Practical Optic Design of Illumination Coverage for Indoor Visible Light Communications

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***Abstract*— Practical issues including LED choices, concentrators, and assembling an optical lens and a photodetector have significant impacts on an optical wireless communication link. This paper studied behaviors of the illumination coverage of an indoor VLC. Firstly, effect of diffuse lens is investigated. Array of LEDs with diffuse lens of three different degrees, namely 15, 30, and 60 degree are employed in the experiment at three distinct distances—2, 2.5, and 3 m. Secondly, calculation of the maximum radius of the LED array at the transmitter is discussed in details. Finally, at receiver side, a photodetector is attached with two types of concentrators: bi-convex and hemispherical lens. Based on all of our experimental results concerns and recommendation were provided for link design of indoor visible light communications.**

Keywords*— Visible light communications, LED, non-imaging, illumination, LED choices, concentrators, optical lens, photodetector, bi-convex, hemispherical lens, link design, coverage area.

I. INTRODUCTION

In indoor visible light communications (VLC), it is vital to design a system to provide users with promising quality of signal strength throughout a room. Therefore, a coverage area is an important issue that needs a proper design and implementation.

Development of the indoor optical wireless LAN system requires fulfillment of crucial communication parameters encompassing data rates, coverage and mobility. In [1] researchers from HHI reported that the coverage area of their system was 90 square feet with a data speed of 100 Mbps. In addition, an aspect of uniform illumination is also important. In [2] diffuse lens was employed to give as much uniform illumination as possible. However, practical optic design of illumination coverage has not been addressed in the literature in indoor visible light communications. Some work was proposed in illumination and display areas such as [3][4].

In this paper behaviors of the illumination coverage of the indoor VLC link arranged in a specific configuration are studied. Details of the optic design including angle degrees of diffuse lens and the maximum radius of LED arrays at the transmitter, concentrators, and concentrators and assembling the optical lens and the photodetector at the receiver are explored. This work focuses on the effect of diffuse lens and concentrators for a practical low cost prototype; therefore, passive optic diffuse lens and concentrators that are cost-effective are opted.

The remainder of this paper is organized as follows. Section II describes an analog front-end part of the indoor visible light communication link and revisits some principles of illumination that are related to this study. In Section III, important issues of practical optic design are studied and discussed. Conclusions are drawn in Section IV.

II. BACKGROUND

The background of the VLC system and theory of illumination are described in details.

A. System

The indoor visible light communication link consists of the analog front-end part which is mainly optoelectronic parts, and digital circuit modules which are normally implemented over a field-programmable gate array (FPGA). In this paper only the analog front-end modules are focused. Figure 1 depicts the basic setup which is composed of driving circuit, an array of LEDs and diffuses lens, concentrators, photodiode, and a resistor load.

B. Theory of Illumination

Based on the method proposed in [3], we can arrange the LEDs so that the uniform illumination system can be achieved. The minimum LED-to-LED separation distance can be obtained from Sparrow's criterion [4].

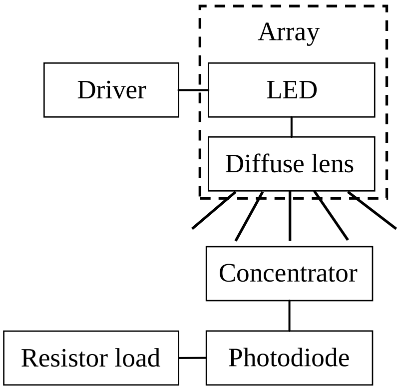

Fig. 1. Basic block diagram of the indoor visible light communication link, mainly focusing on the analog front-end part.

The radiation pattern of a single LED yields the Lambertian distribution. When the LED is considered as a point source, the distribution of radiation from the LED in a cosine function is given as follows:

$$E(r,\theta) = E_0(r)\cos^m \theta \tag{1}$$

where θ denotes the viewing angle, $E_0(r)$ is the irradiance on axis at distance r from the LED, and m is a value that indicates the relationship of light intensity from LED at various angles relative to the center line. For any perfect Lambertian source $m = 1$. The value of m depends on the angle $\theta_{1/2}$ which is the angle at the light intensity reducing to a half of its maximum intensity in a straight line, and is given by

$$m = \frac{-\ln 2}{\ln(\cos\theta_{1/2})} \tag{2}$$

For the simplest case of two LED sources, the maximum distance d_{max} between adjacent LEDs for the uniform illumination can be expressed as [4]

$$d_{\max} = \sqrt{\frac{4}{m+3}}z \tag{3}$$

where z is the distance from the LED to a detector. It is noted that the maximum distance d_{max} can result in the uniform illumination at the screen. Another parameter is the maximum radius r_{max} of circular ring LED arrays including totally four LEDs with radius r for the uniform illumination which can be computed by [4]

$$r_{\max} = \sqrt{\frac{4}{m+2}}z \tag{4}$$

Similarly, the maximum radius of the circular ring distance can create the flat illumination at the screen.

C. Theory of concentrator

For the VLC system, a photodiode with a large area can detect more optical power. Increasing photodiode area is increase capacitance of photodiode and it is expensive. The concentrator can increase the effective area of a receiver. The optical gain of concentrator is given as follows [5]:

$$G(\phi) = \frac{A_{eff}(\phi)}{A\cos(\phi)} \tag{5}$$

where ϕ denotes the angle of incidence, $A_{eff}(\phi)$ is a photodiode area, A is a detector physical area.

III. PRACTICAL OPTIC DESIGN

In this section practical aspects of the optic design including choices of LED diffuse lens, the maximum radius of LED arrays, concentrators, and assembling the optical lens and the photodetector are explored in order to gain insights into impacts of the optic implementation on the indoor optical wireless communication link. The study focuses on effect of diffuse lens and concentrators in practical non-industrial assembly.

The whole demonstration of the experiments consists of both a transmitter and a receiver. From Fig. 1 the transmitter module includes arrays of high-power LEDs and diffuse lens as well as other components, such as driving circuits, heatsinks, and cooling fans. The receiver is composed of the concentrator, the PD, and a resistor load. The transmitter has a white linear array of eight LEDs with an LED-to-LED horizontal spacing gap of 3.0 cm and the vertical spacing gap of 4.0 cm along, as shown in Fig. 2

A. Effect of diffuse lens at the transmitter

In Fig. 3, measurement of the LED luminance is demonstrated. In this experiment, Luxeon LXML-PW21 is chosen and the number m of LEDs from Eq. (2) is m=1. LED was driven by electric current of 650 mA. LED diffuse lens of various degree, that is 15°, 30°, and 60° for light distribution, are selected in this study. The illumination distribution was measured by a light meter which was Digicon LX70 at three different distances 2.0 m, 2.5 m and 3.0 m away from LEDs.

Fig. 4 shows the illumination distribution from the rectangular array of eight LEDs shown in Fig. 2.

For indoor scenario such as office and home, a distance between a source and a user module is about 2.5 m, so the illumination distribution at a distance of 2.5 m is illustrated in Table 1.

Table 1 shows the comparison of suitable illumination for an office use which requires 500 Lux and uniform distribution. The 60° LED diffuse lens for each of eight LEDs are assembled as shown in Fig. 3.

Fig. 2. *Experimental setup for LED illumination*.

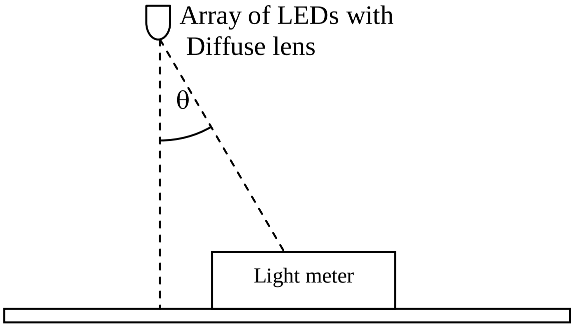

Fig. 3. Diagram of illumination measurement at any degree from the direct line.

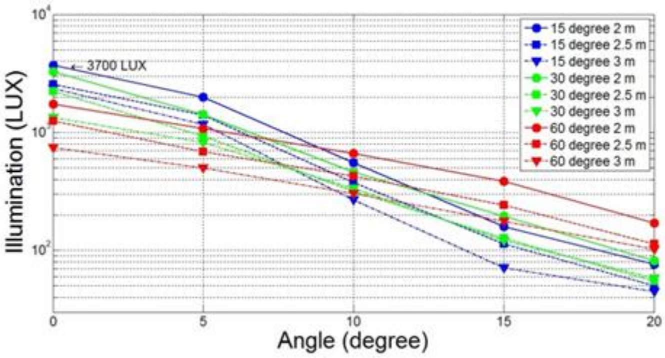

Fig. 4. Illumination distribution in case of 15°, 30°, and 60° diffuse lens.

TABLE I. ILLUMINATION IN CASE OF DIFFUSE LENS WITH THREE DIFFERENT ANGLES

Angle from direct line (degree)	Illumination according to diffuse lens with specific angle (Lux)		
	15°	30°	60°
0°	2552	2222	1248
5°	1401	930	690
10°	377	317	425
15°	114	127	241
20°	50	55	113

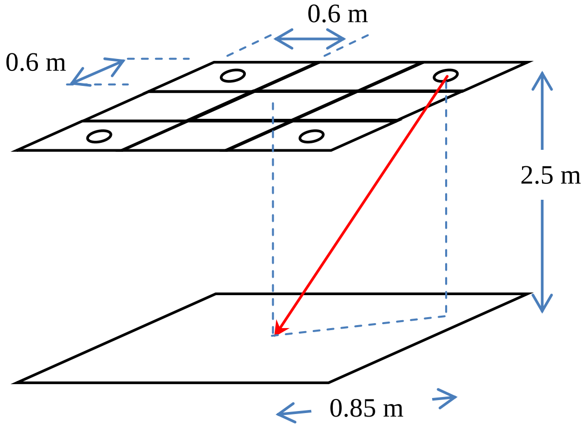

Fig. 5. The layout of the LED sources in the room.

B. *Calculation of the maximum radius of LED arrays at the transmitter*

Fig. 5 show that illumination minimum position is a halfway between four LED modules, which from the distance of each LED lights in a horizontal direction is 0.85 m. A degree between the distances from the high ceilings to user is 19.5°. We estimated the illumination from each LED by 20° from Table 1 is 113 Lux.

Considering the module of 8 LEDs, it have m=181 from Eq. (2). We can find maximum radius of four LEDs circular ring from Eq. (4), r approximately 37 cm. The LED module must be arranged shapes to installation in the office for uniform illumination because the distance from module to module is very narrow space for use. We can improve the configuration of the LED module in indoor environment by some techniques including increasing LED distribution or tilting each LED to achieve better uniform light distribution.

C. *Effect of Concentrators at the receiver*

The demonstration of the receiver consists of the photodiode PD (S6968, Hamamatsu) with integrated lens, lens, and module of four LEDs with 60° LED lens. It is noted that in this experiment the configuration and the number of LEDs are different to those in the subsection of the effect of diffuse lens. The photodiode was connected in series with a resistor of 100 Ω and a voltage reverse bias is 20 V. A focusing lens was used to focus the light to the PD. We use the lens of two types: convex lens (LB1723, D = 50.8, mm f = 60 mm: Thorlabs) and hemisphere lens (KPA034-. C, D = 32.5 mm, f = 23 mm: Newport). We set the light source from four LED (LXML-PW21) with 60° LED placed 1 meter apart from PD. The angle θ of the LED and PD was adjusted from 0°, 5°, 10°, 15°, and 20° respectively, as show in Fig. 6.

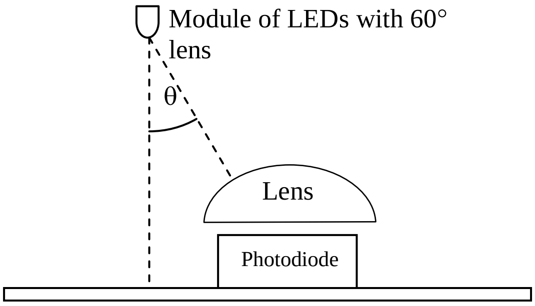

Fig. 6. Diagram of light measurement by photodiode at θ°.

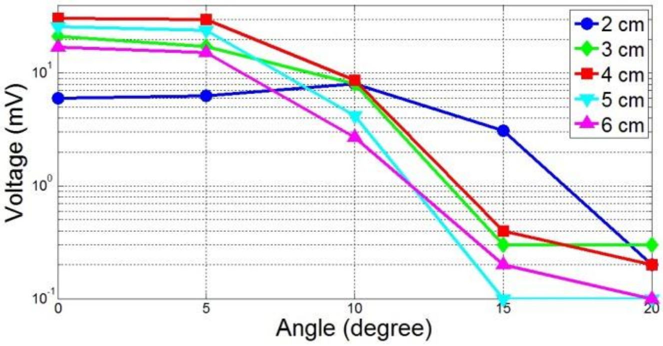

Fig. 7. An average signal intensity in term of the voltages across a resistor versus an angle of the LED and the PD in case of a convex lens.

Fig. 7 shows how an average signal intensity in term of the voltages across a resistor varies according to an angle of the LED and the PD in case of a convex lens for focusing the beam.

Likewise, the voltages across the resistor were altered comparing to the angle of the LED and the PD in case of a hemisphere lens as illustrated in Fig. 8.

Fig. 7 and 8 show the voltage measurement between 0 and 20 degree. From the result we should use hemisphere lens because it has uniform illumination better than convex lens at wide angle and hemisphere lens smaller than convex lens, making it suitable for practical use. The distance between lens and PD is 2.5 cm in order to make a wide-angle detection leading to the large coverage area.

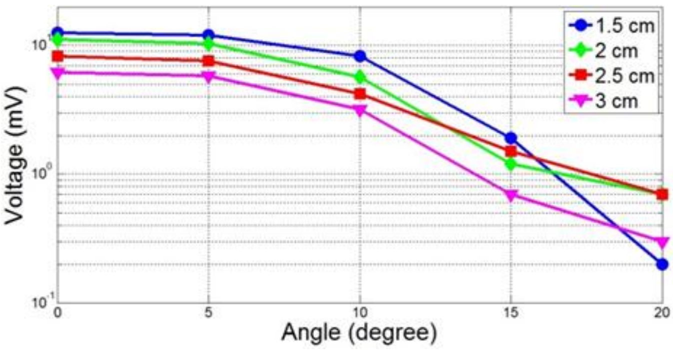

Fig. 8. An average signal intensity in term of the voltages across a resistor versus an angle of the LED and the PD in case of hemisphere lens.

IV. CONCLUSIONS

Overall, this paper presents the study of illumination coverage design for our VLC setup in indoor environment. Considered as a special case, our work focuses on low cost design which is different from the other existing configurations. The light distribution with 60 degrees lens is the most suitable for indoor illumination, but to ensure the uniform distribution more distribution and tilting of LEDs are recommended. Furthermore, at the receiver the hemispherical lens are suggested to employ in the system with the best allowable gap of 1.5 cm from the PD.

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