBm received power (as reference) for 500 m length, BER is  $10^{-9}$ ; for 1000 m length, BER is  $10^{-5}$ . Accordingly, for 1500 m, 2000 m, and 2500 m,  $BER > 10^{-6}$ . So it is justified that for 1500 m, 2000 m, and 2500 m, bit error rate is higher(Fig. 11).

In the case of 16-PSK modulation using different link distances, from the figure, at distance of link  $L = 500$  m, the SNR is about  $-12.9$ , and at distance of link  $L = 2500$  m, the SNR is approximately  $-4$  dB. Taking 500 m length as a reference, with increased length from 500 m to 1000 m, the required power is increased by 5.8 dB. Similarly, for length 500 m–1500 m, the required power is increased by 8 dB. For link distance from 500 m 2000 m, the required power is increased by 8.7

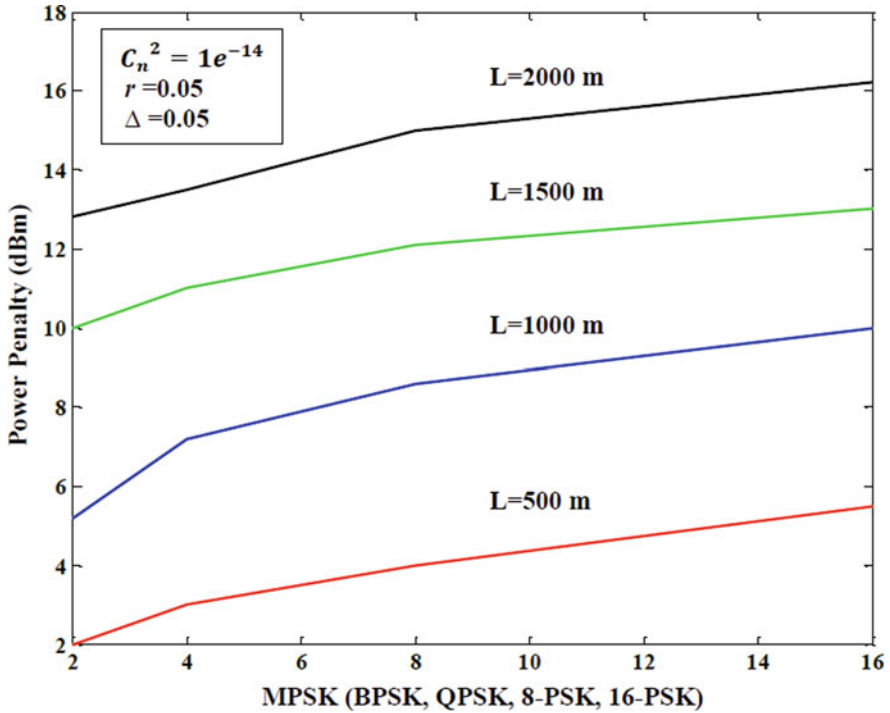


Fig. 7 Power penalty vs. M-PSK (BPSK, QPSK, 8-PSK, 16-PSK), where L varies from 500 m to 2500 m

dB. For length from 500 m to 2500 m, the required power is increased by 8.9 dB. Hence, with the enhance in length, the required power also gets enhanced. Again at  $-12.9$  dBm received power (as reference) for 500 m length, BER is  $10^{-9}$ ; for 1000 m length, BER is  $10^{-5}$ . Accordingly, for 1500 m, 2000 m, and 2500 m, BER  $> 10^{-6}$ . So it is noticed that for 1500 m, 2000 m, and 2500 m, bit error rate is higher.

From Figures 8 until 11, it is confirmed that the increase in link distance power of 16-PSK is much more than that of BPSK; hence, the power penalty of 16-PSK is larger than other PSK. Here for a specific link distance (1000 m), the required SNR (power) for BPSK, QPSK, 8-PSK, and 16-PSK are 5.1 dB, 5.5 dB, 5.9 dB, and 6.3 dB, respectively. So the required power for BPSK is lower than other modulations. But if we consider both the performance analysis and power penalty, then 8-PSK has power less than 6dB and gives better BER than 16-PSK. So 8-PSK can be considered as optimum modulation.

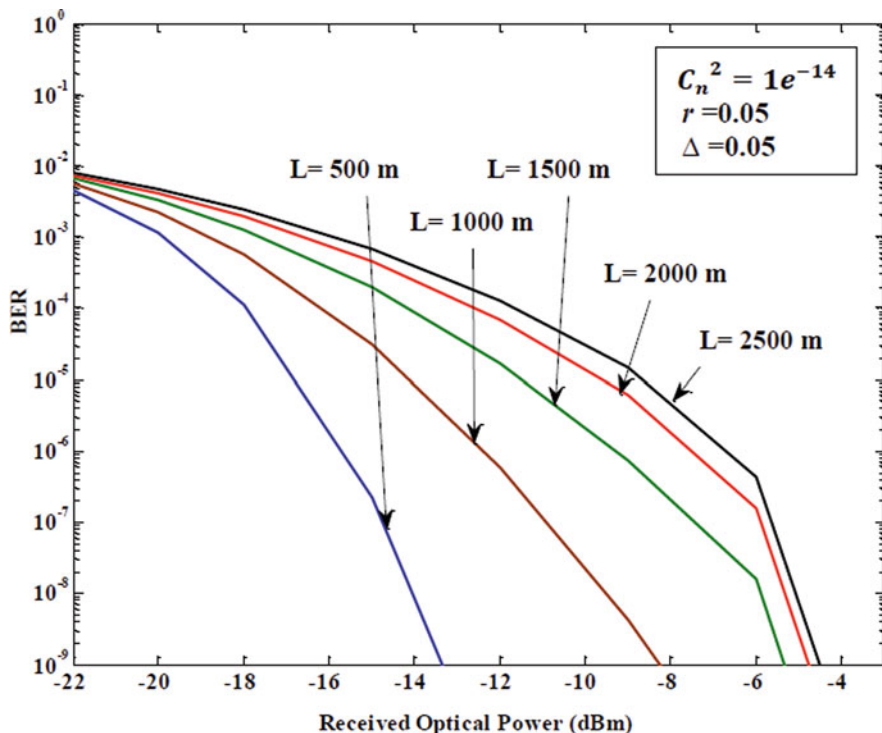
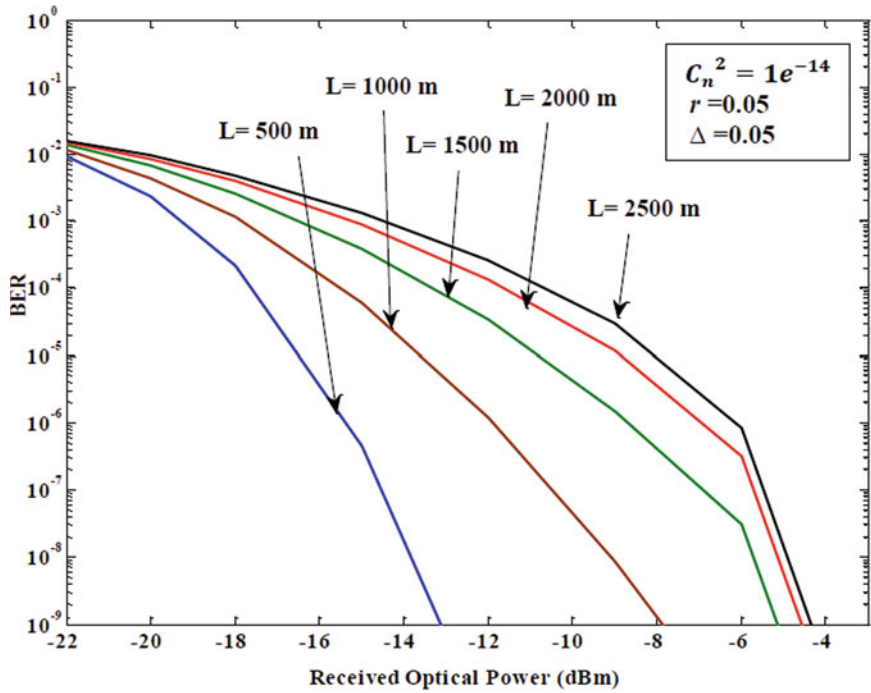


Fig. 8 BER vs. SNR of BPSK over variant distances of link (L), where L varies from 500 m to 2500 m

### 4 Conclusion

In the paper, at first, we introduced the model of FSO system and then the various multiple modulation techniques and finally discussed the M-PSK technique briefly. We analyzed different modulation techniques for different link distances using MATLAB by simulating data due to weak turbulence. Considering different link distances, we have found different values of received power at the same BER. The effect of BER on different link distances has been calculated and simulated also. Link distance from 500 m to 2500 m and BPSK, QPSK, 8-PSK, and 16-PSK modulation techniques are considered for the analysis. In the simulation, two power penalty curves are finally driven. One is the power penalty for different M-PSK modulations ( $M = 2, 4, 8, 16$ ); another is the power penalty for different link distances. Here we observe that BPSK and QPSK BER are comparatively higher than others, whereas power loss is comparatively less at different link distances. For 8-PSK, 16-PSK BER is comparatively less, whereas power loss is comparatively high at different link distances. Comparing all the power loss for different modulation techniques, 8-PSK gives the optimum parameter. At link



**Fig. 9** BER vs. SNR of QPSK over variant distances of link (L), where L varies from 500 m to 2500 m

distance 1500 m power penalty becomes less steeper and stable, it represents less power deviation for all the modulation technique. From the above analysis, we can say that 1500 m is the optimum link distance. So, by analyzing all the parameters (BER, power loss, link distance) and Figures 7 and 12, we can consider 8-PSK as the optimum modulation technique, and 1500m is considered the optimum link distance.

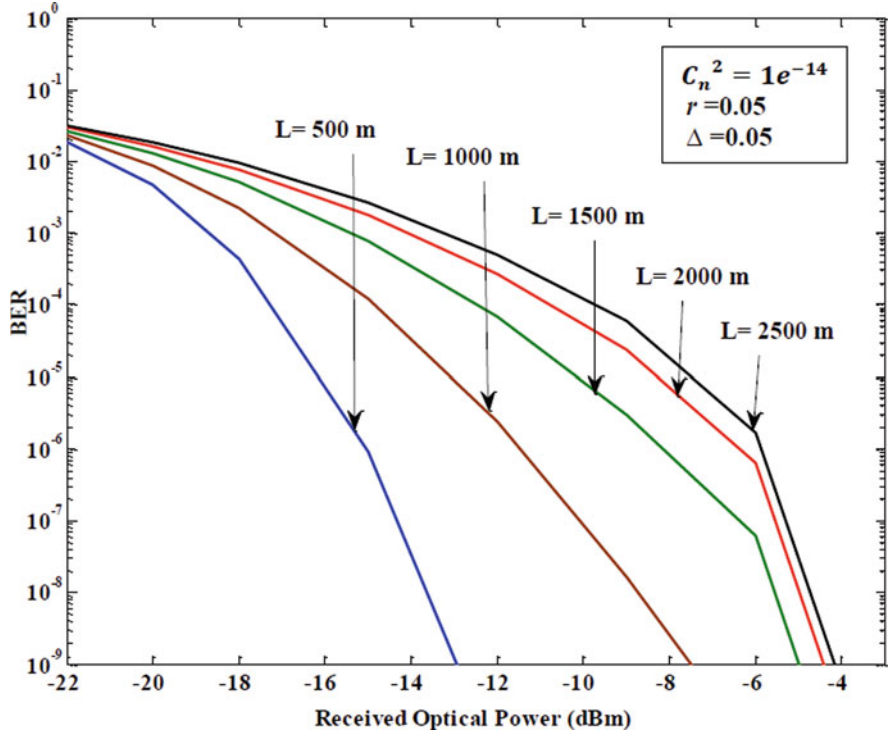


Fig. 10 BER vs. SNR of 8-PSK over variant link distances (L), where L varies from 500 m to 2500 m



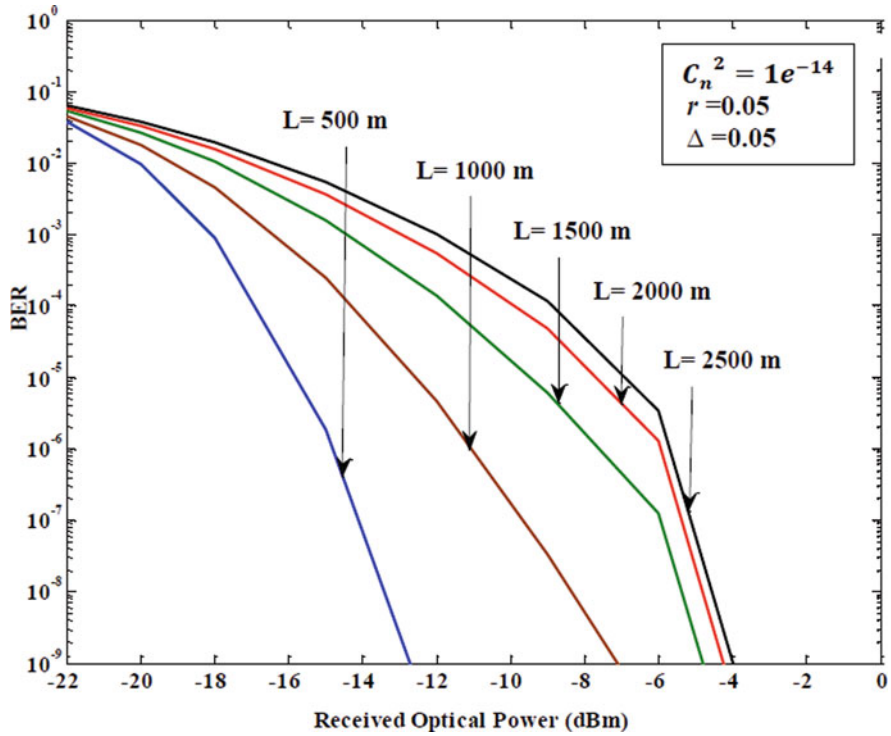


Fig. 11 BER vs. SNR of 16-PSK over different link distances (L), where L varies from 500 m to 2500 m

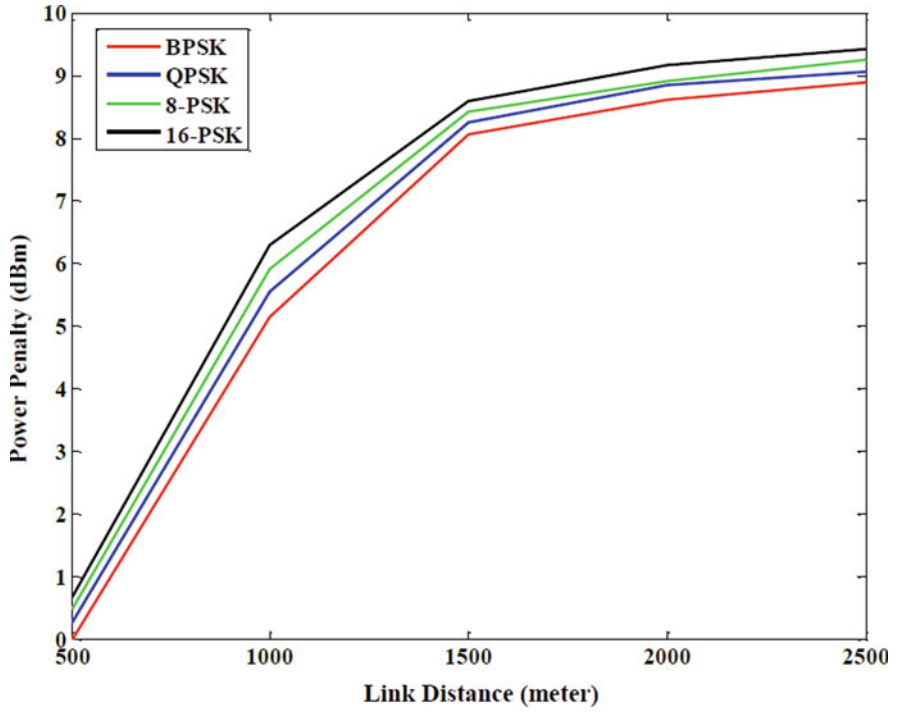


Fig. 12 Power Penalty vs. Link Distance, where L is from 500 m to 2500 m

## References

1. M. A. Khalighi, M. Uysal, Survey on free space optical communication: a communication theory perspective. *IEEE Commun. Surv. Tutor.* **16**(4), 2231–2258, Fourthquarter 2014, <https://doi.org/10.1109/COMST.2014.2329501>
2. H. Hemmati, *Near-Earth Laser Communication*, CRC Press; ISBN-13: 978-0-8247-5381-8 (2008)
3. C. Deepak Kumar, Md Khaliluzzaman, Comparative performance of BER in the simulation of digital communication systems using raised cosine filter. in *Third International Conference on Advances in Computing, Electronics and Electrical Technology - CEET 2015*, <https://doi.org/10.15224/978-1-63248-056-9-25>, pp. 29–33 (2015)
4. A.C. Motlagh, V. Ahmadi, Z. Ghassemlooy, K. Abedi, The effect of atmospheric turbulence on the performance of the free space optical communications, in *Proceedings of the 6th International Symposium on Communication Systems, Networks and Digital Signal Processing*, pp. 540–543 (2008)
5. L.C. Andrews, R.L. Phillips, Laser beam propagation through random media, in *Washington: SPIE Optical Engineering Press* (1998)
6. L.C. Andrews, R.L. Phillips, C.Y. Hopen, *Laser beam scintillation with applications* (SPIE Optical Engineering Press, Washington, 2001)
7. H. Yuksel, Studies of the effects of atmospheric turbulence on free space optical communications, Dissertation for the Doctoral Degree. University of Maryland, pp. 76–78 (2005)
8. X. Song, M. Niu, J. Cheng, Error rate of subcarrier intensity modulations for wireless optical communications. *IEEE Commun. Lett.* **16**, 540–543 (2012)
9. X. Song, F. Yang, J. Cheng, Subcarrier intensity modulated optical wireless communications in atmospheric turbulence with pointing errors. *J. Opt. Commun. Netw.* **5**(4), 349–358 (2013)
10. S. Krishna, BER for BPSK in OFDM with Rayleigh multipath channel. *Int. J. Sci. Adv. Technol.* (ISSN 2221-8386), August 26 (2008)
11. T. Singh Hanzra, G. Singh, Performance of free space optical communication system with BPSK and QPSK modulation. *J. Electron. Commun. Eng. (IOSRJECE)* **1**, 38–43 (2012)
12. R. Ramirez-Iniguez, M. Sevia Idrus, Z. Sun, *Optical wireless communications IR for wireless connectivity*, (Taylor & Francis Group, Book, CRC Press, 2007) ISBN-13: 978-0-8493-7209-4
13. N.I. Othman, A.F. Ismail, M.K. Hasan, W. Hashim, K. Badron, Dynamic spectrum allocation scheme for heterogeneous network: BER analysis. *J. Telecommun. Electron. Comput. Eng. (JTEC)* **9**(3–10), 99–104 (2017)
14. S. Islam, A.H. Abdalla, M.K. Hasan, Novel multihoming-based flow mobility scheme for proxy NEMO environment: a numerical approach to analyse handoff performance. *SCIENCEASIA* **43**, 27–34 (2017)
15. M.K. Hasan, S.H. Yousoff, M.M. Ahmed, A.H. Hashim, A.F. Ismail, S. Islam, Phase offset analysis of asymmetric communications infrastructure in smart grid. *Elektronika ir Elektrotechnika* **25**(2), 67–71 (2019)
16. M.K. Hasan, A.F. Ismail, S. Islam, W. Hashim, M.M. Ahmed, I. Memon, A novel HGBBDSA-CTI approach for subcarrier allocation in heterogeneous network. *Telecommun. Syst.* **70**(2), 245–262 (2019)
17. S. Islam, O.O. Khalifa, A.H. Hashim, M.K. Hasan, M.A. Razzaque, B. Pandey. Design and evaluation of a multihoming-based mobility management scheme to support inter technology handoff in PNEMO. in *Wireless Personal Communications*. 2020 May 1.
18. M. Park, H. Jun, J. Cho, N. Cho, D. Hong, C. Kang. PAPR reduction in OFDM transmission using Hadamard transform. in *2000 IEEE International Conference on Communications. ICC 2000. Global Convergence Through Communications*. Conference Record 2000 June 18 (Vol. 1, pp. 430–433). IEEE
19. S. Sarowa, N. Kumar, S. Agrawal, B.S. Sohi, Evolution of PAPR reduction techniques: a wavelet based OFDM approach. *Wirel. Pers. Commun.* **115**(2), 1565–1588 (2020)