SECOND EDITION

MICROWAVE FILTERS FOR COMMUNICATION SYSTEMS

FUNDAMENTALS, DESIGN, AND APPLICATIONS

RICHARD J. CAMERON
CHANDRA M. KUDSIA
RAAFAT R. MANSOUR

WILEY

Microwave Filters for Communication Systems

Microwave Filters for Communication Systems

Fundamentals, Design, and Applications

Second Edition

Richard J. Cameron
Chandra M. Kudsia
Raafat R. Mansour

WILEY

This second edition first published 2018

Edition History
John Wiley & Sons, Inc. (1e, 2007)

Registered Offices
John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA

Editorial Office
111 River Street, Hoboken, NJ 07030, USA

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: Cameron, Richard J., author. | Kudsia, Chandra M., author. | Mansour, Raafat R., author.
Title: Microwave filters for communication systems : fundamentals, design and applications / by Richard J. Cameron, Chandra M. Kudsia, Raafat R. Mansour.
Description: Second edition. | Hoboken, NJ, USA : Wiley, 2018. | Includes bibliographical references and index. |
Identifiers: LCCN 2017036462 (print) | LCCN 2017037258 (ebook) | ISBN 9781119292395 (pdf) | ISBN 9781119292388 (epub) | ISBN 9781118274347 (hardback)
Subjects: LCSH: Microwave filters. | Telecommunication systems–Equipment and supplies. | BISAC: TECHNOLOGY & ENGINEERING / Microwaves.
Classification: LCC TK7872.F5 (ebook) | LCC TK7872.F5 C35 2018 (print) | DDC 621.3841/2–dc23
LC record available at https://lccn.loc.gov/2017036462

Cover design by Wiley
Cover image: © John Lund/Gettyimages

Set in 10/12pt WarnockPro by SPi Global, Chennai, India

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

The authors wish to acknowledge the many engineers, technologists, and manufacturing staff at COM DEV who contributed in advancing the state of the art and in maintaining sustained leadership position for the design and implementation of microwave filters and multiplexing networks for communication satellite systems from 1970s to 2015.[1]

1 COM DEV was sold to Honeywell in 2016.

Contents

Preface

Three new chapters are introduced in the second edition. Chapters on multiband filters and tunable filters are added to reflect the emerging markets for wireless systems. The third chapter is devoted to the practical aspects of design and implementation of microwave filters and multiplexing networks. Chapters from edition 1 have undergone a thorough review and minor revisions. New sections have been added in Chapters 1, 6, 8, 16, and 20.

The book begins with a simple model of a communication system. It addresses the issues on: (i) whether there is a limitation on the available bandwidth for a wireless communication system, (ii) what the limitations are for transmitting information in the available bandwidth, and (iii) what the cost-sensitive parameters of a communication system are. Each issue is then addressed to gain understanding of various system parameters with emphasis on the role and requirements of filter networks in different parts of the communication system. This sets the stage to address the fundamentals of filter design based on circuit theory approximation. It continues with a description of classical filters. This is followed by the development of computer-aided techniques to generate a general class of prototype filter functions, exhibiting a symmetrical or asymmetrical frequency response. This general formulation is accomplished by incorporating hypothetical *frequency invariant reactive* (FIR) elements in the lowpass prototype filter design. The FIR elements show up as frequency offsets of resonant circuits in real bandpass or bandstop filters. Absence of FIR elements represents the classical filter function that gives rise to symmetrical frequency response. From this general formulation of the filter function, synthesis techniques are described to realize the equivalent lumped parameter circuit model of filter networks. The next step in the synthesis procedure is to translate the circuit model of the filter into its equivalent microwave structure. As a first approximation, this can be achieved by making use of the extensive existing data that relates circuit models to the physical dimensions and properties of structures used for microwave filters. For more accurate determination of physical dimensions, modern electromagnetic (EM)-based techniques and tools are described to determine filter dimensions with near-arbitrary accuracy. This knowledge is carried through in the design of multiplexing networks having arbitrary bandwidths and channel separations.

Separate chapters are devoted to computer-aided tuning and high-power considerations in filter design. Our goal has been to give the reader a broad view of filter requirements and design and sufficient depth to follow continuing advances in this field. Throughout the book, emphasis has been on fundamentals and practical considerations in filter design. Distinct features of the book include (i) system considerations in the design of filters, (ii) the general formulation and synthesis of filter functions including the FIR elements, (iii) synthesis techniques for lowpass prototype filters exhibiting symmetrical or asymmetrical frequency response in a variety of topologies, (iv) application of EM techniques to optimize physical dimensions of microwave filter structures, (v) design and tradeoffs of various multiplexer configurations,

(vi) computer-aided filter tuning techniques, and (vii) high-power considerations for terrestrial and space applications. The material in the book is organized in 23 chapters:

- Chapter 1 is devoted to an overview of communication systems, more specifically to the relationship between the communication channel and other elements of the system. The intent here is to provide the reader with sufficient background to be able to appreciate the critical role and requirements of radio frequency (RF) filters in communication systems.
  - In the second edition, Digital Transmission, The Channelizer Section, Frequency Plan, and Limitations of Microwave Filter Technology have been revised. The section on RF Filters for Cellular Systems is modified to reflect the requirement of additional frequency bands to meet the explosive growth in wireless services. A section has been added on Ultra Wideband (UWB) Wireless Communication. The summary at the end of the chapter has been revised to reflect the changes.
- The principles that unify communication theory and circuit theory approximations are explained in Chapter 2. It highlights the essential assumptions and the success of the frequency analysis approach that we take for granted in analyzing electrical networks.
- Chapter 3 describes the synthesis of the characteristic polynomials to realize the classical maximally flat, Chebyshev, and elliptic function lowpass prototype filters. It includes a discussion of FIR elements and their inclusion to generate filter functions with asymmetrical frequency response. This leads to transfer function polynomials (with certain restrictions) with complex coefficients, a distinct departure from the more familiar characteristic polynomials with rational and real coefficients. This provides a basis to analyze the most general class of filter functions in the lowpass prototype domain, including minimum and nonminimum phase filters, exhibiting a symmetrical or asymmetrical frequency response.
- Chapter 4 presents the synthesis of characteristic polynomials of lowpass prototype filters with arbitrary amplitude response using computer-aided optimization technique. The key lies in making sure that the optimization procedure is highly efficient. This is accomplished by determining the gradients of the objective function analytically and linking it directly to the desired amplitude response shape. It includes minimum phase and nonminimum phase filters exhibiting a symmetrical or asymmetrical frequency response. To demonstrate the flexibility of this method, examples of some unconventional filters are included.
- Chapter 5 provides a review of the basic concepts used in the analysis of multiport microwave networks. These concepts are important for filter designers since any filter or multiplexer can be divided into smaller two-, three-, or N-port networks connected together. Five matrix representations of microwave networks are described, namely, $[Z]$, $[lY]$, $[ABCD]$, $[S]$, and $[T]$ matrices. These matrices are interchangeable, where the elements of any matrix can be written in terms of those of the other four matrices. Familiarity with the concepts of these matrices is essential in understanding the material presented in this book.
- Chapter 6 begins with a review of some important scattering parameter relations that are relevant for the synthesis of filter networks. This is followed by a discussion of the general kind of Chebyshev function and its application in generating the transfer and reflection polynomials for the equi-ripple class of filter characteristics with an arbitrary distribution of the transmission zeros. In the final part of this chapter, the special cases of predistorted and dual-band filtering functions are discussed.
  - The second edition has two added features: a section for finding the positions of the in-band reflection maxima and the out-of-band transmission maxima of the generalized Chebyshev prototype filter and an appendix extending the two-port S-parameter analysis and synthesis to multiport networks with complex terminations. A section has been added describing the relationship between the characteristic polynomials, S-parameters, short-circuit admittance, and $[ABCD]$ transfer matrix parameters.

- In Chapter 7, filter synthesis based on the [$ABCD$] matrix is presented. The synthesis procedure is broken down into two stages. The first stage involves lumped element lossless inductors, capacitors, and FIR elements. The second stage includes the immitance inverters. Use of such inverters allows for the prototype electrical circuit in a form suitable for realization with intercoupled microwave resonators. The technique is applicable for synthesizing lowpass prototype filters with symmetrical or asymmetrical response, in ladder form, as well as cross-coupled topologies. A further generalization is introduced to allow the synthesis of singly terminated filters. The synthesis process described in this chapter represents the most general technique for synthesizing lumped element, lowpass prototype filter networks.
- In Chapter 8, the concept of $N \times N$ coupling matrix for the synthesis of bandpass prototype filters is introduced. The procedure is modified by including FIR elements to allow synthesis of asymmetric filter response as well. The procedure is then extended to $N + 2$ coupling matrix by separating out the purely resistive and purely reactive portions of the $N \times N$ matrix. The $N + 2$ coupling matrix allows multiple couplings with respect to the input and output ports, in addition to the main input/output couplings to the first and last resonators as envisaged in the $N \times N$ coupling matrix. This allows synthesis of fully canonical filters and simplifies the process of similarity transformations to realize other filter topologies. This synthesis process yields the general coupling matrix with finite entries for all the couplings. The next step in the process is to derive topologies with a minimum number of couplings, referred to as canonical forms. This is achieved by applying similarity transformations to the coupling matrix. Such transformations preserve the eigenvalues and eigenvectors of the matrix, thus ensuring that the desired filter response remains unaltered. There are two principal advantages of this synthesis technique. Once the general coupling matrix with all the permissible couplings has been synthesized, it allows matrix operations on the coupling matrix to realize a variety of filter topologies. The second advantage is that the coupling matrix represents the practical bandpass filter topology. Therefore, it is possible to identify each element of the practical filter uniquely, including its Q value, dispersion characteristics, and sensitivity. This permits a more accurate determination of the practical filter characteristics and an insight into ways to optimize filter performance.
  - In the second edition, two new sections have been added: (i) $N + 2$ Coupling Matrix Synthesis for Networks with Complex Terminations and (ii) Even and Odd Mode Coupling Matrix Synthesis Technique: The Folded Lattice Array.
- Chapter 9 develops methods of similarity transformations to realize a wide range of topologies appropriate for dual-mode filter networks. Dual-mode filters make use of two orthogonally polarized degenerate modes, supported in a single physical resonator, be it a cavity, a dielectric disc, or a planar structure, thereby allowing a significant reduction in the size of filters. Besides the longitudinal and folded configurations, structures referred to as cascade quartets and cul de sac filters are also included. The chapter concludes with examples and a discussion of the sensitivity of the various dual-mode filter topologies.
- In Chapter 10, we introduce two unusual circuit sections: the extracted pole section and the trisection. These sections are capable of realizing one transmission zero each. They can be cascaded with other circuit elements in the filter network. Application of these sections extends the range of topologies for realizing microwave filters. This is demonstrated by synthesizing filters that include cascaded quartet, quintet, and sextet filter topologies. Lastly, the synthesis of the box section, and its derivative, the extended box configuration, are explained. Examples are included to illustrate the intricacies of this synthesis procedure.
- Theoretical and experimental techniques for evaluating the resonant frequency and unloaded Q-factor of microwave resonators are described in Chapter 11. Resonators are the basic building blocks of any bandpass filter. At microwave frequencies, resonators can take

many shapes and forms. The chapter includes two approaches for calculating the resonant frequency of arbitrarily shaped resonators: the eigenmode analysis and the *S*-parameter analysis. Examples are given illustrating the implementation of these two techniques using EM-based commercial software tools such as high frequency system simulator (HFSS). It also includes a step-by-step procedure for measuring the loaded and unloaded *Q* values using either the polar display of a vector network analyzer or the linear display of a scalar network analyzer.

- Chapter 12 addresses the synthesis techniques for the realization of lowpass filters at microwave frequencies. Typical bandwidth requirements for lowpass filters in communication systems are in the gigahertz range. As a consequence, prototype models based on lumped elements are not suitable for realization at microwave frequencies. It requires the use of distributed elements for the prototype filters. The chapter begins with a description of the commensurate line elements and their suitability for realizing distributed lowpass prototype filters. It then goes into a discussion of characteristic polynomials that are best suited for modeling practical lowpass filters and methods to generate such polynomials. This is followed by a detailed description of the synthesis techniques for the stepped impedance and the lumped/distributed lowpass filters.
- Chapter 13 deals with the practical design aspects of dual-mode bandpass filters. It includes the use of dual-mode resonators that operate in the dominant mode, as well as in the higher order propagation modes. A variety of examples are included to illustrate the design procedure. These examples include longitudinal and canonical configurations, the extended box design, the extracted pole filter, and the filters with all inductive couplings. The examples also include symmetrical and asymmetrical response filters. The steps involved in the simultaneous optimization of amplitude and group delay response of a dual-mode linear phase filter are described. Examples in this chapter span the analysis and synthesis techniques described in Chapters 3–11.
- Chapter 14 presents the use of EM simulator tools for designing microwave filters. It is shown how one can couple the filter circuit models with EM simulation tools to synthesize the physical dimensions of microwave filters with near-arbitrary accuracy. The starting point for such computations is usually the physical dimensions derived from the best circuit model of the filter. Methods are described to compute, with much greater accuracy, the input/output and inter-resonator couplings by using the commercially available EM simulator software. The techniques can be adapted for a direct approach to determine the physical dimensions of filters from the elements of the coupling matrix $[M]$, using K-impedance inverter, or J-admittance inverter models. Numerical examples are given in this chapter to illustrate, step by step, the application of this approach to the design of dielectric resonator, waveguide, and microstrip filters. For simple geometries with negligible coupling between nonadjacent resonators, this approach yields excellent results. Use of EM tools represents a major advance in the physical realization of microwave filters.
- Chapter 15 presents several techniques for EM-based design of microwave filters. The most direct approach is to combine an accurate EM simulation tool with an optimization software package and then optimize the physical dimensions of the filter to achieve the desired performance. This is effectively a tuning process where the tuning is done by the optimization package rather than a technologist. The starting point for this technique is the filter dimensions obtained using methods described in Chapter 14. Direct optimization approach, without any simplifying assumptions, can be still very computation intensive. A number of optimization strategies including adaptive frequency sampling, neural networks, and multidimensional Cauchy technique are described to reduce optimization time. Two advanced EM-based techniques, the space mapping technique (SM), and the coarse model technique

(CCM), are described in detail, offering a significant reduction in computation time. The chapter concludes with examples of filter dimensions obtained by using aggressive space mapping (ASM) and CCM techniques.

- Chapter 16 develops the design of dielectric resonator filters in a variety of configurations. Commercial software packages such as HFSS and CST Microwave Studio can be readily utilized to calculate the resonant frequency, field distribution, and resonator Q of dielectric resonators having any arbitrary shape. Using such tools, mode charts, along with plots, illustrating the field distribution of the first four modes in dielectric resonators are included. It also addresses the computation of the resonant frequency and the unloaded Q (Q_0) of cylindrical resonators, including the support structure. Tradeoffs in terms of Q_0, spurious response, temperature drift, and power handling capability are described. The chapter concludes with a detailed description of the design and tradeoffs for cryogenic dielectric resonator filters. Dielectric resonator filters are widely employed in wireless and satellite applications. Continuing advances in the quality of dielectric materials is a good indication of the growing application of this technology.
  - In the second edition, a new section has been added on miniature dielectric resonators illustrating a concept of realizing a quadruple-mode resonator using a traditional cylindrical shape dielectric resonator. It also illustrates how a half-cut dielectric resonator can be used in the realization of dual-mode filters.
- Chapter 17 deals with the analysis and synthesis of allpass networks, often referred to as equalizers. Such external allpass equalizers can be cascaded with filters to improve the phase and group delay response of filter networks. The chapter concludes with a discussion of the practical tradeoffs between the linear phase filters and externally equalized filter networks.
- Chapter 18 presents the design and tradeoffs for multiplexing networks for a variety of applications. It begins with a discussion of tradeoffs among the various types of multiplexing networks, including circulator-coupled, hybrid-coupled, and manifold-coupled multiplexers, employing single-mode or dual-mode filters. It also includes multiplexers based on using directional filters. This is followed by the detailed design considerations for each type of multiplexer. The design methodology and optimization strategy are dealt with in depth for the manifold-coupled multiplexer, by far the most complex microwave network. Numerous examples and photographs are included to illustrate the designs. The chapter is concluded with a brief discussion of the high-power capability of diplexers for cellular applications.
- Chapter 19 is devoted to the computer-aided techniques for tuning microwave filters. From a theoretical standpoint, the physical dimensions of a microwave filter can be perfected using EM-based techniques with near-arbitrary accuracy. In practice, the use of EM-based tools can be very time consuming and prohibitively so for higher-order filters and multiplexing networks. Moreover, owing to manufacturing tolerances and variations in material characteristics, practical microwave filters cannot duplicate the theoretical design. These problems are further exacerbated by the very stringent performance requirements for applications in the wireless and satellite communication systems. As a result, filter tuning is deemed an essential postproduction process. Techniques discussed in this chapter include (i) sequential tuning of coupled resonator filters, (ii) computer-aided tuning based on circuit model parameter extraction, (iii) computer-aided tuning using poles/zeros of the input reflection coefficient, (iv) time domain tuning, and (v) fuzzy logic tuning. The relative advantages of each technique are described.
- Chapter 20 provides an overview of high-power considerations in the design of microwave filters and multiplexing networks for terrestrial and space applications. It describes the phenomena of multipaction and gas discharge based on the classical theory and simple geometries, in particular the two-surface case under single carrier operation on infinite

parallel plates. It highlights the importance of derating factors that can severely degrade the performance of high-power equipment.

- In the second edition, the phenomenon of multipaction is described in depth. In most practical situations, the geometry of high-power RF equipment rarely corresponds to simple parallel-plate conductors, and the high-power equipment must be capable of handling multicarriers. The simple analysis is augmented to include multipaction and gas discharge analysis using numerical techniques. Such methods allow for a more accurate analysis of both single surface and dual surface multipactions in complex structures including nonhomogeneous fields. Although more complex and computer intensive, this analysis is much closer in taking into account the complex geometries of the high-power equipment and the typical operating environment with different numbers of RF carriers and modulations. A description of the classical setup for measuring RF breakdown effects is included. It highlights the efficacy of the industry-accepted methodology of applying the peak power method and the 20-gap crossing rule for the prediction of multipactor discharge in multicarrier operation.
- The chapter also provides guidelines to minimize passive intermodulation (PIM) in the design of high-power equipment.

Chapter 21

The new Chapter 21 provides an overview of the various techniques for the design of multiband filters, presenting and discussing several examples for dual-band and triple-band filters. The focus in this chapter is on high-Q multiband filters realized in coaxial, waveguide, and dielectric resonator structures. It also presents details of synthesis procedures for multiband filters. The chapter also illustrates how dual-band filters can be employed in realizing miniature diplexers and multiplexers.

Chapter 22

The new Chapter 22 provides an overview of tunable filter technology. It addresses the main challenges in realizing high-Q tunable filters, which include (i) maintaining constant bandwidth and a reasonable return loss over a wide tuning range, (ii) maintaining a constant high-Q value over a wide tuning range, (iii) integration of tuning elements with 3D filters, and (iv) linearity and power handling capability. It includes an approach for achieving a constant absolute bandwidth over a wide tuning range using only tuning elements for the resonators. A comparison between the various tuning elements (semiconductor, piezomotors, MEMS (microelectromechanical system), BST (barium strontium titanate), and PCM (phase change material)) is described. The chapter shows various examples for realizing tunable combline, dielectric resonator, and waveguide filters. Several examples were given with a focus on the use of MEMS in the design of such filters. Techniques are also presented for realizing filters that are tunable in both center frequency and bandwidth.

Chapter 23

The new chapter, entitled "Practical Considerations and Design Examples," is aimed at bridging the gap between theory and practical realization of microwave filters and multiplexing networks. A key feature of this chapter is the participation of Professors Vicente Boria and Santiago Cogollos of the Universitat Politecnica de Valencia, Spain, as co-authors. The chapter consists of a series of examples that highlight the methodology for designing and performing tradeoffs for practical filters and multiplexers. This provides a framework to analyze and optimize filtering requirements in communication systems, making use of this information to conduct filter tradeoffs; taking into account the typical operating environment (terrestrial or space), technology limitations, and manufacturing constraints; developing the circuit and quasi-distributed models of the filter topologies; and finally computing the physical dimensions of the structure using EM techniques. The chapter concludes with a brief overview of EM-based tolerance and sensitivity analysis in filter design.

Appendix E

A new appendix on the Impedance and Admittance Inverters has been added. A simple formulation for the application of inverters in filter design is described in this appendix.

The book is aimed at senior undergraduate and graduate students as well as practitioners of microwave technology. In writing this book, we have borrowed heavily from our industrial experience, giving seminars and teaching courses at universities and interactions with the engineering community at large at various conferences. It reflects a lifetime of experiences in advancing the state of the art in microwave filters and multiplexing networks.

1

Radio Frequency (RF) Filter Networks for Wireless Communications—The System Perspective

This chapter is dedicated to an overview of communication systems, especially the relationship between the communication channel and other elements of the system. The intent here is to provide the reader with sufficient background to be able to appreciate the critical role and requirements of radio frequency (RF) filters in communication systems. A number of standard texts [1–8] have been referred to in developing a significant portion of this chapter.

This chapter is divided into three parts: Part I presents a simple model of a communication system: the radio spectrum and its utilization, the concept of information, and system link budgets. Part II describes the noise and interference environment in a communication channel, the nonideal amplitude and phase characteristics of the channel, the choice of modulation–demodulation schemes, and how these parameters affect the efficient use of the allocated bandwidths. Part III discusses the impact of system design on the requirements and the specifications of microwave filter networks in satellite and cellular communication systems.

PART I Introduction to a Communication System, Radio Spectrum, and Information

1.1 Model of a Communication System

Communication refers to the process of conveying information-bearing signals from one point to another that are physically separate. In ancient times, people communicated over long distances by various means, such as smoke signals, drum beating, homing pigeons, and horseback riders. All such means were slow in the transmission of information over any appreciable distance. It was the invention of electricity that changed the means of communication. Communication became almost instantaneous by transmission of electrons through wires or electromagnetic (EM) waves through empty space or fibers, which is limited only by the speed of light—a fundamental constraint of our universe.

At the highest (simplest) level, communication involves an information source, a transmitter, a communication medium (or channel), a receiver, and an information destination (sink), as depicted in Figure 1.1. Until 1980s, most information was communicated in an

Microwave Filters for Communication Systems: Fundamentals, Design, and Applications, Second Edition.
Richard J. Cameron, Chandra M. Kudsia, and Raafat R. Mansour.

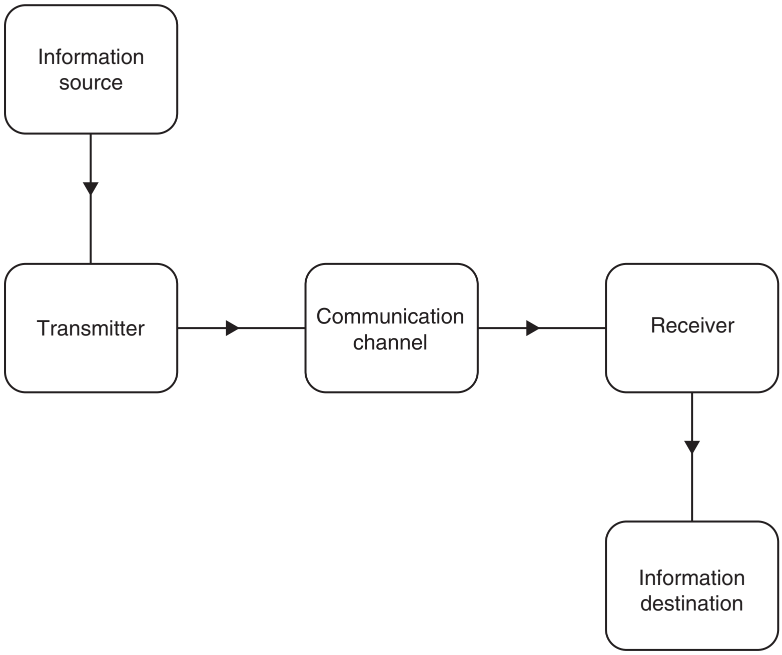

Figure 1.1 Simple model of a communication system.

analog format called *analog communication*. Today, most information is communicated in a digital format called *digital communication*. Even information in analog format is routinely converted into digital format for transmission and then converted back to analog format at the destination.

All communication systems are required to be linear. For such systems, the law of superposition holds. It allows the use of common media for the transmission and reception of an arbitrary number of independent signals, subject only to the constraints of the available bandwidths and adequate power levels. However, all the components of a communication system need not be linear, as long as the overall system is linear over the specified range of bandwidth within an acceptable degree of nonlinearity. In fact, all active devices are inherently nonlinear, which is essential for the purposes of frequency generation, modulation, demodulation, and amplification of signals. However, such intentional nonlinearities can be controlled for a specific application. For broadband wireless communication systems such as line-of-sight (LOS) and satellite systems used for long-distance networks, the frequency spectrum is divided into a number of RF channels, often referred to as *transponders*. Within each RF channel, there can be more than one RF carrier, depending on the system requirements. The channelization of the frequency spectrum provides the flexibility for the communication traffic flow in a multiuser environment. High-power amplifiers (HPAs) can operate with relatively high efficiency, since they are required to amplify a single carrier, or a limited number of signals, on a channel-by-channel basis, incurring a minimum distortion.

Irrespective of the communication format, it should be recognized that the passage of the transmitted signal through the communication channel is a strictly analog operation. The communication channel is a nonideal, lossy medium, and the reception of signals at the receiver involves recovery of the transmitted signal in the presence of impairments, in particular, thermal noise at the receiver, signal distortions (within the channel and from nonideal transmitter and receiver), and interference from other signals or echoes (multipath) seen by the receiver.

1.1.1 Building Blocks of a Communication System

In this section, the building blocks shown in Figure 1.2 are described for both analog and digital communication systems.

1.1.1.1 Information Source

The information source consists of a large number of individual signals that are combined in a suitable format for transmission over the communication medium. Such a signal is referred to as the *baseband signal*. The transducers shown in Figure 1.2 are required to convert the energy of the individual information sources, either acoustic (voice) or electrical, into an appropriate electrical signal suitable for transmission. For an analog system, all the individual signals, as well as the combined baseband signal, are in an analog format as illustrated in Figure 1.2a.

For digital systems, the baseband signal is a digital datastream, whereas the individual signals constituting the baseband can be digital or analog. Consequently, the individual analog signals need to be converted into their equivalent digital format via analog-to-digital (A/D) converters. Another feature of the information source in a digital system is the use of data compression to conserve bandwidth. A compressor takes the digital data and exploits its redundancy and other features to reduce the amount of data that need to be transmitted but still permits the information to be recovered. The information source for a digital communication system is illustrated in Figure 1.2b.

1.1.1.2 Transmitter

The block diagram of a transmitter is presented in Figure 1.3, and the functionality of each element is described as follows:

Encoder. In digital systems, an encoder introduces error correction data into the baseband information stream that permits recovery of the digital information even after significant impairments are created in the communication channel.

Modulator. It transcribes the baseband signal onto a higher intermediate carrier frequency (IF) as an intermediate step in the transmission and reception of the information bearing signals. Use of IF simplifies the filtering and signal processing circuitry in the modulator. The modulator can shift the signal frequencies, change the bandwidth occupancy, or materially alter the form of the signal, making it more suitable and efficient for transmission over the communication medium.

Upconverter. Also referred to as a mixer, shifts the modulated IF carrier frequency to the microwave range of radio frequencies (RF) within the allocated frequency band for RF transmission.

RF amplifier. Is used to amplify the RF signal. RF power has a direct bearing on the communication capacity of a RF channel.

RF multiplexer. It is used to combine the power of a number of RF channels into a composite broadband signal for transmission via a common antenna.

Transmit antenna. Launches the RF power into space and focuses it toward the receiving station.

1.1.1.3 Communication Channel

For wireless systems, the communication channel is free space. As a consequence, the properties of space, including the atmosphere, play a critical role in system design.

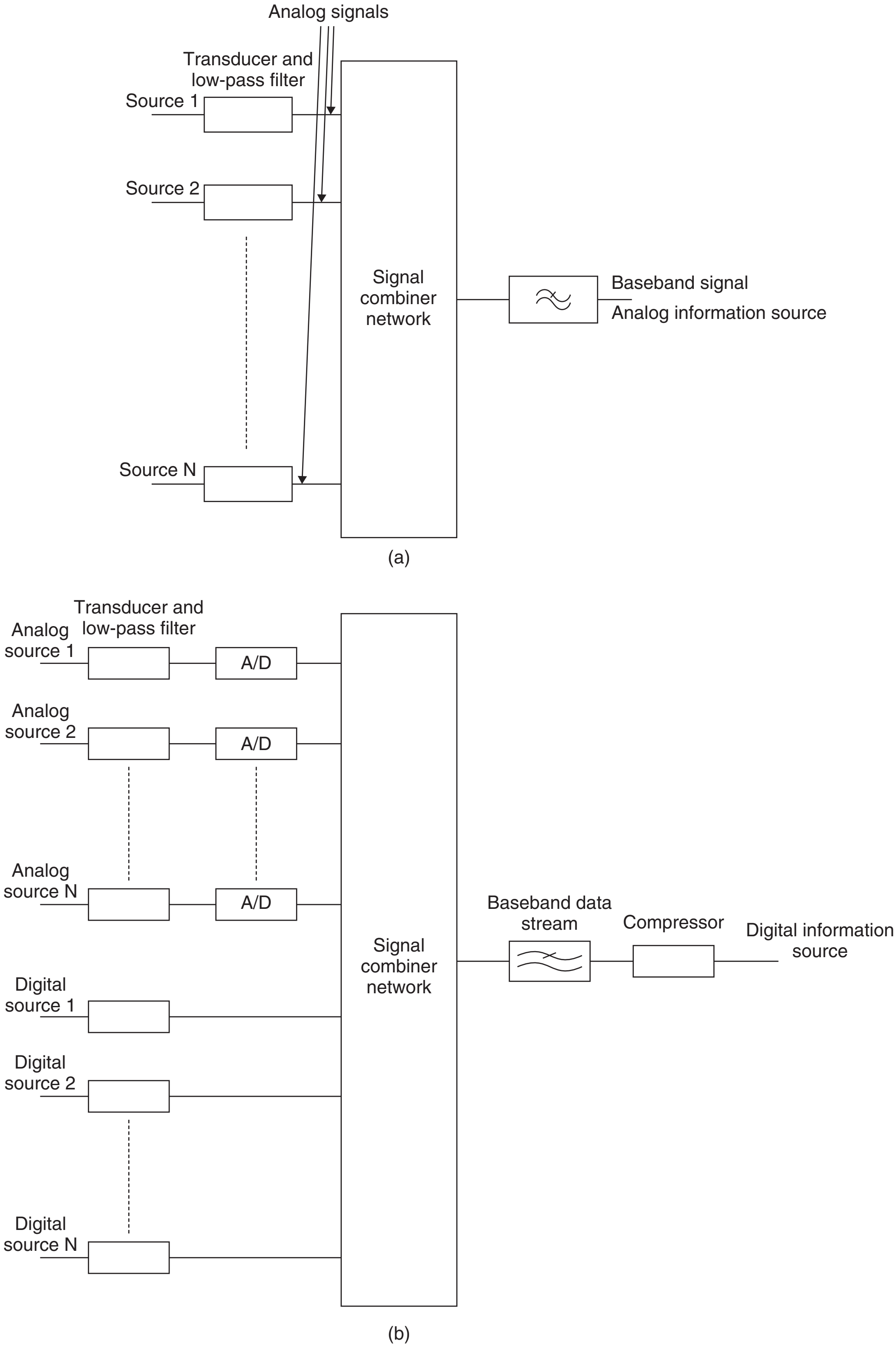

Figure 1.2 Information source: (a) analog system; (b) digital system.

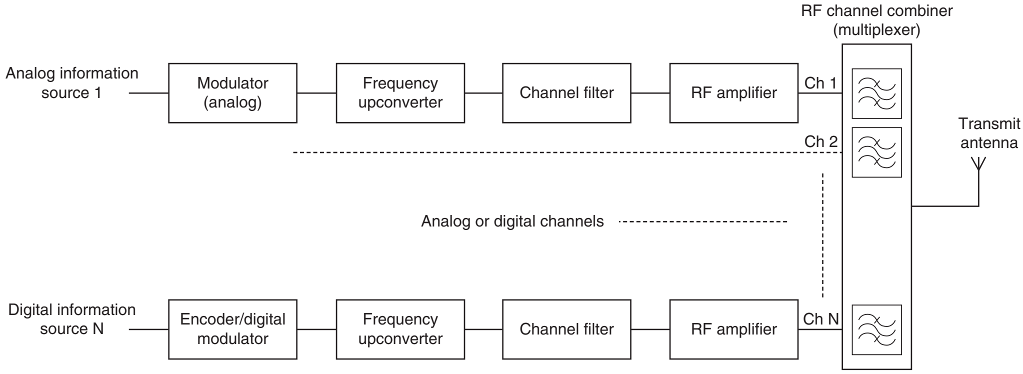

Figure 1.3 Transmitter block diagram.

1.1.1.4 Receiver

The block diagram of a receiver is shown in Figure 1.4, and the functionality of each element is described as follows:

Receive Antenna. It intercepts the RF power and focuses it to a transmission line connected to the low-noise amplifier (LNA).

LNA. It amplifies the very weak received signal with a minimum addition of noise to it.

Downconverter. It serves the function of frequency conversion, which is similar to that required in the transmitter chain. The downconverter converts the uplink frequency band into the downlink frequency band.

Demodulator. It extracts the baseband signal from the RF carrier by a process opposite to that of a modulator.

Decoder. It exploits the error correction data previously inserted into the information stream and uses it to correct the errors made during digital demodulator's recovery of the data.

1.1.1.5 Information Destination

The functionality of the information destination block is opposite to that of the information source. In the case of digital systems, an expander is used to reverse the operation of the compressor as shown in Figure 1.5.

Since a communication system is costly to install, its commercial viability is critically dependent on the number of users who must share the transmission medium. As a result, the

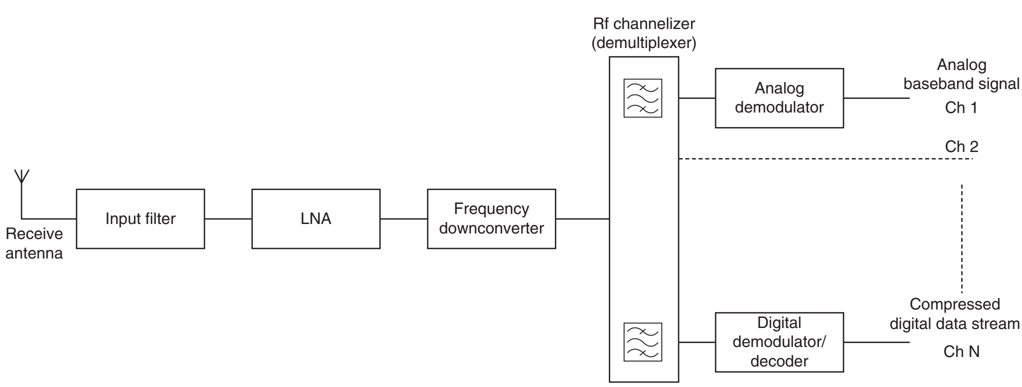

Figure 1.4 Receiver block diagram.

Figure 1.5 Information sink for a digital system.

information source usually consists of a large number of signals, occupying a finite range of frequencies. The width of the range of frequencies is called the *bandwidth* of the system.

Some key questions then arise: Is there a limitation on the available bandwidth for a communication system? What are the limitations of transmitting information over the chosen transmission media in the available bandwidth? What are the cost-sensitive parameters in a communications system?

1.2 Radio Spectrum and its Utilization

To understand the limitations on the available bandwidths for a communication system, it is necessary to understand the radio spectrum and its utilization [4].

EM waves cover an extremely broad spectrum of frequencies, from a few cycles per second to γ rays with frequencies of up to 10^{23} cycles per second. The radio spectrum is that portion of the EM spectrum which can be electronically and effectively radiated from one point in space and received at another. This includes frequencies anywhere from 9 kHz to 400 GHz. Although most of the commercial use takes place between 100 kHz and 44 GHz, some experimental systems reach as high as 100 GHz. The signals employing these same frequencies can also be transmitted over long distances by wire, coaxial cables, and glass fibers. However, since such signals are not intended to be radiated, they are not considered as part of the radio spectrum. A communication system is allowed to access only a portion of the radio spectrum, due to not only technology limitations but also regulatory reasons. The radio spectrum is subdivided into smaller frequency “bands” by national and international agencies, where each band is restricted to a limited set of types of operation. In addition, each band is a controlled commodity that often has a license fee associated with its use. Obviously, this represents a huge incentive to make the most efficient use of the allocated frequency spectrum.

1.2.1 Radio Propagation at Microwave Frequencies

There are many sources of energy loss in the free-space communication medium. The most serious ones include rainfall and presence of oxygen in the atmosphere. The atmospheric losses as a function of frequency are presented in Figure 1.6. The radio energy is absorbed and scattered by the raindrops, and this effect becomes more intense as the wavelength approaches the size of the raindrops. Consequently, rainfall and water vapor produce intense attenuation effects at higher microwave frequencies. The first absorption band, due to water vapor, peaks at approximately 22 GHz, and the first absorption band, due to the presence of oxygen in the atmosphere, peaks at about 60 GHz.

For fixed line of sight (LOS) terrestrial microwave radio links, multipath fading is another major cause of signal loss. Fading results from the variations in the refractive index of air for the first few tenths of a kilometer above the earth’s surface. Such gradients in refraction bend the rays, which, on reflection from the ground or other layers, combine with the direct rays, causing coherent interference.

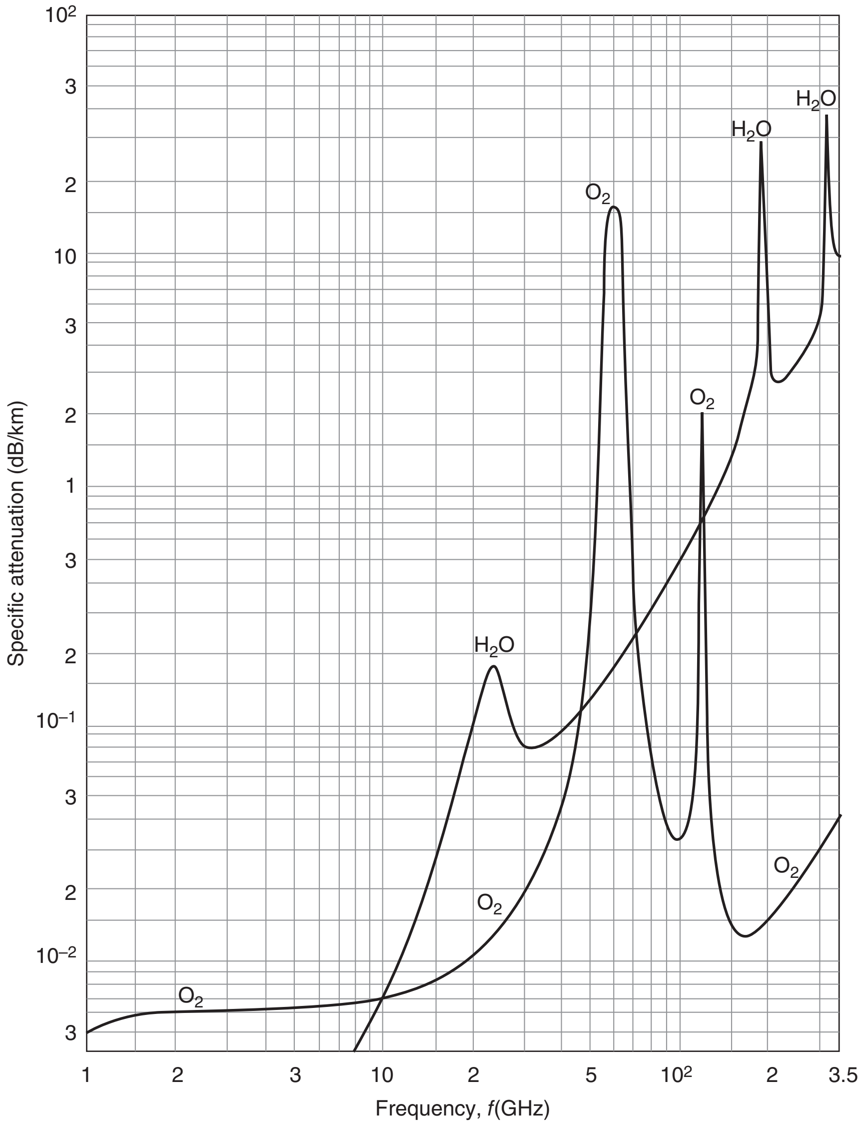

Figure 1.6 Atmospheric losses as a function of frequency. (*Source*: Freeman 2007 [7]. Reproduced with the permission of John Wiley and Sons. CCIR Report., 1990. Reproduced with permission International Radio Consultative Committee.)

Mobile communication adds a new dimension to the propagation problem. Besides the requirements of omnidirectional coverage and the mobility of end users, the communication system must deal with non-LOS and multipath problems caused by the signal reflections from tall buildings, trees, valleys, and other large objects in an urban environment. In addition, the coverage area for mobile services includes the area inside buildings. Also, mobility incurs the *Doppler shift*, a change in the frequency of the received signal, further complicating the issue.

From the foregoing analysis, it is evident that the attenuation due to rain and other atmospheric effects, coupled with multipath fading in an urban environment, severely constrains the available frequency spectrum suitable for commercial communications.

1.2.2 Radio Spectrum as a Natural Resource

The radio spectrum is a natural resource unlike any other communication system. It is a completely renewable resource that can never be permanently depleted. It is also universally available. The limitation comes with its usage. The radio spectrum has a finite capacity that, if exceeded, results in interference, incapacitating the system. For this reason, national governments grant users the privilege of using radio spectra in exchange for agreements to abide by usage rules. Because RF signals often cross national borders where they can interfere with radio frequencies allocated in another country, nations must cooperate to find ways to coordinate their individual allocations. Since communication is vital to all nations, there are national and international agencies that regulate the allocation and usage of the RF spectrum.

The International Telecommunications Union (ITU), part of the United Nations, is the international body that determines the worldwide radio spectrum allocations. The ITU accomplishes this through World Administrative Radio Conferences (WARC), where ITU member nations attempt to reach a consensus on proposals by different countries. These meetings require a consensual approach to decision-making, rendering the process very tedious, and often resulting in delays. Once a consensus is reached, the ITU publishes tables of the frequency allocations, deemed as the *radio regulations* of the ITU. Each country then makes its own detailed frequency allocation plan consistent with the radio regulation tables. In addition, there are other consultative committees such as the International Radio Consultative Committee (CCIR), a part of the ITU assigned to study and recommend the standards for interoperability and guidelines and the control of interference from various services. On the domestic front, most countries have government agencies such as the Federal Communications Commission (FCC) of the United States that regulate all the nonfederal government use of the frequency spectrum. There are other agencies that control frequency allocations for government use, including the military.

In most countries, the priority followed by the regulators for allocating radio spectrum is as follows:

- Military
- Public safety functions such as aeronautical and marine emergency communications, police, fire, and other emergency services
- National telecommunication companies for telephone
- Broadcast radio and television
- Private users such as mobile systems and other services.

Because of the complex web of procedures, priorities, government policies, and so on, once a service has been established and uses a particular portion of the spectrum, it is seldom changed. Incumbency tends to be a big advantage, and often an obstacle in the efficient use of the radio spectrum. The emergence of widespread wireless communications and services has added enormous pressure in both domestic and international regulatory bodies, as well as in original equipment manufacturers (OEMs) to ensure that the frequency allocations and spectrum usage represent the most efficient use of this natural resource.

1.3 Concept of Information

What are the limitations for transmitting information over the chosen transmission media? At the fundamental level, the answer lies in the seminal work of Shannon [9], who developed the concepts of information theory.

In 1948, Claude Shannon from the Bell Labs pointed out that "for a signal to carry information, the signal must be changing; and to convey information, the signal must resolve uncertainty."

Thus, the measure of the amount of information is a probabilistic one. Shannon defined the uncertainty of the outcome between two equally likely message probabilities as a unit of information; thereby, he used, as his measure, the binary digit or bit. Also, he showed that the information capacity of a system is fundamentally limited by a very few parameters. Specifically, he demonstrated that the maximum information capacity C of a channel is limited by the channel bandwidth B and the signal-to-noise ratio (S/N) in the channel as described by the relationship

$$C = B \log_M \left(1 + \frac{S}{N}\right) \quad \text{information messages per second} \tag{1.1}$$

where M is the number of possible source information message states. Here, S/N defines the conditions at the demodulator input, where S is the signal power in watts and N is white Gaussian noise with a mean power of N watts distributed uniformly over the channel bandwidth at the same location. In analog communication, M is difficult to define; however, in digital communication, the binary data ($M = 2$) is considered and the capacity limit is given by

$$C = B \log_2 \left(1 + \frac{S}{N}\right) \quad \text{information bits per second} \tag{1.2}$$

For digital communication, this capacity is defined in the context of information bits, measured at the output of the compressor function before the encoding function, and not at the data source as might be expected; B and S/N are defined within the channel at the input of the receiver section.

Note that the information is not defined at the data source, since there is a significant distinction between "data" and "information":

Data are the raw output from the source, for example, a digitized voice, digitized video, or a sequence of text characters, defining a text document.

Information is the salient content in the raw data. This content is often much less than the data used to represent the raw source output.

For example, consider a voice digitizer. It must continually sample the voice analog source and produce output, even when a person pauses between the words or sentences. Similarly, in a video signal, much of the picture does not change from frame to frame. In a text document, some characters or words are repeated more often than others, but the same number of bits is used to represent each character or word at the data source.

Digital compression exploits the knowledge about the characteristics of the data source type to map the data from one format of representation into another format that reduces the number of digital bits required to provide the salient information. The details of this are not addressed in this book. However, it is important to realize that there can be substantial reductions of raw data prior to their transmission with minimal or no loss of the useful information. For example, the current generation digital TV uses MPEG2 compression that provides at least one order of magnitude reduction in the average data rate required to represent the source data compared with the digitization of the raw video. Digital compression has certainly attracted the interest of the research community over the last few decades, resulting in continual improvement.

Shannon's information theorem proves that as long as the information transmission rate R is less than C, it is possible to limit the error in transmission to an arbitrarily small value. The technique for approaching this limit in digital communication is called *coding*, another favored area of research over the last few decades. The current technology comes within a few