RF MICROELECTRONICS

Second Edition

Behzad Razavi

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To the memory of my parents

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CONTENTS

PREFACE TO THE SECOND EDITION

In the 14 years since the first edition of this book, RF IC design has experienced a dramatic metamorphosis. Innovations in transceiver architectures, circuit topologies, and device structures have led to highly-integrated "radios" that span a broad spectrum of applications. Moreover, new analytical and modeling techniques have considerably improved our understanding of RF circuits and their underlying principles. A new edition was therefore due.

The second edition differs from the first in several respects:

1. I realized at the outset—three-and-a-half years ago—that simply adding "patches" to the first edition would not reflect today's RF microelectronics. I thus closed the first edition and began with a clean slate. The two editions have about 10% overlap.
2. I wanted the second edition to contain greater pedagogy, helping the reader understand both the fundamentals and the subtleties. I have thus incorporated hundreds of examples and problems.
3. I also wanted to teach *design* in addition to analysis. I have thus included step-by-step design procedures and examples. Furthermore, I have dedicated Chapter 13 to the step-by-step transistor-level design of a dual-band WiFi transceiver.
4. With the tremendous advances in RF design, some of the chapters have inevitably become longer and some have been split into two or more chapters. As a result, the second edition is nearly three times as long as the first.

Suggestions for Instructors and Students

The material in this book is much more than can be covered in one quarter or semester. The following is a possible sequence of the chapters that can be taught in one term with reasonable depth. Depending on the students' background and the instructor's preference, other combinations of topics can also be covered in one quarter or semester.

Chapter 1: Introduction to RF and Wireless Technology

This chapter provides the big picture and should be covered in about half an hour.

Chapter 2: Basic Concepts in RF Design

The following sections should be covered: General Considerations, Effects of Nonlinearity (the section on AM/PM Conversion can be skipped), Noise, and Sensitivity and Dynamic Range. (The sections on Passive Impedance Transformation, Scattering Parameters, and Analysis of Nonlinear Dynamic Systems can be skipped.) This chapter takes about six hours of lecture.

Chapter 3: Communication Concepts

This chapter can be covered minimally in a quarter system—for example, Analog Modulation, Quadrature Modulation, GMSK Modulation, Multiple Access Techniques, and the IEEE802.11a/b/g Standard. In a semester system, the concept of signal constellations can be introduced and a few more modulation schemes and wireless standards can be taught. This chapter takes about two hours in a quarter system and three hours in a semester system.

Chapter 4: Transceiver Architectures

This chapter is relatively long and should be taught selectively. The following sections should be covered: General Considerations, Basic and Modern Heterodyne Receivers, Direct-Conversion Receivers, Image-Reject Receivers, and Direct-Conversion Transmitters. In a semester system, Low-IF Receivers and Heterodyne Transmitters can be covered as well. This chapter takes about eight hours in a quarter system and ten hours in a semester system.

Chapter 5: Low-Noise Amplifiers

The following sections should be covered: General Considerations, Problem of Input Matching, and LNA Topologies. A semester system can also include Gain Switching and Band Switching or High-IP_2 LNAs. This chapter takes about six hours in a quarter system and eight hours in a semester system.

Chapter 6: Mixers

The following sections should be covered: General Considerations, Passive Downconversion Mixers (the computation of noise and input impedance of voltage-driven sampling mixers can be skipped), Active Downconversion Mixers, and Active Mixers with High IP_2. In a semester system, Active Mixers with Enhanced Transconductance, Active Mixers with Low Flicker Noise, and Upconversion Mixers can also be covered. This chapter takes about eight hours in a quarter system and ten hours in a semester system.

Chapter 7: Passive Devices

This chapter may not fit in a quarter system. In a semester system, about three hours can be spent on basic inductor structures and loss mechanisms and MOS varactors.

Chapter 8: Oscillators

This is a long chapter and should be taught selectively. The following sections should be covered: Basic Principles, Cross-Coupled Oscillator, Voltage-Controlled

Oscillators, Low-Noise VCOs. In a quarter system, there is little time to cover phase noise. In a semester system, both approaches to phase noise analysis can be taught. This chapter takes about six hours in a quarter system and eight hours in a semester system.

Chapter 9: Phase-Locked Loops

This chapter forms the foundation for synthesizers. In fact, if taught carefully, this chapter naturally teaches integer-N synthesizers, allowing a quarter system to skip the next chapter. The following sections should be covered: Basic Concepts, Type-I PLLs, Type-II PLLs, and PFD/CP Nonidealities. A semester system can also include Phase Noise in PLLs and Design Procedure. This chapter takes about four hours in a quarter system and six hours in a semester system.

Chapter 10: Integer-N Synthesizers

This chapter is likely sacrificed in a quarter system. A semester system can spend about four hours on Spur Reduction Techniques and Divider Design.

Chapter 11: Fractional-N Synthesizers

This chapter is likely sacrificed in a quarter system. A semester system can spend about four hours on Randomization and Noise Shaping. The remaining sections may be skipped.

Chapter 12: Power Amplifiers

This is a long chapter and, unfortunately, is often sacrificed for other chapters. If coverage is desired, the following sections may be taught: General Considerations, Classification of Power Amplifiers, High-Efficiency Power Amplifiers, Cascode Output Stages, and Basic Linearization Techniques. These topics take about four hours of lecture. Another four hours can be spent on Doherty Power Amplifier, Polar Modulation, and Outphasing.

Chapter 13: Transceiver Design Example

This chapter provides a step-by-step design of a dual-band transceiver. It is possible to skip the state-of-the-art examples in Chapters 5, 6, and 8 to allow some time for this chapter. The system-level derivations may still need to be skipped. The RX, TX, and synthesizer transistor-level designs can be covered in about four hours.

A solutions manual is available for instructors via the Pearson Higher Education Instructor Resource Center web site: pearsonhighered.com/irc; and a set of Powerpoint slides is available for instructors at **informit.com/razavi**. Additional problems will be posted on the book's website (**informit.com/razavi**).

—Behzad Razavi
July 2011

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PREFACE TO THE FIRST EDITION

The annual worldwide sales of cellular phones has exceeded \$2.5B. With 4.5 million customers, home satellite networks comprise a \$2.5B industry. The global positioning system is expected to become a \$5B market by the year 2000. In Europe, the sales of equipment and services for mobile communications will reach \$30B by 1998. The statistics are overwhelming.

The radio frequency (RF) and wireless market has suddenly expanded to unimaginable dimensions. Devices such as pagers, cellular and cordless phones, cable modems, and RF identification tags are rapidly penetrating all aspects of our lives, evolving from luxury items to indispensable tools. Semiconductor and system companies, small and large, analog and digital, have seen the statistics and are striving to capture their own market share by introducing various RF products.

RF design is unique in that it draws upon many disciplines unrelated to integrated circuits (ICs). The RF knowledge base has grown for almost a century, creating a seemingly endless body of literature for the novice.

This book deals with the analysis and design of RF integrated circuits and systems. Providing a systematic treatment of RF electronics in a tutorial language, the book begins with the necessary background knowledge from microwave and communication theory and leads the reader to the design of RF transceivers and circuits. The text emphasizes both architecture and circuit level issues with respect to monolithic implementation in VLSI technologies. The primary focus is on bipolar and CMOS design, but most of the concepts can be applied to other technologies as well. The reader is assumed to have a basic understanding of analog IC design and the theory of signals and systems.

The book consists of nine chapters. Chapter 1 gives a general introduction, posing questions and providing motivation for subsequent chapters. Chapter 2 describes basic concepts in RF and microwave design, emphasizing the effects of nonlinearity and noise.

Chapters 3 and 4 take the reader to the communication system level, giving an overview of modulation, detection, multiple access techniques, and wireless standards. While initially appearing to be unnecessary, this material is in fact essential to the concurrent design of RF circuits and systems.

Chapter 5 deals with transceiver architectures, presenting various receiver and transmitter topologies along with their merits and drawbacks. This chapter also includes a number of case studies that exemplify the approaches taken in actual RF products.

Chapters 6 through 9 address the design of RF building blocks: low-noise amplifiers and mixers, oscillators, frequency synthesizers, and power amplifiers, with particular attention to minimizing the number of off-chip components. An important goal of these chapters is to demonstrate how the system requirements define the parameters of the circuits and how the performance of each circuit impacts that of the overall transceiver.

I have taught approximately 80% of the material in this book in a 4-unit graduate course at UCLA. Chapters 3, 4, 8, and 9 had to be shortened in a ten-week quarter, but in a semester system they can be covered more thoroughly.

Much of my RF design knowledge comes from interactions with colleagues. Helen Kim, Ting-Ping Liu, and Dan Avidor of Bell Laboratories, and David Su and Andrew Gzegorek of Hewlett-Packard Laboratories have contributed to the material in this book in many ways. The text was also reviewed by a number of experts: Stefan Heinen (Siemens), Bart Jansen (Hewlett-Packard), Ting-Ping Liu (Bell Labs), John Long (University of Toronto), Tadao Nakagawa (NTT), Gitty Nasserbakht (Texas Instruments), Ted Rappaport (Virginia Tech), Tirdad Sowlati (Gennum), Trudy Stetzler (Bell Labs), David Su (Hewlett-Packard), and Rick Wesel (UCLA). In addition, a number of UCLA students, including Farbod Behbahani, Hooman Darabi, John Leete, and Jacob Rael, "test drove" various chapters and provided useful feedback. I am indebted to all of the above for their kind assistance.

I would also like to thank the staff at Prentice Hall, particularly Russ Hall, Maureen Diana, and Kerry Riordan for their support.

—Behzad Razavi
July 1997

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I have been fortunate to benefit from the support of numerous people during the writing, review, and production phases of this book. I would like to express my thanks here.

Even after several rounds of self-editing, it is possible that typos or subtle mistakes have eluded the author. Sometimes, an explanation that is clear to the author may not be so to the reader. And, occasionally, the author may have missed a point or a recent development. A detailed review of the book by others thus becomes necessary. The following individuals meticulously reviewed various chapters, discovered my mistakes, and made valuable suggestions:

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I am thankful for their enthusiastic, organized, and to-the-point reviews.

The book's production was proficiently managed by the staff at Prentice Hall, including Bernard Goodwin and Julie Nahil. I would like to thank both.

As with my other books, my wife, Angelina, typed the entire second edition in Latex and selflessly helped me in this three-and-a-half-year endeavor. I am grateful to her.

—*Behzad Razavi*

ABOUT THE AUTHOR

Behzad Razavi received the BSEE degree from Sharif University of Technology in 1985 and MSEE and PhDEE degrees from Stanford University in 1988 and 1992, respectively. He was with AT&T Bell Laboratories and Hewlett-Packard Laboratories until 1996. Since 1996, he has been associate professor and, subsequently, professor of electrical engineering at University of California, Los Angeles. His current research includes wireless transceivers, frequency synthesizers, phase-locking and clock recovery for high-speed data communications, and data converters.

Professor Razavi was an adjunct professor at Princeton University from 1992 to 1994, and at Stanford University in 1995. He served on the Technical Program Committees of the International Solid-State Circuits Conference (ISSCC) from 1993 to 2002 and VLSI Circuits Symposium from 1998 to 2002. He has also served as guest editor and associate editor of the *IEEE Journal of Solid-State Circuits, IEEE Transactions on Circuits and Systems,* and *International Journal of High Speed Electronics*.

Professor Razavi received the Beatrice Winner Award for Editorial Excellence at the 1994 ISSCC; the best paper award at the 1994 European Solid-State Circuits Conference; the best panel award at the 1995 and 1997 ISSCC; the TRW Innovative Teaching Award in 1997; the best paper award at the IEEE Custom Integrated Circuits Conference (CICC) in 1998; and McGraw-Hill First Edition of the Year Award in 2001. He was the co-recipient of both the Jack Kilby Outstanding Student Paper Award and the Beatrice Winner Award for Editorial Excellence at the 2001 ISSCC. He received the Lockheed Martin Excellence in Teaching Award in 2006; the UCLA Faculty Senate Teaching Award in 2007; and the CICC Best Invited Paper Award in 2009. He was also recognized as one of the top ten authors in the fifty-year history of ISSCC. He received the IEEE Donald Pederson Award in Solid-State Circuits in 2012.

Professor Razavi is an IEEE Distinguished Lecturer, a Fellow of IEEE, and the author of *Principles of Data Conversion System Design*, *RF Microelectronics*, *First Edition* (translated to Chinese, Japanese, and Korean), *Design of Analog CMOS Integrated Circuits* (translated to Chinese, Japanese, and Korean), *Design of Integrated Circuits for*

Optical Communications, and *Fundamentals of Microelectronics* (translated to Korean and Portuguese), and the editor of *Monolithic Phase-Locked Loops and Clock Recovery Circuits* and *Phase-Locking in High-Performance Systems.*

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CHAPTER 1

INTRODUCTION TO RF AND WIRELESS TECHNOLOGY

Compare two RF transceivers designed for cell phones:

> *"A 2.7-V GSM RF Transceiver IC" [1] (published in 1997)*
>
> *"A Single-Chip 10-Band WCDMA/HSDPA 4-Band GSM/EDGE SAW-Less CMOS Receiver with DigRF 3G Interface and +90-dBm* $\mathrm{IIP_2}$*" [2] (published in 2009)*

Why is the latter much more complex than the former? Does the latter have a higher performance or only greater functionality? Which one costs more? Which one consumes a higher power? What do all the acronyms GSM, WCDMA, HSDPA, EDGE, SAW, and $\mathrm{IIP_2}$ mean? Why do we care?

The field of RF communication has grown rapidly over the past two decades, reaching far into our lives and livelihood. Our cell phones serve as an encyclopedia, a shopping terminus, a GPS guide, a weather monitor, and a telephone—all thanks to their wireless communication devices. We can now measure a patient's brain or heart activity and transmit the results wirelessly, allowing the patient to move around untethered. We use RF devices to track merchandise, pets, cattle, children, and convicts.

1.1 A WIRELESS WORLD

Wireless communication has become almost as ubiquitous as electricity; our refrigerators and ovens may not have a wireless device at this time, but it is envisioned that our homes will eventually incorporate a wireless network that controls every device and appliance. High-speed wireless links will allow seamless connections among our laptops, digital cameras, camcorders, cell phones, printers, TVs, microwave ovens, etc. Today's WiFi and Bluetooth connections are simple examples of such links.

How did wireless communication take over the world? A confluence of factors has contributed to this explosive growth. The principal reason for the popularity of wireless communication is the ever-decreasing cost of electronics. Today's cell phones cost about the same as those a decade ago but they offer many more functions and features: many frequency bands and communication modes, WiFi, Bluetooth, GPS, computing, storage, a digital camera, and a user-friendly interface. This affordability finds its roots in *integration*, i.e., how much functionality can be placed on a single chip—or, rather, how few components are left off-chip. The integration, in turn, owes its steady rise to (1) the scaling of VLSI processes, particularly, CMOS technology, and (2) innovations in RF architectures, circuits, and devices.

Along with higher integration levels, the performance of RF circuits has also improved. For example, the power consumption necessary for a given function has decreased and the speed of RF circuits has increased. Figure 1.1 illustrates some of the trends in RF integrated circuits (ICs) and technology for the past two decades. The minimum feature size of CMOS

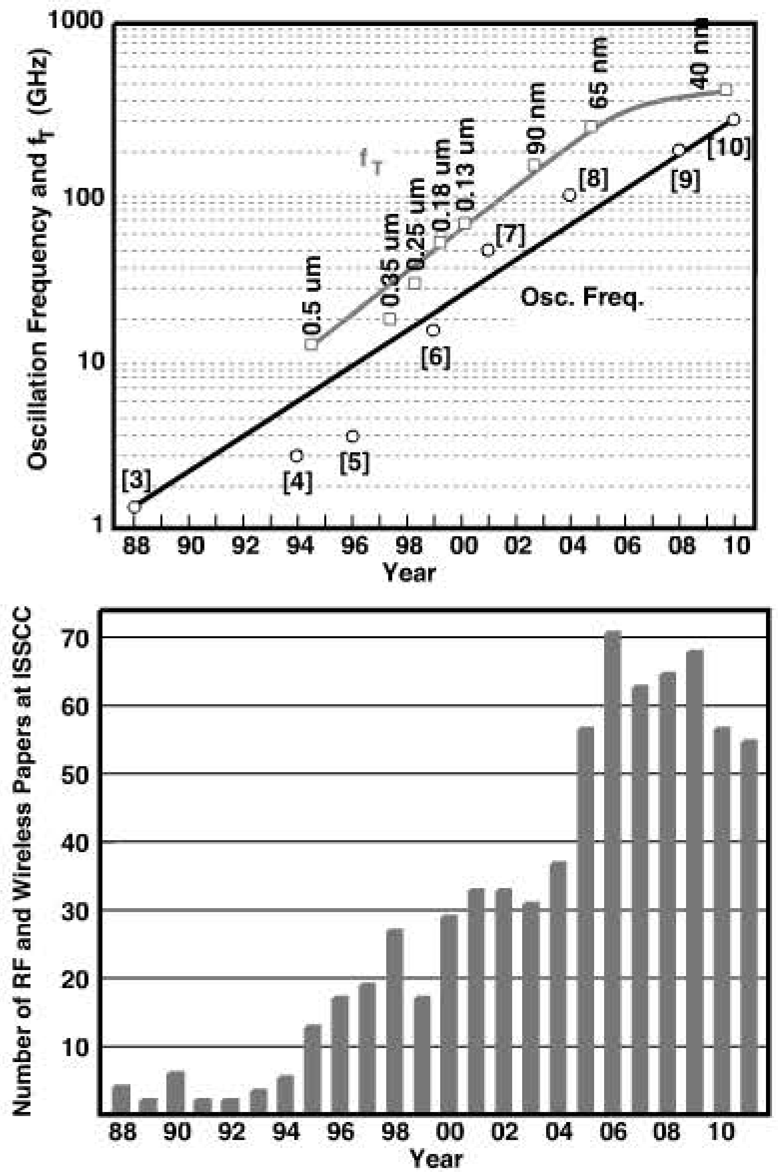

Figure 1.1 *Trends in RF circuits and technology.*

technology has fallen from 0.5 μm to 40 nm, the transit frequency,[1] f_T, of NMOS devices has risen from about 12 GHz to several hundred gigahertz, and the speed of RF oscillators has gone from 1.2 GHz to 300 GHz. Also shown is the number of RF and wireless design papers presented at the International Solid-State Circuits Conference (ISSCC) each year, revealing the fast-growing activity in this field.

1.2 RF DESIGN IS CHALLENGING

Despite many decades of work on RF and microwave theory and two decades of research on RF ICs, the design and implementation of RF circuits and transceivers remain challenging. This is for three reasons. First, as shown in Fig. 1.2, RF design draws upon a multitude of disciplines, requiring a good understanding of fields that are seemingly irrelevant to integrated circuits. Most of these fields have been under study for more than half a century, presenting a massive body of knowledge to a person entering RF IC design. One objective of this book is to provide the necessary background from these disciplines without overwhelming the reader.

Second, RF circuits and transceivers must deal with numerous trade-offs, summarized in the "RF design hexagon" of Fig. 1.3. For example, to lower the noise of a front-end amplifier, we must consume a greater power or sacrifice linearity. We will encounter these trade-offs throughout this book.

Third, the demand for higher performance, lower cost, and greater functionality continues to present new challenges. The early RF IC design work in the 1990s strove to integrate *one* transceiver—perhaps along with the digital baseband processor—on a single chip. Today's efforts, on the other hand, aim to accommodate multiple transceivers operating in different frequency bands for different wireless standards (e.g., Bluetooth, WiFi, GPS, etc.). The two papers mentioned at the beginning of this chapter exemplify this trend. It is interesting to note that the silicon chip area of early single-transceiver systems was

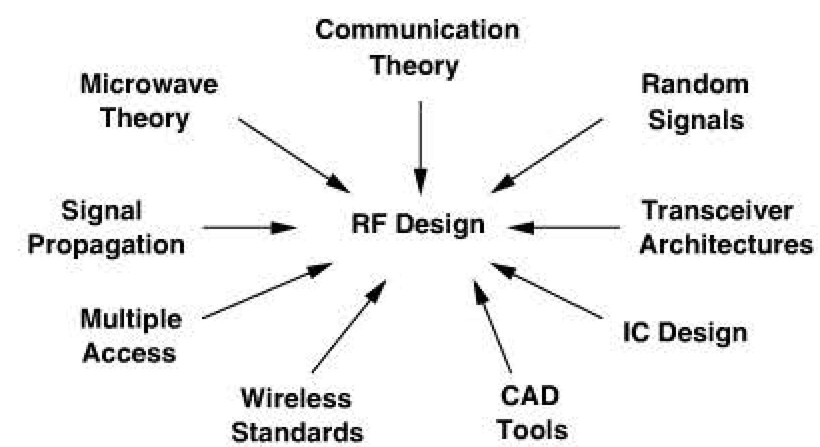

Figure 1.2 *Various disciplines necessary in RF design.*

1. The transit frequency is defined as the frequency at which the small-signal current gain of a device falls to unity.

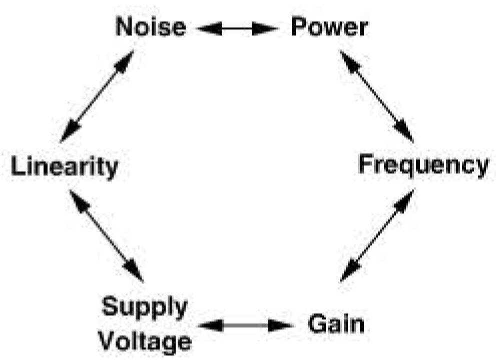

Figure 1.3 *RF design hexagon.*

dominated by the digital baseband processor, allowing RF and analog designers some latitude in the choice of their circuit and device topologies. In today's designs, however, the multiple transceivers tend to occupy a *larger* area than the baseband processor, requiring that RF and analog sections be designed with much care about their area consumption. For example, while on-chip spiral inductors (which have a large footprint) were utilized in abundance in older systems, they are now used only sparingly.

1.3 THE BIG PICTURE

The objective of an RF transceiver is to transmit and receive information. We envision that the transmitter (TX) somehow processes the voice or data signal and applies the result to the antenna [Fig. 1.4(a)]. Similarly, the receiver (RX) senses the signal picked up by the antenna and processes it so as to reconstruct the original voice or data information. Each black box in Fig. 1.4(a) contains a great many functions, but we can readily make two observations: (1) the TX must drive the antenna with a high power level so that the transmitted signal is strong enough to reach far distances, and (2) the RX may sense a small signal (e.g., when a cell phone is used in the basement of a building) and must first amplify the signal with low noise. We now architect our transceiver as shown in Fig. 1.4(b), where the signal to be transmitted is first applied to a "modulator" or "upconverter" so that its center frequency goes from zero to, say, $f_c = 2.4$ GHz. The result drives the antenna through a "power amplifier" (PA). On the receiver side, the signal is sensed by a "low-noise amplifier" (LNA) and subsequently by a "downconverter" or "demodulator" (also known as a "detector").

The upconversion and downconversion paths in Fig. 1.4(b) are driven by an oscillator, which itself is controlled by a "frequency synthesizer." Figure 1.4(c) shows the overall transceiver.[2] The system looks deceptively simple, but we will need the next 900 pages to cover its RF sections. And perhaps another 900 pages to cover the analog-to-digital and digital-to-analog converters.

2. In some cases, the modulator and the upconverter are one and the same. In some other cases, the modulation is performed in the digital domain before upconversion. Most receivers demodulate and detect the signal digitally, requiring only a downconverter in the analog domain.

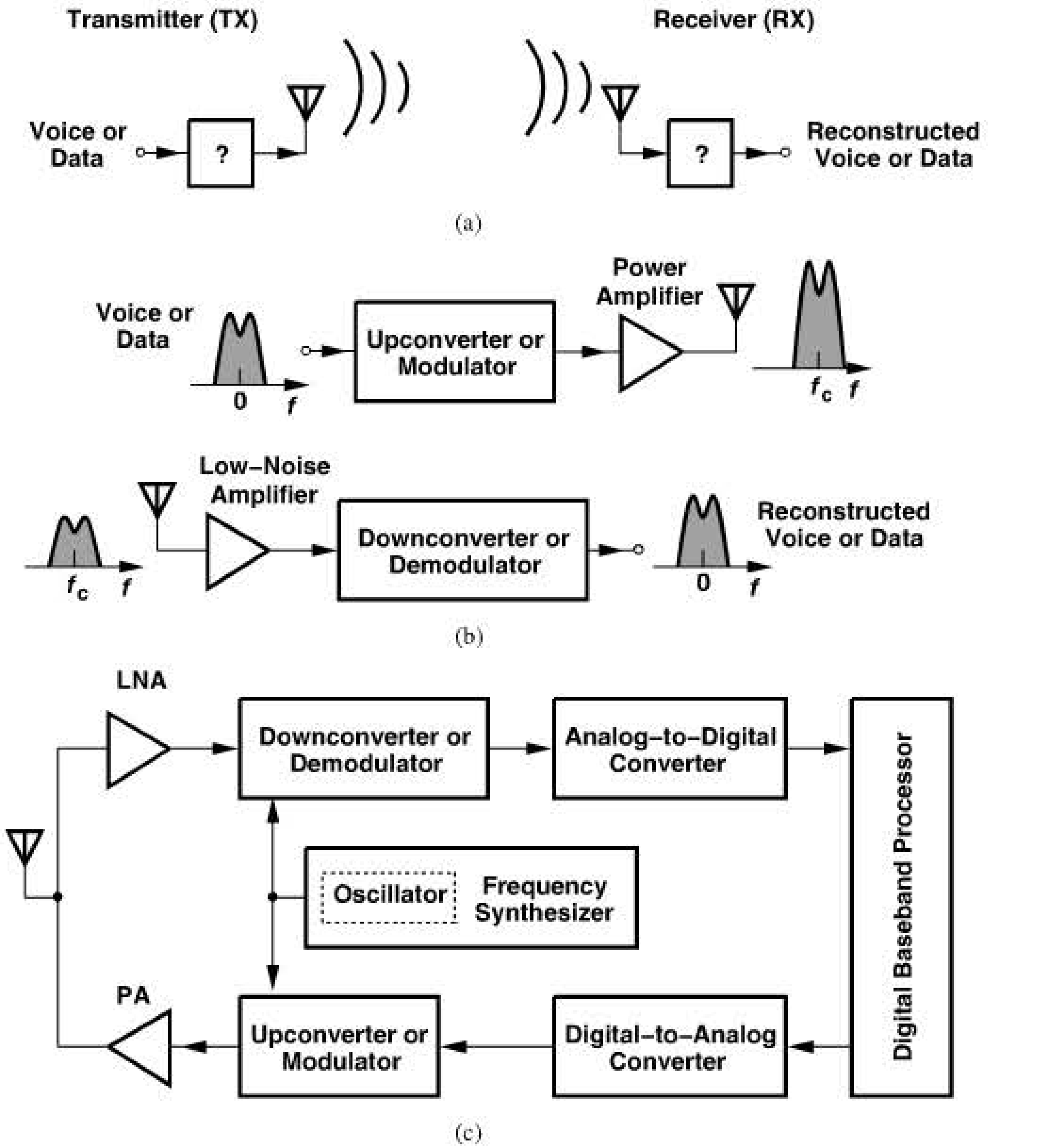

Figure 1.4 *(a) Simple view of RF communication, (b) more complete view, (c) generic RF transceiver.*

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CHAPTER

2

BASIC CONCEPTS IN RF DESIGN

RF design draws upon many concepts from a variety of fields, including signals and systems, electromagnetics and microwave theory, and communications. Nonetheless, RF design has developed its own analytical methods and its own language. For example, while the nonlinear behavior of analog circuits may be characterized by "harmonic distortion," that of RF circuits is quantified by very different measures.

This chapter deals with general concepts that prove essential to the analysis and design of RF circuits, closing the gaps with respect to other fields such as analog design, microwave theory, and communication systems. The outline is shown below.

Nonlinearity	Noise	Impedance Transformation
▪ Harmonic Distortion	▪ Noise Spectrum	▪ Series–Parallel Conversion
▪ Compression	▪ Device Noise	▪ Matching Networks
▪ Intermodulation	▪ Noise in Circuits	▪ S–Parameters
▪ Dynamic Nonlinear Systems		

2.1 GENERAL CONSIDERATIONS

2.1.1 Units in RF Design

RF design has traditionally employed certain units to express gains and signal levels. It is helpful to review these units at the outset so that we can comfortably use them in our subsequent studies.

The voltage gain, V_{out}/V_{in}, and power gain, P_{out}/P_{in}, are expressed in decibels (dB):

$$A_V|_{\mathrm{dB}} = 20\log\frac{V_{out}}{V_{in}} \tag{2.1}$$

$$A_P|_{\mathrm{dB}} = 10\log\frac{P_{out}}{P_{in}}. \tag{2.2}$$