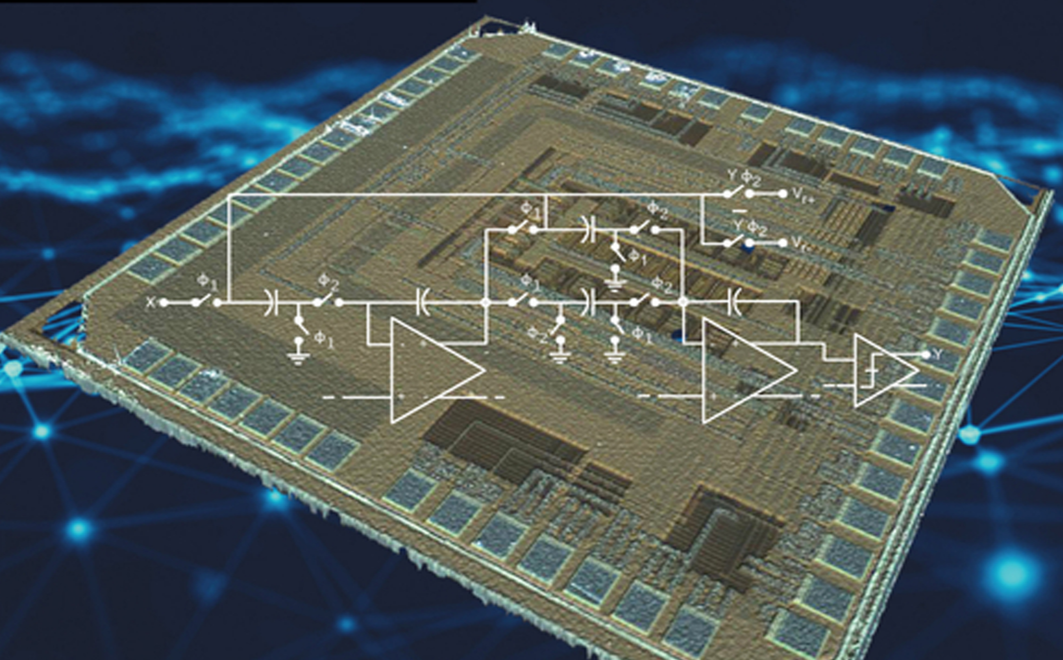
José M. de la Rosa

Sigma-Delta Converters

Practical Design Guide

SECOND EDITION



IEEE PRESS

WILEY

SIGMA-DELTA CONVERTERS

SIGMA-DELTA CONVERTERS

Practical Design Guide

SECOND EDITION

JOSÉ M. DE LA ROSA

Institute of Microelectronics of Seville
IMSE-CNM (CSIC, University of Seville)
Spain

IEEE PRESS

WILEY

This edition first published 2018

Edition History

This edition first published in English copyright year 2013

Registered Offices
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

Editorial Office
John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Wiley also publishes its books in a variety of electronic formats and by print-on-demand. Some content that appears in standard print versions of this book may not be available in other formats.

Library of Congress Cataloging-in-Publication Data

Names: Rosa, José M. de la, author.
Title: Sigma-delta converters : practical design guide / José M. de la Rosa, University of Seville, Spain.
Other titles: CMOS sigma-delta converters
Description: Second edition. | Hoboken, NJ, USA : Wiley-IEEE Press, 2018. | Revised edition of: CMOS sigma-delta converters. | Includes bibliographical references and index. |
Identifiers: LCCN 2018023691 (print) | LCCN 2018026688 (ebook) | ISBN 9781119275756 (Adobe PDF) | ISBN 9781119275763 (ePub) | ISBN 9781119275787 (hardcover)
Subjects: LCSH: Metal oxide semiconductors, Complementary–Design and construction. | Analog-to-digital converters–Design and construction.
Classification: LCC TK7871.99.M44 (ebook) | LCC TK7871.99.M44 R668 2019 (print) | DDC 621.3815/9–dc23
LC record available at https://lccn.loc.gov/2018023691

Cover design by Wiley
Cover image: Courtesy of José M. de la Rosa

Set in 9.5/11.5pt NimbusRomNo9L by SPi Global, Chennai, India

10 9 8 7 6 5 4 3 2 1

This book is dedicated to the memory of two colleagues and friends who have been key persons in my life:

Mariano Marcos Bárcena, professor of professors, and my first teacher of Physics, who inspired my passion for science and technology.

Fernando Medeiro Hidalgo, one of the best analog and mixed-signal IC designers I have known, with whom I was very fortunate to take my first steps in this fascinating world of ΣΔ converters.

God bless you, Mariano, Fernando.

To my wife Visi, my daughter María, my son Jaime
and to the memory of my little son José Manuel

"Engineering isn't about perfect solutions; it's about doing the best you can with limited resources."

Randy Pausch, Professor, Carnegie Mellon (*The Last Lecture*, Hyperion 2008)

CONTENTS

PREFACE

Sigma-Delta modulators (ΣΔMs) have become one of the best choices for the implementation of analog/digital interfaces of electronic systems 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. They are the most efficient way to digitize very diverse types of signal in an increasing number of application scenarios, from high-resolution low-bandwidth data conversions for 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 made more and more engineers today consider ΣΔMs as the first choice for their research projects and their industrial products.

The 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 very 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 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 high-precision digitization 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 for speed of digital signal processing, thus achieving a higher degree of insensitivity to circuit error mechanisms and potentially benefiting from CMOS technology's evolution towards the nanometer scale.

Prompted by these 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 plethora 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 innovative research results and successful industry products.

All these advances and research studies have led (and continue to do so) to a vast amount of technical literature. Indeed, since the publication of pioneering works such as the widely cited papers written by Candy [3, 4] and Boser and Wooley [5], the number of publications has increased significantly, now including hundreds of patents, thousands of research papers, some tutorial papers [6–8], as well as dozens of introductory and specialized monographs [9–31]. However, with so much material and such an abundance of technical information published, many designers – particularly novel designers, but also some experienced designers focused on specific subtopics of ΣΔMs – may become sometimes disoriented and lose their way. This has motivated some authors to put all these pieces of information together in a comprehensive and systematic way.

Apart from 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, which deals with a number of important subjects in ΣΔMs, had contributions by a number of experts in the field, thus making it hard to present its contents in a coherent and consistent way. With this objective in mind, some authors have put their efforts into writing tutorial monographs dealing with the systematic design of ΣΔMs.

Among others, the book written by Schreier and Temes, published in 2005 [21], often referred to as "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 [32]. A revised second edition of this book was written by Pavan, Schreier and Temes, and was published in 2017 [33]. This new edition expanded the contents of the first edition with more sections dealing with continuous-time (CT) circuit implementations and circuit design considerations, without losing the main intention of the first edition, namely to give a basic understanding of the operation of ΣΔ converters.

Some other remarkable and pioneering 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 to date. All of these books, as well as other monographs reported in the technical literature, give incomplete views of ΣΔMs, paying more attention to particular aspects of their design, and/or a type of architecture, circuit technique, or application.

This being the case, and following the spirit of the first edition of this book, this second edition attempts to cover some of these knowledge gaps in the ΣΔ literature, by providing a comprehensive and systematic description of the *universe* of ΣΔMs, their diverse architectures, circuit techniques, analysis and synthesis methods and CAD tools, as well as their practical design considerations. As in the first edition, one of the main purposes of this book is to be an educational and reference textbook for undergraduate and graduate students. With this goal in mind, and based on the courses already given by the author and the feedback received from readers and course attendees, the contents of the second edition of the book have been updated, completed and structured to address a large audience: from senior designers who want to acquire a deeper and up-to-date insight into ΣΔMs, to inexperienced engineers who are looking for a uniform and self-contained reference into this hot topic. The new contents and materials make this new edition a unique monograph, a result of the compiling and updating of the enormous number of technical and research studies reported to date on the topic of ΣΔMs. It presents the results of this compilation in a didactical, pedagogical, and intuitive style.

Another key feature of this book (as mentioned in the title) is that it can be used as a *practical guide for designers*, emphasizing explanations of the multiple trade-offs 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; in other words, going from the theoretical fundamentals, system-level design equations, and behavioral models to circuit, transistor-level, and physical implementations, in order to provide readers with the necessary understanding and insights into the recent advances, trends, and challenges involved in the design of state-of-the-art ΣΔM ICs.

This second edition emphasizes two key points, which were not covered in such depth in the first edition. The first is to include more detailed explanation of ΣΔMs implemented using CT circuits, going from system-level synthesis to practical circuit/physical limitations. The second point is to include more practical case studies and applications, as well giving a deeper description of the synthesis methodologies and CAD tools employed in the design of ΣΔ converters. Due to the quantity of all these new materials, the table of contents of the first edition has been re-organized and expanded, going from five chapters and two appendixes to ten chapters and three appendixes in this second edition.

The top-down approach adopted in this book inspires the hierarchical way in which the contents are structured. Thus, Chapter 1 begins from the top, giving an introduction to data converters and explaining the basic concepts and fundamentals behind ΣΔ modulation, its main building blocks, the signal processing involved, its performance metrics and basic examples to illustrate the concepts of noise shaping and oversampling – the main ingredients of ΣΔ converters. Chapter 2 gives a taxonomical description of the diverse variety of ΣΔM architectures, the nature of signals (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; CT synthesis methods and architectures will be explained in more detail than in the first edition of the book.

Chapters 3 and 4 descend one level in the modulator hierarchy to analyze the effect of the main circuit error mechanisms, as well as architectural and timing nonidealities. The mathematical models, analytical procedures and design guidelines described in this chapter provide an understanding of the main practical issues affecting the performance of ΣΔMs. Chapter 3 mostly focuses on SC circuit error mechanisms, while Chapter 4 updates and expands on the contents of the first edition, dealing with CT circuit nonideal effects and compensation techniques. This is complemented by the state-space analysis of clock jitter in CT-ΣΔMs given in Appendix A.

The knowledge derived from the first four chapters is an essential part of the systematic *top-down/bottom-up* synthesis methodology of ΣΔMs, which is described in Chapters 5 and 6. Thus, Chapter 5 deals with the synthesis methodology of ΣΔ converters, focusing on high-level behavioural modelling and simulation techniques, and giving an introduction to the SIMSIDES simulator. The updates of the new version of this simulator are also included in this second edition and distributed through the book's companion website. Chapter 6 focuses on optimization techniques, illustrating different approaches to combine simulation and optimization for the high-level design of ΣΔ modulators. The contents of this chapter are extended and complemented in Appendices B and C. Appendix B includes a user guide to SIMSIDES and Appendix C provides an overview of all behavioral models and libraries included in this simulator.

The circuit- and physical-level considerations are presented in Chapters 7 and 8, which update and expand on the contents of the first edition. This update and re-organization is motivated by the fact that the previous version (presented in a single chapter) was too long and, according to readers' feedback, needed to be restructured into two chapters. These chapters give 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 system-level model 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 provided to illustrate the practical issues and design considerations addressed in the chapter, which cover everything from electrical analysis and simulation using SPICE-like simulators, to layout design considerations, chip prototyping, and experimental measurements of ΣΔMs in the laboratory. These chapters are complemented by Chapter 9, where some more content dealing with practical chip implementation, case studies and experimental characterization are provided.

To conclude the book, Chapter 10 gives an overview of state-of-the-art ΣΔM ICs, comparing their performance with Nyquist-rate ADCs. Overall, more than 500 state-of-the-art IC references have been studied in detail and considered in this review, including papers published up until August 2017. 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 coming trends, design challenges, as well as the solutions proposed by cutting-edge ICs at the frontiers of ΣΔMs.

As stated above, the book contents are addressed and structured for a wide audience: from senior designers to students starting to work in the area of ΣΔMs. 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 several graduate courses given by the author, including masters and doctorate degree programs, invited lectures, and IEEE conference tutorials, distinguished lectures, and courses. All these materials have been adapted and updated so that a large portion of the book can also be used (and indeed it has been used) in both undergraduate and graduate courses.

However, in spite of the encyclopaedic 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 allow the reader to understand the others, which are only reviewed in brief, or sometimes even omitted. In order to try to palliate these unavoidable deficiencies, a list of references is included at the end of each chapter. Overall, the book contains a list of references in order to guide readers to an increase in their understanding of the diverse research topics in the ΣΔ world.

The huge quantity of information contained in the book is complemented and updated by a number of electronic resources, which enlarge on the resources provided with the first edition. They are freely available on the Web. To this end, all the data analyzed in the state-of-the-art survey presented in Chapter 10 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 [34]. 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 incorporates many examples, including the case studies presented in the book and many more examples. 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 `http://www.imse-cnm.csic.es/~jrosa`.

Last but not least, although the author has done his best to cover the many new and hot topics in the world of ΣΔ converters, there is some content that cannot yet be covered in detail while other areas had to be omitted to allow the book to be completed in a reasonable time and in a reasonable number of pages.

I hope that readers understand these limitations, find this edition of the book useful and practical, and enjoy reading (and using) it as much as I have enjoyed revising and writing it. As in the first edition, your feedback is very important and very welcome!

José M. de la Rosa
Sevilla, January 2018

References

[1] C. C. Cutler, "Transmission System Employing Quantization," *U.S. Patent No. 2,927,962*, 1960.

[2] H. Inose, Y. Yasuda, and J. Murakami, "A Telemetering System by Code Modulation – $\Delta - \Sigma$ Modulation," *IRE Trans. on Space Electronics and Telemetry*, vol. 8, pp. 204–209, September 1962.

[3] J. Candy and O. J. Benjamin, "The Structure of Quantization Noise from Sigma-Delta Modulation," *IEEE Transactions on Communications*, pp. 1316–1323, 1981.

[4] J. Candy, "A Use of Double Integration in Sigma-Delta Modulation," *IEEE Transactions on Communications*, vol. 33, pp. 249–258, March 1985.

[5] B. E. Boser and B. A. Wooley, "The Design of Sigma-Delta Modulation Analog-to-Digital Converters," *IEEE J. of Solid-State Circuits*, vol. 23, pp. 1298–1308, December 1988.

[6] P. M. Aziz *et al.*, "An Overview of Sigma-Delta Converters," *IEEE Signal Processing Magazine*, vol. 13, pp. 61–84, January 1996.

[7] I. Galton, "Delta-Sigma Data Conversion in Wireless Transceivers," *IEEE Trans. on Microwave Theory and Techniques*, vol. 50, pp. 302–315, January 2002.

[8] J. M. de la Rosa, "Sigma-Delta Modulators: Tutorial Overview, Design Guide, and State-of-the-Art Survey," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 58, pp. 1–21, January 2011.

[9] J. Candy and G. Temes, *Oversampling Delta-Sigma Data Converters: Theory, Design and Simulation*. IEEE Press, 1991.

[10] S. R. Norsworthy, R. Schreier, and G. C. Temes, *Delta-Sigma Data Converters: Theory, Design and Simulation*. IEEE Press, 1997.

[11] J. Cherry and W. Snelgrove, *Continuous-Time Delta-Sigma Modulators for High-Speed A/D Conversion*. Kluwer Academic Publishers, 1999.

[12] J. V. Engelen and R. van de Plassche, *BandPass Sigma-Delta Modulators: Stability Analysis, Performance and Design Aspects*. Kluwer Academic Publishers, 1999.

[13] F. Medeiro, B. Pérez-Verdú, and A. Rodríguez-Vázquez, *Top-Down Design of High-Performance Sigma-Delta Modulators*. Kluwer Academic Publishers, 1999.

[14] V. Peluso, M. Steyaert, and W. Sansen, *Design of Low-Voltage Low-Power CMOS Delta-Sigma A/D Converters*. Kluwer Academic Publishers, 1999.

[15] S. Rabii and B. A. Wooley, *The Design of Low-Voltage, Low-Power Sigma-Delta Modulators*. Kluwer Academic Publishers, 1999.

[16] L. Breems and J. H. Huijsing, *Continuous-Time Sigma-Delta Modulation for A/D Conversion in Radio Receivers*. Kluwer Academic Publishers, 2001.

[17] Y. Geerts, M. Steyaert, and W. Sansen, *Design of Multi-bit Delta-Sigma A/D Converters*. Kluwer Academic Publishers, 2002.

[18] J. M. de la Rosa, B. Pérez-Verdú, and A. Rodríguez-Vázquez, *Systematic Design of CMOS Switched-Current Bandpass Sigma-Delta Modulators for Digital Communication Chips*. Kluwer Academic Publishers, 2002.

[19] M. Kozak and I. Kale, *Oversampling Delta-Sigma Modulators*. Springer, 2003.

[20] O. Bajdechi and J. Huising, *Systematic Design of Sigma-Delta Analog-to-Digital Converters*. Kluwer Academic Publishers, 2004.

[21] R. Schreier and G. C. Temes, *Understanding Delta-Sigma Data Converters*. IEEE Press, 2005.

[22] M. Ortmanns and F. Gerfers, *Continuous-Time Sigma-Delta A/D Conversion: Fundamentals, Performance Limits and Robust Implementations*. Springer, 2006.

[23] K. Philips and A. H. M. van Roermund, *Sigma Delta A/D Conversion for Signal Conditioning*. Springer, 2006.

[24] R. del Río, F. Medeiro, B. Pérez-Verdú, J. M. de la Rosa, and A. Rodríguez-Vázquez, *CMOS Cascade ΣΔ Modulators for Sensors and Telecom: Error Analysis and Practical Design*. Springer, 2006.

[25] L. Yao, M. Steyaert, and W. Sansen, *Low-Power Low-Voltage Sigma-Delta Modulators in Nanometer CMOS*. Springer, 2006.

[26] P. G. R. Silva and J. H. Huijsing, *High Resolution IF-to-Baseband ΣΔ ADC for Car Radios*. Springer, 2008.

[27] R. H. van Veldhoven and A. H. M. van Roermund, *Robust Sigma Delta Converters*. Springer, 2011.

[28] A. Morgado, R. del Río, and J. M. de la Rosa, *Nanometer CMOS Sigma-Delta Modulators for Software Defined Radio*. Springer, 2012.

[29] E. Janssens and A. van Roermund, *Look-Ahead Based Sigma-Delta Modulation*. Springer, 2011.

[30] R. Gaggl, *Delta-Sigma A/D Converters: Practical Design for Communication Systems*. Springer, 2013.

[31] M. Bolatkale, L. Breems, and K. Makinwa, *High Speed and Wide Bandwidth Delta-Sigma ADCs*. Springer, 2015.

[32] R. Schreier, *The Delta-Sigma Toolbox*. [Online]. Available: http://www.mathworks.com/matlabcentral, 2017.

[33] S. Pavan, R. Schreier, and G. C. Temes, *Understanding Delta-Sigma Data Converters*. Wiley-IEEE Press, 2nd ed., 2017.

[34] B. Murmann, *ADC Performance Survey 1997–2018*. [Online]. Available: http://www.stanford.edu/~murmann/adcsurvey.html.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my colleagues at the Institute of Microelectronics of Sevilla and the Department of Electronics and Electromagnetism of the University of Sevilla. I am especially indebted to Prof. Bélen Pérez-Verdú and Prof. Angel Rodríguez-Vázquez for so many things I have learned from them, not only related to the topic of this book, but also the other values and skills I have put into practice throughout my professional career. I am also particularly grateful to my friends and colleagues, Dr. Rocío del Río – who coauthored the first edition of this book – and Dr. Fernando Medeiro, with whom I took my first steps in the fascinating world of ΣΔ converters, working side by side in so many research and industrial projects.

I would also like to acknowledge my former students, especially Jesús Ruíz-Amaya, Rafael Romay, Ramón Tortosa, Alonso Morgado, Edwin Becerra, Gerardo García, Gerardo Molina, Luis Guerrero-Linares, Mohammad Honarparvar and Sohail Asghar. Some of the material used for the preparation of this book was adapted from their theses.

I would like to give my thanks to the staff at Wiley, a great team of editors led by Peter Mitchell, as well as the anonymous reviewers of the book proposal for their constructive and valuable comments and suggestions, which became very useful for me in making the second version of this book a reality. I also appreciate the discussions I have had over the years with so many experts in the field of ΣΔ converters, who I met at numerous conferences and technical meetings, most of them organized by the IEEE Circuits and Systems Society and the Solid-State Circuits Society. I was very honoured to coauthor papers with some of the recognized experts in analog and ΣΔ IC design, like Prof. Shanthi Pavan, Dr. Richard Schreier, Prof. Maurits Ortmanns and Prof. Mohamad Sawan.

In addition to all these great people, my work has been supported by a number of national and international research and industrial projects. More recently, it was funded by the Spanish Ministry of Economy, Industry and Competitiveness (with support from the European Regional Development Fund) under contract TEC2016-75151-C3-3-R.

Finally, my most grateful thanks go to my family. Without their love, patience and support, none of this would have been possible. Thank you so much for everything!

LIST OF ABBREVIATIONS

ΣΔ	Sigma-Delta
ΣΔM	Sigma-Delta modulator
AAF	Antialiasing filter
A/D	Analog-to-digital
ADC	Analog-to-digital converter
BB	Baseband
BGA	Ball grid array
BP	Band-pass
CAD	Circuit-aided design
CDS	Correlated double sampling
CIC	Cascaded integrator comb
CIFF	Cascade of integrators in feedforward form
CIFB	Cascade of integrators in feedback form
CLA	Clocked averaging
CMFB	Common-mode feedback
CMOS	Complementary MOSFET
CRFF	Cascade of resonators in feedforward form
CRFB	Cascade of resonators in feedback form
CS	Current-steering
CT	Continuous-time
D/A	Digital-to-analog
DAC	Digital-to-analog converter
DC	Direct current
DCL	Digital cancelation logic
DCR	Direct conversion receiver

DEM	Dynamic element matching
DMT	Discrete multi-tone
DNL	Differential nonlinearity
DR	Dynamic range
DRC	Design rule checker
DSP	Digital signal processor
DT	Discrete-time
DWA	Data weighted averaging
EA	Evolutionary algorithm
ELD	Excess loop delay
ENOB	Effective number of bits
ESD	Electrostatic discharge
FE	Forward-Euler
FIR	Finite impulse response
FFT	Fast Fourier transform
FOM	Figure of merit
FPGA	Field programmable gate array
FS	Full scale
GB	Gain-bandwidth product
GPU	Graphics processing unit
GRO	Gated switched-ring oscillator
GUI	Graphic user interface
HDL	Hardware description language
HPF	High pass filter
HRZ	Half-delay return to zero
IBN	In-band noise power
IC	Integrated circuit
IF	Intermediate frequency
IIR	Infinite impulse response
IIT	Impulse-invariant transformation
ILA	Individual level averaging
INL	Integral nonlinearity
I/O	Input–output
ISI	Intersymbol interference
ITF	Integrator transfer function
LDI	Lossless discrete integrator
LP	Low-pass
LPE	Layout parasitic extractor
LSB	Least significant bit
LTCC	Low-temperature cofired ceramic
LTI	Linear time-invariant
LVS	Layout versus schematic
MASH	Multi-stage noise shaping
MDT	Modulator dependent term
MEM	Micro electromechanical
MICTOR	Matched impedance connector
MiM	Metal-insulator-metal
MOEA	Multi-objective evolutionary algorithm