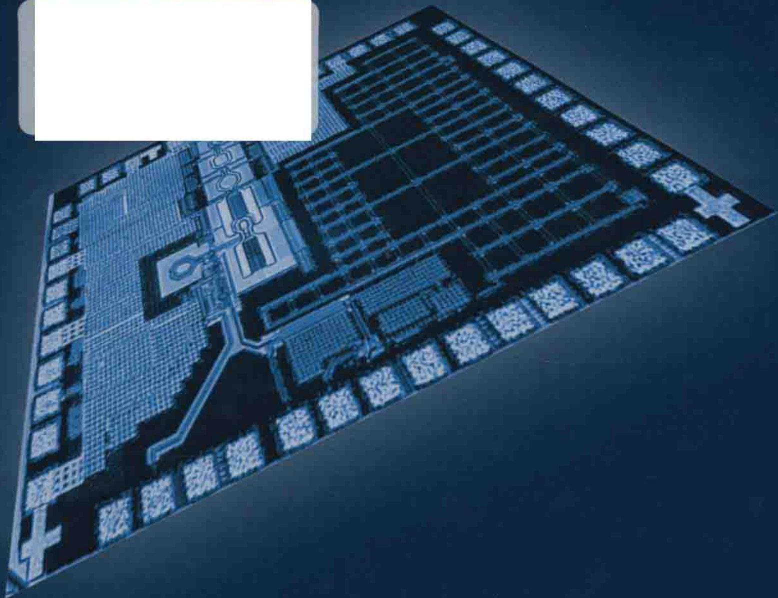

Millimeter-Wave Digitally Intensive Frequency Generation in CMOS

Wanghua Wu
Robert Bogdan Staszewski
John R. Long

MILLIMETER-WAVE DIGITALLY INTENSIVE FREQUENCY GENERATION IN CMOS

WANGHUA WU

ROBERT BOGDAN STASZEWSKI

JOHN R. LONG

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Academic Press is an imprint of Elsevier

Academic Press is an imprint of Elsevier
125, London Wall, EC2Y 5AS.
525 B Street, Suite 1800, San Diego, CA 92101-4495, USA
225 Wyman Street, Waltham, MA 02451, USA
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK

ISBN: 978-0-12-802207-8

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress.

For Information on all Academic Press publications visit our website at http://store.elsevier.com/

Typeset by MPS Limited, Chennai, India
www.adi-mps.com

Publisher: Jonathan Simpson
Acquisition Editor: Tim Pitts
Editorial Project Manager: Charlie Kent
Production Project Manager: Jason Mitchell
Designer: Greg Harris

MILLIMETER-WAVE DIGITALLY INTENSIVE FREQUENCY GENERATION IN CMOS

PREFACE

Over the past few decades, frequency synthesis based on analog-intensive phase-locked loops (PLLs) has been the most popular technique employed to provide local oscillator signals for the radio frontend. With aggressive scaling and technological advancement in silicon-based process technologies, particularly CMOS, digitally assisted RF systems are fast becoming a commonplace in the low-GHz bands (i.e., below 10 GHz). The key enabler there is digital signal processing employed to improve the overall system performance via calibration, and also to provide reconfigurability and ease of testability. Particularly in the area of RF frequency synthesis, many universities, research institutes, and companies have since demonstrated various all-digital phase-locked loop (ADPLL) implementations, and ADPLLs are now replacing traditional analog PLLs in consumer electronics supporting various wireless standards, for example, 2G/3G cellular, IEEE 802.11 a/b/g/n/ac, and Bluetooth.

As the frequency spectrum becomes increasingly congested in the low-GHz regime, millimeter-wave (mm-wave) frequency bands (i.e., above 30 GHz) are gaining popularity as they offer large bandwidth to support Giga-bit per second wireless communication without the need for complex modulation schemes, thus achieving low error rates and low energy consumption per bit. Up to this date, there have been many published silicon-based mm-wave analog PLLs, but very few ADPLLs operating above 30 GHz are reported. Little material has been written on the ADPLL design challenges at mm-wave frequencies and the design techniques to address them. Moreover, testing and debugging PLLs to correctly identify any design or fabrication problems would be equally challenging due to the closed-loop operation of the PLL.

In this book, we detail these technical challenges, and discuss the design and implementation of a 60-GHz ADPLL in a conventional widely available CMOS process. We further elaborate on calibration techniques that are especially useful at mm-wave to improve the system performance. We also explain the implemented testability features that facilitate design for test and characterization. This book is organized as follows:

- Chapters 1–3 go over the introduction and review of existing literature. Chapter 1 lays out the motivation and challenges in building an ADPLL for the mm-wave regime, while Chapter 2 presents various existing mm-wave frequency synthesizer architectures. Chapter 3 reviews the building blocks of a frequency synthesizer, which are common to both analog and digital implementations.
- Chapters 4–6 deal with the theory, design, and realization of a mm-wave ADPLL. Chapter 4 covers the basic concepts which are needed to understand the design and operation of an ADPLL, and Chapter 5 discusses mm-wave digitally controlled oscillator (DCO) designs and implementations. Chapter 6 addresses the designs of other key circuit blocks, and demonstrates a 60-GHz ADPLL for use in an FMCW transmitter.
- Chapter 7 explains several calibration techniques used to improve the performance of the 60-GHz ADPLL, while Chapter 8 describes the measurement challenges of a mm-wave frequency synthesizer, and proposes build-in self-test and self-characterization techniques.

The work presented in this book is a culmination of several years of research. We would like to thank and acknowledge the discussions and help we received from past and present colleagues at the Department of Electronics of Delft University of Technology in The Netherlands. We also thank the staff at Elsevier for their support.

Wanghua Wu
Robert Bogdan Staszewski
John R. Long
April 2015

LIST OF ABBREVIATIONS

ADC	Analog-to-digital converter
ADPLL	All-digital phase-locked loop
AM	Amplitude modulation
BiCMOS	Bipolar and CMOS
BISC	Built-in self-characterization
BIST	Build-in self-test
CB	Coarse-tuning bank
CKM	Modulation clock
CKR	Reference clock retimed by oscillator clock
CKV	Oscillator (variable) output clock
CLK	Clock
CML	Current-mode-logic
CMOS	Complementary metal-oxide-semiconductor
CT	Center-tap
DAC	Digital-to-analog converter
DCO	Digitally controlled oscillator
DDFS	Direct digital frequency synthesizer
DFC	Design for characterization
DFT	Design for test
DNL	Differential nonlinearity
DSP	Digital signal processing
EM	Electromagnetic
ESD	Electrostatic discharge
EVM	Error vector magnitude
FB	Fine-tuning bank
FCC	Federal Communications Commission
FCW	Frequency command word
FET	Field-effect transistor
FM	Frequency modulation
FMCW	Frequency-modulated continuous-wave
FREF	Frequency reference
Gb/s	Gigabit per second
GRO	Gated ring oscillator
GSM	Global system for mobile (communications)
GUI	Graphical user interface
HVAC	Heating, ventilating, and air conditioning
IC	Integrated circuit
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate frequency
IIR	Infinite impulse response
ILFD	Injection-locked frequency divider
INL	Integral nonlinearity
IO	Input/output

IR	Interconnect resistance
ISM	Industrial, scientific and medical
LF	Loop filter
LMS	Least mean squares
LO	Local oscillator
LPF	Low-pass filter
LSB	Least significant bit
MB	Mid-coarse tuning bank
MIM	Metal-insulator-metal
MIMO	Multiple-input and multiple-output
mm-wave	Millimeter-wave
MoM	Metal-oxide-metal
MOS	Metal-oxide-semiconductor
MTBF	Meantime between failures
nDCO	Normalized DCO
NMOS	N-type metal-oxide-semiconductor
NTW	Normalized tuning word
OTW	Oscillator tuning word
PA	Power amplifier
PCB	Printed circuit board
PFD	Phase/frequency detector
PHE	Phase error
PHR	Phase of frequency reference
PHV	Phase of variable oscillator
PI	Proportional-integral
PLL	Phase-locked loop
PM	Phase modulation
PMOS	P-type metal-oxide-semiconductor
PN	Phase noise
PPF	Poly-phase filter
PROM	Programmable read-only memory
PVT	Process, voltage and temperature
QAM	Quadrature amplitude modulation
Q-factor	Quality factor
Rx	Receiver
RF	Radio frequency
RFIC	Radio frequency integrated circuit
rms	Root-mean-square
RO	Ring oscillator
SAFF	Sense-amplifier-based flip-flop
SiGe	Silicon Germanium
SoC	System-on-chip
SPI	Serial peripheral interface
SRAM	Static random-access memory
TDC	Time-to-digital converter
TL	Transmission line
TR	Tuning range

TSPC	True single-phase clocked
Tx	Transmitter
UWB	Ultra-wideband
VCO	Voltage-controlled oscillator
WiGig	Wireless Gigabit Alliance
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless local-area network
WPAN	Wireless personal-area network

CONTENTS

CHAPTER 1

Introduction

Contents

Wireless communication has evolved remarkably since Guglielmo Marconi demonstrated the transmission and reception of Morse-coded messages across the Atlantic Ocean in the early twentieth century. Since then, new wireless communication methods and services have been continuously adopted that revolutionize our lives. Today, cellular, mobile, and wireless local-area networks (WLANs), afforded by breakthroughs in semiconductor technologies and their capability of mass production, are in use worldwide. They enable us to share images of our cherished moments with family and friends anywhere, and at anytime. The current trends toward portable wireless devices with ultra-high-speed (e.g., gigabit per second) connectivity will soon allow us to go online via our notebooks, cell phones, and tablets, simultaneously emailing, chatting with friends, web browsing and downloading movies and music in a fraction of the time it takes today. These devices will have to meet aggressive performance specifications in a sufficiently small and low-cost product at low power dissipation. This has prompted frantic research into new radio frequency (RF)-integrated circuits, system architectures, and design approaches.

This book explores the feasibility, advantages, design, and testing of digitally intensive frequency synthesis in the millimeter-wave (mm-wave) frequency range. An all-digital phase-locked loop (ADPLL)-based transmitter

Millimeter-Wave Digitally Intensive Frequency Generation in CMOS.
DOI: http://dx.doi.org/10.1016/B978-0-12-802207-8.00001-0

demonstrator fabricated in a production bulk CMOS process is described, which operates in the 60-GHz band, and achieves fractional frequency generation and wideband frequency modulation (FM). This digitally intensive design has the potential for low cost in volume production. It is also amenable to scaling in future technology nodes as opposed to other analog-intensive implementations. The silicon area and power consumption of such transmitters may be reduced further in future by harnessing the power of digital signal processing (DSP).

1.1 MOTIVATION

To achieve gigabit per second (i.e., Gb/s) transfer rates, Wi-Fi technology (IEEE 802.11ac in the 5-GHz band) [1] has been developed in recent years. Multistation WLAN throughput of at least 1 Gb/s, and a single link throughput of at least 500 Mb/s is specified. It employs RF bandwidths of up to 160 MHz, multiple-input and multiple-output (MIMO) array transmitter/receiver streams (up to 8), multi-user MIMO, and up to 256-QAM (quadrature amplitude modulation) schemes in order to achieve that level of performance. The mm-wave frequency bands, by contrast, are less crowded than the low-gigahertz radio communication bands and, more attractively, have wider license-free RF bandwidth available (e.g., 7 GHz bandwidth in the 60-GHz band). This will enable the gigabit-per-second short-range communication for consumer multimedia products and support the development of emerging short-range wireless networking in many important areas, for example, commerce, manufacturing, transport, etc., and thus provide significant growth potential in new internet applications in price-sensitive communication markets.

In the following sections, the advantages and challenges of mm-wave transceiver design in CMOS technology will be examined. The focus is on mm-wave frequency synthesis.

1.1.1 Advantages of Millimeter-Wave Radios

The mm-wave frequency band is defined as 30–300 GHz with a wavelength between 1 and 10 mm in the air [2]. There are various aspects of mm-wave bands that make it attractive for short-range applications. One major advantage is the bandwidth available to carry information. To keep operating costs low, regulatory licensed bands should be avoided, thus calling for the exploitation of the unlicensed or the industrial, scientific, and medical (ISM) radio bands. Figure 1.1 plots the available bandwidth

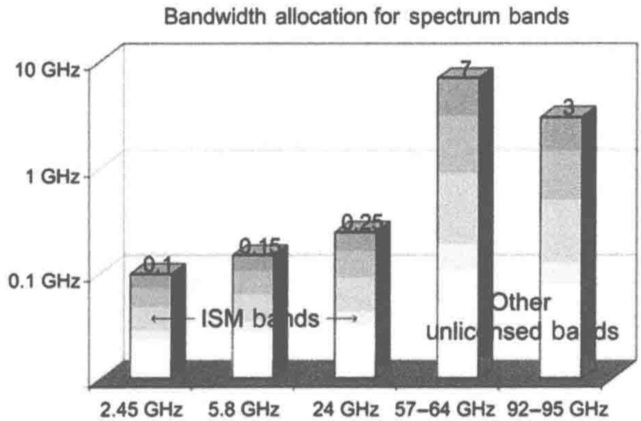

Figure 1.1 Bandwidth allocation for the ISM and unlicensed bands below 100 GHz by the FCC (in the United States) [3].

(indicated in GHz at the top of each column) for ISM and unlicensed bands below 100 GHz in the United States [3]. Below 25 GHz, the RF spectrum is congested due to frequency slots reserved for military, civil, and personal communication services. For reference, most commercial products operate in bands below 10 GHz, for example, the global system for mobile communications operates at 900 and 1,800 MHz (in Europe), and 850 and 1,900 MHz (in the United States), and ultra-wideband (UWB) radios are permitted to operate from 3.1 to 10.6 GHz [4]. Less than 1 GHz of bandwidth in total has been allocated for the license-free ISM bands at 2.45, 5.8, and 24 GHz. On the contrary, there is 7 GHz of bandwidth in the 60-GHz spectrum band allocated for license-free use, which is the largest ever allocated by the Federal Communications Commission (FCC) in the United States below 100 GHz. With such wide bandwidth available, mm-wave wireless links can achieve capacities as high as 7 Gb/s full duplex, which is unlikely to be matched by any of the RF wireless technologies at lower frequencies. The FCC has also recently approved another unlicensed band (92–95 GHz) to meet the growing demand for point-to-point high-bandwidth communication links [5].

For a given antenna size, the beamwidth can be made finer by increasing the frequency. Another benefit of the mm-wave radio is a narrower beam due to the shorter wavelength ($\lambda = c/f_c$, where c is the speed of light and f_c is the carrier frequency), which allows for deployment of multiple, independent links in close proximity. The main limitation of mm-wave radio is the physical range. Due to absorption by atmospheric oxygen and

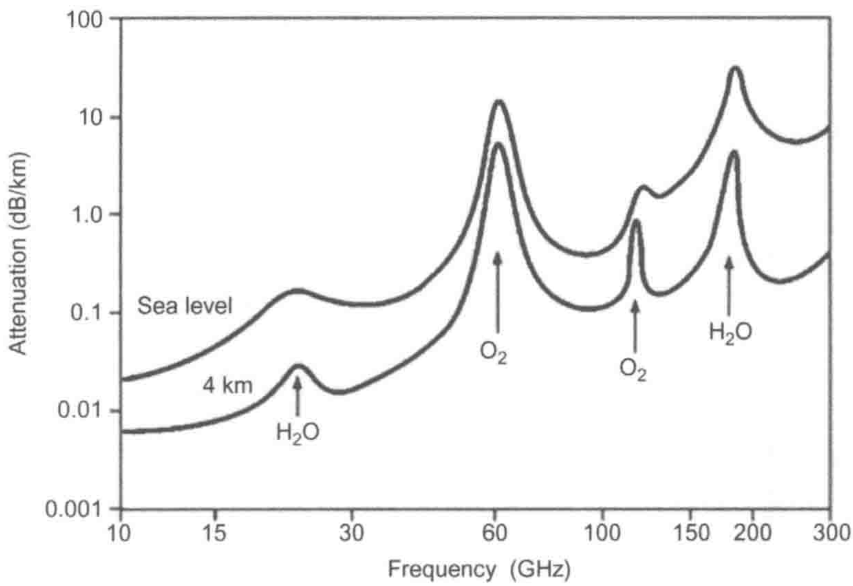

Figure 1.2 Average atmospheric attenuation of radio waves propagating through free space versus frequency [6].

water vapor, signal strength drops off rapidly with distance compared to other bands. Figure 1.2 illustrates the general trend of increasing the attenuation of radio waves with frequency (due only to atmospheric losses; free space path loss is not accounted for) [6]. Atmospheric absorption by oxygen causes more than 15 dB/km of attenuation. The loss of a link budget at 60 GHz is therefore unacceptable for long-distance communication (e.g., >1 km), but can be used to an advantage in short-range indoor communications because the limited range and narrow beamwidths prevent interference between neighboring links. These attributes have led to greatly reduced regulatory burdens for mm-wave communications.

Due to its potential for short-range, gigabit-per-second communications, several standards in the 60-GHz band have been established in recent years. The IEEE 802.15.3c standard was approved in 2009 for wireless personal-area network [7]. A similar standard for Europe (ECMA-387 [8]) was published in 2008. The WirelessHD consortium has released a specification version 1.0a for regulating the transmission of high-definition video in this unlicensed band [9]. Most recently, the IEEE 802.11ad standard (known as WiGig) [10] was adopted in 2013. It provides data rates up to 7 Gb/s, or more than 10× the maximum speed previously supported by the IEEE 802.11 standard. IEEE 802.11ad also adds a "fast session transfer" feature,