LEDs Location Optimization in the Indoor MISO VLC System

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Abstract: An optimal light emitting diodes (LEDs) location approach applied in the indoor multiple-input single-output (MISO) visible light communications (VLC) system is introduced in this paper, which considers the requirements of indoor illumination effect and communication performance simultaneously. By choosing the objective function with the linear combination of the standard deviation of illumination and the bit error rate (BER) of the MISO VLC system, the optimal 4 LEDs location over the ceiling can be reached. Computer simulation results verify the effectiveness of the proposed approach.

I. Introduction

In recent years, the research works of visible light communications (VLC) have been developed rapidly, especially under the circumstances of indoor communications [1~4]. Due to the difference with some traditional indoor wireless communication systems, it should meet the illumination demand first, and then the VLC function is appended to fulfill the indoor communications requirement. In many previous studies, it can be found that these two aspects of demands are always discussed respectively without effective combinations [2,3], which may reduce the performance of the VLC.

Therefore, an objective function combining the standard deviation of illumination and the bit error rate (BER) of the VLC system is introduced to evaluate the overall performance. At the same time, an indoor multiple-input single-output (MISO) environment is considered, where the transmitters are located at the ceiling of a 5x5 square meters room with 3 meters height. Based on the proposed objective function, the optimal location of the transmitting light emitting diodes (LEDs) can be calculated, which ensures both the illumination and communications needs.

The remains of the paper are arranged as follows. The system model is given in Section II with some traditional VLC settings and environments. The proposed approach based on the novel objective function is discussed in Section III. To evaluate the illumination and communications performances, computer simulation results are shown in Section IV, compared with some traditional method. At last, Section V concludes the whole paper.

II. System Model

In the VLC researches within these years, it can be regarded as a kind of alternative access scheme used for wireless communications, especially under the indoor circumstance. In the following, to simplify the analyses, it is assumed that the indoor communication environment is a 5x5 square meters room with 3 meters height. The transmitting LEDs are located at the ceiling, and the receiving device or receiving terminal is on the table with 0.85 meter height, which are traditional assumptions in the researches [1].

In the analyses thereafter, the Lambertian radiant intensity model [1] is used for the LEDs transmission model, which can be expressed as

$$I(\Phi) = I(0)\cos^m \Phi , \tag{1}$$

where $I(\Phi)$ is the radiant intensity corresponding to the irradiance angle Φ, $I(0)$ is the central radiant intensity of LEDs array, and m is the order of Lambertian emission corresponding to the transmitter semi-angle $\Phi_{1/2}$ as [1]

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

Then the illumination at a certain point in the room can be calculated by [1]

$$E(\Phi,\Psi) = \frac{I(0)\cos^m \Phi \cos\Psi}{d^2} , \tag{3}$$

where $E(\Phi,\Psi)$ is the illumination value at a certain receiving point corresponding to the irradiance angle Φ and the incidence angle Ψ, and d is just the line of sight (LOS) route distance between the LEDs transmitter to the receiver on the table. In the ISO standard, the indoor office illumination value should be within 300~1500 lx [4].

At the same time, when the VLC is applied for indoor communications, we can use the BER to evaluate the communication performance. In this study, based on the indoor VLC system model, it can be assumed that the power of the receiving signal is composed of those from the line-of-sight (LOS) channel and from the non-line-of-sight (NLOS) with once reflection from the ceiling, the wall or the floor in the room. So the receiving power P_{rx} at a certain receiver can be written as

$$P_{rx} = (P_{LOS} + P_{NLOS}) \cdot T_f(\Psi) \cdot g(\Psi) , \tag{4}$$

where P_{LOS} and P_{NLOS} are the receiving power from the LOS channel and NLOS channel, respectively; $T_f(\Psi)$ is the

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transmission coefficient of the optical filter, and $g(\Psi)$ is the concentrator gain.

At the receiver, besides the influences introduced by the channel effects in (4), the receiving visible light will also be polluted by some additive noise whose variance is

$$\sigma_n^2 = \sigma_{shot}^2 + \sigma_{amplifier}^2 , \tag{5}$$

where σ_n^2 is the overall noise variance, σ_{shot}^2 and $\sigma_{amplifier}^2$ are the shot-noise variance and the amplifier noise variance, respectively. While the shot-noise variance σ_{shot}^2 is defined by

$$\sigma_{shot}^2 = 2qR\left(P_{rx} + P_n\right)B_n , \tag{6}$$

where q is the electron charge, R is the photodiode responsivity, P_n is the noise power of the ambient light, and B_n is the noise bandwidth with

$$B_n = I_2 R_b , \tag{7}$$

while I_2 is the noise-bandwidth factor and R_b is the transmission data rate.

In (5), the amplifier noise variance $\sigma_{amplifier}^2$ is defined by

$$\sigma_{amplifier}^2 = i_{amplifier}^2 B_a , \tag{8}$$

where $i_{amplifier}$ is the amplifier noise current and B_a is the amplifier bandwidth.

Based on the analyses above, the signal-to-noise ratio (SNR) at the receiver can be calculated as follows

$$SNR = \frac{\left(RP_{rx}\right)^2}{\sigma_n^2} . \tag{9}$$

And according to the selected VLC modulation scheme, the corresponding BER can be reached.

In this study, we first give some performances under a simple indoor VLC circumstance, which considers that only one LED is placed at the central of the ceiling. The simulation parameters and settings are given in Table 1. Fig.1 and Fig.2 show the illumination and BER performances, respectively. From these figures it can easily be found that the illuminations at four corners are far less than those within the central part of the room, and also the BERs at four corners are much higher than in the central, which are not ideal results for indoor VLC.

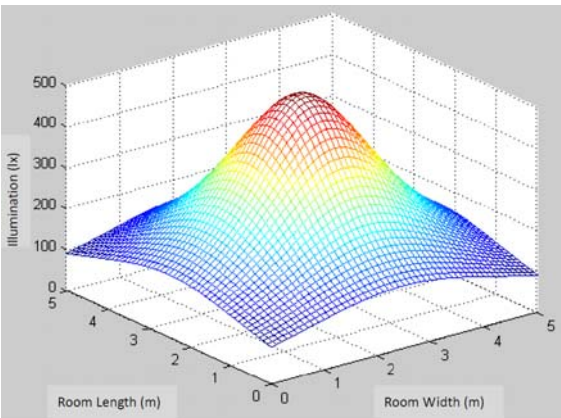

Fig.1. Illumination Distribution with One LED at the Center of the Ceiling

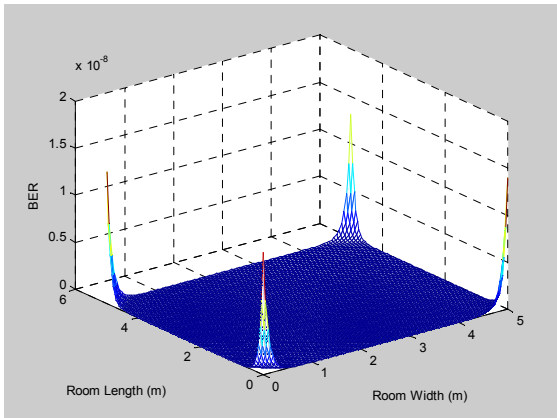

Fig.2. BER Distribution with One LED at the Center of the Ceiling

Table 1. Simulation Parameters and Settings

Room Size	5m*5m*3m
Amplifier Bandwidth	50MHz
Single LED Power	0.02W
Semi-angle at Half Power of LED	70°
Number of LEDs per Array	60*60
Floor Reflectivity	0.15
Wall Reflectivity	0.7
Ceiling Reflectivity	0.8
Field of View (FOV) at the Receiver	140°
Detector Physical Area of PD	$0.5cm^2$
Photodiode Responsivity (R)	0.4
Amplifier Noise Current	50mA
Noise Power of the Ambient Light	2W
Noise-bandwidth Factor	0.562
Transmission Coefficient of the Optical Filter	1
Central Radiant Intensity of LEDs Array	0.14cd
Electron Charge	$1.6*10^{-19}c$
Modulation Scheme	OOK

III. Novel Approach of LEDs Location Optimization

To overcome the problems with just one LED in last Section, some research works have also been carried out [3,4], but they did not consider the performances of illumination and BER at the same time. So in the following, a novel objective function is proposed to realize the optimization in both aspects.

To increase the average SNR and reduce the average BER at the receiving plane, we consider to place four LEDs at the ceiling. At the same time, to compensate the weak illumination at the room corners, suppose the localization of four LEDs is as shown in Fig.3, where one of the room corners is set as the coordinate origin, and four LEDs are set rolling-symmetrical relative to the ceiling center.

From the requirement of indoor environment, it is obvious that the illuminations at each point on the receiving plane should be uniform and it should avoid the scene in Fig.1. So we choose to use the standard deviation at the receiving plane to evaluate the uniformity of illumination, that is

$$\sigma_E(x_0,y_0)=\sqrt{D_E(x_0,y_0)}=\frac{1}{S}\iint_{\substack{0\le x\le 5\\0\le y\le 5}}\left[E(\Phi,\Psi)-\bar{E}\right]^2 dxdy\,, \tag{10}$$

where $\sigma_E(x_0,y_0)$ is the illumination standard deviation corresponding to the first LED location with its coordinate (x_0,y_0) in Fig.3, $D_E(x_0,y_0)$ is the illumination variance, S is the area of the receiving plane, and $\bar{E}$ is the mean value of the illumination $E(\Phi,\Psi)$ over the receiving plane, while the incidence angle Ψ can be written as a function of certain receiving point (x,y) at the receiving plane, and then the integration in (10) can be calculated accordingly. It can be found that a uniform illumination can be reached when $\sigma_E(x_0,y_0)$ in (10) reaches its minimum.

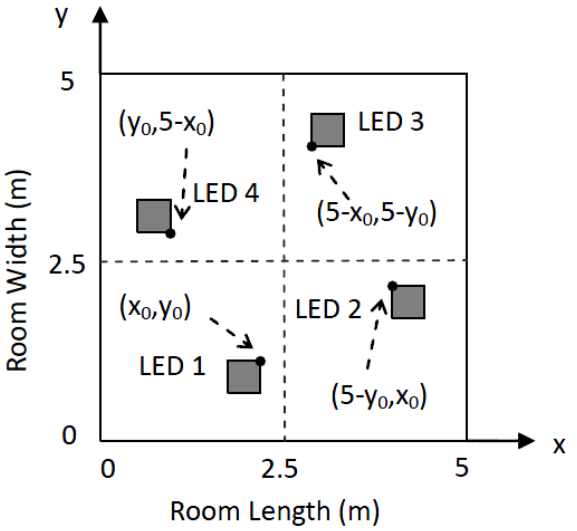

Fig.3. LEDs Localization at the Ceiling

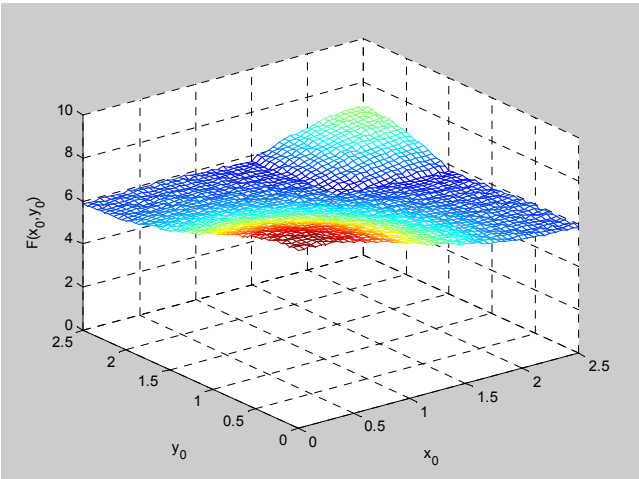

Fig.4. Objective Function Surface

As discussed in the last Section, the BER should also be considered in the indoor VLC system to promote the communication performance. So in the case demonstrated in Fig.3, it can be regarded as a MISO communication system. Based on (9), the SNR at some certain receiving point (x,y) at the receiving plane can be expressed by

$$SNR(x,y)=\frac{R^2\sum_{i=1}^{4}P_{rx(i)}^2(x,y)}{\sigma_n^2}\,, \tag{11}$$

where $P_{rx(i)}(x,y)$ represents the receiving power at (x,y) from the ith LED transmitter.

Suppose the on-off keying (OOK) modulation scheme is utilized in the VLC system, then the average BER over the receiving plane which can also be written as a function of (x_0,y_0), say $\overline{BER(x_0,y_o)}$, is

$$\overline{BER(x_0,y_o)}=\frac{1}{S}\iint_{\substack{0\le x\le 5\\0\le y\le 5}}Q\left(\sqrt{SNR(x,y)}\right)dxdy\,, \tag{12}$$

where $Q(\cdot)$ is the standard Q function defined by

$$Q(x)=\frac{1}{\sqrt{2\pi}}\int_x^{+\infty}e^{-\frac{y^2}{2}}dy\,. \tag{13}$$

It should also be aware that it can reach the ideal communication performance when (12) can get its minimum in the VLC system.

Based on the above analyses, to reach a perfect VLC performance with satisfied illuminations, we propose the following

objective function combining (10) and (12), that is

$$F(x_0, y_0) = a \cdot \sigma_E(x_0, y_0) + b \cdot \overline{BER}(x_0, y_0), \tag{14}$$

where a and b are two constants to regulate the values of the former and the rear parts in (14) in the same magnitude. According to the proposed objective function, the optimal LEDs location in the indoor MISO VLC system can be reached by solving the optimization problem with some certain constraints as follows

$$(x_0, y_0)_{opt} = \underset{0 \le x_0, y_0 \le 2.5}{\arg\min} F(x_0, y_0), \tag{15}$$

s.t. (1) $300 \le E(\Phi, \Psi) \le 1500$, (16)

(2) $$0.1 < \left. \frac{a \cdot \sigma_E(x_0, y_0)}{b \cdot \overline{BER}(x_0, y_0)} \right|_{(x_0, y_0) = (x_0, y_0)_{opt}} < 10. \tag{17}$$

Finally, an optimal LEDs location $(x_0, y_0)_{opt}$ can be reached which ensures the VLC performance with the uniform illumination. And in solving the problem in (15), some traditional computational optimization methods can be utilized, so we ignore the solution steps of this problem in details here.

IV. Computer Simulations

To evaluate the performance of the proposed approach, some computer simulation results are presented in this Section. In solving the optimization problem as in (15), the conventional Newton-down method is used to get the minimal value.

For comparison, we give the performances of other two LED(s) localization approaches as:

(1) Only one LED at the ceiling center with the coordinate (2.5,2.5), denoted by "Approach 1";

(2) Four symmetrical LEDs at the locations (1.25,1.25), (3.75,1.25), (3.75,3.75) and (1.25,3.75), as "Approach 2".

The computer simulation parameters and settings are the same as in Table I, and the parameters a and b in (15) are selected as $a = 0.1$ and $b = 10^{10}$, respectively, to satisfy (17). The comparison of the illumination standard deviations is given in Table 2. It can be found that the proposed approach can reach a minimal illumination standard deviation among these three methods, which guarantees the uniform illumination requirement firstly.

Table 2. Comparison of the Illumination Standard Deviations

	Approach 1	Approach 2	Proposed Approach
σ_E	31.28	26.65	17.68

Table 3. Comparison of the Average BER Performances

	Approach 1	Approach 2	Proposed Approach
$\overline{BER}$	1.55×10^{-9}	8.36×10^{-10}	3.69×10^{-10}

Table 3 shows the comparison of average BER performances among three methods as well. It can also be found clearly that the overall BER of the proposed approach is also less than those of other two approaches. From the results in Table 2 and Table 3, the benefits of the optimal LEDs location in the indoor MISO VLC system can be guaranteed.

Fig.4 plots the simulation result of the objective function surface within the area $0 \le x_0 \le 2.5$ and $0 \le y_0 \le 2.5$. It can be found that an optimal LEDs location with the coordinate $(x_0, y_0)_{opt} = (1.912, 0.775)$ has the minimal objective function value with $F(x_0, y_0)\big|_{(x_0, y_0) = (x_0, y_0)_{opt}} = 5.458$, which also corresponds the results in Table 2 and Table 3 well.

V. Conclusion

In this research, an optimal LEDs location algorithm is introduced for the application of indoor MISO VLC system. To enhance the communication performance under the indoor illumination requirement, a novel objective function is proposed, which can guarantee the corresponding lower BER performance and more flat illumination effect compared with some conventional method. Simulation results show the advantages of the proposed approach, and it will be helpful for the indoor VLC system and can certainly be extended to the multiple-input multiple-output (MIMO) circumstance.

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