System Level Modelling of RF Power Amplifiers Based on Large-Signal Measurements

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Abstract— **This paper demonstrates the extraction of three different system level behavioural models of power amplifiers from large signal time domain measurements. The modelling results are evaluated using a common independent CDMA2000SR1 telecommunication input signal. The capability of the models to predict long term memory effects is also evaluated by artificially modifying the bias network in one of the PA prototypes.**

I. Introduction

The integration of more functionality, and thus complexity, in wireless transceivers, turned the traditional circuit level based simulation highly inefficient, which asked for system level analysis, and so reduced order models. Unfortunately, the simplicity of such reduced order models is only apparent when we have interacting nonlinearity and dynamics. This is the case of microwave power amplifiers (PAs) where an increasing interest has been seen to look for compact models that can reproduce their observable input-output behaviour without the need for the complete internal description [1]. Indeed, this model simplicity has a high cost in predictive capability and the measurements required for parameter set extraction, since we are no longer relying on any a-priori knowledge of the PA physics.

Therefore, a great care is paid to the selection of the model format, since not all mathematical formulations are able to reproduce every input-output mapping encountered in nature. For example, no one would try to use a linear S-parameter matrix to reproduce nonlinear behaviour, nor would one use a polynomial, or any other static function, to account for the PA fast (time constants of the order of the carrier period) or slow dynamics (time constants of the order of the inverse of the modulated signal bandwidth). Nonlinear system identification theories have shown that the model of Fig. 1 is one of these possible general formulations as long as (i) enough delays are available in the first linear dynamic block and (ii) the nonlinear static block is a universal approximator [1].

Also, because the model is built from (behavioural) input-output observations, it should be intuitive that its accuracy degrades when its response is tested for signal excitations that are farther and farther away from the signal, or signal class, used to extract it. For example, we should not expect that such a model can predict the response to a signal that exposes some PA property never tested during model extraction. Hence, excitation selection for model extraction and validation plays a vital role on the final model quality [2].

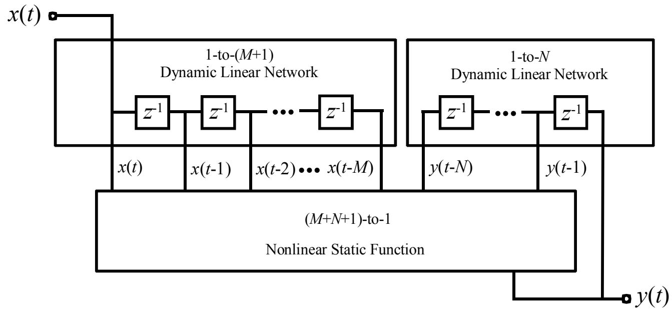


Fig. 1. General microwave PA behavioural model format.

In this paper we present several PA behavioural modelling results obtained with the two most used model formulations, and extracted with quite different excitation stimuli. Indeed, models discussed in Sections III.A and III.B are non-recurrent (N=0) and use a multidimensional polynomial for the static function. So, they are general polynomial filters or Volterra series (VS) [1]

$$y(t)=\sum_{p=1}^{P}\sum_{m_1=0}^{M}\dots\sum_{m_p=0}^{M}h_p(m_1,\dots,m_p)x(t-m_1)\dots x(t-m_p) \quad (1)$$

while the model of Section III.C is a recurrent Time-Delay Artificial Neural Network, whose output is

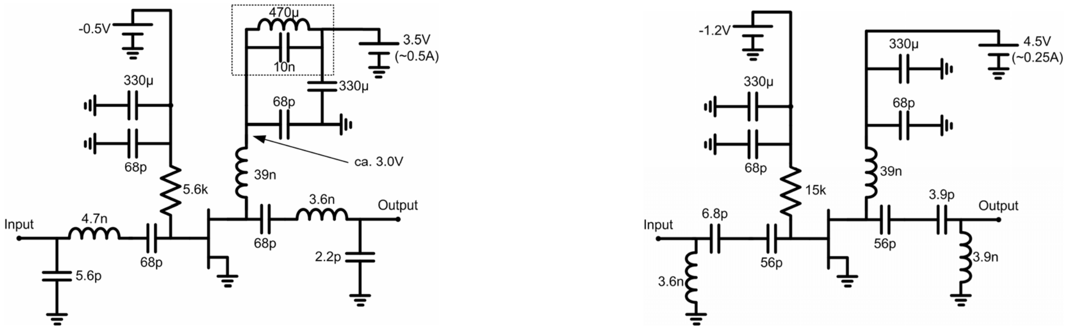
$$y(t)=b_o+\sum_{k=1}^{K}w_o(k)\,\sigma\left[u_k(t)\right], \quad (2a)$$

in which $u_k(t)=\sum_{m=0}^{M}\left[wx_k(m)x(t-m)\right]+\sum_{n=1}^{N}\left[wy_k(n)y(t-n)\right]+b_k$ (2b),

and $h_p(m_1,\dots,m_p)$, b_o, b_k, $w_o(k)$, $wx_k(m)$, $wy_k(n)$ are model parameters and $\sigma[.]$ is a sigmoidal activation function.

II. Power Amplifier Prototypes

Two 950 MHz GaAs FET PA prototypes based on low-pass and high-pass matching network topologies, respectively, were previously evaluated with respect to their differences in terms of two-tone intermodulation characteristics [3]. In this work, the bias network of the low-pass prototype was also modified by adding a resonance in the drain bias line, see Fig. 2. Thereby, adjusting the bias point, severe long term memory effects were artificially introduced in the 1.25 MHz signal bandwidth occupied by the CDMA-2000SR1 signal. This is



(a) (b)

Fig. 2. a) Modified lowpass and b) Highpass PA prototypes.

verified in Fig. 3, which shows measured two-tone distortion versus tone spacing. As desired, the modified low-pass prototype shows significant IMD variation and asymmetries, which are strong indicators for long term memory effects [4]. Conversely, the high-pass PA, whose bias line was not modified, shows an almost constant IMD, across the whole band, and regular symmetry between the sidebands.

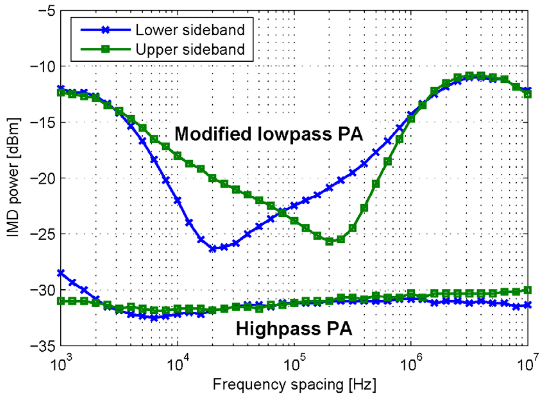


Fig. 3. Measured two-tone intermodulation distortion vs. tone-spacing for the low- and high pass PA prototypes. Total input power = 6 dBm.

III. Behavioural Model Approaches

In this section, three fundamentally different behavioural modelling approaches will be described. In particular, completely different measurement techniques are used to extract the model parameters, which also results in different predictive capabilities as is discussed in following sections.

A. Volterra series based orthogonal model (IT)

The main goal of this modelling approach is to take full profit of the generality and predictive capabilities of the Volterra series. Unfortunately, due to the known difficulty of extracting the huge number of VS parameters, we decided to construct a series that is orthogonal to a predefined stimulus. In this case, we chose a random multisine [2] because it is simple to generate and measure in a RF laboratory.

The theoretical background for the model parameters' determination was already described in [5, 6]. The obtained model is a low-pass equivalent version of the VS formulation shown in (1). Being a low pass equivalent model, it is not able to deal with the possible PA input and output mismatches. It only addresses the input-output nonlinear transfer function (the equivalent of the time-domain S_{21} in linear systems).

The modelling methodology herein proposed is also not devoted to best fit any particular response type, but envisages the general representation of the PA input-output map. Indeed, there are other modelling approaches directed to represent, with highest accuracy, a pre-defined class of responses. In those cases, the model parameter set is extracted with a signal belonging to that same excitation class. In the present situation, however, the signal used for model extraction was a random multisine, although the validation test would be made with a CDMA-2000 SR1 signal. Having statistical properties similar to those of band-limited white Gaussian noise, it is guaranteed to excite all the system input states, which allows the model to distribute its accuracy onto a broader range of input stimuli.

Unfortunately, this comes with high practical cost: a large number (thousands) of randomized phase multisines must be generated and measured on the DUT. To extract the model reported in this paper (M = 7 and P = 5, i.e. a total of 553 different parameters) a set of 5000 randomized multisines were used. The excited bandwidth was 1.25MHz, which is the bandwidth of the CDMA2000 chosen to compare the modelling approaches. Input and output isolators were used to ensure that only the desired incident and reflected waves could be seen.

B. Dynamic deviation reduction-based Volterra model (UCD)

In [7], a new format of representation for the Volterra model in the discrete time domain was proposed, in which the input elements are organized according to the order of dynamics involved in the model. This is similar to the Modified Volterra Series [8], but retains the property of linearity in the parameters of the model, as for the classical Volterra series. Based on this new representation, an effective model order reduction method was proposed, called *Dynamic Deviation Reduction* in which higher order dynamics are removed since the effects of nonlinear dynamics tend to fade with increasing order in many real power amplifiers. Unlike the classical Volterra model, where the number of coefficients increases exponentially with the nonlinearity order and memory length, in the proposed reduced-order model, the number of coefficients increases almost linearly with the order of nonlinearity and memory length. Since the model complexity is significantly reduced after dynamic-order truncation, this Volterra model can be used to accurately characterize a power amplifier with static strong nonlinearities and with long-term linear and low-order nonlinear memory effects.

In this test, both PAs were operated at 950MHz and excited by CDMA 2000 signals with several input power levels. Around 10,000 sampling data points were captured from the input and output envelope signals of the PAs by using the ADS-ESG-VSA connected solution [7]. The Volterra model was truncated to the fifth order nonlinearity, P=5, with second-order dynamics, r=2, and the memory length M=3, so that the model has 54 parameters. Since the output of the model is linear with respect to the coefficients, this model can be directly extracted by employing simple Least Squares (LS) in the discrete time domain. However, due to the nature of LS algorithm, the excitation signal must be carefully selected, so that it excites the relevant characteristics of the PA. Otherwise, the model may not converge, and may only represent certain subset of characteristics of the real system.

C. Recurrent time-delay artificial neural network (KUL)

The large-signal time-domain behavioural modelling approach applied in this work is based on the Large Signal Network Analyser (LSNA) measurements. The goal of the modelling procedure is to derive a functional relationship between the minimal set of independent and the dependent time-domain variables obtained from the measurements, leading to an accurate representation of the dynamic behaviour of the considered amplifier excited with a CDMA-2000 SR1 signal. The basic idea of this measurement-based behavioural modelling method has been described in [9]. The model's formulation that is more suitable for system level analysis, together with some important issues related with applications involving modulated signals, have been discussed in [10].

As already mentioned in Section I, the experiment design essentially determines the valid operating range of the model. Therefore when defining the measurement plan we should take into account the application and the conditions in which the extracted model is expected to work. Moreover, in this work we demonstrate that when the modelled circuit exhibits slow or long-term memory effects, the frequency-time characteristics of these effects should be accounted for when choosing the excitation stimuli and the time-domain variables used for model extractions. In this particular case this strategy can be sufficient to account for the slow-memory effects without altering the set of independent variables.

The time-domain variables required for model extraction are obtained from the LSNA measurements. The incident and scattered travelling voltage waves present in the ports of the considered amplifier are measured in the 8 MHz modulation bandwidth around the carrier frequency and its two harmonics. As the excitation, we apply a 1.6 MHz 63-tone multisine with the amplitudes and phases optimized to approximate the probability density function (PDF) of the 1.25 MHz bandwidth QPSK-modulated CDMA-2000 SR1 signal [11]. The time-domain waveforms contain 4608 samples in 0.1 ms period resulting from 96 RF periods of 48 samples each. The RF periods are evenly spaced in 0.1 ms IF period with a step of ~0.9 μs related with the longer- and shorter-term memory effect time constants identified from the two-tone test results respectively.

The data corresponding to 10 dBm, 9 dBm and 7 dBm input power levels formed training, verification and testing sets for the ANN training procedure, respectively. The model is implemented as an ANN in the form similar to (2), with the parameters b_0, b_k, $w_0(k)$, $wx_k(m)$ and $wy_k(n)$ found by optimization. The total number of 30 model parameters results from 12 hidden neurons, one output and three inputs to the network. The latter corresponds with the set of the independent variables composed of input incident travelling wave $a_1(t)$, its time derivative, and also the derivative of the output scattering travelling wave b_2(t). The choice of these variables is based on the fact that the model will be tested and verified in the transmission configuration. There will be no information given about the input/output mismatch and thus the output incident and input scattered travelling waves and their derivatives might be neglected.

IV. Power Amplifier Modelling Results

The two PAs described in Section II were tested with a 1.25 MHz bandwidth CDMA-2000SR1 input signal with 9 dBm average power. The input signal was generated using an Agilent ESG vector signal generator together with an amplifier and attenuator to reduce the effects of mismatch and signal distortion. The output signal was measured using an Agilent 54854 oscilloscope together with signal processing techniques for reduction of measurement uncertainty [12].

The output signal was also predicted using the models described in the previous section. The measured and modelled spectra are presented in Fig. 4. Fig. 5 shows the spectrum of the modelling error. Clearly, the UCD model presents smallest error, whereas the other two models are quite comparable. The difficulty in predicting the severe long term memory effects in the modified low-pass PA is mainly observed for the IT and KUL models. It is, however, important to note that the UCD model was extracted using measurements with a signal very similar to the one used during the verification.

The modelling error is also expressed in terms of normalized mean square error (NMSE) and adjacent channel leakage ratio (ACLR) in Table I.

Table I. Modelling error comparison.

	NMSE (dB)		**ACLR$_L$ (dB)**		**ACLR$_U$ (dB)**	
	LP	**HP**	**LP**	**HP**	**LP**	**HP**
IT	-15.1	-18.9	29.0	28.3	28.8	27.6
KUL	-16.0	-17.6	27.8	30.5	28.3	30.0
UCD	-31.9	-28.7	27.8	27.1	28.1	26.7
Meas.	—	—	27.6	27.3	27.7	26.5

V. Conclusions

The extraction and evaluation of three distinctly different PA behavioural models have been presented. The predictive capabilities have been evaluated using large signal time domain measurements of two different PA prototypes with a

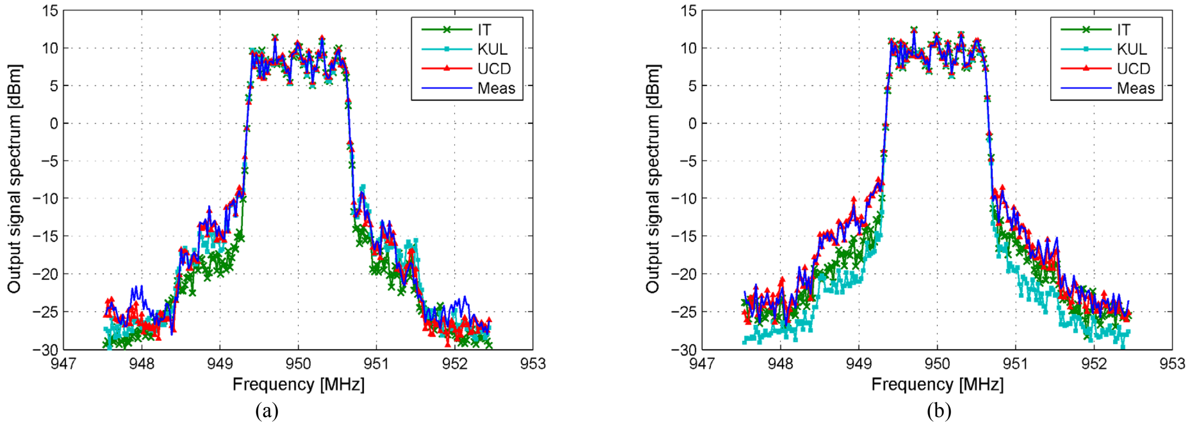


Fig. 4. Measured and modelled output power spectral density for a) Modified lowpass and b) Highpass PA prototypes

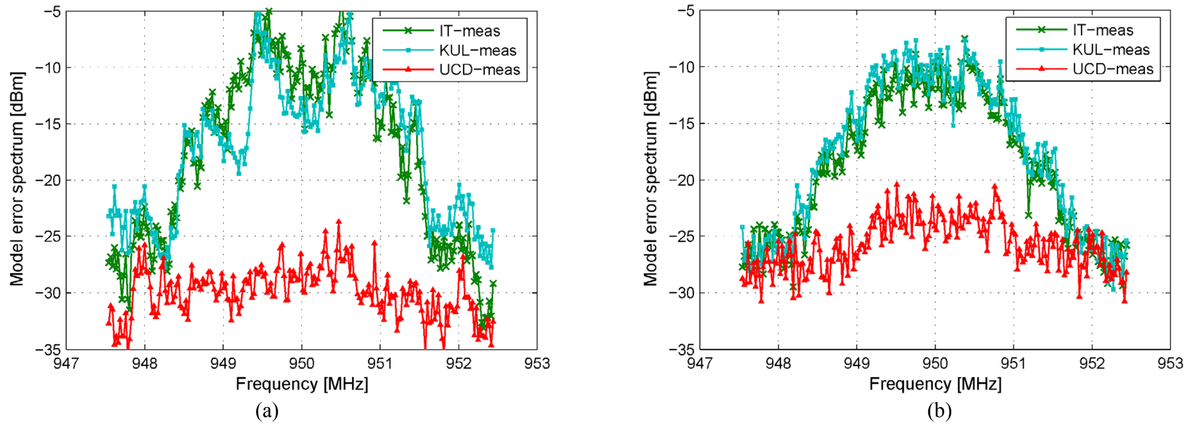


Fig. 5. Model error power spectral density for a) Modified lowpass and b) Highpass PA prototype.

common CDMA-2000 SR1 input signal. By introducing a resonance in the bias network of one of the PA prototypes, the capabilities of the models to predict long term memory effects were also evaluated. The differences between the models were found to be larger than between the PA prototypes. Further investigations will be performed to evaluate the models with different sets of input signals.

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