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Citation for published version:
Elgala, H, Mesleh, R & Haas, H 2009, 'Non-Linearity Effects and Predistortion in Optical OFDM Wireless Transmission using LEDs', *International Journal of Ultra Wideband Communications and Systems*, vol. 1/2, pp. 143-150.

Non-linearity effects and predistortion in optical OFDM wireless transmission using LEDs

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Abstract: Orthogonal frequency division multiplexing (OFDM) is a promising technique to realise high-speed indoor optical wireless (OW) links through the exploitation of the high peak-to-average power ratio (PAPR) for intensity modulation (IM). However, the non-linear characteristic of a light emitting diode (LED) imposes limitations on the performance. In this paper, the impact of the non-linear characteristic on bit-error performance is analysed using a commercially available LED (OSRAM, SFH 4230). Also, the paper proposes a predistorter to overcome the non-linearities. The performance without compensation and after compensation is analysed via simulations in an additive white Gaussian noise (AWGN) 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 non-linearity can significantly degrade the performance. It is also demonstrated that this degradation can greatly be mitigated by using the proposed predistortion technique.

Keywords: orthogonal frequency division multiplexing; OFDM; optical wireless communication; light emitting diode; LED; non-linearity; predistortion; free space optics.

Reference to this paper should be made as follows: Elgala, H., Mesleh, R. and Haas, H. (2009) 'Non-linearity effects and predistortion in optical OFDM wireless transmission using LEDs', *Int. J. Ultra Wideband Communications and Systems*, Vol. 1, No. 2, pp.143–150.

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Harald Haas received a Best Paper Award at the *International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)* in Osaka, Japan in 1999 and holds more than 15 patents in the area of wireless communications. He co-authored a book entitled *Next Generation Mobile Access Technologies: Implementing TDD* with Cambridge University Press. His work on optical wireless communication was selected for publication in *100 Produkte der Zukunft (100 Products of the Future)* authored by Nobel Laureate T.W. Hänsch. Since 2007, he is a Regular High Level Visiting Scientist supported by the Chinese '111 program' at Beijing University of Posts and Telecommunications.

1 Introduction

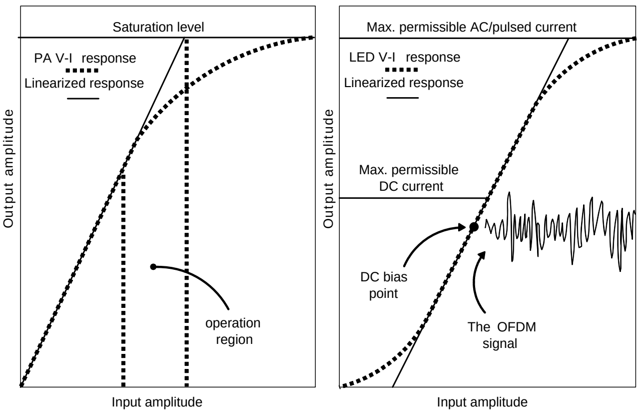
Due to the ever increasing demand for wireless data rates, especially indoors, new frequency bands are explored such as the license-free 60 GHz band (Cabric et al., 2005). Recently, also the optical spectrum has enjoyed growing interest for use in indoor wireless data transmission (Kahn and Barry, 1997; Schmitt et al., 2006; Wilson and Ghassemlooy, 1993). The multi-carrier orthogonal frequency division multiplexing (OFDM) modulation is a promising modulation scheme to realise indoor optical wireless (OW) links (Elgala et al., 2007). OFDM offers high data rate capabilities as well as high bandwidth efficiency and inherently provides a means to combat inter-symbol-interference (ISI) resulting from multipath propagation. However, the performance of OFDM with its high peak-to-average power ratio (PAPR) can be severely affected by the non-linear behaviour of the light emitting diode (LED). High peak signal values in OFDM stem from the superposition of a large number of usually statistically independent sub-channels that can constructively sum up to high signal peaks in the time domain. Therefore, the OFDM signal suffers from significant in-band and out-of-band distortions due to non-linearities introduced at the transmitter. The in-band component determines the system bit-error ratio (BER) degradation (Dardari et al., 2000), whereas the out-of-band component affects adjacent frequency bands (Li and Cimini, 1998).

In radio frequency (RF) systems, the main source of non-linearity is the power amplifier (PA) as shown in Figure 1(a). The PA operates near the saturation point in order to achieve the maximum power efficiency. In this operation region, undesirable non-linear 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 (Bahai et al., 2002). 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 (Li and Stüber, 2006). However, neither power back-off nor PAPR reduction techniques necessarily result in an improvement in system performance and tradeoffs must be considered. Amplifier power back-off might result in a significant power efficiency penalty and can significantly compromise signal coverage (Pratt et al., 2006). PAPR reduction techniques increase the system complexity and/or sacrifice bandwidth efficiency (Ahirwar and Rajan, 2005; Wulich and Tsouri, 2007). Instead, linearisation through predistortion can be applied to compensate for the PA non-linear distortion as shown in Figure 1(a).

In optical systems, the LED is the main source of non-linearity [see Figure 1(b)]. A real valued baseband OFDM signal is used to modulate the instantaneous power of the optical carrier resulting in intensity modulation (IM). DC biased optical OFDM (DCO-OFDM) and asymmetrically clipped optical OFDM (ACO-OFDM) are two forms of OFDM using IM (Armstrong and Lowery, 2006). 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 linearisation technique to compensate for the LED non-linearities. The BER values in additive white Gaussian noise (AWGN) environment without compensation and after compensation are compared.

Section 2 highlights the procedure used to develop the LED model and to define the predistorter. Next, Section 3 introduces the OFDM system model used in the simulations and details the constellation distortion calculation. In Section 4, system performance with binary phase shift keying (BPSK) and 64-quadrature amplitude modulation (QAM) formats for different bias points and power back-off values are compared. Finally, Section 5 concludes the paper.

Figure 1 (a) Non-linear and linearised PA transfer characteristic (b) non-linear and linearised LED transfer characteristic



(a) (b)

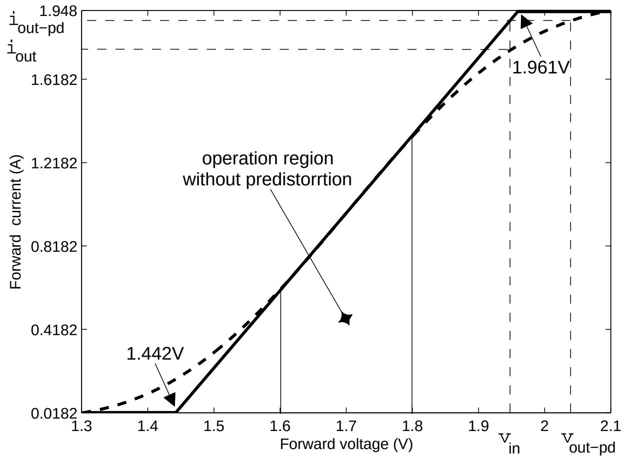
Notes: The non-linear transfer characteristic distorts the OFDM signal in RF as well as in optical applications. Linearisation through predistortion helps to improve system performance.

2 LED and predistorter model

In this paper, a high power IR LED (OSRAM, SFH 4230) is considered (OSRAM GmbH, 2009). 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 modelled 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 Figure 2 shows the non-linear behaviour of the LED using the developed polynomial for forward voltage amplitudes in the range from 1.3 V up to 2.1 V. The LED turn-on voltage is considered to be at 1.3 V. At 2.1 V, the forward current is considered to be the maximum permissible AC current.

Input signal amplitudes below 1.3 V and above 2.1 V are clipped.

Figure 2 The V-I dashed curve using the developed LED polynomial function for the high power IR LED (OSRAM, SFH 4230)



Note: The linearised V-I solid curve with the predistorter.

Predistortion linearises the LED response over the range from 1.3 V up to 2.1 V. The baseband signal is conditioned prior to the LED modulation. The solid curve in Figure 2 illustrates the linearised V-I relation. The concept of 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 linearised 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 below 1.442 V and above 1.961 V 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 Figure 3(a).
- Obtain the polynomial equation, $f(i)$, using the same electrical measurements. See Figure 3(b).
- Obtain the polynomial equation for the required linearised voltage to current relation. See Figure 3(c).
- Substituting in $f(i)$ using the forward current values in the linearised range (1.442 V–1.961 V) to obtain the corresponding values of the forward voltage. See Figure 3(d).
- Obtain the predistorter polynomial equation using the values of the forward voltage obtained in the previous step. See Figure 3(e).
- Figure 3(f) shows the input signal before the distorter (x-axis) and the current through the LED (y-axis). Figure 3(f) demonstrates exact match with Figure 3(c).

Figure 3 (a) V-I curve of the LED polynomial function, $f(v)$ (b) I-V curve of the LED polynomial function, $f(i)$ (c) V-I curve of the linearised LED polynomial function (d) I-V curve of the linearised LED polynomial function (e) the predistorter polynomial function (f) the linearised response of the cascade predistorter and the LED under investigation

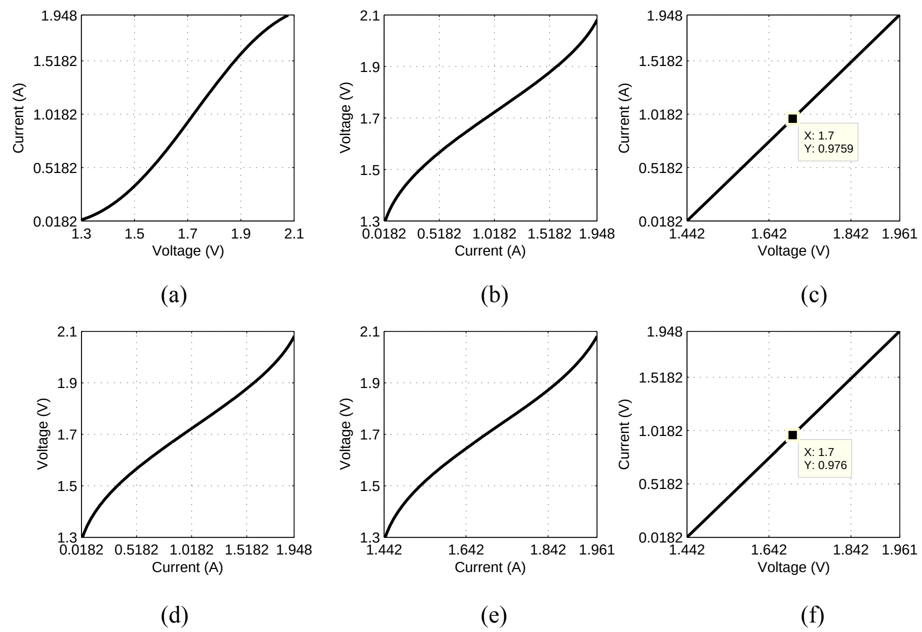
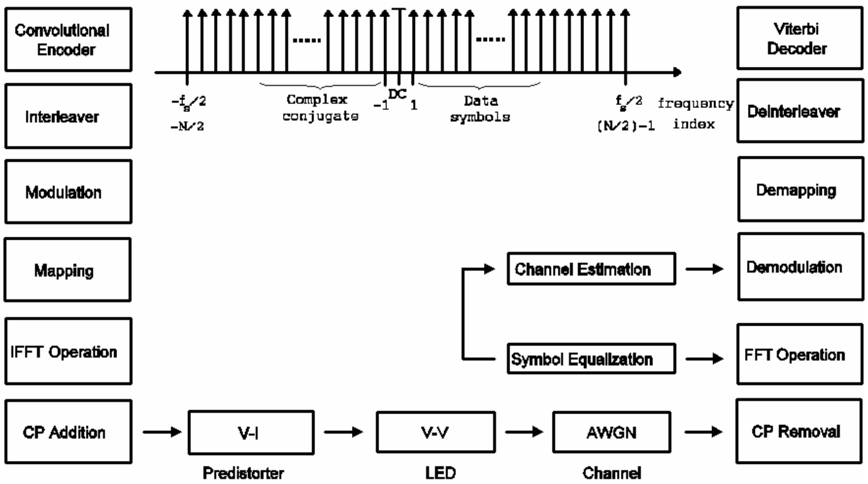


Figure 4 The building blocks of the optical OFDM simulation model implemented in Matlab



Notes: The LED characteristics are modelled through the V-I block. The predistorter is modelled through the V-V block. IFFT bin assignment. f_s is the sampling frequency, N are the number of the IFFT bins (IFFT length or the OFDM sub-carriers), $\frac{f_s}{2}$ is the Nyquist frequency and the sub-carriers separation is equal to $\frac{f_s}{N}$.

3 OFDM system model

The OFDM simulation model is shown in Figure 4. The predistorter and the LED are modelled 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 modelled as AWGN (Carruthers and Kahn, 1996).

The model continuously generates a random stream of bits. Data protection is realised through the use of forward error correction (FEC) coding (convolutional encoder) and interleaving. Different modulation schemes are considered. The generated serial stream of symbols at the modulator output is split into parallel streams; each is transmitted on a separate sub-carrier. The inverse fast Fourier transform (IFFT) operation is used to modulate the available sub-carriers and to generate the time domain OFDM signal. At the input of the IFFT, complex conjugate data symbols are used to produce a real time domain output. For the purpose of channel estimation, training sequences are used (Moose, 1994; Tang et al., 2003). However, the complex conjugate requirements must be fulfilled for the OW OFDM system. The OFDM frame is formed by one OFDM symbol for channel estimation and 20 OFDM symbols with data sub-carriers. Attaching a cyclic prefix (CP) to the transmitted OFDM symbols converts the linear convolution of the channel with the OFDM signal to a circular convolution (Andrews et al., 2007). As a result, simple frequency domain equaliser can be employed. Frequency domain equalisation is realised using conventional OFDM zero-forcing (ZF) detection. The equalised symbols are demodulated and the encoded symbols are decoded by the Viterbi hard-decision algorithm. The decoded bits are deinterleaved to obtain the estimated stream of data bits.

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) (Gharaibeh et al., 2004). 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 error vector magnitude (EVM) is the root mean square value of the error vector over time and used as distortion indicators in this paper. 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 1.

Table 1 Simulation model parameters

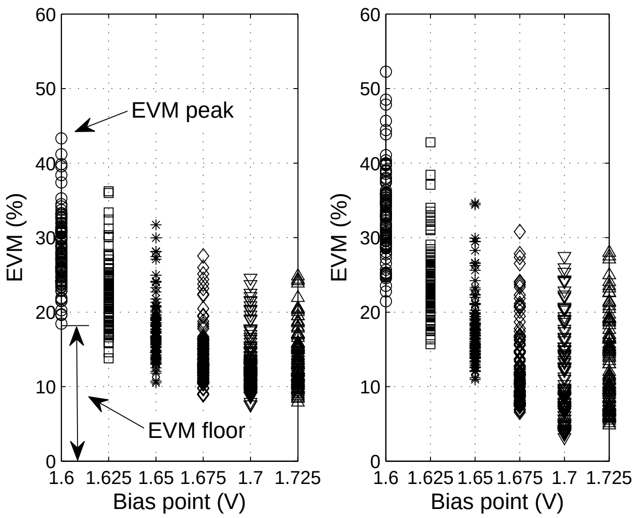
OFDM	
IFFT length	64
Data sub-carriers	31
CP length	6 (samples)
Training symbols	1

4 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, a noiseless channel is 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 for one

OFDM symbol. In all figures, a 20 mW electrical average power is considered the 0 dB power back-off. The power back-off indicates relative decrease in the signal power to the initial signal at 20 mW. The distortion is characterised by the EVM in percentage which is also computed over one OFDM symbol.

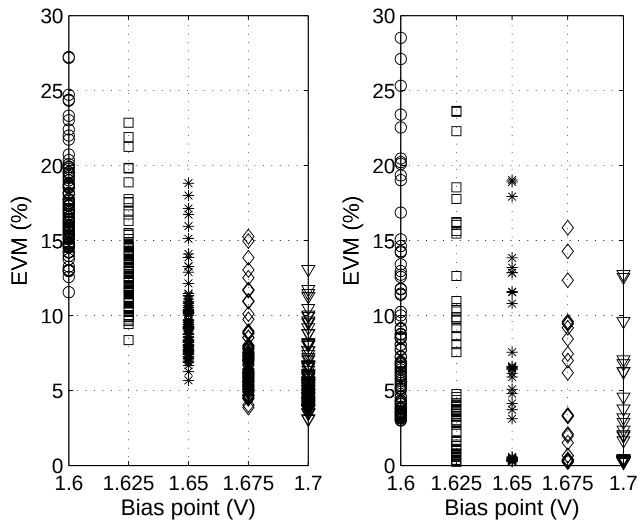
Figure 5 The EVM scatter plot of 100 OFDM symbols versus bias points at 0 dB power back-off, (a) without using a predistorter (b) with predistorter



(a) (b)

At 0 dB power back-off, the obtained EVM values for 100 OFDM symbols without the predistorter and after applying the predistorter are plotted in Figures 5(a) and 5(b), respectively. Before applying the predistorter [Figure 5(a)], the 1.7 V bias points 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 1.725 V 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 1 A (forward current is equal to 1.07 A@1.725 V) 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 1.6 V, 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 Figure 5(b), the predistortion indeed achieves better EVM floor values for the 1.7 V and the 1.675 V bias points. However, degradation is noticed at the 1.6 V, 1.625 V and 1.65 V bias points. This can be related to the fact that the input signal amplitudes above 1.961 V and below 1.442 V are clipped in the presence of the predistorter while amplitudes above 2.1 V and below 1.3 V are clipped in the absence of the predistorter. Therefore, at high inputs signal powers (20 mW), signal clipping distortion is expected to dominate the bit-error performance rather than amplitude distortion.

Figure 6 The EVM scatter plot of 100 OFDM symbols versus bias points at 2 dB power back-off, (a) without using a predistorter (b) with predistorter



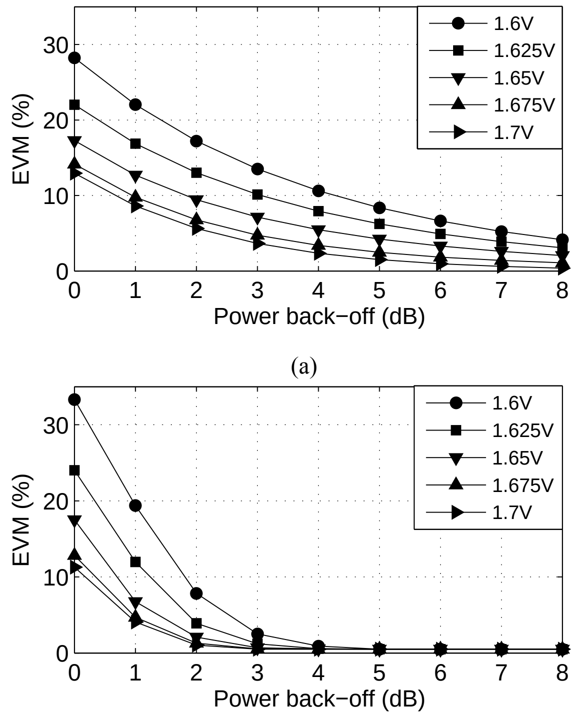
(a) (b)

In addition to linearisation with the applied predistorter, different power back-off values are applied to the 20 mW OFDM signal to investigate the influence of the power reduction on the generated distortion. For example, Figures 6(a) and 6(b) show the obtained EVM values at 2 dB 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 1.6 V bias point which shows an EVM floor value greater than 3%. The 1.6 V bias points suffers significantly from negative peaks clipping at 1.442 V.

Figures 7(a) and 7(b) show the average EVM values without predistortion and with predistortion, respectively, over 1,000 simulated values of all bias points under investigation for power back-offs in steps of 1 dB up to 8 dB. As expected, the EVM values at 0 dB are better without the predistorter for the 1.6 V, 1.625 V and 1.65 V bias points. With the predistorter, however, slight improvement in the EVM values of the 1.7 V and 1.675 V bias points is noticed. At 2 dB power back-off, less than 10% EVM is achieved with the 1.7 V, 1.675 V and 1.65 V bias points without the predistorter, while the 1.625 V and the 1.6 V 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 3 dB power back-off, while 8 dB power back-off values is needed for the 1.7 V 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 approximate SNR values required to achieve a target BER of 2.5×10^{-5} for BPSK and 64-QAM are 6 dB and 22 dB, respectively.

Figure 7 The mean EVM over more that 1,000 simulated values versus bias points, (a) without using a predistorter (b) with predistorter

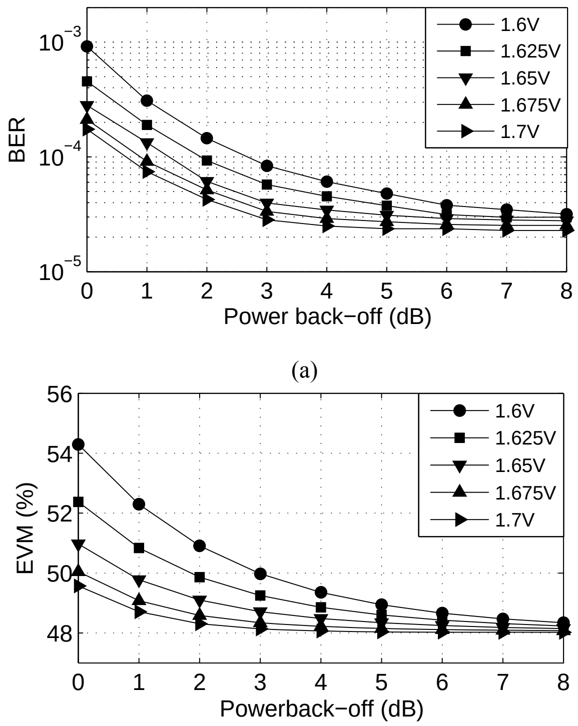


(a)

(b)

Note: power back-off values up to 8 dB are considered.

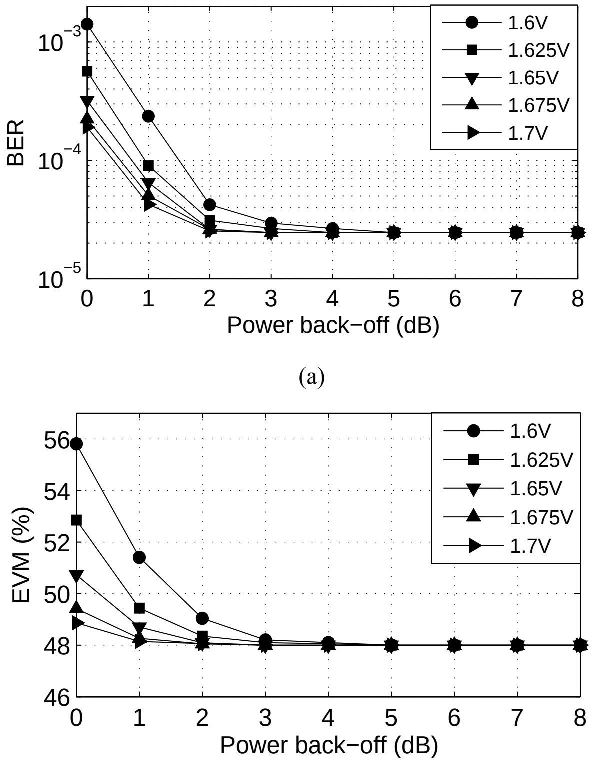
Figure 8 (a) The BER for BPSK in the presence of LED non-linearity and AWGN channel without a predistorter (b) the corresponding EVM values



(a)

(b)

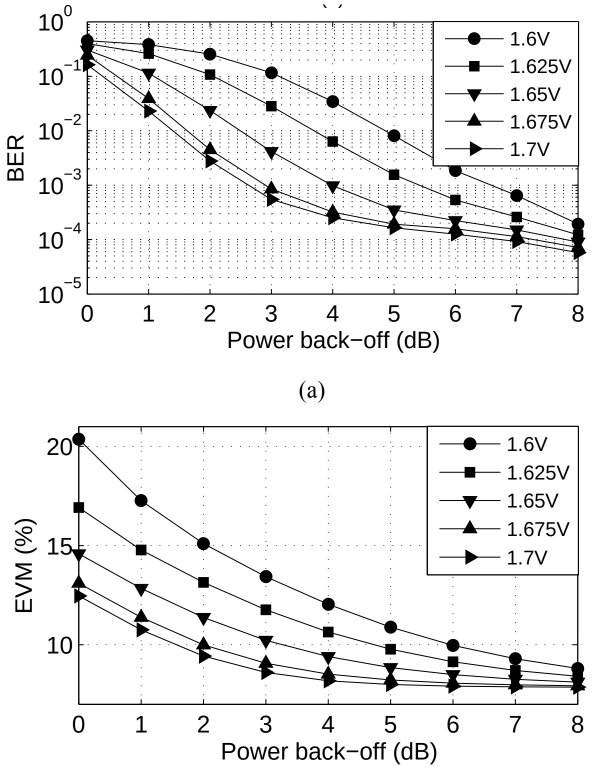
Figure 9 (a) The BER for BPSK in the presence of LED non-linearity and AWGN channel with a predistorter (b) the corresponding EVM values



(a)

(b)

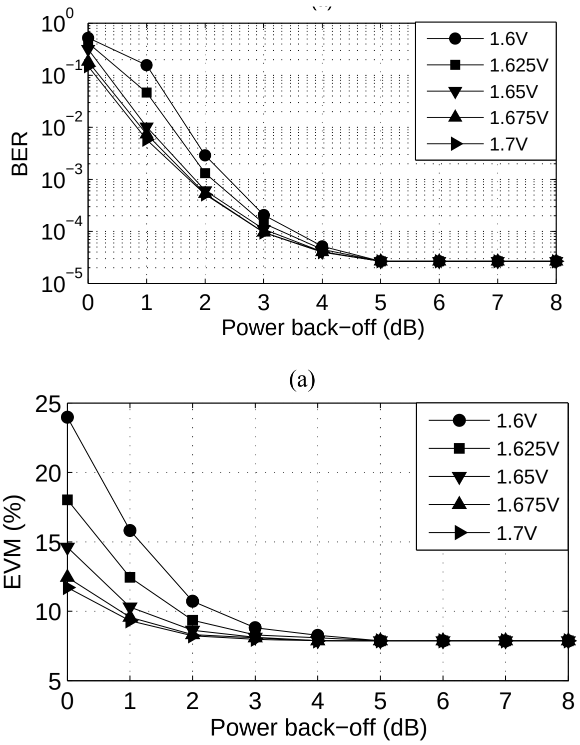
Figure 10 (a) The BER for 64-QAM in the presence of LED non-linearity and AWGN channel without a predistorter (b) the corresponding EVM values



(a)

(b)

Figure 11 (a) The BER for 64-QAM in the presence of LED non-linearity and AWGN channel with a predistorter (b) the corresponding EVM values



(a)

(b)

Using these SNR values, the BER and EVM for 1,000 OFDM symbols (more than 10 Mbits) 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 Figures 8, 9, 10 and 11, 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 Figure 8 and at 0 dB power back-off, the BER values are higher than 10^{-4} for all bias points. The target BER of 2.5×10^{-5} is achieved for 1.7 V bias points at 4 dB 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 cannot be achieved even at 8 dB power back-off. In Figure 9 and when using the proposed predistorter, significant enhancements are noticed and the target BER is achieved for 1.7 V, 1.675 V and 1.65 V bias points with only 2 dB power back-off. For the other bias points, 4 dB power back-off is sufficient to achieve the target BER.

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 Figure 10, even at 6 dB power back-off, the BER values are higher than 10^{-4} for all bias points. The target BER cannot be achieved with any bias point even at 8 dB power back-off. However, with the predistorter and 5 dB power back-off, the target BER is achieved for all bias points (see Figure 11).

5 Conclusions

LED non-linearity has a significant impact on the performance of optical systems based on OFDM. The distortion depends on LED characteristics, input power and the DC bias point. The performance of the compensated system through predistortion is tremendously enhanced. For example, to achieve the target BER of 2.5×10^{-5} using BPSK with 3/4 channel coding rate at 1.7 V bias point, a 2 dB 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 5 dB power back-off.

Acknowledgements

We gratefully acknowledge support for this work from Airbus Germany. In addition, we acknowledge the support from the German Federal Ministry of Economics and Technology (BMWi) under grant 20K0806G as part of the Lufo 2nd Call project SINTEG.

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