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Optimization of LED's SAHPs to simultaneously enhance SNR uniformity and support dimming control for visible light communication

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A B S T R A C T

In this paper, we propose a method to enhance signal to noise ratio (SNR) uniformity and simultaneously support dimming control via optimization of LEDs' semi-angle at half power (SAHP) for visible light communication (VLC) systems. The uniformity of SNR performance is analyzed. Subcarrier-4pulse position modulation (SC-4PPM) is employed to supply light brightness control. Performance evaluation demonstrates that the overall SNR variation can be managed within 0.5 dB and the lowest SNR can be improved by nearly 5 dB for different dimming factors. A linear dimming control model is presented for the modulation parameters under optimal conditions. Tolerance analysis shows that our method is robust against practical parameters deviations. Feasibility evaluations show that the optimization demonstrates better performance than the non-optimized situations, both in SNR value and its distribution for various LED powers, receiver FOVs (field of view), LED numbers and room dimensions.

1. Introduction

In the past few years, visible light communication has aroused emerging interests due to its advantages of low cost, low power consumption, high security and unlicensed spectrum [1]. Though many issues have been addressed through intensive study, there are still a few challenges to be solved in VLC. One is the communication performance uniformity [2].Traditionally, identical wide SAHP LEDs are used to maintain large area of lighting, which usually results in relatively low SNR with large variation due to multipath effect [1]. Users located in different positions may suffer from large performance fluctuation. Many methods have been proposed to increase the uniformity of indoor VLC via optimization of LED's power, alignment or angle divergence. Genetic algorithm is employed to optimize the power of each LED or LED group to maintain uniform lighting [3,4]. Evenly distributed LED alignment with extra LEDs at the corners is deployed to mitigate the SNR fluctuation from 14.5 dB to 0.9 dB [2]. Spotlight LEDs with narrow SAHP are utilized in combination with wide-angle LEDs to enhance data rate and maintain uniform lighting [5]. Holographic light shaping diffusers in front of the LED are engaged to extend coverage area and then maintain uniform power distribution [6]. The effect of SAHPs on the VLC's power uniformity has also been investigated [7]. However, the SAHP for each LED are considered as identical. Up to date, the effect of LEDs with nonidentical SAHPs on the SNR uniformity has not been investigated yet. Nonidentical SAHPs placement could balance distinct channel response for differently located receivers, and thus provide uniform performance. Particularly, LEDs with narrow SAHPs placed above lower SNR locations are able to increase received signal power, so as to smoothen the overall SNR.

Dimming control is another challenge in VLC [8]. Several modulation schemes have been proposed in order to provide brightness control while sustaining communication [9]. Pulse width modulation (PWM) and pulse amplitude modulation (PAM) are conventional methods for dimming control [10]. A wide dimming range is supplied by using a rate-compatible punctured code [11]. A sub-carrier pulse position modulation (SC-PPM) is proposed in [12] to achieve a communication with constant data rate while supporting brightness control from 0% to 100%.

These two challenges in VLC are usually considered separately. However, they are both affected by the received power and modulation scheme, which indicates that they could be addressed together in system design. In this paper, we investigate these two challenges jointly to achieve high and uniform SNR and dimming control simultaneously by employing optimal SAHPs and SC-4PPM (sub-carrier 4pulse position modulation) parameters. Evenly distributed LEDs are divided according to their symmetry into different groups with identical SAHP. Optimization, with its objectivity and constraints being capable of evaluating the SNR performance and realizing the dimming control function, is designed

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to determine the SAHP of each group and modulation parameters. The optimization is implemented by OptQuest Non-Linear Programs (OQNLP) MultiStart algorithm, embedded in Matlab Global Optimization Toolbox. The evaluation results show that this method can effectively increase the SNR and smoothen its distribution while supporting dimming control. Tolerance test against potential deviations on parameters, including SAHPs, room dimension and modulation parameters, etc., demonstrates that the proposed optimization is robust. Feasibility analysis in terms of LED power, receiver FOV, LED numbers and room size verifies that it is effective for various applications. The rest of the paper is organized as follows. In Section 2, theoretical VLC models together with LED alignment setup and the optimization objectivity are presented. The optimization process and results are described in Section 3. Two optimization objectivities, i.e. SNR variance and Q_{SNR} factor, are compared and the optimized modulation parameters are analyzed. The parameter deviations tolerance ability of the optimization results are discussed in Section 4. Then, the optimization feasibility against other parameters is investigated in Sections 5 and 6 draws the conclusion.

2. Theoretical models

2.1. LED illuminance and dimming models

Illuminance is the brightness of a lighting surface. The illuminance by an LED source is given by:

$$E = I(0)\cos^{m}(\theta)\cos(\psi)/d^{2}, \tag{1}$$

where $I(0)$ is the center luminous intensity of an LED, θ and ψ are the angle of irradiance and incidence respectively, and d is the distance between LED and receiver. m is the order of lambertian emission, given by SAHP of an LED, $\theta_{1/2}$, as

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

We employ SC-4PPM modulation scheme which is capable of providing dimming range of 0–100% [13]. A SC-4PPM symbol interval is divided into 4 time slots, as illustrated in Fig. 1. It is composed of two parts: subcarrier (SC) and DC parts. The SC is transmitted only during 1 time slot with amplitude of a and c, and the DC component is maintained during other time slots with amplitude of b. A symbol of SC-4PPM has 2 data bits. Bits are transmitted by the position where the subcarrier exits. The subcarrier frequency should be higher than 2 times of the data rate for SC-4PPM modulation, so as to ensure the subcarrier component can be recognized during ¼ SC-4PPM symbol interval [12]. The illuminance of an LED modulated by such scheme is denoted as:

$$E_{SC-4PPM} = N \times E, \tag{3}$$

where N is the dimming factor that indicates the ratio of dimmed illluminance to maximum illuminance, given by:

$$N = 0.125 \times (a + c) + 0.75 \times b, \tag{4}$$

The range of a, b and c is [0, 1]. It shows that adjusting a, b or c individually can only provide dimming range of 12.5%, 75% or 12.5% respectively. 100% dimming control is achieved by adjusting them all together.

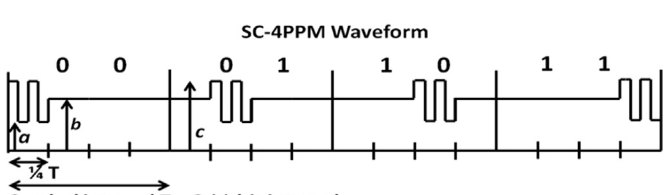

Fig. 1. SC-4PPM waveform.

2.2. LED communication models

The transmitted optical power of an LED for communication employing SC-4PPM scheme is considered only during the subcarrier part, given by [13]:

$$P_t = (c - a) \times P_0, \tag{5}$$

where P_0 is the maximum transmitted power. Received power of a given location is denoted as:

$$P_r = \sum_{i=1}^{LEDs} h_i(t) \times P_t, \tag{6}$$

where $h_i(t)$ is the impulse response of *ith* LED, denoted as:

$$h_i(t) = (m + 1)A\cos^{m}(\theta)\cos(\psi)/(2\pi d^{2}), \tag{7}$$

where A is the area of the receiver. In our analysis, the line of sight (LOS) and first order reflection are considered and the spatial resolution corresponding to the LOS and first order reflection is set as 0.5 m and 1 m respectively, and reflectivity is set to 0.8. In order to compute SNR, subcarrier signal during only one time slot is considered. The optical signals simultaneously sent from LEDs at different locations experience individual time of arrival. The power received inside and outside a time slot are considered as signal and ISI (intersymbol interference) noise, respectively. They denoted as $P_{rSignal}$ and P_{rISI}, are given by:

$$P_{rSignal} = \int_0^{T/4} \left(\sum_{i=1}^{LEDs} h_i(t) \otimes X(t) \right) dt, \tag{8}$$

$$P_{rISI} = \int_{T/4}^{\infty} \left(\sum_{i=1}^{LEDs} h_i(t) \otimes X(t) \right) dt, \tag{9}$$

where, for SC-4PPM, $X(t)$ represents the transmitted subcarrier pulse within a time slot. Then the SNR can be expressed as [1]:

$$SNR = \frac{S}{N} = (\gamma^2 P_{rSignal}^2)/(\sigma_{shot}^2 + \sigma_{thermal}^2 + \gamma^2 P_{rISI}^2), \tag{10}$$

where σ_{shot}^2 and $\sigma_{thermal}^2$ are the power of shot noise and thermal noise respectively, and their relevant parameters are chosen to be consistent with those in [1], except for the equivalent noise bandwidth which refers to the subcarrier frequency for SC-4PPM. We assume that the subcarrier frequency is 4 times of the data rate in the optimization. γ is the responsivity of the receiver.

2.3. Optimization objectivity

As denoted in (1) and (7), illuminance and received power are depended on LED's SAHPs. Conventionally, identical wide SAHP LEDs for all sources are employed for uniform lighting coverage. For communications, however, this may decrease signal power and increase ISI noise, thus deteriorating the entire performance, due to the factor that the light from distant LEDs has large incident angle and the delays spread broadly. In order to solve this, we use LEDs with optimized nonidentical SAHPs. The SAHPs of LED is determined by LED optics, which is either commercially available for general applications or can be customized [14,15]. Our work is to find out a set of SAHPs that produces system optimal performance. Fig. 2 shows the LEDs alignment in the ceiling, where 144 LEDs are evenly distributed. Owing to the symmetry of LED placement with respect to the center, we straightforwardly divide them into 6 groups of identical SAHP LEDs as marked using