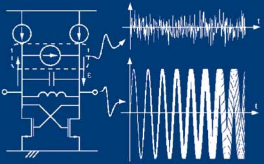
SYSTEMATIC MODELING AND ANALYSIS OF TELECOM FRONTENDS AND THEIR BUILDING BLOCKS

Piet Vanassche, Georges Gielen
and Willy Sansen



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to my Parents

Foreword

Analog circuits are fascinating artifacts. They manipulate signals whose information content is rich compared to digital signals that carry minimal amount of information; they are delicate in that any perturbation due to parasitic elements, to delays, to interactions with other elements and with the environment may cause a significant loss of information. The difficulty in dealing with these artifacts is to protect them from all possible attacks, even minor ones, from the physical world. The irony is that they are often used to funnel information from and to the physical world to and from the abstraction of the digital world and for this function, they are irreplaceable. No wonder then that analog designers form a club of extraordinary gentlemen where art (or magic?) rather than science is the shared trade. They are difficult to train since experience and intuition are the traits that characterize them. And they have difficulties in explaining what is the process they use to reach satisfactory results. Tools used for design (simulation) are mainly replacing the test benches of an experimental lab. However, the growing complexity of the integrated systems being designed today together with the increasing fragility of analog components brought about by shrinking geometries and reduced power consumption is posing severe challenges to traditional analog designers to produce satisfactory results in a short time. At the same time, the need for experienced analog designers has increased constantly since almost all designs, because of integration, do contain analog components. This situation has created a strong interest in developing design methodologies and supporting tools that are based on rigorous, mathematically literate, approaches. Doing so will make it possible to leverage the expertise of seasoned analog designers and to train new generations faster and better.

In the past, several attempts have been made in academia and industry to create these methodologies and to extend the set of tools available. They have had questionable acceptance in the analog design community. However, recently, a flurry of start-ups and increased investment by EDA companies in novel tools signal a significant change in market attention to the analog domain. I personally believe that to substantially improve quality and design time, tools are simply insufficient. A design methodology based on a hierarchy of abstraction layers, successive refinement between two adjacent layers, and extensive verification at every layer is necessary. To do so, we need to build theories and models that have strong mathematical foundations. The analog design technology community is as strong as it has ever been. Mathematically astute researchers are advancing the state of the art of simulation technology at a pace as fast as I have ever seen in my entire career. Reduced order modeling, relaxation-based techniques, Krylov subspace accelerations have made it possible to verify relatively large circuits with a degree of accuracy that was unthinkable only a few years ago. At the same time, (semi-) automatic layout and parametric optimization for analog circuits have made it in the commercial world. Yet, much research still needs to be done to bring productivity at the appropriate level. As we move towards submicron designs, there is an increasing fear that second-order physical effects can possibly not be compensated for challenging analog components. Hence, the benefits of integration may not be enough to warrant the increased design problems unless significant advances are made to build analog circuits that are robust with respect to submicron undesirable effects.

RF circuits are even more difficult to deal with. Next generation wireless devices are likely to be multi-standard (they are often referred to as software-defined radios) and pose two fundamental challenges: the design of the multi-frequency RF front-end and the reconfigurability needed at base-band. At this time, there has not been a satisfactory design that could yield a successful industrial product. It is safe to say that a good part of the reasons why this is so resides in the lack of methodologies and tools.

This book is about modeling, analysis and verification of RF circuit behavior addressed in a rigorous way. It is directed to a category of engineers who are between design and EDA. It has a good tutorial dimension so that it can be used in a course. In particular, the simple description in plain words of the essence of the different methods, this before diving into the mathematical details, makes reading this book a pleasant experience without sacrificing precision and rigor. Its strength is in its informed review of linear periodically time varying system analysis and the analysis of oscillator dynamics, including phase noise in oscillators. Both topics are essential in the design of analog and RF circuits.

Alberto Sangiovanni-Vincentelli

Contributing Authors

Piet Vanassche received the MSc and PhD degrees in Electrical Engineering from the Katholieke Universiteit Leuven in 1997 and 2003 respectively. His Ph.D. research dealt with techniques for high-level exploration and trade-off analysis for mixed signal telecommunication systems. For this work he obtained a fellowship from the Institute for Science and Technology (IWT). His research interests are in simulation and synthesis of telecommunication systems, network analysis, control theory and engineering education. Currently, he is working for Siemens on advanced process control. He is a member of IEEE.

Georges Gielen received the MSc and PhD degrees in Electrical Engineering from the Katholieke Universiteit Leuven in 1986 and 1990 respectively. He is now a full–time professor at the Katholieke Universiteit Leuven. His research interests are in the design of analog and mixed-signal integrated circuits, and especially in analog and mixed-signal CAD tools and design automation (modeling, simulation and symbolic analysis, analog synthesis, analog layout generation, analog and mixed-signal testing). He has authored or coauthored two books and more than 160 papers in edited books, international journals and conference proceedings. He regularly is a member of the Program Committees of international conferences (ICCAD, DAC, DATE, ...), he is a Deputy Editor of the IEEE Transactions on Circuits and Systems, part II, and is a member of the Editorial Board of the Kluwer international journal on Analog Integrated Circuits and Signal Processing. He is a member of the Board of Governors of the IEEE Circuits and Systems (CAS) Society, and is the Chairman of the IEEE Benelux CAS Chapter. He was the 1997 Laureate of the Belgian Royal Academy of Sciences, Literature and Arts, in the category of engineering sciences. He also received the 1995 Best Paper award of the John Wiley international journal on Circuit Theory and Applications. He is a Fellow of IEEE.

Willy Sansen has received the MSc degree in Electrical Engineering from the Katholieke Universiteit Leuven in 1967 and the PhD degree in Electronics from the University of California, Berkeley in 1972. In 1969 he received a BAEF fellowship. In 1972 he was appointed by the National Fund of Scientific Research (Belgium) at the ESAT laboratory of the K.U.Leuven, where he has been a full professor since 1980. During the period 1984-1990 he was the head of the Electrical Engineering Department. Since 1984 he has headed the ESAT-MICAS laboratory on analog design, which counts about fifty members and which is for 75 % active in research projects with industry. He is a fellow of the IEEE and is a member of several boards of directors. In 1978 he was a visiting professor at Stanford University, in 1981 at the EPFL Lausanne, in 1985 at the University of Pennsylvania, Philadelphia and in 1994 at the T.H. Ulm. Prof.Sansen is a member of several editorial and program committees of journals and conferences. He is cofounder and organizer of the workshops on Advances in Analog Circuit Design in Europe. He is a member of the executive and program committees of the IEEE ISSCC conference. He is program chair of the ISSCC-2002 conference. He has been involved in design automation and in numerous analogue integrated circuit designs for telecom, consumer electronics, medical applications and sensors. He has been supervisor of over forty PhD theses in these fields. He has authored and coauthored eleven books and more than 550 papers in international journals and conference proceedings.

Contents

Symbols and Abbreviations

Conventions

We use the following notations for the scalars, vectors and matrices:

x, X	scalar, slanted lower- and upper-case letters
$\mathbf{x}$	vector, bold lower-case letters
$\mathbf{X}$	matrix, bold upper-case letters. Sometimes, this is also used to denote a vector in its interpretation of a matrix with a single column.
$X_{i,j}$	matrix element located at the i-th row and the j-th column
$\tilde{\mathbf{X}}$	harmonic transfer matrix, bold upper-case letters with a tilde on top
$\overline{x}$, $\overline{\mathbf{x}}$	averaged scalar- or vector-quantity corresponding to x, $\mathbf{x}$
$x^*, \mathbf{x}^*, \mathbf{X}^*$	complex conjugate of a scalar, vector or matrix

Operators

$\lvert \cdot \rvert$	Absolute value of a real number or modulus of a complex number
$\lVert \cdot \rVert_p$	p-norm of a vector or matrix
$\lVert \cdot \rVert$	Shorthand notation for the two-norm of a vector or matrix
$\mathcal{F}\{\cdot\}$	Fourier-transform operator
$\mathcal{L}\{\cdot\}$	Laplace-transform operator
$\mathrm{Im}\{\cdot\}$	Imaginary part of a complex number
$\mathrm{Re}\{\cdot\}$	Real part of a complex number

Symbols

$[a,b]$	interval of real numbers located between a and b.
A	oscillating signal's amplitude
C	symbol for a capacitance
f	frequency in [Hz]
G	symbol for a conductance
$\mathbf{I}$	unity matrix
$\mathbf{I}_N$	unity matrix belonging to $\mathbb{R}^{N \times N}$
j	complex number that equals $\sqrt{-1}$
L	symbol for an inductance
$O(\varepsilon^n)$	the Landau symbol also called big-O. A function $f(\varepsilon)$ is said to be $O(\varepsilon^n)$ if $\exists K > 0 : \lvert f(\varepsilon) \rvert < A \lvert \varepsilon^n \rvert$
$\mathbf{p}$	state vector of an oscillator's core system

R	symbol for a resistance
s	Laplace transform variable (complex frequency variable)
t	time
ε	perturbation variable
$\Phi(t,\tau)$	autocorrelation function of a non-stationary stochastic process $n(t) \in \mathbb{R} \to \mathbb{R}$. It is defined as $\Phi(\tau) = E\{n(t)n(t-\tau)\}$. If $n(t)$ is stationary, then $\Phi(t,\tau) = \Phi(\tau)$ does not depend on t.
θ	oscillating signal's phase
σ	Standard deviation of a stochastic variable
τ	normalized time
ω	(angular) frequency in [rad/sec]
$\mathbb{C}$	set of complex numbers
$\mathbb{R}$	set of real numbers
$\mathbb{Z}$	set of integer numbers

Abbreviations

CAD	Computer-Aided Design
CMOS	Complementary Metal Oxide Semiconductor
CT-LTI	Continuous-Time Linear Time-Invariant
DAE	Differential Algebraic equation
DCS	Digital Cellular System
DT-LTI	Discrete-Time Linear Time-Invariant
EDA	Electronic Design Automation
FPGA	Field Programmable Gate Array
HTF	Harmonic Transfer Function
HTM	Harmonic Transfer Matrix
HPSD	Harmonic Power Spectral Density
IC	Integrated Circuit
IF	Intermediate-Frequent
ISF	Impulse Sensitivity Function
LNA	Low-Noise Amplifier
LPTV	Linear Periodically Time-Varying
LTI	Linear Time-Invariant
LTV	Linear Time-Varying
LO	Local Oscillator
MIMO	Multi-Input Multi-Output
MOS	Metal Oxide Semiconductor
MOST	MOS Transistor
ODE	Ordinary differential equation
PAM	Pulse Amplitude Modulation
PCA	Principal Component Analysis

PDF	Probability Density Function
PFD	Phase-Frequency Detector
PLL	Phase-Locked Loop
PPV	Perturbation Projection Vector
PSK	Pulse Shift Keying
PSD	Power Spectral Density
QPSK	Quadrature Pulse Shift Keying
RF	Radio Frequent
RMS	Root Mean Square
SAW	Surface Acoustic Wave
SISO	Single-Input Single-Output
SPICE	Name of a circuit simulator originally developed at Berkeley
SPICE-like	In this text, the word "SPICE-like" is used to indicate simulation algorithms that either build on a Runge-Kutta method or on numerical differentiation formulas.
VCO	Voltage-Controlled Oscillator
Verilog	A language to describe the operation of digital electronic systems and circuits.
Verilog-AMS	A language to describe the operation of mixed-signal electronic systems and circuits
VHDL	Very high speed integrated circuit Hardware Description Language. A language to describe the operation of digital electronic systems and circuits.
VHDL-AMS	Very high speed integrated circuit Hardware Description Language with Analog and Mixed-Signal extensions. A language to describe the operation of mixed-signal electronic systems and circuits.
WLAN	Wireless Local Area Network

Chapter 1

Introduction

To those who do not know mathematics it is difficult to get across a real feeling as to the beauty, the deepest beauty, of nature ... If you want to learn about nature, to appreciate nature, it is necessary to understand the language that she speaks in. —*Richard Feynmann*

Mathematics is too important to be left to the mathematicians.
. —*David Hestenes*

The ability to analyze system or circuit behavior is one of the key requirements for successful design. To put an idea to work, a designer needs both the knowledge and tools for analyzing the behavior of that new system architecture or that experimental circuit topology. Design decisions are grounded on the results obtained from analysis.

Producing dedicated methods for analyzing each particular problem at hand is of course inefficient. It's like reinventing the wheel time and again. Therefore, successful methods should be applicable to large classes of system and circuit behavior. This implies a classification that makes abstraction of the underlying implementation details. This process of abstraction can be considered as a formalization of design knowledge. This formalization is important for two reasons: in the short run, it speeds up the future design of similar systems by enabling us to reuse exsiting methods; in the long run, it eases a transfer of knowledge to generations to come.

This book reports on research in the field of methods for modeling and analysis of telecommunication frontends and their building blocks. In doing so, it deals with fundamental theory and algorithms for behavioral model extraction.

1.1 Structured analysis, a key to successful design

1.1.1 Electronics, a competitive market

Since the birth of the first transistor at Bell-Labs (1947) over the creation of the first integrated circuit (IC) at Texas Instruments (1958), electronics has experienced a tremendous growth, both technologically and economically. Fig. 1.1 shows both the evolution of the transistor dimensions and the transistor count of the Intel processors over the last couple of decades. This gives a clue as to the tremendous pace with which technology evolves. With the latest Intel Pentium 4 containing over 100 million transistors

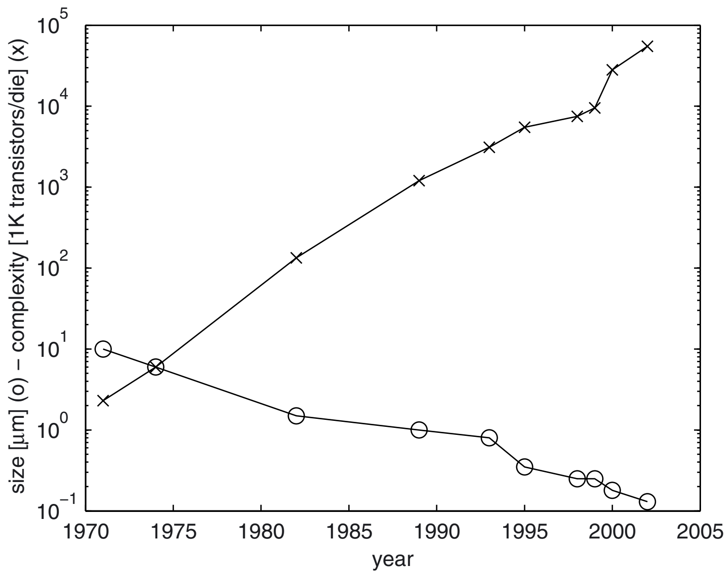

Figure 1.1: Evolution of transistor sizes and number of transistors per die for the Intel processor [source: Intel].

and with the first 1 billion transistor processor expected by 2007, integrating complex functionalities on a single die is becoming reality.

Packing more transistors onto a single chip has resulted into a dramatic cost reduction. Fig. 1.2 shows that the average transistor cost drops exponentially with time. This price evolution drives a huge number of commercial applications, making them affordable for mass markets. These applications have pervaded almost all aspects of our daily lives: computers are used to run complex administrations; electronic control systems are omnipresent, from chemical plants to automobiles; electronic signal processing has made global communication a reality.

As a consequence of these successes and of many years of high-paced growth, the electronics industry has become a highly competitive business. There are a lot of companies that want market share. Often, the first company to offer a particular product at a reasonable price acquires a substantial share in overall sales. A short time-to-market is therefore of vital importance in being successful. The electronics industry is a business where complex systems need to be developed in a minimum of time.

1.1.2 Analog design: A potential bottleneck

In order to cope with the requirements of a demanding market, systems are made highly programmable. This is accomplished using field programmable gate arrays (FPGAs), micro-processors and reconfigurable logic. Introducing software components on chip