Predistortion in Optical Wireless Transmission using OFDM

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Abstract—The nonlinear characteristic of an LED (light emitting diode) imposes limitations on the performance of indoor optical wireless (OW) systems when using intensity modulation in combination with OFDM (orthogonal frequency division multiplexing). First, the impact of the nonlinear characteristic on bit-error performance is analyzed using a commercially available LED (OSRAM, SFH 4230). Second, the paper proposes a predistorter to overcome the nonlinearities. Key features of the predistorter reside in the use of the LED inverse characteristics as nonlinear distortion compensator. A DC biased optical OFDM (DCO-OFDM) system is considered and the performance without compensation and after compensation is analyzed via simulations in an AWGN (additive white Gaussian noise) environment. In this context, the bit-error performance is determined for different bias points and power back-off values applied to the OFDM signal modulating the LED intensity. It is shown that LED nonlinearity can significantly degrade the performance. However, it is demonstrated that this degradation can greatly be mitigated by using the proposed predistortion technique.

Index Terms—OFDM, LED, optical wireless communication, nonlinearity distortion, PAPR.

I. INTRODUCTION

Due to the ever increasing demand for wireless data rates, especially indoors, new frequency bands are explored such as the license-free 60GHz band [1]. Recently also the optical spectrum has enjoyed growing interest for use in indoor wireless data transmission [2–4]. The multi-carrier OFDM modulation is a promising modulation scheme to realize indoor OW links [5]. OFDM offers high data rate capabilities as well as high bandwidth efficiency and inherently provides a means to combat ISI (inter-symbol-interference) resulting from multipath propagation. However, the performance of OFDM with its high PAPR (peak-to-average power ratio) can potentially be severely affected by the nonlinear behavior of the LED.

In RF (radio frequency) systems, the main source of nonlinearity is the power amplifier (PA) as shown in Fig. 1(a). The PA operates near the saturation point in order to achieve the maximum power efficiency. In this operation region, undesirable nonlinear effects due to amplitude and phase distortions are introduced. Additionally, signal clipping at the PA saturation level is a critical source of distortion, in particular for OFDM because of its high PAPR [6]. Backing-off the average power of the input signal ensures that the PA operates in a quasi-linear region of operation and avoids saturation. Alternatively, the reduction of the PAPR through methods such as clipping, filtering, constrained coding, and selective mapping are considered [7]. However, neither power back-off nor PAPR reduction techniques necessarily result in an improvement in system performance and trade-offs must be considered [8, 9]. In addition, linearization through predistortion can be applied to compensate for the PA nonlinear distortion as shown in Fig. 1(a).

In optical systems, the LED is the main source of nonlinearity (see Fig. 1(b)). A real value baseband OFDM signal is used to modulate the instantaneous power of the optical carrier resulting in IM. DCO-OFDM and asymmetrically clipped optical OFDM (ACO-OFDM) are two forms of OFDM using IM. In DCO-OFDM, the bipolar OFDM signal is superimposed on a bias point to produce a positive signal. In ACO-OFDM, however, the OFDM signal is made unipolar by modulating the odd sub-carriers only and clipping the signal at the zero level [10].

In this paper, the DCO-OFDM is considered. Several bias points are selected to investigate the bias point influence on the generated distortion. Power back-off values are applied to the OFDM signal to control the distortion levels by operating the LED in a quasi-linear segment of its characteristic around the chosen bias point. The paper also focuses on applying a digital
predistortion as a linearization technique to compensate for the LED nonlinearities. The BER values in AWGN environment without compensation and after compensation are compared.

The rest of the paper is organized as follows. Section II highlights the procedure used to develop the LED model and to define the predistorter. Next, Section III introduces the OFDM system model used in the simulations and details the constellation distortion calculation. In Section IV, system performance with BPSK (binary phase shift keying) and 64-QAM (quadrature amplitude modulation) modulation formats for different bias points and power back-off values are compared. Finally, Section V concludes the paper.

II. LED AND PREDISTORTER MODEL

In this paper, a high power IR LED (OSRAM, SFH 4230) is considered [11]. The proposed procedure to model the LED and its predistorter is valid for any LED. The relation between the forward voltage across the LED and the current through the LED is modeled through a polynomial using the least-square curve fitting technique. A polynomial of the sixth degree shows the best fit for the LED transfer characteristic. The dashed curve in Fig. 2 shows the nonlinear behavior of the LED using the developed polynomial for forward voltage amplitudes in the range from 1.3V up to 2.1V. At 2.1V, the forward current is considered to be the maximum permissible AC current. Input signal amplitudes above 2.1V and below 1.3V are clipped.

Predistortion linearizes the LED response over the range from 1.3V up to 2.1V. The baseband signal is conditioned prior to the LED modulation. The solid curve in Fig. 2 illustrates the linearized V-I relation. The idea of the predistortion is illustrated on the same figure. Assuming $v_{in}$ is the input signal amplitude and $i_{out-pd}$ is the desired output current known from the linear response. Then, the original input amplitude, $v_{in}$, is adjusted to produce $v_{out-pd}$ which produces the correct output current amplitude, $i_{out-pd}$, that gives the overall predistorted-LED chain a linear response. Through predistortion, a linear response curve is achieved over a large range of the input signal amplitudes. However, the region which can be linearized is limited. The maximum input amplitude that will be modulated linearly depends upon the maximum permissible AC current through the LED. Therefore and for the considered LED in this paper, input signal amplitudes above 1.961V and below 1.442V are clipped.

The polynomial for the predistorter is obtained by the following procedure:

- Obtain the polynomial equation, $f(v)$, using the measured data of the LED forward voltage and forward current relation. See Fig. 3(a).
- Obtain the polynomial equation, $f(i)$, using the same electrical measurements. See Fig. 3(b).
- Obtain the polynomial equation for the required linearized voltage to current relation. See Fig. 3(c) where the dashed curve illustrates the nonlinear behavior of the LED.
- Substituting in $f(i)$ using the forward current values in the linearized range (1.442V-1.961V) to obtain the corresponding values of the forward voltage. See Fig. 3(d).
- Obtain the predistorter polynomial equation using the values of the forward voltage obtained in the previous step. See Fig. 3(e).
- Fig. 3(f) shows the input signal before the distorter (x-axis) and the current through the LED (y-axis). Fig. 3(f) demonstrates exact match with Fig. 3(c).

III. OFDM SYSTEM MODEL

The OFDM simulation model is shown in Fig. 4. At the input of the IFFT (inverse fast Fourier transform), complex conjugate data symbols are used to produce a real time domain output. For the purpose of channel estimation, training sequences are used [12, 13]. The OFDM frame is formed by one OFDM symbol for channel estimation and 20 OFDM symbols with data sub-carriers. Frequency domain equalization is realized using conventional OFDM zero-forcing (ZF) detection. The predistorter and the LED are modeled through the V-V and the V-I blocks, respectively. Shot noise due to background light is assumed to be the dominant source of noise and is modeled as AWGN [14].

The error vector is a common figure of merit for system linearity in digital wireless communication standards. It is a measure of the fidelity of a digital communication system and is related to in-band distortion and signal-to-noise ratio (SNR) [15]. On a constellation diagram, the error vector is a measure of the departure of signal constellation points from its ideal reference. The error vector is the scalar distance between the ideal constellation vector and the measured vector of the displaced constellation point after it has been compensated in timing, amplitude, frequency, phase, and DC offset. The EVM (error vector magnitude) is the root mean square value of the error vector over time. The OFDM demodulator calculates the EVM which is used as distortion indicator. To calculate
the EVM, the model uses the recovered constellations to regenerate the ideal constellations. The EVM is calculated by subtracting the recovered constellations from the corresponding ideal references, taking the absolute values and calculating the RMS value over one OFDM symbol. Important OFDM simulation parameters are listed in Table I.

IV. RESULTS

Simulations are conducted to investigate the influence of the bias point on the generated distortion due to the LED non-linearity. In these simulations, the AWGN channel is not considered and a BPSK modulation scheme with 3/4 channel coding rate is used. The average power of the OFDM signal modulating the LED is calculated over one OFDM symbol. In all figures, a 20mW electrical average power is considered the 0dB power back-off. The power back-off indicates relative decrease in the signal power to the initial signal at 20mW. The distortion is characterized by the EVM in percentage which is also computed over one OFDM symbol.

At 0dB power back-off, the obtained EVM values for 100 OFDM symbols without the predistorter and after applying the predistorter are plotted in Fig. 5(a) and Fig. 5(b), respectively. Before applying the predistorter (Fig. 5(a)), the 1.7V bias point achieves the lowest EVM floor and EVM peak values among the bias points under investigation. The EVM floor is defined as the lowest EVM value whereas the EVM peak is defined as the highest EVM value in a burst of 100 OFDM symbols. Although the 1.725V bias point achieves fair EVM floor and EVM peak values, it will not be considered later for system performance evaluation since the maximum permissible DC current is 1A (forward current is equal to 1.07A@1.725V) according to the data sheet. In addition, lower
bias points improve system power efficiency. It is noticed that the lowest bias point, i.e., at 1.6V, has the highest EVM floor and EVM peak values compared to the other bias points under investigation and the system is expected to show the worst bit-error performance at this bias point. In Fig. 5(b), the predistortion indeed achieves better EVM floor values for the 1.7V and the 1.675V bias points. However, degradation is noticed at the 1.6V, 1.625V, and 1.65V bias points. This can be related to the fact that the input signal amplitudes above 1.961V and below 1.442V are clipped in the presence of the predistorter while amplitudes above 2.1V and below 1.3V are clipped in the absence of the predistorter. Therefore, at high inputs signal powers (20mW), signal clipping distortion is expected to dominate the bit-error performance rather than amplitude distortion.

In addition to linearization with the applied predistorter, different power back-off values are applied to the 20mW OFDM to investigate the influence of the OFDM signal power reduction on the generated distortion. For example, Fig. 6(a) and Fig. 6(b) show the obtained EVM values at 2dB power back-off. Both EVM floor and EVM peak values with and without the predistorter are significantly improved for all bias points. However, EVM floor values still exist without the predistorter while an almost 0% EVM floor is noticed for all biased points with the predistorter, except for the 1.6V bias point which shows an EVM floor value greater than 3%.

Fig. 7(a) and Fig. 7(b) show the average EVM values over 1000 simulated values of all bias points under investigation for power back-offs in steps of 1dB up to 8dB. As expected, the EVM values at 0dB are better without the predistorter for the 1.6V, 1.625V, and 1.65V bias points. With the predistorter, however, slight improvement in the EVM values of the 1.7V and 1.675V bias points is noticed. At 2dB power back-off, less than 10% EVM is achieved with the 1.7V, 1.675, and 1.65V bias points without the predistorter, while the 1.625V and the 1.6V bias points achieve around 13% EVM and 18% EVM, respectively. Correspondingly, with the predistorter all bias points achieve EVM values less than 10%. A 0% EVM is noticed for almost all bias points with the predistorter at 3dB power back-off, while 8dB power back-off value is needed for the 1.7V bias point to achieve a similar EVM value without using the predistorter.

In order to study the effect of LED non-linearity on bit-error performance, first, simulations are conducted without the LED model (only the AWGN channel model is considered) to determine the required SNR to achieve a target BER for two modulation schemes under investigation, BPSK and 64-QAM. The curves are depicted in Fig. 8 and the required SNR values to achieve approximately $2.5 \times 10^{-5}$ BER are shown on the figure.
Using the SNR values from Fig. 8, the BER and EVM for 1000 OFDM symbols (more than 10Mbits) are simulated in the presence of the LED non-linearity and in AWGN environment. The BER and EVM simulation results for BPSK without predistortion, BPSK with predistortion, 64-QAM without predistortion, and 64-QAM with predistortion are shown in Figs. 9, 10, 11, and 12, respectively. The effect of LED non-linearity is obvious in all figures and the degradation in BER performance is consistent with the obtained EVM values.

In Fig. 9 and at 0dB power back-off, the BER values are higher than $10^{-4}$ for all bias points. The target BER of $2.5 \times 10^{-5}$ is achieved for 1.7V bias points at 4dB power back-off value. With further increase in the applied power back-off, the obtained BER values are improved towards the target BER. However, for the other bias points, the target BER can not be achieved even at 8dB power back-off. In Fig. 10 and when using the proposed predistorter, significant enhancements are noticed and the target BER is achieved for 1.7V, 1.675V, and 1.65V bias points with only 2dB power back-off. For the other bias points, 4dB power back-off is sufficient to achieve the target BER.

In contrast to low order modulation schemes, signal distortion is shown to have a great impact on the achieved bit-error performance of higher modulation orders, namely 64-QAM. A slight increase of the EVM leads to a significant degradation in the BER performance. Therefore, and as expected, the 64-QAM modulation is very sensitive to signal distortion. As shown in Fig. 11, even at 6dB power back-off, the BER values are higher than $10^{-4}$ for all bias points. The target BER can not be achieved with any bias point even at 8dB power back-off. However, with the predistorter and 5dB power back-off, the target BER is achieved for all bias points (see Fig. 12).
V. CONCLUSION

Non-linearity of LEDs has a significant impact on the performance of optical systems based on OFDM. The performance of the compensated system through predistortion is tremendously enhanced. For example, to achieve the target BER of $2.5 \times 10^{-5}$ using BPSK with 3/4 channel coding rate at 1.7V bias point, a 2dB gain is achieved. For the 64-QAM with the same channel coding rate and at the same bias point, the target BER could not be achieved without the predistorter. However, with the predistorter, the target BER is achieved at 5dB power back-off.

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REFERENCES


Fig. 11. (a) The BER for 64-QAM in the presence of LED non-linearity and AWGN channel without a predistorter. (b) The corresponding EVM values.

Fig. 12. The BER for 64-QAM in the presence of LED non-linearity and AWGN channel with a predistorter. (b) The corresponding EVM values.