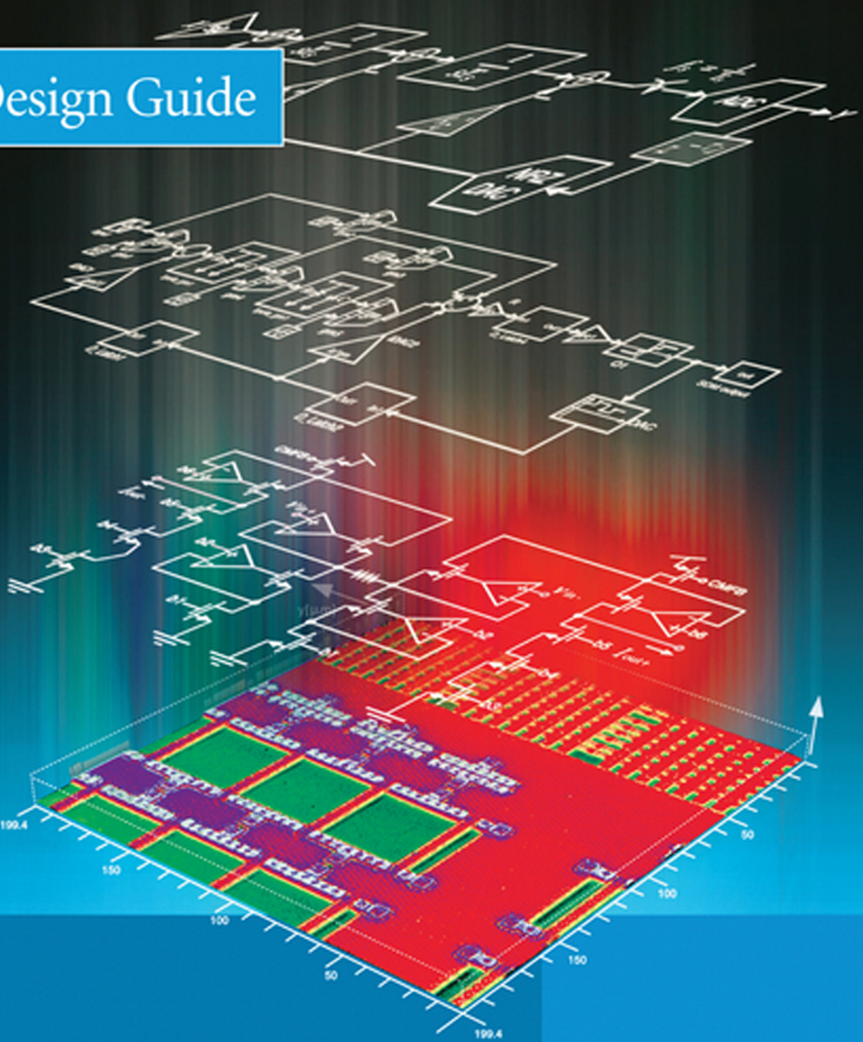
José M. de la Rosa | Rocío del Río

CMOS Sigma-Delta Converters

Practical Design Guide



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PRACTICAL DESIGN GUIDE

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This book is dedicated to the memory of my son José Manuel

José M. de la Rosa

To my wife Visi, my daughter María, my son Jaime,
my parents Carmen and Juan, and my parents-in-law
María Luisa and José Antonio

José M. de la Rosa

To my husband Juanan and my son Mario

Rocío del Río

“If you love what you do and are willing to do what it takes, it’s within your reach. And it’ll be worth every minute you spend alone at night, thinking and thinking about what it is you want to design or build. It’ll be worth it, I promise.”

Steve Wozniak (*iWoz*, 2006)

Contents

List of Abbreviations

$\Sigma\Delta$	Sigma-delta
$\Sigma\Delta$M	Sigma-delta modulator
AAF	Antialiasing filter
AC	Alternate current
A/D	Analog-to-digital
ADC	Analog-to-digital converter
ADSL	Asymmetric digital subscriber line
AMPS	Advanced mobile phone system
ASIC	Application-specific integrated circuit
BB	Baseband
BE	Backward-Euler
BGA	Ball grid array
BP	Band-pass
BP-$\Sigma\Delta$M	Band-pass sigma-delta modulator
BPF	Band-pass filter
CAD	Circuit aided design
CDMA	Code division multiple access
CDS	Correlated double sampling
CLA	Clocked averaging
CMFB	Common-mode feedback
CMOS	Complementary MOSFET
CPU	Central processing unit
CS	Current-steering
CT	Continuous-time
CT-$\Sigma\Delta$M	Continuous-time sigma-delta modulator
D/A	Digital-to-analog
DAC	Digital-to-analog converter
DC	Direct current
DCL	Digital cancelation logic
DEM	Dynamic element matching
DMT	Discrete multitone

DNL	Differential nonlinearity
DOR	Digital output rate
DR	Dynamic range
DRC	Design rule checker
DSP	Digital signal processor
DT	Discrete-time
DT-ΣΔM	Discrete-time sigma-delta modulator
DVB	Digital video broadcasting
DVB-H	Digital video broadcasting - handheld
DWA	Data weighted averaging
EDGE	Enhanced data-rates for global evolution
ELD	Excess loop delay
ENOB	Effective number of bits
ESD	Electrostatic discharge
FE	Forward-Euler
FFT	Fast Fourier transform
FIR	Finite impulse response
FOM	Figure of merit
FS	Full scale
GB	Gain-bandwidth product
GPS	Global positioning system
GSM	Global system for mobile communications
GUI	Graphic user interface
H-ΣΔM	Hybrid sigma-delta modulator
HD	Harmonic distortion
HDL	Hardware description language
HRZ	Half-delay return-to-zero
IBN	In-band noise power
IC	Integrated circuit
IF	Intermediate frequency
IIP	Input-referred intercept point
IIR	Infinite impulse response
IIT	Impulse-invariant transformation
ILA	Individual level averaging
IM	Intermodulation distortion
INL	Integral nonlinearity
I/O	Input–output
I/Q	Inphase/quadrature
ISI	Intersymbol interference
ITF	Integrator transfer function
LDI	Lossless discrete integrator
LNA	Low-noise amplifier
LP	Low-pass

LP-ΣΔM	Low-pass sigma-delta modulator
LPE	Layout parasitic extractor
LPF	Low-pass filter
LSB	Least significant bit
LTE	Long term evolution
LTCC	Low-temperature co-fired ceramic
LTI	Linear time-invariant
LVS	Layout versus schematic
MASH	Multistage noise shaping
MEX	MATLAB executable
MiM	Metal-insulator-metal
MoM	Metal-oxide-metal
MOS	Metal-oxide-semiconductor
MOSFET	MOS field-effect transistor
MOST	MOS transistor
MR	Multirate
MR-ΣΔM	Multirate sigma-delta modulator
MTPR	Multitone power ratio
nMOS	n-channel MOSFET
NRZ	Nonreturn-to-zero
NTF	Noise transfer function
OL	Overload level
OS	Output swing
OSR	Oversampling ratio
OTA	Operational transconductance amplifier
PCB	Printed circuit board
PDF	Probability density function
PDM	Pulse-density modulation
PLL	Phase-locked loop
pMOS	p-channel MOSFET
PSD	Power spectral density
PWL	Piece-wise linear
PWM	Pulse-width modulation
QFP	Quad flat package
RF	Radio frequency
RTF	Resonator transfer function
RZ	Return-to-zero
SAR	Successive approximation register
SC	Switched-capacitor
SDR	Software-defined radio
SFDR	Spurious-free dynamic range
S/H, S&H	Sample and hold

SI	Switched-current
SMASH	Sturdy multistage noise shaping
SMD	Surface-mount device
SNR	Signal-to-noise ratio
SNDR	Signal-to-noise-plus-distortion ratio
SQNR	Signal-to-quantization-noise ratio
SoC	System on chip
SR	Slew rate
STF	Signal transfer function
TDC	Time-to-digital converter
TEQ	Time-encoding quantizer
THD	Total harmonic distortion
UGBW	Unity gain bandwidth
UMTS	Universal mobile telecommunications system
USMR	Upsampling multirate
USTF	Unity signal transfer function
VCO	Voltage-controlled oscillator
VCRO	Voltage-controlled ring oscillator
V/I	Voltage-to-current
WCDMA	Wideband code division multiple access
WiMAX	Worldwide interoperability for microwave access
WLAN	Wireless local area network

Preface

Sigma-Delta modulators (ΣΔMs) have become one of the best choices for the implementation of analog/digital interfaces integrated in CMOS technologies. Compared to other kinds of analog-to-digital converters (ADCs), ΣΔMs cover the widest conversion region of the resolution-versus-bandwidth plane, being the most efficient solution to digitize very diverse types of signals in an increasing number of application scenarios, which span from high-resolution low-bandwidth data conversion (like digital audio, sensor interfaces, and instrumentation) to ultra-low power biomedical systems and medium-resolution broadband wireless communications. This versatility, together with their robustness and their simplicity in many practical situations, has motivated that more and more engineers today consider ΣΔMs as a first choice for their research projects and their industrial products.

The first idea underlying the operation of ΣΔMs was patented by Cutler in 1960 [1], although its application to the construction of data converters was first reported in the published literature by Inose *et al* in 1962 [2]. The operation of ΣΔMs is relatively simple to describe, although sometimes difficult to analyze. Essentially, the fundamental principle behind ΣΔMs is based on the combination of two signal processing techniques, namely *oversampling* and quantization *noise shaping*. The former consists of taking the signal samples at a higher rate than the one dictated by the Nyquist sampling theorem. These samples are commonly quantized with a large error by using a low-resolution quantizer. The resulting oversampled quantization error is filtered in the modulator feedback loop, so that its frequency spectrum is *shaped* in such a way that a large portion of its power is pushed out of the signal band, where it is removed by a digital filter. The outcome of the combined action of oversampling and noise shaping allows ΣΔMs to achieve a high-precision digitization by using a low-resolution coarse quantizer. Therefore, unlike other kinds of ADC architectures that require high-precision analog circuits, ΣΔMs trade the accuracy of their analog circuitry by the speed of digital signal processing, thus achieving a higher degree of insensitivity to circuit error mechanisms and potentially benefiting from CMOS technology evolution towards the nanometer scale.

Prompted by the mentioned benefits and fueled by technology downscaling and industry trends in consumer digital electronics, the original concept of noise shaping described above has evolved over the last five decades through many ΣΔM generations, giving rise to a pleiad of architectures, circuit and system design techniques, and a number of Integrated Circuits (ICs), which have pushed the state-of-the-art on ΣΔMs forward, yielding to innovative research results and successful industry products. All these advances and research works have lead (and continue doing so) to a vast amount of technical literature. Indeed, since the publication of pioneer works like the widely cited papers written by Candy [3, 4] and Boser and Wooley [5], the number of publications has increased significantly including hundreds of patents, thousands of research papers, some tutorial papers [6–8], as well as tens of introductory and specialized monographs [9–29]. However, with so much material and abundance of technical information published, many designers—particularly novel designers and also some experienced designers focused on a specific subtopic of ΣΔMs—may become disoriented and lost. This has motivated some authors to put all these pieces of information together in a comprehensive and systematic way.

Apart from the earlier books aiming to catalogue the existing publications on ΣΔMs [9], one of the first attempts to present a guide for ΣΔM designers is the book edited by Norsworthy *et al* in 1997 [10], also known as "the yellow book" by the ΣΔM community. This book deals with a number of important subjects in ΣΔMs and it was contributed by a number of experts in the field, thus making it more difficult to present its contents in a coherent and consistent way. With this objective in mind, some authors have put their effort on writing tutorial monographs dealing with the systematic design of ΣΔMs.

Among others, the book written by Schreier and Temes, published in 2005 [21], often named "the green book", has become one of the most popular books on ΣΔ converters. This book provides an excellent and comprehensive treatment of ΣΔMs, their operating principles, and main architectures, presenting several design examples constructed using the well-known Schreier's MATLAB toolbox [30]. Although some examples of continuous-time (CT) circuit implementations are given, the book mainly focuses on system-level description, considering a switched-capacitor (SC) implementation. Some other remarkable examples are the book written by Medeiro *et al* in 1999 [13]—focused on the systematic design of SC ΣΔMs—and the book of Ortmanns and Gerfers [22] published in 2006, which is still one of the most complete monographs on CT ΣΔMs reported to date. All these books, as well as other monographs reported in the technical literature, give a partial view of ΣΔMs, paying more attention to some particular aspects of the design of ΣΔMs, and/or a type of architecture, circuit technique, or application.

In this scenario, this book attempts to cover some of these knowledge gaps, by providing a broader and systematic description of the *universe* of ΣΔMs, their diverse types of architectures, circuit techniques, analysis and synthesis methods and CAD tools, as well as their practical design considerations. From this perspective, the book has a twofold purpose. First, it constitutes a unique monograph that results from compiling the enormous number of technical and research works reported to date on the topic of ΣΔMs, and presents the results of such a compilation in a didactical, pedagogical, and intuitive style. The second main objective and a key feature of this book is to serve as a *practical guide for designers*, putting emphasis on explaining practical design issues involved in the whole design flow of ΣΔMs: from specifications to chip implementation and characterization. To this end, a *top-down* approach is followed, presenting the contents in a hierarchical way; that is, going from theoretical fundamentals, system-level design equations, and behavioral models to circuit, transistor-level, and physical implementation, in order to provide readers the necessary understanding and insight into the recent advances, trends, and challenges involved in the design of state-of-the-art ICs.

Indeed, it is the top-down approach adopted in this book that inspires the hierarchical way in which the contents are organized. Thus, following this introduction, Chapter 1 begins from top, giving an introductory survey of ΣΔMs, their principles of operation, fundamental architectures, analysis and synthesis methods, as well as a taxonomical description of the diverse variety of practical ΣΔM topologies, the nature of signal (low-pass and band-pass), as well as the dynamics involved (either discrete-time or continuous-time). In this chapter ΣΔMs are considered ideal systems, except for their inherent quantization error. Chapter 2 descends one level in the modulator hierarchy to analyze the effect of main circuit error mechanisms as well as architectural and timing nonidealities, considered in both SC and CT circuit implementations. The mathematical models, analytical procedures, and design guidelines described in this chapter provide sufficient understanding of the main practical problems affecting the performance of ΣΔMs in practice.

The knowledge derived from the first two chapters is presented in this book as an essential part of the systematic *top-down/bottom-up* synthesis methodology of ΣΔMs, that is described in Chapter 3. This chapter analyzes different strategies for the high-level modeling and simulation of ΣΔMs, focusing on the so-called *behavioral modeling and simulation* techniques. A step-by-step procedure to develop efficient behavioral models in the MATLAB/SIMULINK environment is described and illustrated with a number of examples of the main ΣΔM building-block models. As an application, a time-domain behavioral simulator named SIMSIDES, is described and applied to the high-level sizing and verification of some case studies. The contents of this chapter are extended and complemented in Appendixes A and B. Appendix A gives a more complete user guide of SIMSIDES and Appendix B provides an overview of all behavioral models and libraries included in this simulator.

Chapter 4 moves farther down from the system-level description given in previous chapters to the circuit and physical level. This chapter provides a number of necessary design recommendations and practical recipes to complete the design flow of a ΣΔM, showing the step-by-step methodology to transform a behavioral-model description given in Chapter 3 into an electrical schematic initially based on macromodels, and then implemented with transistors, and finally concluding the design cycle with the layout and chip implementation. Plenty of examples, case studies, and simulation test benches are given to illustrate the practical issues and design considerations addressed in the chapter, that cover from electrical analysis and simulation using SPICE-like simulators to layout design considerations, chip prototyping, and experimental measurements of ΣΔMs in the laboratory.

To conclude the book, Chapter 5 gives an overview of the state-of-the-art ΣΔM ICs, comparing their performance with Nyquist-rate ADCs. Overall, more than 300 state-of-the-art IC references have been studied in detail and considered in this review, including papers published from 1990 to June 2012. Therefore, following the practical philosophy that inspires this book, the diverse families of state-of-the-art ΣΔM architectures and circuit techniques are exhaustively analyzed and compared to extract practical and empirical design guidelines from the statistical data, trying to identify the incoming trends, design challenges, as well as the solutions proposed by cutting-edge ICs that are in the frontiers of ΣΔMs.

The book contents are addressed and structured for a large audience: from senior designers who want to acquire a deeper and updated insight into ΣΔMs, to nonexperienced undergraduate students who are looking for a comprehensive, uniform, and self-contained reference into this hot topic. Bearing this in mind, the style and main purpose of the book is to serve also as an educational and reference textbook for undergraduate and graduate students. Indeed, the book is based on a number of graduate courses given by the authors, including master and doctorate degree programs, invited lectures, and IEEE conference tutorials. All these materials have been adapted and updated so that a large portion of the book can be also used (and indeed it has been used) in both undergraduate and graduate courses.

However, in spite of the *encyclopedic* nature of the book, it is impossible to give an exhaustive description of all the topics contained in the thousands of publications dealing with ΣΔMs. Instead, the book tries to cover the main subtopics, providing sufficient insight to understand the other ones, that are just overviewed and sometimes even omitted. In order to try to palliate these unavoidable deficiencies, an exhaustive list of specific references is included at the end of each chapter. Overall, the book contains around 500 selected references in order to guide readers to increase their understanding of the diverse research topics dealing with the ΣΔ world.

The huge amount of information contained in the book is complemented and updated with a number of electronic resources, that have been prepared by the authors and are freely available on the Web. To this purpose, all the data analyzed in the state-of-the-art survey presented in Chapter 5 have been collected in a spreadsheet, which is available at http://www.imse-cnm.csic.es/~jrosa/CMOS-SDMs-Survey-IMSE-JMdelaRosa.xlsx. This database is periodically kept up to date and aims to be a complement to the popular Murmann's ADC survey data collection [31]. In addition, a fully functional version of the time-domain behavioral simulator SIMSIDES is freely available on demand at http://www.imse-cnm.csic.es/simsides. The simulator includes a number of examples, containing the case studies presented in the book and many more examples and demos. Apart from the SIMSIDES software, the majority of examples and test benches of different CAD tools used throughout the book are also available on the Web at www.wiley.com/go/delarosa_converters.

Last but not least, it is important to mention that the aforementioned web sites will be regularly updated with new pieces of information and updated material related to the state-of-the-art ΣΔM ICs, SIMSIDES examples and demos, as well as new inputs provided by us and hopefully by our readers. Therefore, your feedback is very important and very welcomed!

We hope that you enjoy reading this book as much as we have enjoyed writing it.

José M. de la Rosa and Rocío del Río
Sevilla, October 2012

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