Statistical analysis of SNR and optical power distribution in an indoor VLC System

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Abstract. VLC(Visible Light Communication) is a new and emanating technique which uses light for communication. For indoor wireless communications, it is considered as a promising scheme for both information bearing communication as well as illumination. It provides high data rate performance at reduced cost. The aim of this paper is the analysis of optical power distribution and signal to noise ratio in an indoor VLC system. Analysis of power distribution and SNR is done by changing the direction of LEDs. It is observed that the noise in the optical channel link between the LED and photodetector dominates the data transmitted. Finally, simulation results and various parameters affecting the performance of VLC is also studied.

1. Introduction

Alexander Graham Bell proposed a new concept of communication using light as a communication medium in the year 1880. With the help of a mirror Bell focused the sunlight proceeded by talking into a mechanism that vibrated the mirror. The vibrating beam was collected by the receiver and decoded back to voice signal. But Bell’s experiment failed as he was not able to generate a carrier frequency which is useful. Sunlight, fog and rain interfered Bell’s experiment and he stopped his experiments. In 1927, the invention of LEDs again introduced the concept of VLC that uses white LEDs and sends data at invisible speeds to human eyes by blinking lights [1].

The main advantage of VLC is that it can be used anywhere without any distortion and provides communication with high data rate [2]. In VLC, LED is used as a transmitter and photo diode or photo transistor as the receiver. The transmission medium operates in visible light spectrum. VLC can be used at very high bit rates for cable free communication [3]. One of the most important advantage of VLC is that there is no interference with RF signals. This application made VLC to be used at hospitals and space stations [4][5]. White LEDs can be used as a transmitter since it offers several advantages such as less power consumption, reliability, high brightness and long lifetime[6].

This paper is focused on the analysis of power distribution in a room using array of LEDs rather than a single LED so that maximum area is covered by the position of LEDs for reliable communication. The noise in the optical link between LED and detector affects the performance of VLC system[7]. The effect of SNR and order of Lambertion emission on received power is studied.
2. System Model
An indoor VLC system model (Multiple input multiple output) is considered in this paper as shown in Figure 1. The electrical signal at the LED transmitter is converted into optical intensity. At the receiver end, photodetector or photodiodes converts optical intensity into electrical signal. Two major limitations of communication through VLC that needs to be taken into consideration is:

- Inter-user interference
- The imperfect channel estimates resulting from users' mobility

![Figure 1. Basic Model of an indoor VLC system](image)

Three constraints have to be considered on input electric signal to meet the technical considerations of the VLC system [8]:

- At every transmitter or LED, input electric signal $y_n$ should be equal to a certain value $I_{DC}$ or DC-bias.

\[ E(y_n) = I_{DC}^n \]  \hspace{1cm} (1)

- At each LED transmitter, same brightness level can be imposed which implies that:

\[ I_{DC}^n = I_{DC}, \forall n \]  \hspace{1cm} (2)

- Each LED should operate in its linear dynamic range which implies that:

\[ I_L \leq y_n \leq I_U \]  \hspace{1cm} (3)

where $I_U$ is the upper bound and $I_L$ is the lower bound drive current of the LED in the linear range and $I_U > I_L > 0$. 

Figure 2. Ray diagram model

Figure 3. Direction of an LED

The communication between an LED and a receiver is shown in figure 2. The changing direction of an LED is shown in figure 3. At the transmitter side, it is assumed that the LEDs follow Lambertian radiation pattern. Hence, radiation intensity distribution is given as [9]:

\[
R_0(\phi) = \begin{cases} \frac{m+1}{2\pi d^2} \cos^m(\phi) & 0 < \phi \leq 90 \\ 0 & \phi > 90 \end{cases}
\]  

(4)

where \( m \) denotes the mode number of Lambertian radiation given as:

\[
m = \frac{-\log_2}{\log_e(\cos\phi_1)}
\]  

(5)

At the receiving end, the photodetector is assumed to have an active area \( A \), the optical signal received by the photodetector at an angle \( \phi \). Therefore, the effective collecting area of the receiver is given by:

\[
A_{\text{eff}} = \begin{cases} A\cos(\phi) & 0 < \phi \leq 90 \\ 0 & \phi > 90 \end{cases}
\]  

(6)

The channel gain between the LED and the photodetector can be modeled as:

\[
H(t) = \begin{cases} \frac{(m+1)}{2\pi d^2} \cos^m(\phi)T_s(\phi)G(\phi)\cos(\phi) & 0 < \phi \leq 90 \\ 0 & \phi > \phi_c \end{cases}
\]  

(7)

where:

- \( \phi \) = angle of incidence wrt the receiver
- \( T_s(\phi) \) = Optical Fiber gain

The average received power is defined as:

\[
P_r = P_t \times H(0)
\]  

(8)
The received power is given by the equation:

\[ P_r = \begin{cases} \frac{(m+1)}{2\pi d^2} P_t \cos^m(\phi)T_s(\phi)G(\phi)\cos(\phi) & 0 < \phi \leq 90 \\ 0 & \phi > \phi_c \end{cases} \]  

(9)

3. Signal-to-Noise (SNR) ratio analysis

Signal-to-noise ratio is analysed and explored at the receiving end in this section. In optical channel between the LED and the detector, the data transmitted is dominated by shot noise. The shot noise consists mainly of shot noises caused by signals plus thermal noise induced by intense ambient light.

Let us assume that the noises are AWGN(additive white gaussian noise).

The relation between electrical power S and SNR is denoted as:

\[ S = R^2 \times P_r^2 \]  

(10)

\[ \text{SNR} = S/N \]  

(11)

where:
- \( R \)=photodetector responsivity
- \( N \)=variances of all noises and interferences caused due to optical channel

The noise variance \( N \) is shot noise plus thermal noise which is given by[10]:

\[ N = \sigma_{shot}^2 + \sigma_{thermal}^2 \]  

(12)

The shot noise and thermal noise is defined as:

\[ \sigma_{shot} = 2qRP_rB + 2qI_BI_2B \]  

(13)

\[ \sigma_{thermal} = \frac{8\pi K T_k C_{pd}A I_2 B^2}{G} + \frac{16\pi^2 K T_k \prod T_k C_{pd} A^2 I_3 B^3}{g_m} \]  

(14)

where:
- \( R \)=photodetector responsivity
- \( B \)=electrical filter bandwidth
- \( I_B \)= Photocurrent
- \( I_2 \) and \( I_3 \)=Noise bandwidth factor
- \( K \)=Boltzmann constant
- \( T_k \)=Absolute temperature
- \( G \)=open loop voltage gain
- \( C_{pd} \)=Fixed capacitance of detector per unit area
- \( \prod \)=FET channel noise factor
- \( g_m \)=FET trans-conductance

Substituting equation (9) and (11) in equation (10). Eventually electrical SNR is given by:

\[ \text{SNR} = \frac{(R \times P_r)^2}{\sigma_{shot}^2 + \sigma_{thermal}^2} \]  

(15)
4. Results and Discussion

| Parameters                      | Values                                      |
|---------------------------------|---------------------------------------------|
| Room dimensions LxWxH           | 5mx5mx5m                                    |
| LED arrays                      | 4                                           |
| LEDs per array                  | 4x1                                         |
| LED dimension UxVxW              | (3,3,3)(3,4.5,3)(4.5,3,3)(4.5,4.5,3)cm      |
| LED spacing                     | 1.5 cm                                      |
| LED drive current lower bound I_L| 400 mA                                      |
| LED drive current upper bound I_U| 600 mA                                      |
| Photodetector responsivity R    | 0.4 A/W                                      |
| LED conversion factor c         | 0.44 W/A                                    |
| Bandwidth B                     | 10 MHz                                      |
| Photodetector Area A_PD          | 1 cm²                                       |
| Receiver’s Field of view $\theta_c$| 60°                                        |
| Optical concentrator refractive index q | 1.5                                   |
| Pre-amplifier noise density $i_{\text{amp}}$ | 5 pA/Hz$^{1/2}$                               |
| Background current $i_{\text{bg}}$ | 100 $\mu$A                                   |
| Noise bandwidth factor($I_2$ and $I_3$) | 0.562,0.0868                                 |
| Photo current $I_B$             | 100 $\mu$A                                   |
| Absolute Temperature            | 300 K                                       |
| Fixed capacitance of detector $C_{\text{pd}}$ | 1.12 $\mu$/m²                                |
| FET channel noise factor $\Pi$  | 1.5                                         |

Figure 4 shows the position of LEDs or transmitters on the ceiling of the room with the given dimensions in table 1. Figure 5 shows the 3-D plot of optical power distribution. It is observed that the peaks of the plot is yellowish in colour which represents maximum power is being received as the LEDs are positioned exactly at the top of it. Since square of the distance between LED and detector is inversely proportional to received power as shown in equation 8, as we move slowly from center to corners, the received power value slowly decreases.
Figure 6. SNR vs Angle of elevation

SNR vs angle of elevation is shown in figure 6. It can be investigated that SNR decreases with changing angle of elevation ranging from 50-60 degrees. To acquire higher SNR level, it is difficult to understand which angle will give better performance if only SNR level is considered.

Figure 7. Received power vs Angle of Elevation

Table 2. Pr for different values of angle of elevation

| Angle of elevation | Pr (W)  |
|--------------------|---------|
| 50°                | 0.373   |
| 60°                | 93.57   |
| 70°                | 186.16  |
| 80°                | 192.87  |
| 90°                | 174.77  |
Plot of received power vs Angle of elevation is shown in figure 7. It is analysed that there is an increase in received power for different angles of LEDs. After a certain point it starts decreasing due to greater distance between the LED and the photodetector. Different values of received power for different angles of elevation of LEDs is shown in table 2. The angle of elevation ranges from 50-90 degrees. Hence, SNR value has to be minimum in order to transmit data efficiently in an indoor VLC system.

The parameters for simulation result are set as $\theta_{1/2} = 60^\circ, G=3$, transmitted power $P_t=7.2$ W.

5. Conclusion
The visible light communication cannot be used outdoor due to distortion from sun light which is treated as Gaussian noise. It is analysed in this paper that received power increases as the angle of elevation of LEDs increases. But, SNR decreases as the angle of elevation increases. To acquire higher SNR, it is difficult to understand which angle gives better performance if only SNR is considered. It is better to use array of LEDs instead of single LED. This provides reliable communication due to maximum area covered by the transmitter.

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