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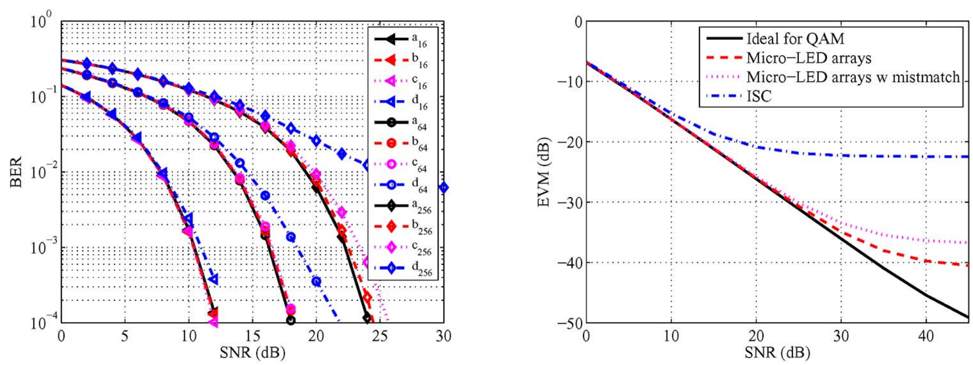


(a) BER performance.

(b) EVM performance.

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# Digitally Controlled Micro-LED Array for Linear Visible Light Communication Systems

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**Abstract:** In a visible light communications (VLC) system, the frequency response of the light-emitting diode (LED) limits the signal bandwidth and, thus, becomes the bottleneck of the transmission data rate. The recent technology breakthrough of the micro-LED array has the potential to improve the modulation bandwidth of the LED by ten times. On the other hand, the nonlinearity of the micro-LED array is significant. Nonlinear distortion degrades system performance in both the achievable data rate and the transmission range. In this paper, we propose a digitally controlled micro-LED array architecture for the VLC system, which enjoys the benefit of wide modulation bandwidth of the micro-LED array and avoids the disadvantage of the nonlinear distortion. Compared with existing multiple LED structures, the proposed micro-LED array architecture shows robustness against nonlinear distortion.

**Index Terms:** Light-emitting diode (LED), micro-LED array, nonlinearity, visible light communications.

## 1. Introduction

The wireless spectrum is limited and becomes a bottleneck of the continuously increasing demand for mobile data transmission [1]. Visible light communication (VLC) has attracted much attention recently as it utilizes the visible light spectrum [2]. As an example, a peak data rate of 4.2 Gbit/s was achieved with the red-green-blue (RGB) LED in [3] and demonstrated the huge potential of the VLC.

High-speed data transmission in VLC is mainly limited by the modulation bandwidth of the LED. The 3 dB bandwidth of conventional LED is 15 to 50 MHz. Advances in materials and processes are called for. Recently, in [4], it is shown that GaN-based micro-LED array with pixels on 100 um scale, could provide wider bandwidths than conventional commercial counterparts. With the new micro-LED array technology, a peak data rate of 1 Gbit/s was achieved without complicated signal processing [4]. In [5], a micro-LED structure based on the A1InGaN alloy

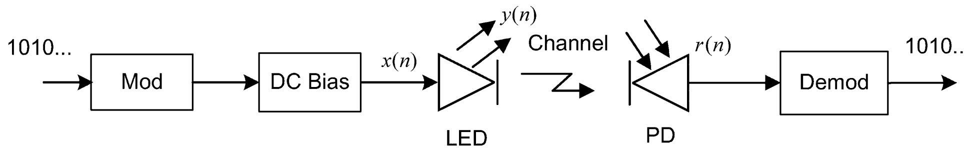


Fig. 1. Block diagram of a typical VLC system.

structures is proposed, and the optical modulation bandwidth of 400 MHz is shown. In [6], an easily-controllable optical multiple input multiple output (MIMO) system with 1.5 Gbit/s is investigated with independent data inputs per CMOS-controlled micro-LED pixels. The advances in the LED materials and designs enable VLC system design for higher data rate.

To further improve the transmission rate, the nonlinearity in the transmitter cannot be ignored [7]. The nonlinearity of the LED becomes significant when the device is driven towards the saturation point. Nonlinear distortion degrades the system performance like error vector magnitude (EVM) and bit error rate (BER). Binary signals such as on-off keying (OOK) modulation and variable pulse-position modulation (VPPM) can be applied to avoid nonlinear effects. However, the spectral efficiency of such signals is as low as 1 bit/Hz, which is not suitable for high speed transmission [8]. The authors in [9] proposed to apply a one-bit sigma–delta modulator converting multi-level input signal to binary input signal, thus avoiding LED nonlinearity. To mitigate the nonlinear distortion of LED, adaptive digital predistortion can be applied in the transmitter at the expense of an additional feedback path [10], [11]. The post-distortion algorithm was proposed in [12]. Other nonlinearity mitigation algorithms, such as feedforward and, feedback, were studied [13]. However, the above mentioned nonlinear mitigation methods were proposed for single LED transmitter and were not optimized for the multi-LED system.

Iterative signal clipping (ISC) was proposed in [14] to reduce the clipping distortion by applying the multi-LED architecture. This approach effectively extended input signal range without heavy clipping. The nonlinear distortion of the LED still existed. With the development of micro-LED arrays, we propose a new system architecture that provides digital controls to each element of the micro-LED array. Each element of the micro-LED array works in the cut-off range or saturation range by transmitting digital bit 0 or 1. Multi-level signal is realized with multiple elements in the micro-LED array. With the proposed architecture, a linear transmission is achieved for signals with large peak-to-average power ratio (PAPR).

The rest of paper is organized as follows. Section 2 starts with a general VLC system containing a nonlinear LED transmitter. Then a multi-LED structure with iterative signal clipping is discussed. A new system architecture is proposed in Section 3 to further improve the system performance with the introduction of micro-LED array. The improvement of system performance with micro-LED array is validated with simulations. Section 4 extends our discussion to dimming control and other impairments mitigation for micro-LED array. Section 5 concludes this paper.

## 2. VLC System Setup

Fig. 1 shows the block diagram of a typical VLC system. The information bits are firstly modulated to baseband signal $x(n)$. With a direct current (DC) bias, the baseband signal drives the LED to illuminate. Denote by $y(n)$ the transmitted signal after the LED. Since only the alternating current (AC) components of the LED output carry information, the DC is omitted in the modeling. In this system, the voltage-to-current (V2I) conversion and the current-to-light-intensity (I2P) conversion are inherently nonlinear. In addition, the output is subject to the frequency response of the LED, which can be modeled as a finite impulse response (FIR) system.

To visualize the nonlinear effects in the VLC system, we show V2I conversion of one micro-LED element from a micro-LED arrays in Fig. 2 [5]. In Fig. 2, the solid line shows the measurement result and the dashed line shows the polynomial curve fitted result. Conventional LED experiences similar nonlinear distortion with differences in the scales of the input voltage and output current [14].

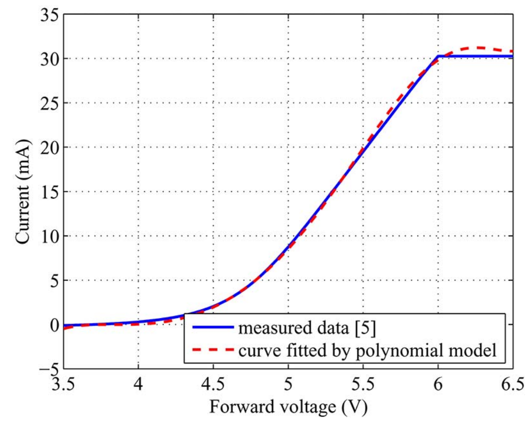


Fig. 2. Current to voltage (I–V) characteristics of one LED element in a micro-LED array [5].

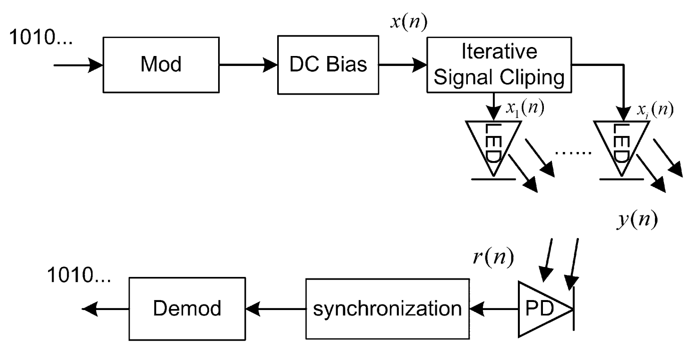


Fig. 3. Block diagram of a multiple-LED VLC system using the ISC method.

The overall input/output relationship of the LED can be described by a memoryless polynomial nonlinear (NL) block and a linear time-invariant (LTI) system block [15]:

$$\begin{aligned} y(n) &= LTI[f(x(n))] \\ &= \sum_{l=0}^{L-1} \sum_{p=1}^{P} b_l a_p x^p(n-l) \end{aligned} \tag{1}$$

where $f(x(n)) = \sum_{p=1}^{P} a_p x^p(n)$ is a memoryless polynomial model, $a_p$ is the pth-order coefficient of polynomial model, $P$ is maximum polynomial order, $L$ is maximum delay tap, and $b_l$ is the coefficient of the LTI system.

A typical multi-path channel with additive white Gaussian noise (AWGN) is added in the VLC system. At the receiver, the received signal $r(n)$ is obtained by the photon detector (PD) with direct detection. In the application of VLC, we assume that the input light intensity does not saturate the PD, thus the nonlinearity of the PD is not significant and can be ignored during the analysis of this paper.

Spectral efficient modulations, such as orthogonal frequency duplex modulation (OFDM) signals have large peak-to-average power ratio (PAPR) and are vulnerable to the LED nonlinearity. To reduce the nonlinear distortion, the authors in [14] proposed the ISC method.

Fig. 3 shows the system diagram of ISC method with a multiple-LED transmitter [14]. In this system, the dynamic range of each LED is limited. If the input signal $x(n)$ is larger than the dynamic range of one LED, the signal is clipped at the highest input level of the LED, the signal after clipping passes through the first LED. The clipped part is sent to the second LED. If the clipped part is larger than the dynamic range of the LED, similar procedure applies. In this way, the input signal is divided into small segments and is transmitted through multiple LEDs. If the LEDs are identical, we have

$$\begin{aligned} y(n) &= \sum_{i} \sum_{l=0}^{L-1} \sum_{p=1}^{P} b_l a_p x_i^p(n-l) \\ &= \sum_{l=0}^{L-1} \sum_{p=1}^{P} b_l a_p \sum_{i} x_i^p(n-l), \end{aligned} \tag{2}$$

where $x_i$ is segmented input signal with ISC.

This approach, however, still suffers nonlinear distortion from each LED. In addition, the combination of the distorted segmented signals does not equal to the nonlinear distortion of the combined signal or the original signal. This fact implies that conventional distortion compensation algorithms, such as predistortion or post-distortion, cannot be directly applied. The performance loss caused by the nonlinear distortion cannot be recovered.

If the ISC algorithm works on part of the LED dynamic range that suffers less nonlinear distortion, the overall dynamic range of the system is sacrificed and additional LEDs are needed. In the next section, we propose a new system architecture that the LED works in the saturation region while still maintaining linear transmission.

## 3. VLC System With Digitally Controlled Micro-LED Array

With recent development of illumination devices, micro-LED arrays arise much attention for their wider modulation bandwidth than the conventional LED. The architecture of micro-LED array is shown in [16] with each element controlled by individual circuits. The modulation bandwidth increase of the micro-LED array can potentially increase the transmission data rate of the VLC by 10 times. In this paper, we propose a VLC system architecture with micro-LED array that removes the impact of nonlinear distortion to the system.

For a digitally-controlled micro-LED array, we may drive each LED element to "on" or "off" that represents digital bit "1" or "0," just like the on-off keying (OOK) modulation. Then the input signal with large dynamic range can be represented by the number of turned-on LEDs. For example, the $n \times n$ micro-LED array can represent $2\log_2 n$-bit digital signal accurately. For each individual LED, it functions as the OOK modulation, the nonlinear distortion does not show up in the expression. If every LED element is consistent, the overall output is linearly related to the input. At the receiver side, a conventional photon detector can still be used by detecting the light intensity, where multiple outputs of the LED array is treated as one.

The proposed architecture is different from the work proposed in [6], where the spatial diversity is explored and the optical MIMO system is developed. In this paper, the proposed architecture assumes the same transmission channel. The benefit of the micro-LED architecture is obtained by eliminating nonlinear effects of the LED.

Next, we provide a simulation example to explain benefits of the proposed micro-LED architecture. In this simulation, information bits are modulated into data symbols in frequency domain with quadrature amplitude modulation (QAM). The modulation schemes used in the simulation are 16-QAM, 64-QAM, and 256-QAM, respectively. The total number of transmitted information bits is $5.12 \times 10^7$. DC-biased optical OFDM (DCO-OFDM) signal is applied to provide real positive signal for the VLC link [17]. The 64-point IDFT is applied to the DCO-OFDM signal. For the micro-LED array architecture, we assume that a 128 micro-LED array is applied, whose nonlinear response is shown in Fig. 2 [5]. With 128 micro-LED elements, the input DCO-OFDM signal needs to be quantized to 7 bits. Such quantization scheme provides sufficient digital dynamic range for VLC transmission as the in-band signal-to-quantization-noise ratio does not introduce

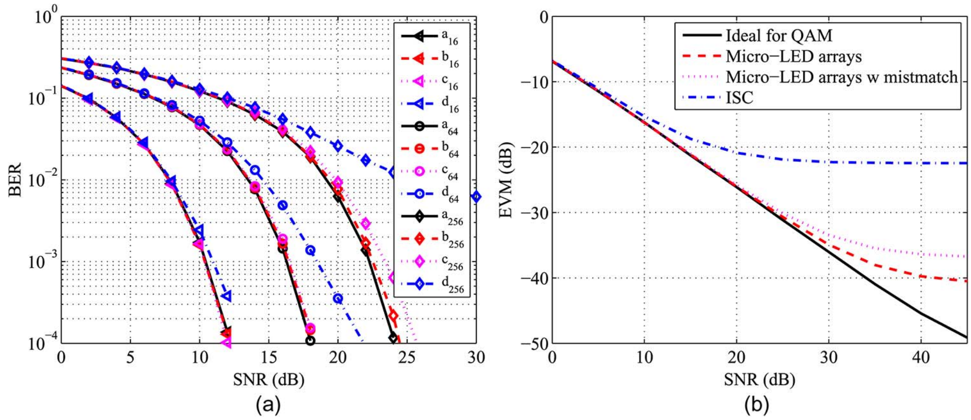


Fig. 4. System performance of nonlinear VLC systems. (a) BER performance. (b) EVM performance.

obvious degradation to the highest supported modulation 256-QAM, and the adjacent channel interference is not an issue in VLC system. The maximum output current for each micro-LED element is about 30 mA. The LED nonlinearity is approximated by a 7th-order polynomial model, which is shown as the red dashed line in Fig. 2. For comparison, the multiple-LED setup in ISC architecture is applied. The LED (model LE UW S2LN from OSRAM) has the maximum output current about 1 A. To provide similar signal dynamic range, a total number of three LEDs is applied in the ISC architecture. To simply the discussion, we assume that the normalized nonlinearity of the LED models for the micro-LED array architecture and for the multiple LED structure with ISC are the same.

In Fig. 4(a), the BER performance of different simulation conditions is presented. In the simulations, the nonlinearity and impairments are assumed to be part of the system. At the receiver side, no impairments compensation is provided. Perfect synchronization is assumed. BER is calculated on the uncoded QAM signal. In Fig. 4(a), the black solid lines labeled with letter *a* show the BER performance of an ideal linear VLC system; the red dashed lines labeled with letter *b* show the BER performance of the micro-LED array architecture; and the blue dash-dotted lines labeled with letter *d* show the BER performance of the multiple LED structure with ISC. The curves marked with "◁" show the simulation results of the 16-QAM modulation, the curves marked with "○" show the simulation results of the 64-QAM modulation, and the curves marked with "◇" show the simulation results of the 256-QAM modulation. From the simulation results, we observe that the BER performance of the micro-LED array architecture is very close to the ideal case, which implies that the quantization noise introduced by the 7-bit quantization is not significant. The BER performance of the ISC, on the other hand, is always worse than that of the micro-LED array architecture and starts to degrade when high-order modulations are applied. When different orders of QAM signals are applied, the nonlinear distortion introduced by the ISC is similar. However, when the order of QAM becomes higher, the signal constellation is closer to each other and is more sensitive to the distortion. The observation in the performance degradation validates the theory.

Similar trend is observed in Fig. 4(b). In Fig. 4(b), the black solid lines show the EVM performance of an ideal linear VLC system; the red dashed lines show the EVM performance of the micro-LED array architecture; and the blue dash-dotted lines show the EVM performance of the multiple LED structure with ISC. The EVM calculation for different QAM modulations with DCO-OFDM are the same. Fig. 4(b) shows that the nonlinear distortion generated by the ISC limits the system performance in high SNR. The quantization noise of the micro-LED array limits the system performance as well. However, the impact of the quantization noise is much lower than that of the nonlinear distortion. In addition, the quantization noise can be well controlled with the increase of the dimension of micro-LED array.

## 4. Practical Considerations

The adoption of micro-LED array can significantly improve the system performance. However, potential issues with the micro-LED array exist. For example, the micro-LED array has high modulation bandwidth due to its capability to work in the high current density regime where its broad area counterpart cannot. With a micro-LED array configuration, the current density flow will be huge. The fabrication of devices should take heat dissipation issue into consideration. Next, we discuss several potential issues with the micro-LED array and provide solutions to detail with practical considerations.

### 4.1 Mismatch Among Micro-LED Array Elements

A major challenge of the micro-LED array VLC system is the mismatch among array elements that results from device parasitics and process variations. Increasing the physical size of micro-LEDs can certainly reduce the mismatch. However, this approach slows down the electrical-optical conversion speed, which in turn limits the data transmission rate of the VLC system. Calibration can be an approach to reduce the mismatch. Digital dithering can be another approach to mitigate the distortion created by the mismatch.

We repeat the above simulation and consider mismatch among array elements. In this simulation, we assume that a uniformly distributed luminous intensity mismatch within $[-5\%, +5\%]$ lies in the 128 micro-LED array. With digital dithering, or random mapping from the digital input to the array elements, the distortion introduced by the mismatch is spread evenly in the system. In Fig. 4(a) and (b), the magenta lines labeled with letter *c* show the BER performance and the EVM performance of the micro-LED array architecture with mismatch, respectively. From the simulation results, we observe that the system performance of the micro-LED array architecture degrades a little bit from the ideal case when the order of modulation becomes high. While the performance of the micro-LED array architecture with mismatch is still better than that of the multiple LED structure with ISC in the presence of nonlinearity. The proposed micro-LED array architecture is robust against mismatch among array elements.

### 4.2 Life Span Consideration

With the proposed micro-LED array architecture, if we map digital bits to the array elements with a fixed pattern, the life span of the micro-LED array may be sacrificed. Some of the LED elements have higher chance to be on than other LED elements since certain light intensity is required for illumination purpose. The conventional mapping from the input signal to the elements of micro-LED arrays can be expressed as follows:

$$x(n) \rightarrow b(n) = [\underbrace{11\cdots1}_{x(n)}\ \underbrace{00\cdots0}_{N-x(n)}] \tag{3}$$

where $x(n)$ is the input voltage that is quantized to integers representing the number of active micro-LED array elements, $n$ is the sample index, $b(n)$ is the mapping algorithm, and $N$ is the total number of elements of the micro-LED array. For example, for the input signal 12 and 32, the first 12 elements of the micro-LED array are "on" in both cases, and the last 96 elements are "off" all the time.

To equalize the life span of the LED array, we may apply a (pseudo) random mapping, or a cyclic mapping that cyclicly rotate the active array elements, between the input digital bits and the mirco-LED array elements. The cyclic mapping can be expressed as follows:

$$x(n) \rightarrow c(n) = \begin{cases} [\underbrace{0\,0\cdots0}_{\mathrm{mod}(n,N)}\underbrace{1\,1\cdots1}_{N-x(n)}\ \underbrace{0\,0\cdots0}_{N-\mathrm{mod}(n,N)-x(n)}], & \mathrm{mod}(n,N)+x(n) \le N \\ [\underbrace{1\,1\cdots1}_{x(n)+\mathrm{mod}(n,N)-N}\ \underbrace{0\,0\cdots0}_{N-x(n)}\ \underbrace{1\,1\cdots1}_{N-\mathrm{mod}(n,N)}], & \mathrm{mod}(n,N)+x(n) > N \end{cases} \tag{4}$$

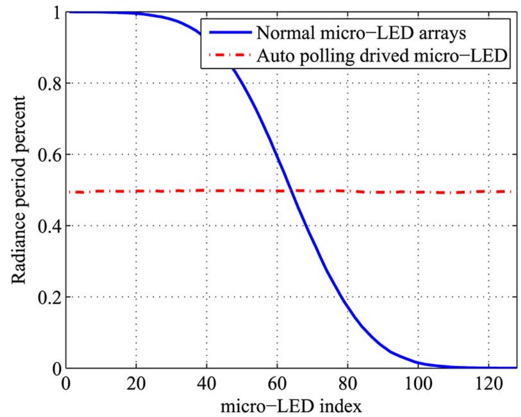


Fig. 5. Emission period for each micro-LED.

where $c(n)$ is the mapping algorithm, and $\mathrm{mod}(n, N)$ is the modulo operation that finds the remainder after division of $n$ by $N$. In the previous example, for the input signal 12 and 32, the active elements of micro-LED array depend not only on amplitude of the inputs, but also on the sample index of the inputs. Statistically, every elements of the micro-LED array can be active with the same probability.

Fig. 5 shows the simulation result on the active probability of each elements in a 128-element micro-LED array. The blue solid line shows the active probability of the micro-LED array elements for normal digitally controlled micro-LED. The red dash-dotted line shows the active probability of the micro-LED array elements for the micro-LED with cyclic mapping. In Fig. 5, we observe that if we do not apply cyclic mapping, 33 elements are on at least 90% of time. At the same time, the same amount elements are off at least 90% of time. With cyclic mapping, all micro-LED array elements are exercised with equal probability. Such a configuration can help to equalize the life span of the micro-LED array.

It is worth to note that the mapping between the input signal and the active elements of the micro-LED array is not unique. The proposed cyclic mapping only shows one example that equalizes the life span of each array elements.

The LED aging may reduce the luminous intensity, cause variations in micro-LED arrays. From the previous discussion, slight mismatches in micro-LED arrays is not the bottleneck of the system performance. The proposed random mapping or cyclic mapping algorithms that equalize the life span of the elements in micro-LED arrays also help to deal with the aging problem.

### 4.3 Dimming Control

Considering the lumination requirement, dimming control is required for the VLC system. With the micro-LED array, the dimming control can be easily achieved. Conventional dimming control method deals with the duty cycle of the input signal, {which sacrifices the transmission capacity}. In the VLC system with micro-LED array, the dimming control can be achieved by dividing the array elements into lumination group and information transmission group. When activated, every individual elements can be driven into saturation separately. The light intensity is determined by the number of active elements in lumination group and the average of the information transmission group. For example, if we divide micro-array elements equally into four groups, a dimming control of 25%, 50%, 75%, or 100% can be achieved. This approach, on the other hand, sacrifices the input dynamic range. When the size of the micro-LED array is limited, the quantization error in the transmitter may show up. Another approach is to modify the input voltage of the micro-LED array. For example, if we map digital “1” with 50% maximum input voltage rather than the maximum input voltage, the light intensity cut roughly by half. Since all elements in the micro-LED array can still be switched independently, the dynamic range of the input signal is preserved. This approach may degrade the linearity of the dimming control a little bit, which is not a sensitive issue in application. Thus, the second approach is recommended for operation.

## 5. Conclusion

The technology breakthrough of micro-LED array has the potential to improve the modulation bandwidth of the LED by 10 times. In this paper, we propose a digitally controlled VLC system with micro-LED array transmitter. The proposed system enjoys the benefit of wide modulation bandwidth of the micro-LED array and avoids the disadvantage of the nonlinear distortion. Simulation shows that the proposed micro-LED array architecture is robust against nonlinear distortion and is advantageous existing multiple LED structure with ISC. Practical considerations of the VLC system with micro-LED array is also discussed.

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