Superposition Based Nonlinearity Mitigation for ACO-OFDM Optical Wireless Communications

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***Abstract*—We propose a superposition based light emitting diode (LED) nonlinearity mitigation scheme for asymmetrically clipped optical-orthogonal frequency division multiplexing (ACO-OFDM) optical wireless communications (OWC) systems, where a non-redundant signal stream is superimposed with an ACO-OFDM source signal stream, requiring no pilot and no side information. Based on the anti-symmetry property that a non-redundant signal and its symmetric signal is equal to zero with the same absolute value, a non-redundant signal is used to reduce the large amplitude of the ACO-OFDM signal and enhance its symmetric ACO-OFDM signal that is clipped to zero due to negative signal clipping, allowing LED nonlinearity mitigation. The proposed scheme is also energy-efficient, as the large-amplitude signal reduction is equal to the symmetric signal enhancement, requiring no extra power. However, the designed non-redundant signals fall on odd subcarriers and interfere with source signals. The even subcarriers include the absolute value of source signals, which can be utilized to recover source signals. The polarity of source signals on even subcarriers can be determined by ensuring that the remaining part is higher than the clipping part of the large-amplitude signal in the process of LED nonlinearity mitigation. Simulation results show that the proposed scheme outperforms a number of state-of-the-art methods in the literature as well as ACO-OFDM systems with no LED nonlinearity mitigation in terms of bit error rate (BER).**

***Index Terms*—ACO-OFDM, nonlinearity mitigation**

I. Introduction

OPTICAL wireless communications (OWC) use light in the complimentary visible light frequency band between 450 THz and 750 THz to transmit high-speed data [1]. For OWC systems, the modulated signal is transmitted by a light emitting diode (LED), and received by a photo detector (PD). Intensity modulation and direct detection (IM/DD) is employed to allow unipolar signals to transmit for OWC systems. Asymmetrically clipped optical-orthogonal frequency division multiplexing (ACO-OFDM) [2]–[5] is one of multi-carrier modulations to transform complex-valued and bipolar signals into real-valued and unipolar signals, by filling even subcarriers with zero in frequency domain and clipping negative signal in time domain. The clipped negative signals fall on even subcarriers, and include the absolute value of source signals, which can be utilized to detect the transmitted signals and improve bit error rate (BER) performance up to 3 dB together with source signals on odd subcarriers [2]–[5].

LED is a nonlinear device, where large-amplitude ACO-OFDM signals are clipped off to work in the limited linear range of LED, resulting in signal distortion and BER degradation. The existing works in [2]–[5] are not robust against LED nonlinearity, as the even subcarriers are utilized for signal detection enhancement, rather than LED nonlinearity mitigation. In the literature, a number of methods can be used for LED nonlinearity mitigation [6]–[8]. In [6], a clipping method was proposed to reduce peak-to-average power ratio (PAPR) of signals to fit in the linear range of power amplifier, which can also be used to clip off the large amplitude of signals for LED nonlinearity mitigation. However, the clipping method causes signal distortion. In [7], a recoverable upper-clipping ACO-OFDM (RoC-ACO-OFDM) method was proposed to reduce the clipping noise. However, the BER performance is still limited in the case with the LED limited bandwidth, causing a number of decision errors. In [8], a spatial optical-OFDM (SO-OFDM) method was proposed to reduce the impact of LED nonlinearity, by dividing an OFDM stream with large-amplitude signals into a number of substreams with small-amplitude signals. However, the spatial efficiency is not high, as a number of LEDs only transmit a single OFDM stream.

In this letter, we propose a superposition based LED nonlinearity mitigation scheme for ACO-OFDM OWC systems, where a non-redundant signal stream is superimposed with an ACO-OFDM source signal stream to reduce the large amplitude of ACO-OFDM signals, requiring no side information and no pilot. Main contributions are summarized as follows:

1) The designed non-redundant signals are based on the anti-symmetry property that the sum of a signal and its symmetric signal is equal to zero, with the same absolute value. To allow LED nonlinearity mitigation, the large-amplitude ACO-OFDM signal is reduced by a

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non-redundant signal, while its symmetric ACO-OFDM signal that is clipped to zero due to negative signal clipping is now enhanced by the same non-redundant signal. The large-amplitude signal reduction is equal to the symmetric signal enhancement, requiring no extra power. Also, a threshold factor is introduced to limit the reduction amount of the large-amplitude signal.

2) The designed non-redundant signals occupy odd subcarriers and interfere with source signals. The even subcarriers include the absolute value of source signals due to negative signal clipping in ACO-OFDM signals, and can be utilized to recover source signals. Thus, the proposed scheme is much more robust against LED nonlinearity than the existing works [2]–[5] with no consideration of LED nonlinearity, where the even subcarriers are combined with the odd subcarriers to enhance signal detection. The polarity of source signals can be determined by ensuring that the remaining part is higher than the clipping part of the large-amplitude signal in the LED nonlinearity mitigation process, while in previous works [2]–[5], the polarity of source signals on even subcarriers is recognized by the polarity of the decoded source signals on odd subcarriers. Also, the proposed scheme provides decision errors in signal detection less than the RoC-ACO-OFDM method [7], as the number of upper-clipping cases in the proposed scheme is less than that in the RoC-ACO-OFDM method [7], resulting in a less number of detected signals within error-prone boundaries between cases.
3) Simulation results show that the proposed approach outperforms a number of existing methods [4], [6]–[8], as well as the ACO-OFDM system with no LED nonlinearity mitigation, in terms of BER.

II. System Model

Assume that N subcarriers are used. Let $S(k)$ denote an M-ary quadrature amplitude modulation (M-QAM) symbol on the k-th subcarrier ($k = 0, \ldots, N-1$). The ACO-OFDM source signals on odd subcarriers are organized based on Hermitian symmetry, and the even subcarriers are null. The time-domain signal is given as $s(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S(k) e^{j\frac{2\pi kn}{N}}$, $0 \le n \le N-1$. Let m denote the time index of the symmetric position of n as $m = n + N/2$ if $n = 0, \ldots, N/2-1$. Due to the anti-symmetry property in ACO-OFDM signals as $s(n) = -s(m)$ [7], we organize a signal and its symmetric signal as a pair, with the negative signal being forced to zero:

$$[s_{\text{ACO}}(n), s_{\text{ACO}}(m)] = \begin{cases} [s(n), 0], & s(m) \le 0 \\ [0, s(m)], & s(n) \le 0. \end{cases} \tag{1}$$

In order to reduce the impact of LED nonlinearity, we design a superposition signal by imposing a source signal $s_{\text{ACO}}(n)$ with a non-redundant signal $s_{\text{nr}}(n)$ as:

$$s_{\text{sup}}(n) = s_{\text{ACO}}(n) + s_{\text{nr}}(n). \tag{2}$$

The superposition signal is clipped off to work in the linear range before passing through an LED as [9]:

$$s_{\text{c}}(n) = \begin{cases} v_{\text{t}}, & s_{\text{sup}}(n) > v_{\text{t}} \\ s_{\text{sup}}(n), & v_{\text{b}} \le s_{\text{sup}}(n) \le v_{\text{t}} \\ v_{\text{b}}, & s_{\text{sup}}(n) < v_{\text{b}}, \end{cases} \tag{3}$$

where v_{b} and v_{t} are the normalized maximum permissible voltage and turn-on voltage relative to a standard normal distribution, respectively [9]. The OWC channel includes the line-of-sight (LoS) channel and the LED limited bandwidth as $h(t) = g(t) \otimes \eta_{\text{LoS}}$, where $g(t) = e^{-2\pi f_{\text{b}} t}$ is the LED impulse response, with f_{b} denoting the 3 dB modulation bandwidth of an LED [1], [10], and η_{LoS} is the LoS channel as [1], [10]:

$$\eta_{\text{LoS}} = \frac{(m_{\text{r}}+1)A}{2\pi d^2} \cos^{m_{\text{r}}}(\phi) \cos(\psi), \tag{4}$$

where $m_{\text{r}} = -\ln(2)/\ln(\cos \phi_{1/2})$ is the order of Lambertian emission, with $\phi_{1/2}$ denoting the half-power semiangle of LED, ϕ and ψ are the light radiance angle of LED and the light incidence angle of PD, respectively, A is the detection area of PD, and d denotes the distance between LED and PD. The OWC channel is sampled resulting in a number of L channel paths, with $h(l)$ denoting the l-th impulse channel response ($l = 0, 1, \ldots, L-1$). Let $S_{\text{ACO}}(k) = 1/\sqrt{N} \sum_{n=0}^{N-1} s_{\text{ACO}}(n) e^{-j\frac{2\pi kn}{N}}$ and $S_{\text{nr}}(k) = 1/\sqrt{N} \sum_{n=0}^{N-1} s_{\text{nr}}(n) e^{-j\frac{2\pi kn}{N}}$ denote the source and non-redundant signals on the k-th subcarrier in frequency domain, respectively. Let $H(k) = 1/\sqrt{N} \sum_{l=0}^{L-1} h(l) e^{-j\frac{2\pi kl}{N}}$ denote the channel frequency response. A cyclic prefix (CP) of length $L_{\text{cp}} \ge L-1$ is prepended in each ACO-OFDM block, and is removed at the receiver. The received signal on the k-th subcarrier in frequency domain is given as:

$$Y(k) = H(k) S_{\text{ACO}}(k) + H(k) S_{\text{nr}}(k) + W(k), \tag{5}$$

where $W(k) = W_{\text{n}}(k) + W_{\text{c}}(k)$, $W_{\text{n}}(k)$ denotes the additive white Gaussian noise (AWGN) with zero mean and the summed variance σ_w^2 including shot noise and thermal noise, $W_{\text{c}}(k) = 1/\sqrt{N} H(k) \sum_{n=0}^{N-1} [s_{\text{c}}(n) - s_{\text{sup}}(n)] e^{-j\frac{2\pi kn}{N}}$ is the clipping noise due to LED nonlinearity.

III. Superposition Based LED Nonlinearity Mitigation

As shown in Fig. 1, we propose a superposition based LED nonlinearity mitigation scheme for ACO-OFDM OWC systems, requiring no side information and no pilot. A number of non-redundant signals are superimposed on source signals to reduce the large amplitude of ACO-OFDM signals for LED nonlinearity mitigation. The designed non-redundant signals cause the interference to the source signals on odd subcarriers, while the even subcarriers include the absolute value of source signals, and can be utilized to detect source signals.

A. Superposition Based LED Nonlinearity Mitigation

As shown in Fig. 2, we design a number of non-redundant signals to reduce the large amplitude of ACO-OFDM signals for LED nonlinearity mitigation via a superposition process,

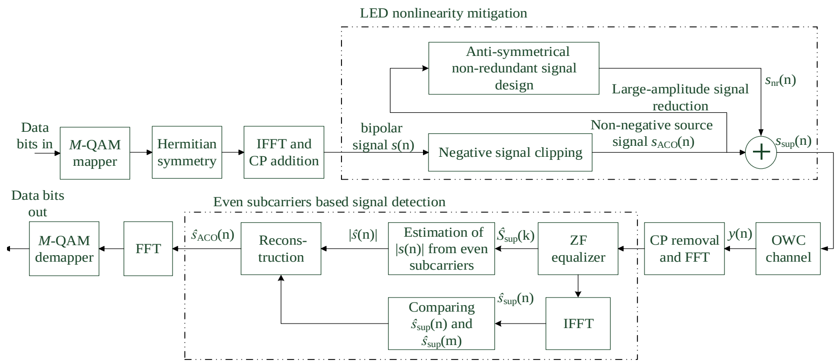

Fig. 1. Block diagram of the proposed superposition based LED nonlinearity mitigation method for ACO-OFDM OWC systems.

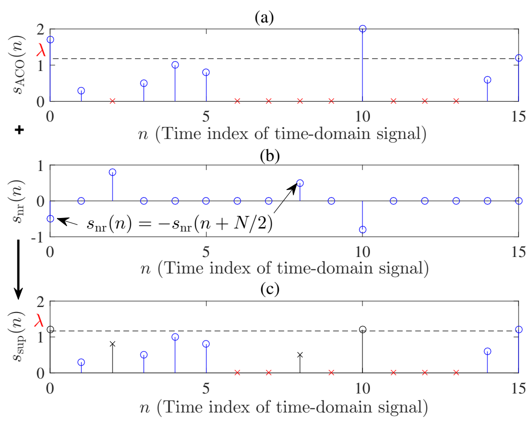

Fig. 2. Superposition signal design. (a) Source signals. (b) Non-redundant signals. (c) Superposition signals.

where the non-redundant signal is superimposed on the source signal. The time index of the peak signal is selected out as:

$$n_{\mathrm{p}} = \arg \max_{0 \le n \le N-1} [s_{\mathrm{ACO}}(n)]. \tag{6}$$

We define a reduction threshold as:

$$\lambda = (1-\alpha) s_{\mathrm{ACO}}(n_{\mathrm{p}}), \tag{7}$$

where α $(0 \le \alpha \le 0.5)$ is the threshold factor. The higher α is, the severer the reduction is, and the lower the PAPR is. The signals with amplitude higher than λ can be reduced by designing a number of non-redundant signals, based on the anti-symmetry property as $s_{\mathrm{nr}}(n) = -s_{\mathrm{nr}}(m)$ [7] in time domain. As a result, a non-redundant signal is used to reduce the large-amplitude ACO-OFDM source signal, and enhance the symmetric signal. The non-redundant signal and its symmetric signal are designed as a pair as:

$$[s_{\mathrm{nr}}(n), s_{\mathrm{nr}}(m)] = \begin{cases} [\lambda - s_{\mathrm{ACO}}(n), s_{\mathrm{ACO}}(n) - \lambda], & s_{\mathrm{ACO}}(n) > \lambda \\ [s_{\mathrm{ACO}}(m) - \lambda, \lambda - s_{\mathrm{ACO}}(m)], & s_{\mathrm{ACO}}(m) > \lambda \\ [0, 0], & \text{otherwise.} \end{cases} \tag{8}$$

As shown in Fig. 2, the superposition pair is obtained by superimposing source signals with non-redundant signals as:

$$[s_{\mathrm{sup}}(n), s_{\mathrm{sup}}(m)] = \begin{cases} [\lambda, s_{\mathrm{ACO}}(n) - \lambda], & s_{\mathrm{ACO}}(n) > \lambda \\ [s_{\mathrm{ACO}}(m) - \lambda, \lambda], & s_{\mathrm{ACO}}(m) > \lambda \\ [s_{\mathrm{ACO}}(n), s_{\mathrm{ACO}}(m)], & \text{otherwise.} \end{cases} \tag{9}$$

The superposition signal in (9) does not require extra power, as the large-amplitude signal reduction is equal to the symmetric signal enhancement. Due to the anti-symmetry property, the non-redundant signals occupy the odd subcarriers in frequency domain, with the even subcarriers being null. As a result, the designed superposition signals allow the odd subcarriers to be occupied by both source signals and non-redundant signals. However, the even subcarriers just include the absolute value of source signals due to the negative signal clipping as in (1), which can be utilized to recover the source signals as follows.

B. *Even-Subcarrier-Based Signal Detection*

The received signal in (5) is equalized by zero-forcing (ZF) equalizer as:

$$\hat{S}_{\mathrm{sup}}(k) = S_{\mathrm{ACO}}(k) + S_{\mathrm{nr}}(k) + \widetilde{W}(k), \tag{10}$$

where $\widetilde{W}(k) = H^{-1}(k)W(k)$. Since $s_{\mathrm{ACO}}(n) = 0.5s(n) + 0.5|s(n)|$ in time domain, we have $S_{\mathrm{ACO}}(k) = 0.5S(k) + 0.5S_{\mathrm{abs}}(k)$ in frequency domain, with $S_{\mathrm{abs}}(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} |s(n)| e^{-j\frac{2\pi kn}{N}}$ corresponding to the negative signal clipping in time-domain ACO-OFDM signals. After arrangement, the equalized signal is expressed as:

$$\hat{S}_{\mathrm{sup}}(k) = 0.5 \underbrace{S(k)}_{\text{source}} + 0.5 \underbrace{S_{\mathrm{abs}}(k)}_{\text{absolute value}} + \underbrace{S_{\mathrm{nr}}(k)}_{\text{non-redundant}} + \underbrace{\widetilde{W}(k)}_{\text{noise}}. \tag{11}$$

When k is even, $S(k) = 0$ and $S_{\mathrm{nr}}(k) = 0$ in (11). With $|s(n)| = |s(m)|$, $S_{\mathrm{abs}}(k)$ can be expanded to:

$$S_{\mathrm{abs}}(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{\frac{N}{2}-1} [|s(n)| e^{-j\frac{2\pi kn}{N}} + |s(n)| e^{-j\frac{2\pi kn}{N}} \cos(k\pi)]. \tag{12}$$

When k is odd, $S_{\mathrm{abs}}(k) = 0$. To sum up, we have

$$\hat{S}_{\mathrm{sup}}(k) = \begin{cases} 0.5S(k) + S_{\mathrm{nr}}(k) + \widetilde{W}(k), & k \text{ is odd} \\ 0.5S_{\mathrm{abs}}(k) + \widetilde{W}(k), & k \text{ is even.} \end{cases} \tag{13}$$

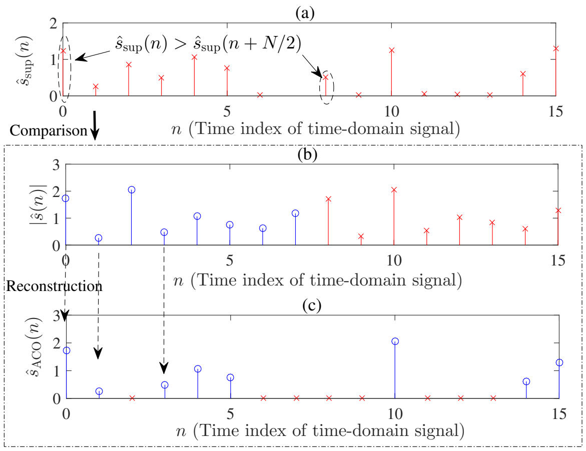

Fig. 3. Signal reconstruction. (a) Equalized superposition signals. (b) Estimated absolute value of source signal. (c) Source signal reconstruction.

Therefore, the absolute value of time-domain signal $|s(n)|$ caused by negative signal clipping can be estimated from $\hat{S}_{\rm abs}(k) = 2\hat{S}_{\rm sup}(k)$ on even subcarriers, while odd subcarriers are occupied by source and non-redundant signals. We pick $\hat{S}_{\rm abs}(k)$ on even subcarriers, and formulate the signal structure by inserting zeros on odd subcarriers as:

$$\tilde{\mathbf{S}}_{\rm abs} = [\hat{S}_{\rm abs}(0),\ 0,\ \cdots, \hat{S}_{\rm abs}(N-2),\ 0]^T, \tag{14}$$

with $\tilde{S}_{\rm abs}(k)$ denoting the formulated signal on the k-th subcarrier. The formulated signals in (14) are transformed to time domain to obtain the estimate of absolute value of the source signal as $|\hat{s}(n)| = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}\tilde{S}_{\rm abs}(k)e^{j\frac{2\pi kn}{N}}$. The equalized signal in (10) is transformed to time domain as $\hat{s}_{\rm sup}(n) = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1}\hat{S}_{\rm sup}(k)e^{j\frac{2\pi kn}{N}}$. The polarity of the source signals on even subcarriers is dependent on threshold factor α in (7), and can be determined by ensuring that the remaining part is higher than the clipping part of the large-amplitude signal in the clipping process. Thus, as shown in Fig. 3, comparing $\hat{s}_{\rm sup}(n)$ and $\hat{s}_{\rm sup}(m)$, the higher value has the higher possibility to be the ACO-OFDM source signal replaced by $|\hat{s}(n)|$, with the symmetric position being 0. The time-domain ACO-OFDM signal is reconstructed as:

$$[\hat{s}_{\rm ACO}(n), \hat{s}_{\rm ACO}(m)] = \begin{cases} [|\hat{s}(n)|, 0], & \hat{s}_{\rm sup}(n) > \hat{s}_{\rm sup}(m) \\ [0, |\hat{s}(m)|], & \hat{s}_{\rm sup}(n) \le \hat{s}_{\rm sup}(m). \end{cases} \tag{15}$$

It is difficult to correctly recognize $\hat{s}_{\rm sup}(n)$ and $\hat{s}_{\rm sup}(m)$, when they are close to each other, with α approaching to 0.5. This makes (15) become invalid, and the probability of decision error is high. Therefore, there is a tradeoff between PAPR reduction and BER performance, depending on the value of α. Also, the transmission power allocation between source and non-redundant signals corresponds to that between even and odd subcarriers, and should be equal. Otherwise, the polarity determination of source signals is easily destroyed in (15).

IV. Performance Analysis

A. Theoretical BER

An ACO-OFDM block is the combination of a number of independent signals, and can be accurately modeled as a Gaussian random process with zero mean and variance σ^2 due to the central limit Theorem [11]. Thereby, the probability density function that, at a given time instance n, $x(n)$ takes the value z, is given by [11]:

$$f(s(n) = z) = \frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{z^2}{2\sigma^2}}. \tag{16}$$

The superimposed signals higher than $v_{\rm t}$ are clipped, including those higher than $lambda$ and those between $v_{\rm t}$ and λ, which produces clipping noise power, given by:

$$\sigma_{\rm c}^2 = \int_{\lambda}^{\infty}[(\lambda - v_{\rm t})]^2 f(z)\,dz + \int_{v_{\rm t}}^{\lambda}[(z - v_{\rm t})]^2 f(z)\,dz. \tag{17}$$

ZF criterion [9] is used to equalize the received signal, which may enhance noise. This effect is incorporated into noise. The effective signal-to-noise ratio (SNR) is written as:

$$\gamma_{\rm SNR} = \frac{\sigma^2}{\sigma_w^2 + \sigma_c^2}. \tag{18}$$

The BER for any M-QAM symbols can be given as [11]:

$${\rm BER} = \frac{\sqrt{M}-1}{\sqrt{M}\log_2(\sqrt{M})}{\rm erfc}\left(\sqrt{\frac{3\times\gamma_{\rm SNR}}{2(M-1)}}\right). \tag{19}$$

The theoretical curve coincides with the numerical curve, verified by Fig. 5.

B. Complexity Analysis

We use the number of multiplication operations to analyze the order of complexity of the proposed scheme with respect to N as $O(2N\log_2 N)$, the same as the RoC-ACO- OFDM method [7]. The existing works [4], [5] provide $O(N^2\ )$ and $O((N^3\ )$ operations, respectively. Compared to the existing methods [4], [5], the proposed scheme provides complexity more than $N/(2\log_2 N)$ times lower.

V. Simulation Results

In the simulation setup, the parameters are consistent with [1] and [9] as follows. All simulation results are averaged over Monte-Carlo methods with independent source data, noise and channel realizations. The number of subcarriers is $N = 64$ with 16-QAM constellation. The length of CP is $L_{\rm cp} = 16$. The light incidence angle of PD is $40^\circ \le \psi \le 60^\circ$. The light radiance angle of LED is $40^\circ \le \phi \le 60^\circ$. The limited bandwidth of LED is 60 MHz $\le f_{\rm b} \le$ 100 MHz. The distance between LED and PD is 2 m $\le d \le$ 4 m. The half-power semiangle of LED is $\phi_{1/2} = 60^\circ$. The detection area is $A = 1$ cm^2. The normalized upper and lower clipping levels of LED respectively are $v_{\rm b} = 0.07$ and $v_{\rm t} = 1.54$. After intensive simulation, the threshold factor is set as $\alpha = 0.4$.

Fig. 4 shows the complementary cumulative distribution function (CCDF) performance of PAPR of the proposed scheme. γ is a specific value exceeded by PAPR. Also, the proposed scheme provides CCDF performance of PAPR, 4 dB better than the SO-OFDM method [8], up to 5 dB better than original ACO-OFDM systems with no LED nonlinearity mitigation, and close to the RoC-ACO-OFDM method with clipping ratio (CR) of 7 dB [7].

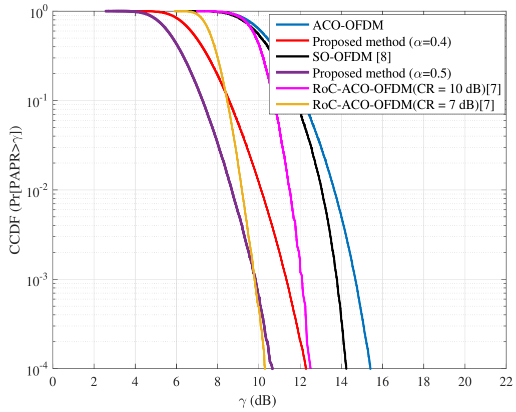

Fig. 4. CCDF performance of PAPR of the proposed superposition based LED nonlinearity mitigation scheme.

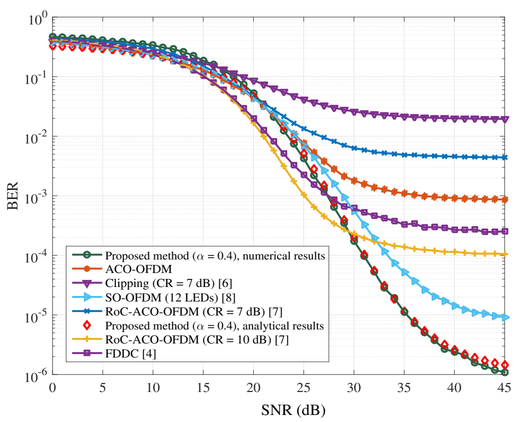

Fig. 5. BER performance of the proposed superposition based LED nonlinearity mitigation scheme.

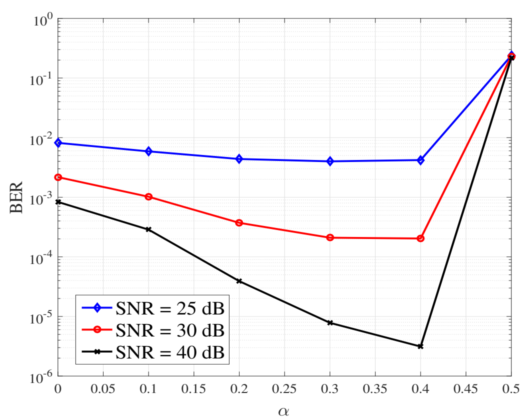

Fig. 6. Impact of threshold factor α on the BER performance of the proposed scheme.

In Fig. 5, the proposed LED nonlinearity mitigation scheme is shown to provide BER performance better than the existing methods: the clipping method with CR = 7 dB [6], the RoC-ACO-OFDM method with CR = 7 dB [7] as well as the SO-OFDM method with 12 LEDs [8] at high SNR, and the frequency-domain diversity combining (FDDC) method [4], to show the benefit of being less affected by the limited linear range of LED. For the proposed scheme, the theoretical curve coincides with the numerical curve.

Fig. 6 shows the impact of threshold factor α on the BER performance of the proposed superposition based LED nonlinearity mitigation method for ACO-OFDM systems. The BER performance of the proposed approach is shown to be convex with the variation of α, where $\alpha = 0.4$ is the optimal value to achieve the best performance. Therefore, we set $\alpha = 0.4$ in the simulation results.

VI. Conclusion

We have proposed a superposition based LED nonlinearity mitigation method for ACO-OFDM OWC systems, where a non-redundant signal stream is superimposed with the ACO-OFDM source signal stream to reduce large-amplitude signals, requiring no side information and no pilot. The large-amplitude signal reduction is the same as the symmetric signal enhancement, requiring no extra power. The even subcarriers are utilized to recover source signals, while the odd subcarriers are occupied by the designed non- redundant signals together with source signals. The value of the threshold factor is investigated. The proposed method outperforms a number of existing methods [4], [6]–[8], in terms of BER.

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