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Implementation of a Behavioral Model of SSPAs taking into account mismatches for efficient System Simulation of Modern AESA

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Abstract— **This paper presents a behavioral modeling approach for solid state power amplifiers (SSPAs) used in Radar applications. This model takes into account strong output loading impedance mismatch, with a VSWR (Voltage Standing Wave Ratio) equal to two. The proposed behavioral model, based on non-linear Scattering functions, is extracted from simple CW measurements or Harmonic Balance (HB) simulations. This model has been implemented in a general purpose system simulation environment, Scilab/Scicos, thanks to a toolbox dedicated to solving implicit problems. In this paper, the proposed behavioral model is extracted from HB simulation results of an S-band 20 Watt power amplifier. Our macromodeling methodology is validated by comparisons of circuit and behavioral model simulations under pulse signal excitation in the case of loading impedance mismatch.**

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Keywords- behavioral modeling; impedance mismatch; non-linear Scattering functions.

I. Introduction

Recently, the development of a new generation of radar, Active Electronically Scanned Array (AESA), has been very important and several European airborne AESA programmes were started [1]. Indeed, AESA have large advantages, like an extremely fast scanning rate or the ability to produce multiple agile beams. It appears that accurate AESA simulations, able to analyse each constitutive element, will permit the decrease of margins taken on components' specifications and thus these simulations will permit a cost reduction of such devices. Today, simulation tools used for this radar describe RF systems only in a unilateral way and without the necessary accuracy. Indeed, design constraints of AESA lead to significant load mismatches (up to VSWR=2) with varying phase in microwave chains that have a severe impact on the performance of the Power Amplifiers (PAs) and, following, on the overall Radar performances. That is the reason why the development of a powerful simulation tool requires an accurate model of a PA in order to quantify its impacts on Transmit/Receive (T/R) modules and then on emitted signal characteristics. Several behavioral models, black-box models, able to predict memory effects [2] [3] or thermal effects [4] were proposed in the past years. However, these models are unilateral and thus only dedicated to Data Flow simulators. More recently, efficient bilateral models were developed [5-7], derived from Scattering parameters. But these models imply that system simulators are able to solve implicit equations. In this paper, we propose a bilateral model and the use of a system environment: Scilab/Scicos coupled with to Modelica language, able to compute bilateral models. Using those coupled tools thus allows us to solve the signal processing issues encountered in Radar applications by taking into account real-world T/R models. This environment is therefore favourable for developing a simulation tool dedicated to radar applications.

In part II, we introduce the mathematical formalism, derived from Scattering parameters and the principle of extraction, based on simple measurements. Part III is dedicated to the model's implementation in Agilent Technologies' Advanced Design System (ADS) and its validation in frequency domain. The implementation in a time-domain system simulation environment is described in section IV. Results obtained in the time domain will be presented in section V and compared to circuit simulation in order to evaluate model capabilities under pulse excitation.

II. Model Theory

A. Principles

The amplifier is described thanks to non-linear Scattering functions, introduced by [5] and developed in [6]. In this paper, this formalism is simplified because we are making the assumption that an amplifier is considered to be a non-linear two-port circuit at the fundamental frequency without memory effects. It is defined by the following relationship:

$$\tilde{b}_1 = f_{NLi}\left(\tilde{a}_1, \tilde{a}_1^*, \tilde{a}_2, \tilde{a}_2^*\right) \tag{1}$$

In the condition of weak to moderate loading impedance mismatch, $\tilde{a}_2$ can be considered weak compared to $\tilde{a}_1$. Thus expanding equation-1 in a first-order Mc Laurin series leads to:

$$\begin{pmatrix}\tilde{b}_1\\ \tilde{b}_2\end{pmatrix}=\begin{pmatrix}S_{11}\left(|\tilde{a}_1|\right) & S_{12}\left(|\tilde{a}_1|\right) & S_{12}^{\Delta}\left(|\tilde{a}_1|\right)\\ S_{21}\left(|\tilde{a}_1|\right) & S_{22}\left(|\tilde{a}_1|\right) & S_{22}^{\Delta}\left(|\tilde{a}_1|\right)\end{pmatrix}\cdot\begin{pmatrix}\tilde{a}_1\\ \tilde{a}_2\\ \tilde{a}_2^*\end{pmatrix} \qquad (2)$$

where $S_{ij}\left(|\tilde{a}_1|\right)$ represent the non-linear Scattering functions that depend only on the incident wave's magnitude.

B. Extraction Procedure

The identification of non-linear Scattering functions is obvious because it requires a simple extraction: CW measurements at the PA's operating frequency.

Input/output currents and voltages are extracted from three different loading impedances as shown in Figure 1, either with measurements provided from a VNA (Vectorial Network Analyzer) load-pull setup [8], or HB simulations. Three load impedances located as shown in Figure 1 are sufficient to solve the 3x3 linear system of equations (2) at different input powers.

III. Model Implementation In Circuit Simulation Environment

The proposed model was applied to an S-band (2.1GHz) PA designed using InGaP/GaAS HBTs. The output stages include four (20x2x70 µm²) high voltage HBTs. The amplifier provides a maximum power of 42.7dBm (18.6 Watts) and a small signal gain of 11.6dB, as shown in Figure 2, and 63.8% PAE.

Extraction and validation of the PA's model have been realized in Agilent ADS in the frequency domain. The model has been implemented thanks to an FDD (Frequency-domain Defined Device) nonlinear block, likewise in [7] where the equation (2) defines the relationships between the input/output ports.

The dashed circle in Figure 1 represents the mismatch for VSWR equal to two and for all phases. The circle, triangle and rhombus plotted on the dotted lines, are load impedances chosen for evaluating the PA performances under mismatch conditions. Figure 3 and Figure 4 show the comparison between circuit-level simulation and the behavioral model at operating frequency, with the PA connected with its optimal load (50Ω) and the three different loads.

We notice that, when the load is equal to identification impedance, i.e. 50Ω, circuit and model responses are identical. For others loads which belong to the disc of VSWR=2, errors are almost null.

In the worst conditions $\Gamma = \frac{1}{3}\cdot\exp\left(j\cdot 3\pi/2\right)$ the gain difference between model and circuit simulation is close to 0.3dB at -4dB compression. These results show the model's abilities to predict the PA's behavior with a good accuracy for impedance mismatch until VSWR=2.

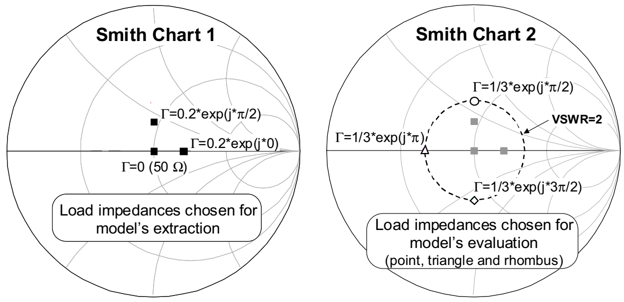

Figure 1. Load impedances chosen for model's extraction (Smith Chart 1) and model's validation (Smith chart 2).

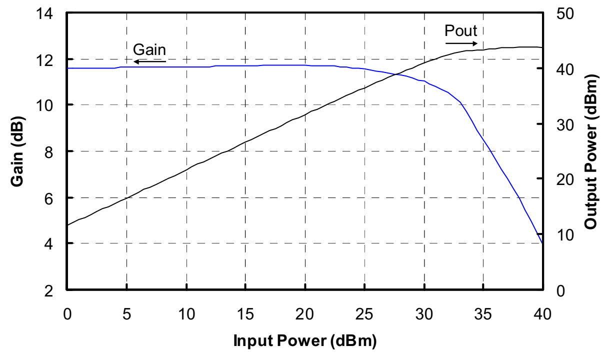

Figure 2. Graphs of power gain (dB) and output power (dBm) versus input power in dBm.

Moreover some experiments were performed up to VSWR=3 showing the capability of the model to take into account moderate VSWR at the price of a small degradation of performances. The bilateral model in the frequency domain is thus validated.

IV. Model Implementation In The System Simulation Environment

The system simulation environment chosen, Scilab/Scicos, is a open-source alternative to Matlab/Simulink. Scicos is a toolbox in the free scientific software package for numerical computations available in Scilab [9]. It is dedicated to the modeling and simulation of dynamic systems. Several RF simulation tools were implemented in Scicos, like numerical transmission chains [10], accurate unilateral black-box models [11] and a co-simulation interface circuit simulator and system simulator. The choice of the system simulator Scicos was driven by the capability to couple Scicos and Modelica, which is a language used for physical problems.

Indeed, bilateral modeling implies that a simulation environment can solve implicit systems, i.e. Differential Algebraic Equation (DAE) in the following form:

$$F\left(\dot{x}, x, \dot{y}, y, t\right) = 0 \qquad (3)$$

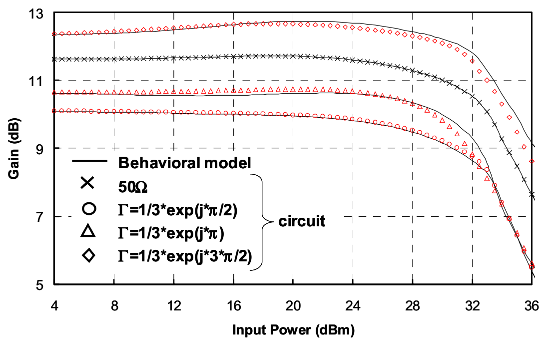

Figure 3. Simulation-based behavior model (solid lines) compared to circuit (cross, circle, triangles and rhombus). Gain in dB versus input (available ?) power in dBm for PA terminated with different loads.

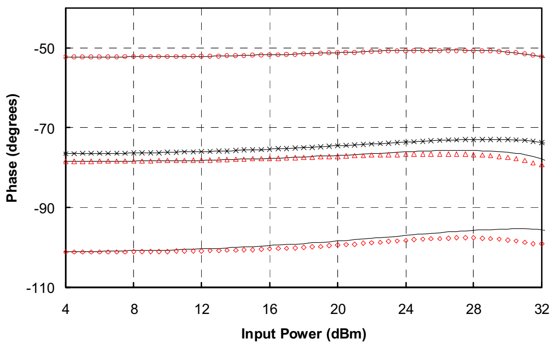

Figure 4. Simulation-based behavior model compared to circuit. AM-PM in degrees versus input power in dBm.

If we take into account the second equation given in (2), the real and imaginary parts of the output wave read:

$$\begin{cases} \tilde{b}_2^R(t) = S_{21}^R(|\tilde{a}_1|)\cdot\tilde{a}_1^R(t) - S_{21}^I(|\tilde{a}_1|)\cdot\tilde{a}_1^I(t) \\ \quad + S_{22}^R(|\tilde{a}_1|)\cdot\tilde{a}_2^R(t) - S_{22}^I(|\tilde{a}_1|)\cdot\tilde{a}_2^I(t) \\ \quad + S_{22}^{\Delta R}(|\tilde{a}_1|)\cdot\tilde{a}_2^R(t) + S_{22}^{\Delta I}(|\tilde{a}_1|)\cdot\tilde{a}_2^I(t) \\ \tilde{b}_2^I(t) = S_{21}^I(|\tilde{a}_1|)\cdot\tilde{a}_1^R(t) + S_{21}^R(|\tilde{a}_1|)\cdot\tilde{a}_1^I(t) \\ \quad + S_{22}^I(|\tilde{a}_1|)\cdot\tilde{a}_2^R(t) + S_{22}^R(|\tilde{a}_1|)\cdot\tilde{a}_2^I(t) \\ \quad + S_{22}^{\Delta I}(|\tilde{a}_1|)\cdot\tilde{a}_2^R(t) - S_{22}^{\Delta R}(|\tilde{a}_1|)\cdot\tilde{a}_2^I(t) \end{cases} \tag{4}$$

Equation (4) shows that the output wave is a non-linear function which depends on $\tilde{a}_1(t)$ and $\tilde{a}_2(t)$. Note that :

$$\tilde{a}_2(t) = \Gamma\cdot\tilde{b}_2(t) \tag{5}$$

where Γ represents the reflected coefficient of the PA's load. Thus, equations (4) and (5) lead us to write the output wave system as:

$$F(\tilde{a}_1, \tilde{b}_2, t) = 0 \tag{7}$$

In the case where non-linear Scattering functions depend on frequency, equation (7) takes the form of equation (3).

In order to simplify diagram construction, acausal (or implicit) blocks, i.e. blocks without input/output ports, are integrated in Scicos thanks to Modelica language [12]. Indeed, equations described in these kind of blocks have no input or output variables and that implies that acausal blocks have non-oriented ports.

Modelica is a freely available, object-oriented language for physical systems modeling, based on DAE systems [13]. Implicit blocks are written obviously in Modelica language but external functions can be called.

Note that, explicit and implicit blocks can be used simultaneously in the same Scicos diagram (in this case, DAE solver is chosen). The compilation of Scicos diagrams generates a Modelica netlist that describes the entire diagram in a temporary file. The Modelica compiler, called Modelicac, receives this netlist and generates an usable C program for Scicos.

V. SIMULATION RESULTS IN SCICOS ENVIRONMENT

A. *Scicos Simulation Principles*

Figure 5 shows the principle, used in Scicos, in order to simulate the PA's model in the time domain. Explicit blocks (Scicos Blocks) are dedicated to signal processing: generating excitation signals and processing simulation results. Implicit blocks (Modelica blocks) are dedicated to solving the bilateral physical system.

Modelica blocks are divided in two ways, real and imaginary parts. The block, named 'Gamma_LOAD', represents the VSWR. An interface permits the selection of its magnitude and phase.

B. *Simulation Results*

The comparison is made between circuit-level envelope simulation (ADS) and its system-level time domain simulation (Scicos) for different load impedances (VSWR=2). The PA is submitted to a signal pulse excitation at its operating frequency. The pulse magnitude is 30dBm, at 1dB compression and 10 microseconds length.

In Figure 6 and Figure 7, a comparison of the circuit simulation with the behavioral model gives an appreciation of good prediction of the model.

However, we note that after the pulse edge, a few microseconds are necessary to obtain the pulse magnitude steady-state. Non-linear memory effects involve these phenomena because the type of stimuli, pulse signal excitations, exhibits them.

Thus, these results permit us to conclude that the model is able to predict the PA's behavior with a high level of accuracy in the time domain.

The time cost of the model in Scicos is equivalent to an AM/AM – AM/PM simulation in a data flow simulator. Thus, we note the time reduction factor $\cong 150$ compares to the circuit simulation level.

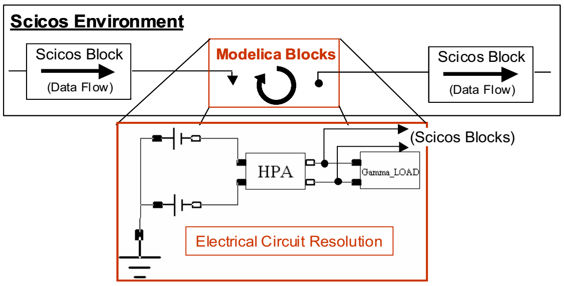

Figure 5. Figure 1 Principle simulation of physical system in Scicos environment

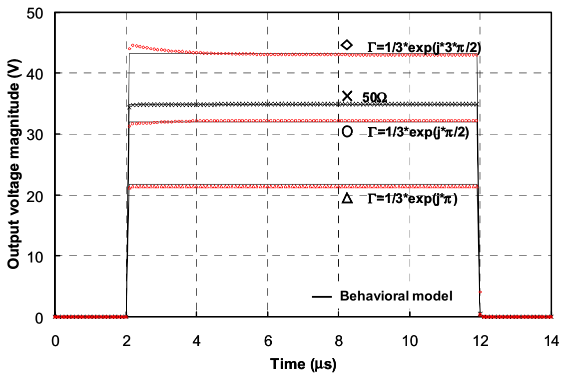

Figure 6. Simulation-based behavior model compared to circuit time response. Output voltage magnitude (V) versus time in micro-second for PA terminated with different loads.

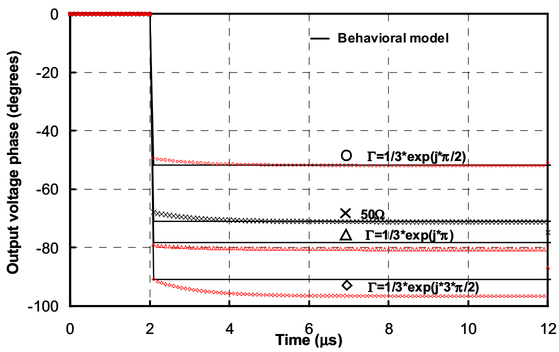

Figure 7. Simulation-based behavior model compared to circuit time response. Phase in degrees versus time in micro-second.

VI. Conclusions

The implementation of behavorial modeling based on non-linear Scattering functions in a high-level simulation tool, Scicos, has been proposed. It allows a good prediction of a PA's behavior in the case of a strong output loading impedances mismatch, i.e. VSWR=2. This proposed model can be extracted from simple CW measurements or HB simulations. For example, this model has been compared with circuit simulations in Agilent ADS.

Most of the system simulation tools are not able to solve "implicit" problems. Thanks to its DAE solver and through Modelica language, the Scicos environment may be considered a very efficient tool dedicated to RF system simulations.

We can also think that this kind of model can be very useful in establishing predictive performances in radar applications, particularly to quantify the impact of its operating on T/R modules.

Moreover, in a circuit environment, the PA's envelope simulation results in convergence failure when the PA's design is very complex. In this case, our model is a good substitute for the execution of this simulation.

Finally, this static model, implemented in Scicos, is a first step. Indeed, the model's abilities could be extended to non-linear memories and the prediction of thermal effects, where non-linear Scattering functions depend on the incident wave's magnitude, frequency spectrum and temperature.

References

[1] H. Hommel, H.P. Feldle, "Current Status of Airborne Active Phased Arrzy (AESA) Radar Systems and Future Trends," *34th European Microwave Conference*, Amsterdam, Netherlands 2004, pp. 1517-1520.

[2] A. Soury, E. Ngoya, J.M. Nebus, " A New Behavioral Model taking into account Nonlinear Memory Effects and Transient Behaviors in Wideband SSPAs," *IEEE MTT-S International Microwave Symposium Digest*-June, 2002, pp. 853-856.

[3] C. Maziere, A. Soury, E. Ngoya, J.M. Nebus, " A system level model of Solid State Amplifiers with memory based on a non linear feedback loop principle," *35th European Microwave Conference*, Paris, France 2005.

[4] S. Boumaiza, J. Gauthier, F.M. Ghannouchi," Dynamic Electro-thermal Behavioral for RF Power Amplifiers," *IEEE MTT-S International Microwave Symposium Digest*-June, 2003, pp 351-354.

[5] J. Verspecht, "Scattering Functions for Nonlinear Behavioral Modeling in the Frequency Domain," Fundamentals of Nonlinear Behavioral Modeling: Foundations and Applications Workshop, *IEEE MTT-S International Microwave Symposium*-June, 2003.

[6] A. Soury, E. Ngoya, J. Rousset, "Behavioral modeling of RF and microwave circuit blocs for hierarchical simulation of modern transceivers," *IEEE MTT-S International Microwave Symposium Digest*-June, 2005, pp.978-981.

[7] D.E. Root, J. Verspecht, D. Sharrit, J. Wood, A. Cognata, "Broad-Band Poly-Harmonic Distortion (PHD) Behavioral Models From Fast Automated Simulations and Large-Signal Vectorial Network Measurements," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, n°11, pp. 3656–3664, Nov. 2005.

[8] T. Reveyrand, T. Gasseling, D. Barataud, S. Mons, J-M. Nebus, "A Smart Load-Pull Method to Safely Reach Optimal Matching Impedances of Power Transistors," *IEEE MTT-S International Microwave Symposium Digest,* June 2007, pp.1489-1492.

[9] R. Nikouhah, S. Steer, "A Dynamic System Builder and Simulator," in *User's Guide – Version 1.0.* [Online]. Available: http://www.inria.fr/rrrt/rt-0207.html.

[10] A. Layec, A. Bennadji, J.C. Nallatamby, R. Quéré, E. Ngoya, "Modeling of a Communication Chain Components & Principles of Simulation in the Scilab/Scicos environment," *Proceeding of the 2005 IEEE Cnference on Control Applications*, Toronto, Canada, August 28-31, 2005.

[11] A. Bennadji, A. Layec, A. Soury, A. Mallet, E. Ngoya, R. Quéré, "Modeling of a communication chain with implementation of a Volterra power amplifier model for efficient system level simulation," *8th European Conference on Wireless Technology*, Paris, France 2005.

[12] M. Nadjafi, S. Furic, R. Nikouhah, "SCICOS: a general purpose modelling ans simulation environment," *Proceeding of the 4th International Modelica Conference*, Hambourg, March 7-8, 2005.

[13] The Modelica website [Online]. Available: http://www.Modelica.org