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Performance of a novel LED lamp arrangement to reduce SNR fluctuation for multi-user visible light communication systems

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Abstract: This paper investigates the performance of our recently proposed LED lamp arrangement to reduce the SNR fluctuation from different locations in the room for multi-user visible light communications. The LED lamp arrangement consists of 4 LED lamps positioned in the corners and 12 LED lamps spread evenly on a circle. Our studies show that the SNR fluctuation under such a LED lamp arrangement is reduced from 14.5 dB to 0.9 dB, which guarantees that users can obtain almost identical communication quality, regardless of their locations. After time domain zero-forcing (ZF) equalization, the BER performances and channel capacities of 100-Mbit/s and 200-Mbit/s bipolar on-off-keying (OOK) signal with most significant inter-symbol interference (ISI) are very close to that of the channel without any ISI caused by this LED lamp arrangement.

OCIS codes: (230.3670) Light-emitting diodes; (060.4510) Optical communications; (060.4080) Modulation; (200.4560) Optical data processing.

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1. Introduction

Visible light communication (VLC) has aroused a lot of research interests in recent years [1–8]. The advantages of VLC include high data rate and not being prone to be eavesdropped and radio frequency (RF) interference, which make VLC be very attractive in hospital and home area networks (HAN) [1, 2]. In indoor VLC system, the light-emitting diode (LED) lamps generally locate in the center of the ceiling (called as centered-LED). This LED lamp arrangement makes the signal to noise ratio (SNR) in terms of received optical power vary significantly from one receiver location to another [5]. Such SNR fluctuation deteriorates the system performance, especially in the corners of the room, limiting the system's ability to provide equal communication quality to multi-users in different places.

In order to solve this problem, we recently proposed a novel LED lamp arrangement, more specifically, 12 LED lamps spreads evenly on a circle (called as circled-LED) and 4 LED lamps are placed in the four corners (called as cornered-LED) [9]. For the sake of simplicity, the word LED refers to LED lamp in the rest of the paper. By adjusting the radius of 12 LEDs-circle and the distance between the cornered-LEDs and their nearest walls, we show that the SNR fluctuation can be reduced from 14.5 dB to 0.9 dB.

In this paper, we focus on the performance, including bit error rate (BER) and channel capacity, of 100-Mbit/s and 200-Mbit/s bipolar OOK signal for the user in the corner, where inter-symbol interference (ISI) is most severe. Simulation results show that ISI, which is caused by different light arrival time from 16 separate LEDs, could be mitigated significantly by time domain zero-forcing (ZF) equalization under such LED arrangement. ZF is a commonly used and easy implemented equalization [10], comparing with other equalization method such as maximum-likelihood sequence estimation (MLSE) [10] and minimum mean square error (MMSE) [11]. To achieve bit error rate (BER) of $5*10^{-4}$, ZF equalization provides 3.2-dB and 5.4-dB power reduction for 100-Mbit/s and 200-Mbit/s bipolar OOK signal, respectively, where the Monte-Carlo simulation and theoretical results match with each other very well. In addition, the maximum channel capacity improvements by ZF equalization are 0.17 bits/symbol for 100-Mbit/s bipolar OOK signal when the total LED power is 2 W and 0.16 bits/symbol for 200-Mbit/s bipolar OOK signal when the total LED power is 4 W. Both the BER performance and channel capacity after applying ZF equalization are very close to that of the channel without ISI. Therefore, the new LED arrangement and ZF equalization provide similar communication qualities to all users, no matter where they locate in the room.

The rest of this paper is organized as follows. The principle and optimum parameters of the LED arrangement with 4 cornered-LEDs and 12 circled-LEDs is described in Section 2. Section 3 shows the influence of ISI and ZF equalization to the BER performances of 100-Mbit/s and 200-Mbit/s bipolar OOK signal under this LED arrangement. The channel capacities with and without applying ZF equalization are given in Section 4. Section 5 shows the conclusions.

2. Principle and optimum parameters

The Lambertian radiation pattern is applied to model the LED radiant irradiance [6, 7]:

$$R(\varphi) = \frac{(m+1)\cos^m(\varphi)}{2\pi}, \qquad (1)$$

where φ is the angle of irradiance from the LED, m is the order of Lambertian emission defined by the LED's semi-angle at half power $\varphi_{1/2}$, which is $m = \ln(1/2) / \ln(\cos(\varphi_{1/2}))$. Hence the channel direct current (DC) gain is described by [5, 7]

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$$H(0)=\frac{R(\varphi)\cos(\theta)A}{d^2}=\frac{(m+1)\cos^m(\varphi)A\cos(\theta)}{2\pi d^2}, \qquad (2)$$

where d is the distance between LED and the photo-detector, A is the physical area of photo-detector, and θ is the angle of incidence. Note that in this paper all the LEDs point vertically to the plane where the photo-detector is located.

After modulation, the optical signal at the output of an LED is given by $p(t) = P_t (1 + M_I * f(t))$; P_t is the launched power of LED Lamp; M_I is the modulation index [12]; $f(t)$ is the modulating bipolar OOK signal. The average received optical power is

$$P_r = H(0)P_t. \qquad (3)$$

After photo-detection, considering that the DC component of the detected electrical signal is filtered out in the receiver, the output electrical signal is given by $s(t) = R * P_r * M_I * f(t)$, where R is the responsivity of the photo-detector. Hence, the SNR of the output detected electrical signal is given by [7],

$$SNR=\frac{\overline{s(t)^2}}{P_{noise}}=\frac{(RH(0)P_tM_I)^2\overline{f(t)^2}}{P_{noise}}, \qquad (4)$$

where $\overline{s(t)^2}$ is the average power of the output detected electrical signal. P_{noise} is the power of noise which is defined in [5], where the background noise is dominant in VLC systems and the other parameters of VLC system is listed in Table 1.

Usually, LEDs are located in the center of the ceiling. Suppose that there are 16 identical LEDs on the ceiling, the interval of adjacent LEDs is 0.2 m. We sample 100 positions that uniformly distribute on the plane where the photo-detector locates. The total power of 16 centered-LEDs is 2 W, i.e., the power of each LED is 125 mW. We also introduce a Q-factor of SNR distribution to evaluate the fairness of whole system to all users, which is defined as

$$Q_{SNR}=\frac{\overline{SNR}}{2\sqrt{\mathrm{var}(SNR)}}, \qquad (5)$$

where $\overline{SNR}$ is the mean value of SNR and $var(SNR)$ represents the variance of SNR. The higher the Q-factor is, the more uniformly the SNR distributes in the room. The SNR distribution is shown in Fig. 1(a), where the fluctuation of SNR is 14.5 dB, while the Q-factor of SNR distribution is only 0.5 dB, which means that the value of SNR varies substantially in the room, i.e., communication quality is associated closely with user's location. The user in the corner will obtain less than 1/10 (10 dB) of the SNR in the center of the room. Note that in the calculation of SNR distribution we do not consider the reflection of walls or the ISI, which will be involved in the analysis of BER performance in Section 3.

Table 1. Parameters of VLC system configuration

Room size (length × width × height)	5m × 5m × 3m
Height of desk where the receiver is located	0.85m
Reflectivity of wall	0. 7
Transmitter's semi-angle at half power	60°
Physical area of photo-detector	10^{-4} m^2
Receiver's field of view (FOV)	170°
Responsivity of photo-detector	1A/W
Modulation index (M_I)	0.2

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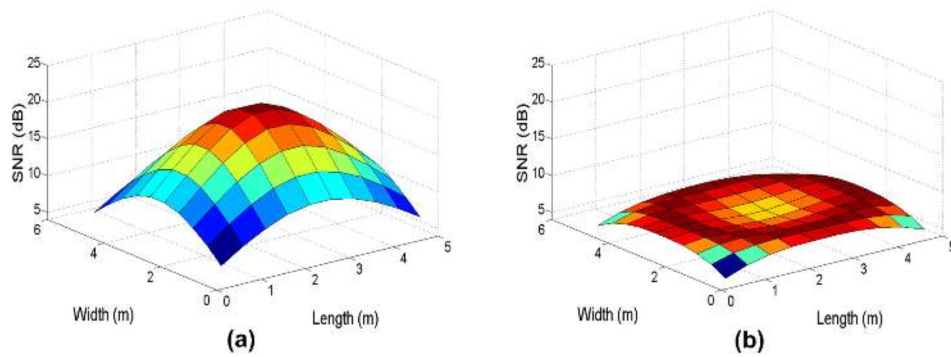

Fig. 1. SNR distribution with 2-W total power: (a) 16 centered-LED lamps, (b) 16 circled-LED lamps.

The poor SNR distribution in Fig. 1(a) is caused by the centered-LED arrangement, where the distances between users in the corners and the LED sources are much longer than the user in the center of the room. Therefore, when the LEDs are located separately and symmetrically to the center of the ceiling, the SNR distribution should get much improved. This is because according to (2), the differences of distances between users and LEDs are reduced. We first propose a circled-LED arrangement, i.e., the LEDs are distributed evenly on a circle on the ceiling with 2.5-m radius. Since the locations of LEDs are symmetric with respect to the center of the ceiling, the SNR distribution will become much more flat. To compare with the SNR distribution of centered-LEDs, both the total number of LEDs and the power of each LED remains the same. As shown in Fig. 1(b), the SNR fluctuation decreases from 14.5 dB to 2.4 dB, while the Q-factor of SNR distribution increases from 0.5 dB to 9.3 dB, which means that under the circled-LED arrangement, the communication qualities at different positions are not associated closely with the user's location. Note that when the LEDs are located separately and distributed evenly on a square in the ceiling, the SNR fluctuation is similar to the case of circle. For example, when the edge length of the square is 1.0 m, the SNR fluctuation is 2.9 dB. In this paper we mainly focus on the performance of the latter case.

Although the Q-factor of SNR distribution is as high as 9.3 dB under the circled-LED arrangement, the SNRs in the corners are still obviously smaller than other places, as shown in Fig. 1(b). Therefore, we add four LEDs in the four corners to give more power to the user in those places. The distances of the four LEDs that locate in the corners to their nearest walls are all 0.1 m, as shown in Fig. 2(a). Again, in order to make the comparison reasonable, the total LED power is 2 W and the number of LEDs that consists of a circle is reduced to 12 so that the total number of LEDs remains 16. In this case, we adjust the power of LED placed in corners and LEDs spread evenly on the circle in order to minimize the variance of received optical power P_r, i.e.,

$$\min \operatorname{var}(P_r) = \min E[(P_{r,j} - E(P_{r,j}))^2], \tag{6}$$

where $E(\cdot)$ represents the mean value and Pr_{j} is the received power at position j, which is described by

$$P_{r,j} = \sum P_{t,corner} H(0)_{corner} + \sum P_{t,circle} H(0)_{circle}. \tag{7}$$

We also change the radius of the LED-circle and the distance between the cornered-LEDs and their nearest walls to find the minimum SNR fluctuation. As shown in Tables 2 and 3, and Fig. 2(b), when the radius of the LEDs-circle is 2.2 m and the distance between the cornered-LEDs and their nearest walls is 0.1 m, the optimum SNR performance is obtained, where the powers of each cornered-LED and each circled-LED are 238 mW and 87 mW, respectively, i.e., the power of each cornered-LED is about 2.7 times higher than that of each circled-LED. The 0.85-dB SNR fluctuation and 12.3-dB Q-factor of SNR distribution mean that this LED arrangement is one feasible LED arrangement to provide almost identical communication quality to multi-user no matter where they locate. When the power of each circled-LED or cornered-LED varies 10% due to the aging of equipment, the SNR fluctuation varies from 0.9 dB to 1.0 dB and the Q-factor of SNR distribution varies from 12.1 dB to 12.2 dB. Therefore this LED arrangement is tolerant to the equipment working condition. Note that the SNR fluctuation is not affected by the value of total LED power. For rooms with different dimensions and layouts, our approach presented in this paper is applicable and similar results could be achieved. However, the LED lamp arrangement should be adjusted according to the room dimension and its layout.

Besides SNR, uniformly-distributed illuminance is also desired in VLC system. As described in [13, 14], visible light power is proportional to luminous flux and the illuminance is defined the total luminous flux incident on a surface. Due to the identical physical areas of photo-detectors at all the receiver locations, the distribution of illuminance has the same shape as that of the received optical power. As mentioned before, the background noise is dominant in VLC system, so the distribution of SNR should be the same as that of the received optical power. Thus, the illuminance is also distributed uniformly in the room. Therefore, this LED lamp arrangement won't introduce undesired illumination effects.

Table 2. SNRs and Q-factors of SNR distribution under LED arrangements of 12 circled-LEDs and 4 cornered-LEDs with different radii, where the distance between cornered-LED and their nearest walls is 0.1 m

Radius (m)	2.1	2.2	2.3	2.5
SNR range (dB)	[5.5, 6.4]	[5.6, 6.5]	[5.5, 6.5]	[5.3, 6.5]
SNR fluctuation (dB)	0.9	**0.9**	1.0	1.2
Q-factor (dB)	12.1	**12.2**	12.2	11.5

Table 3. SNRs and Q-factors of SNR distribution under LED arrangements of 12 circled-LEDs and 4 cornered-LEDs with different distances between the cornered-LEDs and their nearest walls, where the radius of LED-circle is 2.2 m

Distance (m)	0.5	0.25	0.15	0.1
SNR range (dB)	[6.0, 7.4]	[5.9, 6.8]	[5.7, 6.6]	[5.6, 6.5]
SNR fluctuation (dB)	1.4	0.9	0.9	**0.9**
Q-factor (dB)	10.7	11.7	12.1	**12.2**

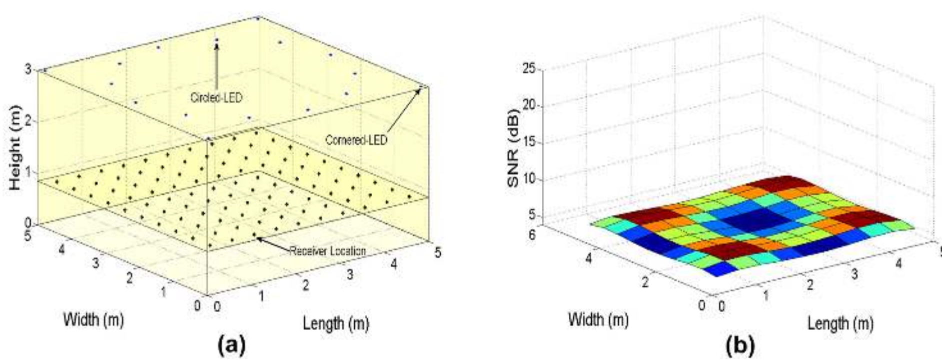

Fig. 2. Arrangement of 12 LED lamps spread evenly on a circle and 4 LED lamps positioned in the corners: (a) LED lamps and 100 receiver locations, (b) SNR distribution with 2-W total power.

3. BER performance under 4 cornered-LED lamps and 12 circled-LED lamps arrangement

Although the LED arrangement of 12 circled-LEDs and 4 cornered-LEDs provides almost identical communication qualities in terms of SNR to users at different locations, it induces more significant ISI, which deteriorates the system performance. When the LEDs are all located in the center of the ceiling, the difference of light arrival time from the LED sources to a particular user is small. However, once the LEDs are located separately on the ceiling,

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such difference becomes significant, thus the ISI is severe. As shown in Fig. 3 without considering reflections, the maximum difference of light arrival time under the proposed LED arrangement is 15.9 ns when the receiver is in the corners; while when the 16 LEDs locate in the center of the ceiling, that maximum difference is only 2.34 ns. In the following analysis, we focus on the BER performance of both 100-Mbit/s and 200-Mbit/s bipolar OOK signal in the corner ([0.25 0.25 0.85]) where the ISI is most severe and take the first order of reflection into account [7].

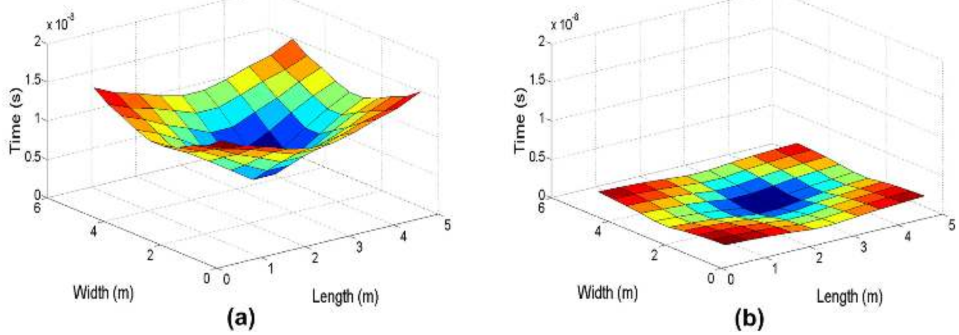

Fig. 3. Maximum difference of light arrival time from LED sources to receiver, without considering reflections: (a) The arrangement of 4 cornered-LEDs and 12 circle-LEDs, (b) 16 LEDs located in the center of the ceiling.

3.1 100-Mbit/s bipolar OOK signal

The pulse shape for bit ‘1’ of 100Mbit/s bipolar OOK signal under the LED arrangement in Fig. 2(a) is shown in Fig. 4(a), when the total LED power is 2 W. The duration of the bit lasts more than 30 ns, which is three periods of original bit, for the period T is 10 ns (= 1/100M).

We suppose that after normalization the channel response is $h=\left[1\ a_1\ \ldots\ a_k\right]$, where $a_i\left(i=1,2,\ldots,k\right)$ represents the ISI; the present received bit is I_m with amplitude $\pm\sqrt{E_b}$ and the previous k received bits are denoted by $I_{m-i}\left(i=1,2,\ldots,k\right)$. The received signal is

$$y_{\mathrm{m}}=I_{\mathrm{m}}+\sum_{i=1}^{k}a_i\,I_{\mathrm{m}-i}+n, \tag{8}$$

where n is the additive white Gaussian noise (AWGN) with power spectral density of $N_0/2$. Then, the conditional error probability when the present received bit is ‘1’, i.e., amplitude is $\sqrt{E_b}$, is given by [10],

$$P(e\,|\,I_{\mathrm{m}}=\sqrt{E_b})=\sum P(I_{m-1},\ldots.,I_{m-k})P(e\,|\,I_{\mathrm{m}}=\sqrt{E_b},I_{m-1},\ldots.,I_{m-k}), \tag{9}$$

where $I_{m-1},\ldots.,I_{m-k}$ is a combination of previous k received bits that $I_{m-i}\left(i=1,2,\ldots,k\right)=\pm\sqrt{E_b}$, i.e., the previous k received bits could either be ‘1’ or ‘0’. Note that bit ‘0’ is mapped to ‘-1’ for bipolar OOK signal. $P(I_{m-1},\ldots.,I_{m-k})$ is the probability of one of such combinations. $P(e\,|\,I_{\mathrm{m}}=\sqrt{E_b},I_{m-1},\ldots.,I_{m-k})$ is the conditional error probability when the present received bit is ‘1’ and one of the combination of previous k received bits occurs. For example, when all the previous k received bits and present received bit are ‘1’, the conditional error probability in (9) is

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$$\begin{aligned}
&P(e \mid I_{\mathrm{m}} = \sqrt{E_b}, I_{m-1} = I_{m-2} = ... = I_{m-k} = \sqrt{E_b}) \\
&= P(y_{\mathrm{m}} < 0 \mid I_{\mathrm{m}} = I_{\mathrm{m-1}} = I_{\mathrm{m-2}} = ... = \sqrt{E_b}) \\
&= P(y_{\mathrm{m}} = \sqrt{E_b}\left(1 + \sum_{i=1}^{k} a_i\right) + n < 0) \\
&= P\left(n < -(1 + \sum_{i=1}^{k} a_i)\sqrt{E_b}\right) \\
&= Q\left((1 + \sum_{i=1}^{k} a_i)\sqrt{2E_b/N_0}\right),
\end{aligned} \tag{10}$$

where $Q(\cdot)$ is the Q-function. Since the occurrence of bit '1' and '0' is equal, the total BER performance is given by,

$$\begin{aligned}
&P(e) \\
&= P\left(I_{\mathrm{m}} = \sqrt{E_b}\right)P\left(e \mid I_{\mathrm{m}} = \sqrt{E_b}\right) + P\left(I_{\mathrm{m}} = -\sqrt{E_b}\right)P\left(e \mid I_{\mathrm{m}} = -\sqrt{E_b}\right) \\
&= P\left(e \mid I_{\mathrm{m}} = \sqrt{E_b}\right) \\
&= \sum P(I_{m-1}, ..., I_{m-k})P(e \mid I_{\mathrm{m}} = \sqrt{E_b}, I_{m-1}, ..., I_{m-k}).
\end{aligned} \tag{11}$$

Time domain zero-forcing (ZF) equalization is commonly used and easy implemented to mitigate ISI [10, 11]. Suppose that the coefficient of ZF equalizer is $\{c_n\}$, the output of the equalizer $\{q_n\}$ is the convolution of $\{c_n\}$ and the channel response h, i.e.,

$$q_n = \sum_{m=-\infty}^{\infty} c_m h_{n-m} = \begin{cases} 1 & (n = 0) \\ 0 & (n \neq 0) \end{cases}. \tag{12}$$

However, for the equalizer with finite number of taps, $q_n \neq 0$ when $n \neq 0$, i.e., the residual ISI could still be found. By replacing h in (8) with $\{q_n\}$ and substituting y_{m} into (11), the improved BER performance is obtained after ZF equalization. Both the theoretical analysis and Monte-Carlo simulation on the BER performance with and without applying ZF equalization have been done. As shown in Fig. 4(b), the two results agree with each other very well. To achieve BER of $5*10^{-4}$, the total LED power is 6.2 W without applying ZF equalization; while the total LED power reduces to 3.0 W after applying ZF equalization. Therefore, ZF equalization provides 3.2-dB (= $10*\log_{10}$ (6.2/3.0)) power reduction. In addition, the BER performance with ZF equalization (red curve) is almost the same as that without ISI (blue curve), i.e., only the present received bit I_m is considered in (11), where the difference between the two curves is negligible, which means that ZF equalization mitigates the ISI in the corner significantly. Note that error free transmission could be implemented at BER of less than 10^{-3} when forward-error correction (FEC) is applied [15].

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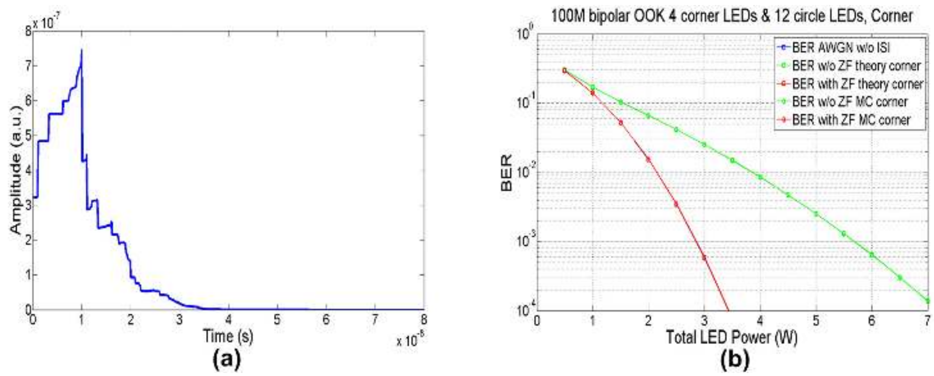

Fig. 4. 100-Mbit/s bipolar OOK signal: (a) one pulse shape of received bit ‘1’ with ISI, when the total LED power is 2 W, (b) BER performances with and without ZF equalization.

3.2 200-Mbit/s bipolar OOK signal

When the pulse rate increases to 200 Mbit/s, the ISI becomes more significant. The period of one bit is shrunk to 5 ns; however the arriving time of the light from the 16 LEDs has not been affected. The pulse shape for received bit ‘1’ of 200-Mbit/s OOK signal is shown in Fig. 5(a), where the ISI lasts for more than six periods (30 ns), which is much more severe than the case of 100-Mbit/s bipolar OOK signal. The expressions of BER performances with and without applying ZF equalization are the same as (11); however the channel response h is changed.

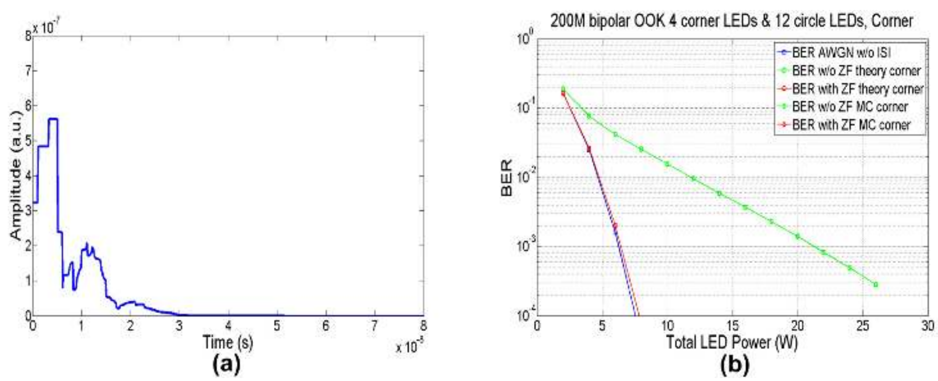

Fig. 5. 200-Mbit/s bipolar OOK signal: (a) one pulse shape of received bit ‘1’ with ISI, when the total LED power is 2 W, (b) BER performances with and without ZF equalization.

As shown in Fig. 5(b), to achieve BER of $5*10^{-4}$, a total LED power of 23.9 W is required without applying ZF equalization; while the power is reduced to 6.9 W when ZF equalization is applied. Therefore, ZF equalization provides 5.4-dB ($= 10*\log_{10}$ (23.9/6.9)) power reduction. The BER performance of 200-Mbit/s bipolar OOK signal without applying ZF equalization is much worse than that of 100-Mbit/s bipolar OOK signal. Because on the one hand the ISI is more severe, on the other hand the power of noise is determined by the data rate [5, 6], i.e., high date rate incurs high noise power. Nevertheless, the BER performance with ZF equalization is very close to that of the channel without ISI, which is to say that with the simplest equalization - ZF - the data rate could be increased to 200 Mbit/s in the LED arrangement in Fig. 2(a) without deteriorating the system performance so much. Note that the ISI in the corner is most severe in a room, with ZF equalization, the BER performances at other places with less severe ISI could also be close to that of the channel without any ISI.

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4. Channel capacity under 4 cornered-LEDs and 12 circled-LEDs arrangement

The channel capacity is the maximum mutual information for the input symbol and output signal over all the possible input distributions $P_X(\cdot)$ [12]. For the discrete-input, continuous-output channel in visible light communications, the channel capacity is given by

$$\begin{aligned} C &= \max_{P_X(\cdot)} I(X;Y) \\ &= \max_{P_X(\cdot)} \sum_{x\in X} P_X(x) \int_{-\infty}^{\infty} f_{Y|X}(y \mid x) \log_2 \frac{f_{Y|X}(y \mid x)}{f_Y(y)} dy, \end{aligned} \tag{13}$$

where x is the discrete-input symbol in the set of X, $f_Y(y)$ is the probability density function of the continuous output signal y, and $f_{Y|X}(y \mid x)$ is the conditional probability density function of y when the input symbol is x. For bipolar OOK signal, $f_{Y|X}(y \mid x)$ is given by,

$$\begin{cases} f_{Y|X}(y \mid x=-1) = \dfrac{1}{\sqrt{2\pi}\sigma_N} \exp\left(-\dfrac{(y+1)^2}{2\sigma_N^2} \right) \\ f_{Y|X}(y \mid x=+1) = \dfrac{1}{\sqrt{2\pi}\sigma_N} \exp\left(-\dfrac{(y-1)^2}{2\sigma_N^2} \right) \end{cases} \tag{14}$$

where σ_N^2 is the variance of noise.

If the received signal is deteriorated by ISI, the conditional probability density function in (14) becomes

$$\begin{aligned} & f_{Y|X}(y_m \mid x_m) \\ &= \sum p(x_{m-1},....,x_{m-k}) f_{Y|X}(y_m \mid x_m, x_{m-1},....,x_{m-k}) \\ &= \sum \frac{p(x_{m-1},....,x_{m-k})}{\sqrt{2\pi}\sigma_N} \exp\left(-\frac{\left(y - [x_m, x_{m-1},....,x_{m-k}][1, a_1,...,a_k]' \right)^2}{2\sigma_N^2} \right), \end{aligned} \tag{15}$$

where $h = [1 \;\; a_1 \;\; ... \;\; a_k]$ is the channel response as described in Section 3, x_m is the present transmitted bit and $x_{m-1},....,x_{m-k}$ are the k previous transmitted bits. Substituting (15) into (13), we will have the channel capacity of bipolar OOK signal with ISI in visible light communications.

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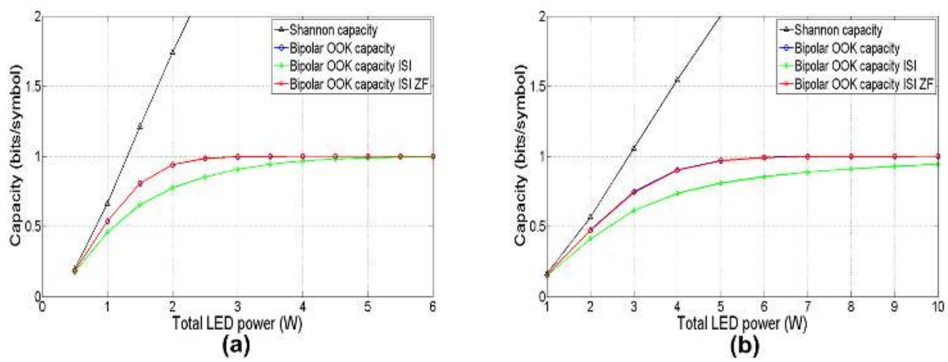

Fig. 6. Channel capacity of visible light communication under the LED arrangement in Fig. 2: (a) 100-Mbit/s bipolar OOK signal, (b) 200-Mbit/s bipolar OOK signal.

As shown in Fig. 6, the ZF equalization improves the channel capacity significantly. For the 100-Mbit/s bipolar OOK signal, the maximum channel capacity improvement by ZF equalization is 0.17 bits/symbol when the total LED power is 2 W; while for 200-Mbit/s bipolar OOK signal, the maximum channel capacity improvement by ZF equalization is 0.16 bits/symbol when the total LED power is 4 W. Note that after ZF equalization, the channel capacity (red curve) is almost the same as that of the channel without ISI (blue curve), and the difference between the two curves are negligible. As described in Section 3, ZF equalization could also make the channel capacity at other places in the room with less significant ISI performs similar to that of the channel without any ISI.

5. Conclusion

We have investigated and analyzed the performance of our recently proposed LED lamp arrangement with 4 LED lamps positioned in the corners and 12 LED lamps spread evenly on a circle to make the communication qualities almost identical for multi-users at different positions of a room. The results show that the SNR fluctuation can be reduced to only 0.9 dB. Meanwhile, ISI that incurred by the LED lamp arrangement could be mitigated significantly by ZF equalization, which provides 3.2-dB power reduction for 100-Mbit/s bipolar OOK and 5.4-dB power reduction for 200-Mbit/s bipolar OOK signal to achieve BER of $5*10^{-4}$. In addition, the maximum improvements of channel capacity by ZF equalization are 0.17 bits/symbol and 0.16 bits/symbol for 100-Mbit/s and 200-Mbit/s bipolar OOK signal, respectively. The BER performance and channel capacity after applying ZF equalization are very close to that of the channel without ISI. Therefore, the new LED lamp arrangement combined with time domain ZF equalization provide similar communication qualities to all users at different locations in a room.

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