Improved Iterative Envelope Simulation for the Efficient Prediction of the Impact of Wideband Modulated Signals on Power Amplifier Performance

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***Abstract*—A previously introduced Iterative Envelope Simulator is expanded upon. The new implementation uses a Matlab-controlled ADS circuit simulator, allowing for the simulation of manufacturer provided nonlinear transistor models. The model is validated with 2-tone and 256-Quadrature Amplitude Modulation (256-QAM) stimuli applied to a power amplifier with a resonant BB network. Its output is compared against 2-tone HB simulations and ADS envelope simulations. The 2-tone results show that the improved simulation captures the same trend as the HB simulator. The new model introduces the ability to predict signal linearity for complex signal modulation schemes. It is capable of predicting the issues related to the resonant networks for the 256-QAM signal, showing a significant Error Vector Magnitude (EVM) degradation when the signal envelope starts overlapping the resonant frequency, while the traditional envelope simulator does not capture this issue.**

***Index Terms*—Baseband terminations, instantaneous bandwidth, wideband power amplifier (PA)**

I. Introduction

Communication systems are shifting to ever-increasing bandwidths to process more data. To accommodate this, Power Amplifier (PA) design has to accommodate more bandwidth, resulting in losses in efficiency and linearity. Meanwhile, PA design practice and theory focus on simplified single-tone simulations for understanding, standardization, and comparing designs. However, only a final test with modulated signals can tell if a PA can be used effectively for a specific application. This mismatch can result in performance loss when transitioning from model to real design.

Investigations in wideband PA performance and linearity recognized that the Baseband (BB) impedance provided to the transistors has a significant effect on Intermodulation Distortion (IMD) products [1] [2], output power, and efficiency. Improved BB matching networks [3], and BB signal injection [4], have been shown to improve signal linearity and efficiency.

A new method of predicting the effect of BB impedance was introduced in 2018 [5]. System performance can be estimated by assuming that the RF and BB signals only indirectly mix but can be derived from each other. The method was rewritten [6] by simulating the BB component using a harmonic balance simulation in Matlab for both the RF and BB. This allowed for the simulation of any theoretical matching network.

In this paper, the iterative steps of the Iterative simulator are expanded to utilize ADS circuit simulation for the RF solver, through the ADS-Matlab interface [7], while the BB is still solved in Matlab. A circuit with a CG2H40010F transistor and an output network consisting of a measured S-parameter file is simulated. Its results are compared between the new Iterative Envelope Simulator and traditional simulations. Finally, a 256-QAM modulated signal is applied, and it is shown that the proposed simulator captures significant effects of the BB impedance on the output signal linearity, efficiency, and power, which the traditional envelope simulator cannot predict.

II. The Improved Envelope Simulation

Harmonic Balance (HB) simulators simulate the signals in time and frequency domain for a minimal amount of points. Specifically, in the frequency domain they simulate the fundamental input tones, their harmonics and a given amount of intermodulation frequency points. This works for simple input signals with limited frequency points, yet scales badly for more complex signals, such as the modulation signals used by modern communications systems. The novel idea introduced in 2018 [5] is that the worst effects of intermodulation occur from BB voltage swings inducing compression in the RF signal. By assuming the BB and RF are separate signals, with known relations, an accurate solution can be calculated, and more importantly, a complex interaction can be understood in a simplified overview.

The Iterative Envelope Simulator uses the following time definitions: τ, for time in the BB domain, and t for time in the RF domain. The model effectively consists of 2 nested harmonic balance simulators, one inner loop for the RF domain, which is simulated in ADS, and one outer loop for the BB domain, which is simulated in Matlab. An overview of the Iterative Envelope Simulator is given in Fig. 1, and described step by step below.

- A modulating signal is generated or read into Matlab, defining the magnitude and phase at each step of τ.

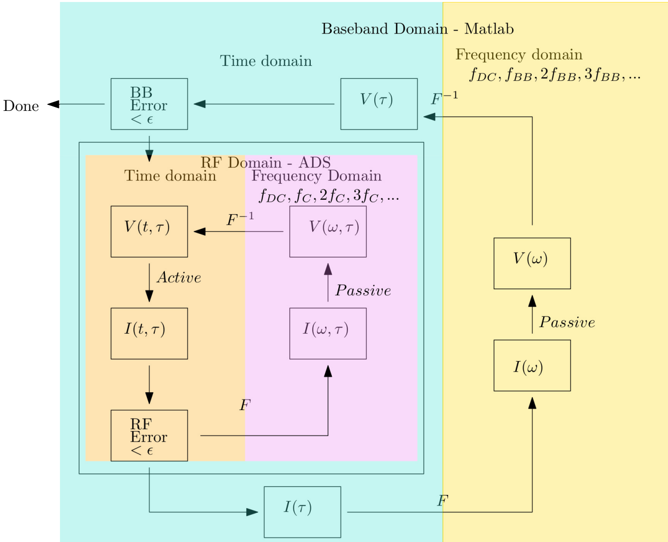

Fig. 1. Overview of the Iterative Envelope Simulation, the Harmonic Balance loops optimize until the error is smaller than ϵ, the acceptable error tolerance defined in Matlab and ADS respectively

- The drain voltage at each transistor is defined as the RF domain DC supply voltage at each step of τ
- The modulation scheme and drain voltages are fed into ADS, where the ADS single-tone HB simulator simulates the circuit at the RF domain, sweeping through each step of τ to calculate circuit performance.
- The results are read back into Matlab, by extracting the DC component at each τ of the RF simulation drain current, the new BB transistor drain current is found
- The BB current is converted into the BB frequency domain, allowing for the calculation, in Matlab, of the BB drain voltage in the BB frequency domain using the passive S-parameters of the matching network.
- The resulting drain voltages are converted back to τ values, fed back into ADS for another HB simulation of the RF domain
- Every loop iterates on the BB drain voltage until it converges to a stable value.

The convergence algorithm of the Iterative Envelope Model uses a weighted average between the new drain voltage values at each step of τ, and those of the previous iteration. The goal of the algorithm is to reduce the difference between the new and old values to 0, resetting and reducing the weight of the new values in cases if the error increases.

The new Iterative Envelope Simulator allows for simulations of the effect of BB impedance on complex signals. Since it operates using Keysight ADS defined circuits it allows for manufacturer provided transistor models, complex matching networks, and multi transistor circuits. This is a clear step forward compared to the work in [6] where the components are represented and modelled in Matlab by means of simplified non-linear models.

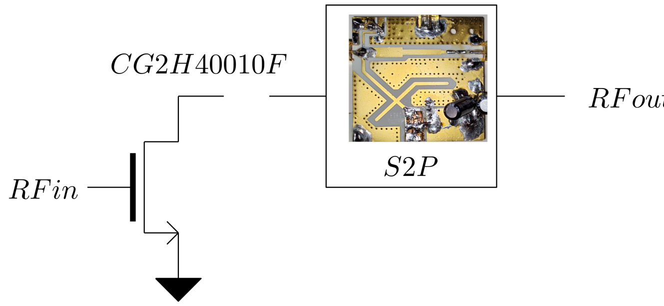

Fig. 2. Schematic of the simulated circuit. A CG2H40010F transistor and a measured S-Parameter block of a real output matching network.

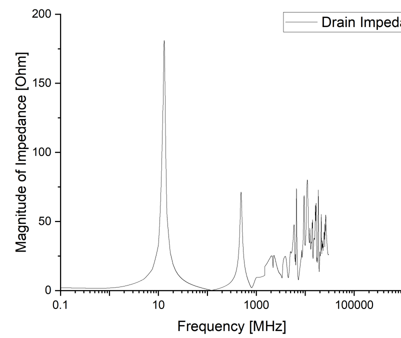

Fig. 3. Measured Impedance of the output matching network, resonant around 14 MHz

III. Validation

To evaluate the envelope simulation performance, it is compared with simulated performance from ADS. The circuit simulated is an example of single-stage PA operating at 2.5 GHz, whose simplified schematic is shown in Fig. 2. The CG2H40010F transistor model from MACOM is used, fed at the input by a 4Ω input power source, which is close to the input impedance of the device. The S-parameters of a PCB previously designed as a matching network were measured and used at the output of the device in ADS. The matching network embeds the drain bias tee for the transistor. Fig. 3 shows the magnitude of the impedance that the matching network presented to the device over frequency, highlighting a resonance around 14 MHz. The PCB was specifically chosen due to its resonance, so that the viability of the simulation in predicting the effects of resonance on PA performance under modulated signal could be investigated.

A 2-tone envelope is generated in Matlab and compared with a 2-tone HB simulation in ADS. The bandwidth of the 2-tone signal is swept to investigate its interaction with the resonant behaviour of the matching network at BB frequencies. The results can be seen in Fig. 4 in terms of output power and efficiency at a drive level corresponding to approximately 3 dB of gain compression. There appears to be a strong overlap in performance trends, with both simulations predicting significant output power and efficiency drops when the tone spacing is near 14 MHz. However, ADS shows more performance loss due to the resonance; this might be explained by the custom implementation of the BB HB simulator in Matlab converging too early.

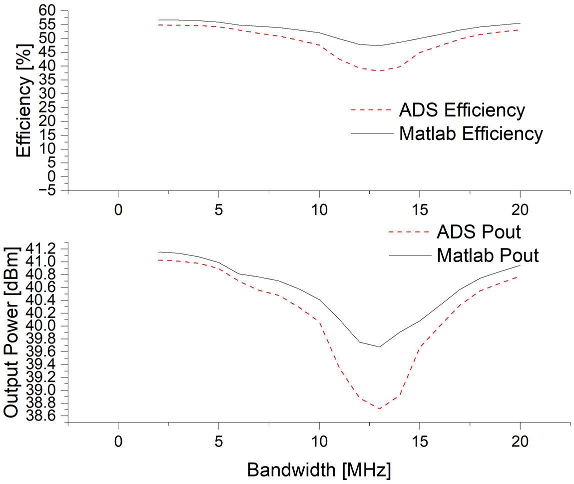

Fig. 4. 2-tone simulation performance comparison of the Iterative Envelope Simulator against ADS 2 tone HB simulation

A 256-QAM signal is compared between the Iterative Envelope Simulator in Matlab and an envelope simulation in ADS. The predefined signal is generated over a swept bandwidth to investigate the effect of the BB impedance. The resulting power and efficiency are shown in Fig. 5. The first noticeable result is that the ADS envelope simulation does not show any interaction with the BB impedance at all, while the Iterative Envelope Simulator predicts a 0.4 dB loss in output power, which, however small, does indicate an interaction. The lower degradation is due to the envelope energy being spread over a large bandwidth compared to the 2-tone case where all the energy is concentrated at the tone-spacing frequency (and its harmonics).

The simulation time is increased by the Iterative Envelope Simulator. The ADS Envelope simulation was completed in 80 seconds, while the Iterative Envelope Simulation required 1170 seconds to complete 14 iterations to resolve the error, roughly corresponding with 14 times the ADS Envelope simulator time. One possible improvement to the simulation time could be made by incorporating the entire algorithm in ADS, removing the interaction with Matlab and the need to run separate ADS simulations. Another possible improvement can be made by changing the conversion algorithm aggressiveness, it could be possible to reduce the amount of iterations required, at the risk of reducing convergence stability. This method is more computationally intensive than the regular Envelope simulator, indicating the main limiting factor. More complex circuits with convergence issues such as load modulating multi-transistor networks can require significant simulation time, also impacting the usefulness of the Iterative Envelope Simulator.

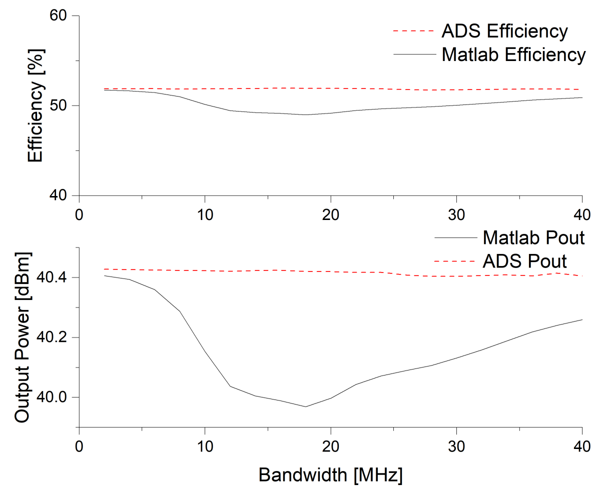

Fig. 5. IQ simulation performance comparison of the Iterative Envelope Simulator against and ADS envelope simulation for a complex 256-QAM modulated signal

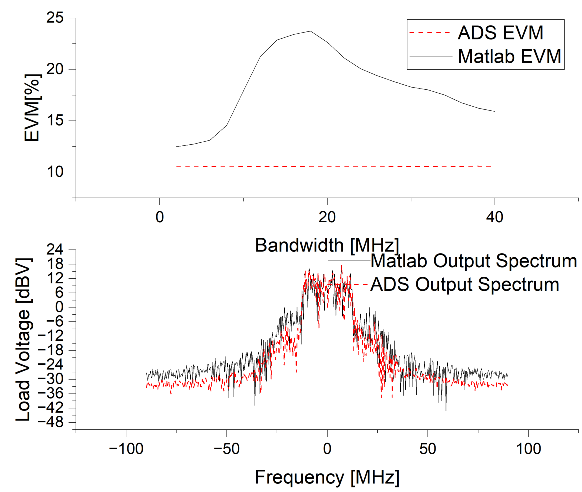

Fig. 6. IQ simulation Linearity comparison of the Iterative Envelope Simulator against and ADS envelope model simulation for a complex 256-QAM modulated signal

One advantage of the new implementation of the Iterative Envelope Simulator is its ability to predict signal linearity including BB interactions. In Fig. 6(top) the resulting EVM is compared over a swept bandwidth. Here the Matlab Iterative Envelope Simulator implementation shows a significant degradation of EVM over the swept bandwidth, also not captured by the conventional envelope simulation. The output spectra comparison at a 18 MHz signal bandwidth is shown in the bottom half of Fig. 6.

IV. Conclusion

An improved version of a previously introduced Iterative Envelope simulator is presented. By simulating the BB and RF domain of complex modulated signals separately, their output power, efficiency and linearity can be estimated. Using ADS combined with Matlab allows for an implementation of the simulator which can simulate matching networks and complex transistor models. The model is used to predict the effect of a resonant BB matching network on a 256-QAM modulated signal, a measurement previously impossible with classical envelope simulators.

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