Digital predistortion technique with in-band interference optimisation applied to DVB-T2

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The efficient transmission and nonlinear modelling of orthogonal frequency division multiplexing (OFDM) signals are difficult to address owing to the special characteristics of this modulation scheme. Proposed is a digital predistortion technique suitable for the implementation in an OFDM transmitter to optimise the in-band interference caused by the nonlinear distortion generated in the amplification chain. The approach is experimentally validated by its application in one of the world's most advanced broadcasting systems, achieving an outstanding linearisation performance in the transmitter; specially for the in-band interference, a modulation error ratio (MER) of 42.1 dB is obtained.

Introduction: The orthogonal frequency division multiplexing (OFDM) technique has been widely applied to various broadcasting systems, such as the new second-generation terrestrial digital video broadcasting (DVB-T2) standard [1]. One of the major drawbacks of the OFDM signals is the high peak-to-average power ratio (PAPR). The active constellation extension (ACE), proposed in [2], is one of the methods defined in the DVB- T2 standard to reduce the PAPR. However, this technique is insufficient by itself to make an efficient usage of the power amplifier (PA) and comply with the distortion requirements in the transmitter. A widely-used technique to mitigate the undesirable effects of the nonlinear distortion is digital predistortion (DPD). Most of the experimental reports on DPD have been carried out over signals based on the wideband code division multiple access (WCDMA) standard and other M-ary QAM digital modulations [3]. However, the specific characteristics and impact of the nonlinear distortion in OFDM signals present additional challenges for behavioural modelling and, therefore, experimental results validating the DPD in OFDM signals are not abundant. In this sense, to the best of the authors' knowledge, the performance achieved in the present Letter is state of the art.

This Letter proposes a DPD technique that, in addition to reducing spectral regrowth, is optimised to deal with the in-band distortion. The technique is based on a two-block structure modelled by a pre-processing filter and a memoryless (ML) nonlinearity, suitable to be applied in OFDM systems. The theoretical justification of the DPD is presented together with the experimental validation of the proposed approach applied to DVB-T2 signals.

Predistortion technique: Baseband time-domain and frequency-domain Volterra representations can be successfully applied to the modelling of PAs. In the frequency-domain, if we denote by $X(k)$ the discrete spectrum of a baseband OFDM input and by N the number of subcarriers, the pth-order spectrum of the PA baseband response is

$$Y_p(k) = \sum_{k_1=-N/2}^{N/2-1} \cdots \sum_{k_p=-N/2}^{N/2-1} |_{k_1+\cdots+k_p=k} H_p(\mathbf{k}_p) \times \prod_{i=1}^{(p+1)/2} X(k_i) \prod_{i'=(p+3)/2}^{p} X^*(-k_{i'}) \quad (1)$$

where $\mathbf{k}_p$ represents the set of subcarrier indices $k_1, \cdots, k_p$ and $H_p(\mathbf{k}_p)$ are the lowpass equivalent transfer functions. In the case of an ML amplifier, $H_p(\mathbf{k}_p) = H_p(\mathbf{0}_p) = H_p(0, \cdots, 0)$, being constant for all $\mathbf{k}_p$. The output spectrum in the ML case will be denoted as $Y_p^{ML}(k)$. The relation between the PA and the ML pth-order output spectra, given by $F_p(k) = Y_p(k)/Y_p^{ML}(k)$, can be used to express the output spectrum as:

$$Y(k) = \sum_{p=1}^{\infty} F_p(k) Y_p^{ML}(k) = F(k) Y^{ML}(k) \quad (2)$$

According to the first equality of (2), the PA can be regarded as a sum of pth-order ML nonlinearities followed by output linear filters $F_p(k)$. The second equality models the PA as an ML nonlinearity with an output linear filter $F(k)$. The proposed scheme to compensate for the PA distortion is based on two blocks placed as shown in Fig. 1: a dynamic filter $F_{PD}(k)$, dependent on the input spectrum $X(k)$, and an ML predistorter denoted by G_{PD}. Ideally, the composed response of the two cascaded nonlinear blocks, $G_{PD}G$, obeys a linear characteristic, therefore the coefficients of $F_{PD}(k)$ are adjusted to equalise the overall response. As can be seen in Fig. 1, the linearisation condition is accomplished when the ML nonlinearities are perfectly matched and $F_{PD}(k) = 1/F(k)$.

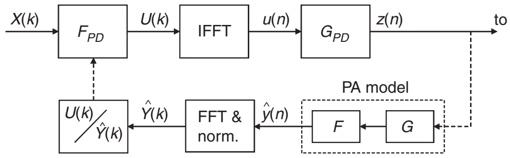

Fig. 1 *Block diagram of proposed system for OFDM compensation*

The forward chain implements the DPD composed by dynamic filter, F_{PD}, and ML nonlinear block, G_{PD}. The reverse chain sets filter coefficients from actual PA model. n and k stand for discrete time and frequency domains, respectively

Once a suitable PA model, as well as the ML block G_{PD}, have been estimated, the signal processing previous to transmission is basically a shape filtering for each OFDM symbol, to equalise the memory effects to be introduced by the PA dynamics. The procedure can be summarised in an open-loop and offline algorithm as follows:

- Given an OFDM block with N M-QAM symbols, generate the predistorter signal $z(n)$ to drive the PA behavioural model and estimate the amplifier output $\hat{y}(n)$. In this step, the predistortion filter $F_{PD}(k)$ is bypassed so that $U(k) = X(k)$.
- After Fourier transforming and normalisation, the pre-processing filter coefficients are computed as $F_{PD}(k) = U(k)/\hat{Y}(k)$.
- Repeat the first step with the input filtered by FPD (k). The predistorted signal $z(n)$ is sent through the PA to be transmitted.

Experimental validation: The experimental setup consists of a Rohde & Schwarz SMU200A signal generator with built-in arbitrary waveform facility and an Agilent PXA-VSA89600 vector signal analyser (VSA). The device-under-test (DUT) was the evaluation board of a MAX2430 device (MAXIM Integrated Products), a silicon medium PA operating in the range 800–1000 MHz. All measurements were performed at 850 MHz, a typical television frequency band, using the bias point of 3.6 V recommended by the manufacturer to operate as a class AB amplifier.

A DVB-T2 32K-mode signal with a long sequence of OFDM symbols was generated with the common simulation platform of [4], employing an oversampling rate of 4. Two types of signals were created: for one, the PAPR reduction technique (ACE) was applied and for the other not. After the addition of the corresponding cyclic prefix, the signal was loaded into the internal memory of the signal generator. The input level was chosen near the 1 dB compression point so that it would drive the DUT in a significant nonlinear region. The output of the DUT was then down-converted and sampled by using the VSA with the same oversampling rate. Once one symbol was used to identify all the coefficients of the models involved in this work, the rest of them were employed to validate the experimental results.

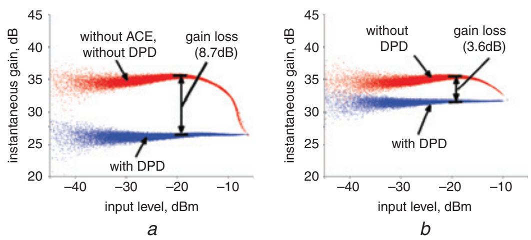

Fig. 2 *Instantaneous gain against input level for DVBT2 signal*

a No PAPR reduction
b PAPR reduction with ACE technique applied. Linearisation achieved for both cases also depicted

The major advantage of using the DPD combined with the ACE technique is shown in Fig. 2. In Fig. 2*a*, when the DPD technique is directly applied to the complex envelope of the original signal, the AM/AM characteristic forces a gain reduction of 8.7 dB to completely linearise the PA output. However, when applying the ACE technique, for the same average input level employed in Fig. 2*a*, the linearised gain is only 3.6 dB below the original without DPD, as Fig. 2*b* shows. In this Figure, we can clearly see that the nonlinear distortion has been satisfactorily compensated for. This was confirmed in the AM/PM characteristic as well, where the phase shift was mitigated with the implementation of the DPD.

For a fixed output back-off (OBO), Table 1 compares the performance of the four cases under study: (a) the case without applying ACE and without the DPD, (b) when only ACE is applied and the signal is transmitted without DPD, (c) the combination of ACE with a standard memory DPD, and (d) the case with ACE and the proposed DPD. The standard memory DPD is a state-of-the-art Volterra-based model formulated in the time-domain that includes memory effects.

Table 1: In-band interference, out-of-band emission and overall performances for OBO = 7.8dB

Cases under study	MER (dB)	ACPR (dBc)		NMSE (dB)
		Lower	Upper	
(a) W/o ACE, w/o DPD	27.4	− 32.9	− 32.9	− 25.3
(b) ACE, w/o DPD	31.6	− 35.3	− 36.5	− 29.0
(c) Standard memory DPD + ACE	39.0	− 43.8	− 45.8	− 37.1
(d) Proposed DPD + ACE	42.1	− 43.5	− 47.5	− 39.1

The major achievement of the proposed DPD is the in-band distortion mitigation. The modulation error ratio (MER), defined in [5], is an excellent figure of merit to evaluate the in-band similarity between the OFDM signal in the frequency-domain after its amplification in the transmitter and the reference signal in the same domain. Table 1 reveals that, when a transmission is directly attempted (case (a)) with OBO = 7.8 dB, the nonlinear distortion produces a high intercarrier interference that reduces the MER to 27.4 dB. To avoid the inefficient solution of increasing the OBO, a PAPR reduction is applied to the original signal according to the standard obtaining an improvement of 4.2 dB in the MER (case (b)). However, when the DPD proposed in this Letter is applied combined with ACE, the MER is improved 14.7 and 10.5 dB above the values achieved for cases (a) and (b), respectively. Furthermore, the proposed DPD accomplished an increase of the MER slightly over 3 dB with respect to the standard DPD with memory. This better performance in the reduction of the intercarrier interference owing to nonlinear distortion is a clear advantage of the proposed DPD technique, which makes it interesting to better satisfy the distortion requirements of modern transmitters.

The results of the adjacent channel power ratio (ACPR) presented in Table 1 confirm the good performance of the implemented DPDs, especially for the proposed DPD, which improves the mean ACPR in 12.6 dBc with respect to the case (a). Fig. 3 shows the power spectrum for all the cases under study. These traces have been taken directly from the spectrum analyser by averaging a large amount of OFDM symbols. This Figure demonstrates a significant reduction of the spectral regrowth when ACE is combined with both DPD techniques.

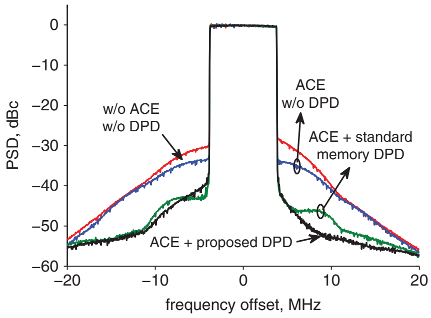

Fig. 3 *Power spectral density for output signals: without ACE and without DPD (original output), with PAPR reduction only, standard memory DPD with ACE and proposed DPD with ACE technique*

The normalised mean square error (NMSE) is a useful time-domain metric for complex samples comparisons. In our case, the NMSE is used to compare the sampled signal in the receiver with the theoretical reference to evaluate the residual distortion after the compensation, in other words, the global linearisation achieved. As can be observed in Table 1, the residual errors of cases (a) and (b) decrease significantly with the implementation of both DPDs; however, our approach is again better by 2 dB than the standard memory DPD.

Conclusions: In this Letter, a DPD technique has been proposed to minimise the in-band distortion that is suitable to be applied in a OFDM environment as demanded by the new wireless standards. Once the PA model has been estimated, the OFDM signal is digitally processed offline with the corresponding predistorter, modelled with a dynamic filter and a static compensator, and then sent to be transmitted. This Letter provides experimental results applied to the DVB-T2 standard with a good performance of the proposed DPD, specially for the intercarrier interference compensation.

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One or more of the Figures in this Letter are available in colour online.

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