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Model-based test for analog integrated circuits

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Abstract – *The basic idea of 'model-based test' is to compute multiple test metrics from a core set of stimulus/response experiments used to fit behavioral models for the test metrics of interest. In other words, a few measurements are done to collect data used to create a behavioral model from which a number of test metrics are computed for example by simulation. One objective of model-based test is the reduction of complexity and cost of measurement systems used in test of analog integrated circuits. The method described here seeks to replace a conventional measurement system with a single broad band source and receiver which would be adequate for multiple tests, when used in conjunction with appropriate models. Application of the method to a digital receiver, including comparison of predicted and measured results, is described.*

Keywords – *analog system testing, measurement system data handling, identification*

I. INTRODUCTION

The basic idea of 'model-based test' is to compute multiple test metrics from a core set of stimulus/response experiments used to fit behavioral models for the test metrics of interest. In other words, a few measurements are done to collect data used to create a behavioral model from which a number of test metrics are computed for example by simulation. The approach contrasts with traditional test, where a measurement is performed for each test metric. Model-based test promises to be advantageous in situations where measurement time is costly, and simulations from behavioral models are more time and cost effective, as might be the case in the manufacturing test of integrated circuits (ICs) for consumer products. Model-based testing has previously been applied to reduce the test time for analog to digital converters [1]. Here we illustrate its application to testing analog circuits with a mixing stage [2] and provide more details than the outline of our approach to model based test presented in [3]. Similar behavioral models, based on both frequency domain and time-domain data, are also being developed for design applications [4].

One objective of model-based test is the reduction of complexity and cost of measurement systems used in test of analog integrated circuits. Figure 1(a) shows a measurement system for such test designed in the usual way. It is hypothetical but has typical features. Multiple signal source instruments produce signals to be fed to the device under test (DUT). Signals are selected for application to the DUT using switches and relays. More switches and relays direct DUT responses to the instruments that will measure them. For each manufacturing specification for the DUT, a test is performed, typically corresponding to one set-up of a signal source, the relays, and one instrument. In essence, the measurement system is a multitude of measurement systems, one for each DUT specification figure of merit, made more efficient and cost-effective by the use of switches and relays. Figure 1(b) shows a measurement system for electronics test as envisioned in this paper. A single, broadband source excites the DUT inputs. The DUT outputs are measured by a single broadband receiver/digitizer combination. A set of measurements are performed sufficient for the system identification of the DUT (or of its deviation from nominal).

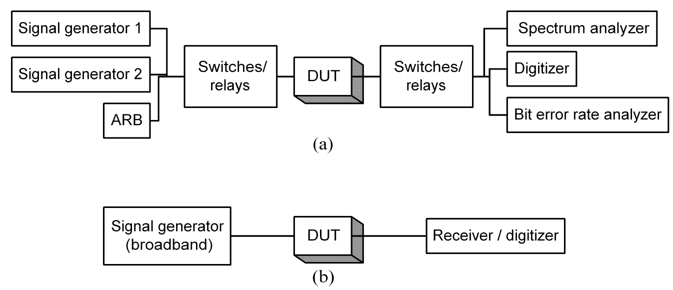

Figure 1. Comparison of (a) hypothetical conventional measurement system used in electronics manufacturing test vs. (b) that envisioned in this paper.

Recently, system identification techniques built from broad band stimulus-response experiments have been applied to predicting test metrics of analog amplifiers [5][6]. In this study we describe a modeling approach applicable to an analog circuit that also contains a frequency translation stage. Specifically, we create a model from measurements that supports computation of the test metrics of a direct conversion W-CDMA receiver for cell phone handsets.

A block-diagram for the design of the type of receiver studied here is shown in Figure 2. The receiver is similar to that described in [7]. For the particular direct conversion receiver studied here we had access to complete circuit level models that allowed us to perform end-to-end (transient) simulations of the device from the RF input (2.1 GHz) to demodulated analog baseband I-Q output.

We previously developed nonlinear system identification methods for application to behavioral modeling of microwave amplifiers [8]. However, these methods are not well suited to systems whose input and output (stimulus and response data) are at vastly different time scales, as is the present method.

The basic idea of the method is to map the complex I/Q signal at RF to a baseband image using a simplified model—based on a block diagram of the signal chain—that allows us to generate an 'output' I-Q baseband time domain signal which we then use as 'input' to an nonlinear time-series analysis model [9]. The output for initial model training can come from complete end-to-end transient simulations or measured data. Informally we think of this as difference modeling (difference between a block diagram based signal model which includes some well know signal impairments) between an 'embedded model' and the actual device data. The method allows us to add some simple, but critical, prior information about the device under test which makes accurate modeling of test metrics easier. The method can be viewed as an extension of the 'time-delay' and related embedding methods described in the nonlinear time series analysis research literature [10]. Most previous descriptions of 'embedded variables' have been limited to linear transformations (time-delays, derivatives, FIR filters, etc) or simple nonlinear filters of the initial input time-series data. The essence of this method is the extension of 'embedded variables' to what we call 'embedded models' for use with nonlinear time series analysis system identification methods [11].

We should also stress that unlike models used for IC designs, models for test are not very faithful or robust outside their intended domain of use. Most analog designers, for example, expect models to function accurately and properly for a large range of input signals and parameter variations. Our requirements are distinctly more pedestrian, as test specifications limit the operation of the device under test (DUT) to certain static and dynamic operating regions. Test engineers typically are supplied with a detailed test specification which gives a complete description of the test signals, and further manufacturing engineers also might have information about skew lot studies showing the measured variations of the process and device parameters. Both sets of information can be used to greatly constrain a behavioral model for test metrics.

Lastly, the method below has a few advantages that are worth pointing out. First, in the case where the method is based on a block level description and measured data, there is no need for the design house to supply detailed circuit level device models to implement the method. That is, the method protects the designer's intellectual property. Second, software tools for system identification are becoming available that should make these methods accessible to a larger engineering community [9].

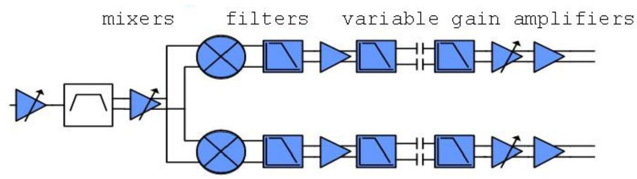

Figure 2. Block diagram of direct conversion receiver used in this paper.

II. METHOD

As with most system identification problems, the method consists of four connected steps: (i) excitation design, (ii) model selection, (iii) model fitting, and (iv) validation. In this application the device under test has bandwidth selectable filters which are set to 2 Mhz in this study. Therefore we want to model test metrics for the base band response between 0 and 2 Mhz, as well as test metrics for the nonlinear response that falls out side of this channel.

The excitation design is naive. We choose a random excitation signal that was broadband enough to capture the devices in-channel behavior as well as nonlinear behavior resulting from low order nonlinear distortion products. (By "random" we mean a random or pseudo-random signal or a multi-sine with a multitude of tones each having uncorrelated phases.) We also choose to sample the device at different power levels to further probe its nonlinear behavior, compression, and distortion. The simplest choice of a excitation signal was a WCDMA waveform designed composed of two 5 Mhz wide signals designed to excite a bandwidth of 10 Mhz centered at 2.1 Ghz. Waveforms of this type are easy to create in Agilent's Advanced Design System (ADS) by using the source simulation design tools [12]. We created five realizations of this signal at different power levels. The total excitation training set consisted of five WCDMA wave forms with a total period of approximately 30ms. Transient simulations where performed in ADS to collect stimulus and response wave forms of both the input RF signal and the resulting response baseband I and Q signals. In addition, we also recorded the local oscillator wave form used by the device to mix the signal down to base band. A model-based test procedure on a real device would also require measurement access to device's local oscillator to implement the method described here. Alternatively, a phase recovery method can be implemented.

The model selection procedure breaks into two parts: generation of 'nominal' baseband signals using a block diagram, and the selection of a nonlinear time series analysis model built from the nominal baseband signals $V_I(t)$ and $V_Q(t)$. The nonlinear time series analysis requires us to match, in the time-domain, stimulus and response signals. A priori, the method is not well matched to the problem at hand because of the vast difference in time scale between the stimulus signal at RF and the response signals at baseband. To overcome this difficulty, and to enhance the model fit, we first transform the excitation signal to baseband using information available from the block diagram specific to each design. To explain the idea, consider Figure 2 showing a simplified block diagram for conversion to baseband. There is typically "nominal" design information for each block, such as the impulse response of filters (h_I and h_Q) in the I and Q channels. If the local oscillator (LO) components are represented by $\cos(\omega t + \theta_0)$ and $\sin(\omega t + \theta_0 + \delta)$, then the nominal base band signals in this example are computed as ($*$ is the convolution operator):

$$V_I(t) = \cos(\alpha) h_I * I(t) - \sin(\alpha) h_I * Q(t),$$

$$V_Q(t) = (1+G)(\sin(\alpha+\delta) h_Q * I(t) + \cos(\alpha+\delta) h_Q * Q(t)).$$

If the LO is available (either in measurement or simulation), then we perform a direct time domain multiplication in computing the nominal base band response. If it is not available, we typically perform a two parameter optimization (over phase and amplitude) to map the nominal (complex) baseband vector to data from the training set (a similar LO preliminary phase recovery step would then be needed in a measurement implementation).

The result of the first modeling stage is a fixed transformation that carries the RF signal into a base band signal which should be well correlated, in the time domain, to the measured base band signal. The second model selection stage is to then use $V_I(t)$ and $V_Q(t)$ as input to a nonlinear time series modeling system estimation procedure which is described in detail in [9]. In this case a fifth order polynomial was used in the final functional fit, and an embedding dimension of two with a lag of two was used is in creating a model of the form:

$$\bar{V}_I(t_n) = F[V_I(t_n), V_I(t_{n-2})]$$

where F is a fifth order polynomial in the example studied here. A similar formula is also estimated for $\bar{V}_Q(t)$. Only the most significant coefficients (typically under ten), determined by a singular value decomposition (SVD), are kept in the final fit that determines the (fixed) model structure. An initial check of this model structure is performed by cross-validation.

Any individual device is then fit to this fixed model structure. An average root mean square error (RMS) in the time domain is used to gage the fit quality. The final validation involves comparison of the of individual test metrics computed from both the model and the conventional test procedure. The model based test metrics are computed in one of two ways, either by simulation or by relating the test metric to model coefficients after model fitting [13].

III. RESULTS

Transient simulations using ADS where performed for a direct conversion receiver. The training stimuli where composed of WCDMA waveforms at RF and the analog I and Q based

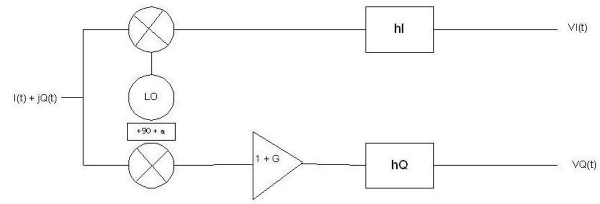

Figure 3. Simplified block diagram for down conversion.

band responses where recorded and correlated to stimulus signals using the method described in the previous section. Additional simulations where performed (using harmonic balance or transient) for the specific tests such as I-Q channel gains, phase mismatch, and intercept points. All these tests where based on out-of-sample stimuli (periodic and quasi-periodic tones) which the model was not trained on, though they covered similar frequency and amplitude ranges. The stability of the model was also checked by varying the underlying process parameters with in know process parameter limits. Typical results are shown in Figures 4 and 5.

Figure 4 shows the time domain fits for the WCDMA training set (upper right) followed by typical matches between the model predictions and direction simulation of one and two-tone test signals. The main observation here is that the model-based test appears to generate reasonable time-domain fits for test signals it was not trained on. A comparison of the power spectral density is shown in the lower left, which can be viewed as a derivative signal of the original time domain signal. Here, the in channel performance is adequate. Out of channel the model performance is poor, this is to be expected since the model was not meant to predict test metrics out of channel.

Figure 5 shows some typical results for third order intercept and I-Q channel related test metrics. The performance is adequate to pick up devices that would fall out of specification due to process parameter variations for some test metrics (less than 1% on TOI, but as great as 10% on I-Q phase mismatch). Further refinement to the modeling and system identification process is required to further improve the accuracy of test metric prediction.

We also verified these methods experimentally on a commercially available direct conversion mobile handset receiver, the QUALCOMM radioOne CDMA2000 RTR6125. Details about the receiver, including a block diagram, are available from QUALCOMM [14]. The test platform is the Verigy 93K automated tester with an Agilent PSG E8267 for RF signal generation and an Agilent PSA E4440 for baseband analog signal capture and analysis. One complication with the lack of direct access to the local oscillator in the modeling procedure. Here we post-processed the stimulus/response data to recover the phase of the LO as shown in Figure 6. This recovered phase is used for down conversion. Impairments in the LO are modeled as an additional nonlinear distortion component in the baseband signal. A time domain comparison of the model and experimental results are shown in Figure 7.

IV. CONCLUSIONS

We described a method that allows replacement of a collection of possibly redundant tests by a single stimulus/response measurement. The method uses system identification as well as strong (but easily available) prior information about the device under test to create a model used to predict a suite of test metrics. In the example shown here, a single test using a pseudo-random analog waveform is suitable to fit a model which can than be used to replace a series of tests called for test specifications. Often the bottleneck in test is not the time for individual measurements, but the transition time between measurements required for switching relays, changing ranges, and so forth. The method described here seeks to replace a conventional measurement system with a single broad band source and receiver which would be adequate for multiple tests.

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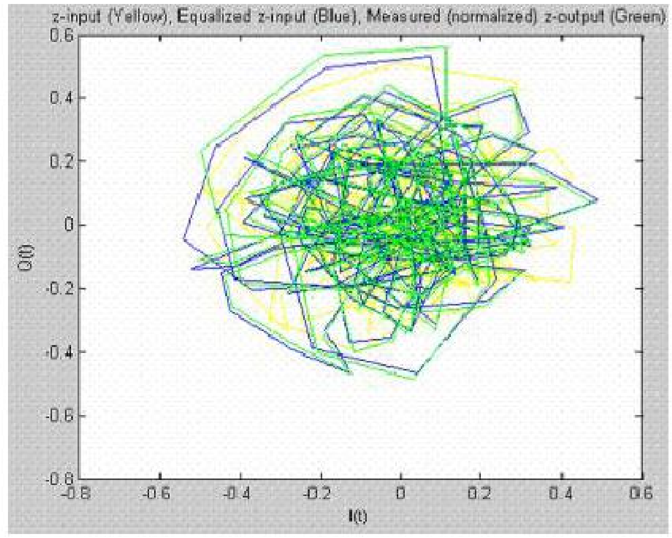

Figure 6. Recovered phase based on stimulus/response data for an experimental direct conversion receiver.

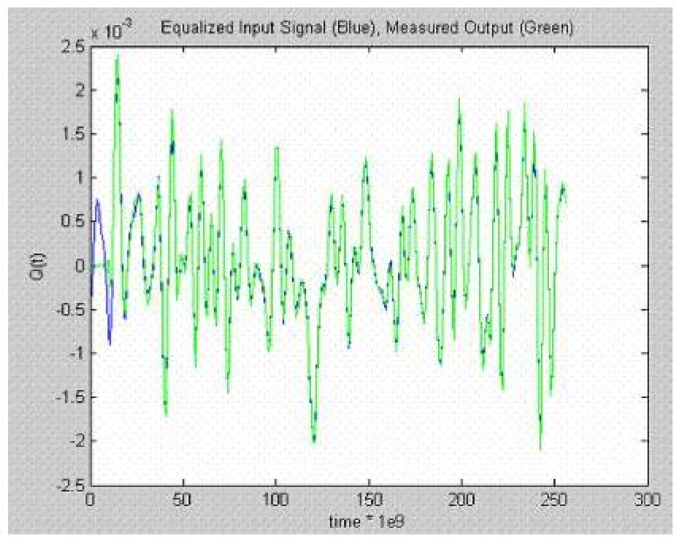

Figure 7. Comparison in time domain of baseband output for experimental and model-based test results.

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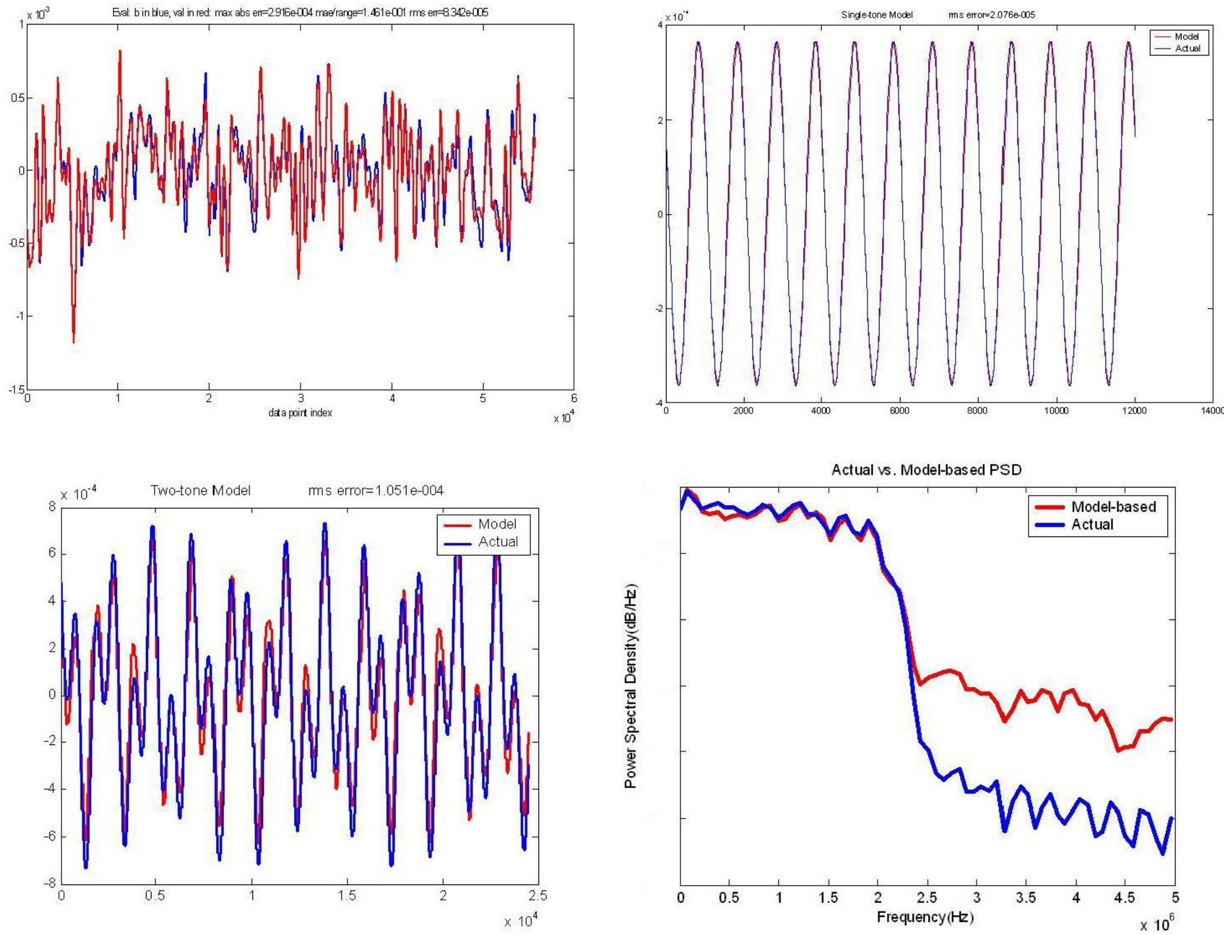

Figure 4. Time domain fit and tests (one tone, two tone, power spectrum): comparison of model-based test results and actual measured results.

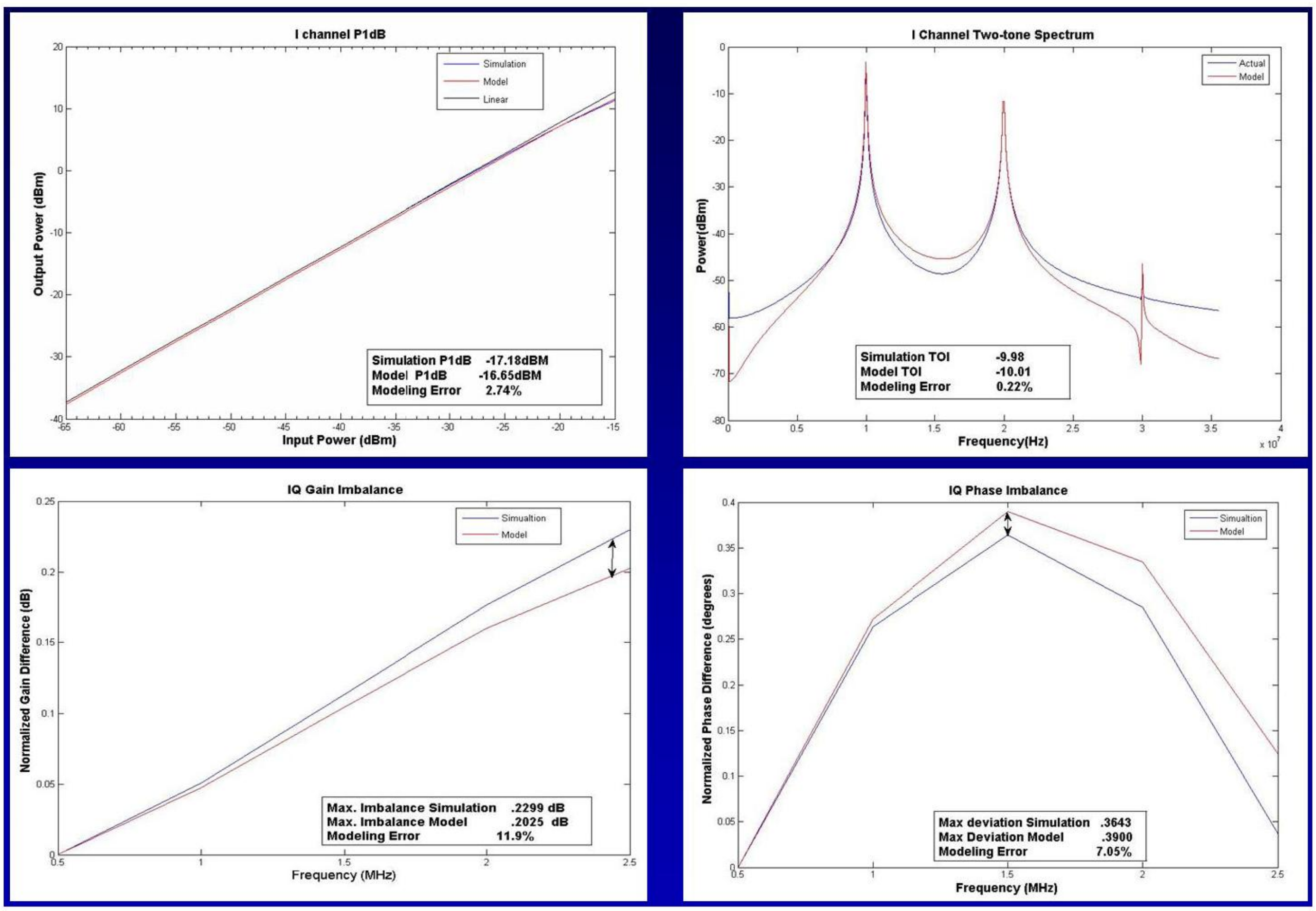

Figure 5. TOI and I-Q channel tests: comparison of model-based test results and measured results.