Performance of Direct-Detection OFDM-UWB Systems with Compensation of Transmitter and Receiver Nonlinearity

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ABSTRACT
A method to compensate the combined nonlinearity of the Mach-Zehnder modulator (MZM) and photo-diode in direct-detection orthogonal frequency division multiplexing - ultra wideband (OFDM-UWB) systems is analysed using numerical simulation. The results show that the proposed nonlinearity mitigation method provides an error vector magnitude (EVM) improvement of 12 dB in the presence of noise can be achieved. In addition, it is also shown that the proposed nonlinearity mitigation method allows obtaining reduction of the optical signal-to-noise ratio (OSNR) required to achieve the EVM limit of UWB of around 7 dB.

Keywords: Orthogonal frequency division multiplexing (OFDM), ultra-wideband (UWB), nonlinearity compensation, intersymbol interference, quadrature phase shift keying (QPSK), 1^{st} order interpolation.

1. INTRODUCTION

Over the last years OFDM has been widely appointed as a good transmission technique solution for wireless and wired systems as it enables the information processing over much smaller bandwidth reducing overall system complexity, provides spectral flexibility increase and it is capable of overcome intersymbol interference [1]. On the other hand, OFDM is sensible to the influence of nonlinear distortion. As a consequence, loss of orthogonality between subcarriers is observed, producing inter-carrier interference [2]. The mitigation of the nonlinearity–induced degradation may be performed by using time domain processing algorithms. However, this type of nonlinearity mitigation may not be able to compensate adequately for the frequency-dependent fibre-dispersion effects induced on the OFDM signals [3]. Another option of nonlinear distortion compensation is the compensation in the frequency domain [4].

In this work, a nonlinearity mitigation approach realized in the frequency domain that allows reducing the combined MZM and PIN nonlinearity degradation induced in OFDM-UWB systems is analyzed through numerical simulation.

2. SYSTEM MODELLING

OFDM-UWB signals are composed by 14 subbands, operating between 3.1 and 10.6 GHz, with 528 MHz spacing, with the central frequency of the 1^{st} subband, used in this work, at 3.432 GHz and band [3168;3696] MHz. The baseband OFDM-UWB signal consists of 128 subcarriers: 10 are used as guard subcarriers, 6 are used as nulls subcarriers for relax electrical filtering, 12 used as pilots subcarriers to provide adaptive electrical equalization and 100 are used as information subcarriers [5].

Fig. 1 depicts the OFDM-UWB system setup investigated. This diagram is divided in 3 main blocks: OFDM TX, OFDM RX and Nonlinearity Estimation. The OFDM TX block is responsible by the generation of the OFDM-UWB signal. At the OFDM-RX block, the signal is converted to baseband and demodulated. At the Nonlinearity Estimation block, the estimation of the system nonlinearity is performed. Fig. 1 shows that the signal generation starts with the mapping of the binary input data (**a**) in QPSK symbols. After this, auxiliary subcarriers (nulls, guards, pilots) are inserted and the OFDM symbols are applied to IFFT block. At the IFFT output, the guard time (GT) is inserted. This process is realized for the OFDM-UWB symbols. The analogue OFDM-UWB signal is filtered by a rectangular filter (-3 dB bandwidth of 265 MHz) to reduce the power of aliasing components. This rectangular filter is present both electric modulator (EM) and electric demodulator (ED) sub block. The resulting signal is amplified and applied to the optical Mach-Zehnder modulator (biased at the quadrature point) where the signal is converted to the optical domain. In the conversion the signal suffers from nonlinear distortion-induced degradation. At the OFDM-RX block, the received signal is filtered by a 2^{nd} order Gaussian optical filter (bandwidth of 30 GHz). The filtered signal is photo-detected where the PIN square nonlinearity degradation is induced. After photo-detection, the signal is down-converted and filtered by an electrical rectangular filter with bandwidth of 265 MHz. After this, the analog to digital conversion, removal of the guard time and FFT operations are realized (**B**) the OFDM-UWB symbols generate in this process will be used in subsequent subtraction of the nonlinearity estimated in the Nonlinearity Estimation block. Finally, the auxiliary subcarriers (nulls, guards and pilots) are removed. The pilots removed are used to estimate the channel. Using the channel estimation, the OFDM-UWB symbols received are equalized.

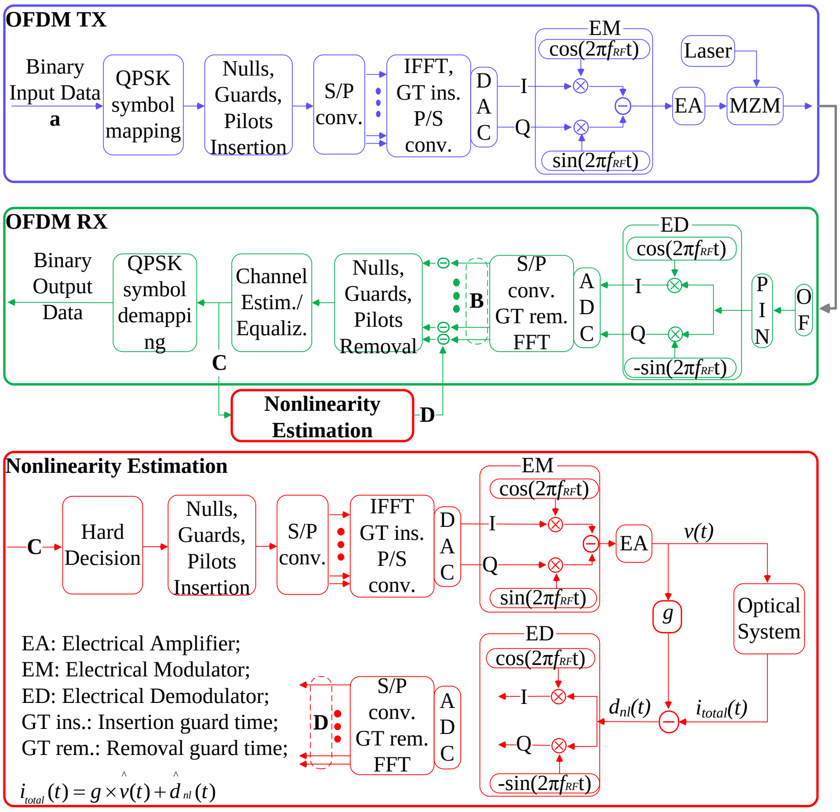

Figure 1: Block diagram of the DD OFDM-UWB system with nonlinearity mitigation.

At the Nonlinearity Estimation block, the nonlinearity estimation starts with the submission of the equalized symbols (**C**) to hard decision. Based on the QPSK symbols obtained from the hard-decision block, an OFDM-UWB signal is generated and sent to the Optical System sub block. In this block, the optical system transmission (Mach-Zehnder and photodiode) is described theoretically to estimate the current at the output of PIN, $i_{total}(t)$. A filter is used to reduce the power of the DC component of the detected current. The linear part of the signal $[g \times v(t)]$ is subtracted from the estimated photo detected current in order to obtaining an estimation of the system nonlinearity $d_{nl}(t)$. The value of g depends on the bias voltage, switching voltage and the laser optical power, $v(t)$ represents the voltage at the output of the electric amplifier (EA). After demodulation of the nonlinearity estimated, the resulting nonlinear symbols (**D**) are subtracted from the received signal (**B**).

3. SIMULATION RESULTS

In this section, the performance improvement of OFDM-UWB provided by the nonlinearity mitigation is assessed though numerical simulation. Back-to-back operation and the nonlinearity mitigation in systems with and without noise are analyzed. Although the results of this work were obtained considering only transmission of OFDM-UWB subband 1, it should be stressed that the conclusions drawn in this work hold also for the individual transmission of the others subbands.
Initially, five methods to evaluate the equalizer transfer function and to provide of channel equalization were analyzed: 1^{st}, 3^{rd} and 5^{th} orders regression methods, 1^{st} and 3^{rd} orders interpolation methods. It was observed that the five methods analyzed provide similar channel estimates. The EVM difference obtained between the worst (5^{th} order regression) and the best method (1^{st} order interpolation) is lower than 1 dB. Hence, the 1^{st} order interpolation was selected and used in the study performed along this work.

3.1 Transmission without noise

Fig. 2(a) presents the EVM without and with nonlinearity compensation as a function of the modulation index, *m,* defined as the ratio between the root mean square voltage of the signal applied to the MZM and the MZM bias voltage. Fig. 2(a) shows also the number of QPSK wrong symbols generated during the hard decision process. Fig. 2(a) shows that the fast EVM increase occurs from a modulation index of 5% when the nonlinearity compensation not is accomplished. Fig. 2 (a) shows that, for modulation indexes of up to 27%, the proposed nonlinearity method allows achieving an EVM of -38 dB. At this point, the EVM difference between the equalized signal with and without nonlinearity compensation is 24.5 dB. Fig. 2 (a) shows also the system nonlinearity is adequately mitigated while no errors are obtained at the hard-decision process. After modulation index equal to 27%, a fast degradation of EVM is observed due less effectiveness of nonlinearity mitigation.

Fig. 2 (b) depicts the EVM as a function of the order of iteration of nonlinearity estimation. Iteration of the order 0 means that the signals are equalized without nonlinearity compensation and while the iteration from of order 1st the equalization is realized after nonlinearity compensation. Fig. 2 (b) shows that, after iteration of the order 1st, the EVM results remain constant for modulation index, *m*, varying between 10% and 40%.

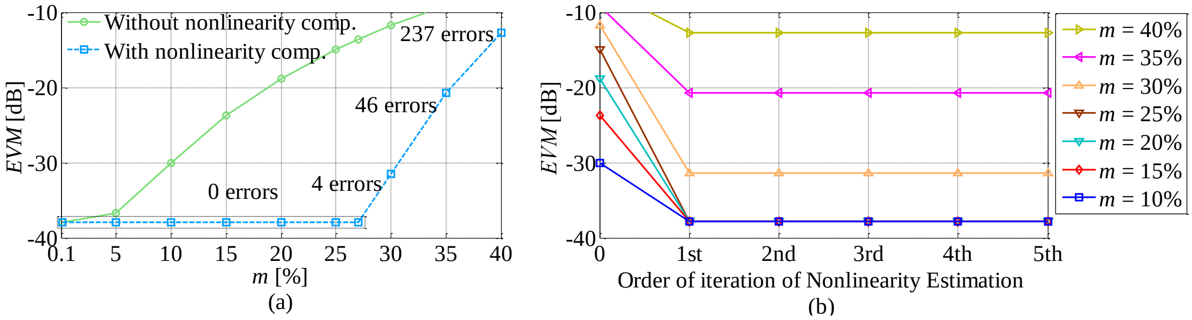

Figure 2: (a) EVM without and with nonlinearity compensation as a function of modulation index and also the numbers of QPSK wrong symbols generated during the hard decision process; (b) EVM as function of order of iteration of Nonlinearity Estimation realized.

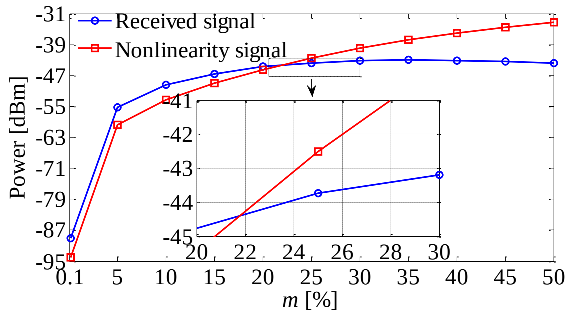

Figure 3: Power of the received signal and of the nonlinearity signal estimated at the FFT input as a function of the modulation index.

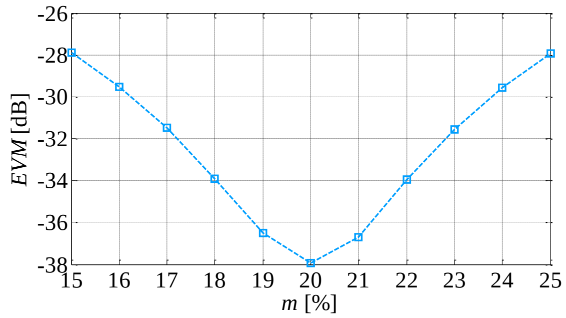

Figure 4: EVM as a function of the modulation index employed at the Nonlinearity Estimation block for a modulation index used at the OFDM TX of 20%.

Fig. 3 presents the power of the received signal and of the nonlinearity signal estimated at the FFT input as a function of the modulation index. Fig. 3 shows that the power of the nonlinear component estimated only exceeds the power of the received signal for modulation index levels higher than 22%. From the comparison of Fig. 3 with Fig. 2 (a), it is concluded that the nonlinearity is adequately estimated while its power is not significantly higher than the power of the received signal.

The results presents up to Fig. 3 considers that the modulation indexes both OFDM TX and OFDM RX are the same, but such situation not occurs always, therefore, it is necessary observing the behavior of the EVM when the estimation of the nonlinearity is realized using modulation indexes levels slightly different from the ones employed at the OFDM TX. For this study, a signal without noise is transmitted with modulation index of 20%. The impact of slightly deviation of the modulation index on the nonlinearity estimation is assessed by changing the modulation index used in the Nonlinearity Estimation block. Fig. 4 depicts the EVM as a function of the modulation index employed at the Nonlinearity Estimation block for a modulation index used at the OFDM TX of 20%. The Fig. 4 shows that a modulation index variation between 15% and 25% leads to an EVM degradation of 10 dB. Therefore, the modulation index should be reasonably will tuned at the Nonlinearity Estimation block.

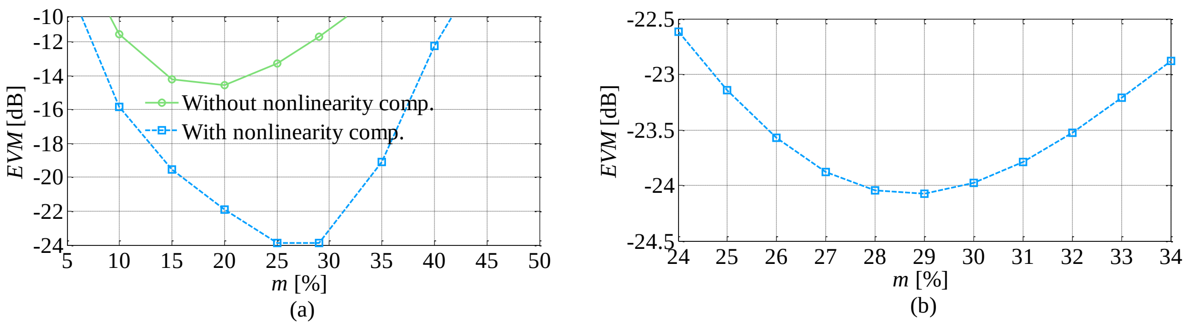

Figure 5: EVM as a function of the modulation index considering (a) the modulation index used in the Nonlinearity Estimation block equal to the modulation index of the OFDM TX and (b) the modulation index of the OFDM TX set to 29% and the modulation index of the Nonlinearity Estimation between 24% and 34%.

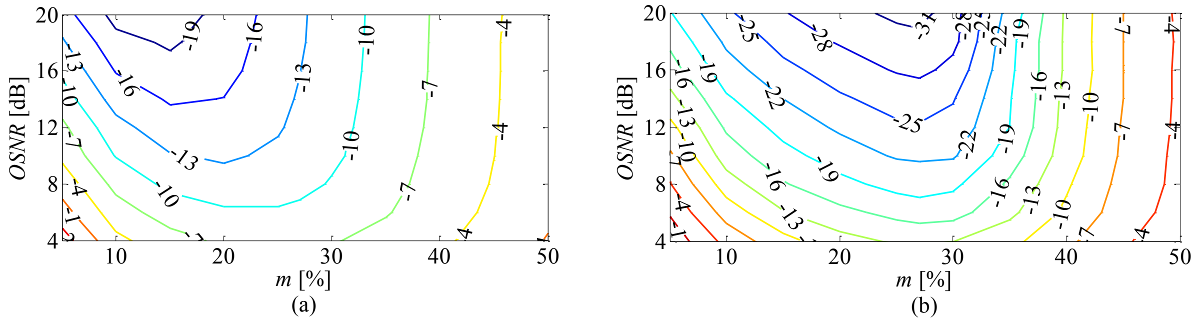

Figure 6: Contour plots of EVM as a function of the OSNR and the modulation index (a) without and (b) with nonlinearity mitigation.

3.2 Transmission with noise

Fig. 5 (a) and (b) show results similar to Fig. 2 (a) and (b), respectively, but considering the amplified spontaneous emission (ASE) introduced by the optical amplifier after the MZM. An OSNR (defined in a reference bandwidth of 0.1 nm) is considered. From the inspection of Fig. 5 (a), two conclusions can be drawn: (i) a significant degradation of the EVM when compared to situation without noise is observed for low modulation indexes due to the OSNR degradation, and (ii) the maximum EVM improvement (obtained for m = 29%) provided by the nonlinearity mitigation is 12 dB. Fig. 5 (b) shows that, while keeping modulation index at 29% at the transmitter side and varying between 24% and 34% at the Nonlinearity Estimation block, the EVM degradation does not exceed 1.5 dB. This small EVM degradation shows that the proposed method presents strong robustness to inaccurate use of modulation indexes levels at the Nonlinearity Estimation block.

Fig. 6 (a) and (b) show contour plots of the EVM as a function of the OSNR and the modulation index. Fig. 6 (a) shows that, in the absence of the nonlinearity mitigation, the EVM limit of -14.5 dB (stated for OFDM-UWB signal employing QPSK mapping) is achieved for an OSNR of 12 dB approximately. Fig. 6 (b) shows also that, by employing the method for nonlinearity mitigation, the same EVM is achieved for an OSNR around of 5 dB.

4. CONCLUSION

In this paper, a method to compensate the degradation induced by the combined MZM and PIN nonlinearity effect in direct-detection OFDM-UWB systems has been investigated using numerical simulation. The results show that, without noise, the nonlinearity induced degradation is adequately mitigated while its power is not significantly higher than the power of the received signal. This condition is verified up to a modulation around 27% and, for this modulation index, the proposed nonlinearity mitigation method enables an EVM improvement of 24 dB. When the optical noise is considered in the analysis, the EVM improvement provided by the nonlinearity mitigation method is approximately 12 dB. In addition, it has been also shown that at the EVM limit of -14.5 dB (stated for OFDM-UWB signals employing QPSK mapping) the application of the nonlinearity compensation method provides a reduction of required OSNR around of 7 dB.

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REFERENCES

[1] W. Siriwongpairat and K. Liu, Ultra-wideband Communications Systems *Multiband OFDM Approach*. Hoboken, NJ: Wiley, 2008.

[2] C. van de Bos, *et al.*: The influence of nonlinear distortion on OFDM bit error rate, *ICC 2000, IEEE International Conference on Communications*, New Orleans, EUA, pp. 65-70, June 2000.

[3] J. Leibrich, *et al.:* Decision feedback compensation of transmitter/receiver nonlinearity for DD-OFDM, *ECOC 2011, 37th European Conference and Exhibition*, pp.1-3, September 2011.

[4] J. Sterba, *et al.:* Iterative algorithm for nonlinear noise cancellation and channel re-estimation in nonlinearly distorted OFDM system, *SAMI 2010, 8th IEEE International Symposium on Applied Machine Intelligence and Informatics*, Herl'any, Slovakia, pp. 65-70, January 2010.

[5] High Rate Ultra Wideband PHY and MAC Standard, 3nd ed. Geneva, Switzerland: ECMA Int., 2008.