

High-frequency nonlinear amplifier model for the efficient evaluation of inband distortion under nonlinear load-pull conditions

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Abstract

Designing complex analog systems needs different abstraction levels to reduce the overall complexity. The required level of abstraction depends on the accuracy and the purpose of the model. High-frequency amplifier models can vary from simple transfer functions for efficient bit-error-rate analysis up to detailed transistor level descriptions for accurate load-pull prediction. This paper introduces a nonlinear black-box model for high-frequency amplifiers. It extends the linear S-parameter representation to enable both efficient system-level simulations and load-pull prediction. Both are demonstrated on the measurements of a high-frequency amplifier excited using a WLAN - OFDM modulation.

1. Introduction

Complex analog system design requires different levels of abstraction. A top-down design starts with behavior models to determine the most important characteristics and gradually refines each subsystem to increase the accuracy. A bottom-up design starts with a detailed specification and determines a behavior model. The latter requires the extraction of behavior models out of either measurements or simulations.

Different nonlinear amplifier models trade-off accuracy with complexity during design. Commonly used models for high-frequency amplifiers are

- linear transfer functions to represent the overall frequency dependent behavior at system-level [1];
- linear S-parameters to include the influence of impedance mismatches [2];
- amplitude-amplitude (AM-AM) and amplitude-phase (AM-PM) compression characteristics to predict the impact of amplitude compression [1];
- black-box nonlinear models to predict the nonlinear distortion using Volterra representations [3] and neural networks [4];
- transistor level simulations to predict the response as accurately as possible.

System-level trade-offs impose contradicting constraints. On the one hand, accuracy is highly important to determine the impact of impedance mismatches, inband nonlinear distortion and - possibly nonlinear - load pull [5]. On the other hand, simulation efficiency is important to

enable Bit-Error-Rate (BER) simulations of a complete transceiver front-end [1].

This paper introduces a behavior model for high-frequency amplifiers that predicts the inband nonlinear distortion under various load conditions and that can be evaluated efficiently. Section 2 introduces the behavior nonlinear model. The different assumptions are motivated and discussed to provide a deeper insight into the applicability, the strength and the weakness of the model. Section 3 describes how to cascade the behavior models and shows its usefulness during analysis. Section 4 demonstrates efficient system-level simulations using the behavior model. Section 5 compares the presented model with measurements of a commercial high-frequency amplifier excited using a WLAN - OFDM excitation.

2. The behavior model

The behavior model is constructed to fulfill the following constraints.

1. It boils down to a classical linear S-parameter representation when modeling linear systems.
2. It predicts the inband nonlinear distortion and is therefore limited to the nonlinear behavior of the device around the modulation carrier at frequency f_c . Hence, the harmonics at $2f_c, 3f_c, \dots$ are not considered.
3. It describes AM-AM and AM-PM compression characteristics. The nonlinear characteristics therefore depend on the instantaneous amplitude of the input signal [1].
4. It predicts the load-pull characteristics - e.g. constant gain circles - accurately [5].
5. It can be simulated efficiently during system-level simulations.

The first four constraints impose that the model be written as a generalized S-parameter matrix where all the S-parameters depend on the instantaneous amplitude of the inputs a_1 and a_2 :

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11}(|a_1|, |a_2|) & S_{12}(|a_1|, |a_2|) \\ S_{21}(|a_1|, |a_2|) & S_{22}(|a_1|, |a_2|) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}. \quad (1)$$

The dependency on the instantaneous amplitudes $|a_1|$ and $|a_2|$ is sufficient to predict the AM-AM and AM-PM characteristics and the load-pull characteristics.

Efficient system-level simulations can be obtained by the removal of linear feedback loops [6]. The linear feedback loop generated by the output of a device can be removed if the load-pull characteristics can be computed explicitly. This removal is possible if the model is linear in the output signal. The model is therefore expressed linearly in the signal a_2 and its complex conjugate a_2^* :

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11}(|a_1|) & S_{12}(|a_1|) & S_{12}^*(|a_1|) \\ S_{21}(|a_1|) & S_{22}(|a_1|) & S_{22}^*(|a_1|) \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_2^* \end{bmatrix}. \quad (2)$$

The contributions described by S_{12}^* and S_{22}^* are introduced from nonlinear system theory point of view. Inband nonlinear contributions around the carrier can be generated through third order nonlinear distortion such as $a_1(f)a_1(f)a_2(-f)$ [3]. This expression explains the linearity in both a_2 and a_2^* .

3. Cascading the model

The impact of the output impedance can be eliminated explicitly if the output impedance behaves linearly. A linear output impedance satisfies

$$a_2 = \Gamma b_2, \quad (3)$$

with Γ the reflection factor of the load impedance. As a consequence, the input wave a_1 and the output wave b_2 satisfy

$$\alpha + \beta b_2 + \gamma b_2^* = 0 \quad (4)$$

with

$$\begin{aligned} \alpha &= S_{21}(|a_1|)a_1 \\ \beta &= S_{22}(|a_1|)\Gamma - 1 \\ \gamma &= S_{22}^*(|a_1|)\Gamma^* \end{aligned} \quad (5)$$

This equation can be solved using the real and imaginary components of the a_1 and b_2 . Therefore rewrite the equation as

$$\begin{bmatrix} \alpha_r \\ \alpha_i \end{bmatrix} + \begin{bmatrix} (\beta_r + \gamma_r) & (\gamma_i - \beta_i) \\ (\beta_i + \gamma_i) & (\beta_r - \gamma_r) \end{bmatrix} \begin{bmatrix} b_{2r} \\ b_{2i} \end{bmatrix} = 0, \quad (6)$$

where \cdot_r and \cdot_i represent the real and imaginary parts respectively. Solving this set of equations results into

$$\begin{bmatrix} b_{2r} \\ b_{2i} \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} (\beta_r - \gamma_r) & (\beta_i - \gamma_i) \\ (-\beta_i - \gamma_i) & (\beta_r + \gamma_r) \end{bmatrix} \begin{bmatrix} \alpha_r \\ \alpha_i \end{bmatrix}, \quad (7)$$

with $\Delta = |\beta|^2 - |\gamma|^2$. The matrix obtained by combining Equations (4) and (7) only depends on the magnitude of the input signal $|a_1|$. The resulting equation enables AM-AM and AM-PM compression characteristics analysis under various load-pull conditions.

4. Efficient system-level simulations

Efficient system-level simulations are obtained when

- eliminating implicit expressions that require iterative solvers by eliminating feedback loops;
- evaluating the model expressions efficiently.

Both enable the use of explicit expressions and vectorized implementations.

4.1. Elimination of implicit expressions

Feedback loops are introduced at both the input and the output by the impedance mismatches. The elimination of the feedback loop at the output of the amplifier is done by the results of section 3. The resulting transfer characteristics only depend on the instantaneous amplitude $|a_1|$ and can be computed off-line. The elimination of the feedback loop at the input requires additional constraints since all model parameters depend - nonlinearly - on the instantaneous amplitude $|a_1|$. Explicit elimination is possible if $S_{11}(|a_1|)$ is independent of $|a_1|$ and if both $S_{12}(|a_1|)$ and $S_{12}^*(|a_1|)$ are negligible. This assumption puts a stringent condition on $S_{12}(|a_1|)$ and $S_{12}^*(|a_1|)$. Approximating the input feedback behavior with its linear behavior is an alternative approach. This linear behavior can be predicted by a purely linear analysis. It gives good approximations for practical circuits due to the overall linear behavior of the devices.

4.2. Efficient evaluation

The efficient evaluation of the model can be done using a table-based or a model-based approach. The evaluation efficiency of both are compared in this section.

A table-based approach requires an interpolation scheme. Such interpolation demands the extraction of the interpolation values first, followed by the interpolation itself. A possible interpolation is a cubic interpolation. The interpolation requires a small search algorithm and some third order nonlinear operation for each point. A model-based approach uses a global model to determine the response of the system. A single nonlinear function needs to be evaluated and no additional search algorithm is required.

To determine which technique is the most efficient, a nonlinear rational model is estimated to predict the nonlinear characteristics. A rational model is preferred over a polynomial model since the former describes saturating characteristics more easily: Polynomials always tend to infinity when the arguments tend to infinity.

The matrix elements of (2) can all be approximated by a rational model

$$\sum_i n_i |a_1|^i / \sum_j d_j |a_1|^j \quad (8)$$

where n_i and d_j represent the complex valued coefficients of respectively the numerator and the denominator. A Total Least Squares (TLS) [7] approach is used to estimate the complex coefficients. Equation (8) is therefore rewritten as

$$\sum_i n_i |a(k)|^i - \sum_j d_j f(|a(k)|) |a(k)|^j = 0 \quad (9)$$

where the index k represents the running index over the K measurements. Equation (9) is rewritten as the matrix equation $AP = 0$ with the parameter vector

$$P^T = [n_0 \ n_1 \ n_2 \ \dots \ d_0 \ d_1 \ d_2 \ \dots] \quad (10)$$

and the matrix

$$A^T = \begin{bmatrix} 1 & \dots & 1 \\ |a(1)| & & |a(K)| \\ |a(1)|^2 & & |a(K)|^2 \\ \dots & \dots & \dots \\ -f(|a(1)|) & & -f(|a(K)|) \\ -f(|a(1)|)|a(1)| & & -f(|a(K)|)|a(K)| \\ -f(|a(1)|)|a(1)|^2 & & -f(|a(K)|)|a(K)|^2 \\ \dots & \dots & \dots \end{bmatrix}. \quad (11)$$

The total least squares solution for the parameter vector P is then given by the column vector of the right unitary matrix of the singular value decomposition that corresponds with the smallest singular value [7].

Experimental results illustrate that low order rational models (order 2 to 4) are sufficient to describe the different transfer functions. The number of floating point operations for a given order N can be estimated as follows:

- 3 flops and 1 square root to determine the amplitude of the input signal, $|a|$.
- $5(N - 1)$ flops for the numerator and denominator.
- 6 flops for the (complex) division of the rational form.

A second order polynomial model (such as in Figure 1) requires only 14 flops and a square root. The numerical complexity of the rational model is therefore smaller than for a table-based interpolation approach. Another

advantage is its smoothness as a function of the input amplitude. This smoothness is especially important for input signals with low signal-to-noise ratios. Measurement points with a low signal-to-noise ratio disturb the interpolation technique significantly since an interpolation relies on a small number of - possibly noisy - measurement points.

5. Experimental results

A high-frequency LNA (Low-Noise Amplifier), i.e. the EC2612 of United Monolithic Semiconductors, has been measured and modelled using the proposed model. This component is provided by IMEC, mounted (flip-chip) on an MCM wafer and initially used as part of their Wireless LAN system running at 5.25 GHz. On-wafer measurements were performed using the NNMS (Nonlinear-Network Measurement System) prototype of Agilent Technologies in combination with a classical passive load-pull setup. It is worthwhile to mention that it is possible to collect the required measurement data using a commercial network analyzer (HP8510) in combination with a slightly modified S-parameter test set (HP8515A) as explained in [8]. Load-pull experiments are required in order to measure the influence of a_2 signals. The model parameters of (2) can be computed using a classical least squares method [9] starting from the measured a_1 , a_2 and b_2 for various input amplitudes $|a_1|$ and load impedances Γ .

5.1. Modeling results

Typical amplitude and phase relationships of $S_{21}(|a_1|)$, $S_{22}(|a_1|)$, $S_{22}^*(|a_1|)$ as a function of the incident input power are shown in Figures 1, 2 and 3. The modeling errors between the models and the measurements are below -50dB for all three figures. The classical AM-AM and AM-PM compression characteristics of the amplifier is represented by $S_{21}(|a_1|)$ (Figure 1). The nonlinear effect of the output impedance as a function of the incident power is given by $S_{22}(|a_1|)$, $S_{22}^*(|a_1|)$ (see Figures 2 and 3 respectively).

Therefore, only simple models (up to the fourth order) are necessary to describe the different transfer functions. The overall transfer characteristic S_{21} can be modelled by a second order rational function. Hence, a moderate order (2 or 3) is required for the nonlinear transfer function (even for 3.5 dB compression). It is also important to notice that (Figure 3) the amplitude of S_{22}^* tends to zero for small amplitudes of a_1 , resulting in the classical small-signal S-parameters.

The accuracy of the model is tested by the comparison of the response of the model with measurements of a nonlinear vectorial network analyzer [10]. The chosen input signal is a multi-carrier system around 5.25 GHz with a 1.6 MHz bandwidth as shown in the spectral plot of Figure 4. The

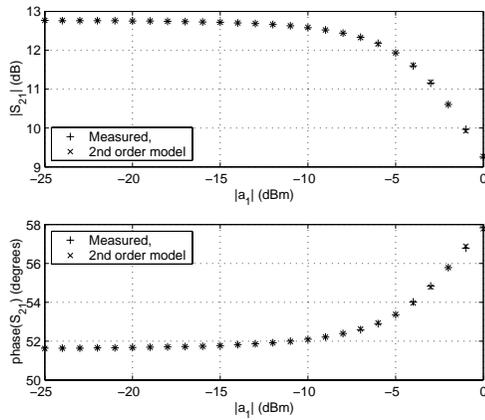


Figure 1: The measured and modelled AM-AM and AM-PM characteristics of S_{21} .

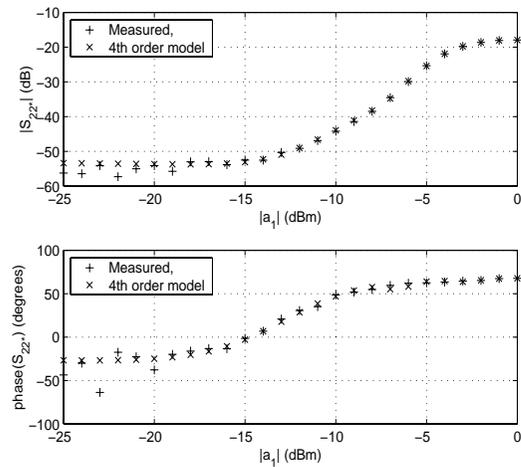


Figure 3: The measured and modelled nonlinear behavior of the output impedance $S_{22}^{*.l}$.

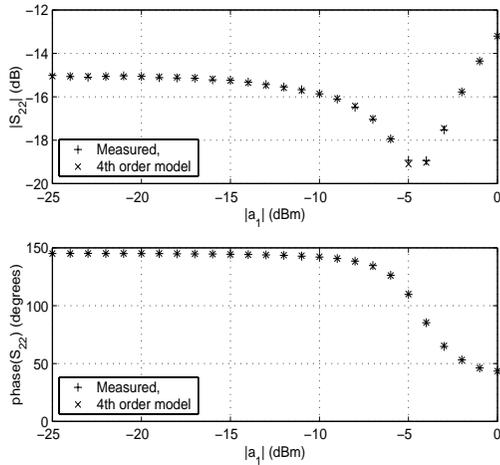


Figure 2: The measured and modelled nonlinear behavior of the output impedance S_{22} .

predicted and measured spectral regrowth at the output are visualized in Figure 5.

The accuracy of the model is tested by comparing the response of the model with modulated measurements using the NNMS. The chosen input signal is a multi-carrier system (52 tones) around 5.25 GHz with a 1.6 MHz bandwidth (actual NNMS limitation) as shown in the spectral plot of Figure 4. This signal was generated using an ESG-D Series Signal Generator of Agilent Technologies providing the corresponding baseband IQ signal, which then is upconverted using the SMIQ 06B of Rohde&Schwarz.

The impact of the nonlinear load-pull is predicted accurately as seen on the time domain plot (Figure 6). Both the measured instantaneous amplitude and the signal

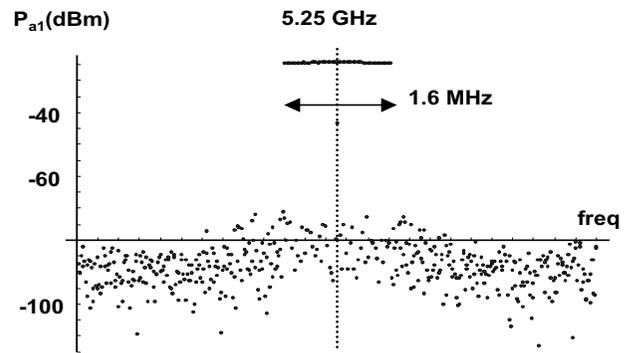


Figure 4: Input power spectrum of a OFDM-like input signal around 5.25 GHz with a bandwidth of 1.6 MHz. The lower dots present the measurement noise floor.

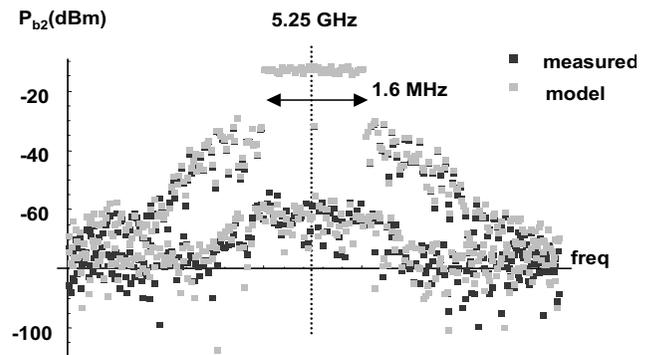


Figure 5: Power spectrum of the measured and predicted output signal.

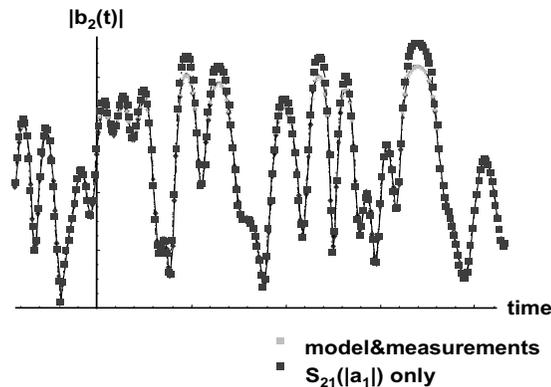


Figure 6: The measured and modelled instantaneous amplitude as a function of time.

predicted by the model coincide very well. The figure demonstrates that it is essential to take both S_{22} and S_{22}^* into account for the larger instantaneous amplitudes.

5.2. Performance evaluation in a system-level simulator

The rational nonlinear function as given by (8) has been implemented into the FAST system-level simulator[6]. The computational time of a second order model is of the order of magnitude of $0.12 \mu s$ on a PIII 500 MHz. This performance is the peak performance of the model when vector processing can be applied.

6. Conclusions

A new nonlinear behavior model has been proposed for weakly nonlinear systems which are excited with narrowband excitations. The model properties include

- the linear S-parameter matrix under small signal conditions;
- the AM-AM and AM-PM compression characteristics;
- the dependency of the AM-AM and AM-PM compression characteristics on the load impedance;
- the ability to perform efficient system-level simulations.

The accuracy of the model is verified by nonlinear measurement of a commercial amplifier. These measurements show that the model is capable to accurately determine the impact of impedance mismatches, inband nonlinear distortion and - possibly nonlinear - load pull.

The efficient system-level simulations are obtained by feedback loop elimination in a preprocessing stage and through the use of rational nonlinear models. The rational nonlinear model is implemented in a inhouse developed systems level simulator. The measured and modeled nonlinear system can be simulated at 8 million samples per second on a PIII 500MHz.

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