Behavioral Model of Solid State Power Amplifiers (SSPAs) for Agile Antennas Application

Georges ZAKKA EL NASHEF[1], François TORRES[1], Tibault REVEYRAND[1], Sébastien MONS[1], Edouard N'GOYA[1], Thierry MONEDIERE[1], Raymond QUERE[1].

1 XLIM – C2S2/OSA departments UMR CNRS n°6172

University of Limoges, 87060 Limoges France Cedex

Email: georges.zakka-el-nashef@xlim.fr

Abstract — **The complexity of modern telecommunication systems requires increasingly important needs for modeling and rigorous analysis. Thus, it is more and more required to predict the performances of power amplifiers (PAs) on the Tx-Rx chains. This paper focuses on behavioral modeling approach for a PAs used in agile antennas application. This approach of active antennas can take into account the interactions between the nonlinear circuits (i.e. PAs) and electromagnetic (i.e. antennas): the matching impedances for each antenna of a specified array are calculated from rigorous electromagnetic analysis, then those calculated matching impedances are used instead of the real antennas to define the load impedances (Zload) of the active circuits (PAs), in order to optimize the overall performances.**

I. Introduction

The interest in design and technological development of active phased array antennas devices has significantly risen. Such antennas may take place in avionic applications, in satellite communication, surveillance radars and many other application fields that should emerge in the next future. In order to study correctly the interactions between the PAs and the antennas, it requires efficient simultaneous modeling and optimization of electromagnetic and circuit issues. In the framework of an agile antennas application, the feeding between antennas and PAs (i.e. the pointing direction) is controlled by modifying the weights (phases and magnitudes) of the global system. This paper focuses particularly on the problem of mismatching between passive (antennas) and active (PAs) elements. Indeed, this mismatching can modify the performance of the PA in term of gain (AMAM) and phase (AMPM). Consequently, the necessary weights for the array (antenna) in a given pointing direction will be also modified once applied to the PA, degrading the array efficiency and its radiation performance [1]. Therefore, it is necessary to develop a powerful simulation tool that requires an accurate behavioral model of the PA in order to quantify all these interaction phenomena (i.e. mismatching) and impacts. Before clarifying the PA model, a technique was used to determine the matching impedances (≠50Ω) of each element of the array according to the frequency and the pointing angle [2], and this without any complex electromagnetic calculation. This technique takes into account the mutual coupling effect between array elements (antennas) and calculates the necessary weights in order to obtain an optimum radiation pattern. This technique permits also to study the impact of mutual coupling between antennas. Then the calculated matching impedances are used as load impedances of the PA. This will let us study the impact of mismatching and frequency on the global performance of the system. For this purpose, a non-linear model is extracted from simple CW measurements of the PA (Nextec-RF NB00422).

Finally, the active circuit model is implemented in Agilent Advanced Design System (ADS), where it will be validated for different loading impedances, up to VSWR=3 (Voltage Standing Wave Ratio).

II. Active Circuit Model Theory and Description

Power amplifiers are modeled thanks to nonlinear scattering functions [3] that consist in defining a nonlinear relation for the [S] parameters:

$$\tilde{b}_i = \left[S_{ij}\right]_{Non-Linear} \bullet \tilde{a}_i \qquad (1)$$

where $\tilde{a}_i$ and $\tilde{b}_i$ are respectively the incident and reflected power waves at the two ports, and $[Sij]_{Nonlinear}$ are the nonlinear scattering functions. In order to establish a bilateral model, the memory effects were not included, which means we are limited to the operating frequency (8.2 GHz). Moreover, this approach is efficient only for VSWR < 3 since the modeling technique was limited to Taylor first order expansion. Therefore we can deduce from equation (1):

$$\tilde{b}_i = f_{NL}\left\{\Re e(\tilde{a}_1), \Im m(\tilde{a}_1), \Re e(\tilde{a}_2), \Im m(\tilde{a}_2)\right\} \qquad (2)$$

In order to simplify the model, we placed the PA under weak conditions of impedance mismatch, and thus $\tilde{a}_2$ can be considered weak compared to $\tilde{a}_1$. And if $\tilde{a}_1$ is considered as the reference wave, the development of Taylor series limited to the first order enables us to write equation (2) as follows [4]-[7]:

$$\begin{pmatrix}\tilde{b}_1\\ \tilde{b}_2\end{pmatrix} = \begin{pmatrix}S_{11}(|\tilde{a}_1|) & S_{12}(|\tilde{a}_1|)\\ S_{21}(|\tilde{a}_1|) & S_{22}(|\tilde{a}_1|)\end{pmatrix}\cdot\begin{pmatrix}\tilde{a}_1\\ \tilde{a}_2\end{pmatrix} + \begin{pmatrix}0 & S_{12}^{\Delta}(|\tilde{a}_1|)\\ 0 & S_{22}^{\Delta}(|\tilde{a}_1|)\end{pmatrix}\cdot\begin{pmatrix}\tilde{a}_1^*\\ \tilde{a}_2^*\end{pmatrix} \qquad (3)$$

where $S_{ij}(|\tilde{a}_1|)$ are the nonlinear scattering functions that depend only on the incident waves magnitude. Thus, equation (3) ensures the validity of nonlinear part of the bilateral model at operating frequency, when $a_2 << a_1$. It can be seen as an AMAM – AMPM bilateral behavioral model, its validity is being limited to VSWR < 3. In order to solve (3), a load-pull characterization of our PA has been carried out. The measurement setup is described in [8], which enables power amplifier characterization driven by radio frequency modulated signals. Incident (a_i) and reflected (b_i) waves at both ports of the device under test (PA) can be measured in a conventional load pull environment.

$$\begin{pmatrix} S_{11} \\ S_{12} \\ S_{12}^{\Delta} \\ S_{21} \\ S_{22} \\ S_{22}^{\Delta} \end{pmatrix} = \begin{pmatrix} \tilde{a}_{11} & \tilde{a}_{21} & \tilde{a}_{21}^{*} & 0 & 0 & 0 \\ 0 & 0 & 0 & \tilde{a}_{11} & \tilde{a}_{21} & \tilde{a}_{21}^{*} \\ \tilde{a}_{12} & \tilde{a}_{22} & \tilde{a}_{22}^{*} & 0 & 0 & 0 \\ 0 & 0 & 0 & \tilde{a}_{12} & \tilde{a}_{22} & \tilde{a}_{22}^{*} \\ \tilde{a}_{13} & \tilde{a}_{23} & \tilde{a}_{23}^{*} & 0 & 0 & 0 \\ 0 & 0 & 0 & \tilde{a}_{13} & \tilde{a}_{23} & \tilde{a}_{23}^{*} \end{pmatrix}^{-1} \cdot \begin{pmatrix} \tilde{b}_{11} \\ \tilde{b}_{21} \\ \tilde{b}_{12} \\ \tilde{b}_{22} \\ \tilde{b}_{13} \\ \tilde{b}_{23} \end{pmatrix} \qquad (4)$$

where $\tilde{a}_{ij}$ and $\tilde{b}_{ij}$ are the incident and reflected measured waves when PA is loaded with a random Zload.

III. Extraction Procedure, Implementation and Numerical Validation

A. *Extraction and Implementation Procedures*

The identification of the non linear scattering functions in equation (3) simply requires CW measurements at the PA operating frequency. Coefficients ($S_{ij}(|\tilde{a}_1|)$) are extracted for low level signal excitation (i.e. $\tilde{a}_2$ =0) from three different loading impedances (Fig. 1) which must have an orthogonal position (on Smith chart) and correspond to a low mismatching (i.e. VSWR=1.2) in order to stabilize the system as well as possible [9].

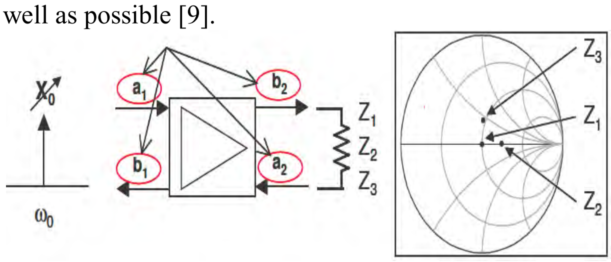

Fig. 1: Load impedances chosen to extract and validate the model

Three load impedances are sufficient to solve the 3x3 linear system of equation (3) for different input powers. The first measured impedance will be the reference; the other two measured impedances are located on a constant VSWR circle. The VSWR is between 1.2 and 1.6, and these values are chosen in order to have a large surface covered by those three impedances, but not large enough to make the system resolution unstable, so a compromise has to be done.

Those measured waves in equation (4) enable us to extract our nonlinear scattering functions S_{ij} which will lead us to establish a "black Box" circuit model implemented into ADS (Agilent). The annotation "black box" refers to the fact that no knowledge is used nor required concerning the internal circuitry of the device under test (PA). The model has been implemented thanks to an FDD (Frequency-domain Defined Device) nonlinear block. Validations are performed by comparisons of PA measurements and model response in the case of loading impedance mismatch.

B. *Numerical Validation*

The characterized device is an 8-14 GHz 27dBm PA from NEX-TEC RF, and no electrical model is provided by the manufacturer. The first validation concerns fundamental AMAM and AMPM characteristics, where they are compared in (Fig. 2 and Fig. 3) respectively for the three extracted impedances (Z_1=49.1-j·4.9, Z_2=38.8-j·18.6, Z_3=67.7-j·19.4), which is enough to verify the validity at extraction points.

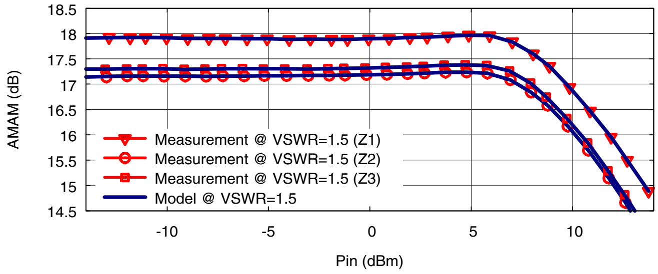

Fig. 2: Fundamental gain compression (AMAM) vs. input power for all extracted impedances (Z1=49.1-j·4.9, Z2=38.8-j·18.6, Z3=67.7-j·19.4). Model (lines) compared to load pull measurement (symbols).

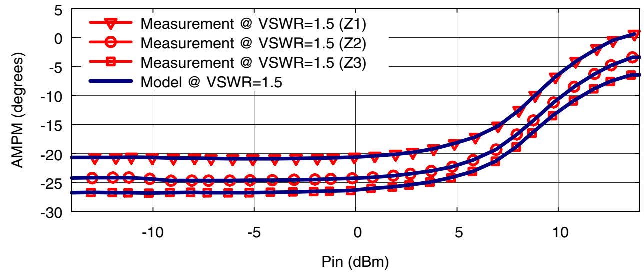

Fig. 3: Fundamental phase variation (AMPM) vs. input power for all extracted impedances (Z1=49.1-j·4.9, Z2=38.8-j·18.6, Z3=67.7-j·19.4). Model (lines) compared to load pull measurement (symbols).

We can notice a good agreement between the model and measurement in Fig. 2 and Fig. 3. Moreover, other experiments on different loads within the VSWR=2 and VSWR=3 circles were performed. Fig. 4 to Fig. 7 present the fundamental AMAM and AMPM for some impedances on each VSWR circle, showing the prediction ability of the PA model to take into account moderate VSWR at the price of a small degradation of performances.

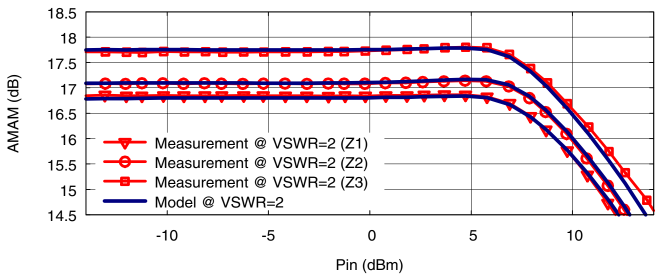

Fig. 4: Fundamental gain compression (AMAM) vs. input power for several impedances (Z1=28.5-j·19.6, Z2=101.9-j·7.6, Z3=37.4+j·21.1) on VSWR=2 circle. Model (lines) compared to load pull measurement (symbols).

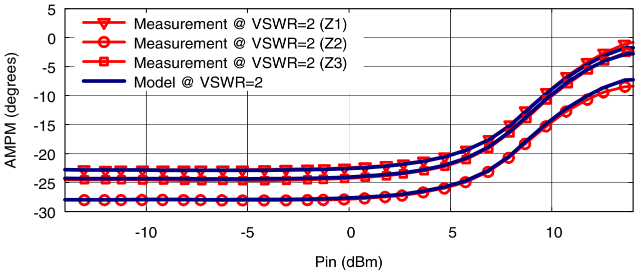

Fig. 5: Fundamental phase variation (AMPM) vs. input power for several impedances (Z1=28.5-j·19.6, Z2=101.9-j·7.6, Z3=37.4+j·21.1) on VSWR=2 circle. Model (lines) compared to load pull measurement (symbols).

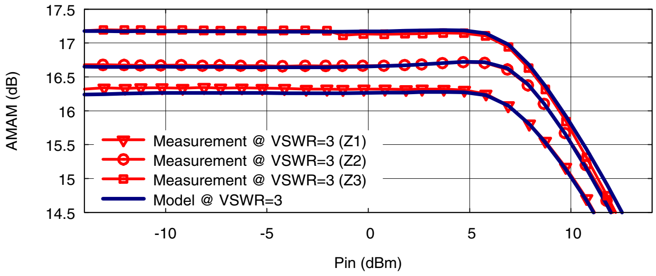

Fig. 6: Fundamental gain compression (AMAM) vs. input power for several impedances (Z1=16.5-j·7.5, Z2=111.6+j·61.9, Z3=21.8+j·21.7) on VSWR=3 circle. Model (lines) compared to load pull measurement (symbols).

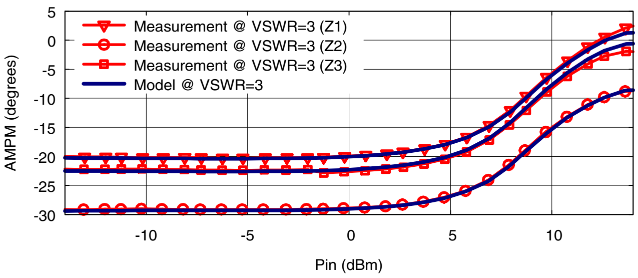

Fig. 7: Fundamental phase variation (AMPM) vs. input power for several impedances (Z1=16.5-j·7.5, Z2=111.6+j·61.9, Z3=21.8+j·21.7) on VSWR=3 circle. Model (lines) compared to load pull measurement (symbols).

Fig. 4 to Fig. 7 show negligible errors that are almost null between the model and the measurements, where output impedances of the device under test belong to the discs of VSWR=2 and 3. We noticed that, when the tested load impedance is not in the covered surface of the extracted impedances (Z3 on VSWR=3 (Fig. 7) is the worst example), the AMAM difference between model and measurement is close to 0.1dB, and for the AMPM the difference reaches 1 degree between the model and the measurement. These results demonstrate the model capacities for predicting PA behavior up to VSWR=3.

Otherwise, we expanded the VSWR boundaries up to VSWR=4, in order to see the prediction limitations of this behavioral model limited to the first order of Taylor development series. Fig. 8 and Fig. 9 show the AMAM and AMPM for some impedances on VSWR=4 circle.

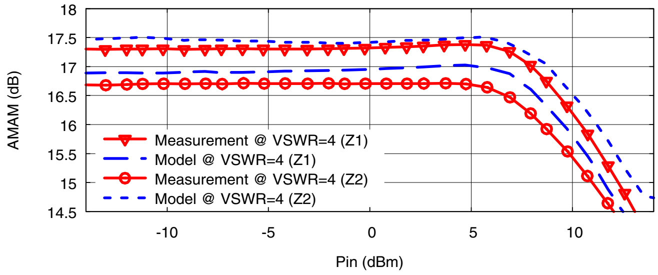

Fig. 8: Fundamental gain compression (AMAM) vs. input power for several impedances (Z1=40.2+j·63.9, Z2=21.5+j·35.8) on VSWR=4 circle. Model (lines) compared to load pull measurement (symbols).

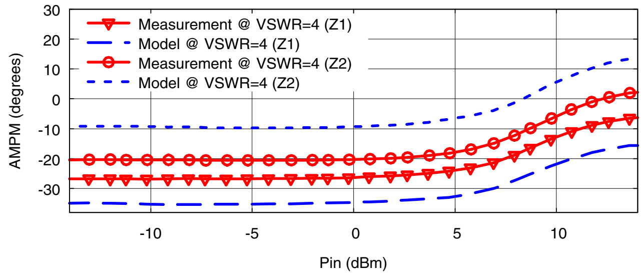

Fig. 9: Fundamental phase variation (AMPM) vs. input power for several impedances (Z1=40.2+j·63.9, Z2=21.5+j·35.8) on VSWR=4 circle. Model (lines) compared to load pull measurement (symbols).

Fig. 8 and Fig. 9 show a small degradation obtained on AMPM and AMAM responses due to the limitation of Taylor series expansion (first order). We can observe a maximum of 0.4dB difference on AMAM response, and 8 degrees maximum on AMPM response.

Moreover, some other experiments were performed using the calculated impedances obtained from rigorous electromagnetic analysis that characterize an array antenna, in order to study the amplifiers behavior in their presence (Fig. 10).

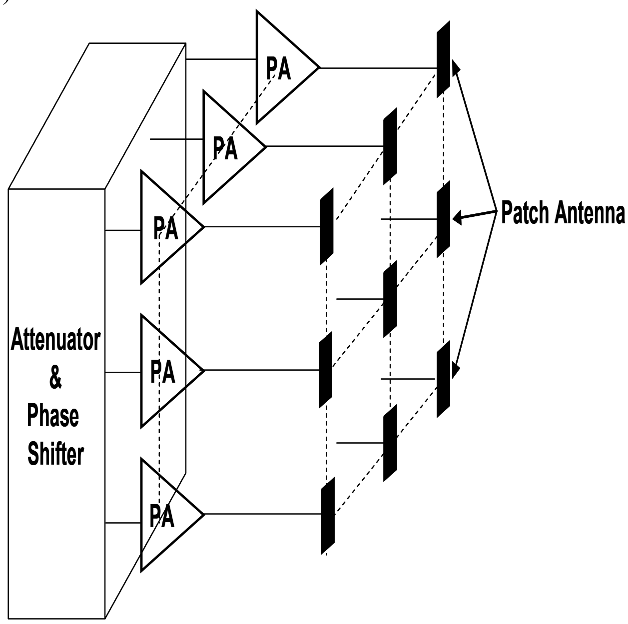

Fig. 10: Synoptic of an Active Antenna.

Fig. 11 and Fig. 12 present the fundamental AMAM and AMPM response in the presence of some calculated impedances (antennas). Those calculated impedances correspond to high pointing angles (i.e. +35°, +40° and -35°) where their VSWR is between 2 and 3.

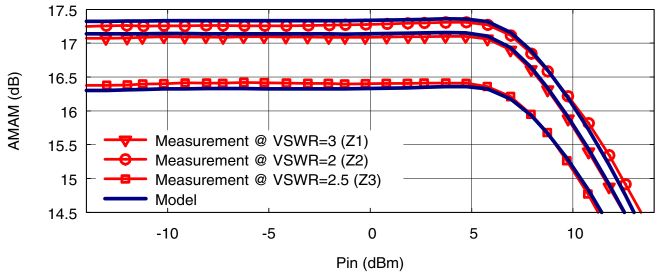

Fig. 11: Fundamental gain compression (AMAM) vs. input power for several calculated impedances (Z1=20.6+j·12.7 (-35°), Z2=26.2-j·0.004 (+40°), Z3=21.6+j·18.8 (+35°)) using the electromagnetic analysis. Model (lines) compared to load pull measurement (symbols).

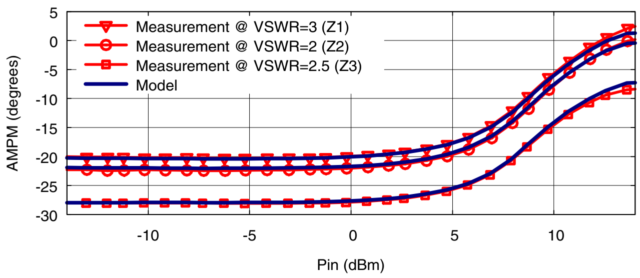

Fig. 12: Fundamental phase variation (AMPM) vs. input power for several calculated impedances (Z1=20.6+j·12.7 (-35°), Z2=26.2-j·0.004 (+40°), Z3=21.6+j·18.8 (+35°)) using the electromagnetic analysis. Model (lines) compared to load pull measurement (symbols).

Fig. 11 and Fig. 12 show almost identical results (0.5% to 1% error). It demonstrates the prediction ability of the PAs model at system level for the amplifier's behavior subject to significant load mismatches (VSWR up to 3), as it may occur in agile antennas applications.

IV. Conclusions

This paper has presented a non linear behavioral model, based on nonlinear scattering functions. Those measured nonlinear scattering parameters have been used to identify an accurate model taking into account the output mismatch impedance (VSWR up to 3). Then this model has been implemented in ADS tool (Agilent). This approach uses the large signal S parameter formalism truncated at a single frequency. This model will be very useful in establishing predictive performances in radar applications, base station (portable phones) and many other fields. We look forward to expand the Taylor Series development into the second order, which will enable us to take into consideration strong output loading mismatches (i.e. VSWR up to 4). Also, our perspective is to develop a scattering parameter approach combining the load mismatch model including the memory effects (dynamic frequency).

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