Investigation of Li-Fi system performance under the influence of ambient noise and external white light

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In this paper, we propose an indoor, short-range communication system using light fidelity model and the performance of the system has been analyzed under the influence of external white light and ambient noise. The system performance has been optimized considering compressed spectrum return-to-zero, return-to-zero and non-return-to-zero modulation formats at different link distances and data rates. Effect of variation of transmitter half-angle, bandwidth of light emitting diode and optical filter respectively on the received signal quality has also been examined. It has been discovered that NRZ modulation format performs better for a given link distance and data rate as compared to other modulation schemes. Ambient noise has significant effect on deteriorating the received signal quality as Q-factor goes below the unacceptable limits for the ambient noise power exceeding -110 dBm.

(Received September 8, 2020; accepted November 24, 2021)

Keywords: Light fidelity, Return-to-zero, Non-return-to-zero, Compressed spectrum return-to-zero, External white light, Ambient noise

1. Introduction

With the advancement in technology, issue of spectral overloading and the need to transfer the data at higher speed from one region to another, interest of many researchers have grown to look beyond wireless fidelity which uses the radio-waves of electromagnetic spectrum for transmission of signals. Present telecommunication industry relies mainly on radio frequency-based networks for data transmission. Wi-Fi uses 2.4 GHz radio frequency and its bandwidth is limited to 50-100 Mbps. With the increase in the users and advancement of new technologies such as 5G, resultant traffic has increased affecting the reliability of the signal. With the rise in the number of customers and devices it is running out of spectrum and is becoming more expensive [1, 2].The speed and security are also some of the important concerns, as in case of Wi-Fi the radio waves can penetrate via walls & hence can be easily intercepted by the hackers. Thus, to overcome the issues of capacity, efficiency, security and availability in case of radio-waves the researchers explored the new technology named Li-Fi. Optical wireless technologies, also called visible light communication, and more recently referred to as Li-Fi offer an entirely new paradigm in wireless technologies in terms of usability, flexibility and communication speed [3-5].

Li-Fi is also referred as light-based Wi-Fi due to its usage of light to transmit data instead of radio-waves. In Li-Fi systems, the spectrum of visible light is 10,000 times wider than the radio waves spectrum. VLC corresponds to the frequencies ranging from 380 to 750 nm in the electromagnetic spectrum and has no limitation of capacity. It has a high-speed data transfer rate over 1 Gbps and can theoretically transmit at speeds of up to 100 Gbit/s [6].

The data is transmitted through illumination by use of LED light bulbs. The LEDs used in Li-Fi system are highly efficient, have long-life expectancy and consume less energy rendering them ideal for widespread use for lighting and indication purposes. In this system, the LED lamps used in the homes, offices or vehicles are used to generate light as well as to transmit and receive the information. The rapid switching of LED on and off at high speeds makes its action so fast that we are not able to see it with naked eye.

VLC can also be used as a wireless connection method for the internet of things [1, 3]. In the Li-Fi system, light cannot penetrate through walls and doors which makes it more secure and provides a controlled access to the network. If the transparent materials are considered, then access to a Li-Fi channel is limited to the devices present inside the room [7]. As the technology uses a free band that does not need a license, it adds an economic value to its usage. It can be used in the sensitive areas such as aircrafts for the transmission of data without causing interference or in the places where it is difficult to lay the optical fibers like operation theaters. Along with this, it can also be used for underwater applications where radio waves cannot propagate. Li-Fi has the ability to safely function in areas that are susceptible to electromagnetic interference e.g., aircraft cabins, hospitals, military and nuclear power plants etc.

The German physicist Prof. Harald Hass had coined the term “Li-Fi” and is the co-founder of pure Li-Fi along with Dr Mostafa Afgani. He gave the demonstration of the Li-Fi technology at TED global talk in Edinburgh and introduced the idea of “wireless data from every light” [8].

The main application of the Li-Fi system is VLC and is first started in 2003 at Nakagawa laboratory in Keio University, Japan. Its features have grown the interest of many researchers for analysing its performance. In VLC system, LEDs used generally offer a huge unregulated bandwidth in visible spectrum region. Usually, the PIN photodiode and APDs are used as detectors in optical communication systems but in VLC system bi-directional LEDs are used to transmit and receive simultaneously [9].

A simple, low power system can be constructed using on-off keying modulation. Different algorithms and techniques have been developed and are applied to enhance the VLC system performance. In the physical layer, coding and different modulation algorithms have been developed to support high speed and reliable optical wireless connections. To achieve the high spectral efficiency, M-ary pulse amplitude modulation has also been explored using VLC [10, 11]. For high-speed transmission the multi-carrier modulation schemes, such as orthogonal frequency modulation scheme have also been proposed for VLC systems [6]. J Lian et al addressed the constraint for peak transmitted power and proposed a clipping-enhanced optical OFDM, to reduce the distortions caused by LED non-linearity [12]. Various cross-layer algorithms have also been designed to support multiple users in VLC systems. Precoding with multiple input multiple outputs has been considered as one of the best approaches to reduce multiple access interference. The VLC system performance has also been analysed using multiple access techniques such as frequency division multiple access [13].

Features and easy availability of this technology have resulted in its usage in different sectors. The COWA, Byte Light, Inc., Smart Lighting Engineering Centre, Omega Project, D-Light Project, UC-Light Centre etc are carrying the numerous research activities focused on VLC [14]. The standardization process of this technology is being carried out within IEEE wireless personal area networks working group (802.15). The rise in robotics research and development brings different challenges and opportunities at the same time. For different robots operating in a cluttered indoor area, such as a warehouse; communications play a critical role for them to understand the environment, locate themselves, and carry out their tasks. The rapid growth in the VLC market, made researchers from different fields to increasingly focus their research efforts in developing VLC systems [9].

In this paper we propose an indoor short-range communication system using Li-Fi model and analyze the system performance considering different data rates, link distances and modulation formats. The performance of the link has been examined and optimized in the presence of external white light and ambient noise. Effect of variation in transmitter half-angle, bandwidth of LED and optical filter respectively has also been investigated. The paper is prepared as follows: The first section describes the introduction of Li-Fi system. Section II includes the system model. Section III discusses the results and finally the conclusion is given in the Section IV.

2. System model

The system, model of Li-Fi system consist of various components including the pseudo-random bit sequence generator which is used to generate a binary sequence of pseudo-random bits. PRBS is further connected to RZ or NRZ pulse generator which allows the user to create RZ or NRZ electrical pulses which are coded by digital input sequence. In the transmitter section the inbuilt LED is connected along with the external white light source to generate the light output which is passed through line-of-sight channel to the optical filter. The optical filter filters out the noise from the external white light of the received signal. The output of the filter has been applied to PIN photodiode which is used to convert optical signals into electrical signals. Electrical signal at the output of PIN photodiode is further combined with the ambient noise source representing the thermal noise arising from the fluctuations in the thermal motion of electrons which will add the noise in the circuit. The combined signal is further fed to a transimpedance amplifier which amplifies and converts the current to a voltage signal. The TIA is recommended to be used for energy- efficient applications. The ambient light rejection system is required to remove the DC interference due to ambient noise [15]. At the receiving end, the bit error rate analyzer has been used to analyze the BER and Q-factor. Fig. 1 depicts the block diagram of proposed Li-Fi system for RZ/NRZ and CSRZ modulation format in the presence of external white light and ambient noise. Fig. 2 depicts the schematic block of CSRZ modulation format.

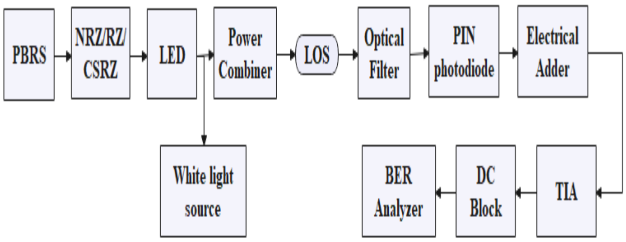


Fig. 1. Proposed Li-Fi system for NRZ/RZ and CSRZ modulation format

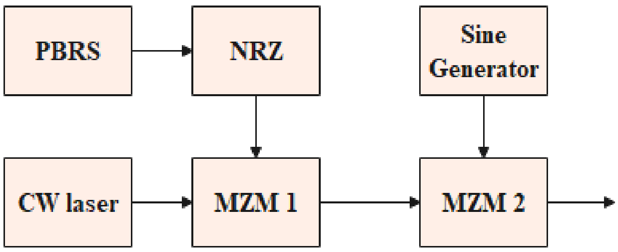


Fig. 2. Schematic block of CSRZ modulation format

The circuit has been designed to analyze the effect of variation of link distance and data rate in the presence of ambient noise source and external white light on the Li-Fi system performance. In the proposed system, it has been analyzed that high value of Q-factor has been achieved at short distance while it gradually reduces with increase in distance. A typical VLC system consist of transmitter, channel or a receiver. In the present work, the Li-Fi system has been designed for short-range indoor applications. Also, with the rapid increase in the number of user's and devices, it becomes quite difficult for the service providers to provide high-speed and more user reliable communication. In view of this Li-Fi based indoor communication system has been proposed. An indoor VLC system and its ray geometry configuration is shown in Fig. 3 and Fig. 4 respectively.

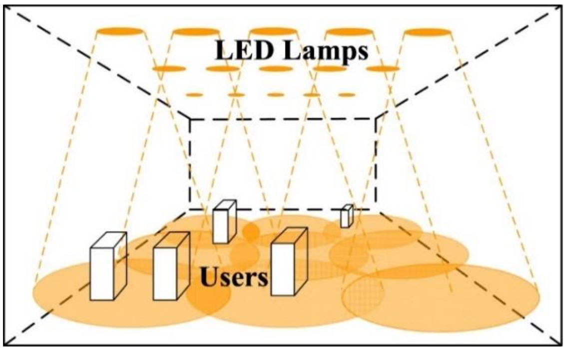


Fig. 3. Indoor visible communication system (color online)

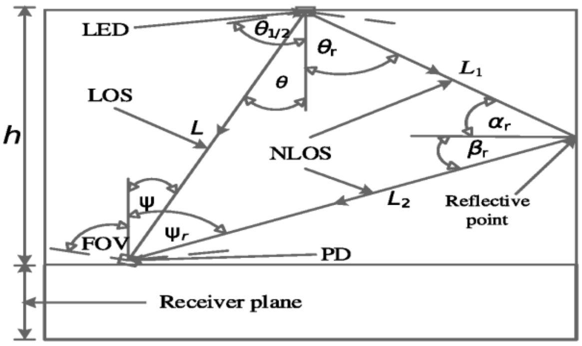


Fig. 4. Ray geometry of a Li-Fi system [18]

In VLC system, simulation link modelling is similar to as that of other wireless technologies. The total energy radiated from a light source and the amount of luminous flux per unit solid angle is expressed as [16]:

$$I = \frac{d\phi}{d\Omega} \tag{1}$$

where, 'ϕ' is the luminous flux and 'Ω' is the solid angle. The energy flux 'φ_e' is used to calculate the value of ϕ and can be expressed as,

$$\phi = (\lambda) \int_{380}^{780} V(\phi)\varphi_e(\lambda)d\lambda \tag{2}$$

where, 'λ' is the optimum visibility level (~ 673 lm / W at 555 nm) and $V(\phi)$ represents the standard luminosity curve. The luminosity factor for spectral luminous efficiency is defined in terms of radiant flux 'λ' at a specific wavelength with radiant flux [17]:

$$(\lambda) = \frac{\varphi V\lambda}{\varphi e\lambda}\ (in\,lm W^{-1}) \tag{3}$$

where, '$\varphi e(\lambda)$' is the radiometric quantity of luminance flux at the wavelength 'λ' and 'φV '' is meaningful only in the visible portion of spectrum (0.38 μm < λ < 0.77 μm). Furthermore, spectral luminous efficiency of radiant flux *V(λ)*, as the ratio of luminous efficiency at a specific wavelength to the value of the maximum luminous efficiency, can be expressed as [18]:

$$(\lambda) = \frac{K(\lambda)}{673} \tag{4}$$

As the main purposes of VLC system model is to evaluate the Lambertian luminous intensity radiation pattern and achieve a required received optical power depending on the light source wavelength. Thus, the focus must rely on the luminous intensity of light wave.

The radiation pattern of the LED optical transmitter is assumed to be Lambertian, which obeys Lambert's cosine law which states the luminous intensity detected from an ideal diffuse radiator is directly proportional to the cosine angle between the normal surface and the direction of incident light. The Lambert's cosine law has the ability to produce same radiance when seen from any angle. The Lambertian radiant intensity in watt/steradian (W/sr) of LED is given as [19]:

$$R_o(\phi) = [\frac{(m+1)}{2\pi}]\cos^m\phi \tag{5}$$

where, 'ϕ' is the radiation angle with respect to the normal axis of transmitting surface. The Lambertian order (m) is given as:

$$m = -\frac{\log 2}{\log\cos(\phi\frac{1}{2})} \tag{6}$$

where, '$\phi_{1/2}$' is the semi-angle at half-power for transmitter ranges in $\Phi 1/2 \in [-\pi/2, \pi/2]$ at half illuminance of optical light.

In the line of sight (LOS) VLC channel, Assume the transmitter emits axial symmetric radiation pattern (W/sr) is $P_t.R_O(\phi)$. Where, 'P_t 'is the LEDs average transmitted optical power.

At the receiver end, the irradiance (W/cm^2) is given as:

$$I_s(d, \phi) = \frac{Pt.R_0(\phi)}{d^2} \tag{7}$$

where, 'd' is the distance between receiver and transmitter and 'ϕ' is the R_x angle with respect to T_x. The received power for the LOS on the receiver end of the VLC system is given as:

$$P = I_s(d, \phi)\, A_{eff}(\psi) \tag{8}$$

where, 'ψ' is the incident angle w.r.t receiver axis. The front end of an optical receiver consists of an optical filter, detector and a TIA. The effective area and field of view are the two most effective constraints related to photodetector. Correlation between effective area and FOV is given as:

$$A_{eff}(\sigma) = \begin{cases} A_d.\cos(\sigma), & |\sigma| < FOV \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

where, 'A_{eff}' is the effective area of PIN diode, 'A_{det}' is the physical area of detector that is considered to be small and 'σ' is the angle of direction between receiving plane and incident ray of light.

The DC gain for LOS Li-Fi channel can be represented as [20]:

$$H.\ Los\ (0) = \begin{cases} \frac{(\mathbf{m+1})\mathbf{Ar}}{2\pi d^2} cos^m(\boldsymbol{\varphi})\mathbf{Ts}(\theta)\mathbf{g}(\boldsymbol{\theta})\mathbf{cos}\ (\boldsymbol{\theta}), & \mathbf{0 \le \theta \le \psi c} \\ \mathbf{0}, & \mathbf{elsewhere} \end{cases} \quad (10)$$

The received power 'P_r' for a LOS Li-Fi receiver can be calculated by considering the DC gain '*H. Los (0)*' of LOS Li-Fi channel and transmitter power 'P_t' which is expressed as:

$$P_r\ Los = H.\ Los\ (0)\ P_t \quad (11)$$

The DC gain for NLOS Li-Fi channel can be represented as:

$$H.\ n\ Los\ (0) = \begin{cases} \frac{(\mathbf{m+1})\mathbf{A}}{2\pi\ d1^2 d2^2} \rho dAwall\ cos^m(\boldsymbol{\varphi})\mathbf{cos}(\boldsymbol{\alpha})\mathbf{cos}(\boldsymbol{\beta})\mathbf{Ts}(\theta)\mathbf{g}(\boldsymbol{\theta})\mathbf{cos}\ (\boldsymbol{\theta}), \mathbf{0 \le \theta \le \psi c} \\ \mathbf{0}, & \boldsymbol{\theta > \psi c} \end{cases} \quad (12)$$

The received power for a NLOS Li-Fi receiver is expressed as:

$$P_r\ n\ Los = (H.\ Los\ (0) + H.\ n\ Los\ (0))\ P_t \quad (13)$$

where, '*H. Los (0)*' and '*H. n Los (0)*' are associated as the DC gain for LOS and NLOS Li-Fi channel respectively and 'P_t' is defined as the transmitter power.

The error probability for transmission system is given by:

$$p(e) = Q\ (\sqrt{\mathbf{SNR}}\ ) \quad (14)$$

$$SNR = \frac{P_s}{P_n} = \frac{(\mathbf{R}P_r)\mathbf{2}}{\sigma^2\mathbf{tot}} \quad (15)$$

$$Q(x) = \frac{\mathbf{1}}{\mathbf{2\pi}}\int_{\mathbf{x}}^{\infty} \mathbf{e}^{\frac{-\mathbf{y2}}{2}}\mathbf{dy} \quad (16)$$

where, 'P_s' is the received signal power, 'P_n 'is the noise power at the receiver, 'R' is the detector responsivity and '$\boldsymbol{\sigma}^2_{tot}$' are the total noise variances. The noise sources present in Li-Fi system includes the shot noise present at the receiver side of the system and are given by:

$$\boldsymbol{\sigma}^2_{shot} = 2qR\ P_r\ B \quad (17)$$

Detector dark current is given by

$$\boldsymbol{\sigma}^2_{dc} = 2qi_{dc}B \quad (18)$$

Background radiation is given by

$$\boldsymbol{\sigma}^2_{bg} = 2qBR\ (P_{sky} + P_{sun}) \quad (19)$$

Thermal noise is given by

$$\boldsymbol{\sigma}^2_{th} = \frac{\mathbf{4KTB}}{\mathbf{RL}} \quad (20)$$

where 'q' is the electron charge, 'R' is the detector responsivity (A/W), 'B' is the electronic bandwidth, 'i_{dc}' is the dark current, 'R_L' is the load resistance, 'K' is the Boltzmann constant, 'T' is the equivalent temperature while 'P_{sky}' and 'P_{sun}' are the radiation from diffused (sky, sun).

The power at the receiver end is determined by various losses present inside the system including shot noise which is also termed as Ambient noise the atmospheric noise present in the environment [19]. Received signal is filtered through the optical filter and is given as the input to the photodiode. The detected signal is further given to DC block followed by BER analyzer. A higher Q-factor is the measure of the extent that the pulse received at the receiver end is relatively noise free. As the Q-factor reduces it indicates the presence of noise in the system. The Q-factor is generally given by [21]:

$$Q\ (dB) = 20 log\sqrt{SNR}\sqrt{}\ B_0\ B_c \quad (21)$$

where, 'B_0' is the optical bandwidth of the photodetector, 'B_c' is the electrical bandwidth of the receiver filter.

Thus,

$$(dB) = SNR + 10 log\ B_0\ B_c \quad (22)$$

from equation 18, Q is proportional to SNR.

The BER analyzer calculates the BER using various algorithms such as Gaussian and Chi-squared and derive different metrices from the eye diagram such as Q-factor, eye opening, eye closure etc for different link distances and data rates. The mathematical formulation of BER is given by:

$$BER = p(1)P(0/1) + p(0)P(1/0) \quad (23)$$

where, 'p (1)' is the probability of receiving a 1 bit, 'p (0)' is the probability of receiving a 0 bit; 'P (0/1)' is the conditional probability of deciding 0 when a 1 is sent and 'P (1/0)' is the conditional probability of deciding 1 when a 0 is sent. The Q-factor may be calculated considering two models:

The Q-factor from BER is calculated mathematically by:

$$P_e = \frac{1}{2} erfc(\frac{Q}{\sqrt{2}}) \quad (24)$$

The Q-factor may also be calculated:

$$Q = \frac{|\mu_1 - \mu_0|}{\sigma_1 + \sigma_0} \quad (25)$$

In equation 22, 'μ_1' is the value of the 1-bit current, 'μ_0' is the value of 0-bit current, 'σ_1'' is the standard deviation of 1-bit current and 'σ_0'' is the standard deviation of 0-bit current.

The eye height, eye amplitude and eye closure is calculated by [22]:

$$E_H = (\mu_1 - 3\sigma_1)\text{-}(\mu_0 + 3\sigma_0) \quad (26)$$

$$E_A = \mu_1 - \mu_0 \quad (27)$$

$$E_C = \min(V_1) - \max(V_0) \quad (28)$$

where, min (V_1) is the minimum value of amplitude and max (V_0) is the maximum value of amplitude respectively.

The eye-opening factor is calculated by:

$$E_0 = \frac{(\mu_1-\sigma_1)-(\mu_0-\sigma_0)}{(\mu_1-\mu_0)} \quad (29)$$

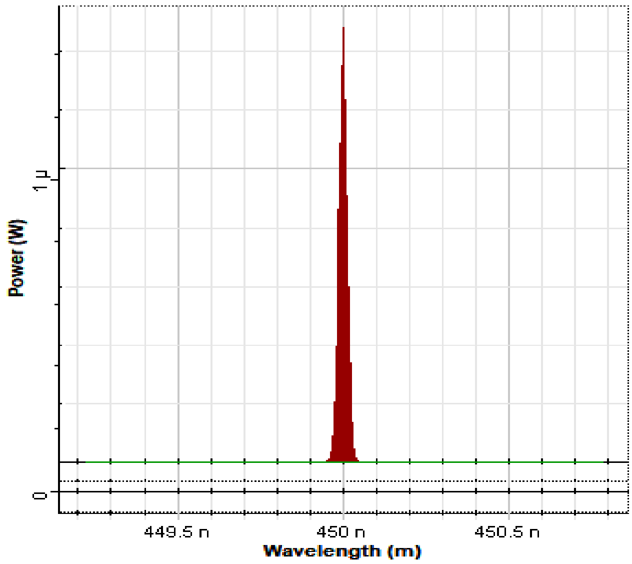
3. Results and discussion

The typical parameters used for the analysis of the performance of Li-Fi system considering LED PIN photodiode and link parameter specifications have been tabulated in Table 1.

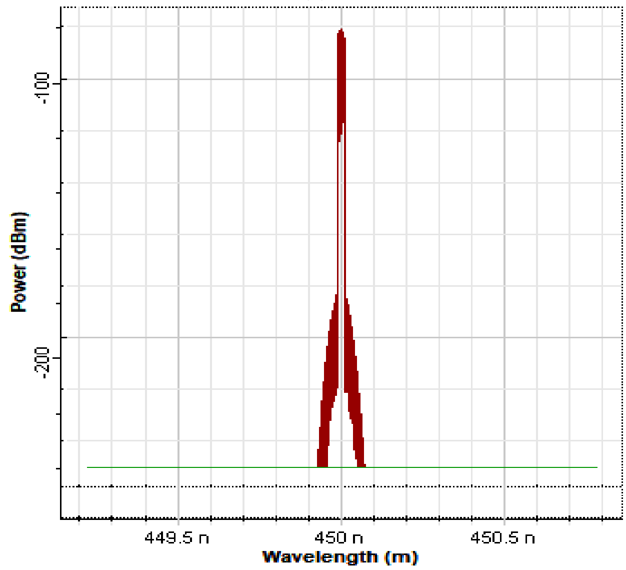
Table 1. Li-Fi system specification details

LED specifications	
Centre frequency	450 nm
Bandwidth	0.03 nm
RC time constant	0.1 ns
Quantum efficiency	0.65
PIN photodiode specifications	
Responsivity type	Silicon
Dark current	10 nA
Shot noise distribution	Gaussian
Link specification	
Distance	2 m
Transmitter half angle	60^0
Incidence half angle	20^0
Index concentration factor	1.5

Practically measured channel parameters have been utilized for analysing the performance of the system for different system conditions. In the proposed Li-Fi system, the LED have bandwidth of 0.03 nm and centre frequency of 450 nm. The emission spectrum of LED and external white light source has been depicted in Fig. 5.



(a)



(b)

Fig. 5. Emission spectrum (a) LED (b) White light source (color online)

First, the system performance has been examined and optimized as a function of external white light power, in the ambient noise absence or vice-versa considering NRZ modulation format. Next, the performance of the system has been investigated as a function of external white light power, data rate and link distance for NRZ, RZ and CSRZ modulation schemes. Further, the effect of variation in bandwidth of optical filter and LED along with variation of transmitter half-angle has been examined.

The ambient noise power is kept as 0 mW and the external white light power is varied from -120 to -80 dBm as shown in Fig. 6. Quality of the signal received deteriorates with increase in the external white light power. The maximum Q-factor achieved in the absence of ambient noise, is 16.56 at -120 dBm and 15.79 at -80 dBm respectively. Increase in the external white light power from

-120 to -80 dBm results in decline in the Q-factor from 16.56 to 15.79 respectively.

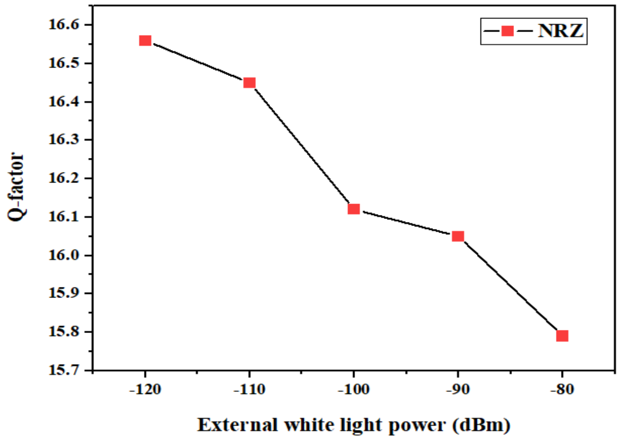


Fig. 6. Q-factor as a function of External white light power for NRZ modulation format (color online)

External white light power is kept 0 mW and the ambient noise source power is varied from -130 to -80 dBm as shown in Fig. 7. The maximum Q-factor achieved in the absence of external white light, is 15.65 at -130 dBm and 5.81 at -110 dBm respectively. Increase in the ambient noise power from -130 to -110 dBm results in decline in the Q-factor from 15.65 to 5.81 respectively. Quality of the received signal goes below acceptable limits after -110 dBm of ambient noise source power for the NRZ modulation. Also it is discovered that the ambient noise has more effect on deteriorating the quality of signal as compared to the effect caused by external white light power.

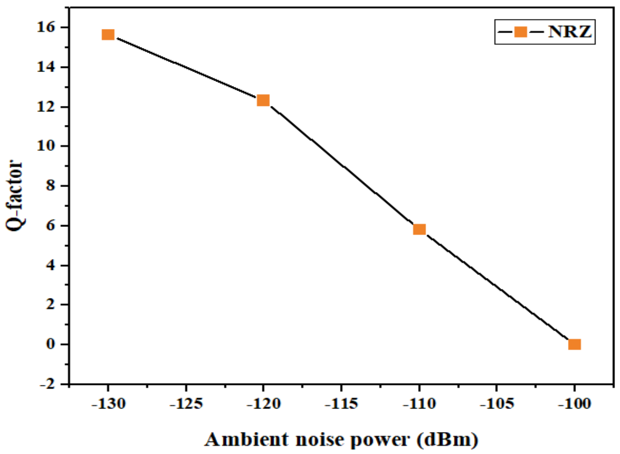


Fig. 7. Q-factor as a function of ambient noise power for NRZ modulation format (color online)

For the rest of the analysis, values of both ambient noise and external white light powers have been fixed at -120 dBm. The system performance has been analyzed in the presence of both external white light and the ambient noise considering CSRZ, RZ and NRZ modulation formats.

The effect of external white light on the Li-Fi system performance considering RZ, NRZ and CSRZ modulation formats has been shown in Fig. 8.The values of Q-factor at a link distance and data rate of 2 m and 10 Mbps respectively has been depicted in Table 2. Maximum Q-factor of 14.20 has been achieved at -120 dBm of external white light power in case of NRZ scheme. Increase in the external white light power from -120 dBm to -80 dBm results in decline in the Q-factor from 14.20 to 12.91 respectively. Quality of the received signal starts deteriorating after -90 dBm of external white light power for the three cases.

Table 2. Q-factor at different values of External white light power

Link distance (m)	External white light power (dBm)	Q-factor (RZ)	Q-factor (NRZ)	Q-factor (CSRZ)
2	-120	12.86	14.20	11.53
	-110	13.64	13.76	12.06
	-100	14.04	13.51	12.54
	-90	14.23	13.67	12.64
	-80	12.40	12.91	11.64

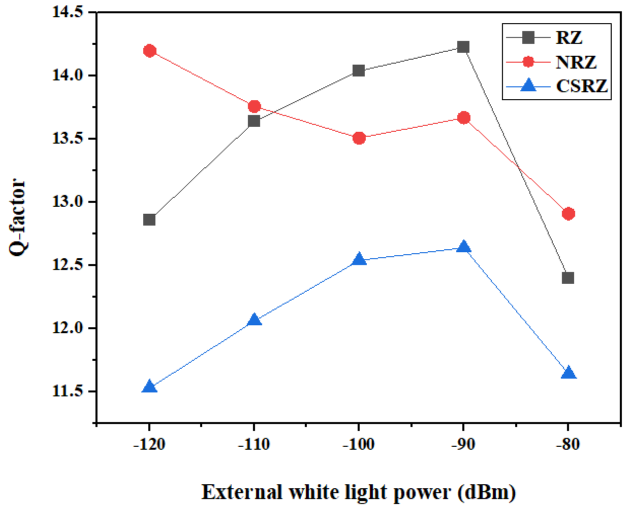


Fig. 8. Q-factor as a function of External white light power for different modulation formats (color online)

The effect of data rate on the performance of Li-Fi system considering RZ, NRZ and CSRZ modulation formats has been shown in Fig. 9. The values of Q-factor has been depicted in Table 3.

Table 3. Q-factor at different values of input Data rate

Link distance (m)	Data rate (Mbps)	Q-factor (RZ)	Q-factor (NRZ)	Q-factor (CSRZ)
2	5	15.03	16.71	14.56
	10	13.29	13.70	12.09
	15	12.11	13.36	11.67
	20	11.85	12.55	10.06
	25	10.12	11.75	8.32

Maximum Q-factor of 16.71 has been achieved at 5 Mbps input data rate in case of NRZ scheme. Increase in data rate from 5 Mbps to 25 Mbps results in decline in the Q-factor from 16.71 to 11.75 respectively. RZ gives better performance as compared to CSRZ scheme. Quality of the received signal in case of CSRZ scheme goes below unacceptable value for the data rate beyond 30 Mbps.

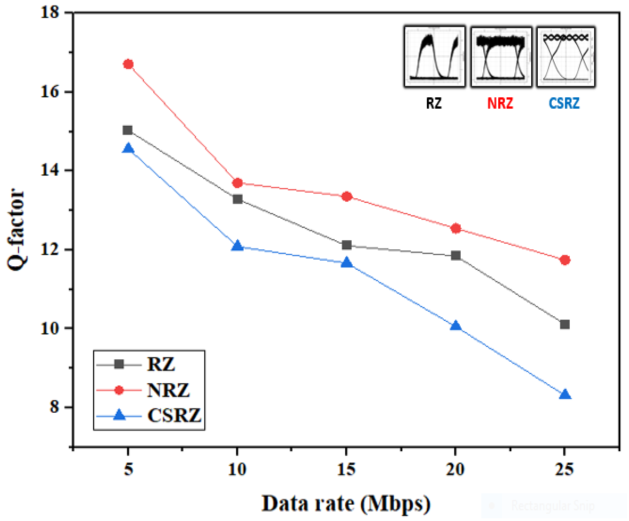
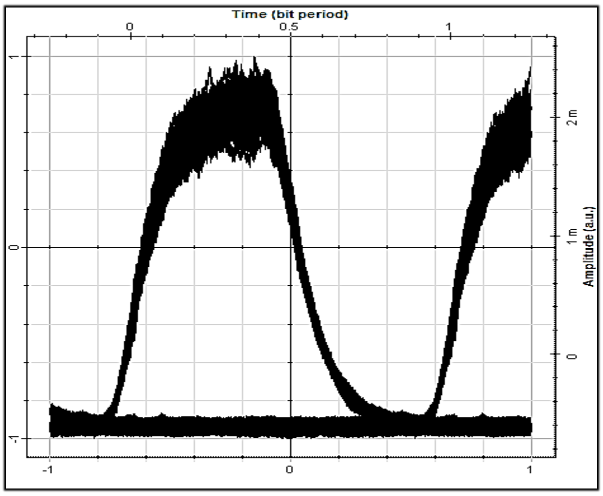
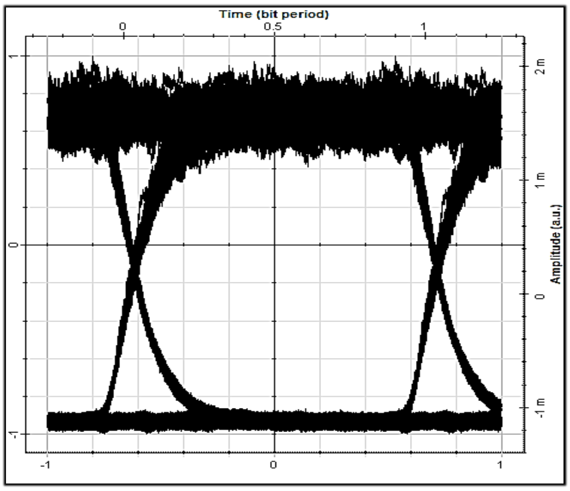


Fig. 9. Q-factor as a function of Data rate considering different modulation formats (color online)

The performance of the Li-Fi system has been analyzed from eye diagrams of different modulation formats at 10 Mbps and 20 Mbps data rates as shown in Fig. 10 and Fig. 11 respectively. The Q-factor of NRZ, RZ and CSRZ modulation format at a link distance of 1 m and data rate of 10 Mbps is 23.73, 22.16, and 18.56 respectively. The corresponding Q values at a data rate of 20 Mbps and a link distance of 2 m are RZ (13.39), NRZ (13.73) and CSRZ (8.94) respectively. Increase in link distance from 1 to 2 m and data rate from 10 to 20 Mbps shows the decline in Q-factor value and reduction in the eye opening.The better eye opening is achieved in case of RZ and NRZ as compared to CSRZ scheme.



(a)



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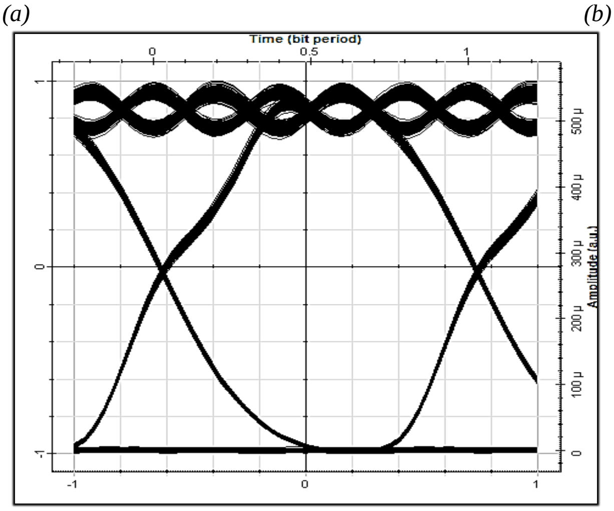
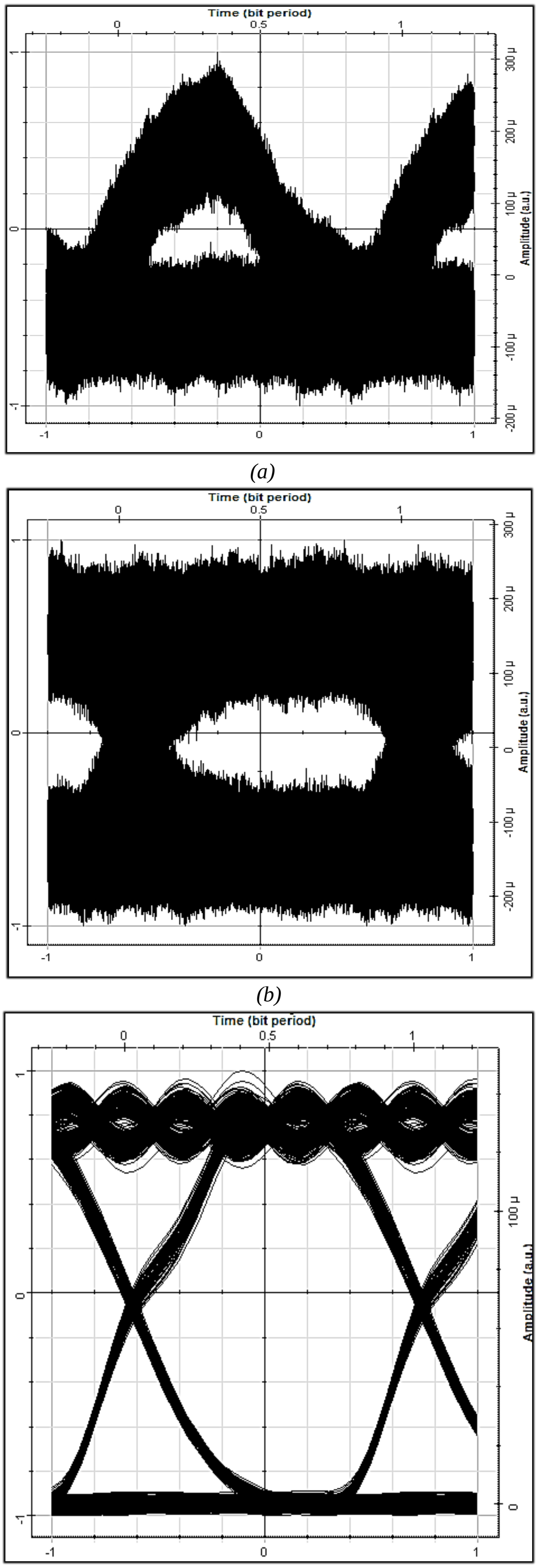


(c)

Fig. 10. Eye diagram at a Data rate of 10 Mbps and a link distance of 1 m (a) RZ (b) NRZ (c) CSRZ



(a)

(b)

(c)

Fig. 11. Eye diagram at a Data rate of 20 Mbps and a link distance of 2 m (a) RZ (b) NRZ (c) CSRZ

The effect of link distance on the performance of Li-Fi system considering RZ, NRZ and CSRZ modulation formats has been depicted in Fig. 12. The values of Q-factor has been depicted in Table 4. Maximum Q- factor of 23.16 has been achieved at 1 m link distance in case of NRZ scheme . Increase in link distance from 1 to 5 m results in decline in the Q-factor from 23.16 to 3.00 respectively. RZ gives better performance as compared to CSRZ scheme. Quality of the received signal in case of CSRZ scheme goes below unacceptable value for the link distance beyond 2.5 m.

Table 4. Q-factor at different values of link distance

Power (dBm)	Link distance (m)	Q-factor (RZ)	Q-factor (NRZ)	Q-factor (CSRZ)
-120	1	21.59	23.16	19.25
	2	13.58	14.14	12.04
	3	6.56	7.59	5.09
	4	3.36	4.55	2.06
	5	2.73	3.00	1.26

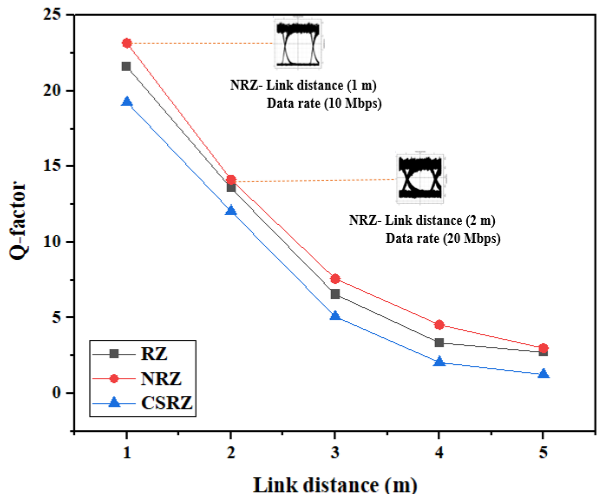


Fig. 12. Q-factor as a function of link distance considering different modulation formats (color online)

As NRZ modulation format gives better results in the presence of ambient noise and external white light, thus NRZ modulation scheme along with a -120 dBm of external white light power and -120 dBm of ambient noise has been fixed for the rest of the analysis.

The performance metrics obtained from simulation results of different modulation schemes have been included in Table 5 by considering data rate, link distance and external white light of 10 Mbps, 2 m and -120 dBm respectively.

Table 5. Performance metrics of different modulation schemes

Modulation	Q-Factor	Eye Height	BER
RZ	13.29	2.15E-39	17.53
NRZ	13.70	3.45E-41	20.05
CSRZ	12.09	1.42E-32	13.21

Furthermore, the effect of variation of bandwidth of optical filter and LED along with the variation of transmitter half-angle has been analyzed for the proposed Li-Fi system.

Fig. 13 depicts the variation in received signal quality with increase in the LED bandwidth. The maximum Q-factor of 13.55 has been achieved at 0.03 nm bandwidth, and an increase in the bandwidth beyond 0.11 nm results in the decrease in the Q-factor to an unacceptable value. LED bandwidth of 0.03 nm is thus selected along with NRZ modulation scheme for the further analysis.

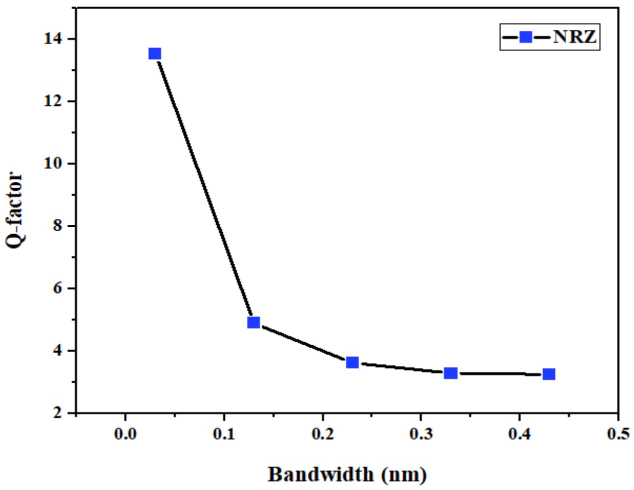


Fig. 13. Q-factor as a function of LED bandwidth (color online)

Fig. 14 depicts the variation in received signal quality with increase in the optical filter bandwidth. A Q-factor value of 14.56 has been achieved at 0.02 nm bandwidth, and a maximum Q-factor value of 23 has been achieved at 0.32 nm bandwidth. Decrease in the bandwidth below 0.01 nm results in the unacceptable quality of the received signal. In NRZ modulation scheme, external white light and ambient noise power of -120 dBm, an optical filter bandwidth of 0.02 nm and LED bandwidth of 0.03 nm has been fixed for further analyzing the performance of the Li-Fi system considering transmitter half-angle.

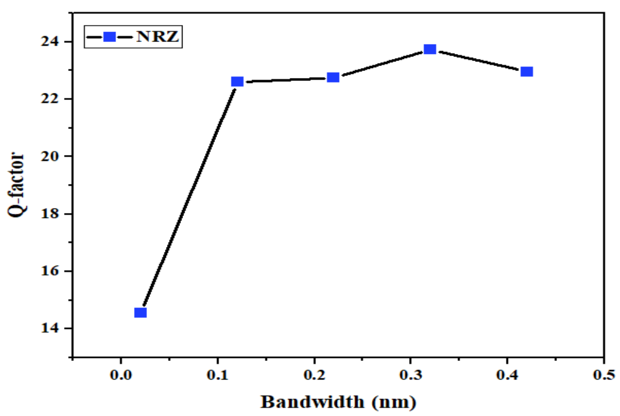


Fig. 14. Q-factor as a function of bandwidth of optical filter (color online)

Fig. 15 depicts the variation in received signal quality with variation in the transmitter half-angle from 20^0 to 60^0.There is a decrease in the quality of received signal with increase in transmitter half-angle. The minimum and maximum values of Q-factor of 14.15 and 21.82 and have been achieved at 60^0 and 20^0 half angle value respectively. Quality of received signal deteriorates beyond an unacceptable value for the transmitter half-angles beyond 80^0.

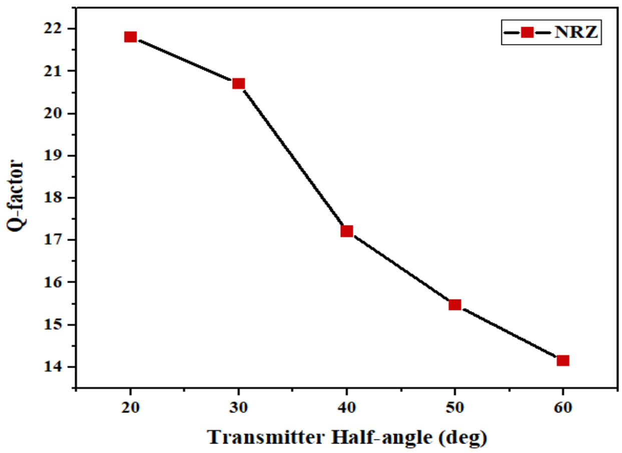


Fig. 15. Q-factor as a function of transmitter half-angle (color online)

The signals waveforms at the outputs of different sections in the Li-Fi system has been visualised through optical time domain visualizers. Figs. 16 and 17 depict the NRZ signal at transmitter and detector side respectively. Figs. 18 and 19 depict the outputs of ambient noise source and DC block respectively whereas, the lines in blue indicate the received signal and the portion in green shows the presence of noise in the proposed system due to external white light and ambient noise.

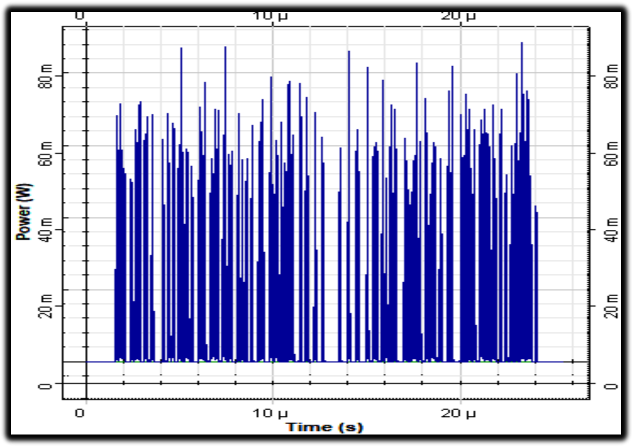


Fig. 16. NRZ signal at transmitter (color online)

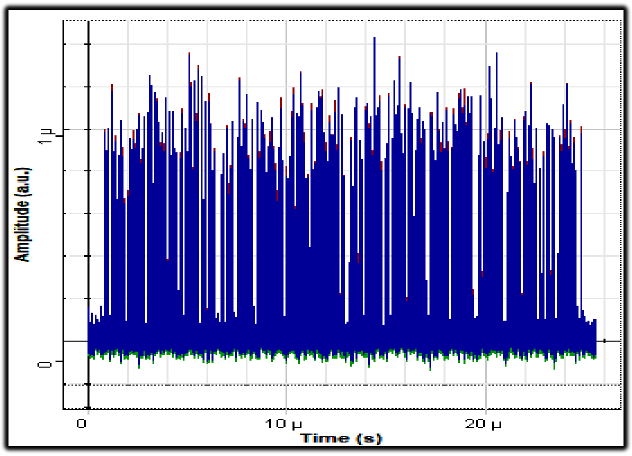


Fig. 17. Received signal at the output at PIN photodiode (color online)

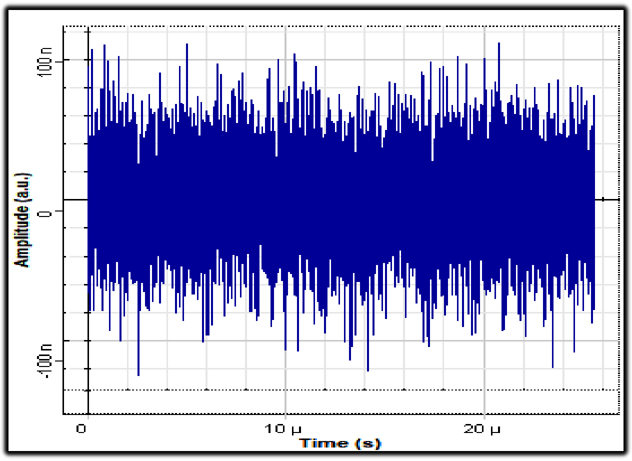


Fig. 18. Ambient noise source output (color online)

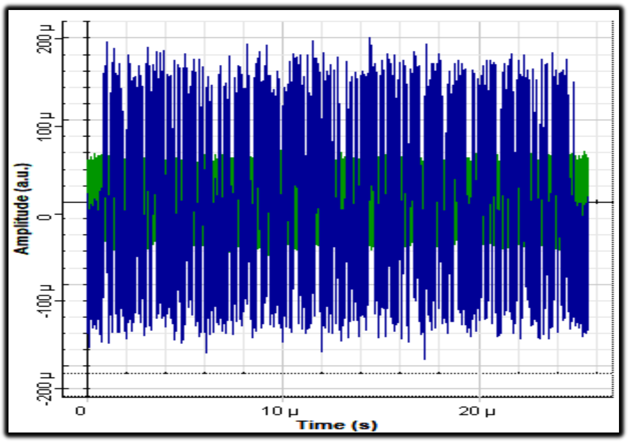


Fig. 19. Received signal output at DC block (color online)

The ambient noise presence results in a major challenge for the robust low-cost and reliable Li-Fi systems [19]. The analysis suggests that an appropriate selection of different parameters results in the enhanced system performance. An increase in the external white light and ambient noise power deteriorates the received signal quality. For the optimum system performance their values should be kept below -120 dBm.

4. Conclusion

In this work, we analyze and investigate the effect of external white light and ambient noise on the performance of Li-Fi communication system. The proposed system performance has been investigated for different link distances and data rates considering RZ, NRZ and CSRZ modulation formats. It has been discovered that the ambient noise has more effect on deteriorating the received signal quality as compared to the effect caused by external white light power. Q-factor goes below the acceptable limits for increase in the ambient noise beyond -110 dBm in case NRZ modulation scheme. NRZ modulation format gives better performance for a given link distance and data rate in the presence of ambient noise and external white light. Further, the effect of variation in bandwidth of optical filter and LED along with variation of transmitter half-angle has also been examined. Advanced modulation techniques and mode division multiplexing methods should be studied and explored to avoid the crosstalk effect at high data rates.

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