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Abstract—White light emitting diode (LED) is viewed as the new generation green solid state lighting (SSL) source by academia and industry based on its charming advantages, such as high brightness, low cost, steadily improved power efficiency and etc. Visible light communication based on white LED which aims to realize lighting and data transmission simultaneously is attracting more and more attention. In this paper, two indoor VLC design schemes which need less power cost are proposed and corresponding illuminance ability is estimated in a moderate size office. One proves that distributed design scheme can improve the power efficiency (add 300 lx in central area) and related SNR performance is improved as well. And the other illustrates the amount of needed chips can be reduced (from 900 to less than 800) maintaining the similar illuminance level. The performance of systems based on improved modulation schemes in terms of pulse position modulation (PPM), multiple pulse position modulation (MPPM) and overlapping pulse position modulation (OPPM) are tested.

Keywords: Visible light communication, white light emitting diode (WLED), illuminance, multiple pulse position modulation (MPPM), overlapping pulse position modulation (OPPM).

I. INTRODUCTION

The emergence of visible light communication (VLC) is the hybrid achievement of conventional optical communication and mature radio frequency (RF) wireless communication. This technique is expected to cope with the wireless spectrum source bottleneck by appealing to huge, unregulated and unlicensed optical spectrum which makes it quite attractive for RF-sensitive operating environment, for example hospital as well as aircrafts [1].

To a large extent, the idea that combines two worlds together is driven by the growing emergence of approaching illuminance level white light emitting diode (WLED). Actually, LED bulbs have show its outstanding advantages over conventional incandescent and fluorescent bulbs in terms of small size, low energy consume (just need 1/8 of energy cost related to incandescent), long life (about several ten thousand hours), quick reaction speed, without causing hydrargyrum pollution as fluorescent and etc [2]. The promising VLC based on new generation semiconductor lighting equipment takes on inherent benefits, among which are the following: no interference with RF circuits electronics, no health concerns as long as eye and skin safety regulations are met, and high degree privacy and security against eavesdropping is offered as the optical signals can not penetrate through opaque walls [3]. As the future proof indoor VLC is based on the fourth indoor lighting equipment, the developing cost will be reduced drastically coupled with investment and research on the low cost, high electronic-to-optical conversion efficiency WLED initiated by key tech-companies such as Japan Nichia, American Lumileds, European Union Osram and etc. At the same time, developing green semiconductor lighting has been included in the Eleventh Five-Year Plan for National Economic and Social Development plan in China [4]-[6].

Up to now many industry organizations [e.g. visible light communication consortium (VLCC)] [7] and academic institutions [e.g. Home Gigabit Access (OMEGA)] [8] have issue relative research framework in indoor optical wireless domain, many challenges still have to be faced, especially how to reduce the power consumption of a VLC system and which modified modulation scheme should be applied to...
realization considering the practical case of existing optical wireless communications components.

The paper is organized as follows. Section II discusses the lighting characteristic and improved indoor green SSL lamp design. In Section III, potential data transmission capacity of VLC systems adopting base band and Orthogonal Frequency Division Multiplexing (OFDM) modulation are analyzed. Consequently, numerical simulation is presented. In subsequent sections, the potential work of following research and conclusion are given.

II. DESIGN AND ILLUMINANCE OF INDOOR SOLID STATE LIGHTING

A. Basic Properties of WLED chips

To simplify the analysis, the WLED is regarded as a point light source [9]. From radiation spectrum measured by corresponding optical spectrum analyzer, one can calculate the luminous flux \( \Phi_v \) [lm] as:

\[
\Phi_v = K_m \int_{\lambda_{min}}^{\lambda_{max}} V(\lambda) \Phi_v(\lambda) d\lambda
\]  

(1)

where \( V(\lambda) \) is the standard eye sensitivity curve, \( K_m \) is the maximum visibility which is approximately equal to 683 lm/W, and \( \Phi_v(\lambda) \) denotes the radiant energy flux. The spectrum between \( \lambda_{max} \) and \( \lambda_{min} \) is the domain of visible light spectrum, and generally the specific number of them is not constant among different person, in this paper this spectrum domain between 380nm and 700nm is included in our evaluation.

\[
I_v = d\Phi_v / d\Omega
\]  

(2)

According to the luminous flux, the luminous intensity is given by equation (2) where \( \Omega \) stands for the spatial angle.

In our model, the source luminous intensity \( I_v(\phi) \) [cd] is given as:

\[
I_v(\phi) = I_v(0) \cos^m(\phi)
\]  

(3)

which depends on the center luminous intensity i.e. \( I_v(0) \) the maximal luminous intensity. The Lambert index \( m \) is given by \( m = -\ln 2 / \ln(\cos(\phi/2)) \). \( \phi/2 \) is the source radiation semi-angle. As other lighting source mentioned previously (such as fluorescent lamp, incandescent lamp), the illuminance \( E \) is used to express the brightness of various surface illuminated by relevant source.

\[
E = d\Phi_v / dA_r = I_v(\phi) / R^2
\]  

(4)

For this source with Lambert radiation distribution and an angle of incidence \( \psi \) [deg], the horizontal illuminance is:

\[
E_h = I_v(\phi) \cos(\psi) / R^2
\]  

(5)

where \( R \) accounts for the distance between one optical sensitive receiver and the WLED transmitter.

B. Design of Green SSL Lamp

One key advantage of WLED as new generation illumination source is that energy saving. However existed
indoor VLC & lighting systems have not showed this strength satisfactorily. Jelena Vucic et al have proposed two design primary design schemes using commercial available WLED chips. One of them represents a ceiling that is uniformly covered with 16-cm spaced WLEDs, whereas in the second scenario four distinct areas of $1 \times 1 \text{ m}^2$ (referred to as lamps), contain 7-cm spaced WLEDs. As a matter of fact, similar design which needed 14 000 chips has been adopted by Masao Nakagawa [10].

Throughout mentioned design, it is liable to be accepted that distributed WLED lamps design has an advantage over uniform design scheme. Based on analysis mentioned above, two gradually distributed ceiling lighting designs are proposed as described in Fig. 2. The relative ceiling style is the same as the conventionally used one [9-10], the corresponding room size is $5 \times 5 \times 3 \text{ m}^3$.

C Performance of Lighting Function

In scenario A, 900 WLED chips (equal to that adopted by Jelena Vucic et al) is used, the distance between chips in one lamp is 10 cm and the amount of lamps is six while in the scenario B only 784 chips (less than any other schemes mentioned above) are brought in, the distance between chips in one lamp is 10 cm as well and 16 same square lamps are fixed.

Table I, outlines the relevant important parameters of the WLED chips used.

Based on above analysis, Fig. 3 shows the distribution of horizontal illuminance at a desk level with ceiling lighting design suggested above. Due to the geometric symmetry of the two scenarios, only the upper right quarter of the desktop surface (directly under the areas within dashed lines in Fig. 2) is considered in Fig. 3.

For convenient comparison with Jelena Vucic’s work [9], the identical lighting standard is obeyed in this paper according to EN 12464-1[9], i.e. 400 lx is regarded as a minimal brightness at the desktop in the working area, and 200-800 lx in the whole room. In Fig. 3, both of the configurations meet the aimed horizontal illuminance level.

By comparing Fig. 3 with Fig. 5 in [9], it is easy to find that the same position in Scenario A (using $3 \times 3$ lamps) can obtain large horizontal illuminance than the existed scenario (using one large lamp) in despite of the equivalent chips is referred. And the peak brightness is increased from ~900 lx to more than 1200 lx in the central working palace. As this brightness can be used to measure the SNR at the user terminal, the corresponding anti noise performance can be improved as well. In [9], this relationship is given as:

$$\text{SNR} = \frac{E_0^2 (A_x \alpha)^2}{(N_0 B)}$$  \hspace{1cm} (6)

Based on the intuitive knowledge of the contours presented in Fig. 3, it can be sure that actual brightness distribution changed slightly when the number of WLED lamp is increased from 4 to 9. The key advantage of Scenario B is that only less than 800 chips are used while 900 chips is needed in Scenario A. This simulation approves that distributed WLED lamps design has the potential to reduced the needed power consumption.

III. DATA TRANSMISSION WITH INDICATING MODULATION SCHEMES

Up to now, many modulation schemes, such as pulse amplitude modulation (PAM) and OFDM, have been investigated for dealing with pointed issues including system capacity deficiency and inter symbol interference (ISI) caused by multipath dispersion. Nevertheless, neither PAM nor OFDM has a satisfactory expression in power efficiency. It must be mentioned that the net transmission ability of OFDM optical wireless systems can be significantly compromised by its inherent high peak-to-average power ratio (PAPR) issue and associative nonlinearity effects of WLED.

In general, pulse position modulation is regarded as an attractive scheme for offering increased power efficiency. For a white light wireless link, the input $X(t)$ represents
instantaneous light power which is evidently differ to the amplitude in usual RF wireless systems, so it must meet:

\[ X(t) \geq 0 \]  

(7)

And the average of input power \( P_i \) must satisfy \( P_i \leq P \) where \( P \) denotes the average power constraint of adopted WLED. Define \( P_i \) as:

\[ P_i = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} X(t)dt \]  

(8)

According to [11], the power required by any other base band modulation scheme to achieve the same bit error rate (BER) is \( P = (d_{\text{ook}} / d_{\text{m}}) P_{\text{ook}} \) approximately, assuming the SNR is high enough at the receiver where \( d_{\text{m}} \) stands for the minimum Euclidean of valid modulation signals:

\[ d_{\text{min}} = \sqrt{\min_{i \neq j} \int_{0}^{T} (x_i(t) - x_j(t))^2 dt} \]  

(9)

In the following subsections, the power efficiency and bandwidth requirement of PPM and its modified types will be analyzed with on-off keying (OOK) as a benchmark.

A. Pulse Position Modulation

The original information bits with rate \( R_s \) are input into the encoder, where each block of \( k-\log_2 L \) bits into one of \( L \) code words \([C_0, C_1, \ldots, C_{L-1}]\), so the transmitted signal of PPM is given by:

\[ X_{\text{PPM}}(t) = LP \sum_{k=0}^{L-1} C_k p(t - kT_{\text{PPM}} / L) \]  

(10)

where is a rectangular pulse of duration \( T_{\text{PPM}} / L \) and unity height. The Euclidean distance between \( L \) signals is equal to:

\[ d_{\text{PPM min}} = \sqrt{2(LP)^2 \frac{T_{\text{PPM}}}{L}} = \sqrt{2LkP^2 \frac{1}{R_b}} \]  

(11)

Therefore the average power needed for PPM is given respectively:

\[ P_{\text{PPM}} = \left( \frac{d_{\text{OOK}}}{d_{\text{PPM min}}} \right) P_{\text{OOK}} = \sqrt{\frac{2}{Lk}} P \]  

(12)

Here as \( k \) is directly proportional to \( L \), the optical power requirement of WLED can be made arbitrarily small by increasing \( L \). But this change is definitely leads to the expense of occupied bandwidth. Corresponding the needed bandwidth is approximately the inverse of chip duration \( B_\text{PPM} = L / T_{\text{PPM}} = LR_s / \log_2 L \).

B. Multiple Pulse Position Modulation

Multiple pulse position modulation (MPPM) is regarded as another important base band modulation scheme proposed here. All signals in MPPM are not orthogonal like PPM any more for \( w \) optical pulses is transmitted during one signal. The input MPPM signal is given by:

\[ X_{\text{MPPM}}(t) = \frac{P\sqrt{nT}}{w} \sum_{k=0}^{L-1} C_k \phi(t - kT_{\text{MPPM}} / n) \]  

(13)

where \([C_0, C_1, \ldots, C_{L-1}]\) is a binary \( n \)-tuple of weight \( w \), \( \phi(t) = \sqrt{nT} p(t) \) is a unit-energy rectangular pulse of chip cycle \( nT \). Actually, \( L \) code words can be chosen from \( C(n, w) \) binary \( n \)-tuples of weight \( w \). For assuring BER performance, the minimum Hamming distance \( d \) should be restricted as large as possible.

For simplifying analysis, it is assumed that \( L = 2^k \leq C(n, w) \). Thus the minimum distance of MPPM can be provided as:

\[ d_{\text{MPPM min}}^2 = \min_{i \neq j} \int_{0}^{T} (x_i(t) - x_j(t))^2 dt \]

\[ = a^2 \left( \sqrt{\frac{nT}{2}} \right)^2 \left( \frac{n-d+1+1}{2} \right) \frac{T}{n} \]  

(14)

where \( a = P\sqrt{nT} / w \) and \( d \) is the minimum Hamming distance of the total MPPM signals. According to existed result, the average optical power required for MPPM is given as:

\[ P_{\text{MPPM}} = \left( \frac{2w}{\sqrt{ndk}} \right) P \]  

(15)

The actual bandwidth needed for MPPM is \( B_{\text{MPPM}} = n / T_{\text{MPPM}} = nR_s / \log_2 L \) i.e. the inverse of chip cycle.

C. Overlapping Pulse Position Modulation

For further improving the bandwidth efficiency of MPPM, overlapping pulse position modulation (OPPM) is defined as a special case of MPPM. During the each symbol
duration $T_{\text{trans}}$ composed by $n$ chips, a rectangular pulse spanning $w$ chips is transmitted. Although the alternative style of $L$ is reduced from $C(n, w)$ to the $(n-w+1)$, the initial motive for decreasing bandwidth need can be realized. and the bandwidth of OPPM is expressed as $B_{\text{oppm}} = n / \left[ w \log_2 (n - w + 1) \right]$. 

The minimum Euclidean distance of OPPM is described as:

$$d_{\text{MPPM min}} = \sqrt{a^2 \left( \frac{n}{T} \right)^2 \frac{T}{n} \left( \frac{0 + \cdots + 0 + 11}{n-2} \right)} \quad \text{(16)}$$

For convenient comparison, the average optical power of OPPM is yielded as well:

$$P_{\text{OPPM}} = \left( \frac{2w}{\sqrt{2n \log_2 (n - w + 1)}} \right)^2 P \quad \text{(17)}$$

When $w=1, n=L$, this equation is transformed to aforementioned (12).

IV. SIMULATION AND DISCUSSION

The power efficiency and bandwidth for various modulation schemes are presented in Fig. 4. It can be seen that the poor bandwidth efficiency of PPM is unacceptable when $L$ is larger than 10. The lines of MPPM show it owns better bandwidth efficiency compared with conventional PPM and the line of MPPM is connected with counterpart of PPM when $w$ is reduced to 1 which proves OPPM is a special case of MPPM.

Through the code choice of OPPM is limited, it owns satisfying power efficiency and bandwidth efficiency at the same time. The last line identifies that PPM can be regarded as a special case of OPPM as well.

V. CONCLUSION

In this paper, two distributed WLED lighting schemes are proposed and corresponding indoor illuminance distributions are given. Scheme A improves that distributive arrangement of WLED lamps can add the average illuminance level (from 900 lx [9] to 1280 lx in central domain) using equal amount of WLED chips. On the other hand, simulation result of scheme B indicates that similar lighting effect can be realized with reduced quantity of chips (from 900 to less than 800) and the power need of the modified system will be reduced to some extent. Considering existed modulation choices used for indoor white light wireless transmission is restricted to the PAM and complicated multi carrier modulation which do not match the low power consuming level of VLC. Actually, PPM and modified PPM (i.e. MPPM, OPPM) present power efficiency in VLC system. Corresponding power efficiency and bandwidth requirement of these modulation schemes are presented.

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