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Research Article

Experimental Demonstration of Special-Shaped 32-Quadrature Amplitude Modulation Constellations for Visible Light Communications

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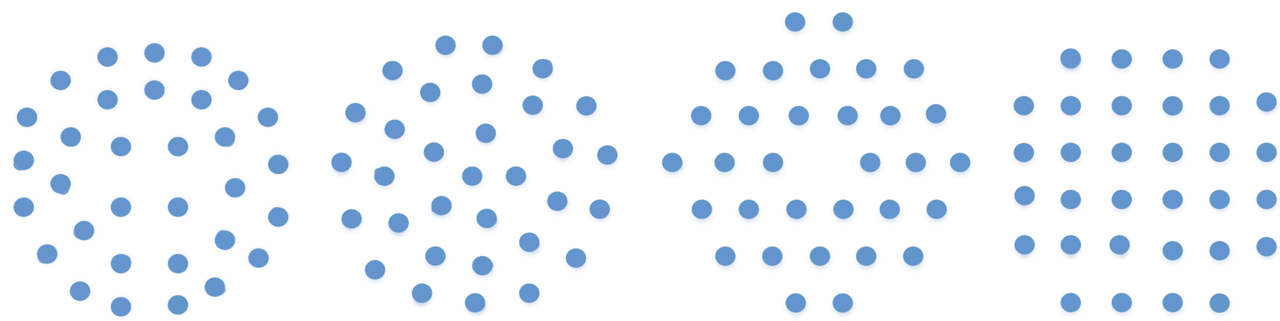
With the rapid development of light-emitting diode, visible light communication (VLC) has become a candidate technology for the next generation of high-speed indoor wireless communication. In this paper, we investigate the performance of the 32-quadrature amplitude modulation (32-QAM) constellation shaping schemes for the first time, where two special circular constellations, named Circular (4, 11, 17) and Circular (1, 5, 11, 15), and a triangular constellation are proposed based on the Shannon's criterion. Theoretical analysis indicates that the triangular constellation scheme has the largest minimum Euclidian distance while the Circular (4, 11, 17) scheme achieves the lowest peak-to-average power ratio (PAPR). Experimental results show that the bit error rate performance is finally decided by the value of PAPR in the VLC system due to the serious nonlinearity of the LED, where the Circular (4, 11, 17) scheme always performs best under the 7% preforward error correction threshold of 3.8×10^{-3} with 62.5Mb/s transmission data rate and 1-meter transmission distance.

1. Introduction

Visible light communication (VLC) based on white light-emitting diodes (LEDs) is garnering increasing attention in both academia and industry. By modulating signals onto LEDs, the dual function of lighting and communication can be realized simultaneously in VLC systems. Compared with traditional radio frequency (RF) communication, VLC shows several advantages, such as being cost effective, license free, electromagnetic interference free, and highly secure. Therefore, it has been considered one of the most compelling technologies for supplementing traditional RF communication [1, 2].

In the VLC system, high-speed transmission is limited by the modulation bandwidth determined by the LED, which is typically in the range of tens of MHz (3-dB bandwidth) only [3]. Several techniques have been proposed to improve the data rates in VLC system, such as orthogonal frequency division multiplexing (OFDM) [4, 5], multiple-input multiple-output (MIMO) [6, 7], wavelength division multiplexing (WDM) [8], preequalization [9], and high-order quadrature amplitude modulation (QAM) [10]. Among the schemes, high-order QAM is considered an efficient and simple way to increase the transmission data rate, which can always be combined with other techniques. However, the interference of ambient light noise, the high frequency attenuation of LED response, and the nonlinear effect of the LED would cause serious performance loss, restricting the application of high-order QAM in VLC system [11]. As a result, the constellation shaping technique has been studied in this paper, where more flexible constellation patterns are designed to fit for the VLC transmission system.

The constellation shaping technique has been firstly studied in wireless communication. Based on the Shannon's criterion, Thomas et al. put forward various special constellation shaping designs for M-QAM formats and provided early theoretical analysis [12]. Then Nölle et al. applied the technique to the fiber optic communications, considering a more complex channel. They compared various constellation shaping designs and reached the conclusion that the circular



(a) Circular (4, 11, 17) (b) Circular (1, 5, 11, 15) (c) Triangular (d) Rectangular

Figure 1: 32-QAM constellation designs.

constellation was the best solution by experiments [13]. Recently, Chi et al. have introduced constellation shaping into VLC system, where circular constellation was still shown to have the best performance when 8-QAM was considered in the experimental demonstration [11]. Afterwards, a special constellation shaping design of 16-QAM named Circular (1, 5, 10) [14] and then a circular constellation shaping scheme were further proposed in VLC systems [15]. Based on these studies, we find that constellation shaping technique is useful in VLC systems, where the circular constellation is proved to be particularly suitable. However, referred modulation orders in the existing research are relatively low. Besides, the circular constellation was simply formed by compressing the high-amplitude constellation points from the rectangular constellation, where the minimum Euclidian distance (ED) is not considered in the constellation design.

In this paper, we investigate the performance of the 32-QAM based on different constellation shaping schemes for the first time, where two special circular constellations, named Circular (4, 11, 17) and Circular (1, 5, 11, 15), and a triangular constellation are designed based on the Shannon's criterion. Compared with the regular rectangular constellation, theoretical analysis shows that the triangular constellation benefits from its minimum ED but suffers from high peak-to-average power ratio (PAPR), while the two circular constellations achieve much lower PAPRs. Finally, experimental demonstration is set up to study the bit error rate (BER) performance of the VLC system with different constellation shaping schemes, where the 7% preforward error correction (pre-FEC) threshold of 3.8×10^{-3} is kept as the BER bound with 62.5Mb/s transmission data rate and 1-meter transmission distance. Experimental results show that both circular constellations achieve a better tradeoff between noise resistance and nonlinearity resistance, leading to a better BER performance.

The rest of the paper is organized as follows. Section 2 provides the constellation shaping design criterions and numerical analysis results in terms of BERs and PAPRs. In Section 3, we describe the experimental setup. Then the discussions of experimental results are given in Section 4. Finally, we come to the conclusion in Section 5.

2. Principle

2.1. Constellation Designs. According to the design guidance of very large signal sets, Shannon has shown that, under an average power constraint, the channel capacity is maximized with a signal that is uniformly distributed in phase and Rayleigh distributed in amplitude, while under a peak power constraint, the capacity is maximized by a signal uniformly distributed in phase with an amplitude probability density that increases linearly with the amplitude values [16].

Following the Shannon's criterion, different constellation shaping schemes are designed in the paper, where the circular and triangular patterns are chosen. In Figure 1, two special circular constellations, named Circular (4, 11, 17) and Circular (1, 5, 11, 15), a triangular constellation, and the most common rectangular constellation are given. As shown, in order to ensure that the minimum ED is large enough, the number of circles is set equal to three in both circular constellations. Then the idea of designing the Circular (4, 11, 17) is described as follows. Firstly, signals on each circle are separated by unit distance, where numbers of points for three circles are decided to be 4, 11, and 17, respectively. Then, phases of all the points can be determined according to the design guidance of uniform phase distribution, with initial phases of three circles being $\pi/4$, $3\pi/22$, and $\pi/34$. Hence, the resulting radiuses of three circles are 0.707, 1.72, and 2.56, respectively. Different from Circular (4,11,17), distances between circles are separated by unit distance in the Circular (1, 5, 11, 15) scheme; that is, radiuses of three circles are equal to 1, 2, and 3. Then the numbers of constellation points for three circles are set as 5, 11, and 15 with the last point placed on the point of origin. Initial phases of three circles in Circular (1, 5, 11, 15) scheme are 0, $6\pi/55$, and $4\pi/165$, which are also determined by the guidance of uniform phase distribution and the consideration of the minimum ED. The approach of designing the triangular constellation is very simple, where each small triangle in the triangular constellation has the same side length, just like the design of the rectangular constellation.

2.2. Theoretical Analysis. In this section, we evaluate the symbol error rate (SER) performance of different constellation shaping schemes. Since signal decision is based on the most adjacent principle during the QAM demapping, the received

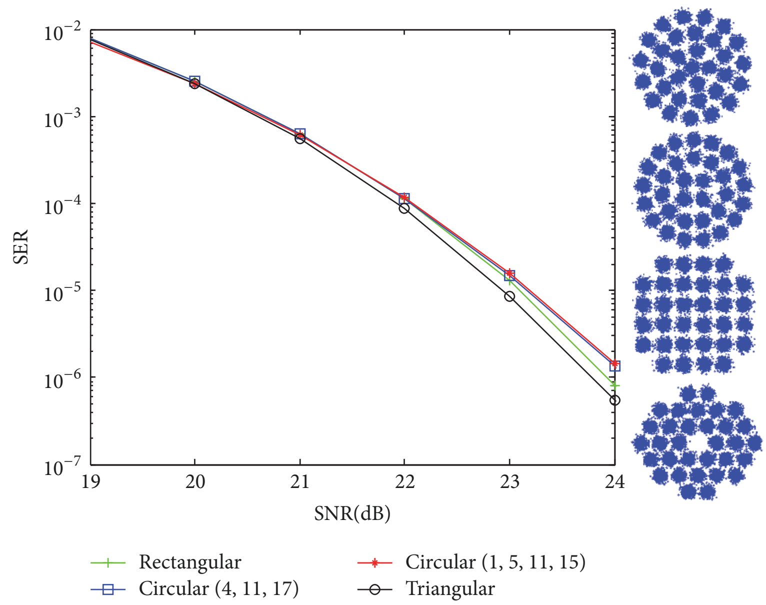


FIGURE 2: SER versus SNR.

TABLE 1: Minimum EDs of different constellation shaping schemes.

Constellation	Minimum ED
Circular (4, 11, 17)	0.4339
Circular (1, 5, 11, 15)	0.4170
Triangular	0.4619
Rectangular	0.4472

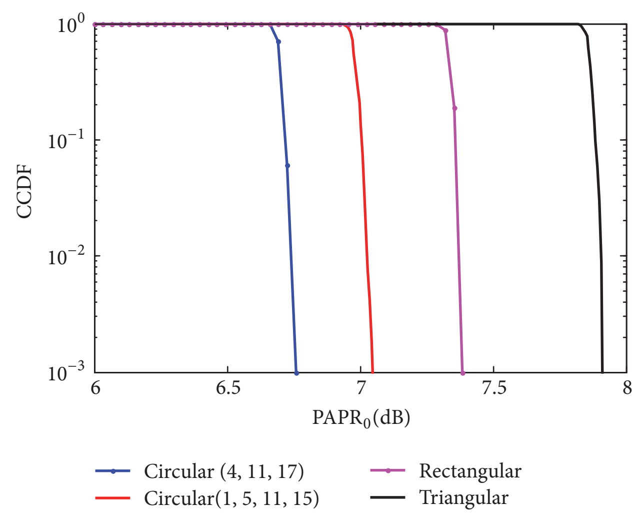


FIGURE 3: CCDF of PAPRs for different constellation shaping schemes.

signal is judged to be the nearest point in the constellation. As a result, minimum ED has been considered an important indicator during the constellation design, which decides the upper bound of the SER.

Under normalized power, minimum EDs of different constellation shaping schemes are listed in Table 1 and the simulation results of SERs under restriction of high signal-to-noise ratios (SNRs) are plotted in Figure 2. As shown, the triangular constellation scheme has the largest minimum ED, indicating its superiority in the ability of noise resistance. Curves in Figure 2 also show that the SERs are very close for different constellation shaping schemes, because the minimum EDs are actually quite close under the constraint of the power normalization.

Moreover, the PAPR of transmitted signals is another important parameter affecting the VLC system performance a lot. As we know, VLC systems suffer signal distortions from nonlinear components, among which the nonlinearity of the LED plays an important role. Because of the nonlinear relationship between the driving voltage and the forward current, the LED causes two kinds of signal distortion. One is the nonlinear mapping in electrical-to-optical conversion within the dynamic range; the other is the hard clipping of signals when the voltage is below the turn-on voltage or beyond the maximum permissible voltage [17]. Hence, high PAPR would lead to a serious distortion of the transmitted signals, which results in a severe performance loss finally. Therefore, PAPR is regarded as the ability of the nonlinearity resistance of the VLC system.

Under normalized power, PAPRs of different constellation shaping schemes are listed in Table 2, and complementary cumulative distribution function (CCDF) curves of PAPRs for different constellation shaping schemes are also plotted in Figure 3 to provide a more general analysis. The CCDF of the PAPR indicates the probability that the PAPR of a symbol block exceeds a certain threshold. It can be defined by the probability $P(PAPR > PAPR_0)$, where $PAPR_0$ stands for the given threshold. Obviously, the Circular (4, 11, 17) achieves the lowest PAPR, while the value of PAPR for triangular constellation is the highest, which is almost

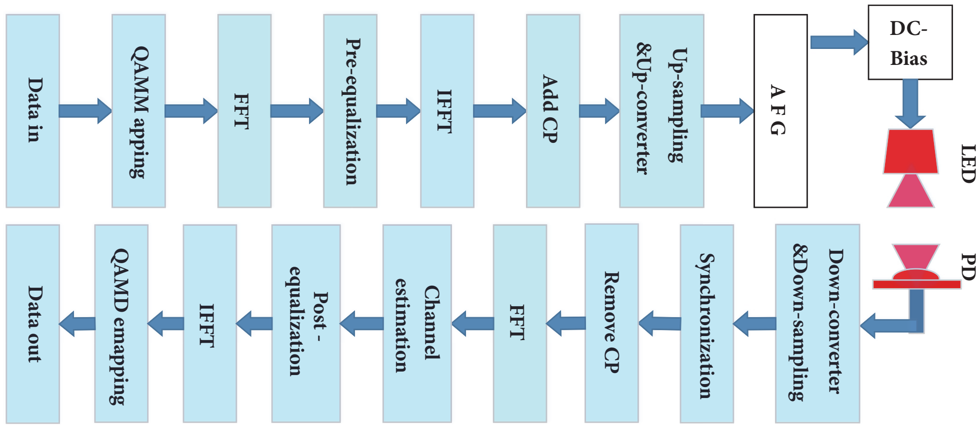


Figure 4: Block diagram of the SC-FDE based VLC system.

Table 2: PAPRs of different constellation shaping schemes.

Constellation	PAPR
Circular (4, 11, 17)	1.6651
Circular (1, 5, 11, 15)	1.9457
Triangular	2.8330
Rectangular	2.3045

twice that of the Circular (4, 11, 17) scheme. This implies that the triangular constellation would be most susceptible to nonlinear effect.

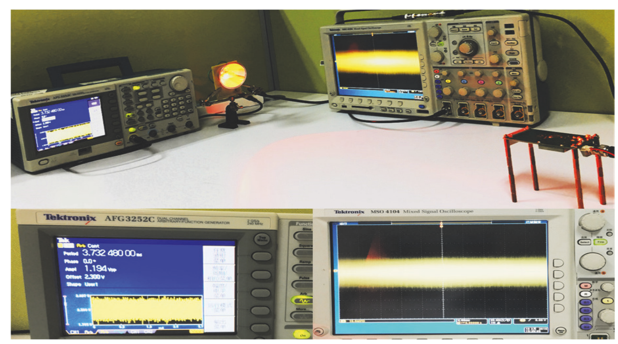


Figure 5: Experimental setup of the VLC system.

3. Experimental Setup

In Figure 4, the principle of the VLC transmission system is depicted. As shown, single carrier modulation combined with frequency domain equalization (SC-FDE) is used in the VLC system, because the PAPR of SC-FDE system is much lower than OFDM system. Meanwhile, simple frequency domain equalization can be applied to SC-FDE system as well. Digital preequalization is performed at the transmitter under the constraint of the power normalization to improve the performance further.

At the transmitter, a stream of random binary input data is firstly mapped into complex signals according to the certain 32-QAM constellation shaping scheme. Through fast Fourier transform (FFT), time-domain signals are transformed to frequency domain and the frequency domain preequalization can be implemented based on the prior knowledge of channel state information (CSI), which is obtained by channel estimation at the receiver. After that, signals are transformed to time domain again by inverse fast Fourier transform (IFFT), and cyclic prefix (CP) is attached to overcome the ISI. We insert a preamble in front of the data stream for synchronization and channel estimation at the receiver. Since only real and positive signals are allowed to transmit in VLC system, the up-sampling and up-converting operations are applied, where real-value signals are obtained by the complex-to-real-value conversion [18]. Finally, positive signals are obtained by simply adding the direct current (DC) offset. At the receiver, frame synchronization, channel estimation, and postequalization are carried out to eliminate the effect of the channel with the help of the preamble. The rest processing is the inverse process of the signal modulation at the transmitter.

Figure 5 shows the experimental setup of the VLC system. Signals are generated offline and uploaded into an arbitrary function generator (AFG: Tektronix AFG3252C). DC is also supplied by AFG to ensure the positivity of the transmitted signals. Then, mixed signals are transmitted through the LED in the form of the optical power. At the receiver, optical signals entering the PD are converted into electrical signals, which are recorded by a high-speed digital oscilloscope (OSC: Tektronix MSO4104). Then, the offline demodulation is processed by the computer. We use a commercially available LED (Cree XLamp XP-E) with center wavelengths of 620 nm as the transmitter. We use a PD module (Hamamatsu C12702-11, 0.42A/W responsivity at 620 nm) with 1 mm^2 active area and about 100 MHz bandwidth as the receiver.

In the experiments, system parameters are listed as follows: the transmission bandwidth is set as 12.5MHz and the up-converted frequency is 6.25MHz; the IFFT/FFT point is 256 and the length of CP is 16; the transmitted data rate is 62.5Mbit/s; the distance between the LED and PD is 1-meter.

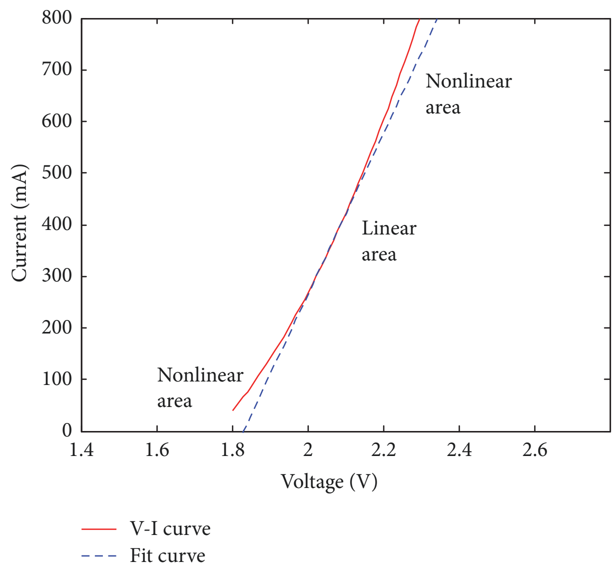


Figure 6: U-I curve of the LED.

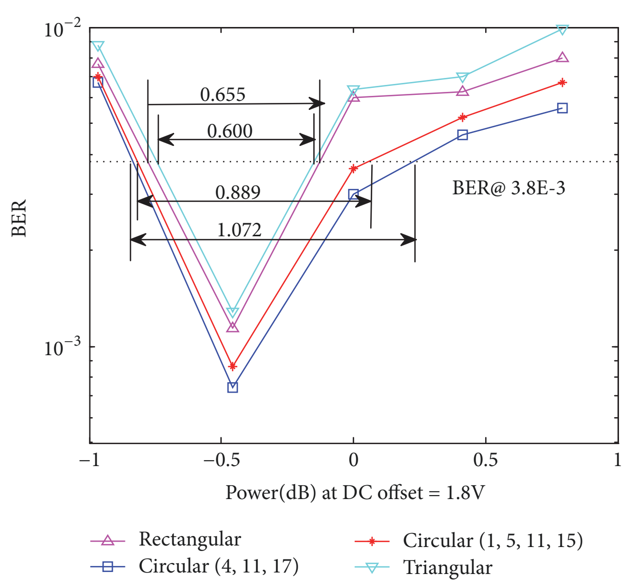


Figure 7: BER versus transmitted electrical power when DC offset is equal to 1.8V.

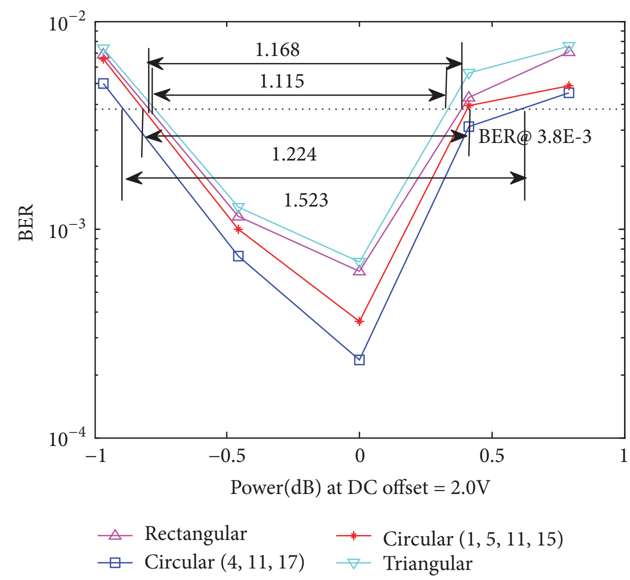


Figure 8: BER versus transmitted electrical power when DC offset is equal to 2.0V.

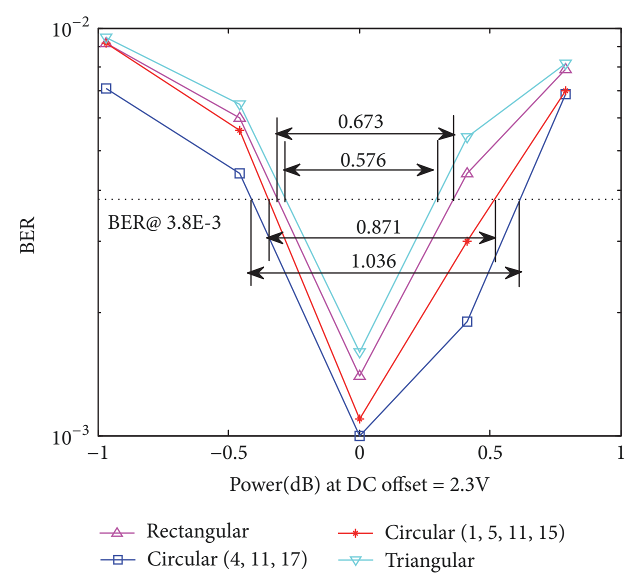


Figure 9: BER versus transmitted electrical power when DC offset is equal to 2.3V.

4. Experimental Results and Discussions

In this section, BER performance of the VLC system based on different constellation shaping schemes is evaluated by experiments, where BERs are measured with different DC offsets and different transmitted electrical power. In Figure 6, U-I curve of the LED used in the experiment is given, which shows that the U-I curve becomes nonlinear when the voltage is below 1.9 V or above 2.3V. Therefore, the DC offsets are set as 1.8V, 2.0V, and 2.3V, respectively. When the DC offset is equal to 1.8V or 2.3V, the LED works in the nonlinear region most of the time; when the DC offset is equal to 2.0V, the LED may work in the linear region more often.

Figures 7, 8, and 9 illustrate the measured BERs versus transmitted electrical power when DC offsets are set as 1.8V, 2.0V, and 2.3V, respectively. The experimental results show that the Circular (4, 11, 17) scheme always achieves the best BER performance while the triangular scheme is the worst, which is quite different from the simulation result in Figure 2. As discussed above, minimum EDs for different constellation shaping schemes are quite close and they would not result in large BER gaps. Therefore, the BER performance mainly depends on the PAPRs, which indicate that the nonlinearity plays a dominant role in BER evaluation in the VLC system. Hence, the Circular (4, 11, 17) scheme with the lowest PAPR achieves the best BER performance. Besides, when keeping the DC offset fixed, BERs are also varied with the transmitted power increasing, where the tendencies of different constellation schemes are almost the same. At the beginning, BER decreases because of the SNR enhancement when the transmitted power is increased. However, BER would increase when the transmitted power continues to grow. It means that the nonlinearity of the LED would affect the BER performance more at that moment, resulting in the deterioration of the BER performance.

Furthermore, we label the dynamic ranges of the transmitted electrical power based on the 7% pre-FEC threshold of 3.8×10^{-3}. Obviously, profiting from the lowest PAPR, the Circular (4, 11, 17) scheme shows a significant advantage in the dynamic range compared with other three schemes. The Circular (1, 5, 11, 15) scheme also gains a wide dynamic range, while the dynamic ranges of the rectangular scheme and the triangular scheme are much narrower than those of the two circular constellation schemes. Compared with the results in the three figures, it can be observed that the dynamic range of the transmitted electrical power is maximized when the DC offset is equal to 2.0V. In particular, the dynamic ranges of the rectangular scheme and the triangular scheme in Figure 8 are almost twice those in Figures 7 and 9. This result proves that the LED works in the linear region more often when the DC offset is equal to 2.0V. Therefore, best BER performance is achieved and performance gaps among different constellation shaping schemes become smaller.

5. Conclusion

In this paper, three kinds of 32-QAM constellation shaping schemes are proposed and demonstrated in an SC-FDE based VLC system, where two special circular constellations, named Circular (4, 11, 17) and Circular (1, 5, 11, 15), and a triangular constellation are designed based on the Shannon's criterion. Then, theoretical analysis including minimum ED and PAPR is studied through computer simulation, indicating that the triangular constellation owns the largest minimum ED and the Circular (4, 11, 17) has the lowest PAPR. Finally, experimental results show that the Circular (4, 11, 17) scheme always achieves the best BER performance with different DC offsets and different transmitted electrical power, which leads to the conclusion that the nonlinearity plays a dominant role in BER evaluation of the VLC system.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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