OPTICAL NETWORKING BEST PRACTICES HANDBOOK

John R. Vacca

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This book is dedicated to Sabrina.

CONTENTS

FOREWORD

From the fundamentals to the level of advance sciences, this book explains and illustrates how optical networking technology works. The comprehensive coverage of fiber technology and the equipment that is used to transmit and manage traffic on a fiber network provides a solid education for any student or professional in the networking arena.

The explanations of the many complex protocols that are used for transmission on a fiber network are excellent. In addition, the chapter on developing areas in optical networking provides insight into the future directions of fiber networking technology. This is helpful for networking design and implementation as well as planning for technology obsolescence and migration. The book also provides superb end-of-chapter material for use in the classroom, which includes a chapter summary and a list and definitions of key terms.

I highly recommend this book for networking professionals and those entering the field of network management. I also highly recommend it to curriculum planners and instructors for use in the classroom.

MICHAEL ERBSCHLOE

Security Consultant and Author
St. Louis, Missouri

PREFACE

Traffic growth in the backbone of today’s networks has certainly slowed, but most analysts still estimate that the traffic volume of the Internet is roughly doubling every year. Every day, more customers sign up for broadband access using either cable modem or DSL. Third-generation wireless is expected to significantly increase the bandwidth associated with mobile communications. Major movie studios are signing agreements that point toward video-on-demand over broadband networks. The only technology that can meet this onslaught of demand for bandwidth in the network core is optical.

Nevertheless, most people still visualize electrical signals when they think of voice and data communications, but the truth is that the underlying transport of the majority of signals in today’s networks is optical. The use of optical technologies is increasing every day because it is the only way in which communications carriers can scale their networks to meet the onslaught in demand affordably. A single strand of fiber can carry more than a terabit per second of information. Optical switches consume a small fraction of the space and power that is required for electrical switches. Advances in optical technology are taking place at almost double the rate predicted by Moore’s law.

Optical networking technologies over the past two decades have been reshaping all telecom infrastructure networks around the world. As network bandwidth requirements increase, optical communication and networking technologies have been moving from their telecom origin into the enterprise. For example, in data centers today, all storage area networking is based on fiber interconnects with speeds ranging from 1 to 10 Gbps. As the transmission bandwidth requirements increase and the costs of the emerging optical technologies become more economical, the adoption and acceptance of these optical interconnects within enterprise networks will increase.

P.1 PURPOSE

The purpose of this book is to bring the reader up to speed and stay abreast of the rapid advances in optical networking. The book covers the basic concepts of optical communications; the evolution of DWDM and its emergence as the basis for networking; the merger of IP and optical, and its impact on future network control structures; as well as the detailed workings of the dominant systems in today’s optical networking world, SONET and SDH.

Optical networking is presented in this book in a very comprehensive way for nonengineers needing to understand the fundamentals of fiber, high-capacity, and high-speed equipment and networks, and upcoming carrier services. The book helps the reader gain a practical understanding of fiber optics as a physical medium, sorting out single- versus multimode and the crucial concept of dense wave division multiplexing. This volume covers the overall picture, with an understanding of SONET rings and how carriers build fiber networks; it reviews broadband equipment such as optical routers, wavelength cross-connects, DSL, and cable; and it brings everything together with practical examples on deployment of gigabit Ethernet over fiber, MANs, VPNs, and using managed IP services from carriers. The purpose of the book is also to explain the underlying concepts, demystify buzzwords and jargon, and put in place a practical understanding of technologies and mainstream solutions—all without getting bogged down in details. It includes detailed notes and will be a valuable resource for years to come.

This book also helps the reader gain a practical understanding of the fundamental technical concepts of fiber-optic transmission and the major elements of fiber networks. The reader can learn the differences between the various types of fiber cable, why certain wavelengths are used for optical transmission, and the major impairments that must be addressed.

This book also shows the reader how to compare the different types of optical transmitters including LEDs, side-/surface-emitting, tuned, and tunable lasers. It also helps the reader gain a practical understanding of why factors such as chromatic dispersion and polarization-mode dispersion become more important at higher bit rates and presents techniques that can be employed to compensate for them.

This book reviews the function of various passive optical components such as Bragg gratings, arrayed waveguides, optical interleavers, and dispersion compensation modules. A practical understanding will be gained of the basic technology of wave division multiplexing, the major areas for increasing capacity, and how SONET, gigabit Ethernet, and other optical formats can be combined on a fiber link.

The reader will also learn the following: to evaluate the gigabit and 10-gigabit Ethernet optical interfaces and how resilient packet ring technology might allow the Ethernet to replace SONET in data applications; to compare and contrast the basic categories of all-optical and OEO switches; and to evaluate the strengths and limitations of these switches for edge, grooming, and core applications.

Furthermore, the book elucidates the options for free-space optical transmission and the particular impairments that must be addressed and then discusses the fundamental challenges for optical routing and how optical burst switching could work with MPLS and GMPLS to provide the basis for optical routing networks.

Finally, the book explores current and evolving public network applications, including wavelength services/virtual dark fiber, passive optical networks (PONs), specialized optical access, and virtual SONET rings. It reviews the OSI model and then categorizes different networking equipment and strategies: optical routers, cross-connects, and optical switches; and SONET multiplexers and ATM. The book also explains jargon such as “IP over light.” The reader can gain practical insight into where telecommunications is headed over the next 5–10 years.

SCOPE

Throughout the book, extensive hands-on examples provide the reader with practical experience in installing, configuring, and troubleshooting optical networking technologies. As the next generation of optical networking emerges, it will evolve from the existing fixed point-to-point optical links to a dynamic network, with all-optical switches, varying path lengths, and a new level of flexibility available at the optical layer. What drives this requirement?

In the metro area network (MAN), service providers now need faster provisioning times, improved asset utilization, and economical fault recovery techniques. However, without a new level of functionality from optical components and subsystems, optical-layer flexibility will not happen. At the same time, optical components must become more cost effective, occupy less space, and consume less power.

This book presents a wide array of semiconductor solutions to achieve these goals. Profiled in this book are high-efficiency TEC drivers; highly integrated monitoring and control solutions for transmission and pump lasers; TMS320TM DSP and MSP430 microcontroller options ranging from the highest performance to smallest footprint; linear products for photodiode conditioning and biasing; unique Digital Light Processing technology; and much more.

By combining variable optics with the power of TI high-performance analog and DSP, dynamic DWDM systems can become a reality. Real-time signal processing, available at every optical networking node, will enable the intelligent optical layer. This means the opportunity for advanced features such as optical signaling, autodiscovery, and automatic provisioning and reconfiguration to occur at the optical layer. The book's scope is not limited to the following:

- Providing a solid understanding of fiber optics, carriers' networks, optical networking equipment, and broadband services
- Exploring how glass fiber (silica) is used as a physical medium for communications
- Seeing how light is used to represent information, wavelengths, different types of fibers, optical amplifiers, and dense wave division multiplexing
- Comparing single- and multi-mode fiber and vendors
- Seeing how carriers have built mind-boggling high-capacity fiber networks around town, around the country, and around the planet
- Reviewing the idea of fiber rings and the two main strategies carriers use to organize the capacity: traditional SONET/SDH channels and newer IP/ATM bandwidth on- demand services
- Exploring the equipment, configurations, and services all carriers will be deploying, including Gig-E service, dark fiber, managed IP services, and VPNs
- Reinforcing the reader's knowledge with a number of practical case studies/projects to see how and where these new services can and will be deployed, and understanding the advantages of each
- Receiving practical guidelines and templates that can be put to immediate use.

Furthermore, the topics that are included are not limited to:

- Avalanche photodiode (APD) receivers
- DSP control and analysis
- Optical amplifiers
- Optical cross-connects
- OXCs and optical add/drop multiplexers (OADMs)
- Optical wireless solutions
- Photodiodes
- Polarization mode dispersion compensation (PMDC)
- Transmission lasers
- Variable optical attenuators
- Physical layer applications
- Serial gigabit
- Basics of SONET
- SONET and the basics of optical networking
- Advanced SONET/SDH
- Basics of optical networking
- Optical networking
- IP over optical networks
- WDM optical switched networks
- Scalable communications integrated optical networks
- Lightpath establishment and protection in optical networks
- Bandwidth on demand in WDM networks
- Optical network design using computational intelligence techniques

TARGET AUDIENCE

This book primarily targets senior-level network engineers, network managers, data communication consultants, or any self-motivated individual who wishes to refresh his or her knowledge or to learn about new and emerging technologies. Communications and network managers should read this book as well as IT professionals, equipment providers, carrier and service provider personnel who need to understand optical access, metropolitan, national, and international IT architects, systems engineers, systems specialists and consultants, and senior sales representatives. This book is also ideal for:

- Project leaders responsible for dealing with specification and implementation of communication and network projects
- Those wanting to expand their knowledge base with fiber optics, optical networking, VPNs, broadband IP services, applications, and trends

- Nonengineering personnel from LECs, CLECs, IXCs, and VPN providers: customer configuration analysts and managers, and marketing and sales managers needing to build a structural knowledge of technologies, services, equipment, and mainstream solutions
- Those new to the business needing to get up to speed quickly
- Telco company personnel needing to get up to speed on optical, IP, and broadband
- Personnel from hardware and infrastructure manufacturers needing to broaden their knowledge to understand how their products fit into the bigger picture
- IS/IT professionals requiring a practical overview of optical networking technologies, services, mainstream solutions, and industry trends
- Analysts who want to improve their ability to sort hype from reality
- Decision makers seeking strategic information in plain English.

ORGANIZATION OF THIS BOOK

The book is organized into 14 chapters and one appendix and has an extensive glossary of optical networking terms and acronyms. It provides a step-by-step approach to everything one needs to know about optical networking as well as information about many topics relevant to the planning, design, and implementation of optical networking systems. The following detailed organization speaks for itself.

Chapter 1, Optical Networking Fundamentals, describes IP and integrated optical network solutions and discusses a network architecture for an optical and IP integrated network as well as its migration scenario. Also, this chapter gives a framework for an incremental use of the wavelengths in optical networks with protection.

Chapter 2, Types Of Optical Networking Technology, reviews the optical signal processing and wavelength converter technologies that can bring transparency to optical packet switching with bit rates extending beyond that currently available with electronic router technologies.

Chapter 3, Optical Transmitters, provides an overview of recent exciting progress and discusses application requirements for these emerging optoelectronic and WDM transmitter sources.

Chapter 4, Types Of Optical Fiber, covers fiber-optic strands and the process; fiber-optic cable modes (single, multiple); types of optical fiber (glass, plastic, and fluid); and types of cable families (OM1, OM2, OM3, and VCSEL).

Chapter 5, Carriers' Networks, discusses the economics, technological underpinnings, features and benefits, and history of EPONs.

Chapter 6, Passive Optical Components, reviews the key work going on in the optical communication components industry.

Chapter 7, Free-Space Optics, discusses the development of an SOI/SOI wafer bonding process to design and fabricate two-axis scanning mirrors with excellent performance.

Chapter 8, Optical Formats: Synchronous Optical Network (SONET)/Synchronous Digital Hierarchy (SDH), and Gigabit Ethernet, provides an introduction to the SONET standard.

Chapter 9, Wave Division Multiplexing, presents a general overview of the current status and possible evolution trends of DWDM-based transport networks.

Chapter 10, Basics of Optical Switching, compares the merits of different switching technologies in the context of an all-optical network.

Chapter 11, Optical Packet Switching, focuses on the application optical networking packet switching. The chapter outlines a range of examples in the field of circuit switching, and then focuses on designs in optical packet switching.

Chapter 12, Optical Network Configurations, provides an approach for the implementation of flow-through provisioning in the network layer, specifically with optical network configurations.

Chapter 13, Developing Areas in Optical Networking, describes an approach to fabricating optical wireless transceivers that uses devices and components suitable for integration and relatively well-developed techniques to produce them.

Chapter 14, Summary, Conclusions, and Recommendations, puts the preceding chapters of this book into a proper perspective by summarizing the present and future state of optical networks and concluding with quite a substantial number of very high-level recommendations.

The appendix, Optical Ethernet Enterprise Case Study, provides an overview of how enterprises can utilize managed optical Ethernet services to obtain the high-capacity scalable bandwidth necessary to transform IT into a competitive advantage, speeding up transactions, slashing lead times, and ultimately enhancing employee productivity and the overall success of the entire company.

The book ends with a glossary of optical networking-related terms and acronyms.

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1 Optical Networking Fundamentals

Throughout the past decade, global communications traffic in both voice and data has grown tremendously. Communications bandwidth capacity and geographic coverage have been substantially expanded to support this demand. These tremendous advances have been enabled by optical signals sent over fiber optics networks. However, the growth in tele- and data-communications traffic is just beginning. People are gaining exposure to a new world of choices and possibilities as an increasing number of them access the Internet via broadband. Streaming audio, teleconferencing, video-on-demand, and three-dimensional (3-D) virtual reality are just a few of the applications. Optical networking, with its inherent advantages, will be the key in making this new world of communications possible.

But how did optical networking come about in the first place? Let us take a brief look at the history of fiber optics.

1.1 FIBER OPTICS: A BRIEF HISTORY IN TIME

Very little is known about the first attempts to make glass. The Roman historian Pliny attributed it to Phoenician sailors [1]. He recounted how they landed on a beach, propped a cooking pot on some blocks of natron that they were carrying as cargo, and made a fire over which to cook a meal. The sand beneath the fire melted and ran in a liquid stream that later cooled and hardened into glass, to their surprise.

Daniel Colladon, in 1841, made the first attempt at guiding light on the basis of total internal reflection in a medium [1]. He attempted to couple light from an arc lamp into a stream of water. A large metal tube was filled with water and the cork removed from a small hole near the bottom,demonstrating the parabolic form of jets of water. A lamp placed opposite the jet opening illustrated total internal reflection. John Tyndall, in 1870, demonstrated that light used internal reflection to follow a specific path [2]. Tyndall directed a beam of sunlight at a path of water that flowed from one container to another. It was seen that the light followed a zigzag path inside the curved path of the water. The first research into the guided transmission of light was marked by this simple experiment.

In 1880, William Wheeling patented this method of light transfer, called *piping light* [2]. Wheeling believed that by using mirrored pipes branching off from a single source

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of illumination (a bright electric arc), he could send light to many different rooms in the same way that water, through plumbing, is carried within and throughout buildings. However, the concept of piping light never caught on due to the ineffectiveness of Wheeling's idea and to the concurrent highly successful introduction of Edison's incandescent lightbulb.

Also in 1880, Alexander Graham Bell transmitted his voice as a telephone signal through about 600 feet of free space (air) using a beam of light as the carrier (optical voice transmission)—demonstrating the basic principle of optical communications [2]. He named his experimental device the *photophone.* In other words, the photophone used free-space light to carry the human voice 200 meters. Specifically placed mirrors reflected sunlight onto a diaphragm attached within the mouthpiece of the photophone. A light-sensitive selenium resistor mounted within a parabolic reflector was at the other end. This resistor was connected to a battery that was in turn wired to a telephone receiver. As one spoke into the photophone, the illuminated diaphragm vibrated, casting various intensities of light onto the selenium resistor. The changing intensity of light altered the current that passed through the telephone receiver, which then converted the light back into speech. Bell believed this invention was superior to the telephone because it did not need wires to connect the transmitter to the receiver. Today, *free-space optical links*[1] find extensive use in metropolitan applications. Bell went on to invent the telephone, but he always thought the photophone was his greatest invention.

1.1.1 The Twentieth Century of Light

The first fiber optics cable was created by German medical student Heinrich Lamm in 1930 [1]. He was the first person to assemble a bundle of optical fibers to carry an image. Lamm's goal was to look inside inaccessible parts of the body. He reported transmitting the image of a lightbulb during his experiments.

In the second half of the twentieth century, fiber-optic technology experienced a phenomenal rate of progress. With the development of the fiberscope, early success came during the 1950s. This image-transmitting device, which used the first practical all-glass fiber, was concurrently devised by Brian O'Brien at the American Optical Company and Narinder S. Kapany (who first coined the term *fiber optics* in 1956) and colleagues at the American College of Science and Technology in London. Early on, transmission distances were limited because all-glass fibers experienced excessive optical loss—the loss of the light signal as it traveled the fiber [2].

So, in 1956, Kapany invented the glass-coated glass rod, which was used for non-telecommunications applications. By providing a means of protecting the beam of light from environmental obstacles, the glass-coated glass rod helped eliminate the biggest obstacle to Alexander Graham Bell's photophone [1].

In 1958, Arthur L. Schawlow and Charles H. Townes invented the laser and published "Infrared and Optical Masers" in the American Physical Society's *Physical*

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[1] Free-space optical links are also called free-space photonics. It is the transmission of modulated visible or infrared (IR) beams through the atmosphere via lasers, LEDs, or IR-emitting diodes (IREDs) to obtain broadband communications.

Review. The paper describes the basic principles of light amplification by stimulated emission of radiation (laser), initiating this new scientific field [1].

Thus, all the preceding inventions motivated scientists to develop glass fibers that included a separate glass coating. The innermost region of the fiber, or *core*,[2] was used to transmit the light, while the glass coating, or *cladding*, prevented the light from leaking out of the core by reflecting the light within the boundaries of the core. This concept is explained by Snell's law, which states that the angle at which light is reflected is dependent on the refractive indices of the two materials—in this case, the core and the cladding. As illustrated in Figure 1.1 [1,3], the lower *refractive index* of the cladding (with respect to the core) causes the light to be angled back into the core.

The fiberscope quickly found applications in the medical field as well as in inspections of welds inside reactor vessels and combustion chambers of jet aircraft engines. Fiberscope technology has evolved over the years to make laparoscopic surgery one of the great medical advances of the twentieth century [2].

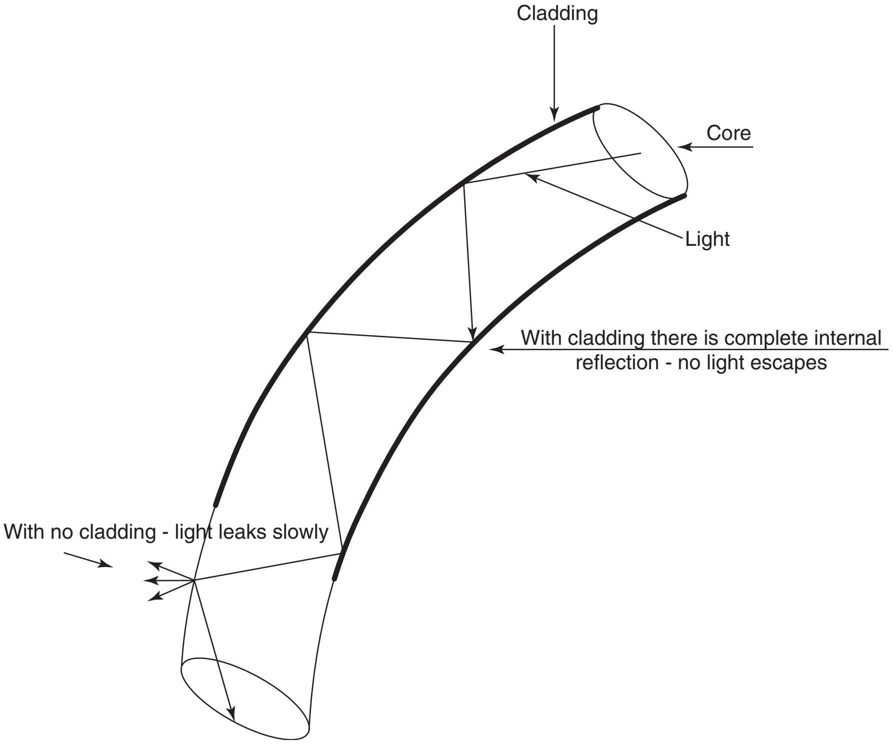

Figure 1.1 Optical fiber with glass coating/cladding.

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[2] A core is the light-conducting central portion of an optical fiber, composed of material with a higher index of refraction than the cladding. This is the portion of the fiber that transmits light. On the other hand, cladding is the material that surrounds the core of an optical fiber. Its lower index of refraction, compared to that of the core, causes the transmitted light to travel down the core. Finally, the refractive index is a property of optical materials that relates to the speed of light in the material versus the speed of light in vacuum.

The next important step in the establishment of the industry of fiber optics was the development of *laser* technology. Only the *laser diode* (LD) or its lower-power cousin, the *light-emitting diode* (LED), had the potential to generate large amounts of light in a spot tiny enough to be useful for fiber optics. As a graduate student at Columbia University in 1957, Gordon Gould popularized the idea of using lasers.[3] He described the laser as an intense light source. Charles Townes and Arthur Schawlow at Bell Laboratories supported the laser in scientific circles shortly thereafter [2].

Lasers went through several generations of development, including that of the ruby laser and the helium–neon laser in 1960. Charles Kao proposed the possibility of a practical use for fiber-optic telecommunication. Kao predicted the performance levels that fiber optics could attain and prescribed the basic design and means to make fiber optics a practical and significant communications/transmission medium. Semiconductor lasers were first realized in 1962. Today, these lasers are the type most widely used in fiber optics [2].

Because of their higher modulation frequency capability, lasers as important means of carrying information did not go unnoticed by communications engineers. Light has an information-carrying capacity 10,000 times that of the highest radio frequencies in use. However, because it is adversely affected by environmental conditions such as rain, snow, hail, and smog, lasers are unsuited for open-air transmissions. Working at the Standard Telecommunication Laboratory in England in 1966, Charles Kao and Charles Hockham (even though they were faced with the challenge of finding a transmission medium other than air) published a landmark paper proposing that the optical fiber might be a suitable transmission medium if its *attenuation*[4] could be kept under 20 decibels per kilometer (dB/km). Even for this attenuation, 99% of the light would be lost over just 3300 feet. In other words, only 1/100th of the optical power transmitted would reach the receiver. Optical fibers exhibited losses of 1000 dB/km or more at the time of their proposal. Intuitively, researchers postulated that these high optical losses were the result of impurities in the glass and not the glass itself. An optical loss of 20 dB/km was within the capability of the electronics and optoelectronic components of the day [2].

Glass researchers began to work on the problem of purifying glass through the inspiration of Kao and Hockham's proposal. In 1970, Robert Maurer, Donald Keck, and Peter Schultz of Corning succeeded in developing a glass fiber that exhibited attenuation of less than 20 dB/km, the threshold for making fiber optics a viable technology. In other words, Robert Maurer and his team designed and produced the first optical fiber. Furthermore, the use of fiber optics was generally not available until 1970 when Robert Maurer and his team were able to produce a practical fiber. Experts at the time predicted that the optical fiber would be useable for telecommunication

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[3] A laser is a light source that produces coherent, near-monochromatic light through stimulated emission. Now, a laser diode (LD) is a semiconductor that emits coherent light when forward biased. However, a light-emitting diode (LED) is a semiconductor that emits incoherent light when forward-biased. Two types of LEDs include edge-emitting and surface-emitting LEDs.

[4] Attenuation is the decrease in signal strength along a fiber optic waveguide caused by absorption and scattering. Attenuation is usually expressed in dB/km.

transmission only if glass of very high purity was developed such that at least 1% of the light remained after traveling 1 km (attenuation). This glass would be the purest ever made at that time [2].

Early work on fiber-optic light *sources*[5] and *detectors* was slow and often had to borrow technology developed for other reasons. For example, the first fiber-optic light sources were derived from visible indicator LEDs. As demand grew, light sources were developed for fiber optics that offered higher switching speed, more appropriate wavelengths, and higher output power [2].

Closely tied to wavelength, fiber optics developed over the years in a series of generations. The earliest fiber-optic systems were developed at an operating wavelength of about 850 nm. This wavelength corresponds to the so-called first window in a silica-based optical fiber, which refers to a wavelength region that offers low optical loss. It is located between several large absorption peaks caused primarily by moisture in the fiber and *Rayleigh scattering*[6] [2].

Because the technology for light emitters at this wavelength had already been perfected in visible indicator LEDs, the 850-nm region was initially attractive. Low-cost silicon detectors could also be used at the 850-nm wavelength. However, the first window became less attractive as technology progressed because of its relatively high 3-dB/km loss limit [2].

With a lower attenuation of about 0.5 dB/km, most companies jumped to the *second window* at 1310 nm. In late 1977, Nippon Telegraph and Telephone (NTT) developed the *third window* at 155 nm. It offered the theoretical minimum optical loss for silica-based fibers, about 0.2 dB/km. Also in 1977, AT&T Bell Labs scientists' interest in lightwave communication led to the installation of the first lightwave system in an operating telephone company. This installation was the world's first lightwave system to provide a full range of telecommunications services—voice, data, and video—over a public switched network. The system, extending about 1.5 miles under downtown Chicago, used glass fibers that each carried the equivalent of 672 voice channels [2].

In 1988, installation of the first transatlantic fiber-optic cable linking North America and Europe was completed. The 3148-mile cable can handle 120,000 telephone calls simultaneously.

Today, systems using visible wavelengths near 660 nm, 850 nm, 1310 nm, and 1550 nm are all manufactured and deployed along with very low-end short-distance systems. Each wavelength has its advantages. Longer wavelengths offer higher performance, but always come with higher costs. The shortest link lengths can be handled with wavelengths of 660 or 850 nm. The longest link lengths require 1550-nm wavelength systems. A *fourth window*, near 1625 nm, is being developed. While it is not a lower loss than the 1550-nm window, the loss is comparable, and it might

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[5] A source in fiber optics is a transmitting LED or laser diode, or an instrument that injects test signals into fibers. On the other hand, a detector is an opto-electric transducer used to convert optical power into electrical current. It is usually referred to as a photodiode.

[6] Rayleigh scattering is the scattering of light that results from small inhomogeneities of material density or composition.

simplify some of the complexities of long-length, multiple-wavelength communications systems [2].

1.1.2 Real World Applications

Initially, the U.S. military moved quickly to use fiber optics for improved communications and tactical systems. In the early 1970s, the U.S. Navy installed a fiber-optic telephone link aboard the U.S.S. Little Rock. The Air Force followed suit by developing its airborne light optical fiber technology (ALOFT) program in 1976. Encouraged by the success of these applications, military R&D programs were funded to develop stronger fibers, tactical cables, ruggedized high-performance components, and numerous demonstration systems showing applications across the military spectrum [2].

Soon after, commercial applications followed. Both AT&T and GTE installed fiber-optic telephone systems in Chicago and Boston, respectively, in 1977. These successful applications led to an increase in fiber-optic telephone networks. Single-mode fibers operating in the 1310-nm, and later in the 1550-nm wavelength windows became the standard fiber installed for these networks by the early 1980s. Initially, the computer industry, information networks, and data communications were slower to embrace fiber. Today they too find use for a transmission system that has lighter-weight cable, resists lightning strikes, and carries more information faster and over longer distances [2].

Fiber-optic transmission was also embraced by the broadcast industry. The broadcasters of the Winter Olympics in Lake Placid, New York requested a fiber-optic video transmission system for backup video feeds in 1980. The fiber-optic feed, because of its quality and reliability, soon became the primary video feed, making the 1980 Winter Olympics the first fiber-optic television transmission. Later, fiber optics transmitted the first ever digital video signal at the 1994 Winter Olympics in Lillehammer, Norway. This application is still evolving today [2].

The U.S. government deregulated telephone service in the mid-1980s, which allowed small telephone companies to compete with the giant, AT&T. Companies such as MCI and Sprint quickly went to work installing regional fiber-optic telecommunications networks throughout the world. These companies laid miles of fiber-optic cable, allowing the deployment of these networks to continue throughout the 1980s by taking advantage of railroad lines, gas pipes, and other natural rights of way. However, this development created the need to expand fiber's transmission capabilities [2].

Bell Labs transmitted a 2.5-Gb/s (gigabits per second; giga means billion) signal over 7500 km without regeneration in 1990. For the lightwave to maintain its shape and density, the system used a soliton laser and an erbium-doped fiber amplifier (EDFA).[7] In 1998, they went one better as researchers transmitted 100 simultaneous optical signals—each at a data rate of 10 Gb/s for a distance of nearly 250 miles (400 km).

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[7] An EDFA is an optical fiber doped with the rare earth element, erbium, which can amplify light in the 1550-nm region when pumped by an external light source.

In this experiment, dense wavelength-division multiplexing (DWDM)[8] technology, which allows multiple wavelengths to be combined into one optical signal, increased the total data rate on one fiber to one terabit per second (10^{12} bits /s) [2].

1.1.3 Today and Beyond

DWDM technology continues to develop today. Driven by the phenomenal growth of the Internet, the move to optical networking is the focus of new technologies as the demand for data bandwidth increases. As of this writing, nearly 800 million people have Internet access and use it regularly. Some 70 million or more households are *wired*. The World Wide Web already hosts over 5 billion web pages. And according to estimates, people upload more than 6.8 million new web pages every day [2].

The increase in fiber transmission capacity is an important factor in these developments, which, by the way, has grown by a factor of 400 in the past decade. Extraordinary possibilities exist for future fiber-optic applications because of fiber-optic technology's immense potential bandwidth (50 THz or greater). Already, and well underway, is the push to bring broadband services, including data, audio, and especially video, into the home [2].

Broadband service available to a mass market opens up a wide variety of interactive communications for both consumers and businesses. Interactive video networks, interactive banking and shopping from the home, and interactive distance learning are already realities. The *last mile* for optical fiber goes from the curb to the television set. This is known as fiber-to-the-home (FTTH) and fiber-to-the-curb (FTTC),[9] thus allowing video on demand to become a reality [2].

Now, let us continue with the fundamentals of optical networking by looking at distributed IP (Internet protocol) routing.

1.2 DISTRIBUTED IP ROUTING

The idea behind the distributed IP router is to minimize routing operations in a large optical network. In the distributed IP router, the workload is shared among nodes and the routing is done only once.

Thus, the optical network model considered in this section consists of multiple optical crossconnects (OXCs) interconnected by optical links and nodes in a general topology (referred to as an *optical mesh network*). Each OXC is assumed to be capable of switching a data stream from a given input port to a given output port. This

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[8] DWDM is the transmission of many of closely spaced wavelengths in the 1550-nm region over a single optical fiber. Wavelength spacings are usually 100 or 200 GHz, which corresponds to 0.8 or 1.6 nm. DWDM bands include the C-band, the S-band, and the L-band.

[9] Fiber-to-the-home (FTTH) is a fiber-optic service to a node located inside an individual home. Fiber-to-the-curb (FTTC), on the other hand, is a fiber-optic service to a node connected by wires to several nearby homes, typically on a block. And, video on demand (VOD) is a term used for interactive or customized video delivery service.

switching function is controlled by appropriately configuring a crossconnect table. Conceptually, the crossconnect table consists of entries of the form <input port i, output port j>, indicating that the data stream entering input port “i” will be switched to output port “j.” A *lightpath* from an ingress port in an OXC to an egress port in a remote OXC is established by setting up suitable crossconnects in the ingress, the egress, and a set of intermediate OXCs such that a continuous physical path exists from the ingress to the egress port. Lightpaths are assumed to be bidirectional; the return path from the egress port to the ingress port follows the same path as the forward path. It is assumed that one or more control channels exist between neighboring OXCs for signaling purposes.

1.2.1 Models: Interaction Between Optical Components and IP

In a hybrid network, some proposed models for interaction between IP and optical components are

- integrated/augmented
- overlay
- peer.

A key consideration in deciding which model to choose from is whether there is a single/separate distributed IP routing and signaling protocol spanning the IP and the optical domains. If there are separate instances of distributed IP routing protocols running for each domain, then the following questions arise.

- How would IP QoS (quality of service) parameters be mapped into the optical domain?
- What is the interface defined between the two protocol instances?
- What kind of information can be leaked from one protocol instance to the other?
- Would one label switching protocol run on both domains’? If that is the case, then how would labels map to wavelengths?

The following sections will help answer some of these questions.

1.2.1.1 Overlay Model IP is more or less independent of the optical subnetwork under the overlay model; that is, IP acts as a client to the optical domain. In this scenario, the optical network provides point-to-point connection to the IP domain. The IP/multiprotocol label switching (IP/MPLS) distributed routing protocols are independent of the distributed IP routing and signaling protocols of the optical layer. The overlay model may be divided into two parts: static and signaled.

1.2.1.1.1 Static Overlay Model The static overlay model path endpoints are specified through a network management system (NMS), although the paths may be laid out statically by the NMS or dynamically by the network elements. This would