Measurement & Extraction of the Low-Frequency Dynamics of an Envelope Tracking Amplifier using Multisine Excitations

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Abstract—Both efficiency and linearity of an Envelope Tracking Power Amplifier depend on the tight synchronization between a Low- and High-Frequency path. The presence of reactive elements in this Low-Frequency path, as well as an inevitable delay difference between both paths, results in a dynamic mismatch that can seriously degrade the overall performance of the device. This work introduces a method that is able to extract these Low-Frequency dynamics without requiring access to any internal nodes of the device. The proposed extraction procedure makes use of the combination of a linear parameter-varying framework and a specific signal excitation strategy which uses a multisine excitation to mimic the operational conditions of the amplifier. A trustworthy model for the Low-Frequency dynamics is an important component necessary for building an adequate pre-distortion tool that is able to eliminate a bad dynamic match.

Index Terms—Envelope Tracking, Envelope Shaping, Digital Pre-Distortion, Linear-Parameter Varying Model

I. INTRODUCTION

The correct operation of an Envelope Tracking (ET) Power Amplifier (PA) depends on a tight synchronization between the High-Frequency (HF) and Low-Frequency (LF) path [1], where the LF signal is derived from the envelope of the HF input as seen in Fig. 1. A mismatch between these paths can have devastating results, negating all of the potential performance increase that such an amplifier architecture offers. Compensating for this mismatch, and thus extracting the existing unwanted dynamics, is an essential part of the design procedure.

![Fig. 1. General model structure of an Envelope Tracking Power Amplifier.](image)

The actual origin of these dynamics can be quite diverse as any reactive element, part of the LF path, contributes to the overall dynamic behaviour [2], [3]. While a significant part of these dynamics can be safely captured and compensated for with the aid of a lone delay term, such leniency is bound to become inadequate when the signal bandwidth increases beyond the current scope [4].

Currently available extraction methods are mostly invasive, requiring the availability of a measurement probe on the interface between the Dynamic Power Supply (DPS) and the PA [5]. The main issue here is that this interface is in most cases not accessible. The dynamically distorted version of the supply voltage (which is necessary for extracting these LF dynamics) cannot be directly measured and, consequently, is not available for pre-distortion purposes.

In this work, the LF dynamics are estimated without the help of any invasive methods, using only the available in- and output interfaces. The resulting extracted model gives a measure for the total unwanted dynamics that the LF signal perceives before reaching the intrinsic drain of the amplifier. This allows for the introduction of a direct pre-distortion tool that works by compensating the digital LF signal with the inverse dynamics before feeding it to the DPS. This work discusses the necessary extraction procedure and uses a measurement example to validate this proof-of-concept.

II. EXTRACTION PROEDURE

The proposed procedure makes heavy use of the Linear Parameter-Varying (LPV) framework and in particular the method described in [6], that allows for the estimation of a dynamic dependence between a scheduling parameter (which is the LF signal in this case) and an internal time-varying coefficient, estimated as discussed in [7]. The model that will be used in this work, heavily simplified compared to the full-blown LPV framework, is shown in Fig. 2.

The following assumptions are to be made for this preliminary proof-of-concept:

- The HF input-output behaviour can be adequately described with a single complex coefficient; or in other words: the device is assumed to be quasi-static. The LPV model structure allows the introduction of multiple branches to model these dynamics when required.
Fig. 2. The Fourier transformed input wave $A_{in}$ is multiplied by a complex coefficient $D_0$, after which it is convolved with the dynamically modified LF signal $H_0V_s$. In which $V_s$ denotes the optimal supply voltage as defined by the shaping function.

- The amplification device can be correctly modelled using a Single-Input Single-Output (SISO) approach. However, the extension to a Multiple-Input Multiple-Output (MIMO) LPV model is possible if required.

The LPV framework is a strictly linear framework. An actual ET transmitter will also possess a differing degree of non-linear behaviour. Extracting the model structure, shown in Fig. 2, from measured data will thus become difficult since the non-linear and parameter-varying effects cannot be separated at the device output as is. In this work, this challenge is resolved by the use of a specific excitation strategy that introduces an additional, independent signal at $v_s$.

A. Excitation Strategy

The method for separating the non-linear and parameter-varying contributions is based on the techniques introduced for the out-of-band Best Linear Approximation (BLA) [8]. A so-called ‘tickler’ Random Phase Multisine (RPM) excitation is added to the input to expand the BLA outside of its excited region. This tickler excitation is chosen as small as possible, so small in fact that it does not influence the actual operational conditions. In this work, the tickler is not added alongside the HF input signal, but is added to the LF input instead. As is discussed in [8], for separation purposes, the frequency grid of the large HF input RPM is restricted to an even grid, while the tickler lies on an odd grid. Spectral regrowth due to non-linearities will then only fall on even bins, because the sum of even numbers is always another even number [9]. Spectral content that appears at odd output bins thus only has a single possible origin: A combination of an even bin of the HF input with an odd bin of the tickler. Such a combination is most definitely of a parameter-varying nature.

The measured spectrum of the output wave $B_{out}$ is shown in Fig. 3 and clearly shows that alongside the spectral regrowth coming from the non-linearities there is spectral content present at the odd bins. These are parameter-varying skirts coming from the combination of the LF tickler and the HF input. The LPV estimation procedure of [6] is performed, but only uses the frequency bins that can be directly related to the parameter-variation due to the presence of the LF tickler.

III. MEASUREMENT EXAMPLE

To validate the proposed method, a Texas Instruments’ LM3290-91 Evaluation Board is measured and the relevant LF dynamics are extracted.

Fig. 3. The spectrum of the output wave $B_{out}$ clearly distinguishes between spectral regrowth due to non-linear behaviour, at the even bins ($\times$), while the spectral content at odd bins ($) is predominantly of a parameter-varying nature as is desired.

A. Measurement Setup

Both the HF and LF input signals are generated using the two channels available in Keysight’s M8190 8 GSa/s Arbitrary Waveform Generator (AWG) which furthermore ensures that both signals are correctly synchronized in phase. The sampling frequency of the generator is chosen equal to 4.8 GHz. The HF input signal is first amplified using Mini-Circuits’ LZY-2X+ Ultra-Linear RF Amplifier to obtain an input signal with the correct power for the testboard. The actual input power was calibrated using Keysight’s 8487A Power Sensor. Measurement of the output spectrum was done using a Keysight’s N9030A PXA Signal Analyzer which acquires complex IQ data at a sampling frequency of 140 MHz. A photograph of the measurement setup, with the relevant instruments annotated, is shown in Fig. 4.

Furthermore, a 10 MHz reference clock is shared between the AWG and the PXA to allow for frequency synchronization between measured and generated data. The data acquisition and signal generation is controlled with the aid of a MATLAB script. Since input and scheduling signals were not measured, all possible non-idealities introduced by the AWG and
pre-amplifier are considered to be part of the Device under Test (DUT). Unfortunately, the Local Oscillator (LO) of the PXA could not be synchronized to the AWG and is as a result an unknown variable. The consequence of this is two-fold; the measured phase needs to be normalized to be able to compare different measurements and, secondly, the estimate of the quasi-static model coefficient $D_0$ will be incorrect. This should not pose a problem as the dynamic model coefficient $H_0$ is independent of the LO phase as is seen in Fig. 2.

B. Experiment Design

This particular transmitter is designed to accommodate an LTE signal at E-UTRA Band 5. The carrier frequency, $f_c$, is 836 MHz for this particular band and the allowed channel bandwidths are 1.4, 3, 5 and 10 MHz. The bandwidth of the input multisine, $A_{in}$, is chosen accordingly, at both 1.4 and 10 MHz to showcase the method’s versatility. The chosen properties of the HF input are given in Table I.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>HF INPUT PROPERTIES</th>
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<tbody>
<tr>
<td>$f_c$</td>
<td>836 MHz</td>
</tr>
<tr>
<td>Nr. of Tones</td>
<td>[29, 201]</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>(1.4, 10) MHz</td>
</tr>
<tr>
<td>$P_{RMS, in}$</td>
<td>$-5$ dBm</td>
</tr>
</tbody>
</table>

The bandwidth of the tickler is chosen wide enough to get an idea of the general trend of the LF dynamics. A bandwidth of 60 MHz was presumed adequate. Relevant properties for the tickler input are listed in Table II and are common for both bandwidths of the HF input.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>LF TICKLER PROPERTIES</th>
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</thead>
<tbody>
<tr>
<td>Nr. of Tones</td>
<td>40</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>60 MHz</td>
</tr>
<tr>
<td>$P_{RMS, in}$</td>
<td>$-20$ dBm</td>
</tr>
</tbody>
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A total of 28 experiments with different phase realizations (modifying both the random phase of the tickler as the input RPM simultaneously), for both bandwidths, is measured with the PXA. The relevant parameter-varying spectral content is extracted from the measurements and the resulting culled data is processed with a MATLAB script that implements the LPV modelling method described in [7].

IV. ESTIMATION RESULTS

Estimation results for both of the measured HF signal bandwidths are shown in Fig. 5 and 6. These plots show the amplitude as well as the phase of the estimated dynamic model $H_0$. The estimated dynamics are non-conjugate as they interact with both in-phase and quadrature component of the HF signal in a different manner. The direct HF path itself does not perceive any dynamics as verified by the measurements, allowing the use of the quasi-static assumption in this particular example. For pre-distortion purposes, in which the pre-distortion of a real LF signal is intended, only a conjugate model is allowed. Hence the in-phase component of the LF dynamics is also shown as the most likely candidate for future pre-distortion efforts.

As can be seen from these estimates the match between the DPS and the ET amplifier is, in this case, quite good as the dynamics seem to have quite a low dynamic range, even in a spectrally wide bandwidth. Important dynamic behaviour could of course always be hidden inbetween the sparsely excited grid of the LF tickler.

Both of the extracted LF dynamics behave quite similarly in frequency, prompting the conclusion that the HF signal bandwidth has a lesser influence on the actual LF dynamics. However, as is clearly seen, the extraction procedure has more trouble getting a decent estimate out of the 10 MHz measurement data which is most definitely caused by the higher number of tones present in the HF input signal.
V. CONCLUSION

In this work, a new extraction procedure for the LF dynamics of an ET PA was introduced. As a proof-of-concept, the technique was successfully tested on a measurement example, using multisine excitations, for different signal bandwidths. Future work will see the implementation of these estimates as pre-distortion templates.

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REFERENCES