A MATLAB-based simulation program for indoor visible light communication system

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Abstract—**We report a simulation program for indoor visible light communication environment based on MATLAB and Simulink. The program considers the positions of the transmitters and the reflections at each wall. For visible light communication environment, the illumination light-emitting diode is used not only as a lighting device, but also as a communication device. Using the simulation program, the distributions of illuminance and root-mean-square delay spread are analyzed at bottom surface.**

I. INTRODUCTION

Due to fast-growing demand of high-speed data transport and mobility, wireless communication is very important technology in our lives. Recently, the indoor wireless communication technology using light-emitting diodes (LEDs) is a new research field [1-3]. Using LEDs, there are a lot of advantages in viewpoints of lighting and wireless communication:

- The lighting equipment with LEDs is easy to install, nice looking and safe for human eye.
- The LED lighting can be equipped with various shapes which were difficult with traditional lightings such as incandescent bulbs and fluorescent lamps.
- The low cost, low electric power consumption and long life expectancy are the considerable advantages.
- The possibility of high-speed data communication is the indispensable characteristic for using LED infrastructure for lighting as communication devices.

From these advantages, it is expected that the indoor optical wireless communication using LEDs will be used widely in the near future.

The fundamental physical characteristics and problems of wireless communication using LEDs are studied and researched by many labs, for example, impulse response [3,4], optical power distribution [5,6], bit error ratio (BER), signal-to-noise ratio (SNR), and shadowing [8], reflection [9], feasibility of communication link [10-12], the way to enhance date rate [13,14], modeling a cluster of LEDs as a directional point source according to the LED radiation pattern, arrangement of LEDs, and the number of LEDs, the far-field condition and the precise optical model of LED radiation have been reported in [15].

In this paper, we report a simulation program developed based on MATLAB and Simulink which calculates the illumination distribution, RMS delay spread, and received signal waveform considering the positions of the transmitters and the reflections on walls.

This paper is organized as follows. In Section II, the modeling of physical structure is described. Section III describes the illuminance performance and Section IV describes the root mean square (RMS) delay spread for our system model. Finally, our conclusion is given in the section V.

II. MODELING OF OPTICAL CHANEL

We assume the physical parameters for developing the sinmulation program. The size of the office room size is 5m x 5m x 3m and the LEDs are installed on the ceiling; the height of desk is 0.85 m and the receiver is placed on the working plane (the bottom surface in the room model shown in Fig. 1). The other simulation parameters are listed in Table 1.

TABLE I. SIMULATION PARAMETERS.

Semi-angle at half power	30 [deg]
Center luminous intensity	0.73 [cd]
Number of LED each group	3600 (60x60)
Field of view	50 [deg]
Reflection coefficient	0.8

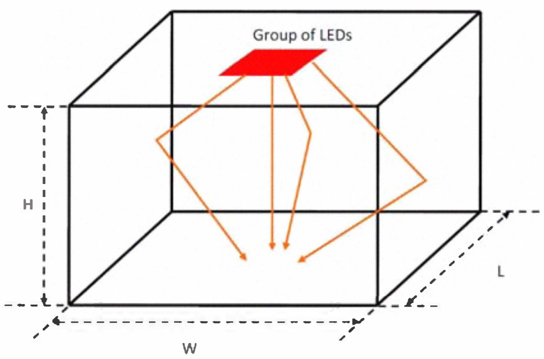

Fig. 1. Indoor visible light communication environment.

The distribution of illuminance at a working plane is discussed. It is assumed that the source of emission and the reflected points on wall have a Lambertian radiation pattern [1, 6, 7]. 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. Following the function for an optical link [1, 5-10], the luminous intensity in angle ϕ is given by:

$$I(\phi) = I(0)\cos^m(\phi) \quad (1)$$

Where *I(0)* is the center luminous intensity of the group LEDs, ϕ is the angle of irradiance, m is the order of Lambertian emission and is given by the semi-angle at half illuminance of the LED $\phi_{1/2}$ as:

$$m = -\ln 2 / \ln(\cos\phi_{1/2}) \quad (2)$$

A horizontal illuminance E_{hor} at a point (x,y,z) on the working plane is given by :

$$E_{hor}(x,y,z) = \frac{I(0)\cos^m(\phi)}{D_d^2 \cdot \cos(\psi)} \quad (3)$$

Where D_d is the distance between transmitter and receiver, ψ is the angle of incidence.

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 four transmitters the transmitters are located at the position like Fig. 2.

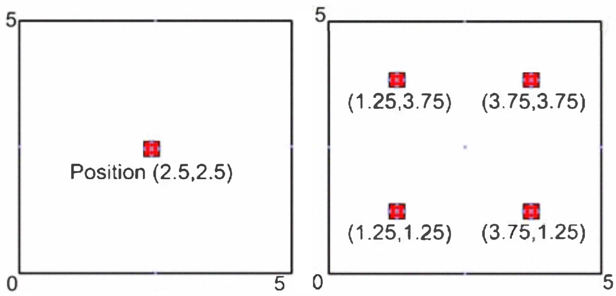

Fig. 2. The position of transmitters on the ceiling.

We used MATLAB2007R program to develop the simulation program. First, the program calculates the direct illumination, and the reflected illumination for one or plural transmitters with Lambertian radiation pattern (the results are given by many previous researches [6, 7]). Also, the program calculates the RMS delay spread for this effect.

III. ILLUMINANCE PERFORMANCE

The distribution of illuminance of our system is shown in figure below:

Fig. 3 shows the illuminance with 1 transmitter, the semiangle at half power is 30 degree. The maximum value of luminous flux in the center is 768.10 lx. Fig. 4 below shows the distribution for 4 transmitters with the semiangle of 30 degree. The performance of LEDs with narrow field of view is shown in here. It opens a chance for improvement LEDs with the wide field for illuminance. The value is in the range from 62.80 to 803.91 lx. The average value is 371.53 lx.

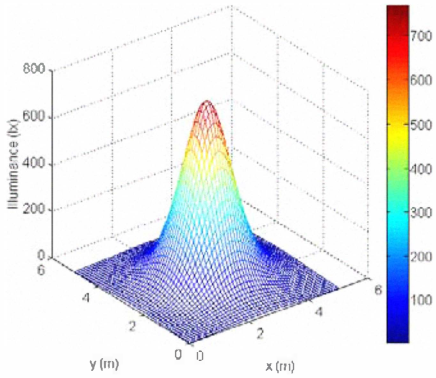

Fig. 3. Distribution of illuminance in case of one transmitter. Maximum value= 768.10 lx.

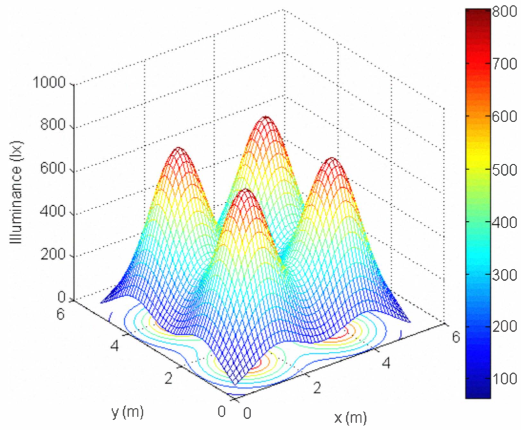

Fig. 4. Illuminance distribution incase of 4 transmitters with the LED semiangle of 30 degree. Max= 803.91 lx; Min= 62.80 lx; Avarage= 371.53 lx.

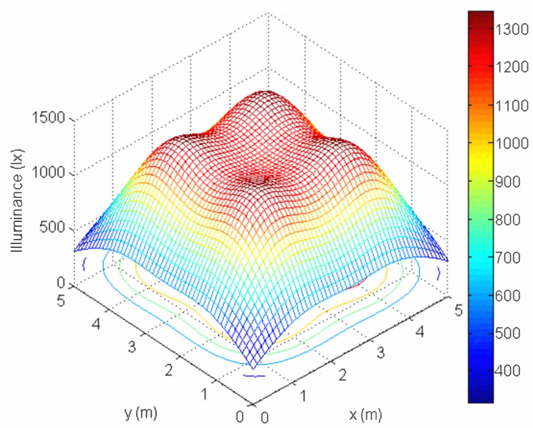

Fig. 5. Distribution of illuminance with 4 transmitters with the LED semiangle of 70 degree. Max= 1342.50 lx; Min=315.90 lx; Average=958.11 lx.

Fig. 5 is given for comparing our study with previous researches [6, 7]; the numerical calculation in illuminance distribution of our system at the semiangle of 70 degree is shown in here. All of parameters are same.

According to the standardized by International Organization for Standardization (ISO), the illuminance of this system is from 300 to 1500 (lx), it is sufficient for office work.

In our case, we assume that the reflections at the reflected point have Lambertian patterns. After calculation (including direction, reflection with Lambertian pattern) and comparing with the illuminance without Lambertian pattern at reflected points, the value is larger than 10.8 % (in the same conditions) in case of four transmitters.

IV. ROOT MEAN SQUARE DELAY SPREAD

The term of RMS delay spread is the standard deviation (or root-mean-square) value of the delay of reflections. Considering both the direct path and the first order reflected path, the received optical power at a point can be calculated by dividing the reflection walls into points of reflections as follows:

$$P_r = \sum^{LEDs}\left\{P_t \cdot H_d(0) + \sum^{reflections} P_t \cdot dH_{ref}(0)\right\} \quad (4)$$

P_t is the optical power transmitted from an LED, $H_d(0)$ is the channel DC gain on directed paths, which is given in [5-9] as

$$H_d(0) = \begin{cases} \dfrac{(m+1)A}{2\pi D_d^2}\cos^m(\phi)T_s(\psi)g(\psi)\cos(\psi), & 0<\psi<\Psi_c \\ 0 & \psi>\Psi_c \end{cases} \quad (5)$$

$T_s(\psi)$ is the gain of an optical filter, and $g(\psi)$ is the gain of optical concentrator. ψ is the angle of incidence. Ψ_c denotes the width of a field of vision at a receiver. The optical concentrator $g(\psi)$ can be given as

$$g(\psi) = \begin{cases} \dfrac{n^2}{\sin^2(\Psi_c)} & 0 \le \psi \le \Psi_c \\ 0 & \psi > \Psi_c \end{cases} \quad (6)$$

n denotes the refractive index.

$dH_{ref}(0)$ is the channel DC gain on reflection points [5-9] and is given as:

$$dH_{ref}(0) = \begin{cases} \dfrac{(m+1)A}{2\pi D_1^2 D_2^2}\rho dA_{wall}\cos^m(\varphi)\cos(\alpha)\ldots \\ \quad \times \quad \cos(\beta)T_s(\psi)g(\psi)\cos(\psi), & 0<\psi<\Psi_c \\ 0 & \psi>\Psi_c \end{cases} \quad (7)$$

Where D_1 is the distance between an LED and a reflective point, D_2 is the distance between a reflective point and a receiver, ρ is the reflectance factor, dA_{wall} is a reflective area of small region, α is the angle of incidence to a reflective point, β is the angle of irradiance to the receiver.

With M direct paths from transmitters to a specific receiver and N reflection paths to the same receiver, the total power of the received optical signals is calculated as

$$P_T = \sum_i^M P_{d,i} + \sum_j^N P_{r,j} \quad (8)$$

Where $P_{d,i}$ is the received optical power of a direct light at the i^{th} point and $P_{r,j}$ means the received optical power of a reflected light at the j^{th} point. M denotes the number of components for direct light and N denotes the number of components for reflected light.

The RMS delay spread provides an estimate for a kind of normalized delay time due to multiple reflections. Therefore, the RMS delay spread will be a critical performance criterion for the upper bound of the data transmission rate.

The mean excess delay is defined [16] to be

$$\bar{\tau} = \left(\sum_i^M P_{d,i}t_{d,i} + \sum_j^N P_{r,j}t_{r,j}\right)\Big/P_T \,. \quad (9)$$

$t_{d,i}$ is the propagation time for the i^{th} direct light $P_{d,i}$ and $t_{r,j}$ is the propagation time of the j^{th} reflected light $P_{r,j}$.

The RMS delay spread τ_{RMS} is given by:

$$\tau_{RMS} = \sqrt{\overline{\tau^2} - (\bar{\tau})^2}\,, \quad (10)$$

where

$$\overline{\tau^2} = \left(\sum_i^M P_{d,i}{t_{d,i}}^2 + \sum_j^N P_{r,j}{t_{r,j}}^2\right)\Big/P_T \,. \quad (11)$$

It is noted that the RMS delay spread depends on the relative levels of optical power components within P_T.

Fig. 6 shows the distribution of RMS for one transmitter. The maximum value is 3.2 ns (nanosecond), the minimum is 0.86 ps. Fig. 7 shows the distribution of

RMS for one transmitter. The maximum value is 3.57 ns the minimum is 0.17 ns.

It is accepted that the maximum bit rate that can be transmitted through the channel without needing an equalizer will be limited as follows [11, 16]

$$R_b \le 1/(10 \times \tau_{RMS}) \quad (12)$$

Therefore, it is estimated that the maximum data rate from Eq. (9) will be limited to 28 Mb/s considering whole bottom surface.

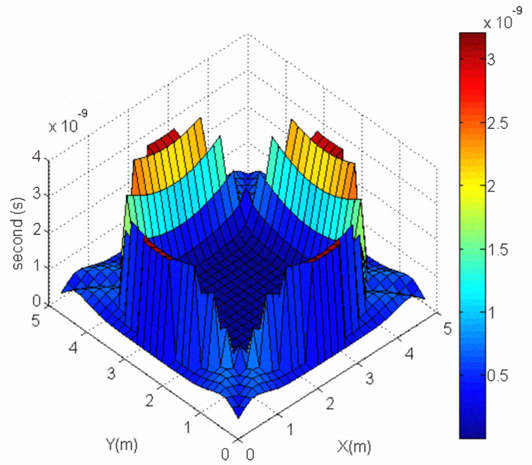

Fig. 6. Distribution of RMS delay spread for one transmitter. The position of the transmitter is (2.5, 2.5) with the LED semiangle of 30 degree.

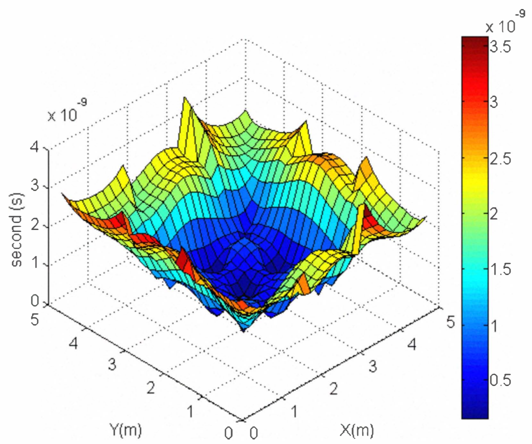

Fig.7. Distribution of RMS delay spread for four transmitters. The positions of the transmitters are (1.25, 1.25), (1.25, 3.75), (3.75, 1.25), (3.75, 3.75) with the LED semiangle of 30 degree.

Fig. 8 shows the RMS delay spread performance at some sample points. The RMS delay spread of system at some specific points in case 4 transmitters usually larger than the value in case 1 transmitter. The main reason is the multipaths of light for four transmitters.

TABLE II. SAMPLE POINTS, FOLLOWING THE CUTTING PLANE (2.5, Y, Z) ON THE CARTESIAN'S COORDINATE.

point	Co-ordinate
1	(2.5,0.5)
2	(2.5,1.0)
3	(2.5,1.5)
4	(2.5,2.0)
5(centre)	(2.5,2.5)
6	(2.5,3.0)
7	(2.5,3.5)
8	(2.5,4.0)
9	(2.5,4.5)

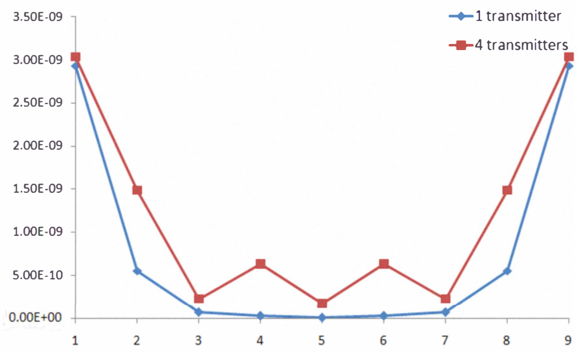

Fig. 8. RMS delay spread at several sample receiver positions.

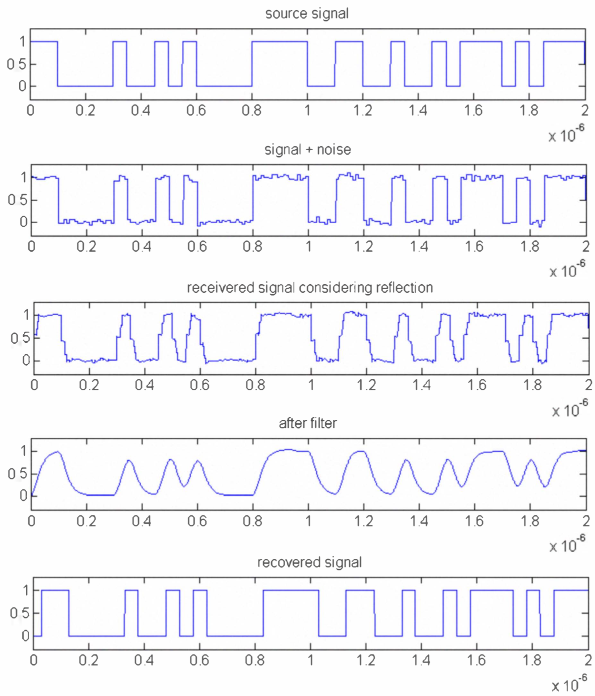

Fig. 9. Waveforms from the simulation using MATLAB/Simulink. The transmitted signal is in the NRZ-OOK modulation format. The bit rate is set to be 20Mbps.

Fig. 9 shows the simulation for NRZ-OOK modulation format using MATLAB/Simulink. The noise components from ambient light sources are implemented based on the measurements in [17]. The waveform calculation considering reflections with Lambertian pattern at the reflection points are displayed. The simulation program needs to be upgraded by implementing the various physical parameters including the size of active area, the responsivity, the noise components in the photodetectors, the asymmetric reflections on walls, and various advanced modulation formats.

V. CONCLUSION

In this paper, we have reported the simulation program for indoor visible light communication environment based on MATLAB and Simulink. The program considered first-order reflections at each wall. Using the simulation program, the distributions of illuminance and RMS delay spread were analyzed at bottom surface. Also, the waveforms for NRZ-OOK have been demonstrated. It is expected to be upgraded with more realistic physical parameters and various advanced modulation formats.

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