NONLINEAR DISTORTION MITIGATION IN VISIBLE LIGHT COMMUNICATIONS

KAI YING, ZHENHUA YU, ROBERT J. BAXLEY, HUA QIAN, GEE-KUNG CHANG, AND G. TONG ZHOU

ABSTRACT

Many physical devices used in VLC systems exhibit nonlinear effects, which can significantly degrade the overall system performance. For example, the LED is the major source of nonlinearity. The forward current is zero unless the forward voltage exceeds a turn-on value. The forward current is also limited with a maximum permissible value. In addition, the electrical-to-optical conversion is also nonlinear. In this article, we provide an overview of techniques related to modeling and distortion mitigation techniques of the nonlinearity in VLC systems. Appropriate models and robust nonlinearity mitigation techniques are crucial to support high-speed transmissions in practical VLC systems.

INTRODUCTION

In recent years, with the improvement of light emitting diode (LED) chip design and massive deployment of LED devices, visible light communication (VLC) systems have become an attractive method. VLC can help address the current challenges in wireless communications such as the bandwidth limitation, energy efficiency, electromagnetic radiation, and safety [1]. VLC is on the road to standardization and commercialization [2, 3].

Similar to RF systems, nonlinear components in VLC systems distort the signal and degrade system performance. Nonlinear distortions in VLC systems may come from driving circuits of the LEDs, digital-to-analog converters (DACs), analog-to-digital converters (ADCs), LEDs, and photodiodes (PDs). Since the optical front-end tends to employ simple intensity modulation and direct detection (IM/DD) techniques, the system performance is also sensitive to nonlinearities in the electrical-to-optical conversion and optical-to-electrical conversion. Among all nonlinear sources, the LED is the major source of nonlinearities. Both the voltage-current relationship and the current-light intensity relationship in the LED are nonlinear [4–8]. At the receiver, the PD operates in a narrow range, so the distortion is not as significant as in the LED [8]. Moreover, to drive the LED, the input electric signal must be positive and exceed the turn-on voltage of the device. On the other hand, the signal is also limited by the saturation point or maximum permissible value of the LED. As a result, the nonlinearity in a VLC system can be treated as a family of dynamic-range-limited nonlinearities.

The overall VLC system can be modeled as follows. Denoted by $x(n)$, a real-valued input signal, the received signal $y(n)$ is modeled by

$$y(n) = h(x(n)) + v(n), \tag{1}$$

where $v(n)$ is additive noise, and $h(\cdot)$ is a nonlinear mapping or transfer function with dynamic range constraint $A_{\min} \le h(x(n)) \le A_{\max}$. The dynamic range is determined by the characteristics of the LED.

For the signal beyond the dynamic range of the device, double-sided clipping can be used to model such nonlinear effects. For the signal within the dynamic range, a nonlinear transfer function may be applied to model the nonlinear effects. Both distortions impact the overall system performance.

Nonlinearity modeling is essential for the discussion of the impact of nonlinearities and mitigation methods. Nonlinear models can be divided into memory models and memory-less models, based on whether we take into account the memory effects of nonlinearities. On the other hand, according to whether or not the dynamic characteristics of LEDs are considered, we can also categorize the nonlinear models into dynamic and static models. Current research mainly concentrates on static memory-less LED nonlinearity modeling [4, 9]. In these cases, present output only depends on present input. The nonlinearity does not change over time, either. To model such nonlinearities, one approach is to fit the nonlinear transfer function using measurement data with power series (e.g., Taylor expansion). However, the memory-less polynomial model is inadequate to describe the LED nonlinearity, especially for high-speed transmission. Actually, the current-voltage response of the LED is frequency-dependent, thus introducing nonlinearities with memory effects [4, 12]. In these cases, the output of the

Kai Ying, Gee-Kung Chang, and G. Tong Zhou are with the Georgia Institute of Technology.

Zhenhua Yu is with Texas Instruments.

Robert J. Baxley is with Bastille Networks.

Hua Qian is with the Chinese Academy of Sciences.

LED depends not only on the present input, but also on past input values. In addition, the LED characteristics may change over time due to component aging and temperature changes [4]. The dynamic nonlinearities can degrade the accuracy of the nonlinearity mitigation techniques. Careful and adequate modeling of nonlinearities in VLC is required to design the mitigation methods.

With appropriate models, we can work on mitigating the impact of nonlinear distortions. One straightforward approach is to choose or modify input signals such that they are insensitive to nonlinear distortions. For example, we can use on-off keying (OOK) or pulse position modulation (PPM), which produces two-level signals and is immune to system nonlinearities. For orthogonal frequency-division multiplexing (OFDM) signals, peak-to-average power ratio (PAPR) reduction techniques can be utilized. With smaller dynamic range, the signal after PAPR reduction is less vulnerable to nonlinearities than the original input signal. Another approach is to compensate for nonlinearities by predistortion or postdistortion. After compensation, the overall system response is approximately linear. Predistortion or postdistortion has been widely used in different areas [17, 18]. In this article, we show the particular characteristics in VLC. To take into account memory effects and time-varying characteristics, robust mitigation techniques are necessary to adapt to system dynamics.

We summarize current and potential topics related to LED nonlinearities for VLC in Fig. 1. The remainder of this article is organized as follows. We first present the modeling of LED nonlinearities and discuss the impact of nonlinear distortions. We also point out that the LED exhibits time-varying characteristics, which should be taken into account for robust nonlinear distortion mitigation design. Afterward, both waveform-specific mitigation techniques and waveform-agnostic mitigation techniques are discussed. For the former, some specific modulation schemes are studied, and PAPR reduction techniques for OFDM signals are presented. For the latter, we show the optimal nonlinear mapping for dynamic-range-limited nonlinearities, and then show the linearization approaches such as predistortion and postdistortion. Finally, we point out challenges of nonlinear distortion mitigation in VLC and conclude the article.

Nonlinearities in LED

LED is the major source of nonlinearities in VLC. Figure 2 shows the nonlinear characteristics of the LED's voltage-current (V-I) conversion and current-optical power (I-O) conversion. In [7, 14], details on nonlinearities of V-I relationship were presented. The authors in [5, 6, 12] concentrated on the I-O nonlinear curve. In this article, we consider modeling both of them with one nonlinear transfer function. Since VLC employs light intensity modulation, and the voltage of an electrical signal always serves as the control variable, the overall system function can be described by the V-O curve.

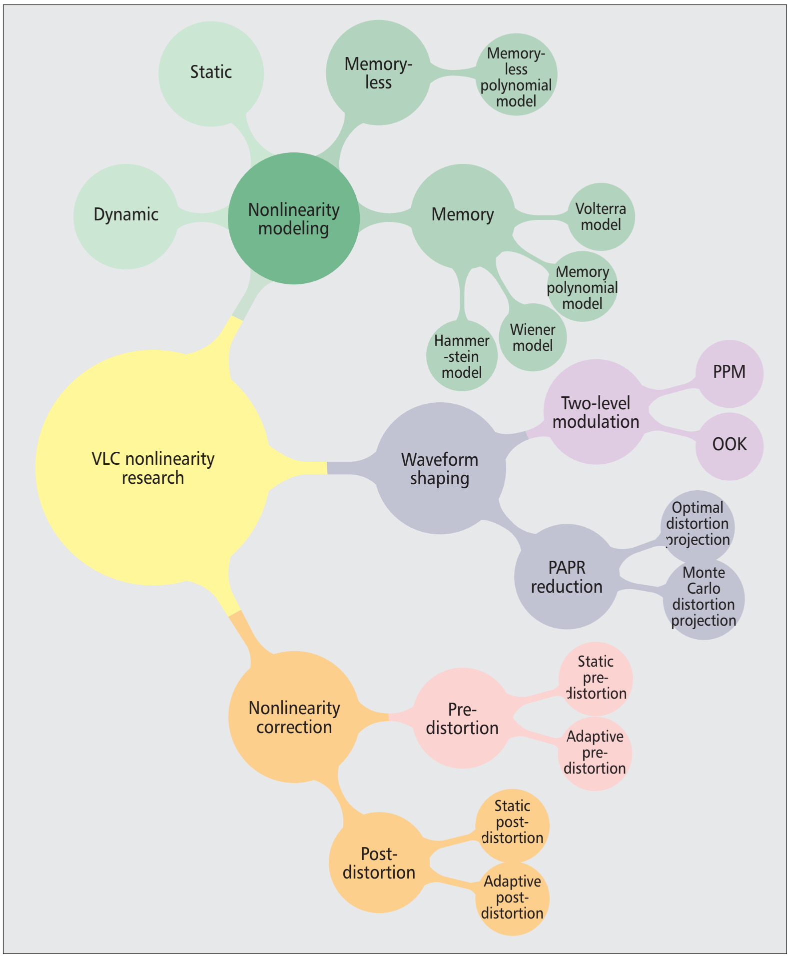

Figure 1. Study topics of nonlinear distortion mitigation in VLC.

Memory-less vs. Memory

Models for LED nonlinearities can be divided into two categories: memory-less and memory models.

A power series or a polynomial model is popular to describe a memory-less LED because a smooth instantaneous nonlinear transfer function can be expanded by Taylor series. Figure 3a shows the input-output relationship of the memory-less polynomial model. After obtaining the measurement data of an LED, we need to figure out two sets of parameters of the polynomial model. The first one is the best polynomial order K since we truncate the Taylor series for complexity reasons. In [5, 6], the authors showed that a fifth-order polynomial is adequate to model measured transfer functions, and a second-order polynomial already provides a satisfying description for the devices they tested. Second, we can use least square fitting to calculate the coefficients α_k of the polynomial. The memory-less polynomial is adequate to model the LED nonlinearities when the input signal is a narrowband signal.

Similar to the Taylor series for the memory-less nonlinear model, the Volterra series is a general approach to model a nonlinear system with memory. Since the LED has a frequency-dependent nature, memory effects cannot be ignored, especially when signal bandwidth is

Since nonlinear distortions degrade system performance, distortion mitigation is an important issue in VLC system design. The most straightforward approach is to design the signal waveform such that the signal is not sensitive to the nonlinear distortion. Another approach is to linearize the nonlinearity.

large. Figure 3b shows the general structure of the Volterra model, where $h_m(\cdot)$ is the mth-order Volterra kernel and h_0 is a constant. The contribution of the mth order nonlinearity to the output signal can be expressed as

$$p_m(n) = \sum_{k_1=0}^{D_m} \cdots \sum_{k_m=0}^{D_m} h_m(k_1,\cdots,k_m) \times x(n-k_1)\cdots x(n-k_m), \quad (1)$$

where D_m is the memory length for the mth order nonlinear kernel, and M is the nonlinear order. The authors in [12] showed that a second-order Volterra expansion can provide a fair approximation for the power spectrum up to 14 MHz. The LED nonlinearity with memory can be properly represented by the Volterra series. However, the main limitation of the Volterra model is its complexity. The number of coefficients increases exponentially as the nonlinear order and memory length increase. Thus, the full Volterra series is not practical for real-time applications. To avoid the complexity issue, simplifications of the Volterra series are studied.

The memory polynomial model is a special case of the Volterra model with only diagonal kernels. The general structure of the memory polynomial model is shown in Fig. 3c. Compared to the memory-less polynomial model, the output of the memory model depends not only on the present input, but also on past input values.

The Wiener model is another subset of the Volterra model. The Wiener model, as shown in Fig. 3d, is constructed by a linear time-invariant (LTI) system followed by a memory-less nonlinearity. In [14], authors modeled the LED nonlinearities with a Wiener model.

Similarly, the Hammerstein model is a memory-less nonlinearity followed by an LTI system, which is opposite the Wiener model. Figure 3e shows the structure of Hammerstein model. It offers similar complexity to that of the Wiener model. Depending on the nature of the nonlinearity, the Hammerstein model can also be an appropriate model with reduced complexity.

Static vs. Dynamic

Nonlinear models can also be classified into static and dynamic models. Static indicates that the LED nonlinearity does not change over time. This kind of nonlinearity is relatively easy to deal with. The accuracy of the model can be improved with sufficient data collected over time. Most research in the existing literature concentrates on the static model. However, LED nonlinearity may change over time due to component aging and temperature drift [4]. Hence, the dynamic model is required to capture these changes. In addition, dimming control should be supported in VLC implementation since the principal functionality of the LED is for lighting [2]. Different illumination levels result in changes in temperature, which in turn affect the system nonlinearity. Figures 2c and 2d illustrate typical changes of both LED V-I conversion and I-O conversion under different temperatures ($T_1 < T_2 < T_3$). More specific measurements can be found in [19, 20]. Typically, at constant forward current, the driving voltage decreases at increasing LED temperature [19]. On the other hand, optical power decreases with an increase in LED temperature for the same driving current [20]. In these cases, LEDs work with time-varying nonlinearities. The mitigation techniques for LED nonlinearities will be influenced by the dynamic characteristics. Thus, careful modeling and robust mitigation methods should adapt to these dynamics. Finding robust mechanisms to model and estimate these dynamics is an open research problem.

The Impact of Nonlinear Distortions

There are two kinds of nonlinear distortions. One is caused by the nonlinear mapping of LED electrical-to-optical conversion within the dynamic range. The other results from the hard clipping of signals below the turn-on voltage or exceeding the maximum permissible value of the LED. The impact of soft nonlinear mapping has been extensively discussed in [5–7]. The authors of [9] studied the clipping noise. To illustrate the impact of nonlinear distortion as well as the memory effects, we compare constellation diagrams among three cases:

- Linear LED model
- Memory-less nonlinear LED model (polynomial model)
- Nonlinear LED model with memory (Wiener model)

In the simulation, a DC-biased optical OFDM (DCO-OFDM) VLC system with uncoded 64-quadrature amplitude modulation (QAM) is tested. The memory-less nonlinearity is modeled by a polynomial model ($K = 5$, $\alpha_1 = 1.3985$, $\alpha_2 = 0.0269$, $\alpha_3 = -1.8732$, $\alpha_4 = -0.0387$, and $\alpha_5 = 1.0001$). For the case with memory effects, an LTI block ($F(z) = 1 + 0.15z^{-1} + 0.1z^{-2}$) is added before the memory-less nonlinearity. A line-of-sight (LOS) channel with additive white Gaussian noise (AWGN) is applied. The simulation results are shown in Figs. 4a–c, respectively. Comparing Figs. 4a and 4b, we observe that the nonlinear distortion created by the memoryless nonlinearity is obvious. The distortion is larger than the mismatch created by the noise from the channel. From Fig. 4c, we observe that the distortion created by the nonlinearity with memory effects is more severe than that with memory-less nonlinearity. The output signal is blurred and cannot easily be distinguished as data symbols.

Waveform Shaping

Since nonlinear distortions degrade system performance, distortion mitigation is an important issue in VLC system design. The most straightforward approach is to design the signal waveform such that the signal is not sensitive to nonlinear distortion. Another approach is to linearize the nonlinearity.

In waveform-specific mitigation techniques, the overall system nonlinear mapping is not modified. Instead, the signaling waveform is changed such that it is less sensitive to the nonlinear effect.

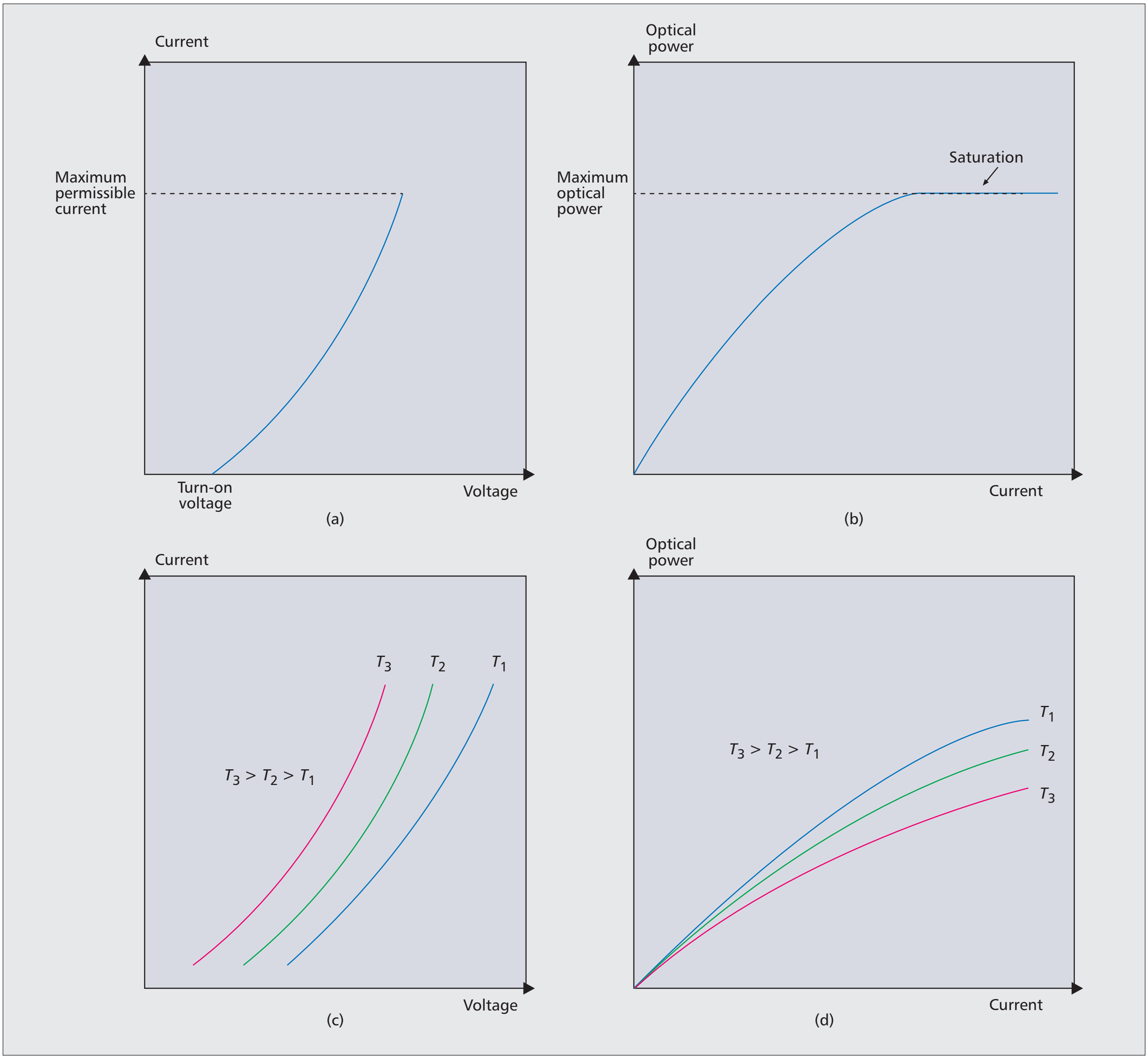

Figure 2. Nonlinearities of LED: a) V-I curve: static; b) I-O curve: static; c) V-I curve: dynamic with temperature dependence; d) I-O curve: dynamic with temperature dependence.

Two-Level Modulation

Two types of single-carrier modulation methods are predominantly used in VLC:
- Amplitude modulation such as OOK and *M*-ary pulse amplitude modulation (*M*-PAM)
- Pulse-position modulation (PPM) [2]

To avoid or mitigate the impact of nonlinear distortion, OOK and PPM can be utilized since they only produce two-level signals that are not sensitive to nonlinearity. OOK transmits bit 1 by "turning on" the light and transmits bit 0 by "turning off" the light. PPM encodes the information bits in the position of the pulse within a time period. 0 is represented by a positive pulse at the beginning of the period followed by a lower-level pulse, and 1 is represented by a lower-level pulse at the beginning of the period followed by a positive pulse. However, the main drawback of these single-carrier modulation signals is their low spectrum utilization efficiency and transmission speed. In most cases, multi-carrier modulations like discrete multitone (DMT) modulation or OFDM are preferred.

PAPR Reduction for OFDM

OFDM has been considered for VLC due to its ability to boost data rates and effectively combat intersymbol interference (ISI). OFDM can support bit-loading technology, which allows allocating different numbers of bits to different subcarriers based on signal-to-noise ratio (SNR) [10, 11]. With IM/DD techniques, the baseband signal in VLC needs to be real-valued and unipolar (positive-valued). This constraint is different from an RF communications system, where the baseband signals are complex-valued. To ensure that the OFDM time domain signal is

In VLC-OFDM systems, since the LED acts as a low-pass filter, the out-of-band subcarriers cannot be leveraged to transmit information to other users. Thus, we do not need to consider the out-of-band interference. This actually gives us additional degrees of freedom to develop PAPR reduction schemes for VLC-OFDM systems.

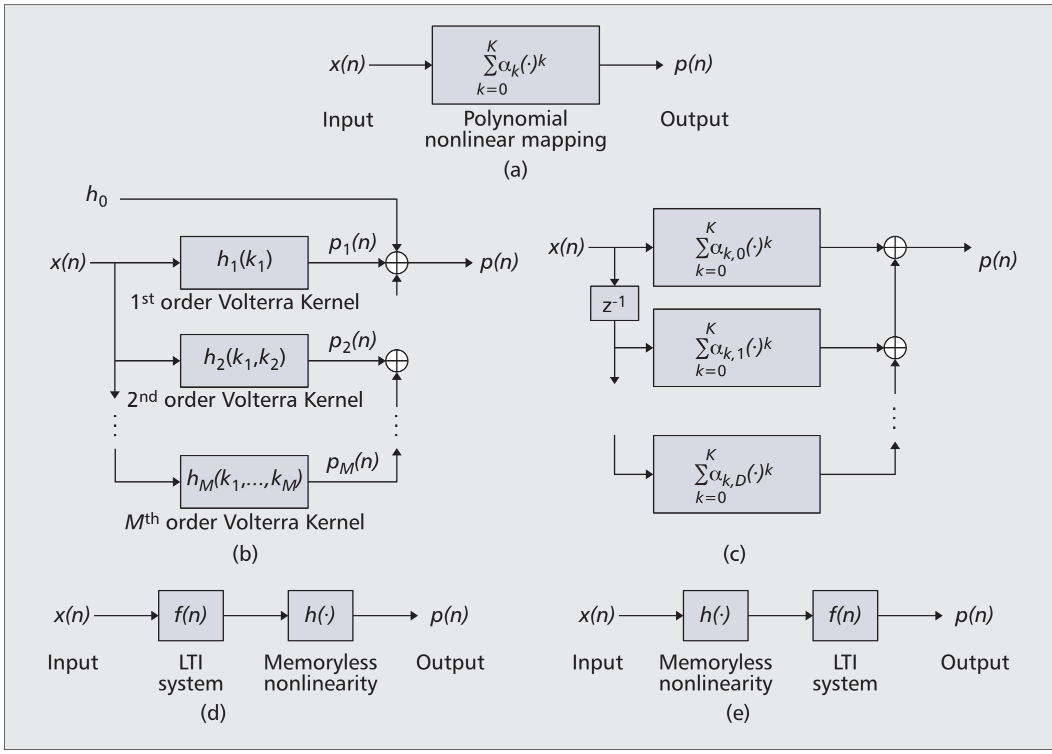

Figure 3. Nonlinear models for LED: a) memory-less polynomial model; b) Volterra model; c) memory polynomial model; d) Wiener model; e) Hammerstein model.

real-valued, Hermitian symmetry must be satisfied in the frequency domain, where the right subcarriers are the conjugate of the left subcarriers. In addition, a DC bias can be applied to convert a bipolar signal into unipolar format. A signal with such modifications is called DCO-OFDM.

Meanwhile, OFDM is also known for its disadvantage of high PAPR. VLC-OFDM inherits the disadvantage of high PAPR from RF-OFDM. High PAPR makes VLC-OFDM very sensitive to the nonlinearity of LEDs [10, 11]. Moreover, high PAPR requires large biasing to convert the bipolar OFDM signal into a unipolar version, which causes serious degradation of optical power efficiency. Therefore, PAPR reduction is an indispensable module in VLC-OFDM systems. However, there are some differences between RF-OFDM and VLC-OFDM to prevent applying conventional PAPR reduction methods to VLC-OFDM systems directly. First, the RF-OFDM baseband signal is complex-valued and has only one PAPR. But for a real-valued bipolar VLC-OFDM signal like DCO-OFDM, the baseband signal $x(n)$ before biasing is zero mean, and has one maximum value and one minimum value. The maximum value of $x(n)$ can be seen as the positive peak, and the minimum value of $x(n)$ can be seen as the negative peak. We define the positive optical PAPR as $\max x(n)/\sigma_x$ and the negative optical PAPR as $-\min x(n)/\sigma_x$, where σ_x denotes the standard deviation of $x(n)$. Note that we put a negative sign in the negative optical PAPR because the minimum value of $x(n)$ is negative and the PAPR is always positive. It is worthwhile pointing out that when we calculate σ_x, both positive points and negative points are considered. The positive peak and negative peak often have distinct constraints in VLC, depending on where the signal is biased within dynamic range of LEDs. For example, in a dimming condition, the DCO-OFDM is biased at the lower part of LEDs' dynamic range, and thus the negative peak is more sensitive to the nonlinear distortions than the positive peak. In this case, we need to reduce more negative optical PAPR. Second, in RF communications, both in-band distortions and out-of-band power leakage should be taken into account in PAPR reduction schemes. However, in VLC-OFDM systems, since the LED acts as a low-pass filter, the out-of-band subcarriers cannot be leveraged to transmit information to other users. Thus, we do not need to consider out-of-band interference. This actually gives us additional degrees of freedom to develop PAPR reduction schemes for VLC-OFDM systems.

Optimal Distortion Projection — Among PAPR reduction algorithms proposed for OFDM, distortion-based methods are particularly favored for practical scenarios because the modification of the receiver is avoided. Clipping is the simplest distortion-based method to reduce the PAPR of OFDM signals. For real-valued OFDM signals, a pair of positive clipping level and negative clipping level are predefined to serve as thresholds. All the time domain pulses that are beyond the thresholds will be set equal to them. Clipping generates distortions on all subcarriers in the frequency domain. If we only measure the signal-to-distortion ratio at the transmitter, clipping definitely degrades the performance. However, if we take channel noise into consideration and measure the signal-to-noise-plus-distortion ratio, clipping may improve the effective SNR and the performance of the whole system since clipping enables a larger scaling factor to the input signal. Thus, given the channel SNR, a pair of optimum clipping levels can be selected to maximize the effective SNR and achievable data rates. Generally, when channel SNR is large, more clipping distortions are allowed. When channel SNR is small, clipping distortions will dominate the noise source. Thus, mild clippings are favored.

The relative amounts of positive clipping and negative clipping are determined by the biasing level or illumination scenario. If the OFDM signal is biased at the lower part of the dynamic range of LED, the negative peak should be clipped more severely than the positive peak, and vice versa. Besides deciding the amount of distortions, the other question is how to allocate the distortions in the frequency domain. In VLC, a white LED acts as a low-pass filter. To make the best use of the available modulation bandwidth, more bits are allocated to low-frequency subcarriers and fewer bits are allocated to high-frequency subcarriers. Since high-order constellations are more sensitive to noises than lower-order constellations, given a certain amount of distortions allowed, the ideal case would be allocating more distortions to high-frequency subcarriers and less distortions to low-frequency subcarriers. However, in the simple clipping method, although we can control the total amount of distortions by adjusting the clipping thresholds, we are not able to determine the spectral shape of clipping distortions. Actually, the clipping distortions are almost equally distributed on all in-band subcarriers, which makes the low-frequency subcarriers with higher-order modulations vulnerable to clipping noises. This can degrade the performance of the whole system.

This issue can be addressed by iterative clipping and noise shaping. In each iteration, after clipping the positive and negative peaks, the clipping noises on different subcarrier sets are scaled proportionally according to the order of modulations. After a number of iterations, more distortions will be allocated to high-frequency subcarriers. To get an optimal solution, we can model a quadratically constrained linear optimization problem in which the minimization of weighted positive optical PAPR and negative optical PAPR is set as the objective, and the distortions for different subcarrier sets are constrained by different thresholds. A customized interior point method can be developed for real-time implementation. Another aggressive allocation mechanism is pushing all distortions to an out-of-band subcarrier, but oversampling is required.

Side Information — There have been a number of PAPR reduction proposals requiring receiver side modifications. Selective mapping (SLM) is one of these approaches. In SLM, the phases of original OFDM frequency-domain symbols are rotated according to a predefined phase table. The phase table is assumed to be known to both

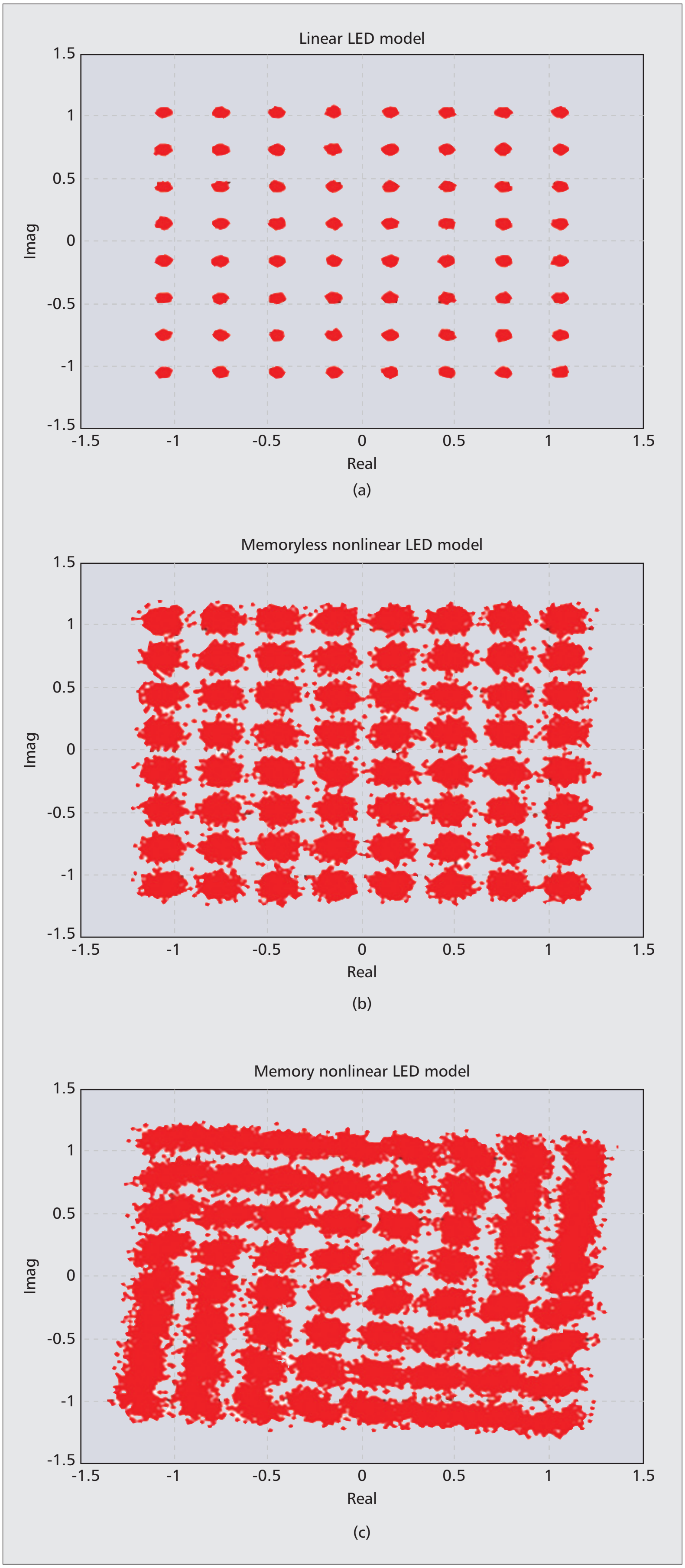

Figure 4. Impact of nonlinear distortions: a) linear model; b) memory-less polynomial model; c) Weiner model.

Waveform-agnostic techniques mainly work by linearizing the overall system nonlinearity so that the input signal can be passed approximately undistorted within the dynamic range. This linearization can take place at either the transmitter or the receiver.

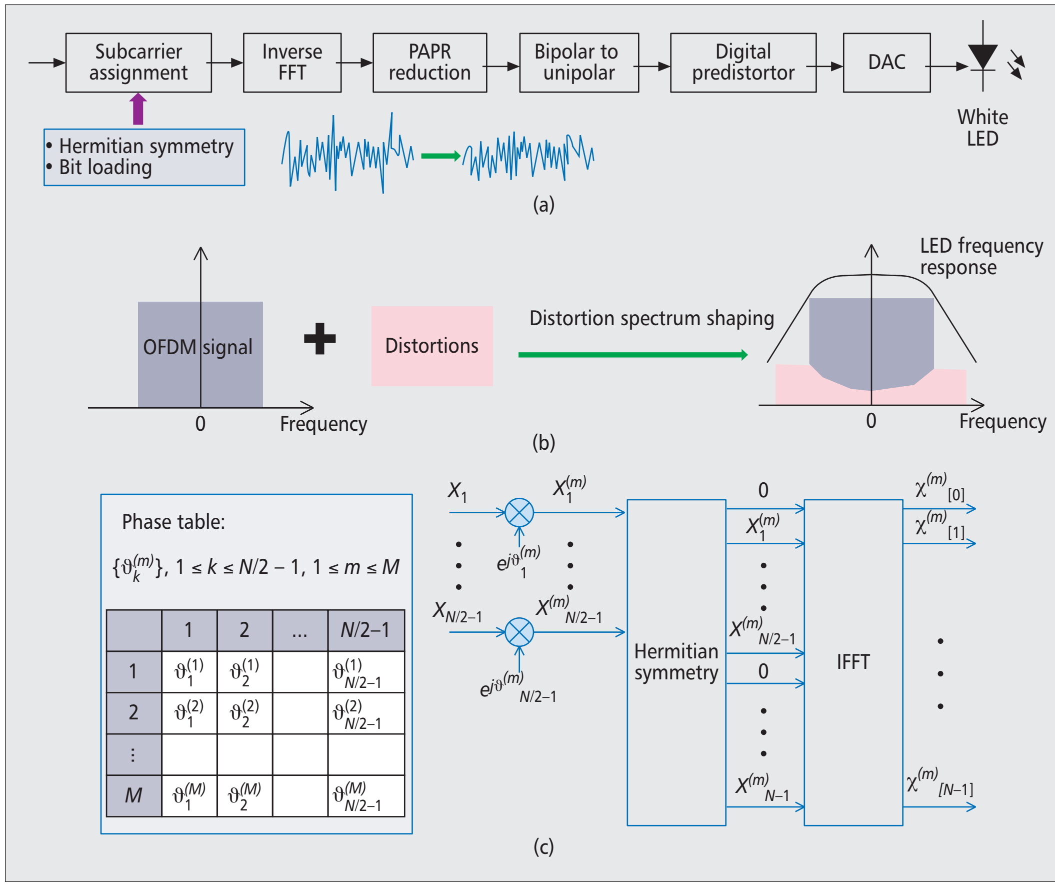

Figure 5. PAPR reduction in dynamic-range-limited VLC-OFDM: a) VLC-OFDM transmitter front-end; b) PAPR reduction: distortion based; c) PAPR reduction: selected mapping method.

transmitter and receiver. Then a mapped OFDM sequence with minimum PAPR is selected for transmission. For VLC-OFDM, the selection criteria is to minimize the maximum of weighted positive optical PAPR and negative optical PAPR. Rather than sending the selected phase sequence to the receiver, the transmitter only needs to send the index of the selected phase sequence as side information. The number of bits included in side information depends on the size of the phase table. At the receiver, the phase sequence is obtained by looking up the received index information from the phase table. This may be difficult to deploy in existing VLC systems. Such approaches also include companding, partial transmit sequence, tone injection, tone reservation, and coding.

Although the above discussions are based on a DCO-OFDM signal, the PAPR reduction methods can be modified and generalized to other real-valued unipolar OFDM schemes, such as asymmetrically clipped optical OFDM (ACO-OFDM), U-OFDM, and Flip-OFDM by considering only the positive optical PAPR.

Nonlinearity Correction

Waveform-agnostic techniques mainly work by linearizing the overall system nonlinearity so that the input signal can be passed approximately undistorted within the dynamic range. This linearization can take place at either the transmitter or the receiver.

Optimal Nonlinear Mapping

Recall that LED nonlinearity belongs to a family of dynamic-range-limited nonlinearities. Different from the amplitude-limited nonlinearities in RF systems, the signal here is subject to a double-sided clipping to meet the dynamic range constraint, and a bias is always used to shift the signal to an appropriate level. In [15], the authors proved that the optimal nonlinear mapping in terms of signal-to-noise-plus-distortion ratio is a double-sided limiter with a certain linear gain and a certain bias value, which can be expressed as

$$h(x) = \begin{cases} A_{\min}, & x \le \dfrac{A_{\min} - B}{G}, \\ B + Gx, & \dfrac{A_{\min} - B}{G} \le x \le \dfrac{A_{\max} - B}{G}, \\ A_{\max}, & x \ge \dfrac{A_{\max} - B}{G}, \end{cases} \tag{3}$$

where B is the bias, G is the gain, and $[A_{\min}, A_{\max}]$ is the dynamic range constraint. The choices of bias and gain values are also important. The selection of the bias can help put the most important part of the signal into the available dynamic range. For the selection of the gain, there is a trade-off between the signal power and the distortion. If the gain is large, the signal power is high but the distortion is severe. On the contrary, a small gain can help keep the signal

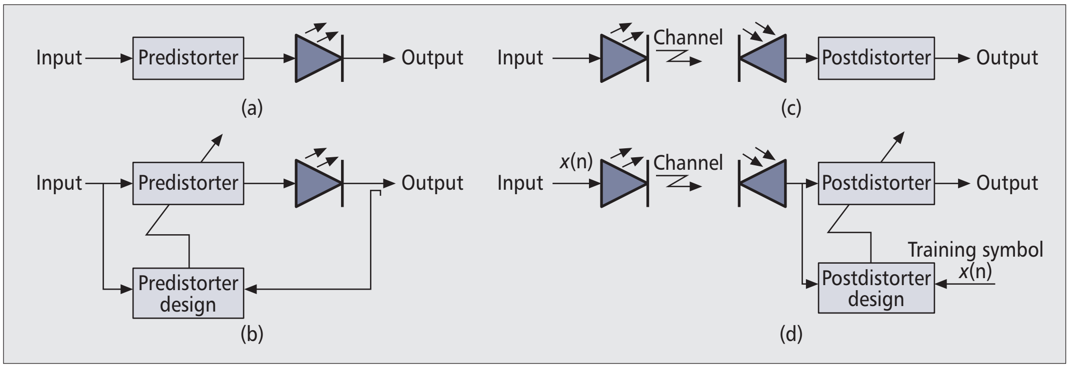

Figure 6. Waveform-agnostic mitigation methods: a) static predistortion; b) adaptive predistortion; c) static postdistortion; d) adaptive postdistortion.

If we consider multipath effects or the modulation bandwidth is relatively broad, the channel response is no longer flat. In this case, pre-equalization or post-equalization may need to be combined with predistortion or postdistortion to compensate for the channel response.

less distorted but degrade the SNR. Thus, the parameters require careful consideration and selection. The authors of [15] introduced the topic of how to calculate these parameters theoretically based on the distribution of the input signal, noise power, and dynamic range constraint.

With knowledge of the optimal nonlinear mapping, the next step is to modify the overall system mapping by predistortion or postdistortion.

Predistortion

To construct digital predistorters for LEDs, we can first identify the LED nonlinear transfer function and then find the inverse of it so that the cascaded function is in accordance with the desired mapping that we design. This approach can be called static predistortion. Figure 6a shows a general structure of this approach. To simplify the description, we omit modulation, demodulation, DAC, and ADC from the figure. In practice, for memory-less nonlinearities, the static predistorter can easily be implemented with lookup tables that map the original input constellation points to the desired locations after we know the LED nonlinearity. For nonlinearities with memory, memory-less predistortion can only achieve limited linearization performance, so predistorters also need to have memory structures. Similar to nonlinearities modeling, the models for predistorters include the Volterra series and its special cases like the Hammerstein model and the memory polynomial model. When the system dynamic changes, static predistortion is not suitable. Adaptive predistortion can be used.

In most cases, obtaining the inverse of a nonlinear system, especially with memory or time-varying characteristics, is not easy. Another type of approach is to model and estimate the predistorter directly from sampled data by reversing the data flow and assuming the output of the LED as the input of the predistorter and the input of the LED as the output of the predistorter. The advantage of this approach is that it eliminates the need for model assumption and parameter estimation of the LEDs.

Figure 6b shows the general structure of this approach, which is also called adaptive predistortion. The principle of the adaptive predistortion is shown as follows. We first choose the predistorter with a specific model such as the memory polynomial model. Then we compare the output of the LED with the desired value so that we can adjust the parameters of the predistorter to minimize the difference. The difficulty is how to obtain the feedback of the LED output since we care about the light intensity. In RF predistortion systems, it is straightforward to tap off an electrical signal after the power amplifier. However, in VLC, the LED is the source of distortion and the output of the LED is light, which is harder to measure. One possible way is to put a PD beside the LED transmitter to feedback for predistorter training. However, the PD is a nonlinear device as well, and the implementation cost is not favorable. For this reason, there is very little discussion of adaptive predistortion of LEDs in the literature.

Postdistortion

Postdistortion is a receiver-side technique to mitigate nonlinear distortion. Figures 6c and 6d show the general structures of the static postdistortion and the adaptive postdistortion techniques. Similar to static predistortion, static postdistortion only takes the offline data of the nonlinearity and cannot support the LED nonlinearity dynamics. For dynamic postdistortion, no additional feedback physical circuits are needed as in adaptive predistortion. In [13], compensation for an LED nonlinearity is achieved by means of Volterra receivers. The authors of [14] proposed an adaptive postdistortion technique with the memory polynomial model and improved system performance. Postdistortion can also be combined with frequency domain equalization (FDE) to compensate for the memory effect caused by non-flat frequency response of LED [16]. In most cases, only the line-of-sight link is considered for channel modeling since it is usually much stronger than the diffuse link. In addition, the signal bandwidth is narrow due to the limited LED response. Thus, the frequency response of an IM/DD channel is relatively flat. However, if we consider that multipath effects or the modulation bandwidth is relatively broad, the channel response is no longer flat. In this case, it may be necessary to combine pre-equalization or post-equalization with predistortion or postdistortion to compensate for the channel response.

The designing of the robust mitigation techniques catching these dynamics is of value and challenge. Another challenge of the future work lies in the hardware implementation of these mitigation techniques, especially the adaptive predistorter and postdistorter.

CONCLUSION

In this article, we summarize topics related to LED nonlinearity distortion mitigation in VLC. First, we show different ways to model the LED nonlinearity, including memory-less/memory models and static/dynamic models. LED memory effects and time-varying dynamics should be taken into account to model the nonlinearity and design mitigation techniques, especially for high-speed transmission. Then we present two major approaches to mitigation techniques: waveform-specific mitigation and waveform-agnostic mitigation. Waveform-specific mitigation focuses on how to select the signal waveforms to reduce the nonlinear distortions. Waveform-agnostic mitigation compensates for the nonlinear distortion with linearization methods. We show the optimal nonlinear mapping for the VLC system and then study how to linearize the overall system by predistortion and postdistortion. Additionally, both static and adaptive approaches are discussed. Nonlinear distortion mitigation is crucial in future high-speed VLC system design. The dynamic characteristics caused by the device nature, environmental changes, and illumination requirements cannot be ignored. The design of robust mitigation techniques catching these dynamics is of value and challenging. Another challenge for future work lies in the hardware implementation of these mitigation techniques, especially the adaptive predistorter and postdistorter.

REFERENCES

[1] H. Elgala, R. Mesleh, and H. Haas, "Indoor Optical Wireless Communication: Potential and State of the Art," *IEEE Commun. Mag.*, vol. 49, no. 9, Dec. 2011, pp. 56–62.

[2] IEEE Std 802.15.7, "IEEE Standard for Local and Metropolitan Area Networks — Part 15.7: Short-Range Wireless Optical Communication Using Visible Light," Sept. 2011.

[3] A. Jovicic, J. Li, and T. Richardson, "Visible Light Communication: Opportunities, Challenges and the Path to Market," *IEEE Commun. Mag.*, vol. 51, no. 12, Dec. 2013, pp. 26–32.

[4] E. F. Schubert, *Light Emitting Diodes*, 2nd ed., Cambridge Univ. Press, 2006.

[5] B. Inan *et al.*, "Impact of LED Nonlinearity on Discrete Multitone Modulation," *J. Opt. Commun. Net.*, vol. 1, no. 5, Oct. 2009, pp. 439–51.

[6] I. Neokosmidis *et al.*, "Impact of Nonlinear LED Transfer Function on Discrete Multi-Tone Modulation: Analytical Approach," *J. Lightwave Tech.*, vol. 27, no. 22, Nov. 2009, pp. 4970–78.

[7] H. Elgala, R. Mesleh and H. Haas, "Non-Linearity Effects and Predistortion in Optical OFDM Wireless Transmission Using LEDs," *Int'l. J. Ultra Wideband Commun. and Systems*, vol. 1, no. 2, Nov. 2009, pp. 143–50.

[8] D. Tsonev, S. Sinanovic, and H. Haas, "Complete Modeling of Nonlinear Distortion in OFDM-Based Optical Wireless Communication," *J. Lightwave Tech.*, vol. 31, no. 18, Sept. 2013, pp. 3064–76.

[9] Z. Yu, R. J. Baxley, and G. T. Zhou, "EVM and Achievable Data Rate Analysis of Clipped OFDM Signals in Visible Light Communication," *EURASIP J. Wireless Commun. and Networking*, vol. 2012, no. 321, Oct. 2012, pp. 1–16.

[10] Z. Yu, R. J. Baxley, and G. T. Zhou, "Peak-to-Average Power Ratio and Illumination-to-Communication Efficiency Considerations in Visible Light OFDM Systems," *IEEE Int'l. Conf. Acoustics, Speech and Signal Processing*, May 2013, pp. 5397–5401.

[11] Z. Yu, R. J. Baxley, and G. T. Zhou, "Distributions of Upper PAPR and Lower PAPR of OFDM Signals in Visible Light Communications," *IEEE Int'l. Conf. Acoustics, Speech and Signal Processing*, May 2014, pp. 355–59.

[12] T. Kamalakis *et al.*, "Empirical Volterra-Series Modeling of Commercial Lightemitting Diodes," *J. Lightwave Tech.*, vol. 29, no. 14, July 2011, pp. 2146–55.

[13] G. Stepniak, J. Siuzdak and P. Zwierko, "Compensation of a VLC Phosphorescent white LED Nonlinearity by Means of Volterra DFE," *IEEE Photon. Technologies Lett.*, vol. 25, no. 16, Aug. 2013, pp. 1597–1600.

[14] H. Qian *et al.*, "Adaptive Postdistortion for Nonlinear LEDs in Visible Light Communications," *IEEE Photonics J.*, vol. 6, no. 4, Aug. 2014, pp. 1–8.

[15] K. Ying *et al.*, "Optimization of Signal-to-Noise-Plus-Distortion Ratio for Dynamic-Range-Limited Nonlinearities," *Digital Signal Processing*, vol. 36, Jan. 2015, pp. 104–14.

[16] Y. Wang *et al.*, "Enhanced Performance of Visible Light Communication Employing 512-QAM N-SC-FDE and DD-LMS," *Optics Express*, vol. 22, no. 13, June 2014, pp. 15,328–34.

[17] J. Zhang *et al.*, "Time-Domain Digital Pre-Equalization for Band-Limited Signals Based on Receiver-Side Adaptive Equalizers," *Optics Express*, vol. 22, no. 17, Aug. 2014, pp. 20,515–29.

[18] Z. Dong *et al.*, "8 × 9.95-Gb/s Ultra-Dense WDM-PON on a 12.5-GHz Grid with Digital Pre-Equalization," *IEEE Photon. Technologies Lett.*, vol. 25, no. 2, Jan. 2013, pp. 194–97.

[19] T.-P. Sun and C.-H. Wang, "Specially Designed Driver Circuits to Stabilize LED Light Output without a Photodetector," *IEEE Trans. Power Elctronics*, vol. 27, no. 9, Sept. 2012, pp. 4140–52.

[20] K. H. Loo *et al.*, "On Driving Techniques for LEDs: Toward A Generalized Methodology," *IEEE Trans. Power Electronics*, vol. 24, no. 12, Dec. 2009, pp. 2967–76.

BIOGRAPHIES

KAI YING (kying3@gatech.edu) received his B.S. degree from the Department of Electronic Engineering, Shanghai Jiao Tong University, China, in 2010. He received his M.E. degree from the Department of Electronic Engineering, Shanghai Jiao Tong University, and his M.S. degree from the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, both in 2013. Currently, he is pursuing his Ph.D. degree in Georgia Institute of Technology. His research interests include nonlinear signal processing and optical wireless communications.

ZHENHUA YU is a system engineer/member of technical staff at Texas Instruments Inc., Dallas. He obtained his Ph.D. degree in electrical and computer engineering from Georgia Institute of Technology in May 2014, and his M.S. degree in communication and information engineering and B.S. degree in information engineering from Shanghai Jiao Tong University in 2010 and 2007, respectively. His research interests include OFDM, visible light communications, signal processing, and optimizations.

ROBERT J. BAXLEY [SM] received his B.S., M.S., and Ph.D. degrees, all in electrical engineering, from Georgia Tech. In the course of his graduate work, he was the recipient of the Sigma Xi Award, the National Science Foundation Graduate Research Fellowship Program award, the Grand Prize in the SAIC student paper competition, and the Georgia Tech Center for Signal & Image Processing Outstanding Research Award. From 2008 to 2014, he was employed at the Georgia Tech Research Institute where he served as the director of the Software Defined Radio Laboratory among other roles. While at GTRI, he led the GTRI team that placed second out of 90 teams in the DARPA Spectrum Challenge. He is currently the chief engineer at Bastille. He also holds an adjunct faculty appointment in the Georgia Tech School of Electrical and Computer Engineering. His research interests are in the areas of cognitive radio, wireless security, and signal processing for communications systems. From 2012 to 2014 he served as an Associate Editor for *Digital Signal Processing*. He is a member of the Association of Old Crows.

HUA QIAN [SM] received his B.S. and M.S. degrees from the Department of Electrical Engineering, Tsinghua University, Beijing, China, in 1998 and 2000, respectively. He obtained his Ph.D. degree from the School of Electrical and Computer Engineering, Georgia Institute of Technology, in 2005. He is currently with the Shanghai Research Center for Wireless Communications, Shanghai Institute of Microsystem and Information Technology Research Institute, Chinese Academy of Sciences as a full professor. His current research interests include nonlinear signal processing and system design of wireless communications.

GEE-KUNG CHANG [F] received his B.S. degree in physics from National Tsinghua University, and his M.S. and Ph.D. degrees in physics from the University of California, River-

side. He is the Byers Eminent Scholar Chair Professor in the School of Electrical and Computer Engineering, Georgia Institute of Technology. He is an Eminent Scholar of the Georgia Research Alliance. He devoted a total of 23 years of service to Bell Systems-Bell Labs, Bellcore, and Telcordia Technologies, where he served in various research and management positions, including as the director and a chief scientist of Optical Internet Research, director of Optical Networking Systems and Testbed, and director of Optical System Integration and Network Interoperability. He is the holder of 56 U.S. and international patents, and has co-authored over 450 peer-reviewed journal and conference papers. He is a Fellow of the IEEE Photonics Society and a Fellow of the Optical Society of America (OSA) for his pioneer contributions to DWDM optical networking and optical label-switching technologies. He has served on many IEEE and OSA conference committees. He has also served several times as a Guest Editor for Special Issues of the *Journal of Lightwave Technology* and *Journal of Optical Communications and Networks*.

G. TONG ZHOU [F] received her B.S. degree in biomedical engineering and instrumentation from Tianjin University, China, in July 1989. From September 1989 to May 1995, she was with the University of Virginia, Charlottesville, where she obtained an M.S. degree in biophysics in May 1992, an M.S. degree in electrical engineering in January 1993, and her Ph.D. degree in electrical engineering in January 1995. She has been with the School of Electrical and Computer Engineering at Georgia Tech since September 1995 where she is now a professor. In 1997, she received the National Science Foundation CAREER Award. She was also the recipient of the 2000 Meritor Teaching Excellence Award at Georgia Tech. His research interests are in the general areas of statistical signal processing and communications applications. She was elected Fellow of IEEE in 2012 for contributions to the analysis of nonlinear signals and systems.