Investigation of Behavioral Model Accuracy Using a State-Space and Convolution-Based Transient Simulator

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***Abstract* — Behavioral modeling of high-frequency systems offers the prospect of more efficient simulation at the expense of some loss of accuracy. In this work, a new state-space/convolution type transient simulator is introduced which provides a large-signal amplifier analysis capability featuring extremely high accuracy and robustness. This simulator is used to 'benchmark' the accuracy performance of different forms of behavioral model for a realistic PHEMT single-ended amplifier with distributed matching circuitry.**

I. INTRODUCTION

There is increasing interest in high-level or 'behavioural modelling' for the simulation of high-frequency communications sub-systems and components [1][2]. However some uncertainty remains regarding the limitations of the commonly used approaches, for example using an AM-AM- and AM-PM- based characterisation of a power amplifier. These limitations are more evident in systems containing a significant degree of 'memory' or when it is attempted to use this type of characterisation with multiple carrier inputs.

This contribution first introduces a novel and highly accurate 'benchmark' transient simulator developed at UCD. This simulator uses a state-space formulation of the non-linear device model equations in combination with a discrete convolution technique for incorporating linear network blocks. This simulator is then used to assess the potential and limitations of different forms of behavioural model by testing their predictions against the results of what is in effect close to an exact numerical analysis. Results obtained to date indicate that so-called 'envelope models' are generally inferior to the direct use of AM-AM characteristics and that the accuracy of behavioural modelling may quickly deteriorate with multi-carrier inputs.

II. STATE-SPACE/CONVOLUTION TRANSIENT SMULATOR

For concreteness, this paper concentrates on the behavioral modeling of a single-ended PHEMT amplifier with realistic distributed matching structures, as shown in Fig. 1. The linear networks are arbitrary time-invariant causal systems which are assumed to be described in the frequency domain by their scattering matrices. The non-linear active device is described by a detailed equivalent circuit model [3], and this can be used to derive state equations in the form of a set of ordinary integro-differential equations in the time-domain.

For the simulator developed in the course of this work, a novel convolution-based technique is used to incorporate the linear circuit blocks at input and output within a true transient simulation. Only an outline of this method is given here in the interests of brevity. The first step involves the transformation of the continuous complex-valued scattering parameters of each S-parameter block into equivalent discrete real-valued impulse response sequences, essentially following the method described in [4]. This form of impulse response converts the normal convolution integrals of linear analysis into exact sum-of-products calculations, which may be efficiently and accurately calculated. In effect, the linear network presented to each port of the non-linear device at each time step is represented by an instantaneous load-line, with parameters determined in part by the past history of the port variables. Consider as an example the input network in Fig. 1. Suppose the scattering parameters $S_{21}^{in}(f)$ and $S_{22}^{in}(f)$ are described by equispaced impulse response sequences $h_{21}^{in}(k\Delta t)$ and $h_{22}^{in}(k\Delta t)$ respectively, of finite length N and with a time step Δt. Using the definition of the scattering parameters and transforming to the time-domain, we have:

$$\begin{aligned} b_1(t) &= h_{11}^{in}(t) * a_1(t) + h_{12}^{in}(t) * a_2(t) \\ b_2(t) &= h_{21}^{in}(t) * a_1(t) + h_{22}^{in}(t) * a_2(t) \end{aligned} \tag{1}$$

Where '$*$' denotes convolution. In the case of the input port shown in Fig. 1, where the port variables $v_1(t)$ and $i_1(t)$ are assumed to be solved with a uniform time step Δt and G_{o1} and G_{o2} are the reference conductances of the S-matrix, it can be shown that at the n[th] time-step:

$$v_1(n\Delta t)=\frac{1}{G_{o2}}\cdot\left[\frac{1+\underline{\Delta t}\cdot h_{22}^{(in)}[0]}{1-\underline{\Delta t}\cdot h_{22}^{(in)}[0]}\right]\cdot i_1(n\Delta t)+\left(\frac{1}{1-\underline{\Delta t}\cdot h_{22}^{(in)}[0]}\right)\cdot\sqrt{\frac{G_{o1}}{G_{o2}}}\cdot\sum_{i=0}^{N}h_{21}^{(in)}[i\underline{\Delta t}]\cdot v_{gen}(n\Delta t-i\underline{\Delta t})+$$
$$\left(\frac{1}{1-\underline{\Delta t}\cdot h_{22}^{(in)}[0]}\right)\cdot\sum_{i=1}^{N}h_{22}^{(in)}[i\underline{\Delta t}]\cdot\left[v_1(n\Delta t-i\underline{\Delta t})+\frac{i_1(n\Delta t-i\underline{\Delta t})}{G_{o2}}\right] \tag{2}$$

or more simply in the form of a dynamic linear load line:

$$v_1(n\Delta t)=\alpha_{in}\cdot i_1(n\Delta t)+\beta_{in}(n\Delta t)$$

The term $b_{in}(nDt)$ depends on the current and past history of the excitation but only on the past history of the port variables. In this way, the linear circuits, described initially in the frequency domain, may be incorporated efficiently within a full transient time-domain analysis.

The simulator resulting from the application of these (and other numerical techniques not detailed here) has demonstrated exceptional accuracy and robustness. As an example Fig. 2 shows the computed steady-state load spectrum across the output of Fig. 1 for an input of +20dBm. Note that the effective dynamic range is of the order of 300dB. A series of verification tests have further validated the accuracy of the simulator analysis.

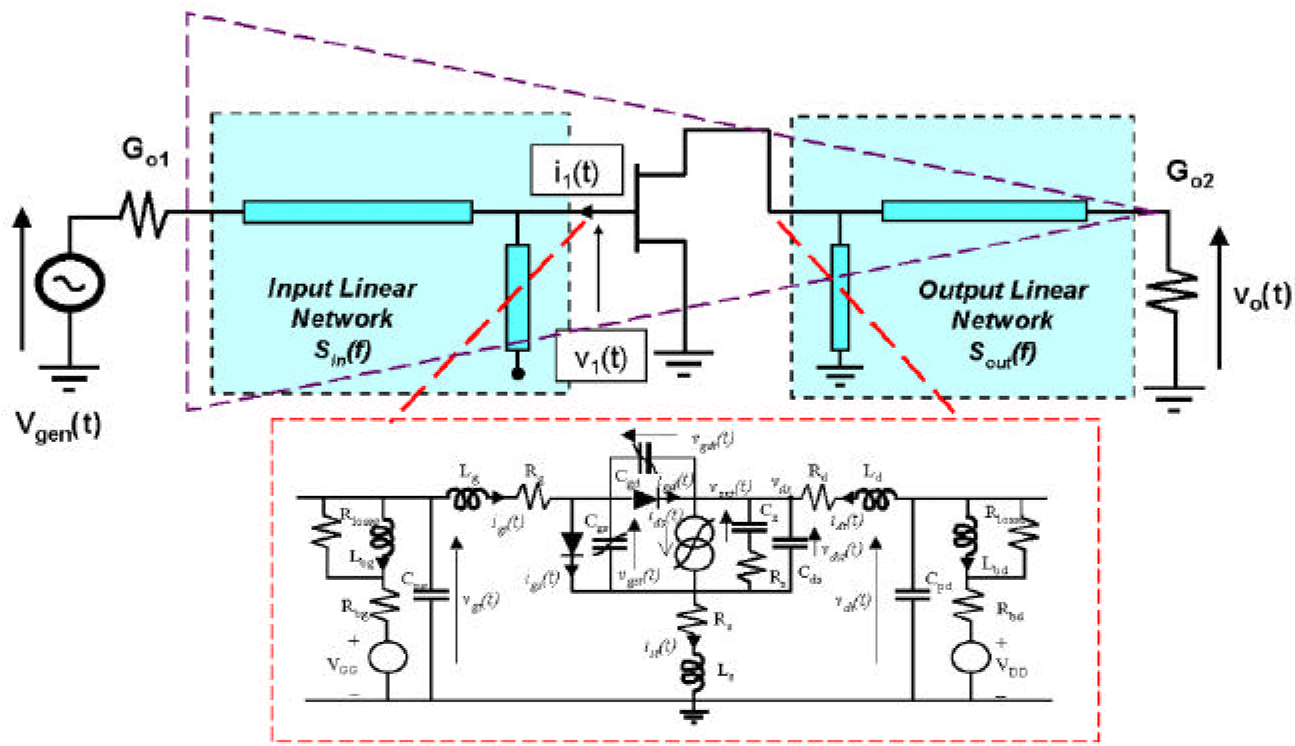

Fig. 1. PHEMT Amplifier with Distributed Matching Networks Used for Simulation and Behavioral Modeling.

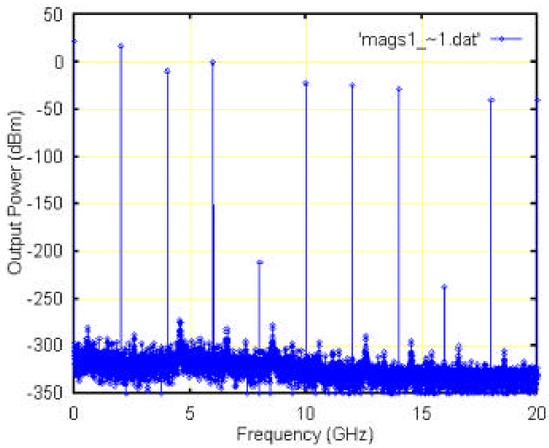

Fig. 2. Simulated Steady-State Load Voltage Spectrum for Single Tone Excitation of Circuit of Fig. 1 at 2GHz, P_{in}= +20dBm.

III. Behavioral Models

While direct circuit-level simulation of systems of the form of Fig. 1 is possible, such simulations may become prohibitively expensive in complex systems or when long simulations such as those required for BER analysis are required. Indeed, full information at the circuit level may not even be available, e.g. for proprietary or other reasons. In all these situations, high-level or behavioral modeling may be of considerable value [1]-[2].

In the remainder of this contribution, we use the simulator described in Section II to evaluate the accuracy of some common approaches to behavioral modeling. The advantage of this kind of simulator for such a task, as opposed to other techniques such as circuit envelope or harmonic balance, is that the numerical error is extremely low and well-controlled. We first use the simulator to perform an AM-AM and AM-PM characterization of the amplifier, taking 2GHz as reference, and seeking in this way to create a behavioral representation of the entire network shown within the dashed triangle in Fig. 1.

An AM-AM representation is often proposed as valid for a 'narrowband' signal excitation and when the system is memoryless. Obviously, the system of Fig. 1 is not of the latter kind, but with the addition of the AM-PM characteristic and by proposing that the delay is essentially uniform around the carrier and each of its harmonics (including DC), the concept may in principle be extended. Different combinations of AM-AM and AM-PM representations are possible. Furthermore, it can be shown that if the AM-AM characteristic represents a true memoryless non-linearity, then using a fitting procedure based on a first-order Bessel function expansion allows reconstruction of the 'exact' non-linear transfer characteristic from the AM-AM data. This is often referred to as the 'Envelope Characteristic' [2]. Figs. 3 and 4 show the results of this kind of characterization for the amplifier in Fig. 1.

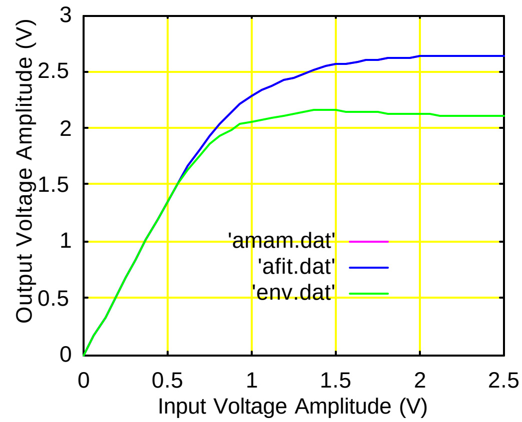

Fig. 3. AM-AM Characterisation of Amplifier Together with Bessel Function Fit leading to Envelope Characteristic (lower curve)

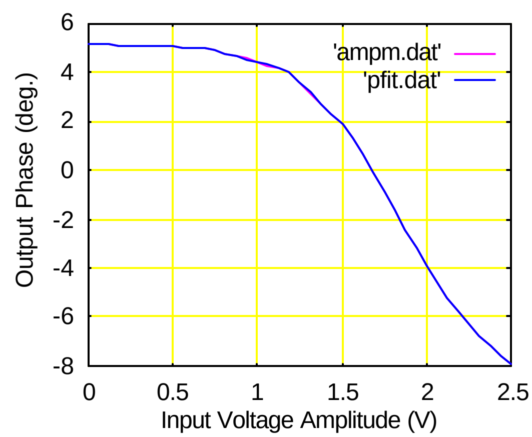

Fig. 4. AM-PM Characteristics and Result of Series Fit.

IV. Model Verification

A number of comparison tests have been carried out using excitation waveforms which are separately generated and then passed through a particular behavioral model to produce a distorted output. The same waveform is also imported into the transient simulator and used for direct analysis (interpolation errors thereby reduce the dynamic range compared to Fig. 2, but to a predictable degree). Figs. 5 and 6 show the results for a multitone randomly-phased input, and a single WCDMA signal, respectively, all centered on 2GHz. These diagrams show a comparison between results obtained using the AM-AM characteristics and the Envelope

Characteristics. The spectral distribution obtained from the transient simulator, which are expected to be highly accurate, are also indicated. These results are representative of a number of tests to date in the sense that use of Envelope Characterization is generally found to give inferior results compared to direct use of the AM-AM characteristics.

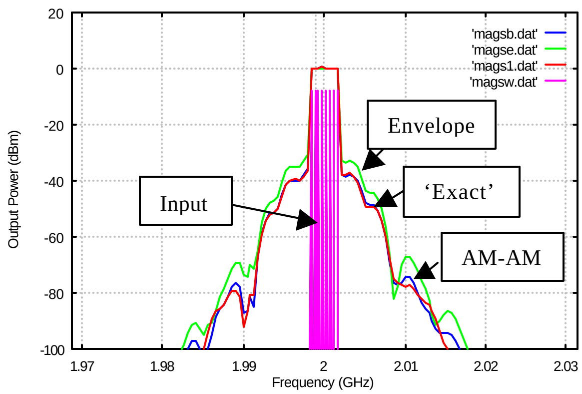

Fig. 5. Output Spectrum for 8-tone, Randomly-Phased Input Signal: Comparison between 'Exact' Results and Data from AM-AM and Envelope Characteristics

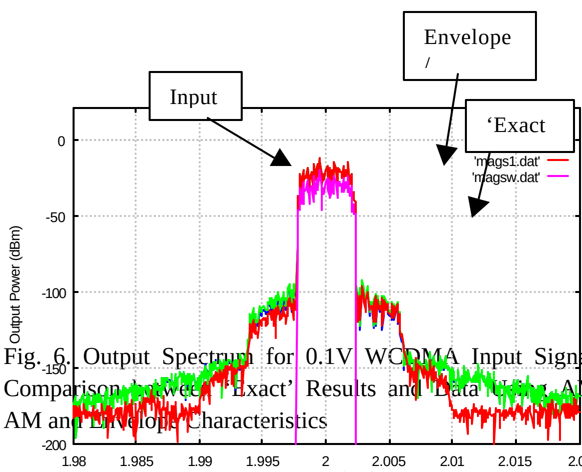

Fig. 6. Output Spectrum for 0.1V WCDMA Input Signal: Comparison between 'Exact' Results and Data Using AM-AM and Envelope Characteristics

A further concern in using 'narrowband' behavioral models is the extent of their validity with signals which are broadband or have asymmetric spectra around the center frequency. Fig. 7 shows an example of three WCDMA modulated carriers passed through the amplifier of Fig. 1. In this case the green curve is the result of the AM-AM model, and the red is again exact. It is clear that use of the behavioral model produces serious errors for this excitation condition.

'Exact' AM-

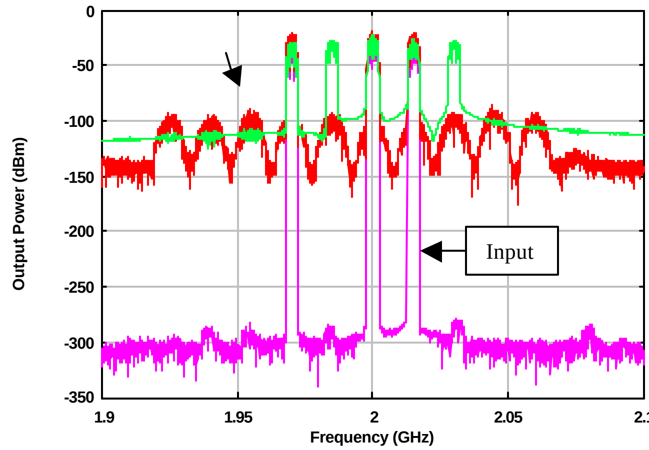

Fig. 7. Output Spectrum for Three WCDMA tones: Comparison between 'Exact' and AM-AM Behavioral Model.

V. CONCLUSION

A new state-space and convolution-based transient solver for high frequency systems has been introduced. The simulator allows very accurate simulations of non-linear distortion and has been used to assess the accuracy of different kinds of behavioral model. This work is continuing, but results to date show better results from AM-AM characteristics rather than Envelope, and indicate that narrowband models may produce significantly erroneous results in certain cases.

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