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Optimal Transmission Power in a Nonlinear VLC System

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Abstract

In a visible light communication (VLC) system, the light emitting diode (LED) is nonlinear for large signals, which limits the transmission power or equivalently the coverage of the VLC system. When the input signal amplitude is large, the nonlinear distortion creates harmonic and intermodulation distortion, which degrades the transmission error vector magnitude (EVM). To evaluate the impact of nonlinearity on system performance, the signal to noise and distortion ratio (SNDR) is applied, defined as the linear signal power over the thermal noise plus the front end nonlinear distortion. At a given noise level, the optimal system performance can be achieved by maximizing the SNDR, which results in high transmission rate or long transmission range for the VLC system. In this paper, we provide theoretical analysis on the optimization of SNDR with a nonlinear Hammerstein model of LED. Simulation results and lab experiments validate the theoretical analysis.

Keywords

nonlinearity; light emitting diode (LED); SNDR

1 Introduction

Visible light communication (VLC) systems become attractive as they utilize the unlicensed visible light spectrum that has 1000 times larger bandwidth than the conventional radio frequency (RF) spectrum [1]. Moreover, existing illumination devices and illumination infrastructure can be easily upgraded to accommodate wireless data transmission [2].

In a VLC system, spectrum efficiency is very critical because the frequency response of the light emission diode (LED) is limited. Orthogonal frequency division modulation (OFDM), which is widely used in wireless communications because of its high spectral efficiency, can be applied to the VLC system with modifications. In the VLC system, the signal is modulated on light intensity (IM) of LED [3]. At the receiver side, the photon detector (PD) is applied with direct detection (DD) of the light intensity. Since the LED at the transmitter and the PD at the receiver only deal with real and positive signals, conventional OFDM signals need to be modified to meet such the requirement. The real-valued OFDM can be obtained by introducing Hermitian symmetry, such as direct current biased optical OFDM (DCO-OFDM) [4], asymmetrically clipped optical OFDM (ACO-OFDM) [5], pulse-amplitude-modulated discrete multitone modulation (PAM-DMT) [6], and unipolar OFDM (U-OFDM) [7].

Many efforts have been made to improve the transmission rate of the VLC system. The authors in [8] achieved 40 Mb/s data rate on 25 MHz bandwidth at a distance of 2 m with the normal room illumination level. In [9], 1.1 Gb/s data rate was achieved at a distance of 23 cm by employing carrier-less amplitude and phase modulation (CAP). Besides, 4.2 Gb/s data rate was achieved using wavelength multiplexing division with red-green-blue (RGB) LED at a distance of 10 cm [10]. It can be found that there is an inverse relationship between the transmission range and data rate. In conventional wireless communication systems, the data rate and transmission range can be improved simultaneously if the transmission signal power increases. However, nonlinear effects in the VLC system are more severe with large input signals than those with small signals. The nonlinear effects significantly degrade system performance and limit the application of spectral efficient modulation schemes. Therefore, the research on nonlinear effects in the VLC system is necessary.

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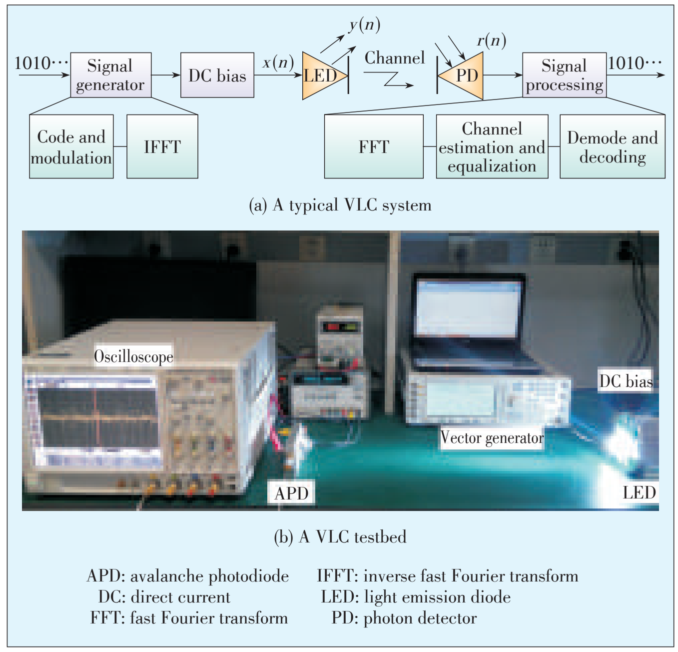
The authors in [11] studied the VLC system performance with clipping effects. In order to compensate for the nonlinear effects of LED, digital predistortion (DPD) was applied in the transmitter at the expense of an additional feedback path [12], [13]. Adaptive post-distortion algorithm for nonlinear LEDs delivered similar performance as the DPD at no additional hardware cost [14]. The Volterra equalization used to compensate for the nonlinearity of LEDwith memory effects was discussed in [15]. The authors in [16] optimized the SNDR in the family of dynamic-constrained memoryless nonlinearities and found out the optimal nonlinear mapping. In order to mitigate the nonlinearity of LED, we have also proposed two methods. We used a one-bit sigma-delta modulator to convert the multi-level input signal into the binary input signal with signal LED, thus avoiding LED nonlinearity [17]. Moreover, a new system architecture was proposed with micro-LED arrays, which provides digital controls to each element. The multi-level signal is realized with multiple elements in the micro-LED array, and a linear transmission is achieved for signals with large peak-to-average power ratio (PAPR) [18]. In this paper, we study the LED nonlinearity and provide theoretical analysis on the optimization of SNDR with a general nonlinear Hammerstein model of LED.

The rest of paper is organized as follows. Section 2 provides a setup of VLC system. The performance metric SNDR is introduced for the nonlinear LED model. The optimal transmission power is obtained with theoretical derivation. Section 3 shows simulation results as well as experiment measurements of the SNDR optimization. These results validate the theoretical analysis. Section 4 concludes this paper.

2 Optimization of SNDR

In a typical VLC system (**Fig. 1a**), the information bits are coded and modulated first. The transmit signal is generated by the inverse discrete Fourier transform (IDFT), which is realized by inverse Fast Fourier transform (IFFT) algorithm. A direct current (DC) bias is applied to ensure that the LED works properly as an illumination device. The input signal $x(n)$ directly modulates the lighting intensity of the LED and generates the lighting signal $y(n)$. A typical power delay profile of the VLC channel with additive white Gaussian noise (AWGN) is considered [19]. The received signal $r(n)$ is obtained by PD at the receiver. The DC component is ignored since it carries no information. The received information bits can be obtained by the baseband processing including synchronization, discrete Fourier transform (DFT), channel estimation, equalization, and demodulation. Similar with IDFT, the DFT is realized by the Fast Fourier transform (FFT) algorithm. **Fig. 1b** shows an experimental VLC system. The vector signal generator Agilent E4438 is used to generate the baseband signal. With a bias power amplifier, the signal is applied to drive the LED. At the receiver side, the avalanche photodiode (APD) is used for reception. The digital signal analyzer Agilent DSA 90804 is used to capture the received signal.



(a) A typical VLC system

(b) A VLC testbed

▲**Figure 1. Setup of a visible light communication system.**

The LED and PD are both nonlinear devices. At a reasonable radiant flux range, the nonlinearity of the PD is not significant and is ignored during the analysis of this paper. Besides, the PD works in linear region in our simulation and experiment. For the intensity modulated LED, the output signal is a nondecreasing function of the input signal, and the output becomes saturate when the input signal is large. Furthermore, most LEDs have limited bandwidths (from kHz to MHz) and the frequency response or the memory effect shows up. The nonlinearity with memory effects between input voltage and output luminous flux can be described by the Hammerstein model that consists of a memoryless polynomial nonlinear block and a linear time-invariant (LTI) system block [20].

The memoryless nonlinearity can be described by a polynomial model $f(\cdot)$:

$$f\left(x(n)\right)=\sum_{p=1}^{P}a_p x(n)^p \qquad (1)$$

The LTI system can be modeled by an FIR filter $g(\cdot)$ as

$$y(n)=g\left(f\left(x(n)\right)\right)=\sum_{l=0}^{L-1}b_l f(x(n-l)) \qquad (2)$$

In (1) and (2), $y(n)$ is the output luminous flux of LED; $x(n)$ is the input voltage signal; a_p is the pth order coefficient of polynomial model, where the model coefficients can be estimated with LS/RLS solution adaptively, and the computational complexity of RLS algorithm is on the order of $O((K*(D+1))^2)$ [14]; l is the maximum delay tap; and b_l is the coefficient of filter.

Decomposing the output of polynomial nonlinearity $f(x(n))$ into the linear signal part and the distortion part, the nonlinear mapping (1) can be rewritten as [21]

$$f(x(n)) = \alpha x(n) + d(n) \tag{3}$$

where $d(n)$ is the distortion term that is orthogonal to $x(n)$, i.e., $E[x(n)d(n)]=0$; α is a constant given by $\alpha = E[xf(x)]/E[x^2] = E[xf(x)]/\sigma_x^2$, where σ_x^2 is the variance of $x(n)$. By definition, we have $E[f^2(x(n))] = \alpha^2\sigma_x^2 + \sigma_d^2$.

For a typical VLC channel, the received signal $r(n)$ is

$$r(n) = h(y(n)) + v(n) = h(g(f(x(n)))) + v(n) \tag{4}$$

where $h(\cdot)$ is channel model for VLC [19] and $v(n)$ is the total noise including ambient lighting noise and thermal noise.

Without loss of generality, we assume that the frequency response of the LED and that of the channel are perfectly equalized with conventional equalization algorithms. We have

$$\varnothing(r(n)) = \alpha x(n) + d(n) + Gain_{\varnothing(\cdot)} v(n) \tag{5}$$

where $\varnothing(\cdot)$ is the inverse function of the cascaded frequency response of the LED and the channel response. $\varnothing(\cdot)$ satisfies

$$\varnothing(\cdot) \star h(g(\cdot)) = 1 \tag{6}$$

where $\star$ denotes the time domain convolutional.

Normalizing the channel gain of the VLC system $\varnothing(\cdot)$, the variance of the noise remains the same as σ_v^2. The optics SNDR is defined as the linear signal power over the noise power and the distortion power, or

$$SNDR = \frac{\alpha^2\sigma_x^2}{\sigma_x^2 + \sigma_v^2} = \frac{E\left[xf(x(n))^2\right]/\sigma_x^2,}{E\left[f^2(x(n))\right] - \dfrac{E\left[x(n)f(x(n))\right]^2}{\sigma_x^2} + \sigma_v^2} \tag{7}$$

From (7), we observe that the SNDR is determined by the input baseband signal power, nonlinearity of the LED and the noise power. Intuitively, when the input signal is small, the SNDR is small, and vice versa. However, when the input signal becomes very large, the nonlinear distortion dominates and the SNDR degrades. There exists an optimal transmission power for a given noise level.

To simplify the discussion, we assume that the input signal $x(n)$ follows a Gaussian distribution. This assumption is quite accurate if modified OFDM signal, which significantly improves the spectral efficiency, is used for VLC systems [5]. For a Gaussian random variable, the expectation on the polynomial term $E[xp(n)]$ is given by [22]:

$$E\left[x^p(n)\right] = \begin{cases} (p-1)!!\,\sigma_x^p & p\ even \\ 0 & p\ odd \end{cases} \tag{8}$$

where $(\cdot)!!$ denotes the double factorial operation and $(p-1)!! = (p-1)(p-3)\cdots 3\cdot 1$ when p is even.

Substituting (1) and (8) into (7), we have (9).

$$SNDR = \frac{E\left[\sum_{p=1}^{P} a_p x^{p+1}(n)\right]^2 \Big/ \sigma_x^2}{E\left[\left(\sum_{p=1}^{P} a_p x^p(n)\right)^2\right] - E\left[\sum_{p=1}^{P} a_p x^{p+1}(n)\right]^2 \Big/ \sigma_x^2 + \sigma_v^2} = \frac{\sum_{i=1}^{P}\sum_{j=1}^{P} a_i a_j E\left[x^{i+1}(n)\right]E\left[x^{j+1}(n)\right]/\sigma_x^2}{\sum_{i=1}^{P}\sum_{j=1}^{P} a_i a_j E\left[x^{i+j}(n)\right] - \sum_{i=1}^{P}\sum_{j=1}^{P} a_i a_j E\left[x^{i+1}(n)\right]E\left[x^{j+1}(n)\right]/\sigma_x^2 + \sigma_v^2} = \frac{\sum_{i,odd}\sum_{j,odd} i!!j!!\,a_i a_j \sigma_x^{i+j}}{\sum_{i,odd}\sum_{j,odd}\left((i+j-1)!! - i!!j!!\right)a_i a_j \sigma_x^{i+j} + \sum_{i,even}\sum_{j,even}(i+j-1)!!\,a_i a_j \sigma_x^{i+j} + \sigma_v^2} \tag{9}$$

As an example, for a 5th order nonlinearity, $P = 5$. The SNDR in (9) reduces to (10).

$$SNDR = \frac{a_1^2\sigma_x^2 + 6a_1a_3\sigma_x^4 + \left(9a_3^2 + 30a_1a_5\right)\sigma_x^6 + 90a_3a_5\sigma_x^8 + 225a_5^2\sigma_x^{10}}{3a_2^2\sigma_x^4 + 6a_3^2\sigma_x^6 + \left(105a_4^2 + 120a_3a_5\right)\sigma_x^8 + 720a_5^2\sigma_x^{10} + \sigma_v^2} \tag{10}$$

The nonlinear function of LED is nondecreasing and convex for the input signal range, which implies the first-order derivative $\partial f(x)/\partial x > 0$ and the second - order derivative $\partial 2f(x)/\partial x2 < 0$. After some mathematical derivations, the numerator of (9) is concave and the denominator of (9) is convex. From [23], we conclude that the SNDR expression is pseudo-concave, which guarantees that a global maximum can be achieved within the input signal range. Optimization tools can be used to find the optimal value numerically [24].

As an example, for a 3th order nonlinearity, $P = 3$. The SNDR in (9) reduces to (11)

$$SNDR = \frac{a_1^2\sigma_x^2 + 6a_1a_3\sigma_x^4 + 9a_3^2\sigma_x^6}{3a_2^2\sigma_x^4 + 6a_3^2\sigma_x^6 + \sigma_v^2} \tag{11}$$

$$SNDR = \frac{1.9557\sigma_x^2 - 15.7179\sigma_x^4 + 31.5799\sigma_x^6}{0.0022\sigma_x^4 + 21.0541\sigma_x^6 + \sigma_v^2} \tag{12}$$

We define (13) and (14) and have (15) and (16)

$$P\left(\sigma_x^2\right) = a_1^2\sigma_x^2 + 6a_1a_3\sigma_x^4 + 9a_3^2\sigma_x^6, \tag{13}$$

$$Q\left(\sigma_x^2\right) = 3a_2^2\sigma_x^4 + 6a_3^2\sigma_x^6 + \sigma_v^2 \tag{14}$$

$$\partial P\left(\sigma_x^2\right)/\partial\sigma_x^2 = a_1^2 + 12a_1a_3\sigma_x^2 + 27a_3^2\sigma_x^4 = 1.9558 - 31.4360\sigma_x^2 + 94.7397\sigma_x^4, \tag{15}$$

$$\frac{\partial Q\left(\sigma_x^2\right)}{\partial\sigma_x^2} = 6a_2^2\sigma_x^2 + 18a_3^2\sigma_x^4 = 0.0044\sigma_x^2 + 63.1623\sigma_x^4 \tag{16}$$

When the signal-to-noise ratio (SNR) is estimated, σ_v^2 can be express as σ_x^2/SNR, the optimal signal power σ_x^2 is calculated by

$$\frac{\partial SNDR}{\partial \sigma_x^2}=\frac{\partial P(\sigma_x^2)/\partial\sigma_x^2\cdot Q(\sigma_x^2)-P(\sigma_x^2)\cdot\partial Q(\sigma_x^2)/\partial\sigma_x^2}{Q(\sigma_x^2)^2} \quad (17)$$

The valid input range of signal for the nonlinear coefficient a_1, a_2, a_3 is [−0.5, 0.5]. When the thermal noise is 0 dBm, $\sigma_v^2 = 0.001$. When the optimal input signal power is -15.93 dB, $\sigma_x^2 = 0.0255$.

3 Simulation and Experiment

To validate the optimal SNDR result, a VLC system was set up for simulation (Fig. 1b). A white LED (LE UW S2LN) from OSRAM was used in our experiment [25]. The LED's turn on voltage (TOV) is 2.7 V. The maximum input voltage is 3.7 V, which is limited by the maximum permissible current of the LED. The input signal is clipped when it is above the maximum voltage 3.7 V. A DC bias with VDC = 3.2 V is superimposed on the input signal using a bias power amplifier (LZY-22+) from Minicircuits to obtain a reasonable operation region. The normalized polynomial model coefficients with highest nonlinear order P = 5 and the frequency response of the LED are obtained by the real-time measurement. The coefficients of polynomial model are shown in **Table 1**, and the coefficients of the LTI system shown in **Table 2**. **Fig. 2a** compares the P-V transfer characteristics of the polynomial model and the combination of P-I and I-V curves from the datasheet. The APD C12702-12 from Hamamatsu is used in the receiver. The communication distance of the VLC system is 50 cm during the experiment, which make the PD works in linear region. The blue solid line in the figure shows the combined P-V curve from the datasheet, while the red dotted line shows the P-V curve obtained by the curve fitting of a 5th order polynomial model. The approximation error can be ignored between the blue line and the red dash line. **Fig. 2b** shows the measured frequency response of LTI system for the Hammerstein model.

A DCO-OFDM signal is applied in Fig. 1a [4]. The information bits are modulated with uncoded 64-quadrature amplitude modulation (QAM). The IDFT size of the DCO-OFDM is 256; the positive subcarriers are assigned with modulated data symbols and the negative subcarriers are loaded with their complex conjugates. The signal bandwidth is 10 MHz. We consider a typical realization of the DCO-OFDM signal, and the average power is at least 10 dB lower than the peak power, that is $\sigma_x^2 < 0.3$, to avoid the clipping distortion at the analog-to-digital converter (ADC). With the measured model coefficients in Table 1, the SNDR in (10) can be expressed as (18).

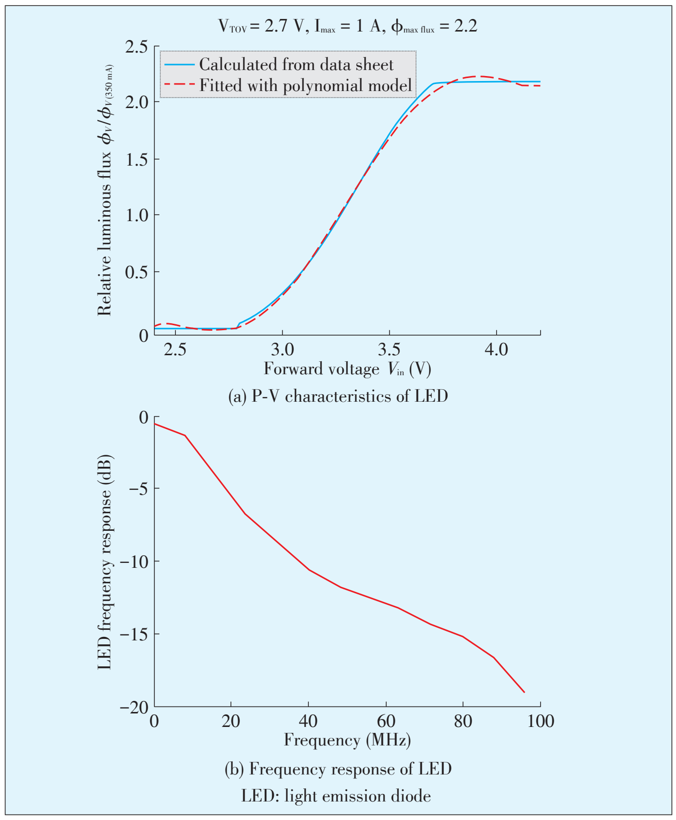
$$SNDR=\frac{1.9557\sigma_x^2-15.7179\sigma_x^4+73.5396\sigma_x^6-168.61\sigma_x^8+225.0496\sigma_x^{10}}{0.0022\sigma_x^4+21.0541\sigma_x^6-224.6562\sigma_x^8+720.1587\sigma_x^{10}+\sigma_v^2} \quad (18)$$

▼**Table 1. Normalized polynomial coefficients of a measured white LED**

Model coefficient	a_1	a_2	a_3	a_4	a_5
Normalized value	1.3985	0.0269	-1.8732	-0.0387	1.0001

▼**Table 2. LTI coefficients of a measured white LED (spectrum response)**

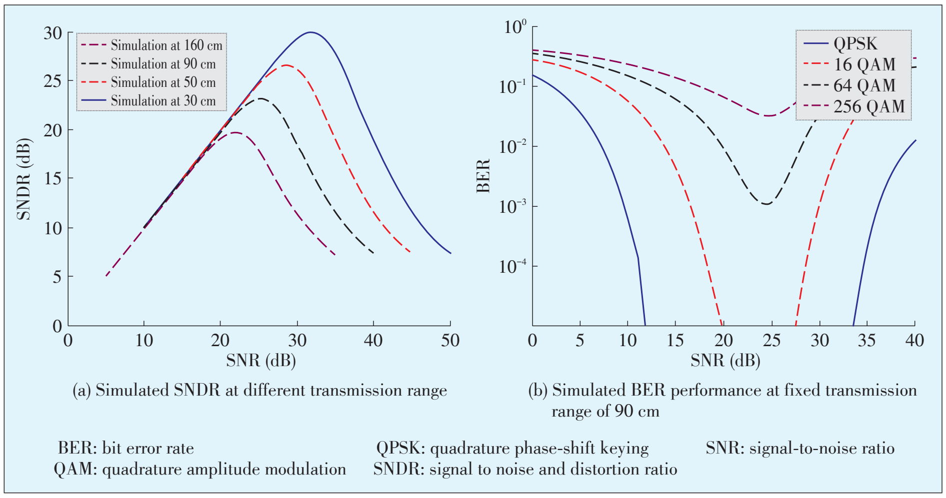
Coefficient	b_0	b_1	b_2	b_3	b_4	b_5
Value	0.0189	0.2976	0.2288	0.1348	0.1176	0.0695
Coefficient	b_6	b_7	b_8	b_9	b_{10}	b_{11}
Value	0.0578	0.0374	0.0258	0.0189	0.0133	0.0097



▲**Figure 2. Characteristics of LED in experiment.**

The numerical results show that the second order derivative of the numerator in (18) is negative when $\sigma_x^2 < 0.37$, and the second order derivative of the denominator is positive when $\sigma_x^2 < 0.56$. The numerator in (18) is concave and the denominator in (18) is convex during the input signal range within $\sigma_x^2 <$ 0.3. From the previous discussion, we know that the SNDR expression is pseudo-concave and hence a global optimum can be efficiently found via numerical methods.

Fig. 3a shows the SNDR results from SNR with the transmission ranges of 30 cm, 50 cm, 90 cm, and 160 cm. The signal power is determined by the transmission range and the constant noise comes from APD and the ambient lighting noise. According to Fig. 3a, the SNR is determined by the communication distance, with a constant noise level which comes from

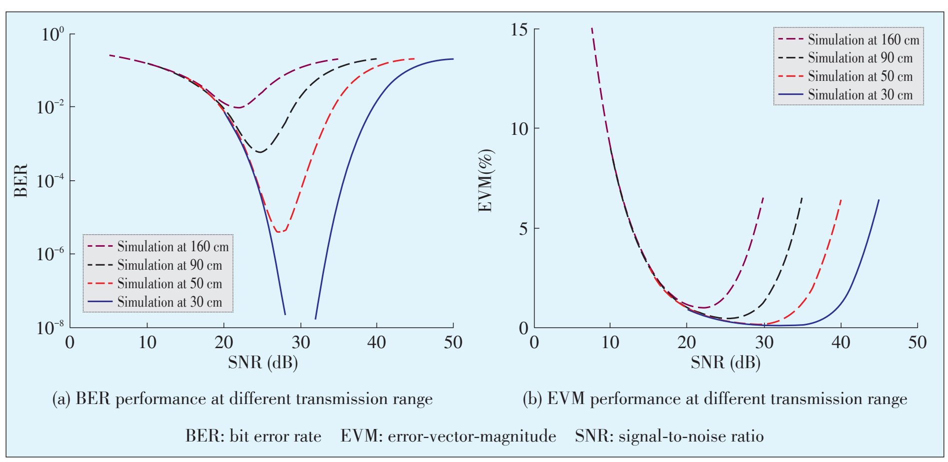


▲**Figure 3. System performance of a 5th order nonlinear DCO-OFDM system with uncoded QAM modulation.**

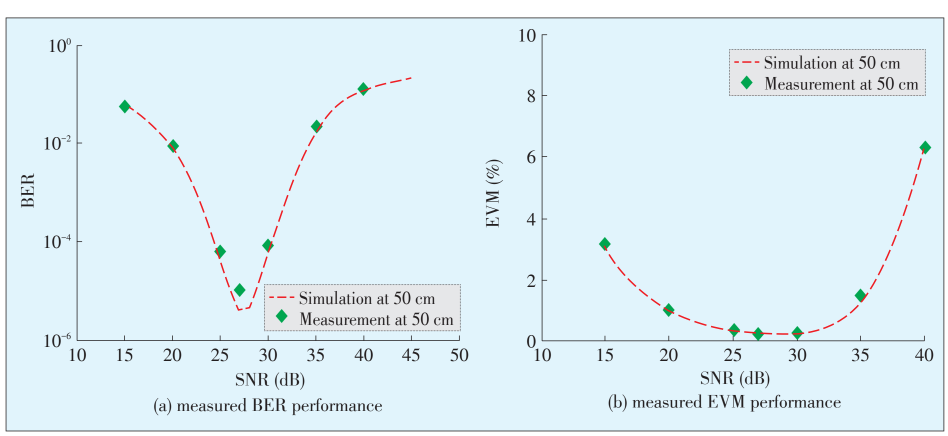
LED and APD. In addition, there always exists an optimal value for the SNDR. When the input signal is very small, the distortion is negligible. The SNDR increases with the SNR increase. When the signal power increases, the distortion also increases. For the red dashed line, a maximum SNDR of 27 dB is achieved when the SNR is 28 dB. When the signal is too large, the SNDR decreases and the system performance is degraded. Moreover, different optimal SNDR values are achieved at different communication distances in Fig. 3a. Higher optimal SNDR can be achieved at a higher SNR level with shorter communication distance, which agrees with our theoretical analysis.

The optimal transmission power for the maximum SNDR can be validated by the bit error rate (BER) performance. **Fig. 3b** shows system BER performance for different modulations. The transmission range is fixed at 90 cm. A total number of 1.92 × 108 information bits are transmitted. In Fig. 3b, the lines from top to bottom show the BER performance of QPSK, 16QAM, 64QAM and 256QAM signals, respectively. The optimal BER performance is yielded at SNR of 25 dB (or SNDR of 23.2 dB). To achieve the same BER level, a higher order modulation requires higher SNDR than a lower order modulation. At the same transmission range, the nonlinearity limits the application of high - order modulation schemes. In other words, the nonlinearity of the LED becomes the bottleneck of the communication range of the system.

The optimal transmission power for the maximum SNDR was also validated by error-vector-magnitude (EVM) performance. A total number of 1.92 × 108 information bits are transmitted for each test. **Fig. 4** shows the BER and EVM performance of QPSK, 16QAM, 64QAM and 256QAM modulation, while **Fig. 5** shows the measured performance at distance of 50 cm (the green diamond dots) and the simulated performance for the same communication distance (the red dashed lines). EVM in Fig. 4 gets the samesystem performance as the SNDR in Fig. 3. Besides, the measurement results agree with the simulation results (Fig. 5).According to Fig. 4a, with the 64QAM modulation, the VLC transmission range is limited within 1 meter. The nonlinearity



▲**Figure 4. System performance of a 5th order nonlinear DCO-OFDM system with uncoded QAM modulation.**



▲**Figure 5. System performance of a 5th order nonlinear DCO-OFDM system with uncoded QAM modulation at 50 cm transmission range.**

becomes the bottleneck of the system performance. The long communication range demands high transmission power, which in turn creates large nonlinearity and limits the overall system performance. Compensation of the system nonlinearity is needed to improve the transmission data rate or extend the transmission range.

4 Conclusions

The nonlinear distortion created by LED limits the performance of VLC systems. Large signals are distorted by the nonlinearity and small signals are vulnerable to noise. In this paper, we perform theoretical analysis on the optimization of SNDR, which provides a guidance of choosing optimal transmission power for a given thermal noise level. Simulation results and experimental measurements validate our theoretical analysis. Compensation of the system nonlinearity is critical for improving the transmission data rate or extending the transmission range.

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