Physical Layer Analysis of Visible Light Indoor Communication

Brajendra Kumar Ahirwar[1] Dr. Prabhat Patel[2]
[1,2]Department of Electronics & Communication Engineering
[1,2]J.E.C, Jabalpur (M.P.), India

Abstract— The number of personal computers and personal digital assistants for indoor use are rapidly growing in offices, manufacturing floors, shopping areas and warehouses. In near future, one will find very often several such devices clustered within small indoor areas. To meet these requirements optical wireless (IR) technology seems to be ideal for wireless communication systems of the future. It can provide cable free communication at very high bit rates (a few Gbps as compared to tens of Mbps supported by radio). In indoor optical wireless systems, laser diodes (LDs) or light emitting diodes (LEDs) are used as transmitter and photo-diodes as the receivers for optical signals. These LED are Lambertian source, therefore light is not uniformly distributed and thus power variation and in turn BER varies. In this paper it is shown that by adding SOAs in photo-detector can improve BER performance.

Key words: Visible Light Communication (VLC)

I. Introduction

The visible light communication (VLC) denotes a communication technology which uses visible light as optical carrier for data transmission and illumination. Nowadays, light emitting diode (LED) at visible wavelengths (380 nm ~ 780 nm) has been actively developed and can be used as a communication source and, naturally, the silicon photodiode which shows good responsively at visible wavelength region is used as receiving element [1]. The transmission channel is the air, whether it is indoor or outdoor.

A. An Indoor Optical Wireless System

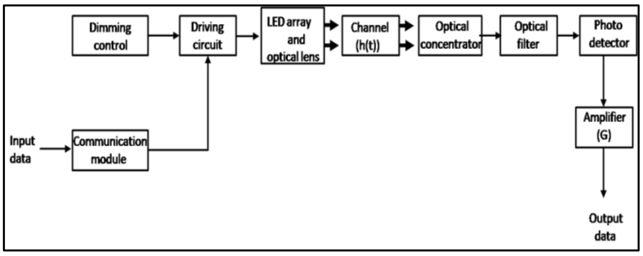

Fig. 1: Block Diagram of VLC Systems

A block diagram of a typical indoor optical wireless system is shown in Figure 1. A basic optical wireless system consists of a transmitter (using LEDs or LDs), free space as the propagation medium and the receiver (using APDs or PIN diodes). Information, typically in the form of digital data, is input to electronic circuitry that modulates the transmitting light source (LEDs/LDs). The source output passes through an optical system (typically has telescope and optical diplexer) into the free space (propagation medium). The received signal also comes through the optical system and passes along the optical signal detectors (PIN diodes/APDs) and thereafter to signal processing electronics [2-5].

We can directly modulate the drive current of an optical source by modulating signal m (t), which thusly changes the optical source intensity x (t) (refer Figure 2). A photo detector is employed by the receiver, along with a response which is the incorporation of huge number of quite small wavelengths of the incident optical signal by which a photocurrent y (t) is produced. This photocurrent is straightforwardly related to the immediate optical power incident on it. In other words, it is directly related to the square of received electric field. An IM/DD-based optical wireless framework has a comparable baseband model that conceals the high- frequency character of the optical carrier [6]. The model is demonstrated in Figure 2. In the figure, the parameter R represent the photo detector responsively, n (t) is the signal-independent shot noise, and h(t) represents the baseband channel impulse response and modelled throughout the book as the additive white Gaussian noise (AWGN) with a double-sided power spectral density (PSD) of N0/2 Non-LOS links, especially in indoor applications, are liable to the impacts of multipath propagation in the similar manner as RF frameworks and these impacts are more robust. This kind of link can experience the ill effects of extreme multipath-induced execution penalties, as we will explain in the following sections. Multipath propagation results in the electric field to experience the bad effects of extreme amplitude fades on the wavelength scale. The detector would encounter multipath fading in the event of the detector size (i.e., the surface area) was corresponding to one wavelength or less. It is fortunate that OWC receivers make use of detectors with a surface area commonly of millions of square wavelengths. Moreover, the aggregate photocurrent produced is directly related to the integral of the optical power over the whole photo detector surface; this gives an inherent spatial diversity as illustrated in Figure 3 [7]. We will summarize the equivalent baseband model of an IM/DD optical wireless link with the help of the accompanying equation

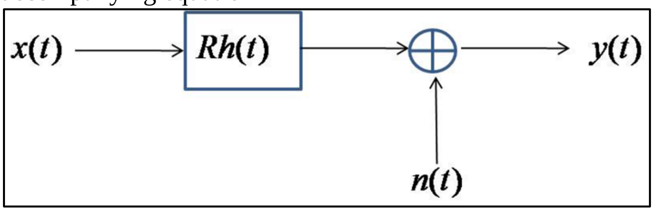

Fig. 2: VLC Communication Block Diagram

$$y(t) = Rh(t) \otimes x(t) + n(t) \qquad (1)$$

Or $$y(t) = \int_{-\infty}^{\infty} Rh(t-\tau)x(\tau)d\tau + n(t). \qquad (2)$$

This model of LTI illustrates the execution of VLC. We can use the impulse response h (t) to simulate or analyses or the impacts of multipath dispersion in indoor OWC channels. Gfeller and Bapst modeled the channel impulse response as

$$h(t) = \begin{cases} \dfrac{2t_0}{t^3 \sin^2(FOV)} & t_0 \le t \le \dfrac{t_0}{\cos(FOV)} \\ 0 & \text{elsewhere} \end{cases} \quad (3)$$

Here t_0 is defined as the minimum delay.

Even with the fact that Equation 1 is just a linear filter channel with AWGN, optical wireless frameworks are different from typical radio or electrical frameworks due to the reason that the instantaneous optical power is related to the produced electrical current $x(t)$ represents the power instead of the amplitude signal. This forces two limitations on the transmitted signal [8]. First one is, $x(t)$ must be nonnegative, i.e.

$$X(t) \ge 0 . \quad (4)$$

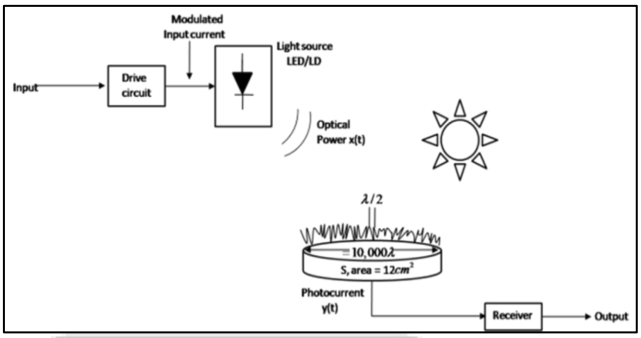

Fig. 3: IM/DD VLC System

The second one is the requirements of the eye safety restricts the highest optical transmit power that may be applied. Normally, it is the average requirement of power that is the extreme restrictive and therefore, the average value of $x(t)$ must not goes beyond a particular maximum power value P_{max}, given as

$$P_T = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} X(t)dt . \quad (5)$$

These distinctions profoundly influence the design of the system. On typical RF channels, the signal-to-noise ratio (SNR) is related to the average power received, while on the other hand, in the case of optical wireless links, it is related to the square of the average received optical signal power as given below [40]

$$SNR = \frac{(RP)^2}{R_b N_0} = \frac{R^2 H^2(0) P_t^2}{R_b N_0} \quad (6)$$

Here, the received power is estimated as

$$P_r = H(0) P_t \quad (7)$$

We can calculate the DC part of the impulse response by

$$H(0) = \int_{-\infty}^{\infty} h(t)dt$$

II. Loss Propagation Model

Generally, the indoor OWC frameworks make use of an LED as a source and huge-area photo detectors.

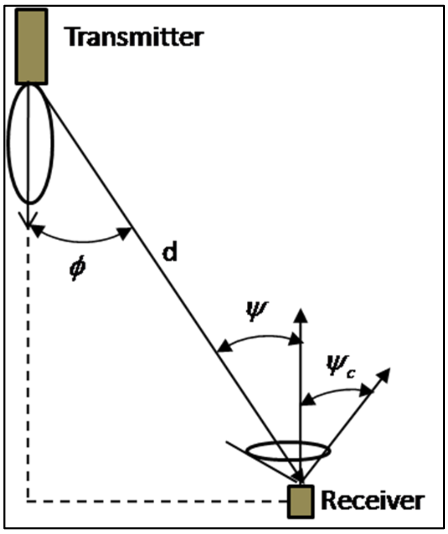

Fig. 4: Loss Propagation Model

With the help of a generalized Lambertian radiant intensity, we can model the angular distribution of the radiation intensity pattern with the accompanying distribution

$$R_0(\phi) = \frac{(m_1 + 1)}{2\pi} \cos^{m_1}(\phi) \quad \text{for } \phi \in [-\pi/2, \pi/2] \quad (8)$$

Here the parameter m_l represents the Lambert's mode number denoting directivity of the source beam, also here $\phi = 0$ defines the angle of maximum radiated power. The order of Lambertian emission m_l is related to the LED semi angle at half-power $\Phi_{1/2}$ by

$$m_t = \frac{1n(2)}{1n(\cos \Phi_{1/2})} \quad (9)$$

The radiant intensity is as

$$S(\phi) = P_t \frac{(m_1 + 1)}{2\pi} \cos^{m_1}(\phi) \quad (10)$$

We model the detector as an active area A_r gathering the radiation incident at angles Ψ not greater than the detector FOV. We can estimate the impressive collection detector area by

$$A_{eff}(\Psi) = A_r \operatorname{Cos}(\Psi) \quad 0 \le \Psi \le \pi/2 \quad (11)$$

The optical gain of an ideal non-imaging concentrator having internal refractive index n is

$$g(\Psi) = \begin{cases} \dfrac{n^2}{\sin^2 \Psi_{con}} & 0 \le \Psi \le \Psi_{con} \\ 0, & 0 \ge \Psi_{con} \end{cases} \quad (12)$$

Here $\Psi_{con} \le \pi/2$ is the FOV.

$$A_{coll} \operatorname{Sin}\left(\frac{\Psi_c}{2}\right) \le A_r \quad (13)$$

We have a small length of the link for indoor OWC and therefore attenuation because of the very low scattering and absorption. Taking into consideration an OWC link with a Lambertian source, a non-imaging concentrator of gain $g(\psi)$, a receiver with an optical band-pass filter of transmission $Ts(\psi)$ and the DC gain for a receiver located at a distance of d and angle ϕ with respect to transmitter (see Figure 4) can be approximated as [8-10]

$$H_{los}(0) = \begin{cases} \dfrac{A_r(m_t+1)}{2\pi d^2}\cos^{m_t}(\phi)T_s(\psi)g(\psi)\cos(\psi) & 0 \le \psi \le \psi_c \\ 0 & elsewhere \end{cases}$$

The received power hence turns out to be

$$P_{r-los} = H(0)P_t \qquad (15)$$

Parameter	Value
Semi angle of half power	70^0
Transmitted LED power	20dBm
Area of Photo-detector	10^{-4} m^2
Refractive Index	1.5
Field of View	60^0
Room Dimension	5×5×3 m^3
Position of LED	At the centre of floor (0,0)

Table 1: Simulation Parameters

The received power distribution at the various distances between transmitter and the ceiling is shown in figure 4 while considering distance as 1, 2, 2.5 and 3 meters.

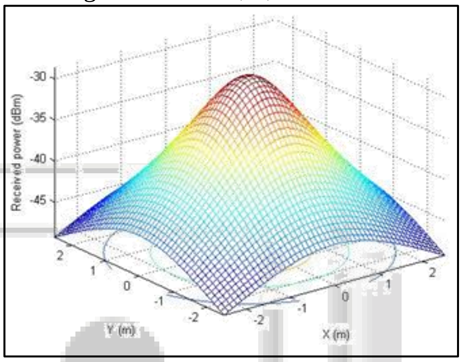

Fig. 5

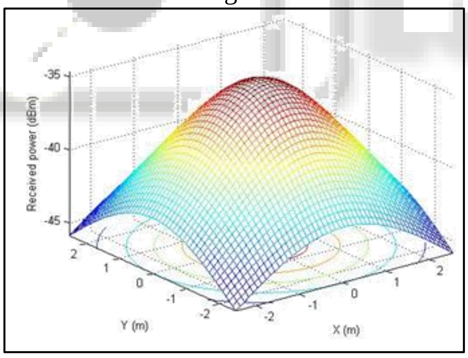

Fig. 6

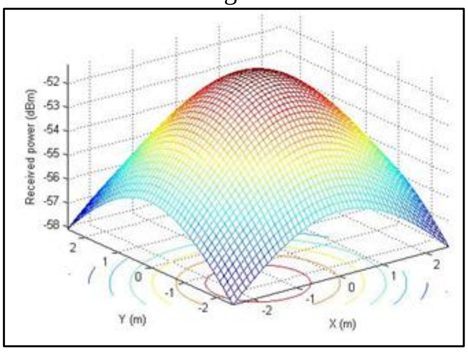

Fig. 7

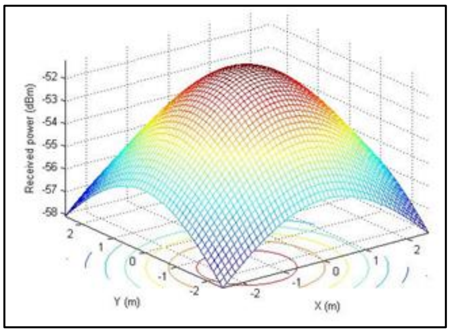

Fig. 8

Fig. 4 Received power distributions for various distances between Transmitter and Receiver in case of Single LED system.

In case of 1 meter minimum received power is -49.27 dBm while the maximum received power is -28.67 dBm. In case of 2 meter minimum received power is -45.9 dBm while the maximum received power is -34.67 dBm. In case of 2.5 meter minimum received power is -45.31 dBm while the maximum received power is -34.67 dBm and finally in case of 3 meters minimum received power is -45.09 dBm while the maximum received power is -38.2 dBm. The received power by receiver is also depends on lens and covered cone area. The power received by receiver mainly depends on the distance from the transmitter and cone angle. Because of variation in power the BER at the received also fluctuates. In the next section BER performance is highlighted.

III. BER PERFORMANCES

In this section BER performance is evaluated.

$$SNR = \frac{(RP_r)^2}{\sigma^2_{shot} + \sigma^2_{thermal}} \qquad (16)$$

$$\sigma^2_{shot} = 2qRP_rB + 2qI_BI_2B \qquad (17)$$

$$\sigma^2_{thermal} = \frac{8\pi\kappa T_k}{G_{ol}}C_{pd}AI_2B^2 + \frac{16\pi^2\kappa T\Gamma}{g_m}C^2_{pd}A^2I_3B^3 \qquad (18)$$

The received power at the receiver is very less at the corner of the room; therefore BER for the receiver at these locations will be very high.

$$\sigma^2_{ASE} = n_{sp}(G-1)h\nu B_0 \qquad (19)$$

In presence of ASE noise, SNR will be modified as

$$SNR = \frac{(RP_r)^2}{\sigma^2_{shot} + \sigma^2_{thermal} + \sigma^2_{ASE}} \qquad (20)$$

Finally, BER is given by

$$BER = 0.5erfc(\sqrt{SNR}) \qquad (21)$$

IV. SIMULATION RESULTS

Parameters	Value
Speed of Light	3×10^8 m/s
Theta	70^0

Total Transmitted Power	20 mW
Detector Physical Area	10^{-4} m^2
Distance between LED and ceiling	2.15 m
Gain of Optical filter	1
Refractive index of lens	1.5
FOV	60^0
Room Dimension	5×5×3 m^3 (L×L×H)

Table 2: Simulation Parameters

The entire ceiling is considered as receiver plane. The received power distribution is shown in Figure 4.

As LED is placed at the center of the room at the position (2.5 m, 2.5 m, 0) defining this as (x_L, y_L) and receiver can be located anywhere on the ceiling. Defining position of receiver as (x_R y_R) then the distance between LED and PD can be calculated as

$$d = \sqrt{(x_R - x_L)^2 + (y_R - y_L)^2 + H^2}\ , \quad (22)$$

Here 'h' is the height of the ceiling from LED position. Therefore, minimum distance between LED and PD is

$$d_{\min} = H \quad \text{And } d_{\max} = \sqrt{\frac{L^2}{4} + \frac{L^2}{4} + H^2} = \sqrt{\frac{L^2}{2} + H^2}\ . \quad (23)$$

Using room dimensions we get,

$d_{\min} = 3$ m And $d_{\max} = 3.91$ m .

The power received by PD at minimum distance is maximum and at the maximum distance received power is minimum.

Now considering position of LED as (2.5 m, 2.5 m, h m)

$$d = \sqrt{(x_R - x_L)^2 + (y_R - y_L)^2 + h^2}\ , \quad (24)$$

Here 'h' is the height of the ceiling from LED position.

In figure 5, probability of error vs. distance between LED and photo-detector is presented. As due to the variation in direct distance between LED and photo-detector power at various positions in the room varies. For a particular distance between LED and PD there is a min and maximum power available somewhere inside the room. We consider these two values in probability of error calculations. In the simulation experiment we found that the minimum received power is some ~10 nW, which is very less power thus obtained probability of error is very high. However, the maximum received power is ~µW, for lower distance between LED and PD, probability of error is less which increases with distance, and becomes un-acceptable when distance between LED and PD is more than 1.5 m.

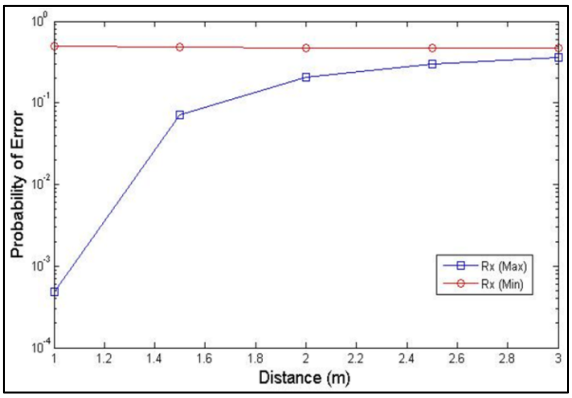

Fig. 5: Probability of Error for Various Values of Height h.

Thus, due to the non-uniform distribution of power, a significant variation in error probability is observed, which is not good for VLC. There are two solutions for this

1) Use amplification process by adding SOA in PD circuitry.
2) Apply array of LEDs and PDs for uniform illumination of light.

In this chapter, we have considered first approach; second approach will be discussed in next chapter.

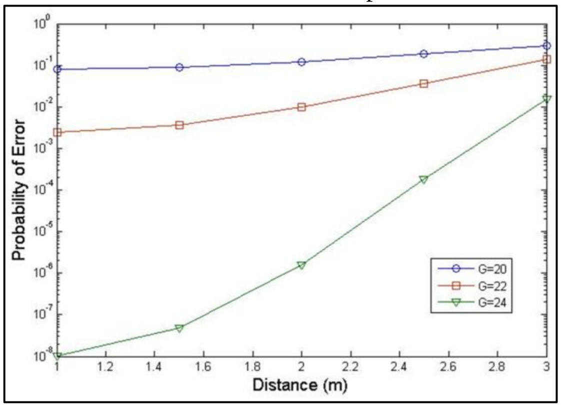

Fig. 6: Probability of Error for Various Values of Distance between LED and PD under Different SOAs Gains

However, a very good error performance can be obtained using SOAs. It is noted that each SOA can provide maximum gain of 30 dB. In case more than 30 dB gain is desired then array of SOA need to be used, which is again not a very effective solution.

V. CONCLUSIONS

In this paper a single LED and single PD based VLC system is simulated, and it has been found that due to the non-uniform power reception at various places in room a significant variation in error probability is observed. It is also shown that using SOAs in received circuitry probability of error can be significantly reduced.

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