Analog Circuits and Signal Processing

Series editors

Mohammed Ismail, Dublin, USA
Mohamad Sawan, Montreal, Canada

More information about this series at http://www.springer.com/series/7381

David del Rio · Ainhoa Rezola
Juan F. Sevillano · Igone Velez
Roc Berenguer

Digitally Assisted, Fully Integrated, Wideband Transmitters for High-Speed Millimeter-Wave Wireless Communication Links

Springer

David del Rio
Ceit-IK4 Technology Center
Donostia, Spain

Ainhoa Rezola
Ceit-IK4 Technology Center
Donostia, Spain

Juan F. Sevillano
Ceit-IK4 Technology Center
Donostia, Spain

Igone Velez
Ceit-IK4 Technology Center
Donostia, Spain

Roc Berenguer
Tecnun-University of Navarra
Donostia, Spain

ISSN 1872-082X ISSN 2197-1854 (electronic)
Analog Circuits and Signal Processing
ISBN 978-3-319-93280-4 ISBN 978-3-319-93281-1 (eBook)
https://doi.org/10.1007/978-3-319-93281-1

Library of Congress Control Number: 2018945089

© Springer International Publishing AG, part of Springer Nature 2019
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by the registered company Springer International Publishing AG part of Springer Nature
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

To our families.

Preface

The millimeter-wave (mmW) range of the electromagnetic spectrum, which includes frequencies from around 30 to 300 GHz, offers some unique propagation properties and a vastly available bandwidth. Therefore, it enables relieving the overpopulated lower part of the spectrum and satisfying the huge data demands from the users. It also allows the proliferation of new applications such as automotive radar, high-speed personal area networks, and noninvasive surveillance, just to name a few of them. In addition, while in the past working at mmW frequencies was only possible using III–V technologies, the successive scaling of silicon-based technologies like CMOS and BiCMOS has brought mmW circuit designs and applications to the mass market.

Many excellent books on RFIC design using silicon technologies have been published, and with the aid of the existing powerful simulation software, one can design RF circuits with acceptable performance quickly and with moderate effort. However, when it comes to mmW circuit design, succeeding is not that simple. Semiconductor technologies are struggled to their limits in terms of operation frequency and available power, and PVT variations can greatly jeopardize the device performance. This is especially critical in transmitters, which need to provide enough output power to compensate for the high path loss, while at the same time maintaining the bandwidth in a power-efficient way. Furthermore, the wide bandwidth and data throughput required by current communication applications are also pushing digital design to the limits in terms of sampling speed and power consumption, and it is, therefore, not straightforward to use DSP techniques to compensate for the RF imperfections.

In this book, we present an approach to mmW circuit design using advanced RF circuit design and digital processing techniques at the same time. This way, front-end architectures that balance the requirements of the RF and DSP blocks can be selected, and it is possible to sense the operating conditions of the critical circuits in order to compensate for the imperfections and bring the performance back to the optimum values. All the design stages of a typical mmW transmitter are covered, from the link budget analysis to transistor-level design and system tests using high-order modulated signals. The procedure to present the different designs and subsystems is to first explain the concepts from a theoretical point of view, and then apply them to the design of an E-band 10-Gbps BiCMOS-integrated transmitter. Some previous knowledge of semiconductor devices, transmission systems, and signal theory is assumed from the reader, although theoretical concepts and expressions are introduced when required for the discussion. These prior concepts are sometimes explained in a rather intuitive way, as our intention is to focus more on the actual scope of the book: revisiting the traditional approaches and proposing new techniques appropriate for wideband and power-efficient mmW IC design. Nevertheless, references where the information is more thoroughly explained are provided, in case the reader feels some concepts are oversimplified or seeks further explanation.

Chapters are intended to be self-contained, each with its own introduction and conclusion sections, so that most of them can be read independently. Nevertheless, they are ordered according to the natural design flow, starting from the system-level analysis and going down to the transistor-level design. Chapter 1 is a general introduction to millimeter waves, explaining the motivations to explore this frequency range and the technologies that make it possible. In Chap. 2, considerations for the link budget and system-level analysis are given, whereas Chap. 3 analyzes the typical imperfections that degrade the performance of mmW communication systems, showing how they affect the signal. One of the imperfections that most affects wideband mmW systems is transmitter I/Q imbalance. It is typically addressed as non-frequency selective, but in wideband and spectrally efficient systems this assumption is no longer true and different correction techniques need to be applied. Therefore, Chap. 4 is dedicated to I/Q imbalance analysis and compensation. The rest of the chapters deal with the circuit-level design of the core blocks of an integrated mmW transmitter front-end. Chapter 5 outlines a design methodology for BiCMOS mmW integrated circuits. Chapters 6–8 deal with the design of upconverters, power amplifiers, and power detectors, respectively. Different alternatives and trade-offs for the design of these blocks are first presented, and then design examples of real implemented circuits are given. These circuits are designed aiming at wideband operation and transmission of multi-Gbps signals, and they allow implementing the digitally assisted correction, self-healing and built-in integrated self-test (BIST) techniques outlined in the previous chapters. Finally, Chap. 9 presents an integrated and digitally assisted BiCMOS transmitter, which is able to transmit at 10-Gbps speeds in the E-band. The techniques presented in the previous chapters have been applied to its design.

This book comes after years of research in the field of wideband-integrated mmW transmitters for high-speed communications. We have tried to gather all the wisdom and experience we have acquired in the way, because we believe that knowledge only grows when it is shared. This way, future designers can learn from our mistakes and take our experience as a starting point for their future designs. We hope you will enjoy your reading!

Donostia, Spain

David del Rio
Ainhoa Rezola
Juan F. Sevillano
Igone Velez
Roc Berenguer

Acknowledgements

This book would not have been possible without the help of so many organizations and individuals. It is mostly based on the experience we have gained from our research at Ceit-IK4 Research Centre and at the University of Navarra, where we have benefited from the help and experience of other researchers, such as Hector Solar, Iñaki Gurutzeaga, Andoni Beriain, Andoni Irizar, and Fernando Arizti.

It is also fair to mention the organizations that have funded the research leading to the results presented in this book: the University of Navarra itself, the Basque Government through its Ph.D. scholarship program, and the European Commission through its FP7 Research Program.

Contents

Acronyms

AC	Alternating current
ACC	Automatic cruise control
ADC	Analog-to-digital converter
AGC	Automatic gain control
AIF	Analog intermediate frequency
ALC	Automatic level control
AM	Amplitude modulation
AWG	Arbitrary waveform generator
AWGN	Additive white Gaussian noise
BB	Baseband
BBC	Baseband controller
BBU	Baseband unit
BEOL	Back end of line
BER	Bit error rate
BiCMOS	Bipolar CMOS
BiSC	Built-in-self-Calibration
BIST	Built-in self-test
BJT	Bipolar junction transistor
BPF	Band-pass filter
BPSK	Binary phase-shift keying
BV	Breakdown voltage
BW	Bandwidth
CB	Common-base
CC	Common-collector
CE	Common-emitter
CG	Conversion gain
CMOS	Complementary metal–oxide–semiconductor
CPRI	Common Public Radio Interface
C-RAN	Centralized-RAN (or Cloud-RAN)
CS	Channel separation

CS	Common-source
CW	Continuous wave
DAC	Digital-to-analog converter
DBB	Digital baseband
DC	Direct current
DCI	Data clock input
DCO	Data clock output
DRC	Design rule check
DS0	Digital sub-band centered at −500 MHz
DS1	Digital sub-band centered at 500 MHz in
DSB	Double side-band
DSP	Digital signal processing
DUT	Device under test
EC	European Commission
ECC	European Communications Committee
ED	Envelope detector
EM	Electromagnetic
ERR	Envelope elimination and restoration
ESD	Electrostatic discharge
ET	Envelope tracking
ETSI	European Telecommunications Standards Institute
EU	European Union
EVM	Error vector magnitude
eWLB	Embedded wafer level ball grid array
FCC	Federal Communications Commission
FDD	Frequency-division duplex
FEC	Forward error correction
FET	Field-effect transistor
FIFO	First in, first out
FIR	Finite impulse response
FPGA	Field-programmable gate array
FS	Frequency selective
GPIB	General Purpose Interface Bus
GSG	Ground-signal-ground
HBT	Heterojunction bipolar transistor
HD	High definition
HDMI	High-definition multimedia interface
HEMT	High-electron-mobility transistor
HIPO	High-ohmic polycrystalline
I/Q	In-phase/quadrature
IC	Integrated circuit
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate frequency
IL	Insertion loss
IP	Internet protocol

IP1dB	Input 1-dB compression point
IP3	Third-order intercept point
IRR	Image rejection ratio
ITU	International Telecommunication Union
LDPC	Low-density parity-check
LNA	Low-noise amplifier
LO	Local oscillator
LoS	Line of sight
LPF	Low-pass filter
LRR	Long-range radar
LSB	Lower side-band
LTE	Long-Term Evolution
MAG	Maximum available gain
MD	Measuring device
MER	Modulation Error Ratio
MIM	Metal–insulator–metal
MIMO	Multiple-input multiple-output
MMIC	Monolithic microwave integrated circuit
MMSE	Minimum mean square error
mmW	Millimeter-wave
MN	Matching network
MOM	Metal–oxide–metal
MoM	Method of moments
MOSFET	Metal–oxide–semiconductor field-effect transistor
MRR	Medium-range radar
MSG	Maximum stable gain
NF	Noise figure
NFC	Near-field communication
NFS	Non-frequency Selective
OFDM	Orthogonal frequency-division multiplexing
OP1dB	Output 1-dB compression point
PA	Power amplifier
PAE	Power-added efficiency
PAN	Personal area network
PAPR	Peak-to-average power ratio
PCB	Printed circuit board
PDK	Process design kit
PLL	Phase-locked loop
PLS	Post-layout simulation
PM	Phase modulation
PPF	Poly-phase filter
PrC	Prototype Controller
PSA	Power spectrum analyzer
Psat	Saturation power
PSD	Power Spectrum Density

PTAT	Proportional to absolute temperature
PVT	Process, voltage and temperature
QAM	Quadrature amplitude modulation
QPSK	Quadrature phase-shift keying
RAM	Random-access memory
RAN	Radio access network
RBW	Resolution bandwidth
RF	Radio frequency
RFID	Radio-frequency identification
RRC	Root-raised-cosine
RRH	Remote radio head
RS	Reed–Solomon
RX	Receiver
RX-DBB	Receiver baseband controller
SA	Spectrum analyzer
SC	Single-carrier
SGS	Signal-ground-signal
SMA	Sub-miniature version A
SMT	Surface-mount technology
SNR	Signal-to-noise ratio
SOI	Silicon on insulator
SPI	Serial peripheral interface
SRAM	Static random-access memory
SRR	Short-range radar
SSB	Single side-band
TL	Transmission line
TX	Transmitter
TxBB2IF	Transmitter part that comprises baseband and IF
TX-DBB	Transmitter digital baseband processor
USB	Upper side-band
UWB	Ultra-wideband
VCO	Voltage-controlled oscillator
VGA	Variable-gain amplifier
VLSI	Very-large-scale integration
VNA	Vector network analyzer
WCDMA	Wideband Code Division Multiple Access
WG	Waveguide