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# Optical Wireless Channel Characterization For Indoor Visible Light Communications

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## Abstract

**Background/Objectives**: This paper investigates the Line of Sight (LOS) Optical Wireless Channel (OWC) characterization for Visible Light Communications (VLC) designing a realistic indoor environment adding path loss along with Additive White Gaussian Noise (AWGN) to the channel. **Methods/Statistical analysis**: A comprehensive mathematical model is derived and simulated to investigate the performance of the proposed system considering the effect of different parameters such as Eb/No, Signal to Noise Ratio (SNR), distance between transmitter and receiver, signal power on the Bit Error Rate (BER), propagation delay, and spectral efficiency. **Findings:**The results are very promising, as the transmission distance has been significantly increased maintaining the optimal quality of transmission. The quality of transmission is evaluated by measuring the quality of images received under various channel impairments. The effect of various channel impairments on data transmission has been discussed and elaborated generating various simulation scenarios. **Applications/Improvements:**The propose indoor OWC for VLC enhances the transmission range from 4 meters to 6 meters having optimal quality of transmission in a channel representing real indoor environment.

**Keywords:** AWGN, Intensity Modulation, Indoor VLC, OWC

## 1. Introduction

Optical wireless communications based on Light Emitting Diodes (LEDs) has been of great interest for indoor applicationsdue to the co-existent dual facility of illumination and communications[1,2,3,4]. LEDs based Visible Light Communications (VLC) is an emerging technology, which achieves high propagation power with little shadowing due to required illumination level and distributed lighting fixtures.

Indoor VLC systems may be classified as Line of Sight (LoS) and Non Line of Sight (NLoS). LoS based VLC systems help in understanding the channel characteristics such as channel impulse response and scaling delta function representing amplitude degradation to the transmitted signal[5].

This paper presents a VLC system that converts the electrical signal to optical signal transmitting data via LED's through Optical Wireless Channel (OWC). The proposed VLC system includes optical photo detector, electrical pre-amplifier and corresponding post equalization circuit for maximizing Signal-to-Noise Ratio (SNR) and minimizing the error probability. The performance of the proposed system is evaluated considering the effect of different parameters such as Eb/No, Signal to Noise Ratio (SNR), distance between transmitter and receiver, signal power on the Bit Error Rate (BER), propagation delay, spectral efficiency, and quality of received image while transmitting images.

The remaining paper is organized as follows: Section 2 describes the related work. Section 3 presents the Optical Wireless Communication System and Mathematical

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analysis of OWC in which the channel coefficients for the considered indoor LoS scenario are developed and derived. In Section 4, Enhanced OWC design and features effecting the simulation are described. The performance is evaluated in Section 5, where the results are compared and discussed thoroughly. Section 6 provides Future Work and Section 7 Concludes the paper.

## 2. Related Work

This section provides a brief overview of recent trends towards VLC design, research challenges and its applications. Channel modeling and modulation techniques are the major research issues and challenges of VLC involving Intensity Modulation (IM) of LED's at transmitter end and Direct Detection (DD) of data at receiver end.

N. Kumar et al[6] presents a VLC system for an indoor environment transmitting data at 1 Mbps up to 0.30 meters and in outdoor environment targeting the 70-90 meters range with On-Off Keying (OOK) modulation. The system consists of light source, which emits light and data simultaneously, and a photodiode is used as receiver following IM/DD on both the terminals. Their proposed emitter architecture may have two kind of lighting devices characterized on the basis of superficial area and angle of irradiance. They also provide a basic design for optical wireless USB interface as a demonstrator of VLC indoor potentiality. However, it does not provide optimum performance results and needs improvements in channel characterization, modulation and coding schemes.

Optical communications research group[7] designed a VLC systems with multiple input multiple output (MIMO) overcoming the restriction of limited modulation bandwidth of few MHz. MIMO is implemented by using multiple arrays of LEDs, which provides parallel data transfer. In some scenarios, when MIMO technique is employed, system does not perform consistently at all receiver positions. Simulation results show that aggregate speed up to 12 Mbps can be achieved using BER performance so it reduces the signal power[7]. The performance of optical wireless systems is limited by power constraints at the transmitter and limited receiver sensitivity, as well as limits on the optical gain that is available[8]. Resonant cavity LEDs is used at transmitter end with OOK and Manchester modulation techniques, which provide basis for OMEGA project design.

Within indoor environment diffuse optical wireless links, multipath dispersion limits the maximum transmission data rate. OFDM system is investigated by inducing multipath, reducing Inter Symbol Interference and applying different modulation techniques to achieve high data rates[9]. But this paper do not addressed all the parameters like delays, BER and spectral efficiency etc.

Some key issues of practical LoS Visible Light Communication system design are discussed, covering transmitting and receiving devices, channel path loss, and system noise sources[10]. Optimized receiver front-end is designed consisting of optical filter, Photodetector, pre-amplifier, post-equalizer and electrical filter. Post equalization improves the performance parameters such as BER, data rate and LEDs modulation bandwidth utilization. Simulation results are analyzed and validated for short distance of 2.9 and 3.5 meters. Parallel Wireless Optical Communication (PWOC) uses high-speed cameras as optical receivers for VLC in vehicular communication, which assists in providing different kind of information explained in [11].

The incorporation of VLC components in everyday technology has been resulted in the creation of the Japan Electronics and Information Technology Industries Association's JEITA standards (2007) for a 'visible light ID system', and a Specification Standard in 2008 by the Visible Light Communications Consortium (VLCC) - as a result of its joint cooperative agreement with the Infrared Data Association (IrDA) [12].

The Institute of Electrical and Electronics Engineers (IEEE) Wireless Personal Area Networks working group 802.15.7 Task Group 7 has also developed a standard for VLC technologies finalized by the end of 2010, whilst the EU-funded OMEGA project is investigating ways in which such technology can be incorporated into home networks [13].The two year D-Light project is midway through its funding. The main commercial goal is the formation of a University of Edinburgh spinout company, started in 2012. D-Light technology offers a secure medium for communication in an office/building environment [14].

All the related work has evaluated the performance of the VLC systems considering a fixed indoor OWC characteristic whereas this paper proposes a realistic AWGN channel model based on path loss due to air and LoS communication link.

## 3. Optical Wireless Communication System Design

Optical Wireless Communication systems uses modulation techniques to transmit the data through LED

based opto-electrical components. Low cost, off-the-shelf Avalanche Photo Diode (APD) offers a large area of reception with minimum noise at the receiver end [15]. Figure 1 represents an Optical Wireless Communication system with light based transmitter, typical OWC channel and light detector based receiver. Channel is characterized as per deployment scenarios such as indoor/outdoor environments and coherent or non-coherent OWC systems. In the proposed OWC system design, indoor OWC is characterized by adding path loss along with the Additive White Gaussian Noise (AWGN) channel to represent realistic indoor environment.

### 3.1 OWC Mathematical Model

Equation 1 models the channel where y(t) represents the received signal current, x(t) represents the transmitted optical pulse, n(t) represents the AWGN noise, and the symbol '*' denotes convolution. n(t) is observed in the optical-to-electrical (O/E) converted signal x(t). R represents O/E conversion efficiency at a user terminal´s Photo Detector. The Photo Detector is the major source of shot noise; its power spectral density is proportional to the detected optical power given in [16, 17].

$$y(t) = R * X(t) + n(t) \tag{1}$$

Equation 2 presents a general LoS VLC scenario and evaluates corresponding path loss that will be used for the performance evaluation of the proposed system. The receiver distance to the source is D and the receiver aperture radius is r. The angle from the source-receiver line and receiver normal is α and to the source beam axis is β (viewing angle). Ωr is the receiver solid angle seen by the transmitter and $A_r$ is the receiver area [5].

$$A_r \cos(a) \approx D^z \Omega_r \tag{2}$$

Equation 3 denotes receiver ingested luminous flux.

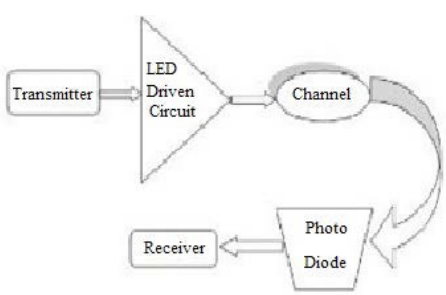


**Figure 1.** Optical Wireless Communication System.

$$F_r = l_o g_s(\beta)\Omega_r \tag{3}$$

Luminous path loss can be expressed as follows[18].

$$L_L = \frac{r_r}{F_s} \tag{4}$$

$$L_L = \frac{L_o g_s(\beta)\Omega_r}{I_o \int_0^{\theta_{max}} 2\pi g_s(\theta)\sin\theta d\theta} \approx \frac{g_s(\beta) A_r \cos a}{D^2 \int_0^{\theta_{max}} 2\pi g_s(\theta)\sin\theta d\theta} \tag{5}$$

In equation 4and 5, Let $F_r$ and $F_s$ be the received and transmitted luminous flux of LED based transmitter. Assume that transmitter LED has the spatial luminous intensity distribution $I_0 \cdot g_s(\theta)$, where $I_0$ is the axial intensity with unit candela and $g_s(\theta)$ is the normalized spatial distribution function usually provided by a vendor. During the above process, path loss is derived in photometric domain. For short range LoS free space propagation, power path loss is reasonably assumed independent of wavelength λ within the spectrum of interest. By simplifying the integration of equation 5, LoS path loss for the Lambertian source is obtained with the order $m = \frac{-\ln(2)}{\ln\left(\cos a \frac{1}{2}\right)}$ and the transmitter semi angle $\alpha_{1/2}$. In equation 6, β denotes Field of View (FoV) or viewing semi angle of the receiver, $A_r$ is the detector area of the receiver. Hence, the channel coefficients depend on the specific position of each transmitter and receiver within the setup scenario[19].Commercial lighting LEDs without any beam-shaping component can be treated as Lambertian sources with spatial distribution function (θ), which depends on m. And m is the order of Lambertian emission [20].

$$L_L \approx \frac{(m+1)A_r}{2\pi D^2} \cos a \cos^m(\beta) \tag{6}$$

## 4. Enhanced Optical Wireless Channel

Figure 2 presents the enhanced optical wireless channel adding AWGN and Path Loss blocks to simulate the more realistic indoor environment.

Proper channel modeling can significantly improve performance of the system. Lumens of light emitted by LED depend on the current passing through the LED. This will decrease proportionally with 1 over the square of distance. Equation 7 gives a conversion of current flowing through the LED to lumens obtained by simplifying equation 5.

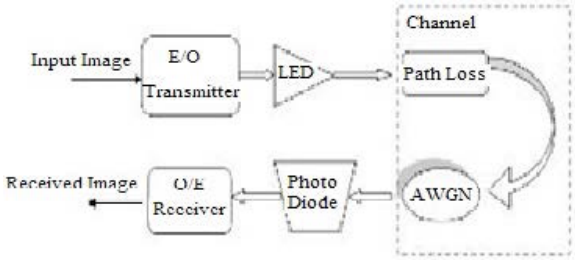


**Figure 2.** Enhanced Optical Wireless Channel (OWC).

$$L_L = \frac{1}{D^2} * emitted\ power\ of\ LED \tag{7}$$

Optical receivers are capable of receiving these amounts of light. Combined effect of AWGN and path loss blocks give real time indoor environment for the transmission of optical power emitted by LED. The enhanced system can be analyzed on the basis of some control and performance evaluation parameters. Change in values of control parameters effects performance evaluation. Controls parameters for proposed OWC are Distance, Eb/No, and Noise.

### 4.1 Distance

The path loss in dB for an open-air site is:

$$PL = 22dB + 20\log\frac{d}{\lambda} \tag{8}$$

Where:

$PL$ is the path loss in dB.

$d$ is the distance between transmitter and receiver.

$\lambda$ is the wavelength of carrier.

### 4.2 Eb/No

In order to relate Eb=No, particular simulation having noise variation is required. We use the following relationships.

$$E_b = ST_b \tag{9}$$

Where:

$S$ is the incoming signal power.

$T_b$ is the bit duration.

Equation 10 represents the relationship between Eb/No and SNR.

$$\frac{E_b}{N_o}(dB) = \frac{S}{N}(dB) + 10\log\left(\frac{BW(Hz)}{Bit\ Rate}\right) \tag{10}$$

### 4.3 Noise

Ambient light sources are the main source of noise in the channel and must be considered in system design. Photo-generated shot noise is a major noise source in the wireless optical link. This noise arises fundamentally due to the discrete nature of energy and charge in the photodiode[21]. In LED based system three types of noise can be generated:

- Power spectral density, it declines with a growly frequency.
- Asynchronous impulsive noise because of switching property of LEDs. This type of noise can reach up to 2KV and voltage length about 10-100 µs.
- Synchronous impulsive noise due to thermistors, light dimmers and copiers etc.

## 5. Results and Discussions

Changes in AWGN channel modes effect the simulation results significantly. This section addresses the effects of change in Eb/No, SNR and distance on BER, spectral efficiency, noise, propagation and transmission delay.

Simulation parameters and input image are presented in Table 1 and Figure 3 respectively.

Figure 4 shows BER, which remains same throughout simulation because correlation between image pixels does not affect the BER in AWGN channel[21].

### 5.1 Evaluating Eb/No

#### *5.1.1 Eb/No = 10 dB*

Received image is blurry due to random noises in the image. Result in Figure 5 shows the received image quality, which contains very high noise.

**Table 1.** Simulation Parameters

| Initial Seed | Bit Per Symbol (bit) | Input Signal Power (watt) | Symbol Period |
|---|---|---|---|
| 51 | 1 | 1 | 1 |

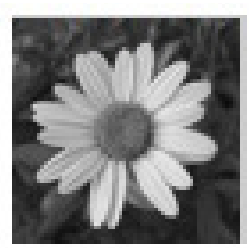

**Figure 3.** Transmitted Image.

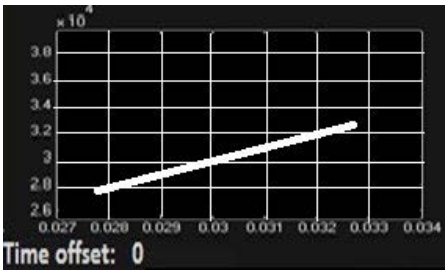


**Figure 4.** Ber = 3.2777e+004.

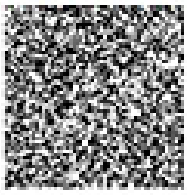

**Figure 5.** Received Image When Eb/No = 10 dB.

Figure 6 (a) shows spectral efficiency at Eb/No=10dB and buffer input size = 128. Gain of spectral efficiency is approaching to zero, which is not an optimal value in an OWC. Spectral efficiency can be improved by increasing Eb/No (dB)[21].

Figure 6(b) shows noise generated during image transmission. Received image is blurry due to large noise impairment. Figure 6(c) and 6(d) show the transmission and propagation delays respectively. In this particular scheme correlation window of size 200 is defined, which process the 200 samples per frame and shows the change after each frame.

### 5.1.2 Eb/No = 50 dB

By changing the value of Eb/No from 10 dB to 50 dB, image quality is improved due to decrease in noise generated. Figure 7 shows improvement in quality of received image.

Figure 8(a) shows improvement in Spectral efficiency due to decrease in noise and increase in Eb/No value. Average gain of squared dB increases and is closer to zero. Figure 8(b) shows noise for Eb/No=50 dB. Increase in dB value reduces noise. Decrease in noise spikes shows intensity of noise effect on the transmission.

Figure 8(c) and Figure 8(d) show transmission and propagation delay. Transmission delay is reduced to 1 second and propagation delay is zero. After threshold value of Eb/No=50 propagation delay remains same at 0 second because proposed system is Single Input Single Output (SISO) system. Transmitter never finds the channel busy and transmits the data every time without waiting for the channel to be free.

### 5.1.3 Eb/No = 100 dB

By changing the value of Eb/No from 50 dB to 100 dB, image quality is improved due to decrease in noise generated. Figure 9 shows that received image quality is same as original image transmitted.

Figure 10(a) shows the significant improvement in the spectral efficiency. Spectral efficiency has an inverse relation with the noise[21]. Figure 10(b) shows high reduction in noise of channel resulting in better image quality and increased bandwidth utilization.

**Figure 7.** Received Image When Eb/No = 50 dB.

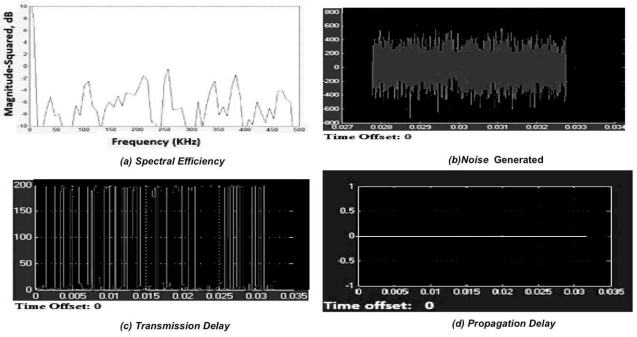


**Figure 6.** Parameter Evaluation Considering Eb/No=10 dB.

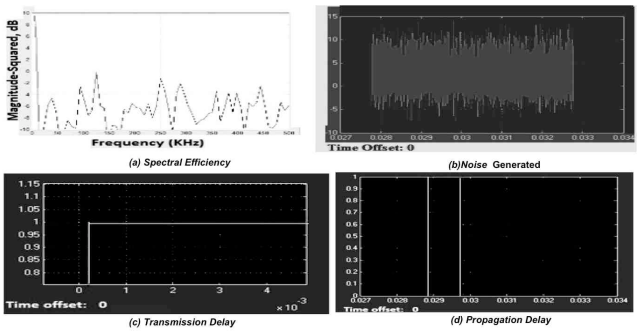


**Figure 8.** Parameter Evaluation Considering Eb/No=50 dB.

**Figure 9.** Received Image When Eb/No = 100 dB.

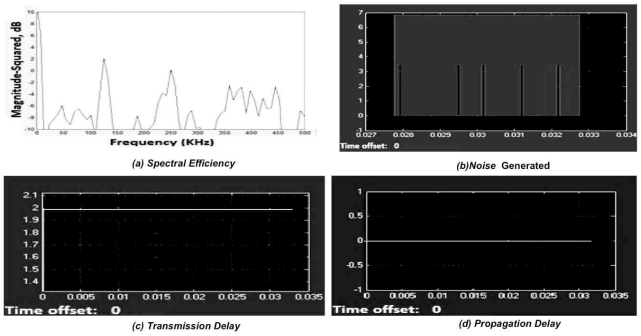


**Figure 10.** Parameter Evaluation Considering Eb/No=100 dB.

Figure 10(c) shows decrease in transmission delay due to decrease of noise effect in transmission. Figure 10(d) shows zero propagation delay because of high Eb/No value.

## 5.2 Evaluating SNR

For an indoor environment optimal threshold value of SNR is 10 dB because at this threshold value least noise is generated. SNR= 10 dB is optimal because in low SNR white Gaussian noise dominates BER, which can be improved by enhancing SNR. While in high SNR phase, estimation error dominates the BER, which cannot be improved by simply enhancing SNR [15]. Proposed system at SNR = 10 dB threshold produces best results and quality of received image is same as original transmitted image as is shown in Figure 11.

Figure 12 shows comparatively better bandwidth utilization. It is almost the same as for Eb/No having value

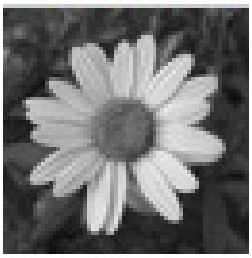

**Figure 11.** Received Image When Snr = 10 dB.

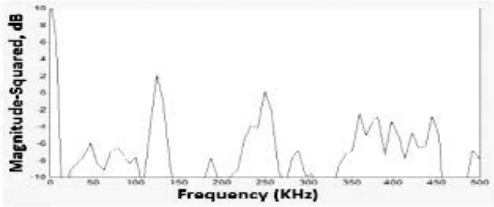


**Figure 12.** Spectral Efficiency When Snr = 10 dB.

100 dB in Figure 9. Figure 13 shows the noise effect with SNR= 10 dB.

## 5.3 Evaluating Distance

### *5.3.1 Distance = 12 m*

Figure 14 shows the received image when distance between transmitter and receiver is 12m. Noise and transmission delay increases significantly which effect the output.

Large increase in distance increases transmission delay and BER performance, which causes bandwidth utilization to be almost zero because of slow frame transmission rate. As distance between transmitter and receiver increases, sources of ambient light in optical wireless channel result in higher noise. This increase in noise results in higher delay and BER. Figures 15(c) and 15(d) show comparison of input and output signals. The difference in transmitted and received signals results in the low quality received image as shown in Figure 14.

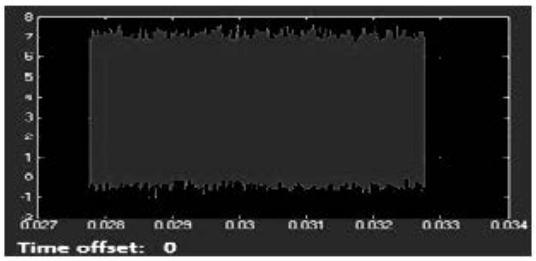


**Figure 13.** Noise Generated When Snr = 10 dB.

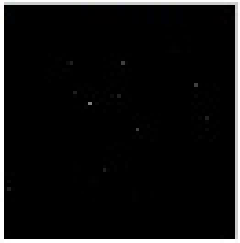

**Figure 14.** Received Image When Distance = 12m.

### 5.3.2 Distance = 8m

Figure 16 shows at distance of 8m, received image is blurred due to increase in path lose.

Figure 17(a) shows increase in spectral efficiency as distance decrease. Figure 17(b) shows decrease in noise generated due to increase distance, which causes successful transmission with optimal transmission delay and less BER. Figures 17(c) and 17(d) show comparison of input and output signals. Transmitted and received signals have great difference due to decrease distance causes the low quality of received image.

### 5.3.3 Distance = 6m

Figure 18 shows that the received image has same quality as original image at the distance of 6m. It is interesting that BER increases as we increase the distance between transmitter and receiver (Table 2).

Figure 19(a) shows increase in spectral efficiency as distance decreases. Figure 19(b) shows decrease in noise generated which causes successful transmission with optimal transmission delay and less BER. Figures 19(c) and 19(d) shows similarity in input and output signals. In [22], authors declare 90 cm the maximum possible distance between transmitter and receiver for a single LED

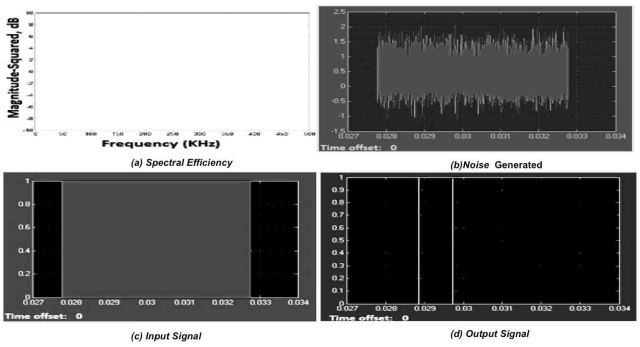


**Figure 15.** Parameter Evaluation Considering Distance = 12m.

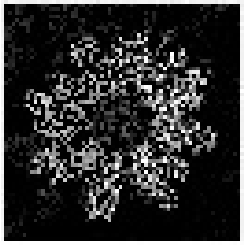

**Figure 16.** Received Image When Distance = 8m.

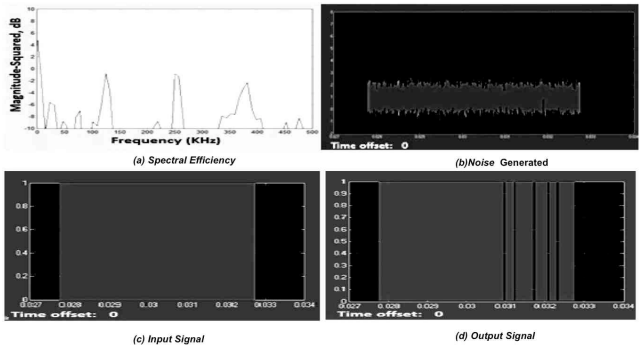


**Figure 17.** Parameter Evaluation Considering Distance = 8m.

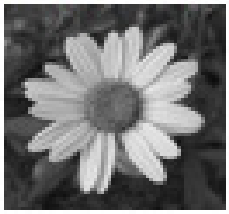

**Figure18.** Received Image When Distance = 6m.

**Table 2.** Results Summary

| Parameters | Values | Noise | Delay | BER | Image Quality |
|---|---|---|---|---|---|
| Eb/No | 10 dB | Increasing | 2 sec | 3.277e+004 | Low |
| | 50 dB | Decreasing | 1 sec | 3.277e+004 | Medium |
| | 100 dB | Decreasing | 1 sec | 3.277e+004 | High |
| SNR | 10 dB | Optimal | 1 sec | 3.277e+004 | High |
| | 50 dB | Optimal | 1 sec | 3.277e+004 | High |
| Distance | 4 m | Optimal | 2 sec | 3.277e+004 | High |
| | 6 m | Optimal | 2 sec | 3.277e+004 | High |
| | 8 m | High | 3 sec | 4.012e+004 | Medium |
| | 12 m | High | 4 sec | 6.203e+005 | Low |

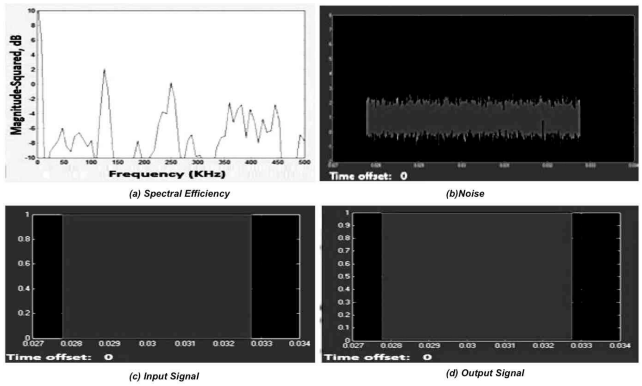


**Figure 19.** Parameter Evaluation Considering Distance = 6m.

with minimum BER=$10^{-5}$, as distance increases BER also increases. Proposed system works at high distance, increased BER and optimal delay.

Table 2 summarizes the simulation results. In recent researches the effective distance for successful image transmission is 3-4m with received image quality same as transmitted image and optimal BER. Proposed system achieves same results up to 6 m distance successfully.

## 6. Conclusion

To the best of authors' knowledge a novel LOS OWC for VLC has been proposed and investigated. The proposed system is mathematically analyzed and simulated against the various quality of transmission parameters such as Eb/No, Signal to Noise Ratio (SNR), distance between transmitter and receiver, signal power on the Bit Error Rate (BER), propagation delay, and spectral efficiency. Introducing the path loss and AWGN resulting in a closer to real channel has enhanced the traditional model of VLC channel. The results are very promising, as the transmission distance has been significantly increased from 4 meters to 6 meters maintaining the optimal quality of transmission. The quality of transmission is evaluated by measuring the quality of images received under various channel impairments. The effect of various channel impairments on data transmission has been discussed and elaborated generating various simulation scenarios.

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