Nonlinear Models of Microwave Power Devices and Circuits

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***Abstract* — This paper presents an overview of activities on RF non-linear modeling of power devices and amplifiers throughout Europe.**

I. INTRODUCTION

The background of having an extensive modeling activity within the TARGET NoE [1] is the observation that in most papers, researchers show what they would like to show when they compare their model with measurements, which could mislead the reader when ignoring other significant measurements. Several efforts to validate and compare models in a systematic way were initiated [2]-[6], but those methodologies are not well-founded and incomplete. Based on this motivation, the development of a modeling validation and comparison framework is undertaken within TARGET.

To make this approach as general as possible, several modeling techniques on both the device and circuit level are taking part in this activity. Table 2 presents an overview of the transistor modeling expertise across the TARGET partners. Table 3 presents the corresponding overview of expertise on circuit-level modeling across the TARGET partners. Modeling approaches range from physical based methods ([14]-[16]), ([29]), equivalent circuit-based and empirical methods ([17]-[25]), ([30]-[32]) to behavioral modeling methods ([24]-[28]), ([33]-[34], [13]) for devices and circuits modeling, respectively.

In this paper, we pick-out three of these modeling techniques to present a flavor of the recent developments in this field. Sections II and III cover examples of transistor modeling techniques, i.e., equivalent circuit and behavioral modeling, while Section IV presents a case of behavioral amplifier modeling.

II. TRANSISTOR EQUIVALENT CIRCUIT MODELING

Due to the requirements imposed by the new communication systems, conventional electrical equivalent circuit modeling schemes must go further and should be able to describe accurately not only harmonic content but also IMD distortion, spectral re-growth (ACPR, NPR), sweet-spot evolution, thermal dependence and self-heating, LF dispersion, optical interaction, etc.

Successive differentiation of I/V and S-parameter measurements can lead [7] to erroneous derivations of the third order and cross derivatives which are responsible of the linearity of the device for highly linear and efficient power amplifier applications. One solution is to use continuous and derivable functions having well designed polynomial argument (e.g., the well known Angelov and Cobra models).

A second approach could be to modify in an intelligent manner any classical nonlinear model (e.g., Materka model) through the use of a kind of effective gate control voltage that assures continuity of the high order derivatives [8]. Fig.1 shows the behavior of the high order derivatives using this modification for a power FET. The evolution of the null of Gm3 in the high gain region will be a good candidate for the design of a highly linear high efficient amplifier in deep B operation.

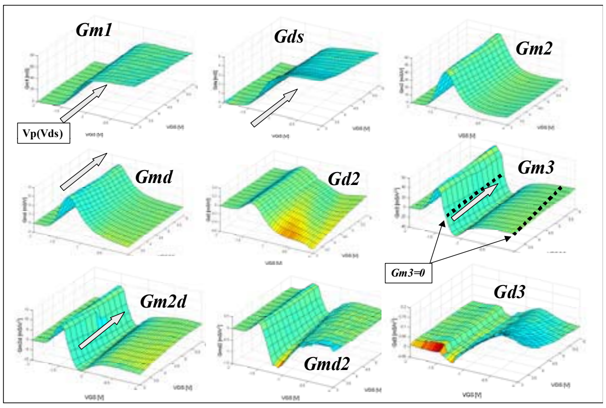

Fig.1 High Order Derivatives of a 6 mm power MESFET

The potentiality of these continuous and derivable models can be seen in Fig.2 for a QPSK driven medium power device, where the agreement between simulation and measurement validates these approaches.

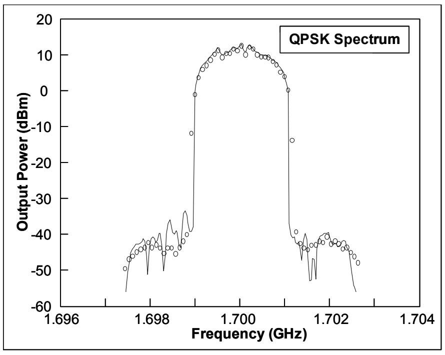

Fig.2 Output QPSK spectrum

III. Transistor Behavioral Modeling

The state-space behavioral modeling approach aims to identify a black-box dynamical description of a microwave device. The method is measurement based and makes use of large-signal vector measurements. The basic principle of the modeling method involves that the considered two-port microwave devices can be described by equations of the form:

$$
\begin{aligned}
I_1(t) &= f_1\left(V_1(t),V_2(t),\dot{V}_1(t),\dot{V}_2(t),\ddot{V}_1(t),\ddot{V}_2(t),\cdots,\dot{I}_1(t),\dot{I}_2(t),\cdots\right) \\
I_2(t) &= f_2\left(V_1(t),V_2(t),\dot{V}_1(t),\dot{V}_2(t),\ddot{V}_1(t),\ddot{V}_2(t),\cdots,\dot{I}_1(t),\dot{I}_2(t),\cdots\right)
\end{aligned} \qquad (1)
$$

with $I_1(t)$ and $I_2(t)$ the terminal currents, $V_1(t)$ and $V_2(t)$ the terminal voltages, and the superscript dots representing the (higher order) time derivatives. The objective of the modeling technique is to find the number of independent or state variables, and consequently to determine the functional relationships $f_1(.)$ and $f_2(.)$ by fitting the measured currents to the measured state variables.

This technique was first successfully applied to low-power devices, such as diodes, HEMTs, and amplifiers. In Ref. [9], we studied a SiGe HBT and found that the self-heating could not be neglected. We included the dissipated power as additional independent variable in the model description and, when using an artificial neural network as fitting function, the training error had reduced by a factor of ten. In Ref. [10], we built a model for GaN HEMTs in order to have a model that is suitable for PA designs. The model was constructed from load-pull measurements. To collect data near the optimal load in an efficient way, we combined passive and active load-pull in our measurement set-up. A passive tuner was used to apply a high load (which is an optimal load condition for these devices), and excursions from this position were realized using active injection. In this way, we obtained a model that is accurate when being evaluated at loads not part of the data set for model training.

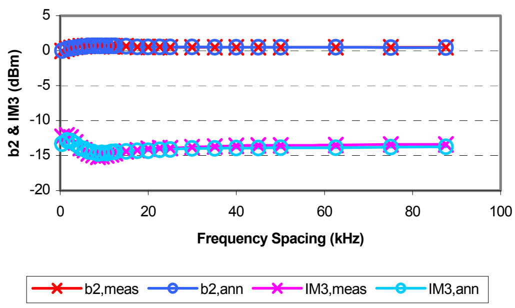

Fig. 3 Measured ('x') and state-space model simulated (circles) b_2 ($=P_{out}$) at f_1 (top) and b_2 at $2f_1$-f_0 (bottom) for a three-tone excitation around 3 GHz.

So far, this state-space modeling approach was based on single-tone measurements, which is in contrast to the actual signal types being present in telecommunication systems. Therefore, we adopted the modeling procedure to be able to deal with multi-sine excitations. It is known that device characteristics may vary as function of tone spacing due to slow-memory effects. To take this into account, the model equations (1) are expanded by adding independent variables that represent time lags related to the envelope period [11]. This extended formalism was applied to a HEMT device, and modeling results are compared to measurements in Fig. 3. We notice that the tone-spacing dependency is well predicted.

IV. Power Amplifier Behavioral Modeling

Behavioral modeling of PAs is widely accomplished on the basis of quasi-static AM/AM and AM/PM input/output characteristics, which are fine for narrow-band modulated signals. However, modern high-capacity multi-carrier digital radio links involve large signal bandwidths, and therefore PA models should also take into account the amplifier distortion due to both the large amplitude and the large bandwidth of the input signal.

A non-linear dynamic modeling approach based on a modified Volterra-like integral series expansion has been recently proposed [12]. According to this method, the in-band complex modulation envelope $b(t)$ of the output signal around an equivalent carrier frequency f_0, may be expressed as:

$$
\begin{aligned}
b(t) &= a(t)H\left(f_0,|a(t)|\right) + \int_0^{T_B} h_1(\tau_1)\cdot\left[a(t-\tau_1)-a(t)\right]\cdot e^{-j2\pi f_0\tau_1}\,d\tau_1 + \\
&+ \int_0^{T_B} g_1(\tau_1,f_0,|a(t)|)\cdot\left[a(t-\tau_1)-a(t)\right]\cdot e^{-j2\pi f_0\tau_1}\,d\tau_1 + \\
&+ a^2(t)\int_0^{T_B} g_2^*(\tau_1,f_0,|a(t)|)\cdot\left[a^*(t-\tau_1)-a^*(t)\right]\cdot e^{j2\pi f_0\tau_1}\,d\tau_1
\end{aligned} \qquad (2)
$$

Where $a(t)$ represents the input signal complex envelope. The function H in (2) describes the non-linear memoryless contribution in the PA envelope response, which corresponds to the quasi-static AM/AM-AM/PM characteristics. According to the more general approach [12], additional integral terms, extended over the finite *memory time* T_B of the system, describe both the linear and non-linear non-quasi-static dynamic (i.e., memory related) effects. More precisely, the first integral in (2) takes into account the purely-linear dynamic contribution, while the last two integral terms describe the non-linear memory effects due to the non-negligible bandwidth of the input signal, respectively. In the presence of a constant input envelope $a(t)$ (non-modulated carrier) or a very narrow-band signal, all the memory-dependent contributions vanish and the corresponding output is given by the first term only (classical approaches). Instead, in the presence of a wide-band modulated signal, the integrals in (2) become progressively more important as the bandwidth of $a(t)$ increases.

The model (2) was characterized and identified for a single-ended PHEMT amplifier operating at 2 GHz. More precisely, in order to validate the behavioral model, the actual measurements to be carried out for the amplifier characterization were numerically simulated at the device-level by using the commercial CAD tool ADS. Predictions in accordance with (2) were compared to results obtained on the basis of conventional quasi-static AM/AM-AM/PM characteristics and also to accurate circuit simulations using device-level models of the same amplifier. Some of the preliminary results presented in [13] are here also shown in Table 1.

Two Tone Test Output Spectrum		
Simulation	Tones	
	-50MHz	50MHz
AM/AM-AM/PM Behav. Mod.	10.8 dBm	10.8 dBm
Device-level Mod. (Circ. Sim.)	12.4 dBm	8.9 dBm
Nonlinear Dynamic Behav. Mod.	12.4 dBm	9.2 dBm

Table 1 – Intermodulation distortion prediction ([13]).

V. CONCLUSION

This overview demonstrates the diversity in modeling approaches and the high expertise of European research groups in the field of nonlinear microwave modeling.

ACKNOWLEDGEMENT

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Partners	Modeling Focus
TUWien	- Physical modeling of HEMT's, HBT's, and MOSFET's, with the simulation modes: DC, S-parameter, large-signal transient, and thermal interaction (2D and 3D).
NTUA [14]	- Device models based on electromagnetic simulations
Univ. Ferrara [15]	- Models for low-frequency dispersion: Back gating and equivalent voltage approaches. - Distributed models based on electromagnetic simulations
INT [16]	- Direct extraction based modeling techniques for FETs, with special attention to low-frequency dispersion effects, self-heating in case of high-power devices, e.g., GaN HEMTs, and scalability - Model parameters are physical based, such that model is attractive not only for circuit design engineers, but also for the scientists involved into the technology optimization
Univ. Cardiff [17]	- Table-based models employing single-tone large-signal measurements including harmonic load-pull, and two-tone large-signal measurements, including load-pull at IF frequencies
IEMN	- Equivalent circuit modeling using pulsed DC and S-par. meas., to be well correlated with devices' technology (small and large band gap devices)
IRCOM	- Modeling using pulsed large-signal measurements - Modeling of non-linear stability
LAAS [18]	- Low-frequency noise and high frequency noise modeling (with electrical small-signal parameters) used for process improvement and (non-)linear circuit design (narrow and wide band gap devices)
Chalmers Univ.[19]	- Empirical large-signal and thermal noise modeling of MOSFETs, HEMTs, and HBTs
Cantabria Univ. [20]	- Empirical and Neural based large-signal modeling of FETs, HEMTs with focus on IMD behavior from DC, S, Pulsed I/V and High Order Derivatives Measurements
IMST	- Equivalent circuit based modeling, with focus to power measurements
MIDRA [21]	- Nonlinear device models combining electrical, thermal and electromagnetic simulations
Univ. Malaga [22]	- Distributed and scalable models - Models paying special attention to: non-quasi-static effects
Univ. Vigo [23]	- Table-based non-quasi-static non-linear FET modeling from DC & S-parameter measurements up to 120 GHz, and from large signal waveform measurements - Small- and large-signal modeling of HBTs
Univ. Aveiro [24]	- Compact models supported by nonlinear equivalent circuits - Volterra series based models
K.U.Leuven [25]	- Equivalent circuit based modeling - State-space modeling using large-signal vector measurements
Univ. Bologna [26]	- Non-linear discrete-convolution models - General-purpose multi-bias parasitic identification
Tor Vergata [27]	- Device modeling using artificial neural networks, with special attention to the higher-order derivatives of the current
Univ. Limerick	- Device Instantaneous Fourier series and complex Bessel function series approximation models - Extraction of behavioral characteristics under specific system and signal configurations
Univ. Crete [28]	- Electro-thermal modeling for power transistors

Table 2: Overview of device-level modeling approaches at European Institutes.

Partners	Modeling Focus
TUWien	- Mixed mode analysis based on physical models and (external) compact models with the simulation modes: DC, S-parameter, large-signal transient, and thermal interaction (2D and 3D).
NTUA [29]	- Amplifier models making use of electromagnetic simulations
LAAS [30]	- Low-frequency noise modeling, phase noise modeling for non-linear low phase noise applications (MIC or MMIC VCOs, …) + low-noise amplifiers design
Chalmers Univ.	- Volterra-series based modeling for distortion and low frequency dispersion
Cantabria Univ. [31]	- Modeling of distortion and low-frequency dispersion by large-signal measurements. - Empirical large-signal modeling.
Univ. Crete [32]	- Electro-thermal modeling for amplifiers
INT	- Direct extraction based modeling techniques, with special attention to self-biasing, dynamic breakdown voltage, and possible deviations between optimum load conditions deduced from static measurements and dynamic ones. Also, thermal effects and packaging aspects. - Modeling using large-signal measurements.
Univ. Aveiro	- Volterra series based modeling
K.U.Leuven [33]	- Behavioral modeling using large-signal vector measurements
Univ. Cardiff	- Modeling using harmonic-load pull large-signal measurements
MIDRA [34]	- Modeling of distortion and low-frequency dispersion by large-signal measurements - Modeling of large-signal stability
Univ. Malaga	- Modeling developments related to harmonic-balance based simulation techniques
Tor Vergata	- Behavioral modeling using power measurements
Univ. Limerick	- Amplifier instantaneous Fourier series and complex Bessel function series approximation models - Extraction of behavioral characteristics under specific system and signal configurations
Univ. Bologna [13]	- Behavioral modeling by means of Volterra-like integral approaches

Table 3: Overview of circuit-level modeling approaches at European Institutes.