

Low-Complexity and Robust PAPR Reduction and LED Nonlinearity Mitigation for UACO-OFDM LiFi Systems

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Abstract—We propose a low-complexity and high-performance joint peak-to-average power ratio (PAPR) reduction and light emitting diode (LED) nonlinearity mitigation approach for unipolar asymmetrically clipped optical-orthogonal frequency division multiplexing (UACO-OFDM) based light fidelity (LiFi) systems. This is the first reported work to apply nonlinear compression based on μ -law companding for UACO-OFDM LiFi systems to reduce PAPR. In order to avoid the effect of the nonlinearity of LED, the transmitted signals are compressed further linearly. The signal distortion caused by nonlinear and linear compression is compensated for using multiple LEDs for simultaneous transmission. The proposed joint PAPR reduction and LED nonlinearity mitigation approach provides low complexity, searching is not required. Also, it is spectrum- and energy- efficient, requiring no pilot and consuming no extra transmission power. Simulation results show that the proposed approach significantly outperforms the state-of-the-art methods in terms of complementary cumulative distribution function (CCDF) and bit error rate (BER), and that it is more robust against the LED nonlinearity than conventional UACO-OFDM LiFi systems and other methods in the literature.

I. INTRODUCTION

The requirements for high speed transmission and low energy consumption are recognized for future wireless communications. However, current frequency band under 5 GHz is very scarce. A solution to this problem is to use higher carrier frequency [1]. Light fidelity (LiFi), which explores light emitting diode (LED) for simultaneous illumination and communications via wide visible light spectrum, is considered as a solution to short-range broadband wireless service communications and can be used for next generation communication systems [2].

Orthogonal frequency-division multiplexing (OFDM) is robust against frequency-selective fading and has been widely employed in wireless communication systems [3]. Unipolar asymmetrically clipped optical-orthogonal frequency division multiplexing (UACO-OFDM) was proposed in [4] for LiFi systems with intensity modulation and direct detection (IM/DD), and is a technique superimposed by asymmetrically clipped optical-OFDM (ACO-OFDM) [5] and unipolar OFDM (U-OFDM) signals [6]. UACO-OFDM achieves the

same energy efficiency as ACO-OFDM and provides higher spectrum efficiency than ACO-OFDM.

Signal distortion due to nonlinearity of LED [7] is a challenging issue for LED based LiFi systems. The peak amplitude of signals are clipped off to protect the LED chip from being overheated, when the power is beyond the limitation of LED. Reducing the peak-to-average power ratio (PAPR) of signals is one of the methods to prevent signals from falling in the nonlinear range of LED. In [8], iterative signal clipping was proposed to reduce the impact of LED nonlinearity on signals. However, the iterative process leads to high complexity. In [8], [9], signal power back-off was mentioned to avoid the LED operating in the nonlinear region. However, the method reduces the transmission power causing the deterioration of bit error rate (BER) performance. Pre-distortion [10] techniques were proposed to eliminate the LED's nonlinearity at the transmitter. However, the peak amplitude of signals are still clipped off, due to the limitation of LED.

High PAPR, as one of the problems for OFDM based systems [11], results from the superposition of a large number of statistically independent data summed up constructively. This causes signal nonlinear distortion due to power amplifier inefficiency and the nonlinearity of LED. In [12], a pilot-aided PAPR reduction method was proposed, by using a number of pilot sequences, without degrading BER performance. However, the spectral efficiency is low. In [13], a PAPR reduction method based on the selective mapping (SLM) scheme, which uses a phase sequence with symmetry and periodicity magnitude extension factors, without transmitting any side information. However, the computational complexity is high due to a large number of searches to select the lowest PAPR time domain signals. The clipping method was introduced in [14], to achieve good PAPR performance. However, the BER performance is poor since the signals are clipped off and distorted. In [15], a subcarrier grouping scheme was proposed to reduce the PAPR of signals using multi-LED transmission. However, power allocation and subcarrier switching results in high computational complexity.

In this paper, a novel joint low-complexity and high-performance PAPR reduction and LED nonlinearity mitigation scheme is proposed for UACO-OFDM LiFi systems. The

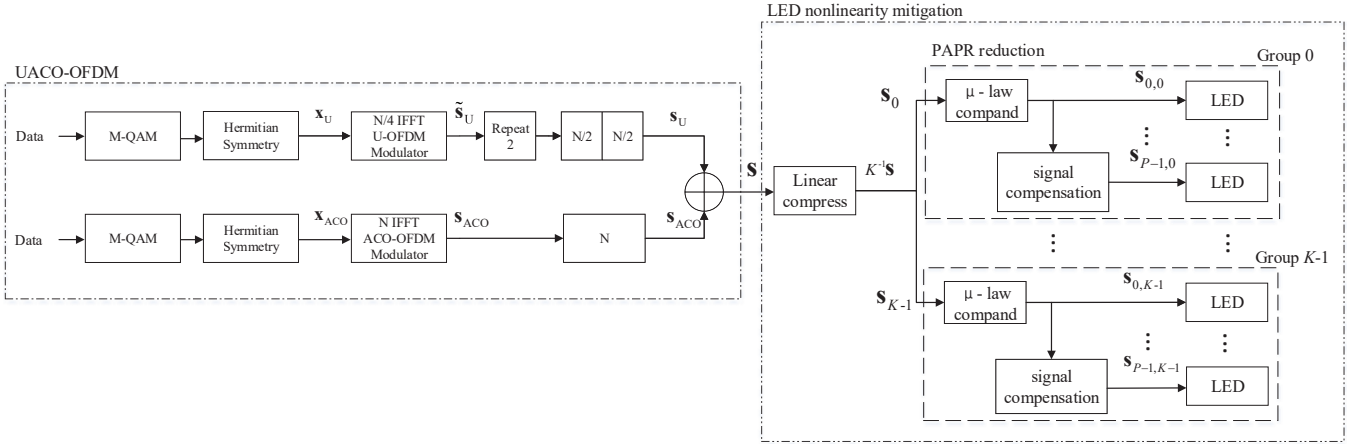


Fig. 1. Block diagram of the proposed PAPR deduction and multi-LED nonlinearity mitigation techniques for UACO-OFDM LiFi systems.

contributions of this paper can be summarized as follows:

- To the best of our knowledge, this is the first work to apply μ -law companding to reduce PAPR for UACO-OFDM LiFi systems. This is a nonlinear approach by compressing strong signals and enlarging weak signals. To avoid LED nonlinearity, the transmitted signals are further compressed linearly. The proposed scheme requires no any training data, contributing to spectrum efficiency higher than [12] which needs a large number of pilots to reduce the PAPR. Also, low complexity is achieved by the proposed method, as a large number of searches are not required for PAPR reduction as in [13], [16].
- In order to compensate for the signal distortion caused by linear and nonlinear compression, we propose to employ multiple LEDs for simultaneous transmission, rather than a single LED as in [12], [13]. The multiple LEDs require no extra transmission power, providing an energy-efficient LiFi system.
- Simulation results show that the proposed scheme significantly outperforms the previous methods in [14], [16] and [17] and a UACO-OFDM LiFi system with a single LED, in terms of complementary cumulative distribution function (CCDF) and BER.

II. SYSTEM MODEL

In this paper, we consider a UACO-OFDM LiFi system [4] where ACO-OFDM signals and U-OFDM signals are superimposed together to transmit simultaneously. Hence, the spectral efficiency is high. ACO-OFDM modulation is used at the first layer. Let N denote the number of subcarriers used. Define $\mathbf{x}_{ACO} = [x_{ACO}(0), x_{ACO}(1), \dots, x_{ACO}(N-1)]^T$ as the ACO-OFDM signals vector of Hermitian symmetry, with $x_{ACO}(n)$ being a quadrature amplitude modulation (QAM) symbol. The symbols on the even subcarriers are set to 0, $x_{ACO}(0) = x_{ACO}(2) = x_{ACO}(4) =$

$\dots = 0$. $\check{s}_{ACO} = \mathbf{F}_N^H \mathbf{x}_{ACO}$ is the bipolar signals vector in the time domain, where \mathbf{F}_N^H is the N -point inverse fast Fourier transform (IFFT) matrix with (u, v) entry $[\mathbf{F}_N^H]_{u,v} = \frac{1}{\sqrt{N}} \exp(j \frac{2\pi uv}{N})$, $(u, v = 0, 1, \dots, N-1)$. The symbol on the n -th subcarrier can be expressed as $\check{s}_{ACO}(n) = \frac{1}{\sqrt{N}} \sum_{m=0}^{N-1} x_{ACO}(m) \exp(j \frac{2\pi mn}{N})$. After clipping the negative signals, the ACO-OFDM symbol in the time domain is written as:

$$s_{ACO}(n) = \begin{cases} \check{s}_{ACO}(n), & \check{s}_{ACO}(n) \geq 0 \\ 0, & \check{s}_{ACO}(n) < 0 \end{cases} \quad (1)$$

Hence, the ACO-OFDM signal vector in the time domain is $\mathbf{s}_{ACO}(n) = [s_{ACO}(0), s_{ACO}(1), \dots, s_{ACO}(N-1)]^T$. U-OFDM modulation is used at the second layer. Define $\mathbf{x}_U = [x_U(0), x_U(1), \dots, x_U(N/4-1)]^T$ as the U-OFDM signals vector of Hermitian symmetry, with $x_U(n)$ denoting the corresponding QAM symbol, $x_U(0) = x_U(N/8) = 0$. After using IFFT, the time-domain signal on the n -th subcarrier can be expressed as $\check{s}_U(n) = \frac{1}{\sqrt{N}} \sum_{m=0}^{N/4-1} x_U(m) \exp(j \frac{2\pi mn}{N})$. After selecting the unipolar signals, the symbol of the *positive* \check{s}_U^+ and *negative* frame \check{s}_U^- in the time domain can be written as:

$$\check{s}_U^+(n) = \begin{cases} \check{s}_U(n), & \check{s}_U(n) \geq 0 \\ 0, & \check{s}_U(n) < 0 \end{cases} \quad (2)$$

$$\check{s}_U^-(n) = \begin{cases} -\check{s}_U(n), & \check{s}_U(n) \leq 0 \\ 0, & \check{s}_U(n) > 0 \end{cases} \quad (3)$$

$\tilde{\mathbf{s}}_U = [\check{s}_U^+{}^T \check{s}_U^-{}^T]^T$ is the U-OFDM signals in the time domain, where $\check{s}_U^+ = [\check{s}_U^+(0), \check{s}_U^+(1), \dots, \check{s}_U^+(N/4-1)]^T$ and $\check{s}_U^- = [\check{s}_U^-(0), \check{s}_U^-(1), \dots, \check{s}_U^-(N/4-1)]^T$. The first layer data is \mathbf{s}_{ACO} , $\mathbf{s}_U = [\tilde{\mathbf{s}}_U^+{}^T \tilde{\mathbf{s}}_U^-{}^T]^T$ is the second layer data which is generated by repeating $\tilde{\mathbf{s}}_U$ twice. They are added together to form UACO-OFDM signal:

$$\mathbf{s} = \mathbf{s}_{ACO} + \mathbf{s}_U \quad (4)$$

Due to the structure of this superimposed signals and the characteristics of ACO-OFDM and U-OFDM signals, original signals of each layer can be recovered well by using interference cancellation method at the receiver.

The LoS channel impulse response can be written as follows [18]:

$$h_{\text{LoS}}(t) = \frac{(m+1)A}{2\pi d^2} \cos^m(\phi) \cos(\psi) \quad (5)$$

where $m = -\ln(2)/\ln[\cos(\phi_{1/2})]$ is the Lambertian emission order related to the half-power semi-angle $\phi_{1/2}$, A is the detection area of the detector, ϕ is the light radiance angle of the transmitter, ψ is the corresponding light incidence angle of the receiver and d denotes the distance between transmitter and receiver. Due to the low-pass characteristic of the optical front-ends, the limited modulation bandwidth of LED can be modelled approximately as follows [19]:

$$h_{\text{LP}}(t) = e^{-2\pi f_b t} \quad (6)$$

where f_b is the cutoff bandwidth of LED. Therefore, the equivalent channel response $h(t)$ can be expressed as follows [19]-[21]:

$$h(t) = h_{\text{LoS}}(t) \otimes h_{\text{LP}}(t) \quad (7)$$

where \otimes denotes linear convolution. $h(t)$ is sample-spaced resulting in a number of L channel path delays inserted by (N-L) zeros as $\mathbf{h} = [h(0), h(1), \dots, h(L-1), \mathbf{0}_{(N-L) \times 1}]^T$, with $h(n)$ being the n -th channel impulse response.

A cyclic prefix (CP) of length N_{CP} is inserted between UACO-OFDM block to avoid inter-block interference (IBI). After passing through the optical channel, the received signals \mathbf{y} can be written as:

$$\mathbf{y} = \mathbf{s} \otimes \mathbf{h} + \mathbf{w} \quad (8)$$

where $\mathbf{w} = \mathbf{n}_w + \mathbf{n}_{\text{clip}}$ is additive Gaussian noise. \mathbf{w} is the sum of white noise \mathbf{n}_w and clipping noise \mathbf{n}_{clip} , $\mathbf{n}_{\text{clip}} = \mathbf{n}_{\text{lc}} + \mathbf{n}_{\text{uc}}$, with \mathbf{n}_{lc} and \mathbf{n}_{uc} are the noise components due to clipping of the lower and upper peaks of the UACO-OFDM signals, respectively [8], [22].

Remark 1: The LED based LiFi system suffers from the inherent disadvantage of LEDs nonlinearity. There is a limited region of LED with maximum voltage and current. The signals are not distorted if passing through the linear area of LED, and are distorted if entering the nonlinear area.

Remark 2: One of the key drawbacks of UACO-OFDM systems is the high PAPR of signals. There are a number of signals with strong amplitudes. Those are either clipped off or distorted, which causes signal distortion and degradation at the LEDs output. Therefore, there is a main challenge between the limited dynamic linear range of LED and high PAPR of signals. Reducing the PAPR of signals is important to prevent signals from being in the nonlinear range of LED.

III. LED NONLINEARITY MITIGATION AND PAPR REDUCTION

Traditionally, a single LED is employed for signal transmission for UACO-OFDM LiFi systems [4], where the transmitted signals suffer from high PAPR and LED nonlinearity. However, one LED lamp contains multiple individual LED chips. Each LED chip can be modulated separately [15]. Therefore, there are a number of LEDs which can be used to achieve the purpose of LED nonlinearity mitigation and PAPR reduction. The transmitted signals are compressed linearly and nonlinearly. In terms of PAPR reduction, μ -law companding method [17], as a nonlinear compression method, is used to compress strong signals and enlarge weak signals. The linear compression is achieved by compressing the signals a number of times. Multiple LEDs are used to transmit signals simultaneously compensating for the signal distortion caused by linear compression and nonlinear μ -law companding. The proposed approach requires no any training data and no side information, contributing to a spectrum-efficient LiFi system. Also, the proposed LiFi system provides low complexity, as a number of complex searches are not required to reduce the PAPR as traditional methods as in [16]. The proposed PAPR reduction and LED nonlinearity mitigation techniques for UACO-OFDM system as shown in Fig. 1.

Assuming that there are a total number of $G = P \times K$ LEDs, where P is the number of LEDs in each group, K is the number of groups. Define $\tilde{\mathbf{s}}_{p,k}(i) \triangleq [\tilde{s}_{p,k}(0, i), \tilde{s}_{p,k}(1, i), \dots, \tilde{s}_{p,k}(N-1, i)]^T$ as the UACO-OFDM signals vector, $\tilde{s}_{p,k}(n, i)$ is the symbol on the subcarrier n ($n = 0, \dots, N-1$) in the i -th block of the p -th LED in group k . Define $\mathbf{h}_{p,k} = [h_{p,k}(0), h_{p,k}(1), \dots, h_{p,k}(N-1)]^T$ as the channel impulse response vector with $h_{p,k}(n)$ denoting the n -th path of the p -th LED in group k . $\mathbf{H}_{p,k}$ is the channel impulse response diagonal matrix in the frequency domain can be expressed as:

$$\mathbf{H}_{p,k} = \text{diag}\{\sqrt{N}\mathbf{F}_N \mathbf{h}_{p,k}\} \quad (9)$$

where $\text{diag}\{\cdot\}$ denotes the diagonal operator. As the LED chips are placed closely in one LED, the channel impulse response is almost identical for all chips [15]: $\mathbf{H}_{0,0} \approx \mathbf{H}_{0,1} \approx \dots \approx \mathbf{H}_{p,k} \dots \approx \mathbf{H}_{P-1,K-1} \approx \mathbf{H}$.

A. LED Nonlinearity Mitigation

For LiFi systems, LED is considered as one of the principal devices causing nonlinearity [7]. In particular, small signals are clipped if the power below the turn-on voltage, and large signals are clipped if the maximum power reaches the saturation interval of the LED [8]. Therefore, LED's nonlinearity degrades the system performance. In order to mitigate the LED's nonlinearity, the transmitted signals are compressed linearly. The caused distortion can be compensated for multi-LED transmission.

Define \mathbf{s}_k as the transmitted signals of group k . Linear compression is performed on UACO-OFDM signals by K times:

$$\mathbf{s}_k = K^{-1}\mathbf{s} \quad (10)$$

The compressed signals are transmitted by K groups of LEDs simultaneously to compensate for signal distortion caused by linear compression. The probability that signals are affected by nonlinearity of LED is decreased.

B. PAPR Reduction

High PAPR causes signal distortion due to the nonlinear characteristics of LED for LiFi systems. The μ -law companding is employed to compand the time-domain transmitted signals. The distortion of companded signals are compensated for using multiple LEDs.

The signals from different LEDs can be linearly superimposed in free space optical channel. Therefore, there no longer requires decompanding process at the receiver. There are P LEDs in each group. The first LED transmits the companded signals, and the others transmit the compensation signals. The signals of the 0-th LED in group k are companded:

$$\mathbf{s}_{0,k} = \frac{\nu}{\ln(1+\mu)} \ln(1 + \frac{\mu}{\nu}|\mathbf{s}_k|)\text{sign}(\mathbf{s}_k) \quad (11)$$

where ν and μ denote the companding threshold and the companding coefficient respectively, and $\text{sign}(\cdot)$ denotes the sign function. The signals of group k can be expressed as:

$$\mathbf{s}_k = \underbrace{\mathbf{s}_{0,k}}_{\text{companded signal}} + \underbrace{\sum_{p=1}^{P-1} \mathbf{s}_{p,k}}_{\text{compensation signals}} \quad (12)$$

C. Signal Recovery

After passing through the optical channel, the received signals $\tilde{\mathbf{y}}$ can be written as:

$$\tilde{\mathbf{y}} = \sum_{k=0}^{K-1} \sum_{p=0}^{P-1} (\mathbf{s}_{p,k} \otimes \mathbf{h}_{p,k}) + \mathbf{w} \quad (13)$$

Zero-forcing (ZF) equalization is applied at the receiver:

$$\hat{\mathbf{x}} = \mathbf{H}^{-1}\mathbf{F}_N\tilde{\mathbf{y}} \quad (14)$$

The second layer signals does not affect the signals on the odd subcarriers, due to the employed signal structure. The useful information at the first layer can be recovered with the conventional ACO-OFDM demodulator from the odd subcarriers. Then, Hermitian symmetry is imposed on the recovered information to reconstruct the first layer frequency domain signals $\hat{\mathbf{x}}_{\text{ACO}}$. The time domain signals of the first layer $\hat{\mathbf{s}}_{\text{ACO}}$ can be recovered by ACO-OFDM modulation according to $\hat{\mathbf{x}}_{\text{ACO}}$. The second layer signals can be recovered

by interference cancellation. The estimated signals of the second layer can be written as:

$$\hat{\mathbf{s}}_{\text{U}} = \mathbf{F}_N^H \hat{\mathbf{x}} - \hat{\mathbf{s}}_{\text{ACO}} \quad (15)$$

At the second layer, the conventional U-OFDM demodulator is used to recover the second layer frequency domain signals $\hat{\mathbf{x}}_{\text{U}}$.

IV. SIMULATION RESULTS

In this section, simulation results are produced to illustrate the CCDF defined as the probability that the PAPR exceeds a specific value γ and BER performance of the proposed scheme. The PAPR of the i -th block is given by:

$$\text{PAPR}\{\mathbf{s}_{p,k}(i)\} = \frac{\max_{0 \leq t < T} \{|s_{p,k}(t,i)|^2\}}{\mathbb{E}_t \{|s_{p,k}(t,i)|^2\}} \quad (16)$$

where $\max_{0 \leq t < T} \{\cdot\}$ denotes the maximum value, with T denotes the period of a UACO-OFDM block, $s_{p,k}(t,i)$ is the output continuous signal, and $\mathbb{E}_t \{\cdot\}$ denotes the statistical expectation. A highly reliable LED (Seoul Semiconductor, SAT802-SC/STA0A14AC) is considered [23]. Clipping effects in the nonlinear region are considered [8].

For Monte Carlo simulations, the UACO-OFDM system is implemented with IFFT of $N=64$ points, and the number of superimposed layers is 2. ACO-OFDM modulation is used at the first layer and U-OFDM modulation is used at the second layer. Each subcarrier is modulated using uncoded 16-QAM constellations. The CP length is $N_{\text{CP}}=16$. The average electrical signal power ranges from -10 dBm to 40 dBm, and the AWGN power is -10 dBm. For PAPR reduction, the companding coefficient setting is $\mu = 3$. We use $K = 2$ groups, each with $P = 2$ LEDs for companding and compensation. The total number of LEDs used is $G = K \times P = 4$ for joint PAPR reduction and LED nonlinearity mitigation. The cutoff bandwidth of LED is $f_b = 81.5\text{MHz}$. The LEDs are located on the ceiling facing straight down. The receiver is placed at the desk facing straight upwards. The distance between the desk and the ceil is 2 m. The half-power semi-angle is $\phi_{1/2} = 60$ degrees is used. The light radiance angle of the transmitter is $\phi = 40$ degrees, and the corresponding light incidence angle of the receiver is $\psi = 40$ degrees respectively. The detection area of $A = 1 \text{ cm}^2$ is used at the receiver.

Fig. 2 shows the CCDF performance of the proposed PAPR reduction scheme. Apparently, it has an obvious PAPR reduction which is about 6 dB better than traditional UACO-OFDM with no PAPR reduction [4], more than 3 dB better than traditional SLM method [16] with a number of two phase sequences and 1 dB better than traditional clipping method [14] with clipping rate $CR=7\text{dB}$.

Fig. 3 shows the impact of number of LEDs used on BER performance for UACO-OFDM LiFi systems with the

impairment of LED nonlinearity. The performance of the proposed scheme varies with the number of LEDs used. It is shown in Fig. 3 that the larger the number of LEDs, the better the effects of nonlinearity elimination. This is because the total transmission power can be allocated on a number of LEDs to mitigate the effect of peak signals into the nonlinear area of LED.

Fig. 4 shows the BER performance of the proposed PAPR reduction and LED nonlinearity mitigation approach. The proposed PAPR reduction approach with μ -law companding and compensation provides BER performance significantly better than traditional companding method with no signal compensation, and clipping method [14], respectively. Although SLM method [16] does not deteriorate BER performance, the complexity is high. The proposed UACO-OFDM system with joint PAPR reduction and LED nonlinearity mitigation outperforms the original system with a single LED, no PAPR reduction as well as no LED nonlinearity mitigation, in terms of BER performance. Due to the effect of LED nonlinearity, the BER performance does not improve with increasing SNR, and presents a turning point at high SNR. The proposed approach significantly outperforms the existing methods in the literature. The existing methods are not suitable for the case with high SNR in the presence of LED nonlinearity.

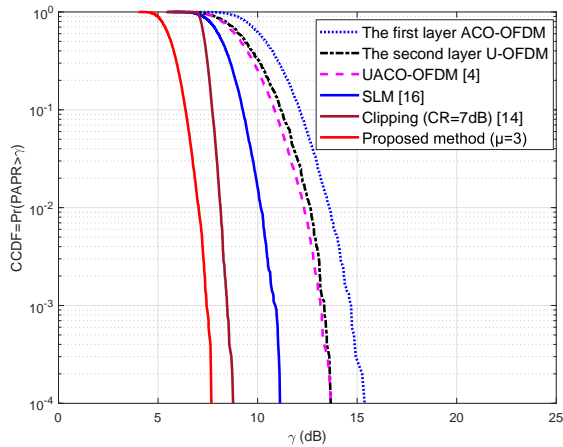


Fig. 2. CCDF performance of the proposed PAPR reduction and nonlinearity mitigation techniques for UACO-OFDM LiFi systems.

V. CONCLUSION

In this paper, a low-complexity and high-performance PAPR reduction and LED nonlinearity mitigation scheme has been proposed for UACO-OFDM LiFi systems. The simulation results demonstrate that the proposed approach can provide obvious CCDF performance. In the presence of the LED's nonlinearity, the proposed scheme can provide obvious BER performance gain compared to the methods in the literature. The proposed UACO-OFDM system significantly

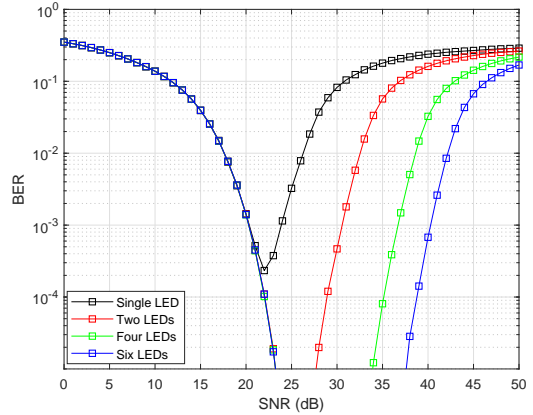


Fig. 3. BER performance of multi-LED transmission systems.

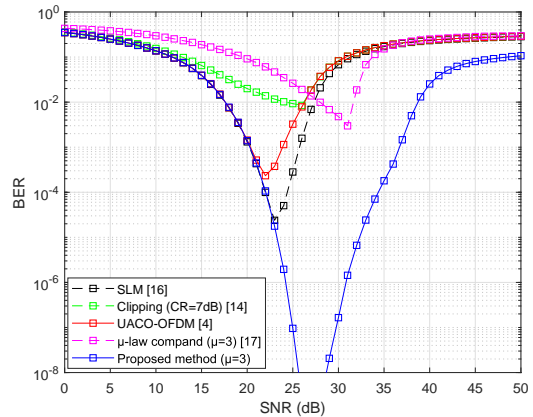


Fig. 4. BER performance of the proposed PAPR reduction and nonlinearity mitigation techniques for UACO-OFDM LiFi systems.

outperforms the traditional UACO-OFDM system with a single LED in terms of the turning point of BER performance. Generally, the larger the number of LEDs, the more effective the nonlinearity elimination and PAPR reduction.

VI. ACKNOWLEDGMENTS

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