RF POWER AMPLIFIER BEHAVIORAL MODELING

If you are an engineer or RF designer working with wireless transmitter power amplifier models, this comprehensive and up-to-date exposition of nonlinear power amplifier behavioral modeling theory and techniques is an absolute must-have. Including a detailed treatment of nonlinear impairments, as well as chapters on memory effects, simulation aspects for implementation in commercial system and circuit simulators, and model validation, this one-stop reference makes power amplifier modeling more accessible by connecting the mathematics with the practicalities of RF power amplifier design. Uniquely, the book explains how systematically to evaluate a model's accuracy and validity, compares model types, and offers recommendations as to which model to use in which situation.

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Notation

$f(\cdot)$	general nonlinear function
$f_{\mathrm{R}}(\cdot)$	nonlinear extension of an IIR digital filter
$f_{\mathrm{D}}(\cdot)$	nonlinear extension of an FIR digital filter
t	continuous-time variable
s	discrete-time variable
T_{s}	sampling time
x	RF input signal or general input signal
y	RF output signal or general output signal
$\tilde{x}$	low-pass complex-envelope input signal
$\tilde{y}$	low-pass complex-envelope output signal
r	envelope amplitude
P	in-phase component of the envelope amplitude
Q	quadrature component of the envelope amplitude
ϕ	envelope phase
ω	angular frequency variable
f	frequency variable
ω_0	carrier angular frequency
f_0	carrier frequency
$G(\cdot)$	RF memoryless nonlinearity
$g(\cdot)$	AM–AM nonlinearity
$\Phi(\cdot)$	AM–PM nonlinearity
Re	real-part operator
Im	imaginary-part operator
$*$	convolution operator

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Abbreviations

ACEPR	adjacent-channel error power ratio
ACI	adjacent-channel interference
ACLR	adjacent-channel leakage ratio
ACPR	adjacent-channel power ratio
ADC	analogue-to-digital converter
ADS	advanced design system
AM–AM/AM–PM	AM–AM and AM–PM model or characterisation
ANN	artificial neural network
APK	amplitude phase-shift keying
ARMA	autoregressive moving average
AWG	arbitrary waveform generator
AWR-MO	Applied Microwave Research's Microwave office
AWR-VSS	Applied Microwave Research's Visual system simulator
BBACS	broadband amplifier characterisation setup
BER	bit error rate
BF	Bessel–Fourier
BPSK	binary phase-shift keying
C/I	carrier-to-intermodulation ratio
C3IM	carrier-to-third-order intermodulation product ratio
CAD	computer-aided design
CCDF	complementary cumulative density function
CDMA	code-division multiple access

CW	continuous-wave
DAC	digital-to-analogue converter
DIDO	dual-input–dual-output
DSO	digital storage oscilloscope
DSP	digital signal processing
DTD	direct-time domain
DUT	device under test
EIRP	equivalent isotropic radiated power
ESDA	electronic system design automatisation
EVM	error-vector magnitude
FCC	Federal Communications Commission
FDMA	frequency-division multiple access
FET	field-effect transistor
FFT	fast Fourier transform
FIR	finite impulse response
FOBF	Fourier-series-optimised Bessel–Fourier
FOM	figure of merit
FPGA	field-programmable gate array
GSM	global system for mobile communications
HB	harmonic balance
HEMT	high-electron-mobility transistor
IBO	input power backoff
IC	integrated circuit
IF	intermediate-frequency
IFFT	inverse fast Fourier transform
IIR	infinite impulse response
IMD	intermodulation
IMP	intermodulation product
IP	intercept point
IRF	impulse response function

I–Q	in-phase–quadrature
IS-95	Interim Standard 95, also known as cdmaOne
LDMOS	laterally diffused metal oxide semiconductor
LF	low-frequency
LNA	low-noise amplifier
LS	least-squares
LSNA	large-signal network analyser
LTI	linear time-invariant
MDL	minimum description length
MESFET	metal–semiconductor field-effect transistor
MFTD	mixed frequency- and time-domain signal representation
MIMO	multiple-input–multiple-output
MLP	multilayer perceptron
MS	modified Saleh
NARMA	nonlinear autoregressive moving-average
NARMAX	nonlinear autoregressive moving-average with exogenous input
NIM	nonlinear integral model
NL	nonlinear
NMSE	normalised mean-square error
NOCEM	non-constant envelope modulated
NPR	noise power ratio
NVNA	nonlinear vector network analyser
OBO	output power backoff
ODE	ordinary differential equation
OFDM	orthogonal frequency-division multiplexing
OOK	on/off keying
PA	power amplifier
PAE	power-added efficiency
PAPR	peak to average power ratio
PCB	printed circuit board

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PDF	probability density function
PL	percentage linearisation
PSB	Poza–Sarkozy–Berger
PSD	power spectral density
QAM	quadrature amplitude modulation
QPSK	quadrature phase-shift keying
RF	radio-frequency
RMS	root-mean-square
RRC	root-raised cosine
SAW	surface acoustic wave
SER	symbol-error rate
SISO	single-input–single-output
SNR	signal-to-noise ratio
SSPA	solid-state power amplifier
SVD	singular-value decomposition
SWANS	scalable wireless ad hoc network simulator
TDNN	time-delay neural network
TWTA	travelling-wave tube amplifier
UML	universal modelling language
VAF	variance accounted for
VCO	voltage-controlled oscillator
VDHL	very high speed IC hardware description language
VIOMAP	Volterra input–output map
VNA	vector network analyser
VSA	vector signal analyser
VSG	vector signal generator
WCDMA	wideband code-division multiple access

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Preface

This book provides a comprehensive treatment of radio-frequency (RF) nonlinear power amplifier behavioural modelling, from the fundamental concepts and principles through to the range of classical and, especially, current modelling techniques.

The continuing rapid growth of wireless communications and radio transmission systems, with their ever increasing sophistication, complexity and range of application, has been paralleled by a similar growth in research into all aspects of electronic components, systems and subsystems. This has given rise to a great variety of new and advanced technologies catering for the breadth of frequencies, bandwidths and powers expected in new and existing air interfaces and in the mobile wireless world, for the ever increasing integration of widely differing interfaces into single devices, with the future likelihood that these devices will be active on two or more interfaces simultaneously. For radio communications, or simply radio transmission systems, from the high-frequency (HF) band to the microwave and millimetrewave bands, the transmitter power amplifier (PA) is a pivotal enabling component. This is especially apparent when setting and satisfying air-interface specifications, the correct transmitted signal power levels and tolerable levels of in-band and out-of-band signal impairment. The reason for this high-profile role of the PA is that it is the major source of signal distortion and spurious signal generation, harmonics and intermodulation products. Further, it is by far the greatest energy-consuming component in the radio transmission path. Depending on the class of amplifier and the operating conditions dictated by the complexity of the signals to be amplified, its DC to RF power-conversion efficiency is generally poor, resulting in power wastage. As this wastage occurs mostly through heat dissipation, in many situations active extraction of this heat through cooling systems is necessitated, which in turn leads to further energy costs. Hence, in all applications, a reduction in energy consumption and heat dissipation through improved efficiency of the PA is a desired goal.

Technically, this increase in PA efficiency is usually achieved at the expense of increased nonlinear distortion effects. Predicting, assessing and quantifying the impact of these detrimental effects on the transmitted signals and on the radio environment requires accurate behavioural models of power amplifiers on the one hand and a detailed knowledge of the radio characteristics of the environment on the other. Accurate behavioural models are also required to support research into nonlinear impairment-reduction techniques (such as power amplifier linearisation), efficiency-improvement techniques, full transmitter and communications-link system design, investigation into new wireless communications systems and concepts (with new signal-modulation techniques and multiple-access techniques) and so forth. For such reasons RF nonlinear PA behavioural modelling has grown to become a topic of great interest for all those involved in radio communications engineering.

It is hoped that this book will provide RF research engineers in industry, research institutes and centres and also students and academics with a comprehensive resource covering this major area of wireless communications research and development engineering. Although there is an abundant literature covering different PA behavioural modelling approaches, mainly comprising specialist journals and books of international conference proceedings, there are few works dedicated to their comprehensive treatment, analysis and comparison. This work seeks to fill this gap, bringing together much of the classical treatment and modern conceptual, theoretical and algorithmic developments.

The theoretical foundations for PA behavioural modelling are presented in Chapter 1. This is a systematic overview and comparative assessment of the various approaches to RF power amplifier modelling that have received widespread attention by the scientific community. The chapter is organised into three sections, on power amplifier modelling basics, system-level power amplifier models and circuit-level power amplifier models. In the first section, a theoretical foundation to support the subsequent PA model classification and analysis is set out. The approach is to address the physical and behavioural modelling strategies and then to classify behavioural models as either static or dynamic with varying levels of complexity. Then a distinction is made between heuristic and systematic approaches, hence creating a theoretical framework for comparing different behavioural model formats with respect to their formulation, extraction and, in most cases, predictive capabilities.

Approaches to PA representations for use in system-level simulators are treated in the second section, on system-level power amplifier models. These are analytic signal- or complex-envelope-based techniques, leading to single-input–single-output (SISO) low-pass equivalent models, whose input and output are the complex functions needed to represent the bidimensional nature of amplitude and phase modulation.

The final section of this chapter, on circuit-level power amplifier models, provides an overview of behavioural models intended for use in conventional PA circuit simulators. Representing the voltage, current or power-wave signals as real entities, these models handle the complete, and computationally demanding – because of the different RF and envelope signal time scales involved – input and output signal dynamics. This includes taking into account the signals' harmonic content and, possibly, the input and output mismatches and other physical circuit features.

Having introduced and classified models according to their mathematical structures, in Chapter 2 we address other important properties and classifications of PA behavioural models that, in one way or another, are not directly related to the models themselves. These arise out of experimentally observed PA characteristics and may be grouped into those properties derived from the model structure, those introduced by the PA modelling application and those reflecting the behaviour of the observed amplifier under a specific excitation. Some of these properties may describe the same model characteristic but from different perspectives. This is borne

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in mind in the approach to their treatment here, where the aim is to provide an integrated and complete overview of behavioural models based on their properties.

Models extracted from amplifier measurements are optimised to mimic the behaviour seen in these measurements, i.e. to produce identical or near identical behavioural results. Such models, therefore, reflect influences of the particular amplifier characterisation technique. Hence an overview of typical amplifier measurement setups together with a compilation of models extracted by these means completes the treatment of PA properties in Chapter 2. The next three chapters deal with memoryless models, models with linear memory and models with nonlinear memory.

In Chapter 3 memoryless nonlinear PA behavioural models are considered; the most popular models presented and investigated are the complex power series expansion, the Saleh model in both polar and quadrature forms and the Bessel–Fourier model. Other models considered are the Fourier model, the Hetrakul and Taylor model, the Berman and Mahle model and the Wiener-based polynomial models. Static envelope characteristics, i.e. the static AM–AM and/or AM–PM characteristics, are taken as the basis for defining a behavioural model as memoryless. Some of these models are well established, though new developments and new insights keep occurring. An example of the latter, included in this chapter, is the new modified Saleh model, developed to overcome some particular weaknesses of the original Saleh model. Generally, a comparative approach is taken in parallel with the exposition of the models. All are applied to a particular memoryless-equivalent AM–AM and AM–PM (AM–AM/AM–PM) characterisation of an LDMOS amplifier amplifying a WCDMA signal, the predicted results being set against actual PA measurements. Other model aspects addressed comparatively include implementation and complexity, intermodulation product decomposition and harmonic handling capacity.

These conventional nonlinear memoryless models, based on static AM–AM and AM–PM representations, are frequency independent and can represent with reasonable accuracy the characteristics of various amplifiers driven by narrowband input signals. However, if an attempt is made to amplify 'wideband' signals, where the bandwidth of the signal is comparable with the inherent bandwidth of the amplifier, a frequency-dependent behaviour will be encountered. This phenomenon is described as a memory effect. The range of memory effects found in modern PA systems, especially higher-power solid state PAs, may be classified as linear or nonlinear or as short or long term. Knowing when and where these arise and how they contribute to system impairment is important to designers and researchers. Approaches to behavioural modelling that take account of both nonlinearities and memory effect phenomena is the theme of Chapters 4 and 5.

In Chapter 4 we focus on investigating those nonlinear models that handle memory effects (i.e. frequency-dependent behaviour) using linear filters. The models described in this chapter are structurally categorised into two-box, three-box or parallel-cascade structure. The two-box models presented are the Wiener and Hammerstein topologies, while the three-box models include the Poza–Sarkozy–Berger (PSB) model and the frequency-dependent Saleh model. These models represent some first attempts at extending the nonlinear static AM–AM models and AM–PM models to cover frequency-dependent effects. The parallel-cascade models presented in this chapter are the Abuelma'atti and polyspectral models. In these a parallel branch structure is used to describe linear memory.

Significantly more challenging is the behavioural modelling of nonlinear PAs that exhibit nonlinear memory effects. Chapter 5 contains a comprehensive overview of this topic and addresses memory polynomial models, the time-delay neural network (TDNN) model, the nonlinear autoregressive moving-average (NARMA) model, the parallel-cascade Wiener model, Volterra-series-based models and the state-space-based model. The simplest modelling approach is the memory polynomial. The introduction of non-uniform time-delay tabs yields better results. The TDNN and NARMA approaches are strongly related to the memory polynomial. In the TDNN model the memoryless nonlinear network is described by an artificial neural network. In the case of the NARMA model, the output depends not only on past values of the input but also on past values of the output. As stability may be an issue, criteria are derived to check for this.

Another way to model nonlinear PAs with nonlinear memory effects is by an extension of the Wiener modelling approach. By introducing parallel branches consisting of a linear time-invariant system followed by a memoryless nonlinear system, nonlinear memory effects can be modelled adequately. The Volterra-series-based models form a large class of models with nonlinear memory. The difficulty in computation and optimisation of the fitting parameters, e.g. the Volterra kernels, of the analytical functions for dynamic (envelope-frequency-dependent) input–output measured data is addressed. It is notable how the complexity of the model increases with increasing memory and nonlinearity order, requiring the extraction of an ever larger number of coefficients to achieve an adequate approximation. A number of extended approaches have been developed to overcome this intrinsic disadvantage of Volterra series models. A parallel FIR-based model has a reduced computational complexity. The Laguerre–Volterra modelling approach yields a reduction in the number of model parameters. The modified or dynamic Volterra model aims to handle higher levels of nonlinearity. Finally, a relationship between Volterra models and TDNN models is presented.

Memory polynomial models and Volterra-series-based models of a lower degree are only really efficient for systems with memory but which are weakly nonlinear. However, state-space-based behavioural models are not so restricted. The dynamics of the PA are determined directly from time-series data, resulting in a compact, accurate and transportable model. Ways in which multisine excitations can render model development more efficient are also presented.

In Chapter 6 PA model validation and comparison are addressed. As PAs are in general complex dynamic systems that combine both short- and long-term memory effects with nonlinear phenomena, there is quite a variety of ways to approach questions of validation and comparison. In contrast with linear systems with memory, where superposition holds, nonlinear dynamical systems must be 'locally' modelled and validated. Therefore, test signals and model comparison criteria must be carefully chosen to suit a particular set of typical operating conditions. In this chapter we set down suitable figures or characteristics of merit (metrics) for model performance comparison in different telecommunication-application contexts. Our overall goal is to present concepts in ways that will help a reader to formulate suitable figure(s) of merit for his or her application.

A two-part approach is taken. General figures of merit (FOMs) are presented first and the main concepts regarding their applicability are explained. Although most of the proposed metrics can be generalised for sampled and or stochastic signals, only deterministic continuous-time signals are considered here. Starting from a general time-domain metric, several variants are proposed each of which is specially suitable for a certain measurement setup. Then more realistic applications are considered. Here most of the proposed figures of merit are formulated for sampled (i.e. discrete-time) signals and in terms of statistical measures such as the covariance and the power spectral density. The stochastic-process approach is seen as potentially useful for modern measurement instruments and system simulators, where complex telecommunication standards test signals are usually characterised statistically. This part of Chapter 6 includes an application example in which different figures of merit are compared.

Simulation tools are widely used for designing and analysing complex communications systems. In Chapter 7, the final chapter, an overview of aspects of system simulation is provided with a view to the integration of RF power amplifier behavioural models into such simulations. Generally communications simulation tools seek to describe the operating characteristics and performances of a complete communications link, whether simple or complex, and to mimic through mathematical models all the analogue and digital signal-processing activities that occur in the real system, whether at baseband, intermediate or radio frequencies. Here distinctions between the different forms of simulation encountered in the telecommunication field are made and examples of the associated software products, mainly commercial ones, are presented. In this way the kind of full-system simulations that are relevant to the behavioural modelling of RF power amplifiers is highlighted.

Following this, in Section 7.3, a general overview of analogue signal behavioural simulators for wireless communication systems, together with figure of merit considerations in behavioural simulations, is presented. First, an explanation of some relevant simulation terminology is given. In this overview distinctions are made between circuit-level and system-level simulations, both of which are closely allied in RF PA behavioural modelling. For the former, harmonic-balance simulation, circuit-envelope simulation and mixed-signal high-frequency IC circuit-level simulation are briefly described and the respective contexts of their application set out.

As this book's focus is on system-level simulation, the latter part of Chapter 7 is concerned mainly with aspects relevant to the theme of the book. These include analogue signal representation, sampling and processing considerations, sampling rate issues – including multirate sampling – and signal decomposability. Continuous-in-time and finite-time-window time-domain simulation modes are also considered. An example of a general schema for the computation flow and execution of a communications-link simulation at system level is also given. This could be considered to be a heterogeneous simulation, or in this case 'co-simulation', as it integrates digital-logic and analogue signal system-level models of computation.

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