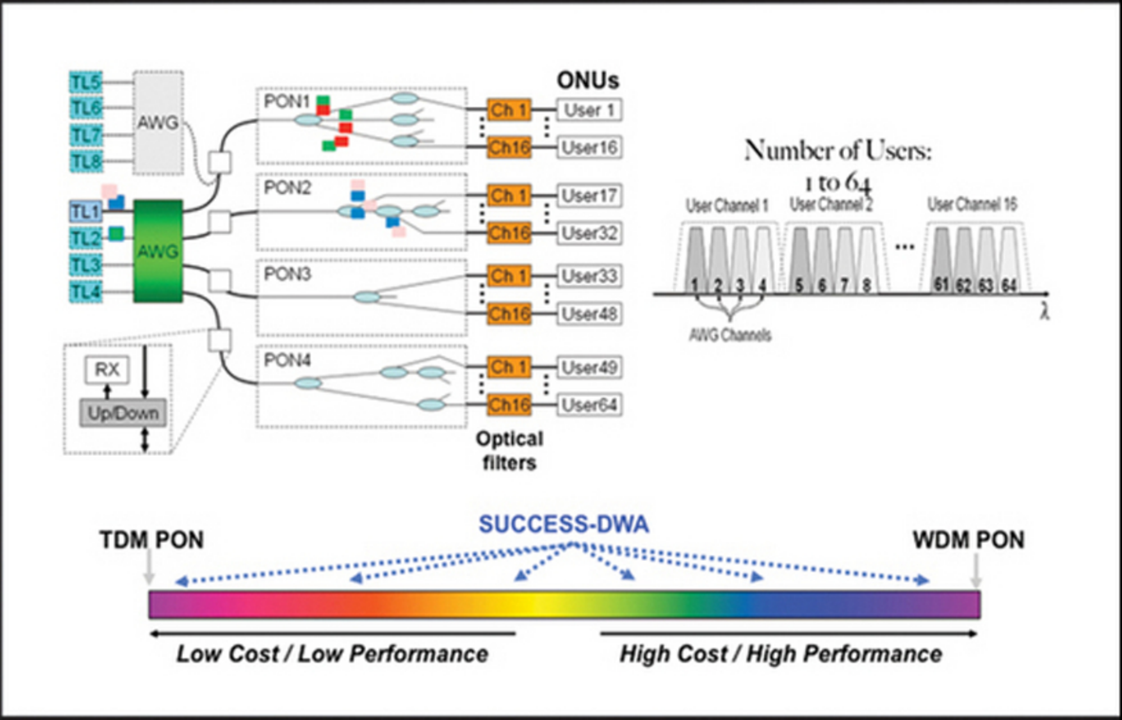
Broadband Optical Access Networks

Leonid G. Kazovsky • Ning Cheng • Wei-Tao Shaw
David Gutierrez • Shing-Wa Wong



WILEY

BROADBAND OPTICAL ACCESS NETWORKS

BROADBAND OPTICAL ACCESS NETWORKS

LEONID G. KAZOVSKY
NING CHENG
WEI-TAO SHAW
DAVID GUTIERREZ
SHING-WA WONG

WILEY

A JOHN WILEY & SONS, INC., PUBLICATION

Copyright © 2011 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 Sections 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 format. For more information about Wiley products, visit our web site at www.wiley.com

Library of Congress Cataloging-in-Publication Data Is Available

Kazovsky, Leonid G.

Broadband optical access networks / Leonid G. Kazovsky, Ning Cheng, Wei-Tao Shaw, David Gutierrez, Shing-Wa Wong.

Includes index.

ISBN 978-0-470-18235-2

Printed in Singapore

oBook ISBN: 978 0470 910931
ePDF ISBN: 978 0470 910924
ePub ISBN: 978 0470 922675

10 9 8 7 6 5 4 3 2 1

CONTENTS

FOREWORD

Broadband optical access networks are crucial to the future development of the Internet. The continuing evolution of high-capacity, low-latency optical access networks will provide users with real-time high-bandwidth access to the Web essential for such emerging trends as immersive video communications and ubiquitous cloud computing. These ultrahigh-speed access networks must be built under challenging economic and environmental imperatives to be "*faster, cheaper, and greener*." This book presents in a clear and illustrative format the technical and scientific concepts that are needed to accomplish the design of new broadband access networks upon which users will surf the wave of the twenty-first-century Internet.

The book is coauthored by Professor Leonid Kazovsky and his graduate students. Professor Kazovsky is a recognized leader and authority in the field and has a long and distinguished track record for making highly timely and significant research contributions within the general area of optical communication systems and optical networks. He has contributed over the last 40 years in the areas of wavelength-division-multiplexed (WDM) and coherent transmission systems for the core network as well as transmission systems and network architectures and technologies at the metro and access levels. This book builds on Professor Kazovsky's research conducted at Bellcore (where he worked in the 1980s), at Stanford University (where he has worked since 1990), and at numerous European research organizations during sabbaticals in the UK, the Netherlands, Italy, Denmark, and (most recently) Sweden. This rich set of influences gives the book and its readers the benefits of broad exposure to diverse research ideas and approaches.

Professor Kazovsky heads the Photonics and Networking Research Laboratory at Stanford University. He and his team of researchers are focusing on broadband optical access networks. They bring their ongoing research results to this unique book, bridging fundamentals of optical communication and networking system design with technology issues and current standards. Once that foundation is laid, the book delves into current high-capacity research issues, including evolution to WDM optical access, converged hybrid optical/wireless access networks, and implementation issues of broadband optical access. Research ideas generated by Professor Kazovsky's research group have been widely adopted worldwide, including in framework projects of the European Union.

We strongly recommend this book, as it offers timely, accurate, authoritative, and innovative information regarding broadband optical access network design and implementation. We're confident that you will enjoy reading the book and learn much while doing so.

Daniel Kilper and Peter Vetter
Alcatel-Lucent Bell Labs, Murray Hill, New Jersey
James F. Kelly
Google, Mountain View, California
Alan Willner
USC Viterbi School of Engineering, Los Angeles, California
Biswanath Mukherjee
University of California Davis, Davis, California
Anders Berntson, Gunnar Jacobsen, and Mikhail Popov
Acreo, Stockholm, Sweden

PREFACE

The roots of this book were planted about a decade ago. At that time, I became increasingly convinced that wide-area and metropolitan-area networks, where much of my group's research has been centered at that time, were in good shape. Although research in these fields was (and still is) needed, that's not where the networking bottleneck seemed to be. Rather, the bottleneck was (and still is in many places) in the access networks, which choked users' access to information and services. It was clear to me that the long-term solution to that problem has to involve optical fiber access networks.

That conviction led me to switch the focus of my group's research to optical access networks. In turn, that decision led to a decade of exciting exceptionally interesting research into the many challenges facing modern access networks. These challenges include rapidly increasing demands for larger bandwidth and better quality of service, graceful evolution to more powerful solutions without complete rebuilding of existing infrastructure, enhancing network range and number of users, improving access networks' resilience, simplifying network architecture, finding better control strategies, and solving the problem of fiber/wireless integration. All these problems would have to be solved while maintaining the economic viability of access networks so that operators would be prepared to make the necessary (and huge) investment in fiber and other infrastructure.

Finding solutions for the foregoing problems occupied most of my research group's time and attention for much of the past decade. In the beginning of that decade (and for a long time after that), my group, the Photonics and Networking Research Laboratory (PNRL) at Stanford University, was one of very few (or perhaps even the only) university research group working on fiber access, as many other optical researchers tended to discount optical access issues as trivial. Although that made funding for our research difficult to find, that position allowed us to make many pioneering contributions widely used and cited today. Later, many other university and industrial research groups entered the field, and several large-scale research efforts were organized, most notably in Europe, where serious research into both passive optical networks (PONs) and active optical networks (AONs) has been conducted over the last several years. Notable European efforts in broadband fiber access include ICT ALPHA (architectures for flexible photonic home and access networks, focused on AON, PON, and technoeconomics), ICT OASE (optical access seamless evolution, focused on PON, technoeconomics, and business models) and ICT SARDANA (focused on PON and optical metropolitan networks). These efforts resulted in extremely fast progress in the field. It was gratifying to see many PNRL research results adopted, used, and developed further by these (and other) efforts, especially in SARDANA.

Many of my colleagues working on optical access research encouraged me over the past few years to integrate results of the PNRL research on optical access networks into a single volume and publish it to ensure the broadest possible dissemination of our results. They feel that our results, when published in a single volume rather than the current combination of conference and journal articles, will further stimulate new research, plant new ideas, and lead to exciting new developments.

For a long while, I was reluctant to do so. The field of broadband fiber access networks is exceptionally broad; in addition, it is still very young and is developing and changing very fast. Thus, writing a comprehensive book on this subject is (nearly) impossible. Eventually, though, a stream of inquiries for additional information about our research convinced me to change my mind, and my research students and myself began the time-consuming process of writing our book.

Our goal was fairly modest: to summarize in one place the research results produced by the PNRL over the past decade or so. The reader should keep this goal in mind. We make no attempt to cover the entire field, just to provide a summary of our research. Even that goal proved to be difficult to achieve, as we are continuing our research as new technologies emerge, so our understanding of the field continues to evolve with time. However, we trust that the reader will consider this book a useful addition to his or her knowledge base of optical access networks.

LEONID KAZOVSKY

Stanford University
Stanford, California

ACKNOWLEDGMENTS

This book is based on research results obtained by our research group, the Photonics and Networking Research Laboratory at Stanford University. Our research on broadband fiber access networks, conducted over a decade or so, required a consistent effort by a large group of exceptionally talented graduate students, postdocs, and visitors. Some of these contributors are co-authors of the book, while others are working in other organizations and on other projects and so were too busy to help with the book-writing process. We are thankful to all of them, however.

Our research on broadband fiber access networks required a sizable team and a substantial amount of experimental, theoretical, and simulation efforts. This would be impossible without the generous and long-term support of our sponsors. We are grateful to our sponsors, who trusted us with the necessary resources. Our main sponsors in that area were, or are, the National Science Foundation under grants 0520291 and 0627085, KDDI Laboratories, Motorola, the Stanford Networking Research Center (no longer in existence), ST Microelectronics, ANDevices, Huawei, Deutsche Telecom, and Alcatel-Lucent Bell Laboratories.

We also thank the many research visitors to our group (mainly postdocs or visiting professors), who helped in a variety of ways, ranging from making research contributions to our book, to providing suggestions and comments on its contents, to taking part in one or more of our broadband access research projects. In particular, we are grateful to Dr. Kyeong Soo (Joseph) Kim of Swansea University; Professor Chunming Qiao of SUNY Buffalo; Dr. Luca Valcarenghi of Scuola Superiore Sant'Anna , Italy; Professor David Larrabeiti of Universidad Carlos III de Madrid, Madrid, Spain; and Dr. Divanilson Campelo of University of Brasilia, Brazil. Many others helped as well; unfortunately, a comprehensive list would be too long to include here.

We are grateful to the challenging, exciting research environment at Stanford University, where the lead author of this book has had the pleasure of working for the past two decades. Without that environment, this book would never have materialized.

Last but not least, we would like to thank our many colleagues all over the world for stimulating discussions, for their friendship, and for their help. We are particularly grateful to Prof. Vincent Chan, MIT; Prof. Alan Willner, USC; Drs. James Kelly and Cedric Lam of Google, Inc.; Prof. Andrea Fumagali, University of Texas; Profs. Ben Yoo and Biswanath Mukherjee, University of California, Davis; Profs. Djan Khoe and Dr. Harm of the Technical University of Eindoven, the Netherlands; Prof. Giancarlo Prati of the Scuola Superiore St. Anna, Pisa, Italy; Prof. Palle Jeppesen of the Danish Technical University, Copenhagen, Denmark; Drs. Gunnar Jacobsen, Mikhail Popov, and Claus Larsen of Acreo, Stockholm, Sweden; Dr. Shu Yamamoto of KDDI, Japan; and Dr. Frank Effenburger of Huawei.

Stanford University
Stanford, California

LEONID KAZOVSKY
NING CHENG
WEI-TAO SHAW
DAVID GUTIERREZ
SHING-WA WONG

CHAPTER 1

BROADBAND ACCESS TECHNOLOGIES: AN OVERVIEW

In past decades we witnessed the rapid development of global communication infrastructure and the explosive growth of the Internet, accompanied by ever-increasing user bandwidth demands and emerging multimedia applications. These dramatic changes in technologies and market demands, combined with government deregulation and fierce competition among data, telcom, and CATV operators, have scrambled the conventional communication services and created new social and economic challenges and opportunities in the new millennium. To meet those challenges and competitions, current service providers are striving to build new multimedia networks. The most challenging part of current Internet development is the access network. As an integrated part of global communication infrastructure, broadband access networks connect millions of users to the Internet, providing various services, including integrated voice, data, and video. As bandwidth demands for multimedia applications increase continuously, users require broadband and flexible access with higher bandwidth and lower cost. A variety of broadband access technologies are emerging to meet those challenging demands. While broadband communication over power lines and satellites is being developed to catch the market share, DSL (digital subscriber line) and cable modem continue to evolve, allowing telecom and CATV companies to provide high-speed access over copper wires. In the meantime, FTTx and wireless networks have become a very promising access technologies. The convergence of optical and wireless technologies could be the best solution for broadband and mobile access service in the future. As new technology continues to be developed, the future access technology will be more flexible, faster, and cheaper. In this chapter

---

Broadband Optical Access Networks, First Edition. Leonid G. Kazovsky, Ning Cheng, Wei-Tao Shaw, David Gutierrez, and Shing-Wa Wong.

we discuss current access network scenarios and review current and emerging broad access technologies, including DSL, cable modem, optical, and wireless solutions.

1.1 COMMUNICATION NETWORKS

Since the development of telegraph and telephone networks in the nineteenth century, communication networks have come a long way and evolved into a global infrastructure. More than ever before, communications and information technologies pervade every aspect of our lives: our homes, our workplaces, our schools, and even our bodies. As part of the fundamental infrastructure of our global village, communication networks has enabled many other developments—social, economic, cultural, and political—and has changed significantly how people live, work, and interact.

Today's global communication network is an extremely complicated system and covers a very large geographic area, all over the world and even in outer space. Such a complicated system is built and managed within a hierarchical structure, consisting of local area, access area, metropolitan area, and wide area networks (as shown in Figure 1.1). All the network layers cooperate to achieve the ultimate task: anyone, anywhere, anytime, and any media communications.

Local Area Networks Local area networks (LANs) mainly connect computers and other electronic devices (servers, printers, etc.) within an office, a single building, or a few adjacent buildings. Therefore, the geographical coverage of LANs is very small, spanning from a few meters to a few hundred meters. LANs are generally not a part of public networks but are owned and operated by private organizations. Common

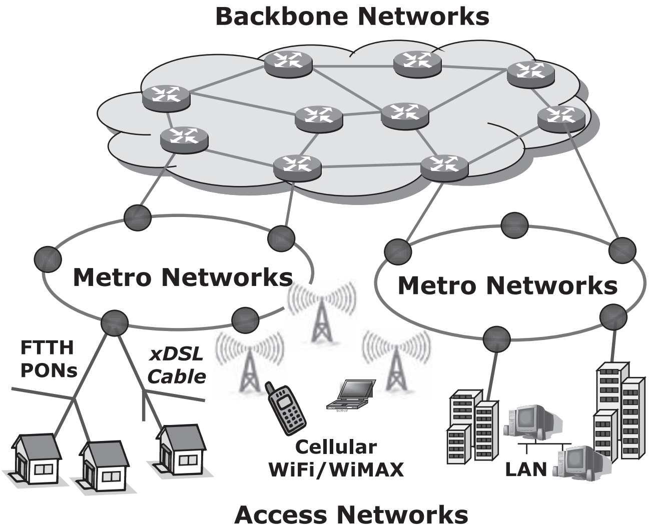


FIGURE 1.1 Hierarchical architecture of global communication infrastructure.

topologies for LANs are bus, ring, star, or tree. The most popular LANs are parts of the Ethernet, supporting a few hundred users with typical bit rates of 10 or 100 Mb/s.

Access Networks The computers and other communication equipment of a private organization are usually connected to a public telecommunication networks through access networks. Access networks bridge end users to service providers through twist pairs (phone line), coaxial cables, or other leased lines (such as OC3 through optical fiber). The typical distance covered by an access network is a few kilometers up to 20 km. For personal users, access networks use DSL or cable modem technology with a transmission rate of a few megabits per second; for business users, networks employ point-to-point fiber links with hundreds of megabits or gigabits per second.

Metropolitan Area Networks Metropolitan area networks (MANs) aggregate the traffic from access networks and transport the data at a higher speed. A typical area covered by a MAN spans a metropolitan area or a small region in the countryside. Its topology is usually a fiber ring connecting multiple central offices, where the transmission data rate is typically 2.5 or 10 Gb/s.

Wide Area Networks Wide area networks (WANs) carry a large amount of traffic among cities, countries, and continents. MAN multiplexes traffic from LANs and transports the aggregated traffic at a much higher data rate, typically tens of gigabits per second or higher using wavelength-division multiplexing (WDM) technology over optical fibers. Whereas a WAN covers the area of a nation or, in some cases, multiple nations, a link or path through a MAN could be as long as a few thousand kilometers. Beyond MANs, submarine links connect continents. Generally, the submarine systems are point-to-point links with a large capacity and an extremely long path, from a few thousand up to 10,000 km. Because these links are designed for ultralong distances and operate under the sea, the design requirements are much more stringent than those of their terrestrial counterparts. Presently, submarine links are deployed across the Pacific and Atlantic oceans. Some shorter submarine links are also widely used in the Mediterranean, Asian Pacific, and African areas.

Service Convergence Historically, communication networks provide mainly three types of service: voice, data, and video (triple play). Voice conversation using plain old telephony is a continuous 3.4-kHz analog signal carried by two-way, point-to-point circuits with a very stringent delay requirement. The standard TV signal is a continuous 6-MHz analog signal usually distributed with point-to-multipoint broadcasting. Data transmission is typically bursty with varying bandwidth and delay requirements. Because the traffic characteristics of voice, data, and video and their corresponding requirements as to quality of service (QoS) are fundamentally different, three major types of networks were developed specifically to render these services in a cost-effective manner: PSTN (public-switched telephone networks) for voice conversation, HFC (hybrid fiber coax) networks for video distribution, and the Internet for data transfer. Although HFC networks are optimized for video broadcasting, the inherent one-way communication is not suitable for bidirectional data or voice. PSTN adopts circuit switching technology to carry information with specific bandwidth or data rates, such as voice signals. However, circuit-switched networks are not very efficient for carrying bursty data traffic. With packet switching, the Internet can support bursty data transmission, but it is very difficult to meet stringent delay requirements for certain applications. Therefore, no single network can satisfy all the service requirements.

Emerging multimedia applications such as video on demand, e-learning, and interactive gaming require simultaneous transmission of voice, data, and video. Driven by user demands and stiff competition, service providers are moving toward a converged network for multimedia applications, which will utilize Internet protocol (IP) technologies to provide triple-play services. As VoIP (voice over IP) has been developed in the past few years and more recently IP TV has become a mature technology, all network services will converge into an IP-based service platform. Furthermore, the integration of optical and wireless technologies will make quadruple play (voice, data, video, and mobility) a reality in the near future.

1.2 ACCESS TECHNOLOGIES

Emerging multimedia applications continuously fuel the explosive growth of the Internet and gradually pervade every area of our lives, from home to workplace. To provide multimedia service to every home and every user, access networks are built to connect end users to service providers. The link between service providers and end users is often called the *last mile* by service providers, or from an end user's perspective, the *first mile*. Ideally, access networks should be a converged platform capable of supporting a variety of applications and services. Through broadband access networks, integrated voice, data, and video service are provided to end users. However, the reality is that access networks are the weakest links in the current Internet infrastructure. While national information highways (WANs and MANs) have been developed in most parts of the globe, ramps and access routes to these information highways (i.e., the first/last mile) are mostly bike lanes or at best, unpaved roads, causing traffic congestion. Hence, pervasive broadband access should be a national imperative for future Internet development. In this section we review current access scenarios and discuss the last-mile bottleneck and its possible solutions.

1.2.1 Last-Mile Bottleneck

Due to advances in photonic technologies and worldwide deployment of optical fibers, during the last decade the telecommunication industry has experienced an extraordinary increase in transmission capacity in core transport networks. Commercial systems with 1-Tb/s transmission can easily be implemented in the field, and the state-of-the-art fiber optical transmission technology has reached 10 Tb/s in a single fiber. In the meanwhile, at the user end, the drastic improvement in the performance of personal computers and consumer electronic devices has made possible expanding demands of multimedia services, such as video on demand, video conferencing,

TABLE 1.1 Multimedia Applications and Their Bandwidth Requirements

Application	Bandwidth	Latency	Other Requirements
Voice over IP (VoIP)	64 kb/s	200 ms	Protection
Videoconferencing	2 Mb/s	200 ms	Protection
File sharing	3 Mb/s	1 s	
SDTV	4.5 Mb/s/ch	10 s	Multicasting
Interactive gaming	5 Mb/s	200 ms	
Telemedicine	8 Mb/s	50 ms	Protection
Real-time video	10 Mb/s	200 ms	Content distribution
Video on demand	10 Mb/s/ch	10 s	Low packet loss
HDTV	10 Mb/s/ch	10 s	Multicasting
Network-hosted software	25 Mb/s	200 ms	Security

e-learning, interactive games, VoIP, and others. Table 1.1 lists common end-user applications and their bandwidth requirements. As a result of the constantly increasing bandwidth demand, users may require more than 50 Mb/s in the near future. However, the current copper wire technologies bridging users and core networks have reached their fundamental bandwidth limits and become the *first-last-mile bottleneck*. Delays in Web page browsing, data access, and audio/video clip downloading have earned the Internet the nickname "World Wide Wait." How to alleviate this bottleneck has been a very challenging task for service providers.

1.2.2 Access Technologies Compared

For broadband access services, there is strong competition among several technologies: digital subscriber line, hybrid fiber coax, wireless, and FTTx (fiber to the x, x standing for home, curb, neighborhood, office, business, premise, user, etc.). For comparison, Table 1.2 lists the bandwidths (per user) and reaches of these competing technologies. Currently, dominant broadband access technologies are digital

TABLE 1.2 Comparison of Bandwidth and Reach for Popular Access Technologies

Service	Medium	Downstream (Mb/s)	Upstream (Mb/s)	Max Reach (km)
ADSL	Twisted pair	8	0.896	5.5
ADSL2	Twisted pair	15	3.8	5.5
VDSL1	Twisted pair	50	30	1.5
VDSL2	Twisted pair	100	30	0.5
HFC	Coax cable	40	9	25
BPON	Fiber	622	155	20
GPON	Fiber	2488	1244	20
EPON	Fiber	1000	1000	20
Wi-Fi	Free space	54	54	0.1
WiMAX	Free space	134	134	5

subscriber loop and coaxial cable. For conventional ADSL (asymmetric DSL) technology, the bandwidth available is a few Mb/s within the 5.5-km range. Newer VDSL (very high-speed DSL) can provide 50 Mb/s, but the maximum reach is limited to 1.5 km. On the other hand, coaxial cable has a much larger bandwidth than twist pairs, which can be as high as 1 Gb/s. However, due to the broadcast nature of CATV system, current cable modems can provide each user with an average bandwidth of a few Mb/s. While DSL and cable provide wired solutions for broadband access, Wi-Fi (wireless fidelity), and WiMAX (worldwide interoperability for microwave access) provide mobile access in a LAN or MAN network. Even though a nominal bandwidth of Wi-Fi and WiMAX can be relatively higher (54 Mb/s in 100 m for Wi-Fi and 28 Mb/s in 15 km for WiMAX), the reach of such wireless access is very limited and the actual bandwidth provided to users can be much lower, due to the interference in wireless channels. As a LAN technology, the primary use of Wi-Fi is in home and office networking. To reach the central office or service provider, multiple-hop wireless links with WiMAX have to be adopted. An alternative technology that is also under development is MBWA (mobile broadband wireless access, IEEE 802.20), which is very similar to WiMAX (IEEE 802.16e). Compared to the fixed access solutions, the advantages of the wireless technologies are easy deployment and ubiquitous or mobile access, and the disadvantages are unreliable bandwidth provisioning and/or limited access range.

The bandwidth and/or reach of the copper wire and wireless access technology is very limited due to the physical media constraints. To satisfy the future use demand ($>$30 Mb/s), there is a strategic urgency for service providers to deploy FTTx networks. Currently, for cost and deployment reasons, FTTx is competing with other access technologies. Long term, however, only optical fiber can provide the unlimited capacity and performance that will be required by future broadband services. FTTx has long been dubbed as a future-proof technology for the access networks. A number of optical access network architectures have been standardized (APON, BPON, EPON, and GPON), and cost-effective components and devices for FTTx have matured. We are currently witnessing a worldwide deployment of optical access networks and a steady increase in FTTx users.

1.3 DIGITAL SUBSCRIBER LINE

Digital subscriber line (also called *digital subscriber loop*) is a family of access technologies that utilize the telephone line (twisted pair) to provide broadband access service. While the audio signal (voice) carried by a telephony system is limited from 300 to 3400 Hz, the twisted pair connecting the users to the central office is capable of carrying frequencies well beyond the 3.4-kHz upper limit of the telephony system. Depending on the length and the quality of the twisted pair, the upper limit can extend to tens of megahertz. DSL takes advantage of this unused bandwidth and transmits data using multiple-frequency channels. Thus, some types of DSL allow simultaneous use of the telephone and broadband access on the same twisted pair.

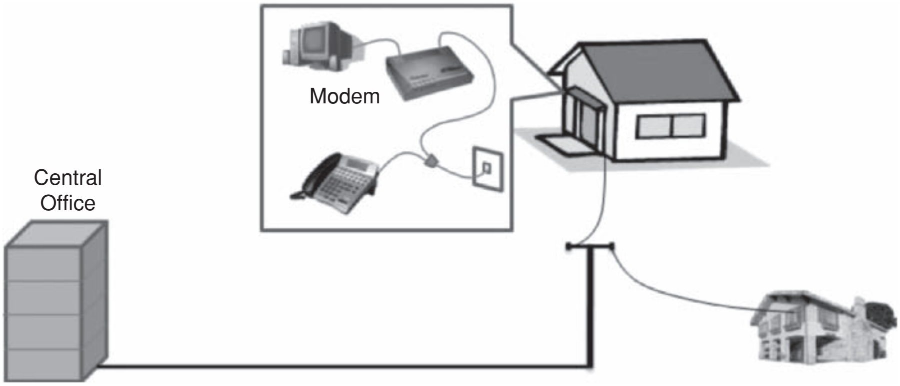


FIGURE 1.2 DSL access networks.

Figure 1.2 shows the typical setup of a DSL configuration. At the central office, a DSLAM (DSL access multiplexer) sends the data to users via downstream channels. At the user side, a DSL modem functions as a modulator/demodulator (i.e., receives data from DSLAM and modulates user data for upstream transmission).

1.3.1 DSL Standards

DSL comes in different flavors, supporting various downstream/upstream bit rates and access distances. DSL standards are defined in ANSI T1, and ITU-T Recommendation G.992/993. Table 1.2 lists various DSL standards and their performance. Collectively, these DSL technologies are referred to as *xDSL*. Two commonly deployed DSL standards are ADSL and VDSL.

As its name suggests, ADSL supports asymmetrical transmission. Since the typical ratio of traffic asymmetry is about 2 : 1 to 3 : 1, ADSL becomes a popular choice for broadband access. In addition, there is more crosstalk from other circuits at the DSLAM end. As the upload signal is weak at the noisy DSLAM end, it makes sense technically to have upstream transmission at a lower bit rate. Depending on the length and quality (such as the signal-to-noise ratio) of the twisted pair, the downstream bit rate can be as high as 10 times the upstream transmission. The maximum reach of ADSL is 5500 m. While ADSL1 can support a downstream bit rate up to 8 Mb/s and an upstream data rate up to 896 kb/s, ADSL2 supports up to 15 Mb/s downstream and 3.8 Mb/s upstream.

To support higher bit rates, the VDSL standard was developed after ADSL. Trading transmission distance for data rate, VDSL can support a much higher data rate but with very limited reach. VDSL1 standards specify data rates of 50 Mb/s for downstream and 30 Mb/s for upstream transmission. The maximum reach of VDSL1 is limited to 1500 m. The newer version of VDSL standards, VDSL2, is an enhancement of

VDSL1, supporting a data rate up to 100 Mb/s (with a transmission distance of 500 m). At 1 km, the bit rate will drop to 50 Mb/s. For reaches longer than 1.6 km, the VDSL2 performance is close to ADSL. Because of its higher data rates and ADSL-like long reach performance, VDSL2 is considered to be a very promising solution for upgrading existing ADSL infrastructure.

ADSL and VDSL are designed for residential subscribers with asymmetric bandwidth demands. For business users, symmetrical connections are generally required. Two symmetrical DSL standards, HDSL and SHDSL, are developed for business customers. While HDSL supports a T1 line data rate at 1.552 Mb/s (including 8 kb/s of overhead) with a reach of about 4000 m, SHDSL can provide a 6.696-Mb/s data rate with a maximum reach of 5500 m. However, HDSL and SHDSL do not support simultaneous telephone service, as most business customers do not have a requirement for a simultaneous voice circuit.

1.3.2 Modulation Methods

DSL uses a DMT (discrete multitone) modulation method. In DMT modulation, complex-to-real inverse discrete Fourier transform is used to partition the available bandwidth of the twisted pair into 256 orthogonal subchannels. DMT is adaptive to the quality of the twisted pair, so all the available bandwidth is fully utilized. The signal-to-noise ratio of each subchannel is monitored continuously. Based on the noise margin and bit error rate, a set of subchannels are selected, and a block of data bits are mapped into subchannels. In each subchannel, QAM (quadrature amplitude modulation) with a 4-kHz symbol rate is used to modulate the bit stream onto a subcarrier, leading to 60 kb/s per channel. Typically, the frequency range between 25 and 160 kHz is used for upstream transmission, and 140 kHz to 1.1 MHz is used for downstream transmission.

1.3.3 Voice over DSL

DSL was designed originally to carry data over phone lines, and DSL signal is separated from voice signal. Recently, new protocols have been proposed to merge voice and data at the circuit level. With advanced coding technologies, a 64-kb/s digitized voice signal can be compressed to 8 kb/s or less, thus allowing more voice channels to be carried over the same phone line. A voice over a DSL (VoDSL) gateway converts and compresses the analog voice signal to digital bit streams, so that calls made over VoDSL are indistinguishable from conventional calls. Usually, 12 to 20 voice channels can be carried over a single DSL line, depending on the transmission distance and the signal quality. A VoDSL system can be integrated into higher-layer protocols such as IP and ATM. Early DSL networks used ATM to ensure QoS, where ATM virtual circuits were used for the voice traffic. ADSL and VDSL networks migrate to packet-based transport, and they use packet-switched based virtual circuits instead of ATM ones.

1.4 HYBRID FIBER COAX

Cable networks were originally developed for a very simple reason: TV signal distribution. Therefore, cable networks are optimized for one-way, point-to-multipoint broadcasting of analog TV signals. As optical communication systems were developed, most cable TV systems have gradually been upgraded to hybrid fiber coax (HFC) networks, eliminating numerous electronic amplifiers along the trunk line. However, before cable access technology can be deployed, a return pass must be implemented for upstream traffic. To support two-way communication, bidirectional amplifiers have to be used in HFC systems, where filters are deployed to split the upstream (forward) and downstream (reverse) signals for separate amplification.

Figure 1.3 presents the network architecture of a typical HFC network. In HFC networks, analog TV signals are carried from the cable headend to distribution nodes using optical fibers, and from the distribution node, coaxial cable drops are deployed to serve 500 to 2000 subscribers. As shown in the figure, an HFC network is a shared medium system with a tree topology. In such a topology, multiple users share the same HFC infrastructure, so medium access control is required in upstream transmission while downstream transmission uses a broadcast scheme. A cable modem deployed at the subscriber end provides data connection to the cable network, while at the headend, the cable modem termination system connects to a variety of data servers and provides service to subscribers.

Compared with the twisted pairs in a telephone system, coaxial cables have a much higher bandwidth (1000 MHz), thus can support a much higher data rate. Depending on the signal-to-noise ratio on the coaxial cable, 40 Mb/s can be delivered to the end users with QAM modulation. For upstream transmission, QPSK can deliver up to a 10-Mb/s data rate. However, as cable systems are shared-medium networks, the bandwidth is thus shared by all the cable modems connected to the network. By contrast, DSL uses dedicated twist pairs for each user, thus no bandwidth sharing for different users. Furthermore, as the transmission bandwidth must be shared by multiple users, medium access control protocol must be deployed to govern upstream transmission. If congestion occurs in a specific channel, the headend must be able to instruct cable modems to tune its receiver to a different channel.

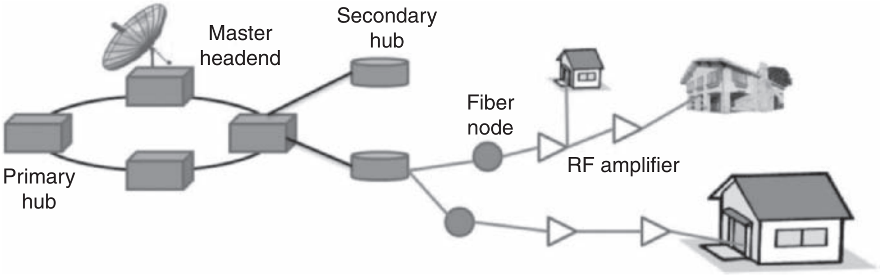


FIGURE 1.3 HFC access networks.

1.4.1 Cable Modem

Cable modems were developed to transport high-speed data to and from end users in an HFC network. Traditional TV broadcasting occupies frequencies up to 1 GHz, with each TV channel occupying 6 MHz of bandwidth (Part 76 in the FCC rules). A cable modem uses two of those 6-MHz channels for data transmission. For upstream transmission, a cable modem sends user data to the headend using a 6-MHz band between 5 and 42 MHz. At the same time, the cable modem must tune its receiver to a 6-MHz band within a 450- to 750-MHz band to receive downstream data. While a QAM modulation scheme is used for downstream data, a QPSK modulation scheme is usually selected for upstream transmission, as it is more immune to the interference resulting from radio broadcasting.

1.4.2 DOCSIS

DOCSIS (Data Over Cable Service Interface Specifications), developed by CableLabs, a consortium of equipment manufactuers, is the current standard for cable access technology. DOCSIS defines the functionalities and properties of cable modems at a subscriber's premises and cable modem termination systems at the headend. As its name suggests, DOCSIS specifies the physical layer characteristics, such as transmission frequency, bit rate, modulation format, and power levels, of cable modem and cable modem termination systems, but also the data link layer protocol, such as frame structure, medium access control, and link security. Three different versions of DOCSIS (1.0/2.0/3.0) was developed during the past decade and were later ratified as ITU-T Recommendation J.112, J.122, and J.222. Although some compromise is needed as cable networks are a shared medium, DOCSIS offers various classes of service with medium access control. Such QoS features in DOCSIS can support applications (such as VoIP) that have stringent delay or bandwidth requirements.

Physical Layer The upstream PMD layer supports two modulation formats: QPSK and 16-QAM, and the downstream PMD layers uses 64-QAM and 256-QAM. The nominal symbol rate is 0.16, 0.32, 0.64, 1.28, 2.56, or 5.12 Mbaud. Therefore, the maximum downstream data rate is about 40 Mb/s and the upstream data rate is about 20 Mb/s. To mitigate the effect of noise and other detrimental channel effects, Reed–Solomon encoding, transmitter equalizer, and variable interleaving schemes are commonly used.

Data Link Layer The DOCSIS data link layer specifies frame structure, MAC, and link security. The frame structure used in HFC networks is very similar to the Ethernet in both the upstream and downstream directions. For the downstream direction, data frames are embedded in 188-byte MPEG-2 (ITU-T H.222.0) packets with a 4-byte header followed by 184 bytes of payload. Downstream uses TDM transmission schemes, synchronous to all modems. In the upstream direction, TDMA or S-CDMA are defined for medium access control. An upstream packet includes physical layer overhead, a unique word, MAC overhead, packet payload, and FEC bytes. MAC layer specifications also include modem registration, ranging, bandwidth allocation, collision detection and contention resolution, error detection, and data recovery. An access security mechanism in DOCSIS defines a baseline privacy interface, security system interface, and removable security module interface, to ensure information security in HFC networks.

1.5 OPTICAL ACCESS NETWORKS

Due to their ultrahigh bandwidth and low attenuation, optical fibers have been widely deployed for wide area networks and metro area networks. To some extent, multimode fibers were also deployed in office buildings for local area networks. Even though optical fibers are ideal media for high-speed communication systems and networks, the deployment cost was considered prohibitive in the access area, and copper wires still dominate in the current marketplace. However, as discussed in Section 1.2, emerging multimedia applications have created such large bandwidth demands that copper wire technologies have reached their bandwidth limits. Meanwhile, low-cost photonic components and passive optical network architecture have made fiber a very attractive solution. In the past few years, various PON architecture and technologies have been studied by the telecom industry, and a few PON standards have been approved by ITU-T and IEEE. FTTx becomes a mature technology in direct competition with copper wires. In fact, large-scale deployment has started in Asia, North America, and Europe, and millions of subscribers are enjoying the benefit of PON technologies.

1.5.1 Passive Optical Networks

Figure 1.4 illustrates the architecture of a passive optical network. As the name implies, there is no active component between the central office and the user premises. Active devices exist only in the central office and at user premises. From the central office, a standard single-mode optical fiber (feeder fiber) runs to a 1 : N passive optical power splitter near the user premises. The output ports of the passive splitter connects to the subscribers through individual single-mode fibers (distribution fibers). The transmission distance in a passive optical networks is limited to 20 km, as specified in current standards. The fibers and passive components between the central office and users premises are commonly called an optical distribution network. The number of users supported by a PON can be anywhere from 2 to 128, depending on the the power budget, but typically, 16, 32, or 64. At the central office, an optical line terminal (OLT) transmits downstream data using 1490-nm wavelength, and the broadcasting video is sent through 1550-nm wavelength. Downstream uses a broadcast and select scheme; that is, the downstream data and video are broadcast to each user with MAC addresses, and the user selects the data packet–based MAC addresses. At the user end, an optical network unit (ONU), also called an optical network terminal (ONT), transmits upstream data at 1310-nm wavelength. To avoid collision, upstream transmission uses a multiple access protocol (i.e., time-division multiple access) to assign time slots to

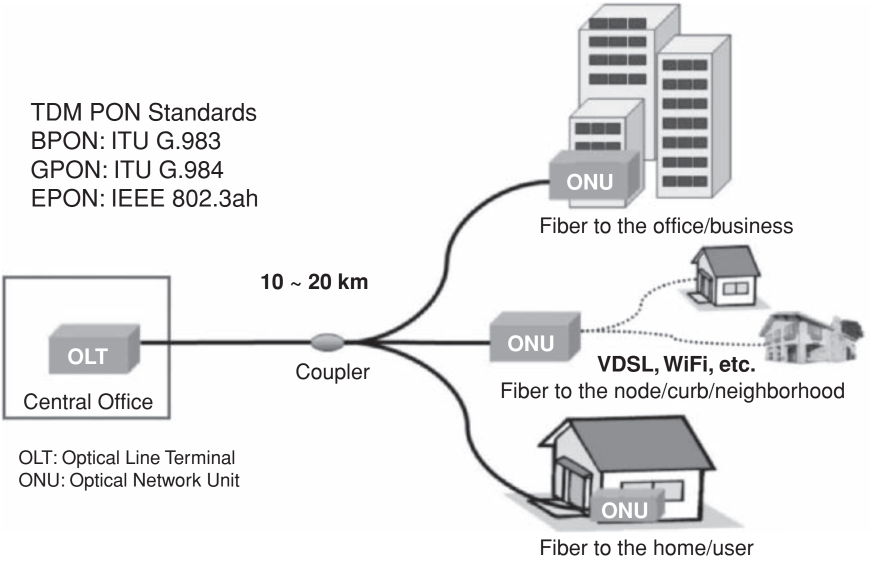


FIGURE 1.4 Passive optical networks.

each user. This type of passive optical network is called TDM PON. The ONU could be located in a home, office, a curbside cabinet, or elsewhere. Thus comes the so-called fiber-to-the-home/office/business/neighborhood/curb/user/premises/node, all of which are commonly referred to as *fiber to the x*. In the case of fiber-to-the-neighborhood/curb/node, twisted pairs are typically deployed to connect end users to the ONUs, thus providing a hybrid fiber/DSL access solution.

1.5.2 PON Standard Development

Early work of passive optical networks started in 1990s, when telecom service providers and system equipment vendors formed the FSAN (full service access networks) working group. The common goal of the FSAN group is to develop truly broadband fiber access networks. Because of the traffic management capabilities and robust QoS support of ATM (asynchronous transfer mode), the first PON standard, APON, is based on ATM and hence referred to as ATM PON. APON supports 622.08 Mb/s for downstream transmission and 155.52 Mb/s for upstream traffic. Downstream voice and data traffic is transmitted using 1490-nm wavelength, and downstream video is transmitted with 1550-nm wavelength. For upstream, user data are transmitted with 1310-nm wavelength. All the user traffic is encapsulated in standard ATM cells, which consists of 5-byte control header and 48-byte user data. APON standard was ratified by ITU-T in 1998 in Recommendation G.983.1. In the early days, APON was most deployed for business applications (e.g., fiber-to-the-office). However, APON networks are largely substituted with higher-bit-rate BPONs and GPONs.