The Behavioral Modeling of Microwave/RF ICs using Non-Linear Time Series Analysis

John Wood, *Senior Member, IEEE*, and David E Root, *Fellow, IEEE*

Agilent Technologies, Inc., Microwave Technology Center, Santa Rosa, CA 95403, USA

Abstract — **A new and powerful, systematic approach for creating nonlinear behavioral models of microwave/RF ICs is presented. The methodology incorporates several techniques from nonlinear dynamics, system identification, and computational geometry to produce models that are an effective compromise between complexity and accuracy, and efficiency and speed of simulation. The models are constructed from large-signal microwave measurements in the time domain, or from simulation, and are implemented in a commercial nonlinear microwave simulator. We illustrate the technique by creating a cascadable, transportable model of a microwave IC amplifier that predicts accurately the DC, large signal, harmonic distortion, inter-modulation, and small-signal S-parameter behavior.**

I. Introduction

Modern microwave and wireless systems are nowadays too complex to permit complete simulation of the non-linear behavior at the transistor level of description. This problem presents a significant productivity bottleneck for design engineers. A solution to this problem is to design at a higher level of abstraction, using behavioral models of the nonlinear blocks or ICs in the system. The behavioral models can represent the nonlinear behavior of the components with sufficient accuracy, yet they are simple enough to allow rapid simulation.

In this paper we shall describe a new, general, and systematic time-domain methodology for generating nonlinear behavioral models, that is based on techniques from nonlinear dynamics, system identification, and computational geometry. We shall illustrate the technique by creating and validating a model of a real microwave IC amplifier. The modeling procedures that we outline are very general: the test signal design, analysis, model generation and simulator implementations are generic and can be applied to amplifiers, mixers, modulators and other microwave components or sub-systems. The resulting models are transportable [1]: in other words, usable in a range of system and simulation environments, and not restricted to a limited domain of applicability. A further advantage of this time-domain modeling technique is that it works for arbitrarily strong non-linearities, unlike common microwave frequency-domain approaches such as Volterra Series analysis, which is limited to weakly non-linear systems [2].

II. Methodology

The motivation for our approach to non-linear systems identification goes under the rubric of Non-Linear Time Series Analysis (NLTSA) [3]. The suggestion to use this approach for describing input-output systems is due to Casdagli [4]. The key idea is to embed the measured or simulated stimulus and response variables in a higher dimensional space built not only from the measured data but also transforms of the measured data, in our case, their time derivatives. Due to a theorem of Takens extended to the driven case by Stark [5], these embedded models can be faithful to the dynamics of the original system. In particular, deterministic prediction is possible from an embedded model that will mimic the dynamics of the actual system.

The models are formulated as non-linear ordinary time-differential equations, which are easily implemented in commercial microwave simulators, in the embedded variables:

$$f\left(i(t), i'(t), i''(t), \ldots, v(t), v'(t), v''(t), \ldots\right) = 0 \qquad (1)$$

The outputs $i(t)$ are assumed to be measurable functions of the internal state of the system, $x(t)$, and the inputs $v(t)$:

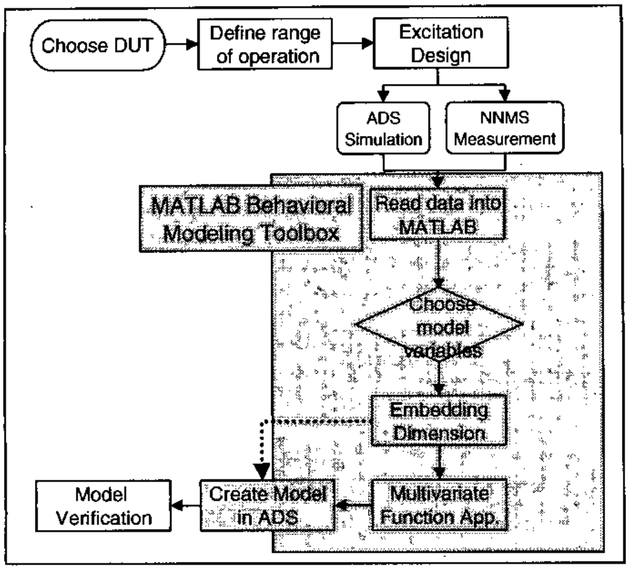
$$\begin{aligned} i(t) &= h\left(x(t), v(t)\right) \\ x'(t) &= g\left(x(t), v(t)\right) \end{aligned} \qquad (2)$$

We use an embedding technique where the trajectory of the output ($i(t)$) is unfolded in a higher dimensional space by increasing the number of derivatives until a single-valued function is obtained. This approach leads to fewer *ad hoc* assumptions, such as model order, compared with other recently-published time-domain techniques [6].

The goals of the modeling process are thus to determine the significant embedding variables of the function, f, and then to find an efficient basis for the function approximation.

0-7803-7695-1/03/$17.00 © 2003 IEEE

III. PROCEDURE



Fig, 1 Flowchart of Behavioral Modeling procedure

A. Generating the Data

The operating range of the DUT is generally specified in a datasheet. The 'power bandwidth' specification of the microwave amplifier was used to determine the range of powers and frequencies for the set of excitation signals that were used to produce the data for the behavioral model generation. In this example, the excitation signal that we applied comprised two offset tones at the amplifier input, and a further tone at the output port, swept over the frequency range from 1.2 to 10.2 GHz, and from small-signal to the P-1dB compression point. These signals generate multiple internal states due to the nonlinear behavior of the transistors in the IC, and hence a significant number of observable states from which the model can be created.

Other excitation signals can be used, including multi-tone inputs, and modulated signals using simple FM or complex CDMA modulation.

The model data can be generated either by simulation of the transistor-level circuit of the amplifier, or by direct measurement of the time-domain waveforms using a large-signal vector network analyzer [7,8]. The time-domain data is then read directly into the Behavioral Modeling Toolbox written by the authors in MATLAB.

B. Behavioral Modeling Toolbox in MATLAB

Historically, Time-Series Analysis has focussed on autonomous time series, examples of which include the Sunspot cycle, Stock Market indices, etc. The predicted output of such time series is found from the current output and its history, by using a 'delay embedding':

$$y(t+1) = f\left(y(t), y(t-\tau), y(t-2\tau), \ldots y(t-n\tau)\right) \quad (3)$$

where the embedding delay is τ, and the dimension of the embedding is n.

The immediate differences between this approach and our application are that we are considering a driven system, which operates over a wide bandwidth. Clearly, a constant time-delay embedding is inadequate to cover the wide timescales (bandwidth) of the excitation signal used here for the amplifier. We use time derivatives of the inputs and outputs for embedding the data.

The algorithm that we use for choosing which of the dynamical variables (time derivatives) are used for the embedding is based on the technique of "False Nearest Neighbours" [9], which is established in principles of computational geometry. We used a method based on that of Rhodes and Morari [10], developed for input-output systems. The algorithm uses the data itself to determine the optimal set of embedding variables, resulting in a compact and efficient model of vastly lower complexity than the original nonlinear system (amplifier).

Having chosen the optimal set of embedding variables, the next task is to determine a suitable function approximation for the nonlinear function *f* in (1). We have considered several techniques, including multivariate polynomials [8], radial basis functions (RBF) [1], and artificial neural networks (ANN) [11] reported here for a real microwave amplifier IC. We use the MATLAB Neural Network Toolbox to carry out the function fitting: the fitting parameters include the number of hidden layers and number of neurons in those layers.

The mathematical model is then exported to the nonlinear circuit simulator, *Agilent* 'Advanced Design System' (ADS). The model is implemented in ADS using the 'Symbolically-Defined Device' (SDD). The SDD also performs the scaling and calculates the time derivatives of the variables at each time step in the simulation. Hence the true terminal currents are evaluated.

IV. RESULTS

The amplifier behavioral model SDD is compared with the transistor-level circuit model of the amplifier in a range of simulation conditions, to establish the validity and accuracy of the behavioral model. In particular, we have carried out a single-tone power sweep simulation to study the large-signal and harmonic behavior, and a two-tone power sweep simulation to study the intermodulation performance. Different power levels and frequencies to those used in the data/model generation were used for validation. In addition, we investigated the limiting cases of linear or small-signal behavior using S-parameter simulation, and DC behavior. Again, it is important to note that neither small-signal nor DC data were used in the model generation procedure.

In Fig. 2, the single-tone Gain Compression characteristic reproduced almost exactly by the behavioral model. The frequency range is 1–11 GHz, the operating bandwidth of the amplifier. The magnitude response of the 3rd harmonic of the output signal is shown in Fig. 3; the phase is reproduced faithfully also.

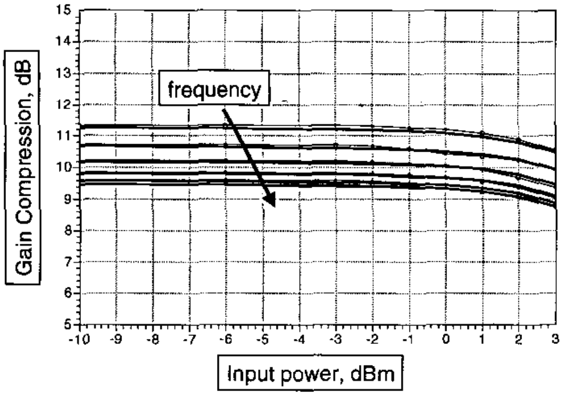


Fig. 2 Gain Compression curves for Time-Series model (–o–) and transistor-level circuit model (—).

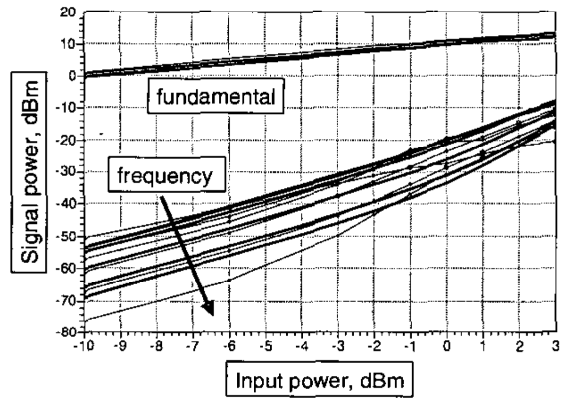


Fig. 3 Third harmonic power output for Time-Series model (–o–) and transistor-level circuit model (—).

Further, in Fig. 4 we show the response up to the 7th harmonic for a single-tone input at 3 dBm, which is the P-1dB compression point. Note also that the DC level is reproduced exactly by the behavioral model.

The two-tone performance of the behavioral model is also very accurate. This is shown in Table 1 below, for fundamental input signals of 2.0 and 2.1 GHz, at 0 dBm.

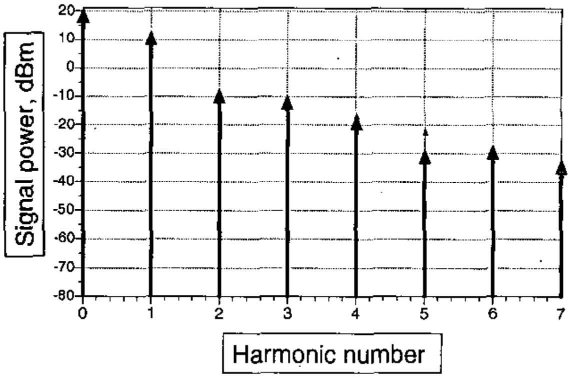


Fig.4 Harmonics up to seventh order at P-1dB compression for the Time-Series model (—) and the transistor-level circuit model (----). Fundamental frequency is 5 GHz, and the input power is 3 dBm.

	Circuit	TS Model
Fundamental Tones	6.138	6.141
3rd-order IM, Lower	-26.39	-27.27
3rd-order IM, Upper	-26.412	-27.299
5th-order IM, Lower	-41.242	-42.717
5th-order IM, Upper	-41.288	-42.713

Table 1 Two-tone IM output powers, in dBm, predicted by the Time-Series and circuit level models

The time-domain output voltage waveforms are shown in Fig. 5. The RF signal is modeled accurately, and the envelope signal at 100 MHz is also reproduced exactly. Again this is an excellent performance as no IF signals were used in the creation of the behavioral model.

The model and circuit S-parameters are also in excellent agreement over the frequency range 1-20 GHz, indicating that the fully non-linear model reduces to the correct linear behavior under small-signal conditions.

While the accurate agreement between the behavioral model results and those from the transistor-level circuit are an essential first step in validating the behavioral model, the usefulness of this model is pertinent in the simulation of a module or system containing several components. To demonstrate that the behavioral model of the amplifier can be used in a system–level simulation, we place two models in cascade, and compare the results with two transistor-level circuit models in cascade. The simulation results for the Gain Compression characteristic are shown in Fig. 6. Excellent agreement between behavioral model and transistor-level circuit is observed. Similar results are found for the harmonic performance, IM behavior, etc. of the cascade also.

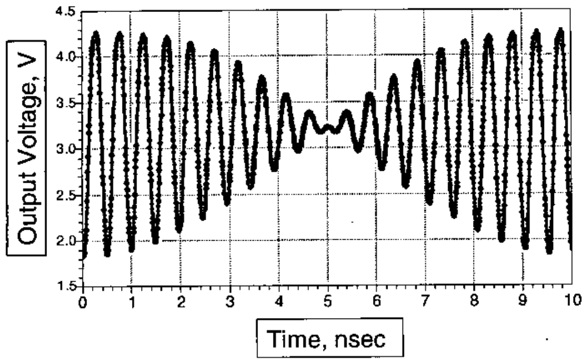


Fig. 5 Time-domain output voltage for 2-tone input: Time-Series model (-o-) and transistor-level circuit model (—)..

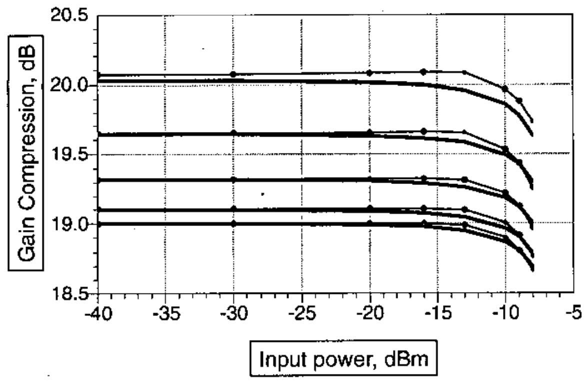


Fig. 6. Gain compression characteristic for two sets of amplifier models in cascade, Time-Series models (-o-) and transistor-level circuit models (—).

V. CONCLUSIONS

We have presented a new, general, and systematic time-domain methodology for generating nonlinear behavioral models, based on well-established techniques from nonlinear dynamics, system identification, and computational geometry. A prototype Behavioral Modeling Toolbox has been developed in MATLAB, that reads measured or simulated time-domain data and generates a model file that can be imported into the *Agilent* ADS nonlinear microwave circuit simulator.

With this toolbox we have generated a behavioral model from simulated data using a transistor-level circuit model of a broadband microwave IC amplifier. The behavioral model faithfully reproduces the circuit model electrical behavior in a wide range of validation exercises, including single-tone and two-tone power-frequency sweeps over the operating space of the amplifier, DC conditions, and S-parameter simulation. The cascading of two microwave amplifiers is also modeled accurately for the first time using time-series models, indicating that these behavioral models can be used in system-level simulations of modules containing several amplifiers.

The modeling technique we have described is general, systematic, and scalable, and can be applied to the creation of behavioral models of a wide range of non-linear components, including transistors, amplifiers, mixers, switches, etc. The models can be used to simulate at the higher level of design hierarchy – module or system level – enabling designers to be more efficient and productive.

ACKNOWLEDGEMENTS

Many thanks to Nick Tufillaro for several stimulating and informative discussions regarding the theoretical background to Non-Linear Time Series Analysis.

REFERENCES

[1] D. M. Walker, R. Brown, N. B. Tufillaro, "Constructing transportable behavioral models for nonlinear electronic devices", *Phys. Lett. A*, 255 pp236-242 (1999)

[2] J. Verspecht, F. Verbeyst, M. Vanden Bossche, P. Van Esch, "System level simulation benefits from frequency domain behavioral models of mixers and amplifiers", *Proc. 29th European Microwave Conf.*, pp29-32.(1999)

[3] H. Kantz and T. Schreiber, *Nonlinear Time Series Analysis*, Cambridge University Press (1997)

[4] M. Casdagli, "A dynamical systems approach to modeling input-output systems", in *Nonlinear Modeling and Forecasting, SFI Studies in the Science of Complexity, vol XII*, M. Casdagli, S. Eubank (eds.), Addison-Wesley (1992)

[5] J. Stark, "Delay embeddings and forced systems", *J. Nonlinear Science*, vol 9, pp255-332 (1999)

[6] J. Xu, M. C. E. Yagoub, R. Ding and Q. J. Zhang, "Neural-based dynamic modeling of nonlinear microwave circuits", *IEEE Int. Microwave Symp. Digest*, pp1101-04 (2002)

[7] J. Verspecht, P. Debie, A. Barel and L. Martens, "Accurate on-wafer measurement of phase and amplitude of the spectral components of incident and scattered voltage waves at the signal ports of a nonlinear microwave device" *IEEE Int. Microwave Symp. Digest*, pp1029-32 (1995)

[8] D. Schreurs, J. Wood, N. B. Tufillaro, D. Usikov, L. Barford, D.E.Root, "The construction and evaluation of behavioral models for microwave devices based on time-domain large-signal measurements", *IEDM* pp819-822 (2000)

[9] M. B. Kennel, R. Brown, H. Abarbanel, "Determining embedding dimension for phase-space reconstruction using a geometrical construction", *Phys. Rev. A* vol 45 pp3403-3411 (1992)

[10] C. Rhodes & M. Morari, "False-nearest-neighbors algorithm and noise-corrupted time-series", *Phys. Rev. E*, vol 55 pp6162-70 (1997)

[11] D. E. Root, J. Wood, N. B. Tufillaro, D. Schreurs, A. Pekker, "Systematic behavioral modeling of nonlinear microwave/RF circuits in the time domain using techniques from nonlinear dynamical systems" *IEEE BMAS Workshop Digest* (2002)