Blind Receiver Distortion Compensation

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***Abstract* — A novel technique to compensate for the nonlinearity of a receiver (RX) is proposed and demonstrated experimentally. The adaptive technique is fully blind and does not require any prior knowledge of the transmitting signal. The technique has the capability to both characterize and compensate for the nonlinearity of the RX, making it suitable for implementations in both communication and instrumentation systems. For the former, two RXs operating simultaneously and an attenuator are required to enable real-time data transmission. For the latter, measurements using a single RX and an attenuator can be done instead. By utilizing the knowledge of the signals received at different input power levels, the proposed technique provides improvements to the RX linearity. The technique is demonstrated experimentally with an RF amplifier, where significant improvements quantified through multiple indicators, e.g., the adjacent channel power ratio, are observed.**

***Keywords* — Blind equalizers, instrumentation and measurement, least squares approximation, nonlinear distortion, receivers, wireless communication.**

I. Introduction

The mitigation of the nonlinearity of a receiver (RX), in complement to the predistortion of a power amplifier (PA) at the transmitter (TX), has been a very active research problem. Such capability improves the RX dynamic range, an important parameter to both the realization of low-cost high-integration mm-wave communication systems and the measurement capability of a mm-wave instrument.

Most of the existing work addresses the nonlinear distortion originating from spurious interference and IM2 [1], so-called "blocking carriers", through means of feedforward interference cancellations [2]–[8] and self-calibration [9]. This is in contrast to the objective and the scope of this work, which proposes a technique to tackle the classical self-distortion of the received signal at any stage in the RX.

Existing results within this scope are mainly built upon [10], which presented the relationship between the nonlinear distortion and the spreading of the spectrum as measurable through the adjacent channel power ratio (ACPR). These existing techniques operate on the principle of minimization of ACPR or spectral regrowth [11]–[15], enabling the compensation to be performed blindly or semi-blindly (without the full prior knowledge of the received signal). The disadvantages of such an approach are three-fold. Firstly, the transmitting signal is assumed to be band-limited with known bandwidth, though this limitation is somewhat alleviated by the variant proposed in [14]. Secondly, memoryless nonlinearity is assumed, and memory effects may be left unaddressed. Thirdly, any nonlinear distortion originating prior to the RX is also mitigated. Perhaps counterintuitively, the latter is not a desirable outcome in various practical scenarios. In communication, if a predistorter with a feedback loop [16] is used, the linearization of the TX and the RX is inseparable: the nonlinearity of the RX will be predistorted in addition to that of the TX. This results in worsened over-the-air (OTA) performance and characteristics. In measurement and instrumentation, the existing blind techniques are inapplicable as the nonlinearity of the device under test (DUT) will be compensated in addition to that of the instrument.

This work proposes a fully blind adaptive post-distortion nonlinear equalization technique, covering both the RX hardware setup requirement and the digital signal processing (DSP) algorithm. The technique uniquely has the ability to compensate solely the RX nonlinearity by utilizing a simple setup consisting of a variable attenuator and either two of the same RXs for real-time data transmission or one RX for instrumentation. The paper is organized as follows: Section II describes the problems addressed by the proposed technique and explains the scope of this work. The proposed technique is described in Section III from the setup requirement to the implementation. Experiments and the corresponding results are shown and interpreted in Section IV. The paper concludes in Section V.

II. Nonlinear Model Description

Fig. 1 shows a simplified equivalent baseband model of a generic nonlinear RX to be considered. Of relevance to this work, the RX is modelled into three distinct operations: nonlinear function, noise generation, and ideal digitization.

The representations of the nonlinear function are in abundance. We shall proceed with a generic memory-polynomial (MP) function, which in our view, presents a practical balance between complexity and reality. The equivalent complex baseband representation of the received signal, $y[n]$, is then [17]

$$y[n] = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} a_{km} x[n-m] \left| x[n-m] \right|^{k} + w[n]. \qquad (1)$$

$x[n]$ is the complex baseband representation of the incoming signal, a_{km} is the complex MP coefficient, K and M are the

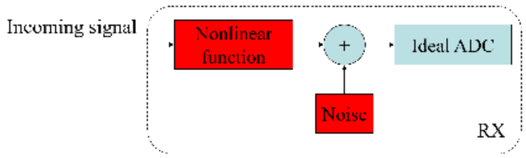

Fig. 1. A simplified model of a generic RX relevant to the scope of this work.

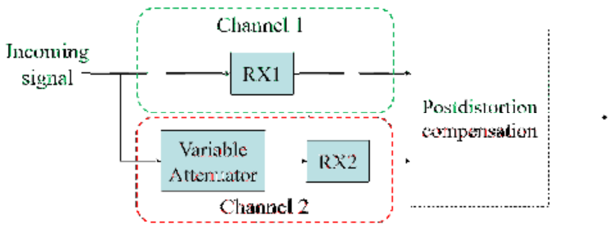

Fig. 2. A simplified block diagram of the setup requirement and implementation used in this work.

Fig. 3. A simplified block diagram of the postdistortion compensation mechanism of the technique.

order and the memory length of the model, respectively. $w[n]$ is the complex additive white Gaussian noise. The goals of this work are to estimate the nonlinearity through the coefficients a_{km} and to subsequently obtain an accurate estimation of $x[n]$, without requiring any pilot signals or prior knowledge of the incoming signal.

III. Technique Description

A. RX-End Setup Requirement

Fig. 2 shows a simplified block diagram of the proposed setup at the RX-end required for real-time applications of the technique. Two signal paths are created, each path contains an RX as described in Fig. 1. One of the paths contains an additional component, namely, a variable attenuator. RX1 and RX2 are assumed to be identical.

B. Operation

Observing the setup in Fig. 2, the incoming signal is received using two RXs simultaneously. The unattenuated upper signal path, named *Channel 1*, will have better signal to noise ratios (SNRs) in the received signal, albeit with higher nonlinear distortion. Conversely, the attenuated lower signal path, *Channel 2*, provides lower SNRs and less nonlinear distortion. The reduction of both the SNR and the nonlinear distortion is dependent on the level of attenuation. This will be illustrated further as part of Section IV.

Let y_1 and y_2 denote the received signal of Channel 1 and 2, respectively. Applying (1) obtained

$$y_1[n] = a_1 x[n] + a_3 x[n] \left| x[n] \right|^2 + w_1[n], \tag{2}$$

$$y_2[n] = a_1 Hx[n] + a_3 Hx[n] \left| Hx[n] \right|^2 + w_2[n], \tag{3}$$

where we simplified the illustration without loss of generality by using K of 3 and M of 0, i.e., any selection of the two parameters is applicable. $H : |H| < 1$ is the attenuation coefficient of the variable attenuator in Channel 2. With a sufficient attenuation, $|H| \ll 1$, (3) is approximated to

$$y_2[n] \approx a_1 Hx[n] + w_2[n]. \tag{4}$$

Channel 2 then effectively provides a reference signal, $\hat{x}[n]$, simply by scaling

$$\hat{x}[n] = \frac{1}{H} y_2[n] = a_1 x[n] + \frac{1}{H} w_2[n]. \tag{5}$$

Subsequently, a standard least-squares estimation [18] of the nonlinear MP coefficients of a conventional postdistorter or a nonlinear equalizer [19], can then be performed as outlined in Fig. 3. The postdistorter then compensates for the nonlinearity of Channel 1, resulting in a linearized high-SNR output signal.

C. Discussion on Implementation

It can be observed that (5) is not an ideal reference due to the noise term, $w_2[n]$, which is especially important due to the lower SNR of Channel 2. This impairs the nonlinear estimation. To alleviate this issue, the procedure in Fig. 3 can be reiterated over a new set of signals with a lower level of attenuation, i.e., a higher SNR, in Channel 2. In each iteration, the postdistorter is cascaded to those from prior iterations. This implementation will be demonstrated experimentally in Section IV.

Alternatively, foregoing the above iterative procedure, a cheaper RX (with worse noise and linearity characteristics) operating in a sufficiently backed-off region can be used in Channel 2 to reduce the implementation cost of the technique. Additionally, for non-real-time applications, such as in instrumentation where the incoming signal is periodic or can be repeated, only one RX and an attenuator are required.

It may be worth noting that other variations of implementation may be of interest depending on the specific application. For example, a rolling window may be included to handle time-varying nonlinear characteristics.

IV. Experiment

A. Methodology and Experimental Setup

The setup in Fig. 2 was implemented in an experimental setup based on Weblab [20]. A National Instrument (NI) PXIe-5646R vector signal transceiver acted as the TX and the RXs. The transmitting signal was a 16-QAM modulated random bit sequence and root-raised cosine pulse shaped with a 3-dB bandwidth of 10 MHz at the center frequency of 2.14 GHz.

To allow for a clear and immediate demonstration of the technique, the nonlinearity of the instrument-class RX was exacerbated by cascading a PA in front of the RX.

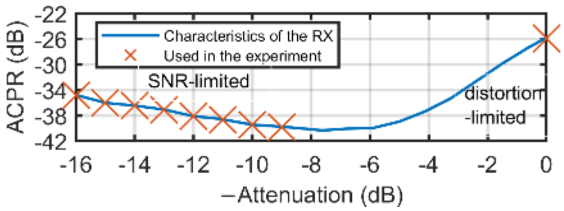

Fig. 4. ACPR of Channel 2 at varying attenuation.

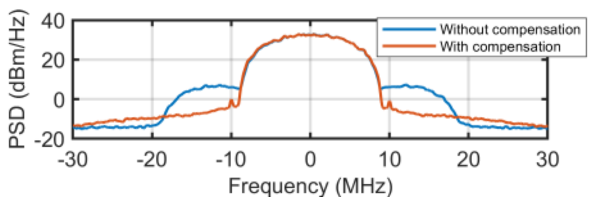

Fig. 5. PSDs of Channel 1, Sequence 8: with and without compensation.

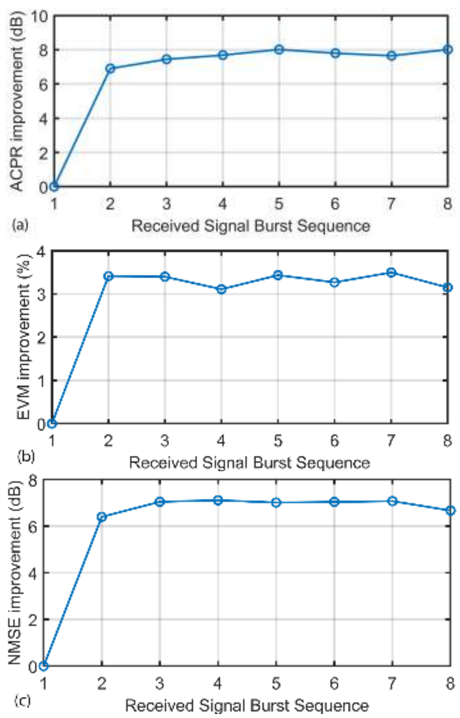

Fig. 6. Improvements of Channel 1: (a) ACPR, (b) EVM, and (c) NMSE.

Minicircuits ZHL-42W PA was chosen. The combination of the PA and the NI RX then acts as a highly nonlinear experimental RX.

The postdistortion compensation mechanism in Fig. 3 was implemented in MATLAB, as well as a standard digital RX functionality. This allows the quantification of the nonlinearity improvement of Channel 1 in terms of communication signal indicators: out-of-band distortion due to odd intermodulation distortion (IMD) products is represented by the ACPR, in-band distortion is quantified through the error-vector magnitude (EVM) which is measured after match-filtering to minimize the out-of-band influence, and the overall error is shown through the normalized mean square error (NMSE) which contains both in-band and out-of-band effects. For the MP, K of 9 and M of 2 were chosen.

The postdistorter was implemented to operate iteratively over decreasing attenuation of Channel 2, as described in Section III. A total of 7 iterations were performed over 8 different sequences (or bursts) of the received signal. Note that the authors chose the term sequence to indicate the rounds of the received signal to emphasize that the signal within each round is different and independent. Furthermore, to represent a real-time operation under real usage scenarios, the MP coefficients estimated from the i-th sequence are only used for the postdistortion of the $> i$-th sequences. Fig. 4 shows the ACPR of Channel 2 at different attenuation levels. This reveals the conventional noise and distortion-limited regions. The eight red markers to the left indicate the attenuation levels used in the experiment, spanning from –16 to –9 dB, which were chosen to be in the noise-limited region. Correspondingly, the average received power spanned from –20.5 to –13.6 dBm. The single red marker to the right indicates the ACPR without attenuation and corresponds to Channel 1 average received power of –5.6 dBm.

At the optimal tipping point between noise and distortion limited regions (around 9 dB attenuation in Fig. 4), the measured ACPR, EVM, and NMSE were –39 dB, 3%, and –30 dB, respectively.

B. Results and Discussion

Fig. 5 shows the power spectral densities (PSDs) of the 8th received sequence of Channel 1 with and without the technique applied. Clear and significant improvement to the intermodulation distortion (IMD) is observed through the suppression of the spectral regrowth. This is further explored in Fig. 6(a), which shows the IMD improvement as more sequences arrived. It can also be seen that an IMD improvement of 7 dB is already observed with the first sequence. After which, the postdistorter gradually improved until the 4th sequence where an improvement of 8 dB, corresponding to –34 dB ACPR, was observed onwards.

In terms of the in-band performance, the EVM shown in Fig. 6(b) indicates a small improvement of 3.5% after the first sequence arrived, resulting in an EVM of 4%, and the performance is stable onwards.

Finally, the overall improvement is shown in Fig. 6(c) through the NMSE. Again, the performance improved significantly by 6 dB after the first sequence arrived. Then the overall improvement converged to 7 dB after the second sequence onwards, which corresponded to –27 dB NMSE.

All results indicate a successful implementation and demonstration of the proposed technique. Near-optimal performance can be obtained from the highly distorted received signals. The capability of the technique in a real usage scenario has been demonstrated through ACPR, EVM, and NMSE.

V. Conclusion

An adaptive technique to compensate solely for the self-nonlinearity of an RX has been proposed. Being the main benefit, the technique operates without any prior knowledge of the received signal and is fully blind. A full description of the technique from the theoretical operation to the implementation has been given. Using a communication signal, the technique was experimentally demonstrated under a real usage scenario to be able to compensate for a strong nonlinear distortion. Significant improvements, using system-level end-user indicators, have been demonstrated for both in-band and out-of-band frequency ranges. Due to these qualities, the technique is suitable for operation in both communication and instrumentation systems.

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