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A Study of LED Lumination Uniformity with Mobility for Visible Light Communications

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Abstract—**this paper investigates the requirements for uniform illumination using white LEDs, showing the balance between lighting and visible light communications. The communications system performance of the is also investigated for mobility with a varying field of view at the receiver, showing that there is a limit that beyond which there are no longer gains to be made in mobility.**

Keywords-Luminance; mobility; optical wireless communications, visible light communications, LED;

I. INTRODUCTION

A common facet throughout modern life that is often taken for granted is the artificial lighting. Almost all homes and offices require illumination in one form or another. Since the first successful test of Edison's carbon filament incandescent light bulb in 1879 that lasted 13.5 hours, engineers have been striving to increase the lifespan, luminance and efficiency of such devices. 1962 saw the first practical demonstration of the first gallium arsenide (GaAs) visible light (red) light emitting diode (LED) using the semiconductor technology. The early LEDs were very expensive not very bright and who's only practical applications were found in indicator lights and seven segment displays. Modern indium gallium nitride (InGaN) high brightness LEDs now boast superior lighting, lifespan and efficiency characteristics over the traditional incandescent and fluorescent lights, and has been firmly set as their future replacements [1].

Besides illumination, it has long been known that LEDs are well suited for optical communication systems (OCS). In 1976 the first high-brightness LEDs where created specifically intended for OCS. Therefore the inevitable communion of the two technologies, combining illumination with OCS was fist postulated in Japan back in 2000 [2]. Indoor visible light communications (VLC) systems employ the white LED fixtures as the primary source of artificial illumination within a room; whilst simultaneously performing data transmission by means of optical wireless communications (OWC). Power in such communication systems isn't an issue due to the high (ISO) luminance standard of 300 to 1500 Lux throughout the room [3].

The majority of research carried out in VLCs tends to concentrate on increasing data rates [4-7], however these incline to take into account the luminance uniformity and communications mobility. Uniformity is important for both luminance and data communication in order to avoid bright and dark areas as well as achieving a uniform signal-to-noise ratio (SNR) throughout the coverage area. Mobility is also an important issue as this defines the communications coverage of wireless systems.

In this paper we present a numerical evaluation of the illumination within a room using white LEDs lighting located in set positions on the ceiling. The luminance is assessed for uniformity throughout the room, whilst a single detector pointing up towards the normal of the transmitter is moved all around the receiving plane (RP). For each lighting configuration the VLC system is gauged for the received power and mobility. Set receiver field of view (FOV) angles are tested for each configuration and compared to show a compromise between lighting, FOV and VLC mobility.

II. ROOM MODEL

The room measures $5\times5\times2.85$ m^3 (width, breadth and height). The walls are all white, have a constant reflection coefficient throughout and are modeled as the first order Lambertian source. There are nine evenly spaced LED transmitters located in the ceiling. In order to analyze the effect of room lighting on VLC, all of the transmitters are initially placed in the centre of the ceiling and moved out evenly towards the walls along the lines of symmetry from the centre (see Fig. 1) through ΔL meters. The RP where all measurements are conducted is located 0.85 m above the floor at the desk level.
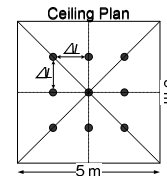

Fig. 1 Ceiling plan for the LED array layout (LED array = dark spots)
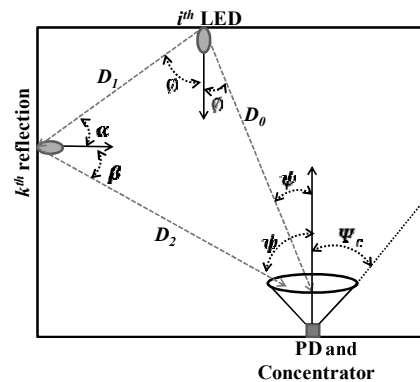
A. Luminance of LED Lighting

Fig. 2 Lighting and received communications power model

Fig. 2 represents the model for the received power from both LOS and reflected beams. The luminous intensity for the LED transmitter is given by [8]:

$$I(\emptyset) = \frac{m+1}{2\pi} I(0)\cos^m(\emptyset), \tag{1}$$

where $I(0)$ is he centre luminous intensity of an LED, $\emptyset$ is the angle of irradiance and m describes the lambertian order of the LED based on the half power angle [8]. The horizontal luminance E_{hor} at point (x,y) along the RP through the line of sight (LOS) path is given by :

$$E_{hor} = \frac{I(\phi)}{D_0^2} \cos(\psi), \tag{2}$$

The reflected power after the first bounce the power is given by [9]:

$$dD = \rho \frac{m+1}{2\pi^2} \frac{I(0)\cos^m(\phi)\cos(\beta)\cos(\alpha)\cos(\psi)}{D_1^2 D_2^2} dA_{wall,} \tag{3}$$

where dA_{wall} represents the small reflective area of the wall, and ρ represents the reflection coefficient of the reflective area. Thus the total luminance from the first reflection is garnered through integrating over the entire reflecting surface and summing over all LED sources, i.e.

$$E_{hor_{ref}} = \sum_i \int_{wall} dD_i, \tag{4}$$

where i indicates the index of the LED transmitter. In order to quantify the uniformity of the luminance levels for this paper, we are normalizing the variance of the light levels defined as:

$$U_L = \frac{\sigma_L^2}{\mu_L^2}. \tag{5}$$

where σ_L^2 is the variance, and μ_L is the mean of the luminance power.

B. Received Optical Power

For an OWC link the LOS DC gain $H(0)$ is given by [10]:

$$H(0) = \begin{cases} \frac{(m+1)A}{2\pi D^2}\cos^m(\phi) T_s(\psi) \\ g(\psi)\cos(\psi), & 0 \le \psi < \Psi_c \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

where A is the physical size of the active area on the detector, $T_s(\psi)$ is the gain of the optical filter and $g(\psi)$ is the gain of the optical concentrator, and Ψ_c denotes the FOV of the optical concentrator. The gain of the optical concentrator $g(\psi)$ is given as [11]:

$$g(\psi) = \begin{cases} \frac{n^2}{\sin^2(\Psi_c)}, & 0 \le \psi < \Psi_c \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

where n denotes the refractive index of the optical concentrator. Similarly the DC gain after the first bounce or reflection is given as [12] :

$$dH_{ref}(0) = \begin{cases} \frac{(m+)A}{2\pi^2 D_1^2 D_2^2}\rho dA_{wall}\cos^m(\phi)\cos(\alpha) \\ \cos(\beta)T_s(\psi)g(\psi)\cos(\psi), \\ \qquad\qquad 0 \le \psi < \Psi_c \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

Hence the received power P_{Rx} can be calculated from the LOS and reflected DC gains and optical transmit power P_{Tx}, given by:

$$P_{Rx} = \sum_i\{P_{Tx}H(0)_i + P_{Tx}\int_{wall} dH_{ref}(0)_i\}. \tag{9}$$

III. NUMERICAL RESULTS

All the parameters required for the simulations are given in Table 1. Each of the lighting configurations where primarily tested for luminance uniformity throughout the RP. The configurations are then considered for VLCs with the receiver FOV (half angle) between 5 and 50°. As mobility is an important factor in OWCs, the percentage of connectivity is analyzed throughout the RP.

TABLE 1: SIMULATION PARAMETERS

Parameters	Value
LED half power angle ($\Phi_{1/2}$)	70 (deg)
Number of LEDs per transmitter array	40
Optical power per LED	200 (mW)
Centre luminous intensity per LED ($I(0)$)	80 (lm)
Rx detector area	$15e^{-6}$ (m²)
Concentrator half FOV (Ψ_c)	5 to 50 (deg)
Concentrator refractive index (n)	1.5
Optical filter gain ($T_s(\psi)$)	1
Room dimensions (width, depth and height)	$5 \times 5 \times 2.85$ (m³)
RP height	0.85 (m)
Wall reflection coefficient (ρ)	0.7
LED array pitch step size (ΔL)	0.25 (m)

A. Luminnace and Luminance Uuniformity

Fig. 3 demonstrates the uniformity of the luminance power footprint throughout the RP from the LOS and a single bounce from the walls as the LED lighting fixtures spread out from the centre of the ceiling along the lines of symmetry with pitch ΔL meters. As the lighting fixtures spread out towards the walls the footprint uniformity increases. Whilst all the LED transmitters are situated in the centre of the room ($\Delta L=0$m) the maximum luminance recorded is 1.926 kLux, whereas when the LED transmitters are situated closest to the walls ($\Delta L=2.25$m) the maximum luminance recorded is 587 Lux. Both satisfy ISO standards although the difference in brightness levels for the first case will be very perceptible to people in comparison to the latter.
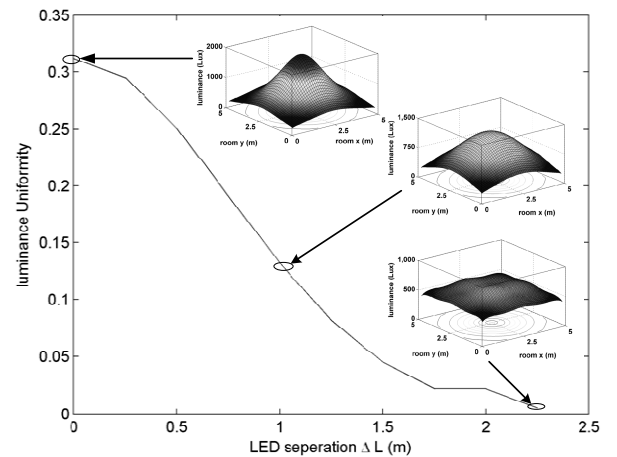

Fig. 3 Luminance uniformity throughout the RP for each configuration

B. VLC Connectivity

Fig. 4 represents the mobility of a VLC system under the varying lighting configurations and the receiver FOV. Here the mobility is defined as the percentage of the RP where the received power is greater than or equal to the receiver sensitivity (-36 dBm). The results show that as room luminance uniformity increases, so does the mobility. A more interesting artifact to come from the analysis is the gain in mobility with respect to the receiver FOV. For all lighting configurations it has been shown that a limit is reached whereby increasing the FOV provides little or no gain in mobility. Therefore increasing the FOV beyond this point will only result in increased noise power through ambient sources and reducing the signal to noise ratio of the communications signal.
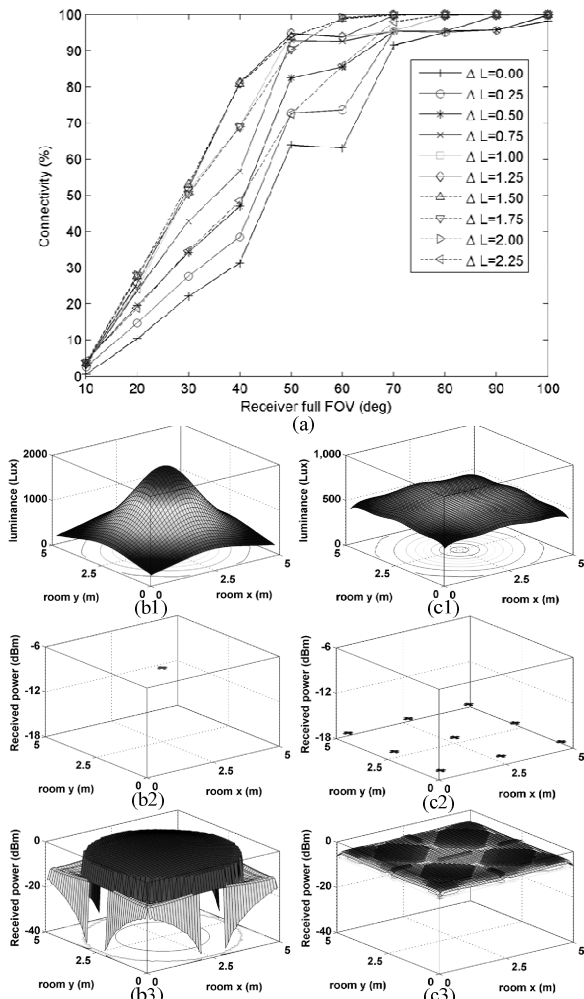

Fig. 4 (a) VLC connectivity percentage throughout the RP; (b1) luminance footprint ΔL=0 m, (b2) received power FOV_{Rx} (full) =10°, (b3) Received power FOV_{Rx} (full) =100°; (c1) luminance footprint ΔL=2.25 m, (c2) received power FOV_{Rx} (full) =10°, (c3) received power FOV_{Rx} (full) =100°.

IV. CONCLUSION

The simulation results presented has demonstrated that uniform illumination throughout the room using LED sources for lighting can be closely achieved however at the cost of the maximum luminance power. Thus to achieve higher brightness in conjunction with uniformity, either the number of LEDs used or the power has to be increased. Concerning the communications aspect of VLC, uniform luminance is preferred for mobility. The FOV of the receiver has also been shown to be a critical selection factor for mobility. In each of the cases studied a FOV is reached to which any increase offers no further gains in mobility.

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