FIBER-OPTIC COMMUNICATION SYSTEMS

Fourth Edition

Govind P. Agrawal
The Institute of Optics
University of Rochester
Rochester, New York

WILEY

A JOHN WILEY & SONS, INC., PUBLICATION

FIBER-OPTIC COMMUNICATION SYSTEMS

WILEY SERIES IN MICROWAVE AND OPTICAL ENGINEERING

KAI CHANG, Editor
Texas A&M University

A complete list of the titles in this series appears at the end of this volume.

FIBER-OPTIC COMMUNICATION SYSTEMS

Fourth Edition

Govind P. Agrawal
The Institute of Optics
University of Rochester
Rochester, New York

WILEY

A JOHN WILEY & SONS, INC., PUBLICATION

Copyright © 2010 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.

Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at http://www.wiley.com/go/permission.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Agrawal, G. P. (Govind P.), 1951–
Fiber-optic communication systems with cd / Govind P. Agrawal. — 4th ed.
p. cm. — (Wiley series in microwave and optical engineering ; 222)
ISBN 978-0-470-50511-3 (hardback)
1. Optical communications. 2. Fiber optics. I. Title.
TK5103.59.A37 2010
621.382'75—dc22 2010023284

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

To the memory of my Parents

To Anne, Sipra, Caroline, and Claire

Contents

Preface

Since the publication of the first edition of this book in 1992, the state of the art of fiber-optic communication systems has advanced dramatically despite the relatively short period of only 18 years between the first and fourth editions. The highest capacity of commercial fiber-optic links available in 1992 was only 2.5 Gb/s. A mere 4 years later, with the advent of wavelength-division multiplexing (WDM), systems with the total capacity of 40 Gb/s became available commercially. By 2001, the capacity of commercial WDM systems exceeded 1.6 Tb/s. At the same time, the capacity of transoceanic lightwave systems installed worldwide exploded. A global network covering 250,000 km with a capacity of 2.56 Tb/s (64 WDM channels at 10 Gb/s over 4 fiber pairs) was planned in 2001 and became operational by 2004 (currently operated by VSNL, an Indian telecommunication company). Although the pace slowed down after 2001 for a few years with the bursting of the so-called "telecom bubble," progress in the design of lightwave systems continued and accelerated after 2006 with the advent of phase-based modulation formats, 100-Gb Ethernet, and orthogonal frequency-division multiplexing.

The third edition of this book appeared in 2002. It has been well received by the scientific community involved with lightwave technology as well as by the educational community, judging from book's adoption as a textbook for courses offered at many universities worldwide. Because of the rapid advances that have occurred over the last 8 years, the publisher and I deemed it necessary to bring out the fourth edition if the book were to continue to provide a comprehensive and up-to-date account of fiber-optic communication systems. The result is in your hands. The primary objective of the book remains the same. Specifically, it should be able to serve both as a textbook and a reference monograph. For this reason, the emphasis is on the physical understanding, but the engineering aspects are also discussed throughout the text.

Because of the large amount of material that needed to be added to provide comprehensive coverage, the book size has increased considerably compared with the first edition. Although all chapters have been updated, the major changes have occurred in Chapters 7–11. I have taken this opportunity to rearrange the material such that it is better suited for a two-semester course on optical communications. In particular, the chapter on WDM systems has been moved earlier and now appears as Chapter 6. With this arrangement, Chapters 1 to 6 provide the basic foundation, while Chapters 7 to 11 cover the issues related to the design of advanced lightwave systems. More specifically, after the introduction of the elementary concepts in Chapter 1, Chapters 2–4 are devoted to the three primary components of a fiber-optic communications—

optical fibers, optical transmitters, and optical receivers. Chapters 5 and 6 then focus on the design issues relevant for single-channel and multichannel systems, respectively. Chapters 7 and 8 are devoted to the advanced techniques used for the management of fiber losses and chromatic dispersion, respectively. Chapter 9 focuses on the impact of nonlinear effects and techniques used to manage them such as the use of optical solitons and pseudo-linear propagation through enhanced dispersion. Chapters 10 and 11 are new to the fourth edition. Chapter 10 focuses primarily on the coherent and self-coherent lightwave systems making use of the novel phase-based modulation formats. Chapter 11 is devoted to all-optical signal processing with emphasis on wavelength conversion and optical regeneration. The contents of the book reflect the state of the art of lightwave systems in 2010.

The primary role of this book is as a graduate-level textbook in the field of *optical communications*. An attempt is made to include as much recent material as possible so that students are exposed to the recent advances in this exciting field. The book can also serve as a reference text for researchers already engaged in or wishing to enter the field of optical fiber communications. The reference list at the end of each chapter is more elaborate than what is common for a typical textbook. The listing of recent research papers should be useful for researchers using this book as a reference. At the same time, students can benefit from it if they are assigned problems requiring reading of the original research papers. A set of problems is included at the end of each chapter to help both the teacher and the student. Although written primarily for graduate students, the book can also be used for an undergraduate course at the senior level with an appropriate selection of topics. Parts of the book can be used for several other related courses. For example, Chapter 2 can be used for a course on optical waveguides, and Chapters 3 and 4 can be useful for a course on optoelectronics.

Many universities in the United States and elsewhere offer a course on optical communications as a part of their curriculum in electrical engineering, physics, or optics. I have taught such a course since 1989 to the graduate students of the Institute of Optics, and this book indeed grew out of my lecture notes. I am aware that it is used as a textbook by many instructors worldwide—a fact that gives me immense satisfaction. I am acutely aware of a problem that is a side effect of an enlarged revised edition. How can a teacher fit all this material in a one-semester course on *optical communications*? I have to struggle with the same question. In fact, it is impossible to cover the entire book in one semester. The best solution is to offer a two-semester course covering Chapters 1 through 6 during the first semester, leaving the remainder for the second semester. However, not many universities may have the luxury of offering a two-semester course on optical communications. The book can be used for a one-semester course provided that the instructor makes a selection of topics. For example, Chapter 3 can be skipped if the students have taken a laser course previously. If only parts of Chapters 7 through 11 are covered to provide students a glimpse of the recent advances, the material can fit in a single one-semester course offered either at the senior level for undergraduates or to graduate students.

The book features a compact disk (CD) on the back cover provided by the Optiwave Corporation. The CD contains a state-of-the art software package suitable for designing modern lightwave systems. It also contains additional problems for each chapter that can be solved by using the software package. Appendix D provides more details about the software and the problems. It is my hope that the CD will help to train the students and will prepare them better for an industrial job.

A large number of persons have contributed to this book either directly or indirectly. It is impossible to mention all of them by name. I thank my graduate students and the students who took my course on optical communication systems and helped improve my class notes through their questions and comments. Thanks are due to many instructors who not only have adopted this book as a textbook for their courses but have also pointed out the misprints in previous editions, and thus have helped me in improving the book. I am grateful to my colleagues at the Institute of Optics for numerous discussions and for providing a cordial and productive atmosphere. I appreciated the help of Karen Rolfe, who typed the first edition of this book and made numerous revisions with a smile. Last, but not least, I thank my wife, Anne, and my daughters, Sipra, Caroline, and Claire, for understanding why I needed to spend many weekends on the book instead of spending time with them.

Govind P. Agrawal

Rochester, NY
April 2010

Chapter 1

Introduction

A communication system transmits information from one place to another, whether separated by a few kilometers or by transoceanic distances. Information is often carried by an electromagnetic carrier wave whose frequency can vary from a few megahertz to several hundred terahertz. Optical communication systems use high carrier frequencies (~ 100 THz) in the visible or near-infrared region of the electromagnetic spectrum. They are sometimes called lightwave systems to distinguish them from microwave systems, whose carrier frequency is typically smaller by five orders of magnitude (~ 1 GHz). Fiber-optic communication systems are lightwave systems that employ optical fibers for information transmission. Such systems have been deployed worldwide since 1980 and have revolutionized the field of telecommunications. Indeed, lightwave technology, together with microelectronics, led to the advent of the "information age" during the 1990s. This book describes fiber-optic communication systems in a comprehensive manner. The emphasis is on the fundamental aspects, but relevant engineering issues are also discussed. In this introductory chapter we present the basic concepts and provide the background material. Section 1.1 gives a historical perspective on the development of optical communication systems. Section 1.2 covers concepts such as analog and digital signals, channel multiplexing, and modulation formats. Relative merits of various lightwave systems are discussed in Section 1.3. The last section focuses on the building blocks of a fiber-optic communication system.

1.1 Historical Perspective

The use of light for communication purposes dates back to antiquity if we interpret optical communications in a broad sense [1]. Most civilizations have used mirrors, fire beacons, or smoke signals to convey a single piece of information (such as victory in a war). Essentially the same idea was used up to the end of the eighteenth century through signaling lamps, flags, and other semaphore devices. The idea was extended further, following a suggestion of Claude Chappe in 1792, to transmit mechanically coded messages over long distances (~ 100 km) by the use of intermediate relay stations [2], acting as *regenerators* or *repeaters* in the modern-day language. Figure 1.1

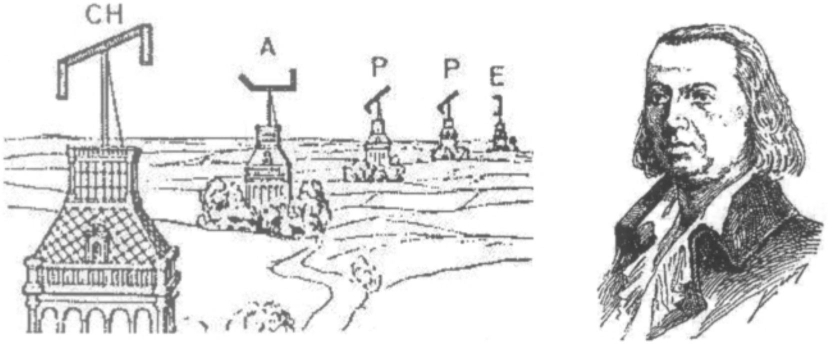

Figure 1.1: Schematic illustration of the optical telegraph and its inventor Claude Chappe. (After Ref. [2]; ©1944 American Association for the Advancement of Science; reprinted with permission.)

shows the basic idea schematically. The first such "optical telegraph" was put in service between Paris and Lille (two French cities about 200 km apart) in July 1794. By 1830, the network had expanded throughout Europe [1]. The role of light in such systems was simply to make the coded signals visible so that they could be intercepted by the relay stations. The opto-mechanical communication systems of the nineteenth century were inherently slow. In modern-day terminology, the effective bit rate of such systems was less than 1 bit per second ($B < 1$ b/s).

1.1.1 Need for Fiber-Optic Communications

The advent of telegraphy in the 1830s replaced the use of light by electricity and began the era of electrical communications [3]. The bit rate B could be increased to $\sim$ 10 b/s by the use of new coding techniques, such as the *Morse code*. The use of intermediate relay stations allowed communication over long distances ($\sim$ 1000 km). Indeed, the first successful transatlantic telegraph cable went into operation in 1866. Telegraphy used essentially a digital scheme through two electrical pulses of different durations (dots and dashes of the Morse code). The invention of the telephone in 1876 brought a major change inasmuch as electric signals were transmitted in analog form through a continuously varying electric current [4]. Analog electrical techniques were to dominate communication systems for a century or so.

The development of worldwide telephone networks during the twentieth century led to many advances in the design of electrical communication systems. The use of coaxial cables in place of wire pairs increased system capacity considerably. The first coaxial-cable system, put into service in 1940, was a 3-MHz system capable of transmitting 300 voice channels or a single television channel. The bandwidth of such systems is limited by the frequency-dependent cable losses, which increase rapidly for frequencies beyond 10 MHz. This limitation led to the development of microwave communication systems in which an electromagnetic carrier wave with frequencies in the range of 1–10 GHz is used to transmit the signal by using suitable modulation techniques.

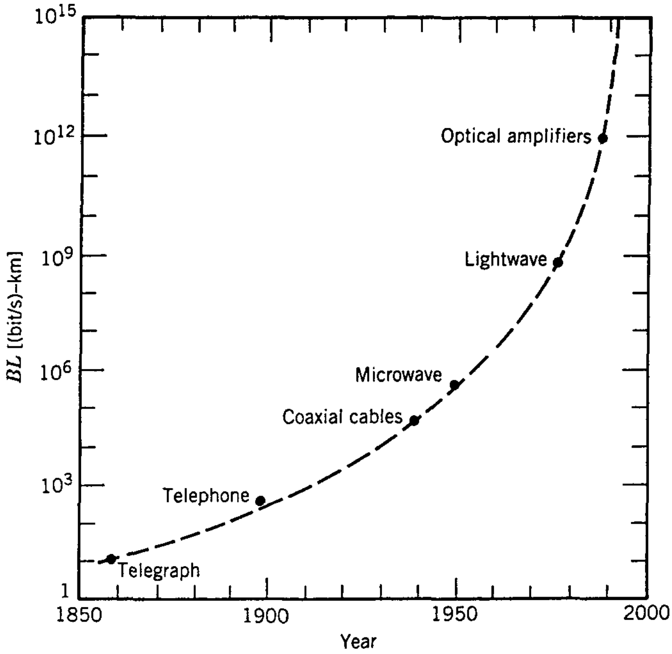

Figure 1.2: Increase in bit rate–distance product *BL* during the period 1850–2000. The emergence of a new technology is marked by a solid circle.

The first microwave system operating at the carrier frequency of 4 GHz was put into service in 1948. Since then, both coaxial and microwave systems have evolved considerably and are able to operate at bit rates ~ 100 Mb/s. The most advanced coaxial system was put into service in 1975 and operated at a bit rate of 274 Mb/s. A severe drawback of such high-speed coaxial systems is their small *repeater spacing* (~ 1 km), which makes the system relatively expensive to operate. Microwave communication systems generally allow for a larger repeater spacing, but their bit rate is also limited by the carrier frequency of such waves. A commonly used figure of merit for communication systems is the *bit rate–distance product*, *BL*, where *B* is the bit rate and *L* is the repeater spacing. Figure 1.2 shows how the *BL* product has increased through technological advances during the last century and a half. Communication systems with *BL* ~ 100 (Mb/s)-km were available by 1970 and were limited to such values because of fundamental limitations.

It was realized during the second half of the twentieth century that an increase of several orders of magnitude in the *BL* product would be possible if optical waves were used as the carrier. However, neither a coherent optical source nor a suitable transmission medium was available during the 1950s. The invention of the laser and its demonstration in 1960 solved the first problem [5]. Attention was then focused on finding ways for using laser light for optical communications. Many ideas were advanced during the 1960s [6], the most noteworthy being the idea of light confinement using a sequence of gas lenses [7].

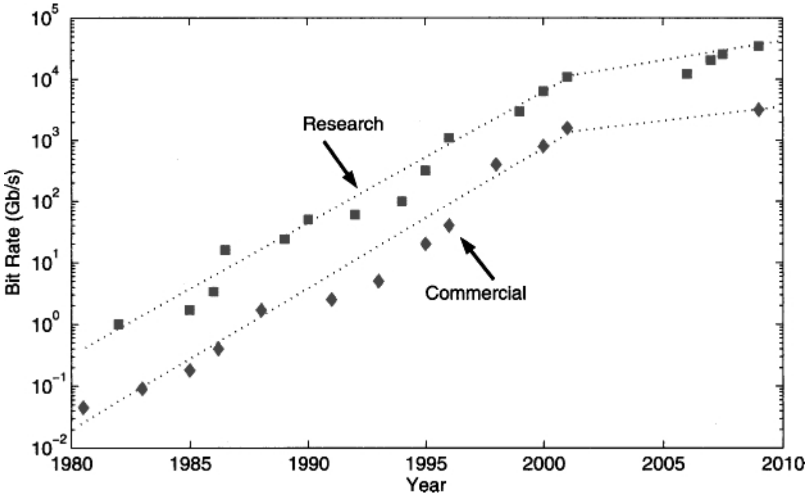

Figure 1.3: Increase in the capacity of lightwave systems realized after 1980. The dotted lines indicate a nearly exponential growth in the bit rate for both the research and commercial systems. Note the change in the slope after 2001.

It was suggested in 1966 that optical fibers might be the best choice [8], as they are capable of guiding the light in a manner similar to the guiding of electrons in copper wires. The main problem was the high losses of optical fibers—fibers available during the 1960s had losses in excess of 1000 dB/km. A breakthrough occurred in 1970 when fiber losses could be reduced to below 20 dB/km in the wavelength region near 1 μm [9]. At about the same time, GaAs semiconductor lasers, operating continuously at room temperature, were demonstrated [10]. The simultaneous availability of *compact* optical sources and a *low-loss* optical fibers led to a worldwide effort for developing fiber-optic communication systems [11]. Figure 1.3 shows the increase in the capacity of lightwave systems realized after 1980 through several generations of development [12]. As seen there, the commercial deployment of lightwave systems followed the research and development phase closely. The progress has indeed been rapid as evident from an increase in the bit rate by a factor of 100,000 over a period of less than 30 years. Transmission distances have also increased from 10 to 10,000 km over the same time period. As a result, the bit rate–distance product of modern lightwave systems can exceed by a factor of 10^7 compared with the first-generation lightwave systems.

1.1.2 Evolution of Lightwave Systems

The research phase of fiber-optic communication systems started around 1975. The enormous progress realized over the 25-year period extending from 1975 to 2000 can be grouped into several distinct generations. Figure 1.4 shows the increase in the *BL* product over this time period as quantified through various laboratory experiments [13]. The straight line corresponds to a doubling of the *BL* product every year. In every

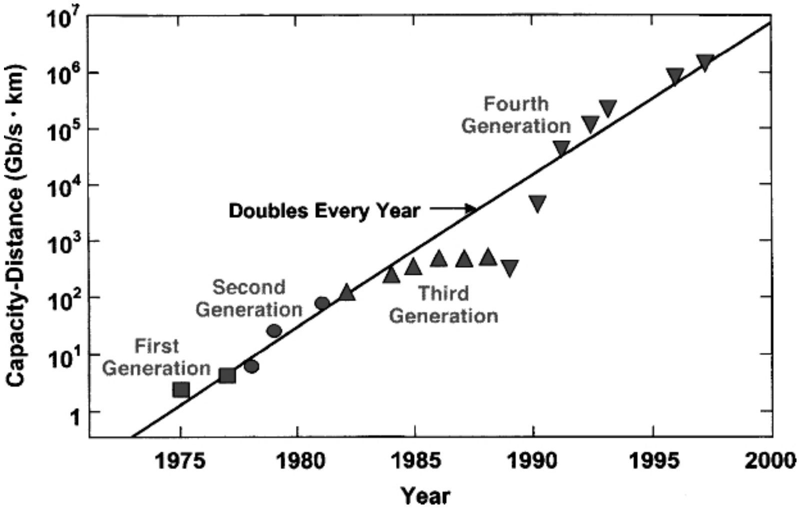

Figure 1.4: Increase in the *BL* product over the period 1975 to 1980 through several generations of lightwave systems. Different symbols are used for successive generations. (After Ref. [13]; ©2000 IEEE; reprinted with permission.)

generation, *BL* increases initially but then begins to saturate as the technology matures. Each new generation brings a fundamental change that helps to improve the system performance further.

The first generation of lightwave systems operated near 0.8 μm and used GaAs semiconductor lasers. After several field trials during the period 1977–79, such systems became available commercially in 1980 [14]. They operated at a bit rate of 45 Mb/s and allowed repeater spacings of up to 10 km. The larger repeater spacing compared with 1-km spacing of coaxial systems was an important motivation for system designers because it decreased the installation and maintenance costs associated with each repeater.

It was clear during the 1970s that the repeater spacing could be increased considerably by operating the lightwave system in the wavelength region near 1.3 μm, where fiber loss is below 1 dB/km. Furthermore, optical fibers exhibit minimum dispersion in this wavelength region. This realization led to a worldwide effort for the development of InGaAsP semiconductor lasers and detectors operating near 1.3 μm. The second generation of fiber-optic communication systems became available in the early 1980s, but the bit rate of early systems was limited to below 100 Mb/s because of dispersion in multimode fibers [15]. This limitation was overcome by the use of *single-mode* fibers. A laboratory experiment in 1981 demonstrated transmission at 2 Gb/s over 44 km of single-mode fiber [16]. The introduction of commercial systems soon followed. By 1987, second-generation lightwave systems, operating at bit rates of up to 1.7 Gb/s with a repeater spacing of about 50 km, were commercially available.

The repeater spacing of the second-generation lightwave systems was limited by the fiber losses at the operating wavelength of 1.3 μm (typically 0.5 dB/km). Losses of silica fibers become minimum near 1.55 μm. Indeed, a 0.2-dB/km loss was realized in 1979 in this spectral region [17]. However, the introduction of third-generation lightwave systems operating at 1.55 μm was considerably delayed by a large fiber dispersion near 1.55 μm. Conventional InGaAsP semiconductor lasers could not be used because of pulse spreading occurring as a result of simultaneous oscillation of several longitudinal modes. The dispersion problem can be overcome either by using dispersion-shifted fibers designed to have minimum dispersion near 1.55 μm or by limiting the laser spectrum to a single longitudinal mode. Both approaches were followed during the 1980s. By 1985, laboratory experiments indicated the possibility of transmitting information at bit rates of up to 4 Gb/s over distances in excess of 100 km [18]. Third-generation lightwave systems operating at 2.5 Gb/s became available commercially in 1990. Such systems are capable of operating at a bit rate of up to 10 Gb/s [19]. The best performance is achieved using dispersion-shifted fibers in combination with lasers oscillating in a single longitudinal mode.

A drawback of third-generation 1.55-μm systems is that the signal is regenerated periodically by using electronic repeaters spaced apart typically by 60–70 km. The repeater spacing can be increased by making use of a homodyne or heterodyne detection scheme because its use improves receiver sensitivity. Such systems are referred to as coherent lightwave systems. Coherent systems were under development worldwide during the 1980s, and their potential benefits were demonstrated in many system experiments [20]. However, commercial introduction of such systems was postponed with the advent of fiber amplifiers in 1989.

The fourth generation of lightwave systems makes use of *optical amplification* for increasing the repeater spacing and of *wavelength-division multiplexing* (WDM) for increasing the bit rate. As seen from Figures 1.3 and 1.4, the advent of the WDM technique around 1992 started a revolution that resulted in doubling of the system capacity every 6 months or so and led to lightwave systems operating at a bit rate of 10 Tb/s by 2001. In most WDM systems, fiber losses are compensated periodically using erbium-doped fiber amplifiers spaced 60–80 km apart. Such amplifiers were developed after 1985 and became available commercially by 1990. A 1991 experiment showed the possibility of data transmission over 21,000 km at 2.5 Gb/s, and over 14,300 km at 5 Gb/s, using a recirculating-loop configuration [21]. This performance indicated that an amplifier-based, all-optical, submarine transmission system was feasible for intercontinental communication. By 1996, not only transmission over 11,300 km at a bit rate of 5 Gb/s had been demonstrated by using actual submarine cables [22], but commercial transatlantic and transpacific cable systems also became available. Since then, a large number of submarine lightwave systems have been deployed worldwide.

Figure 1.5 shows the international network of submarine systems around 2005 [23]. The 27,000-km fiber-optic link around the globe (known as FLAG) became operational in 1998, linking many Asian and European countries [24]. Another major lightwave system, known as *Africa One* was operating by 2000; it circles the African continent and covers a total transmission distance of about 35,000 km [25]. Several WDM systems were deployed across the Atlantic and Pacific oceans during 1998–2001 in response to the Internet-induced increase in the data traffic; they increased the total capacity by orders of magnitudes. Indeed, such a rapid deployment led to a worldwide overcapacity that resulted in the bursting of the so-called "telecom bubble" in 2001.

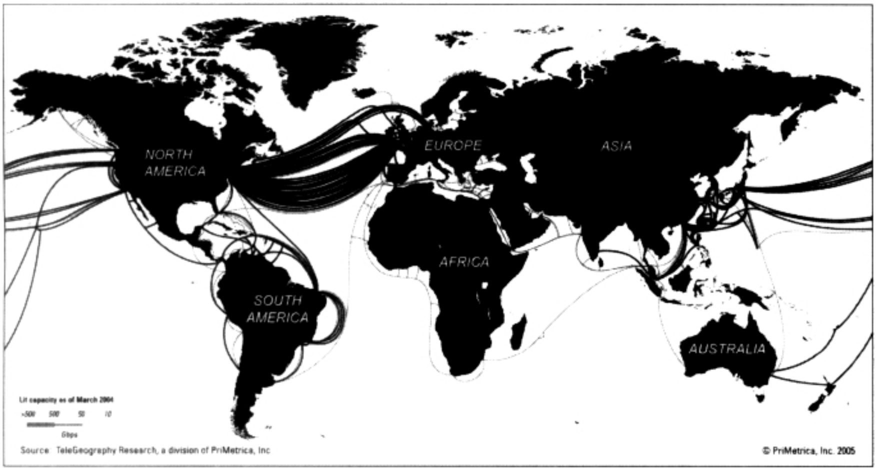

Figure 1.5: International undersea network of fiber-optic communication systems around 2005. (After Ref. [23]; ©2005 IEEE; reprinted with permission.)

The change in the slopes of dotted lines in Figure 1.3, occurring around 2001, reflects this reality.

The emphasis of most WDM lightwave systems is on increasing their capacity by transmitting more and more channels through the WDM technique. With increasing signal bandwidth, it is often not possible to amplify all channels using a single amplifier. As a result, new amplification schemes (such as distributed Raman amplification) have been developed for covering the spectral region extending from 1.45 to 1.62 μm. This approach led in 2000 to a 3.28-Tb/s experiment in which 82 channels, each operating at 40 Gb/s, were transmitted over 3000 km. Within a year, the system capacity could be increased to nearly 11 Tb/s (273 WDM channels, each operating at 40 Gb/s) but the transmission distance was limited to 117 km [26]. In another record experiment, 300 channels, each operating at 11.6 Gb/s, were transmitted over 7380 km, resulting in a *BL* product of more than 25,000 (Tb/s)-km [27]. Commercial terrestrial systems with the capacity of 3.2 Tb/s, transmitting 80 channels (each at 40 Gb/s) with the use of Raman amplification, were available by the end of 2003. Given that the first-generation systems had a capacity of 45 Mb/s in 1980, it is remarkable that the capacity jumped by a factor of more than 70,000 over a period of 25 years.

The fifth generation of fiber-optic communication systems is concerned with extending the wavelength range over which a WDM system can operate simultaneously. The conventional wavelength window, known as the C band, covers the wavelength range 1.53–1.57 μm. It is being extended on both the long- and short-wavelength sides, resulting in the L and S bands, respectively. The Raman amplification technique can be used for signals in all three wavelength bands. Moreover, a new kind of fiber, known as the *dry fiber* has been developed with the property that fiber losses are small over the entire wavelength region extending from 1.30 to 1.65 μm [28]. Availability of such fibers and new amplification schemes may lead to lightwave systems with thousands of WDM channels.

The focus of current fifth-generation systems is on increasing the spectral efficiency of WDM systems. The idea is to employ advanced modulation formats in which information is encoded using both the amplitude and phase of the optical carrier [29]. Although such formats were developed and are used commonly for microwave systems, their use for lightwave systems attracted serious attention only after 2001. It has allowed one to increase the spectral efficiency, typically limited to below 0.8 b/s/Hz for the fourth-generation systems, to >8 b/s/Hz. In a 2010 experiment [30], a new record was established when 64-Tb/s transmission was realized over 320 km using 640 WDM channels that spanned both the C and L bands with 12.5-GHz channel spacing. Each channel contained two polarization-multiplexed 107-Gb/s signals coded with a modulation format known as quadrature amplitude modulation.

Even though the fiber-optic communication technology is barely 30 years old, it has progressed rapidly and has reached a certain stage of maturity. This is also apparent from the publication of a large number of books on optical communications and WDM networks since 2000 [31]–[47]. The fourth edition of this book (first edition published in 1992) is intended to present an up-to-date account of fiber-optic communications systems with emphasis on recent developments.

1.2 Basic Concepts

This section introduces a few basic concepts common to all communication systems. We begin with a description of analog and digital signals and describe how an analog signal can be converted into digital form. We then consider time- and frequency-division multiplexing of input signals, and conclude with a discussion of various modulation formats.

1.2.1 Analog and Digital Signals

In any communication system, information to be transmitted is generally available as an electrical signal that may take *analog* or *digital* form [48]. In the analog case, the signal (e. g., electric current) varies continuously with time, as shown schematically in Figure 1.6(a). Familiar examples include audio and video signals resulting when a microphone converts voice or a video camera converts an image into an electrical signal. By contrast, the digital signal takes only a few discrete values. In the *binary representation* of a digital signal only two values are possible. The simplest case of a binary digital signal is one in which the electric current is either on or off, as shown in Figure 1.6(b). These two possibilities are called "bit 1" and "bit 0" (*bit* is a contracted form of *b*inary dig*it*). Each bit lasts for a certain period of time T_B, known as the bit period or *bit slot*. Since one bit of information is conveyed in a time interval T_B, the bit rate B, defined as the number of bits per second, is simply $B = T_B^{-1}$. A well-known example of digital signals is provided by computer data. Each letter of the alphabet together with other common symbols (decimal numerals, punctuation marks, etc.) is assigned a code number (ASCII code) in the range 0–127 whose binary representation corresponds to a 7-bit digital signal. The original ASCII code has been extended to represent 256 characters transmitted through 8-bit bytes. Both analog and digital signals

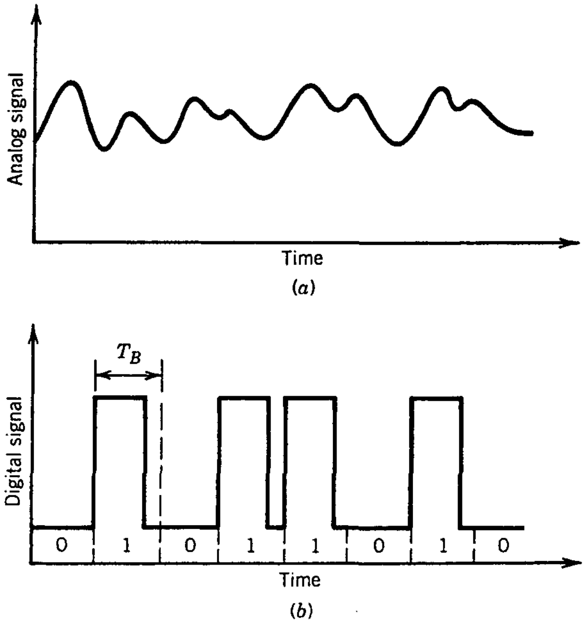

Figure 1.6: Representation of (a) an analog signal and (b) a digital signal.

are characterized by their bandwidth, which is a measure of the spectral contents of the signal. The *signal bandwidth* represents the range of frequencies contained within the signal and is determined mathematically through its Fourier transform.

An analog signal can be converted into digital form by sampling it at regular intervals of time [48]. Figure 1.7 shows the conversion method schematically. The sampling rate is determined by the bandwidth Δf of the analog signal. According to the sampling theorem [49], a bandwidth-limited signal can be fully represented by discrete samples, without any loss of information, provided that the sampling frequency f_s satisfies the *Nyquist criterion* [50], $f_s \geq 2\Delta f$. The first step consists of sampling the analog signal at the right frequency. The sampled values can take any value in the range $0 \leq A \leq A_{\max}$, where $A_{\max}$ is the maximum amplitude of the given analog signal. Let us assume that $A_{\max}$ is divided into M discrete (not necessarily equally spaced) intervals. Each sampled value is quantized to correspond to one of these discrete values. Clearly, this procedure leads to additional noise, known as *quantization noise*, which adds to the noise already present in the analog signal.

The effect of quantization noise can be minimized by choosing the number of discrete levels such that $M > A_{\max}/A_N$, where A_N is the root-mean-square noise amplitude of the analog signal. The ratio $A_{\max}/A_N$ is called the dynamic range and is related to the *signal-to-noise ratio* (SNR) by the relation

$$\mathrm{SNR} = 20\log_{10}(A_{\max}/A_N), \tag{1.2.1}$$

where SNR is expressed in decibel (dB) units. Any ratio R can be converted into decibels by using the general definition $10\log_{10}R$ (see Appendix A). Equation (1.2.1)

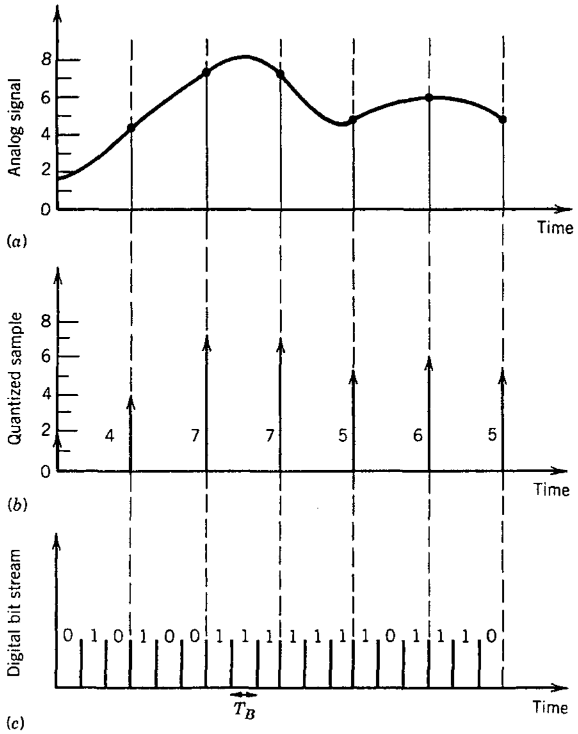

Figure 1.7: Three steps of (a) sampling, (b) quantization, and (c) coding required for converting an analog signal into a binary digital signal.

contains a factor of 20 in place of 10 simply because the SNR for electrical signals is defined with respect to the electrical power, whereas A is related to the electric current (or voltage).

The quantized sampled values can be converted into digital format by using a suitable conversion technique. In one scheme, known as *pulse-position modulation*, pulse position within the bit slot is a measure of the sampled value. In another, known as *pulse-duration modulation*, the pulse width is varied from bit to bit in accordance with the sampled value. These techniques are rarely used in practical optical communication systems, since it is difficult to maintain the pulse position or pulse width to high accuracy during propagation inside the fiber. The technique used almost universally, known as *pulse-code modulation* (PCM), is based on a binary scheme in which information is conveyed by the absence or the presence of pulses that are otherwise identical. A binary code is used to convert each sampled value into a string of 1 and 0 bits. The number of bits m needed to code each sample is related to the number of quantized signal levels M by the relation

$$M = 2^m \quad \text{or} \quad m = \log_2 M. \tag{1.2.2}$$