Li-Fi system performance considering different modulation techniques under the influence of ambient noise

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Light fidelity (Li-Fi) is an indoor optical communication technology used for transmission of information at high data rates using LED light bulbs. This is the most prominent technology of the future as it combines illumination with wireless data communication system. This work investigates the performance of an indoor Li-Fi communication model under the influence of an external white light source and compares the effectiveness of different modulation techniques employed when exposed to an ambient noise source. The study is carried out considering pulse position modulation (PPM), differential phase shift keying (DPSK) and quadrature phase shift keying (QPSK) modulation techniques and the system is analyzed considering varying bit rates and transmission ranges from 1 to 5 meters. QPSK results in better performance as compared to other modulation schemes with an achievement of Q factor of more than 20 over a transmission range up to 2.8 m.

(Received August 16, 2021; accepted June 7, 2022)

Keywords: Light fidelity (Li-Fi), Modulation techniques, PPM, DPSK, QPSK, Thermal noise source, External light source

1. Introduction

In the present scenario, with development in technology, the need for high-speed network access has drastically increased. Up until now we have been dependent on Wireless Fidelity (Wi-Fi) for communication but unfortunately it isn't enough to match the demand [1]. Here, the latest evolving technology known as "Light Fidelity" (Li-Fi) comes into picture. Li-Fi, is a communication technology that is utilized for data transmission wirelessly utilizing 'visible light' sources, hence it falls under visible light communication (VLC) [2,3]. It is being considered as ideal technology for the future due to its several advantages over Wi-Fi. At its current development stage, solely light emitting diodes (LEDs) are employed for transmitting information [4]. The "visible light" emitted by LED flickers extremely fast, so it is impossible to be seen or detected by the human eye. The receivers are designed to observe these subtle alterations in the modulation of light which allows data transmission wirelessly through visible light. This capability limits the data transmission to confined locations as the light is unable to pass via solid objects [5-7].

However, the emitted light is deflected by solid objects which enables it to reach destinations that aren't in the line of sight. Li-Fi operates in a frequency range of about 350 nm to 750 nm [8].

There are extremely limited real-world applications of Li-Fi currently, therefore the goal is to adopt this technology on a larger scale which includes connectivity in homes, vehicles and even through street lamps [9]. Since Li-Fi makes use of "visible" light, it is comparatively less prone to external disturbances or hacking, making it a more secure technology than Wi-Fi. Due to such advantages, it has the potential to completely displace Wi-Fi as the primary method of wireless communication. Its applications include home and building automation, workplace Li-Fi, Li-Fi in hospitals, workplaces, industry automation etc. [10]. Section 2 reports some of previous works on Li-Fi technology.

2. Related work

In 2015 [11], a smart home model for bidirectional VLC utilizing Red-Green-Blue (RGB) LEDs was proposed. The beams from RGB were utilized to transmit data and receiver diversity has been utilized to enhance the performance. Bit rate of 24 Mbps has been achieved for both, uplink and downlink transmission. In 2016 [12], performance investigation of Li-Fi system has been carried out for both, non-return to zero (NRZ) and return to zero on off keying (RZ-OOK) modulation using a white LED. The work achieved a Bit rate of 2 Gbps with acceptable values of link range up to 3 meters. In 2016 [13], the author utilized a red LED operating at 650 nm and reached ranges up to 6 meters at 150 Mbps bit-rate. The system used OOK modulation format and achieved bit error rate (BER) value of 1.3×10^{-6}. In 2016 [14], an indoor positioning system was formed utilizing 2 LEDs. The user's location has been identified by received signal strengths of both the signals and horizontal distance along with angular errors were analyzed. The localization model was able to discover user's position with average error in distance of 20 to 40 cm with a signal-to-noise ratio above 13 dB. In 2017 [15], the authors proposed a VLC model that employs ambient light rejection. It utilized white LED giving permissible BER for bit rates up to 22 Mbps till range of about 2.7 m using NRZ-OOK modulation format. In 2019 [16], the authors proposed a Li-Fi model employing orthogonal frequency division multiplexing technique and achieved bit rates of 10 Gbps up to a distance of 2 meters. In 2020 [17], a Li-Fi model's performance was observed for distinct modulation techniques at 5 Mbps bit rate. The techniques considered were pulse position modulation (PPM), pulse amplitude modulation (PAM) and phase shift keying (PSK).

In the proposed work, first we investigated the performance of a Li-Fi model employing NRZ- OOK modulation under the impact of an external white light source. Next, we analyze the system's performance for pulse Position Modulation (PPM), differential phase shift keying (DPSK) and quadrature phase shift keying (QPSK) modulation techniques under the presence of an ambient noise source. Remaining sections in this paper discuss the following. Sections 3 and 4 discuss the modulation techniques and block diagrams of the models used in the work respectively. Section 5 depicts and discusses results which were achieved and Section 6 concludes the work.

3. Single carrier modulation techniques for Li-Fi

System was implemented using DPSK, QPSK and PPM modulation techniques. PSK is a digital modulation technique in which signal's phase is modulated to convey the transmitted information, where each phase is assigned to certain pattern of bits. DPSK is another technique of binary phase shift keying (BPSK) where two phases separated by 180° are used. In this technique, shift in phase of every symbol is measured with respect to the previous symbols sent. Since it is a non-coherent technique, it is not intricate to implement as compared to normal PSK. Another reason for the popularity of DPSK modulation technique is its improved receiver sensitivity due to which it is extensively used in wireless communication [10].

The following equation is utilized to calculate the probability of error of DPSK:

$$P_e = e\text{\textasciicircum}(-E/N)/2 \quad (1)$$

where "E" is energy of the signal and "N" is the noise power spectral density. This is highly vulnerable to noise & performs poorly when the noise source is present [17].

QPSK is a category of PSK where 2 bits are modulated at once with four possible shifts in carrier wave that are 0°, 90°, 180° and 270°. This allows twice as much of information to be carried in the same bandwidth, therefore QPSK is more favorable modulation scheme when concerning high data rates. While QPSK can carry double the data with equivalent bandwidth and at the same BER compared to BPSK, it's much more intricate to implement and utilize. Therefore, it is sometimes not practical to use this modulation technique. However, with developing modern electronics and evolution of technology, it isn't an issue anymore as penalty in cost is not that high [4, 10].

The probability of error of QPSK is calculated utilizing the following equation-

$$P = (\sqrt{2E/N}) \quad (2)$$

where Q is quality function that is scalar form of complimentary error function [17].

PPM scheme is a form of modulation technique where positions of pulses are varied according to instantaneous values of the message signal. This synchronization helps in maintaining the position of the pulses. In PPM, "M" number of bits are encoded with transmission of each pulse in 2^M probable time-shifts. After every T seconds of interval this is repeated with transmitted bit rate equal to M / T bits/second. This is extremely beneficial for optical communication systems, which often tend to have very less multipath interference [18].

The probability of error of PPM is calculated utilizing the following equation

$$P_e = (s/\sqrt{2N}) \quad (3)$$

where 's' is expressed as P ($\sqrt{L * \log_2{}^{L}} / R_b$) where P = signal power, L = length of the pulse and R_b = bit rate.

4. System model

Fig. 1 and Fig. 2 shows the schematic of proposed Li-Fi system utilized in the work which is modeled using Optisystem- software.

Block diagram in Fig. 1 has been used for analysis of the system's performance under impact of external light. The bit sequence generator generates a random sequence of bits which is converted into pulses using NRZ-OOK modulation scheme. However, before the signal which is generated by the LED enters the free space optical (FSO) channel, it is impeded by an external light created by another white light source operating at -60 dBm power. The combined signal generated by both the sources travels along the FSO channel and is detected by the Si photodiode on receiver side. The photodetector converts signal into electrical form and passes it through low-pass bessel filter (LPBF) which is utilized to keep noise interference caused as a result of external light source to a minimum level. The signal is then returned to original form and is analyzed by BER analyzer that has been utilized to analyze the eye diagrams of signals [12].

The general atmospheric attenuation in FSO link can be described mathematically as [18]:

$$\tau = \exp(-\beta L) \quad (4)$$

where L is the range, τ defines the atmospheric attenuation and β can be represented by the following equation:

$$\beta = \beta abs + \beta scat \quad (5)$$

where, $\beta scat$ and βabs represent the coefficient of scattering and coefficient of absorption, respectively.

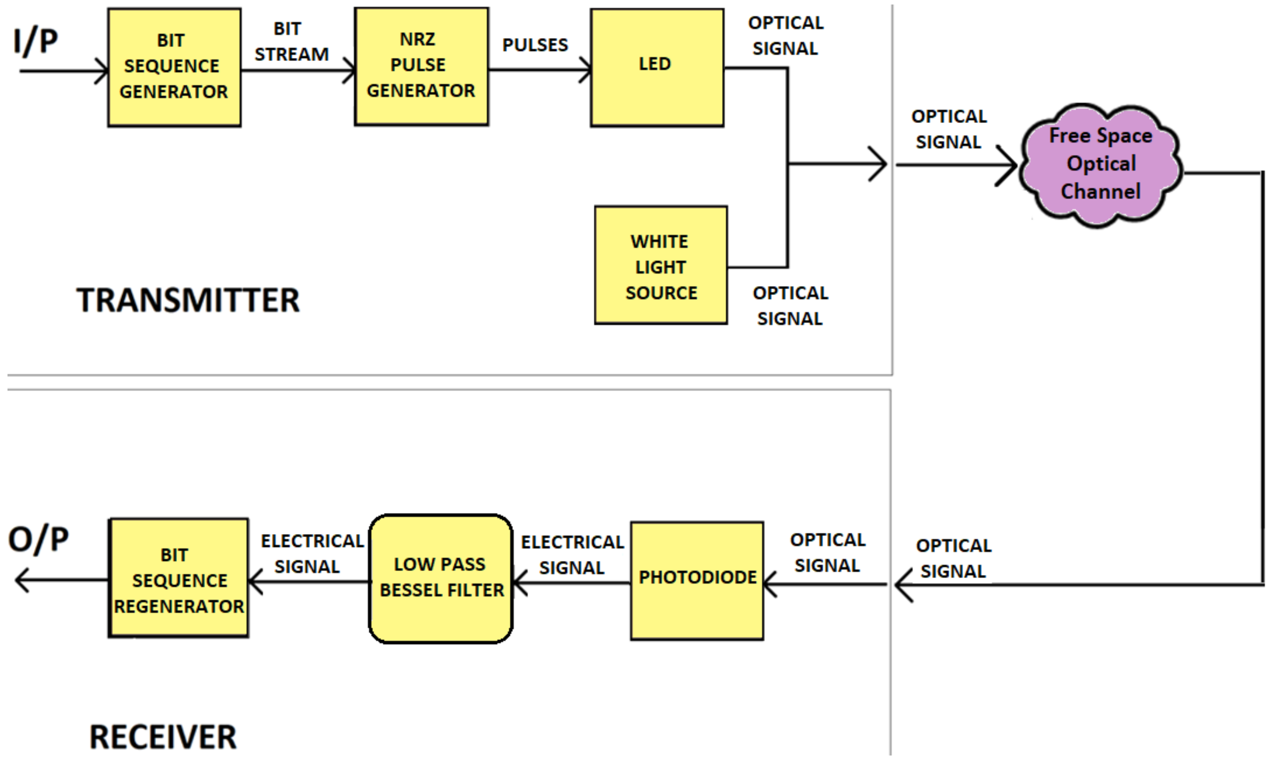

Fig. 1. Schematic and Block diagram of Li-Fi model under the influence of external light (color online)

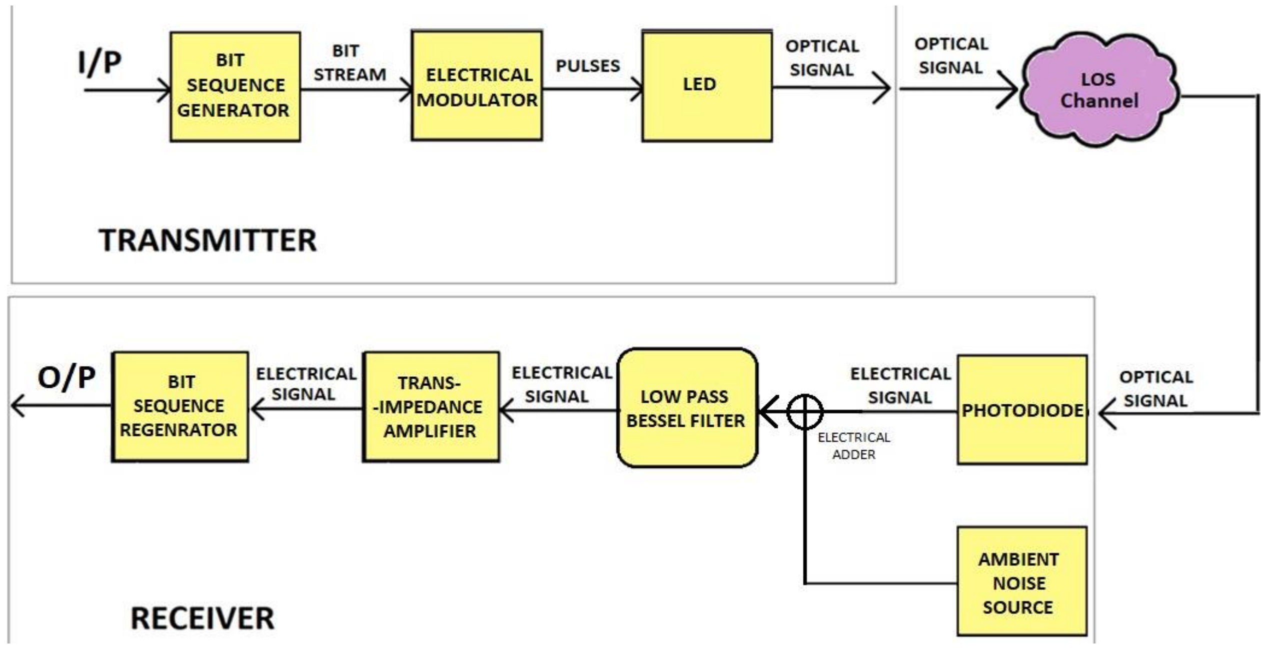

Fig. 2. Schematic and Block diagram of Li-Fi model employing different modulation formats in the presence of ambient noise (color online)

Fig. 2 depicts block diagram of second Li-Fi model proposed. An electrical modulator has been added in this for the modulation techniques utilized. The purpose of it is to modulate the sequence of bits and generate pulses that are delivered to the LED. LED emits light, converting the pulses to the optical signal that travel along the line of sight (LOS) channel. At the receiver side, silicon photodiode is utilized to detect and then convert the obtained optical signal to an electrical signal. Before passing the signal through the LPBF, an ambient noise source is added which adds thermal noise from the photodetector's electric pre-amplifier. The demodulated signal then passed to the trans-impedance amplifier, which amplifies the signal. Finally, the original bit sequence is recovered via the bit sequence regenerator [17, 19].

5. Results and discussion

The results obtained from the proposed Li-Fi models in the work have been discussed in this section. First, we investigate the effect of external white light source on Li-Fi system's performance that is employed utilizing NRZ-OOK modulation format. Next, the system model's performance for 3 distinct modulation formats are compared under the exposure of a thermal noise source of -60 dB. In both systems, signal is passed through the LBPF to obtain the maximum output by suppressing the external noise. Tables 1 and 2 represent the simulation parameters of Li-Fi model under the impact of external light and employing different modulation formats in the presence of ambient noise respectively.

Table 1. Simulation Parameters of Li-Fi model under the influence of external light

Parameters	Value
Bit Rate (Mbps)	100-1000
Link Range (m)	1-3
Transmitter aperture diameter (cm)	7
Receiver aperture diameter (cm)	1.5
Responsivity type of Photodetector	Silicon
Dark Current of Photodetector (nA)	10
Wavelength of LED (nm)	550
Quantum Efficiency of LED	65%

Table 2. Simulation parameters of Li-Fi model under ambient noise

Parameters	Value
Bit Rate (Mbps)	20-40
Link Range (m)	1-5
Transmitter half angle (cm)	60
Irradiance half angle (cm) Incidence half angle (degree)	20 20
Responsivity type of Photodetector	Silicon
Dark Current of Photodetector (nA)	10
Wavelength of LED (nm)	450
Quantum Efficiency of LED Short Noise Bandwidth (MHz)	65% 30

Analysis of model depicted in Fig. 1 was carried out considering 3 distinct data rates- 100 Mbps, 500 Mbps and 1 Gbps for link ranging up to 3 meters. The Q factor [Fig. 3] and BER (Fig. 4) values were observed for analyzing the model's performance in the absence of any noise source with center frequency of the emitting light source at 550 nm. Here, the system's performance utilizing NRZ-OOK modulation has been analyzed.

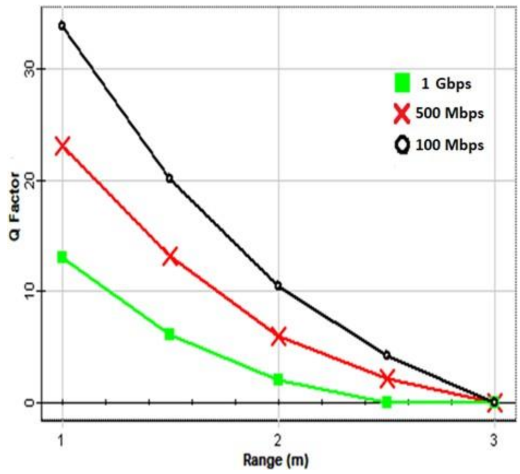

Fig. 3. Q factor of received signal for varying bit rates and link ranges (color online)

As observed in Fig. 3, quality of received signal drops below permissible values for bit rate of 500 Mbps beyond a range of 2 meters. Propagation loss of the transmitted signal and noise effects result in decrease in the quality of the received signal with increase in the transmission distance. Minimum and maximum values of transmission range have been observed for data rates of 1 Gbps and 100 Mbps respectively.

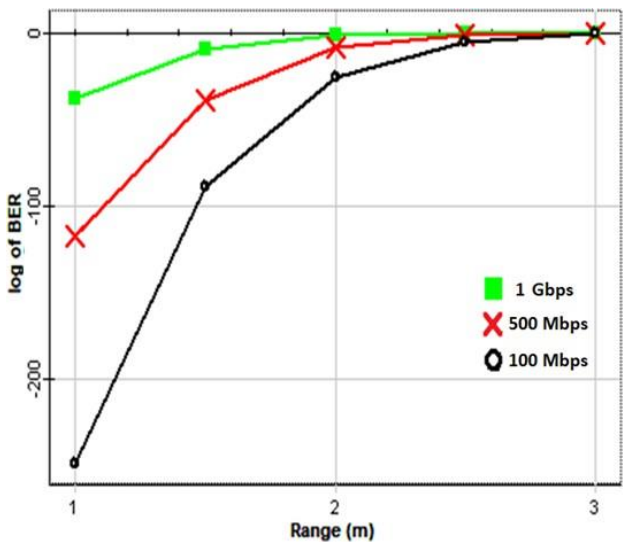

Fig. 4. BER of received signal for varying bit rates and link ranges (color online)

Analysis of the model shown in Fig. 1 is carried out considering data rates of 100 Mbps, 500 Mbps and 1 Gbps for a link range of 1 to 3 meters under impact of an external white light source operating at a power of -60 dBm. Fig. 5 and Fig. 6 depict a comparison of the system's performance for three-bit rates under impact of external light.

System's performance is significantly better in 1st condition depicted in Figs. 3 and 4 when compared to the case with impact of external light shown in Figs. 5 and 6. The Q factor range and BER values indicate that the signal worsens due to interference caused by the presence of another light source.

The latter case gives permissible values for signal up to a range of 1.5 meters. Fig. 7 depicts the comparison of performance of both the systems for 1 Gbps bit-rate.

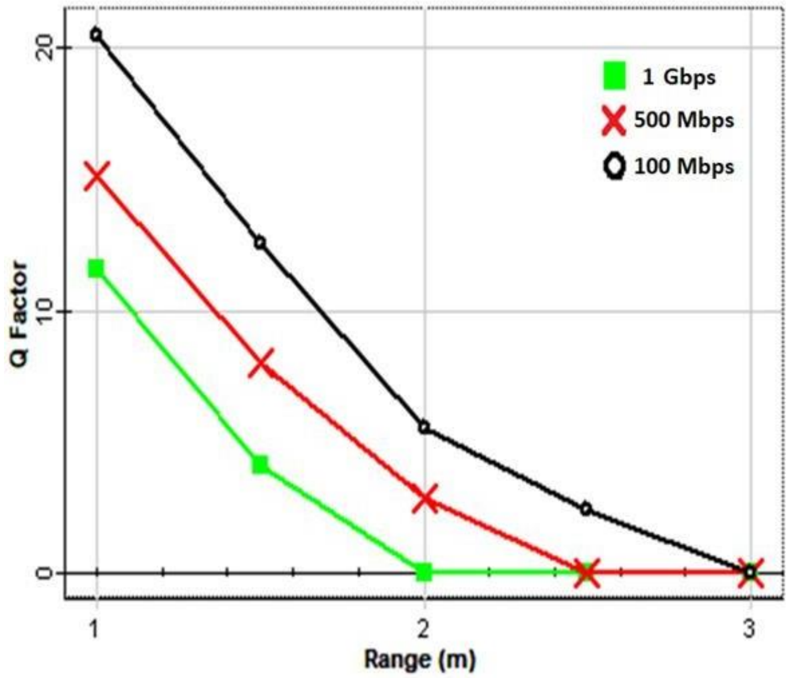

Fig. 5. Q factor of received signal for varying bit rates and link ranges under the influence of external light (color online)

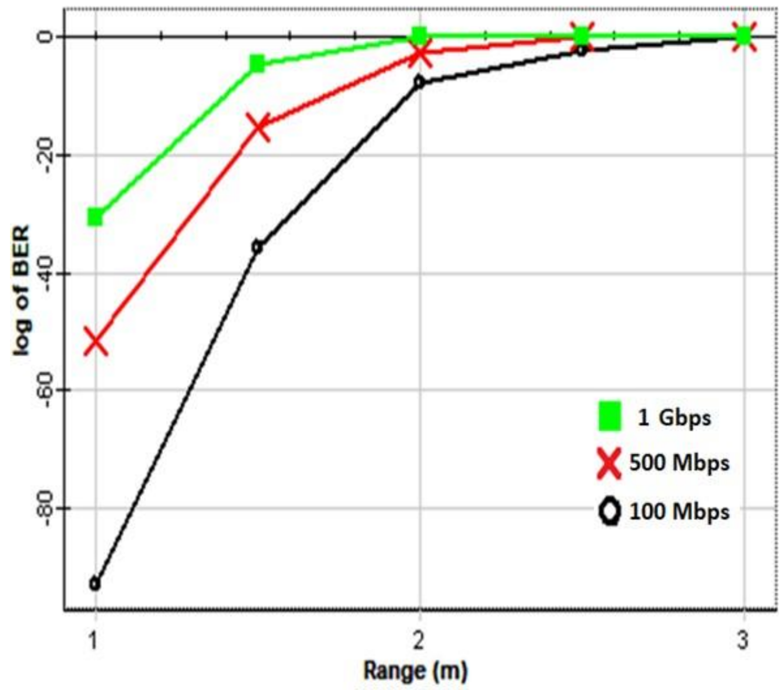

Fig. 6. BER of received signal for varying bit rates and link ranges under the impact of external light (color online)

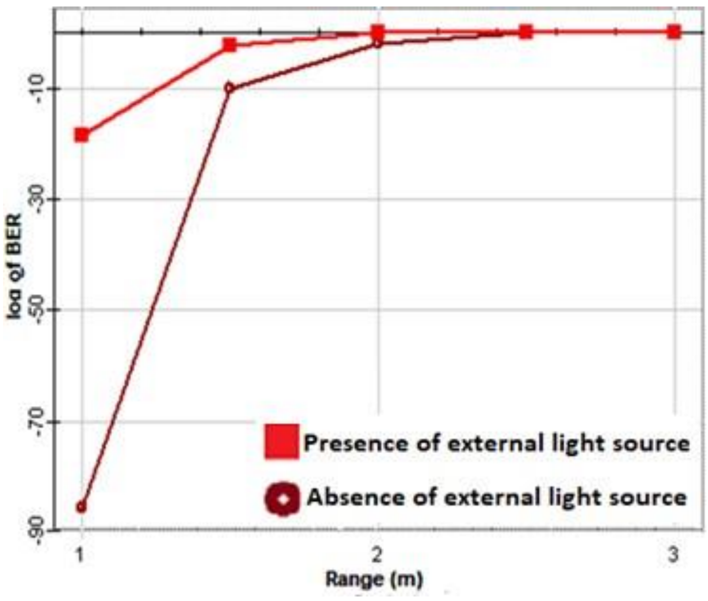

Fig. 7. BER of the signal for with and without external light source at 1 Gbps (color online)

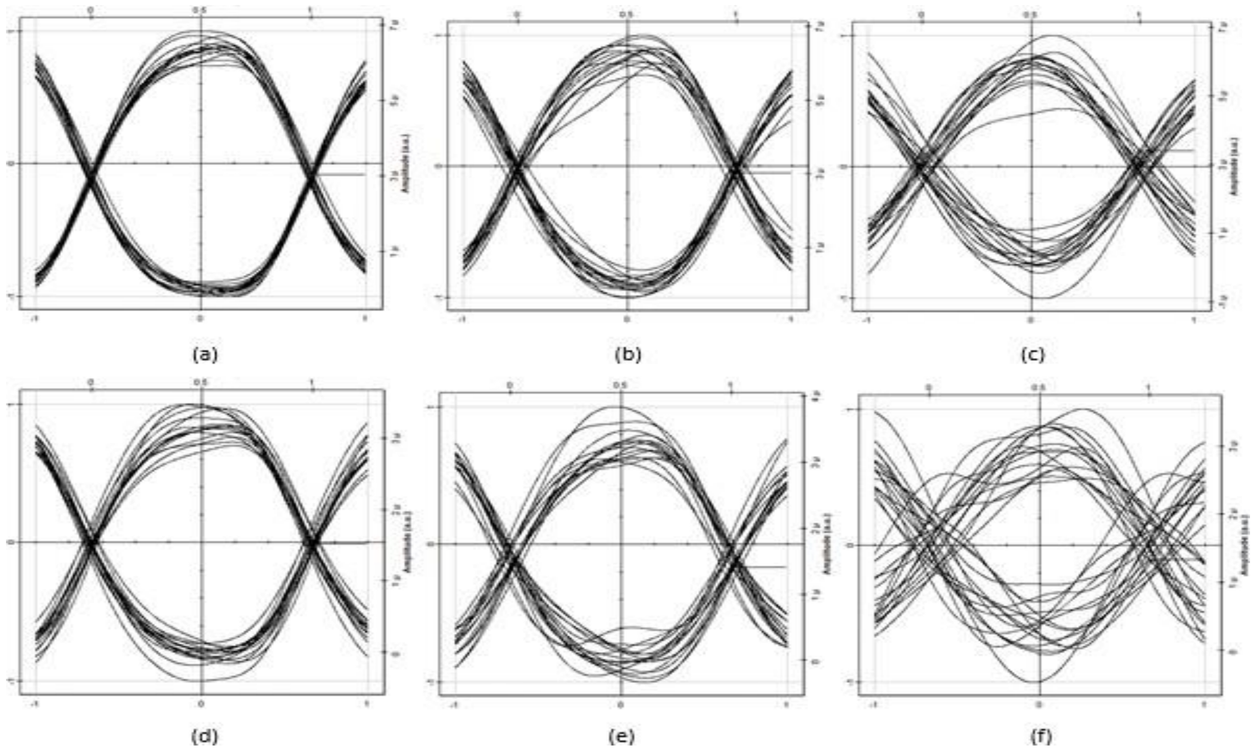

Fig. 8. The eye diagrams observed at the output considering all data rates with transmission range of 1.5 meters

In Fig. 8, eye diagrams of received signal for a transmission range of 1.5 meters at (a) 100 Mbps in the absence of external light (b) 500 Mbps in the absence of external light (c) 1 Gbps in the absence of external light (d) 100 Mbps in the presence of external light (e) 500 Mbps in the presence of external light(f)1 Gbps in the presence of external light are shown.

From observing the eye diagrams, it is concluded that received signal deteriorates with increase in bit rate from 100 Mbps to 1 Gbps. The eye opening gets further distorted as the system is introduced to an external white light source. Table 3 shows the Q factor values of each data rate at 1.5 meters.

Table 3. Q factor at different data rates for a transmission range of 1.5 meters

Data Rate	Q factor in different Noise conditions	
	Noise absent	Noise Present
100 Mbps	21.8	11.42
500 Mbps	11.79	7.49
1 Gbps	6.64	3.42

Analysis of Li-Fi model in Fig. 2 has been performed for three modulation techniques at different data rates under exposure of a thermal noise source. The system's performance is evaluated at data rates of 20, 30 and 40 Mbps for a transmission range of 1 to 5 meters. Figs. 9 and 10 show the Q factors of QPSK and PPM modulation techniques (with M=2) respectively with addition of thermal noise source operating at a power -60 dBm.

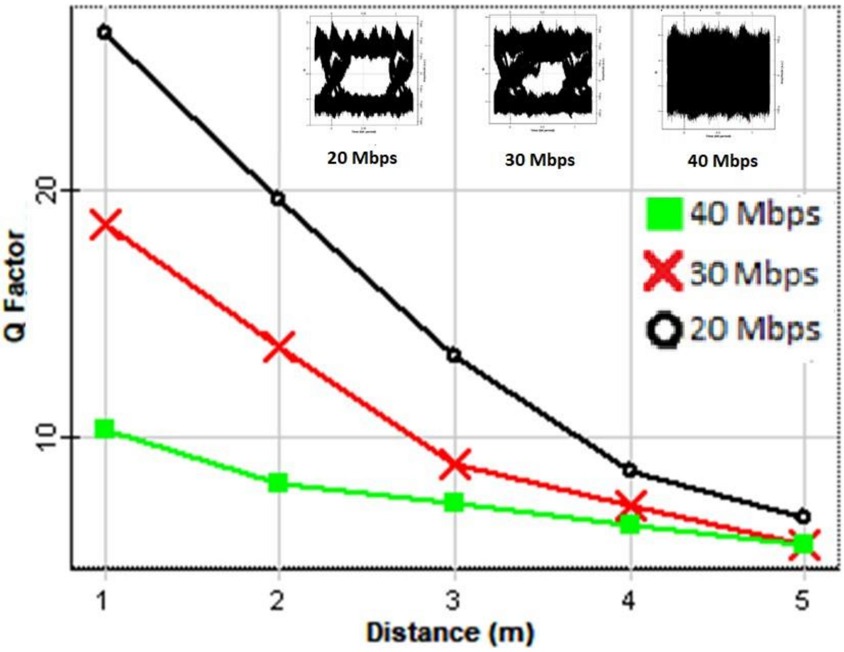

Fig. 9. Received Q factor of QPSK under ambient noise of -60 dBm (color online)

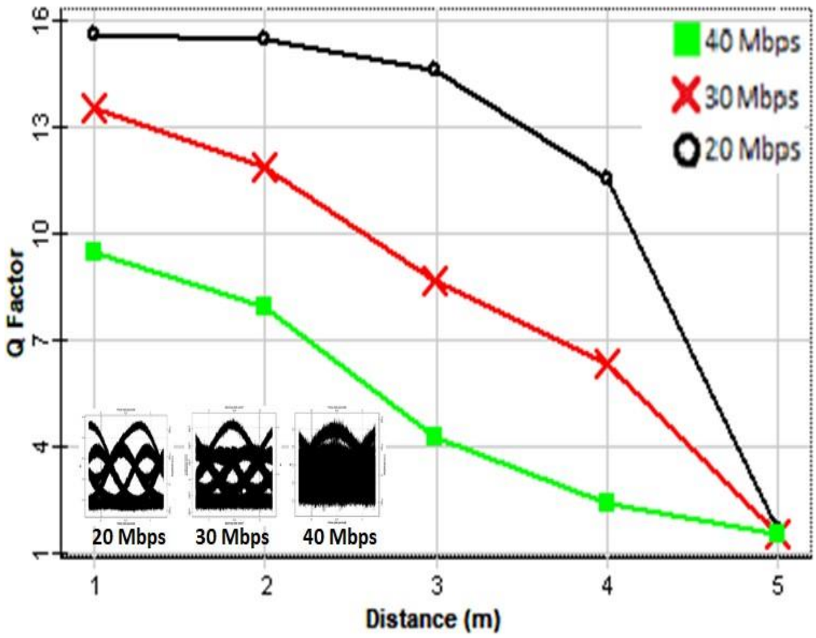

Fig. 10. Received Q factor of PPM under ambient noise of -60 dBm (color online)

As seen from the Figs. 9 and 10, the eye openings of eye diagrams obtained at 3 meters get worse with increasing bit rates and give unacceptable Q factor values for 40 Mbps in all 3 conditions.

Table 4. Q factor at different data rates for varying transmission range

Link Range	Q factor at different data rates		
	20 Mbps	30 Mbps	40 Mbps
1 meter	8	2.2	1.2
2 meters	4	1.7	0
3 meters	0.8	0	0

Table 4 shows the Quality factor values at three different data rates and varying range for Li-Fi model employed with DPSK modulation scheme. It is observed that DPSK is the least effective among all modulation techniques.

It is concluded from results that QPSK is least affected by ambient noise (Fig. 11). It performs the best among other modulation formats considered.

The maximum Q factor achieved in case of QPSK, PPM and DPSK modulation techniques are 27, 18 and 8 respectively.

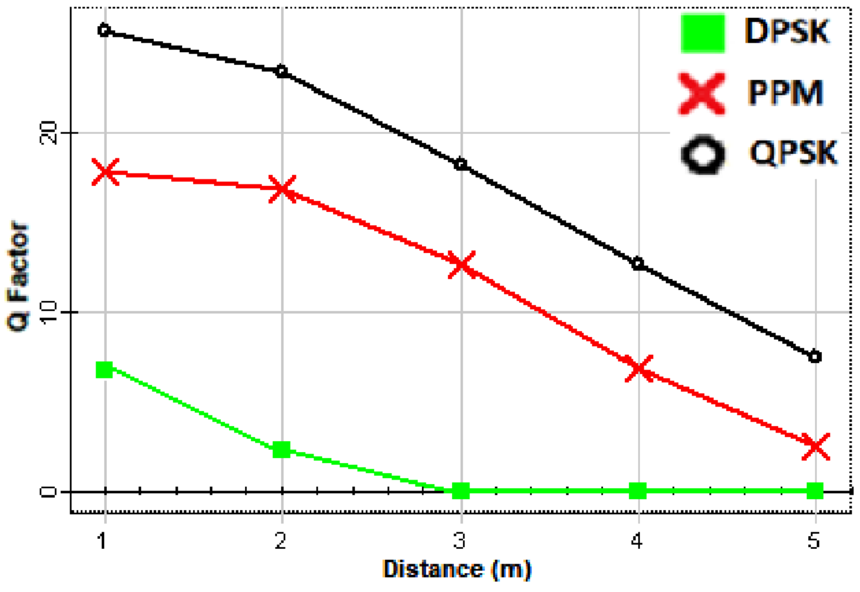

Fig. 11. Received Q factor for QPSK, BPSK and PPM modulation formats for 20 Mbps data rate (color online)

Table 5 outlines the comparison of the proposed work with previous works in literature. The Li-Fi model in the proposed work transmits at higher data rate over longer distances than the previous works on Li-Fi system in the presence of an ambient noise source.

Table 5. Comparison of proposed Li-Fi system with other similar works

Parameters	**[20] (2019)**	**[21] (2019)**	**[17] (2020)**	**[22] (2021)**	**Proposed work**
Modulation scheme	NRZ-OOK	NRZ-OOK RZ-OOK	PAM, DPSK, PPM QPSK	NRZ-OOK	QPSK DPSK PPM
Data rate	145 Mbps	1 Gbps	5 Mbps	10 Mbps	30 Mbps
Condition	No noise source present	No noise source present	Presence of an ambient noise source	Light noise source present	Presence of an ambient noise source
Maximum link range (m)	3.5 m	2.15 m	2.15 m	1 m	3 m

6. Conclusion

First, we investigate Li-Fi system's performance under impact of an external white light source up to a transmission range of 3 meters considering three-bit rates. The Q factor range and BER values indicate that quality of the signal deteriorates due to interference caused by the presence of another light source resulting in achievement of data rate up to 1 Gbps over a transmission range of 1.5 meters in the latter case. Next, the analysis of system's performance has been carried out under the exposure of thermal noise source considering QPSK, PPM and DPSK modulation schemes at different data rates. QPSK is least effected by noise and gives considerably better performance in comparison to the other 2 modulation schemes. In future, multi-carrier modulation techniques may be employed for optimization of bandwidth usage and achievement of higher data rates.

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