Deterministic and Stochastic Behavioral Modeling of RF Front Ends

Michael B. Steer, Kevin Gard, Khalid Gharaibeh, Aaron Walker and Wonhoon Jang

***Abstract*— Behavioral models developed using discrete-tone characterization can be used to capture the response of an RF front end to stochastic signals. It is important that the model architecture capture all nonlinear effects and that the proper translation of the derived envelope model be transformed into an instantaneous model. Here the requirements for the transformation are presented, a multi-slice model architecture that can capture complex behavior from narrow-band measurements is presented together with an extraction procedure.**

***Index Terms*— behavioral modelling, deterministic signal, stochastic signals.**

I. INTRODUCTION

Behavioral models are used extensively for characterizing RF front-ends. The underlying rationale to employing these models is that relatively simple measurements can be used to develop the model and that these can be used with more complex signals. Traditionally single-tone characterization is performed to develop AM-AM and AM-PM transfer functions which can be represented as the RF output phasor as a complex function of the input phasor. The AM-AM and AM-PM models can be conveniently represented in a variety of simulations environments including system, transient (Spice) and harmonic balance simulators. A natural extension is to use two-tone characterizations. Several concerns arise in extending this modeling approach to richer input signals including digitally-modulated signals that can be described as stochastic signals with prescribed characteristics:

1) The need for an instantaneous model to treat general signals while one-tone and two-tone measurements yield envelope characterizations.
2) The need for a behavioral modeling architecture and extraction procedure for two-tone characterizations that can still be implemented in system, transient, and harmonic-balance simulators.
3) Verification that discrete-tone characterizations can be used to model the performance of RF front-ends with stochastic signals.
4) a general understanding of the relationships and differences of discrete and stochastic signals.

These topics are addressed in this paper.

II. INSTANTANEOUS VS. ENVELOPE MODELS

In general RF front-ends can only be partially observed because of bandpass input and output filtering, see Fig. 1. One-tone characterization involves expressing the phasor of a tone at the output while the amplitude of an RF phasor is varied at the input. The AM-AM and AM-PM results are then in terms of amplitudes or an envelope characterizations. Fitting a function to these characterizations results in an envelope RF model. This type of model can be used in system simulators as long as phasors are used. It i snot appropriate to use these models with more complex signals as the instantaneous forms of the models are require dot uncover the true nonlinearity of the model. To illustrate this point ignore phase variations and consider the envelope forms of a limiter response modelled as a tanh model:

$$v_0 = L \tanh g v_{\rm in} / L \tag{1}$$

or as a Cann/Rapp model:

$$v_0 = \frac{g v_{\rm in}}{1 + \left(g v_{\rm in}/L\right)^{1/s}} \ . \tag{2}$$

These are standard limiter models. Varying g, L and s changes the linearity of the curves. These models have the envelope characteristics shown in Fig. 2 The underlying instantaneous RF response is shown in Fig. 3 and is fundamentally different. The major difference is that the instantaneous response is sharper than the envelope response. To understand this we should focus on the instantaneous RF response, Fig. 3. When a sinewave is applied to the nonlinear device the RF signal is swept over a large portion of the response as the amplitude increases. This softens the apparent AM-AM response so that the envelope characteristic, Fig. 2, is softer. It is critically important to use the instantaneous response in translating from discrete-tone characterizations to models that can be used stochastic signals.

The challenge being addressed in this proposal is the remote identification and characterization of electric and electronic devices. Identification ranges from determining the presence of devices to assuring that a device is exactly what it is purported to be. Characterization also relates to the determination of the correct composition of a device to the characterization of complex electronic devices for which electrical terminals are not readily available. For example, the trend in RF front

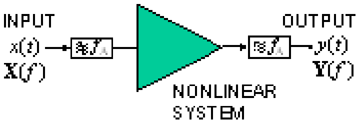

Fig. 1. Figure 2: A unilateral bandpass nonlinear system.

The authors are with the Department of Electrical Engineering, North Carolina State University, Raleigh, NC, 27695-7911, U.S.A email: mbs@ncsu.edu.

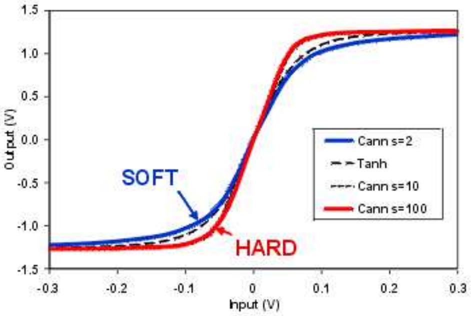

Fig. 2. Carrier response of various limiter models.

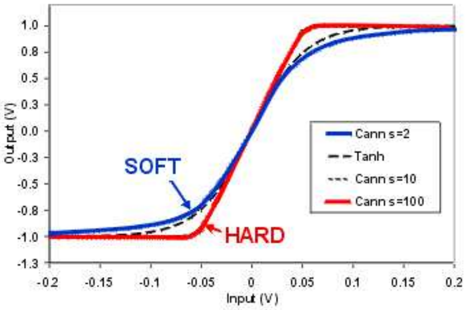

Fig. 3. Instantaneous response of various limiter models.

end technology is the close integration of the subsystem components of an RF front end, e.g. filter, driver and power amplifier, and antenna in a single module. The input to the RF front end could be an RF signal or could indeed be a digital bit stream. The output is the radiated electromagnetic field. These scenarios share much in common: the need to characterize the internal components of a complex system with limited external data. The scenarios all involve the interpretation and thus understanding of the interaction of electromagnetic fields with devices.

III. NARROW BAND BEHAVIORAL MODELING

Here we address behavioral modeling using partially-observed (here bandlimited) charcaterizations. One of the significant difficulties with behavioral modeling is that intermediate frequencies cannot be adequately modelled. In particular, narrow band communication signals passing through a nonlinear system result in the generation of envelope frequency signals as well as signals centered around the harmonics. We believe that to reasonably capture these effects that the behavioral model should be partitioned so that the different frequency regimes can be addressed individually. Thus we are proposing a behavioral model architecture composed of a number of behavioral models, one for each frequency band, the output of each being frequency shifted to model the composite response. The individual behavioral models could be of any form.

An RF module can be described as a bandpass nonlinear system as shown in Figure 1. This model has bandpass filters at the input and the output. Even if the system does not have ideal bandpass filters, the internal spectral components will in general not be observable from external tests. The development of a useful behavioral model requires that a testing scheme be used that completely tests the internal response of the nonlinear system at the non-observable frequencies. The input to the bandpass nonlinearity is represented by $x(t)$, which has a frequency domain representation $\mathbf{X}(f\ )$. Similarly the output is represented by $y(t)$ which has a frequency domain representation $\mathbf{Y}(f\ )$.

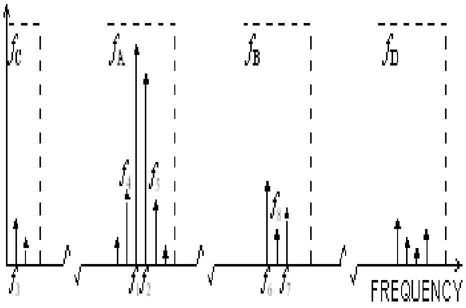

Fig. 4. Spectrum of the internal signals of the nonlinear system.

A two tone-test, with tones of frequency $f_1$and f_2, generates signals internal to the nonlinear system that can be described by the spectrum in Fig. 4. The frequency components generated fall in a number of bands: $f_C$denotes the difference frequency band resulting from the second order mixing of tones within the main channel band f_A; $f_C$denotes the secondharmonic band; and $f_D$denotes the thirdharmonic band . All of the frequency components in band $f_A$see the same impedance levels. The components in band $f_B$see the same impedances as do the components in band f_B. However, the components in band f_C see impedance levels that are frequency dependent across the band.

A. BEHAVIORAL MODEL DEVELOPMENT

The behavioral model currently being developed is shown in Fig. 5 where a quantity $z(t)$ with frequency representation $\mathbf{Z}(f)$ is introduced to described components internal to the bandpass system. The view implicit to this model is termed the intermodulation view and the various horizontal slices are termed intermodulation levels. There can be many levels dependent on the level of sophistication desired. $\mathbf{N}_A$, $\mathbf{N}_B$, and $\mathbf{N}_C$, represent frequency independent nonlinear transformations that could be described by complex power series or any other describing functions. The nonlinear transformations are frequency independent. $\mathbf{L}_A$, $\mathbf{L}_B$, and $\mathbf{L}_C$, represent linear transformations, which in general could be frequency dependent. In the case of frequency dependent one-tone AM-AM or AM-PM data frequency dependence would be captured by $\mathbf{L}_A$. With a narrow band signal the frequency dependence in the f_A and f_B bands is negligible. In this case, all of the linear transformations are frequency independent except for $\mathbf{L}_{C,}$ which captures the frequency dependence of the internal impedances at the envelope (difference) frequency. Of the linear transformations only $\mathbf{L}_C$, will be distinguishable from the nonlinear transformations. The final multiplication stage translates components of $z(t)$ back to the $f_A$band.

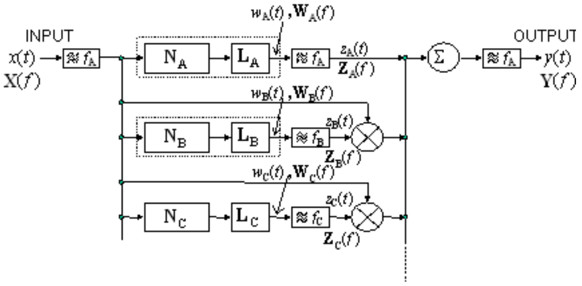

Fig. 5. Behavioral model of a bandpass nonlinear system.

The key feature behind the development of this model is that during characterization a measured spectrum can be divided by another spectrum using the Arithmetic Operator Method described in Reference 10. Thus the model can be evolved in much the same way that the Volterra method of nonlinear analysis is performed. So referring to Fig. 5. The one-tone response is captured by the first slice of the model (with $\mathbf{N}_A$, $\mathbf{L}_A$,f_A) evaluated using a tone-tone AM-AM and AM-PM test for example. The second slice of the model (with $\mathbf{N}_B$, $\mathbf{L}_B$,f_B) is evaluated by taking the measured response, subtracting the response of the ($\mathbf{N}_A$, $\mathbf{L}_A$,f_A) slice, and then dividing the result by the original spectrum. Then the components in frequency band $f_B$are used to fit $\mathbf{N}_B$ and $\mathbf{L}_B$.

The extraction procedure for the composite model is described more fully in the following. Our development makes use of the arithmetic operator method. Let the spectral vectors of$x(t)$, $z(t)$, and $y(t)$ be denoted by $\mathbf{s}_X$,$\mathbf{s}_Z$, and$\mathbf{s}_Y$respectively.

1) I One-Tone Test: Use one-tone test to find $\mathbf{N}_A$ fit a complex power series to AM-AM and AM-PM data. The input and output signals become

$x(t)$ = Re$\{\mathbf{X}\mathrm{e}^{j\omega t}\}$ = $|\mathbf{X}|$ cos($\omega t + \angle\mathbf{X}$) = $\mathbf{X}$ cos(ωt)

since the phase of $\mathbf{X}$ is zero and

$y(t)$ = Re$\{\mathbf{Y}\mathrm{e}^{j\omega t}\}$ = $|\mathbf{Y}|$ cos(ωt+$\angle\mathbf{Y}$) = $|\mathbf{Y}|$ cos(ωt+$\tau(|\mathbf{X}|)$)

The results of a one-tone test are shown in Fig. 6.

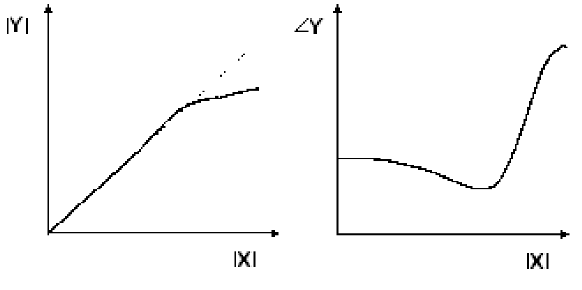

Fig. 6. AM-AM and AM-PM characterizations from a one-tone test: (a) AM-AM data; and (b) AM-PM data.

In conventional behavioral models based on AM-AM and AM-PM data each of the above characteristics are fitted to a polynomial or describing function. However as we want to develop a behavioral model that will be compatible with a circuit simulator we need to avoid dealing with absolute quantities. What we want is the relation between $y(t)$ and $x(t)$, at least within the f_A band.

2) Two-Tone Test:

- Apply input as in a two-tone test. $\mathbf{X}(f)$ = $\mathbf{s}_X$is known.
- Measure $\mathbf{Y}(f)$ = $\mathbf{s}_Y$
- Calculate $\mathbf{Y}_A(f)$ = $\mathbf{s}_{Z,A}$
- Calculate $\mathbf{s}_Z$ - $\mathbf{s}_{Z,A}$= ($\mathbf{s}_Z$ - $\mathbf{s}_{Z,A}$)/ $\mathbf{s}_X$ and break into frequency bands f_A, f_B, $f_C$and designate components $\mathbf{s'}_{Z,A}$, $\mathbf{s}_{Z,B}$, $\mathbf{s}_{Z,C}$, etc. $\mathbf{s'}_{Z,A}$is the residual spectrum of $z_A(t)$ and should be zero. Perhaps if it is not zero $\mathbf{N}_A$ could be re-optimized but I do not think that it will be necessary but we can use this number as a check of the method..
- The two-tone test will need to be repeated at several amplitudes to obtain $\mathbf{Z}_B(f)$ = fn($\mathbf{X}(f)$) and obtain $\mathbf{Z}_C(f)$ = fn($\mathbf{X}(f)$). $\mathbf{N}_B$, the fit to $\mathbf{Z}_B(f)$ = fn($\mathbf{X}(f)$), can be obtained as for the one-tone fit. This fit should be frequency independent so $\mathbf{L}_B$ can be treated as one. $\mathbf{N}_C$and$\mathbf{L}_C$ will not be so simple. and used to extract $\mathbf{N}_C$. The two-tone test will need to be repeated for different spacing of f_1 and f_2 to extract the frequency dependent $\mathbf{L}_C$.

IV. RELATIONSHIP OF DETERMINISTIC AND STOCHASTIC SIGNALS

We are now in a position to contrast the performance of a behavioral model in capturing the distortion characteristics of deterministic and stochastic signals. In the particular examples we are considering here we have used only the first slice of the behavioral model. Single-tone and two-tone measurements were performed on a 2 GHz RF amplifier and an envelope model developed. The complex power series model developed here was transformed into an instantaneous model using the algorithm contained in Reference [2]. It should be noted that a power series is the only function for which an analytic transformation is known. Transforming other functions requires an iterative solve, (e.g. a genetic algorithm) to relate the two forms).

In Fig. 7 the measured intermodulation ratio is shown together with various orders of instantaneous model. Even a fifth-order model does a reasonably good job at matching simulations to measurements. Things are quite different with a CDMA input signal investigated in Fig. 8. Here it is necessary to consider up to a thirteenth-order model to obtain good agreement. The interpretation of these results is that stochastic signals and relative rare but large peak excursions which dominates the spectral regrowth response.

V. CONCLUSION

IN the presentation and final version of this paper results for WCDMA and GSM/Edge will be presented. We will also show how the response of the model can be calculated using the statistics of the digitally-modulated signal and the device characterizations. The difference between the results obtained with instantaneous and envelope behavioral models is shown to be about 3 dB for common digitally-modulated signals. The use of an envelope behavioral model were an instantaneous RF model is reuired is common place and shows up with dgitally-modulated signals and is masked in discrete-tone measurements.

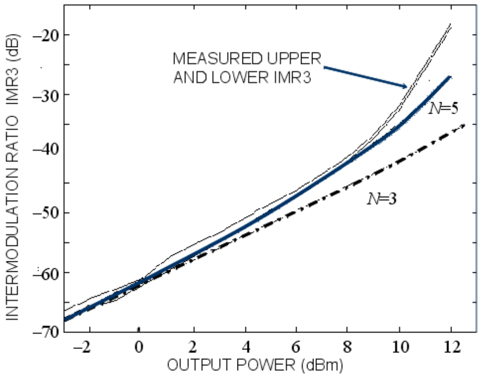

Fig. 7. Modelled and measured intermodulation ratio showing the impact of the order of a model.

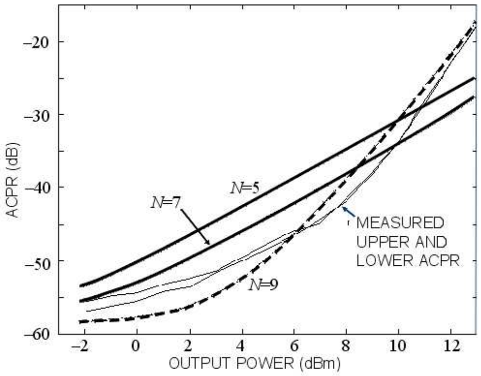

Fig. 8. Modelled and measured ACPR showing the impact of the order of a model.

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