Received Power Based Area Estimation for Indoor Visible Light Communication

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ABSTRACT: *This paper investigates the maximum area covered by single light emitting diode (LED) or multiple LEDs for indoor visible light communication on the basis of received power. The main aim of this research is to predict how to find the right location of LED's to provide minimum acceptable power in the receiver plane and number of LEDs required to cover the whole area of a room. The result showed that a single transmitter may cover 27.5m² area at a 5m height with the acceptable value of received power, $P_r = 1 \times 10^{-4}$mW The transmitter and receiver are line of sight (LOS).*

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1. Introduction

Recently, the rapid development of solid-state lighting (SSL), especially high-brightness light emitting diodes (LEDs), has attracted much attention and inspired significant research activities in indoor visible light communication (VLC) [1-7]. VLC refers to short range optical wireless communication using visible light spectrum from 380 to 780*nm*. Many researchers emphasize the potential of this technique to provide wireless communications and illumination simultaneously within the indoor environment.

Received signal strength (RSS) is a measure of the signal power detected at the receiver. The power diminishes with distance from the transmitter, and so the distance of the receiver from the transmitter can be calculated. Being mainly line of sight (LOS), the RSS attenuates according to a square law in free space. The received signal also does not suffer from constructive and destructive interference in indoor environment. Therefore, the optical RSS can be used as a relatively accurate distance measurement if the emitted power and beam pattern is known. Positioning accuracy can also be increased by using high resolution image sensors or by increasing the separation between the image sensors as proposed in [1]. If multiple LEDs are used to transmit signals, better performance can be achieved within a certain covered area and worse performance away from that area as shown in [2]. In this paper, we report a simulation program developed based on MATLAB R2012A which calculates the area of illumination distribution, distance between LEDs and number of LEDs required to cover the whole area of a room based on the minimum acceptable power of receiver.

This paper is organized as follows. Section II gives an overview on indoor optical wireless channel characteristics and power constrains of LED chips. Section III gives the parameters required to measure the received power at different locations of the room. Section IV and V provide the maximum covered area for a single LED and multiple LEDs, respectively. Finally, results of our investigations are summarized and major conclusions are drawn in Section VI.

2. Optical Wireless Channel

If the transmitter and receiver are in the LOS environment, performance varies greatly depending on the distance between transmitter and receiver and the receiving angle of the photo diode (PD) [3]. The most viable modulation scheme for free space optical is intensity modulation (IM) with direct detection (DD). The received signal can be modeled according to the expression below [7]:

$$y_r(t) = R\,H(t) * x(t) + w(t) \tag{1}$$

where $y_r(t)$ is the received signal, R is responsivity of the PD, $x(t)$ is the transmitted optical signal, $H(t)$ is the channel response, $w(t)$ and is channel noise.

In this paper the value of received power is calculated to study the relation between distance and signal quality by using a single source and multiple sources.

The average transmitted power is.

$$P_t = lim_{T\to\infty}\left(\frac{1}{2T}\int_{-T}^{T} x(t)\,dt\right) \tag{2}$$

And the average received power is given by

$$P_r = H(t)_{LOS} \,.\, No_{LED} \,.\, P_t \tag{3}$$

No_{LED} denotes the number of LEDs, $H(t)_{LOS}$ is channel impulse response, and

$$H(0) = \begin{cases} \dfrac{(m+1)A}{2\pi d^2}\, cos^m(\phi)\, g(\psi)\, cos(\psi), & 0 \le \psi \le \psi_c \\ 0, & \psi < \psi_c \end{cases} \tag{4}$$

where d is the distance between the receiver and the transmitter, m is order of lambertian emission, A is receiver area, ϕ is the irradiance angle, ψ is the angle of incidence, $g(\psi)$ is the gain of the optical concentrator, ψ_c and is the field of view (FOV).

$$g(\psi) = \begin{cases} \dfrac{n^2}{sin^2\psi_c} & 0 \le \psi \le \psi_c \\ 0, & 0 \ge \psi_c \end{cases} \tag{5}$$

where n is the refractive index.

The FOV basically depends on the design of the receiver, usually ≤ 90degrees. The narrower FOV will result in a higher gain that is suitable for directed links.

From equations (3) and (4)

$$P_r = \frac{(m+1)A}{2\pi d^2}\, cos^m(\phi)\, g(\psi)\, cos(\psi)\, P_t\, No_{LED} \tag{6}$$

Let constant value C

$$C = \frac{(m+1)A}{2\pi}\, cos^m(\phi)\, g(\psi)\, cos(\psi) \tag{7}$$

From equations (6) and (7);

$$P_r = \frac{C}{d^2}\, P_t\, No_{LED} \tag{8}$$

Equation (8) is the simplest form to show the relation between received and transmitted power, with distance.

3. Received Power

We assume the physical parameters for developing the simulation program. The size of the office room is 10m × 10m × 5m and the LEDs are installed on the ceiling; the height of desk is not defined and the receiver is placed on the working plane (the bottom surface in the room model is shown in Figure 1). The other simulation parameters are listed in Table 1.

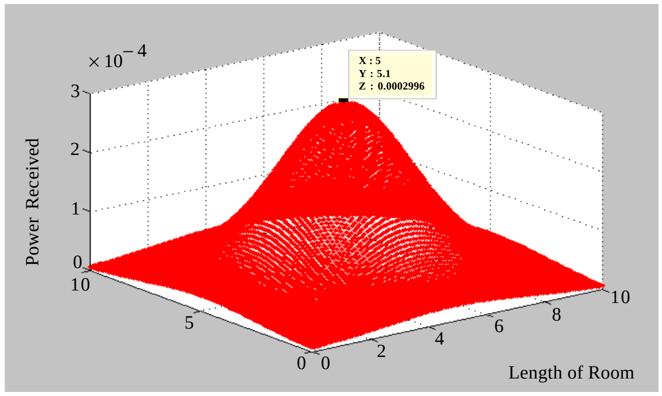

Figure 1. Received power with single LED

The distribution of illuminance at a working plane is discussed. It is assumed that the source of emission have a lambertian radiation pattern. The lambertian emission means that the light intensity emitted from the source has a cosine dependence on the angle of emission with respect to the surface normal as discussed in [4]. To survey the illuminance distribution of LEDs system, we assume two configurations for LED position on the ceiling. In case of one transmitter, the position is the center of the ceiling, and for multiple transmitters the transmitters are located at equal distances as can be seen in Figure 2. At the shortest distance R_{min}, maximum power is received. As the receiver moves away from the nearest location the received power will be decreased.

Parameters	Values
Transmit power	120 mw
Dimension of room (*m*)	L = 10,W = 10, H = 5
Area of Receiver	7.854E – 005
Location of Tx	[5, 5, 5]
Location of Rx	[x, y, 0]
Receiver FOV	60°
FOV of detector	Rx_FOV * pi / 180
Order of Lambertian *m*	4

Table 1. The Parameter for Simulation

Received power and brightness varied with the different modulation techniques, transmit power, and the number of LEDs. The shadowed area represents a received power greater then $1 \times 10^{-4} mW$ as shown in figure 2.

Multiple LED's footprint can overlap each other and increase the brightness in the room.

As shown in Figure 1 we need to calculate the radius of LED footprint. For this purpose, we measure the minimum and maximum distances. Distances can be calculated from equations (9) and (10),

$$R_{(min)} = \sqrt{\frac{C}{P_{r\,(max)}} P_t \, No_{LED}} \tag{9}$$

$$R_{(max)} = \sqrt{\frac{C}{P_{r\,(min)}} P_t\, No_{LED}} \quad (10)$$

On the basis of the minimum received power which is acceptable for the receiver the coverage area can be measured.

As shown in Figure 3, there are four boundaries of received power. The smallest boundary shows the maximum power level $P_r \geq 3 \times 10^{-4}\, mW$ and the second boundary shows $P_r \geq 2 \times 10^{-4}\, mW$. The 3rd and 4th boundaries cover more area of the room, and the received power levels are $P_r \geq 1 \times 10^{-4}\, mW$ and $P_r \geq 1 \times 10^{-5}\, mW$ respectively. This implies that the minimum power receivers occupy the maximum area of the room.

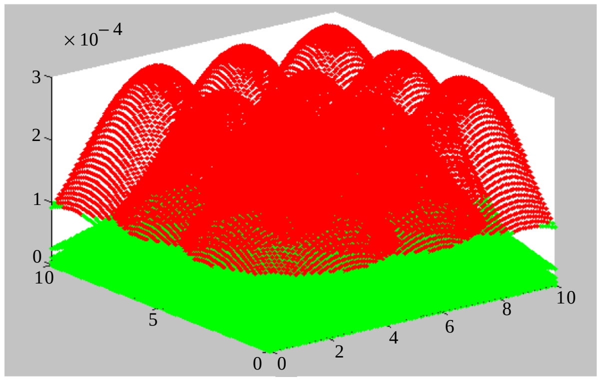

Figure 2. Multiple LED received power

4. Covered Area

Using established environment for typical VLC system we measure the area of the LED footprints. The covered area can be measured between the minimum distance R_{min} to the maximum distance R_{max}. The area can be calculated as follows;

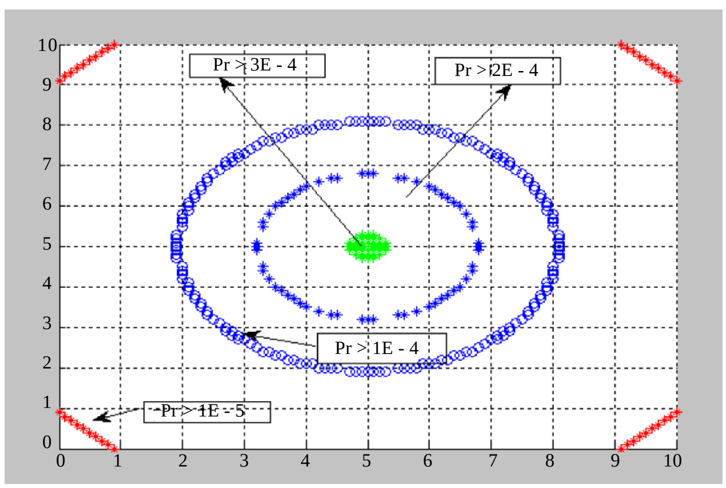

Figure 3. Boundaries of received power

Taking square of equations (9) and (10) then subtract equation (9) from (10)

$$P_{r\,(min)} - P_{r\,(max)} = CP_t\, No_{LED} \left(\frac{1}{R^2_{max}} - \frac{1}{R^2_{min}} \right)$$

$$R^2_{min} - R^2_{max} = \frac{(P_{r\,(min)} - P_{r\,(max)})}{CP_t\, No_{LED}} R^2_{max}\, R^2_{min}$$

Substituting values of $P_{r\,(min)}$, $P_{r\,(max)}$ and multiplying π both sides of the equation results in;

$$Covered\ Area = \pi\,(R_{max}^2 - R_{min}^2) = \pi\,R_{adius}^2 \qquad (11)$$

where $R_{adius}^2 = R_{max}^2 - R_{min}^2$

Figure 4 is simulated at $P_{r\,(min)} = 1 \times 10^{-4} mW$ in the room. The shadowed area represents the power greater than or equal to $P_{r\,(min)} = 1 \times 10^{-4} mW$. In this figure the location of the transmitter is varying from (5, 5, 1) to (5, 5, 9).

The result shows that the covered area may increase at some range of distances, and after reaching at a certain level it decreases with the distance.

As shown in Figure 5, the covered area changes from $7.5m^2$ to $27.7m^2$ by varying the height of the transmitter from $2m$ and $5m$ the acceptable power for receivers is $1 \times 10^{-4} mW$. As we increase the height, from $6m$ to $9m$, the covered area decreases from $28.7m^2$ to $0m^2$. The intensity of light also decreases on the surface and its covered area shrinks.

To estimate the right location of LED to cover the maximum area of the room we have simulated the system at different received power levels in Figure 6. Figure 6 plots the relation between covered area, distance of transmitter and receivers at different received power levels.

It shows that the lower receiving power sensitivity receivers can cover more area of the room. Moreover, distance is the main factor on which covered area is dependable.

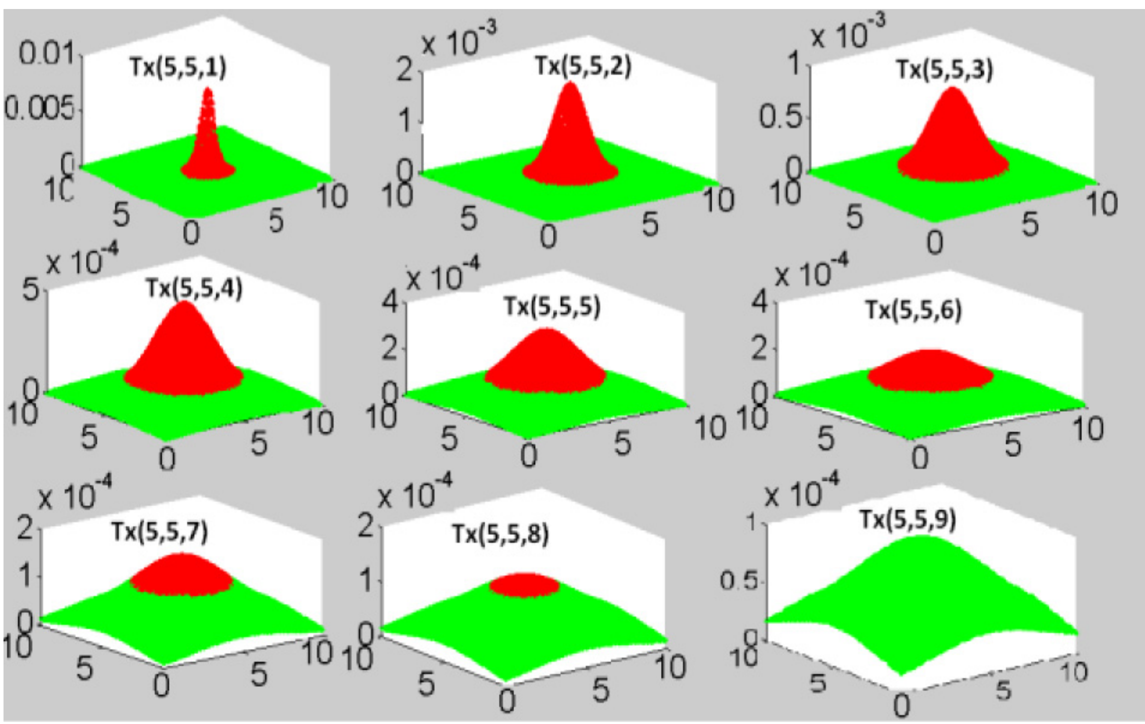

Figure 4. Distance between transmitter and receiver is 1 to 9m

5. Multiple LEDs

Multiple LEDs can improve the covered area for receivers once we find the right location (*x*, *y*, *z*) and the area of a single LED. Covered area can be increased by the number of LEDs. If one LED can cover $28m^2$ area of the room then two LEDs can cover double of this area. This is how we can cover the whole receiver's area of the room as shown in Figure 7.

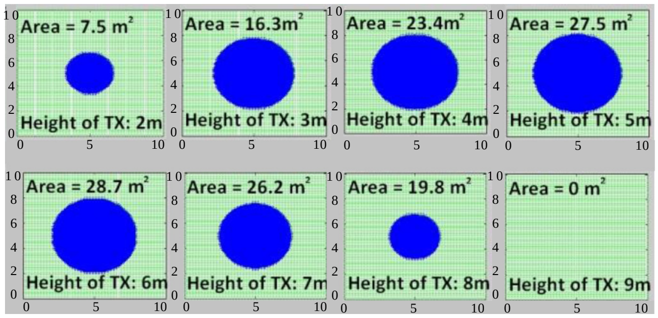

Figure 5. Footprints of LED

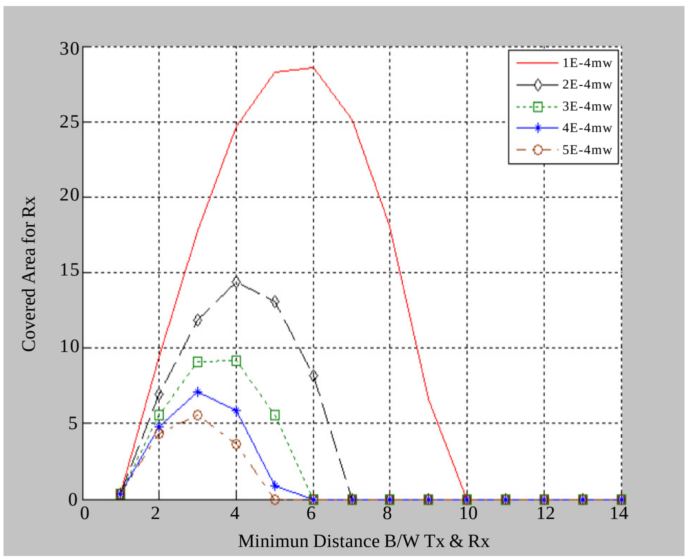

Figure 6. Covered area and distance

$$Area\ Covered\ by\ n\ LEDs = \sum_{n=1}^{LED} \pi R_n^2 \quad (12)$$

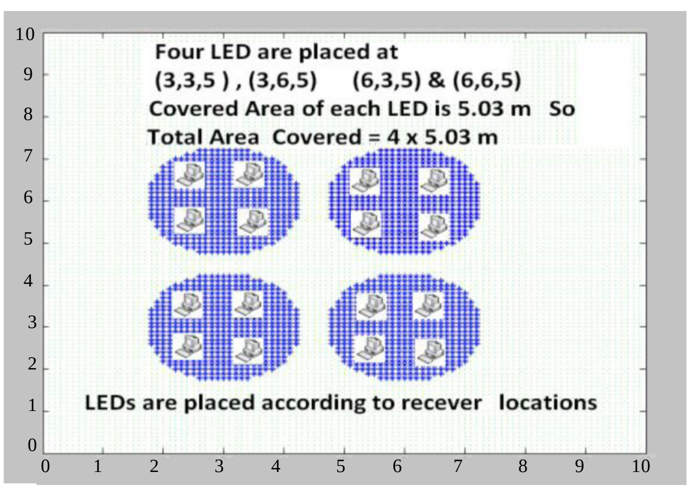

Figure 7. Multiple LED footprints

Equation (12) is only for a specific condition when footprints of all LED's should not overlap each other, and all are placed at the same height and transmitting the same power.

The covered area is also dependent on distance between LEDs. If the LEDs are close enough the images will overlap to each other and this will reduce the covered area of the room.

If we need to cover the whole area of the room as shown in figure 8, multiple LEDs must be placed close-by in large proportions so that the entire area of the room is covered. As can be seen in this figure, multiple LEDs are placed near one another and the area covered by an individual LED is assumed to be a circle of area πR^2. The minimum distance between two LEDs is chosen to be such that the shadows (assumed to be circles) overlap each other and cover an overlapping area defined by:

$$Over\ Lap\ Area = 4\{2R^2(\pi - 2)\} \tag{13}$$

By placing multiple LEDs at this minimum distance ($R\sqrt{2}$– *where R is the radius of one LED image*) the total area of the room can be covered as is indicated by:

$$Area = \sum_{n=1}^{LEDs} N_{LED} * 2 * R^2 \tag{14}$$

and as shown in figure 8. This total area is equal to the sum of all individual LED areas subtracted by the sum of all overlap areas. Usually the shape of a room is either square or rectangle, therefore through these results the number of LEDs required to cover the whole area of a room can be measured as shown in figure 9.

Figure 9 is simulated from equation (14) at different acceptable power.

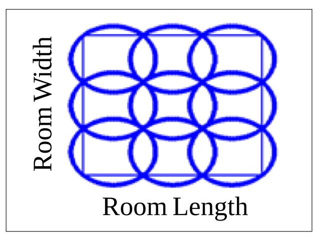

Figure 8. Minimum overlap to cover whole area of room

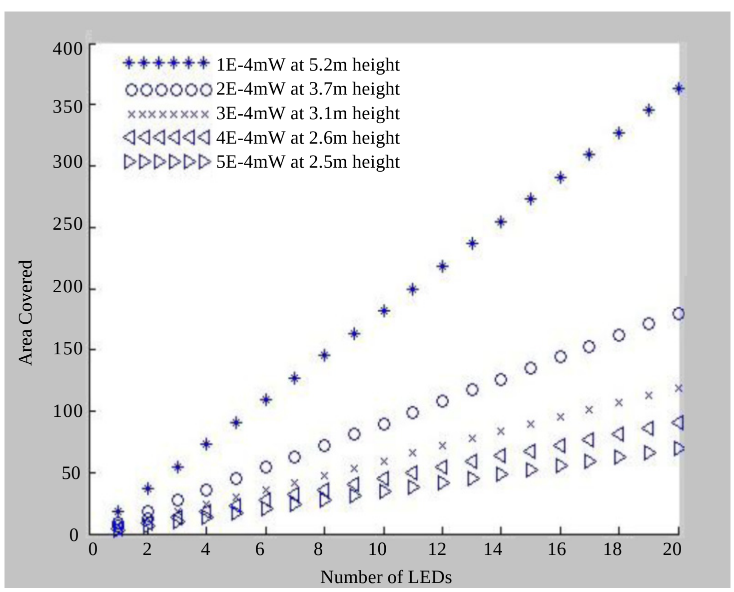

Figure 9. Covered area of Multiple LED

6. Conclusion

In this paper, we have reported the simulation program for indoor visible light communication environment based on MATLAB. The simulation results indicate that by increasing the distance of light source the footprint or covered area increases but power decreases. Therefore, the covered area is dependent on two factors namely distance and acceptable power of the receivers. Therefore a relation between covered area and number of LEDs can be devised.

All the simulations in this paper are based on distance, received power, number of LEDs, and covered area as given in equations (8), (14) and (11). Figure 4 and Figure 5 are simulated at $P_r = 1 \times 10^{-4} mW$ and conclude that the transmit power is more concentrated at a shorter distance but covers less area as compared to higher distances covering larger area. Figure 3 and Figure 6 are simulated received power levels, and conclude that the minimum acceptable power can cover more area of the room. For a distance larger than the minimum receiver sensitivity, power drops according to equation (8), as a result of which covered area shrinks, as is evident from Figure 6. Figure 8 and figure 9 shows the minimum distance between LEDs and number of LED required covering whole area of room.

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