Optical WDM Networks

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To my family:

my parents Dhirendranath and Gita Mukherjee,

my wife Supriya Mukherjee,

and my daughters Bipasha and Suchitra Mukherjee.

Preface

New Materials

Before discussing the book's topic, intended audience, etc., we remark that another book, entitled *Optical Communication Networks*, was published by the same author in 1997. Eight years is a long time in our fast-moving field. Relative to the old book, a brief outline of the new materials in the new book is provided below, followed by brief descriptions of what has been revamped and what has been deleted.

New Chapters:

- Optical Access Networks (Chapter 5)
- Optical Metro Networks (Chapter 6)
- Survivable Optical Networks (Chapter 11)
- Light-Trees: Optical Multicasting (Chapter 12)
- Traffic Grooming in Optical Mesh Networks (Chapters 13 and 14)
- Impairment-Aware Routing (Chapter 15)
- Optical Packet Switching (Chapter 17)
- Optical Burst Switching (Chapter 18)

Revamped Materials:

- Chapter 1 (Introduction) has been enhanced with six new sections to lead the discussion on telecom network overview, business models, traffic models, role of software (and computer science) in optical networks, etc.
- Chapter 2 (Enabling Technologies) has been updated, especially with a significant amount of new switching material.
- The materials on single-hop and multihop networks (Chapters 3 and 4) have been condensed, but still retained. Because these topics are quite mature, we see less activity on them in academic research and industry today. But we all know that what seems practical today might not be so tomorrow, and vice versa. Thus, a student of optical networking must be educated on this subject; and a practitioner may find this material to be of easy reference.
- Network Control and Management (Chapter 16) has undergone very significant revision.

- Routing and wavelength assignment (RWA) (Chapter 7) has been enhanced with discussions on the routing subproblem and wavelength-assignment heuristics.
- Chapter 9 has also been enhanced with material on virtual-topology adaptation under dynamic traffic.
- The materials in Chapters 8 (Elements of Virtual-Topology Design) and 10 (Wavelength Conversion) have been retained.

Deleted Materials:

- The material on optical time-division multiplexing (OTDM) and code-division multiplexing (OCDM) has been deleted; thus, the current book's focus is solely on WDM networks, as reflected in its title.
- The following chapters have also been deleted: (i) wavelength distributed data interface (WDDI), a multi-wavelength version of FDDI; (ii) all-optical cycle elimination in all-optical networks; and (iii) optimal amplifier placement in all-optical networks.

Interested readers should consult the old book [Mukh97] for these materials.

The Topic

The basic premise of our subject – optical communication networks – is that, as more users start to use our data networks, and as their usage patterns evolve to include more bandwidth-intensive networking applications such as data browsing on the world wide web, Java applications, video conferencing, etc., there emerges an acute need for very high-bandwidth transport network facilities, whose capabilities are much beyond those that current networks (e.g., today's Internet) can provide. Given that a single-mode fiber's potential bandwidth is nearly 50 terabits per second (Tbps), which is nearly four orders of magnitude higher than electronic data rate (of a few tens of Gigabits per second (Gbps) today), every effort should be made to tap into this huge opto-electronic bandwidth mismatch. Wavelength-division multiplexing (WDM) is an approach that can exploit this bandwidth mismatch by requiring that each end-user's equipment operates only at electronic rate, but multiple WDM channels from different end-users may be multiplexed on the same fiber.

Research and development on optical WDM networks have matured considerably over the past decade, with commercial deployment of WDM systems being common. Most such deployments are for WDM optical transmission systems with wavelength channel counts of 32 to 64. Channel counts as high as 160 are practical today, and expected to increase to 320 per fiber strand. While WDM transmission systems are quite mature, the technologies for optical WDM switching, e.g., optical crossconnects (OXCs) are significantly behind. While a lot of efforts have been spent on building *all-optical* (or *transparent*) switches, the switching that is mature today is based on *optical-electronic-optical (OEO)* (or *opaque*) technology. However, besides these hardware platforms, note that *intelligence* in any network (including an optical network) comes from "software," namely for network control, management, signaling, traffic engineering (or routing), network planning (or optimization), etc. Unfortunately, the role of software – or more generally, the role of computer science and engineering – has been paid little attention in optical network research and development. As a result, the progress in the field of optical networking has not been commensurate with its promise from a decade back.

The above problem needs to be rectified. And everyone with a stake in the field of optical networking (researchers, government funding agencies, telecom network operators, equipment vendors, etc.) needs to realize the important roles which *optics*, *electronics*, and *software* play in building a successful optical network (see Fig. 1.2). These players also need to be mindful of the importance of "cross-layer design" issues involving the physical layer (optics and electronics), the network layer (architecture), and the applications (software) (see Fig. 1.3).

Interest on this topic has been growing to better understand the issues and challenges in designing such networks. It is anticipated that the next generation of the Internet will employ WDM-based optical backbones.

Intended Audience

The intended audience of this book includes researchers, industry practitioners, and graduate students (both as a graduate textbook and for doctoral students' research).

Many electrical engineering, computer engineering, and computer science programs around the world have been offering a graduate course on this topic. That is, research and development on optical communication networks have matured significantly to the extent that some of these principles have moved from the research laboratories to the formal (graduate) classroom setting. While there are several good books that deal mainly with the physical-layer issues of optical communications, e.g., [RaSi01, DuDF02, Agra04], few books exist on the "networking" side of optical networking. However, these books are also getting outdated by the fast pace of research and development in the field. These observations led me to write this updated textbook on this topic.

I expect that instructors will find the book useful for teaching a graduate course on optical networking. At my home institution, University of California, Davis, I regularly teach a one-quarter graduate course, ECS 259, "Optical Communication Networks," using materials from the book. Actually, I find that the book's contents are longer than what one can cover in a typical quarter-long course (30 hours of lecture) or a semester-long course (45 hours of lecture). Thus, I wish to provide the following helpful guidelines for those who may wish to skip some materials.

- Each chapter is typically organized in a stand-alone and modular fashion, so any of them can be skipped, if so desired.

- Chapters 3 and 4 on single-hop and multihop networks can be skipped.
- Courses which are more computer-science oriented may wish to treat enabling technologies (Chapter 2) at an overview level and skip Chapter 15 on impairment-aware routing.
- Some instructor may wish to skip the longer-term research problems on optical packet switching (OPS) and optical burst switching (OBS) (Chapters 17 and 18).
- Chapter 12 (Optical Multicasting) may also be skipped by some instructors.
- Some instructors may have less interest in metro networks (Chapter 6) and/or access networks (Chapter 5), but I don't recommend skipping Chapter 5.
- For teaching short courses (of duration 15 hours +/- 5 hours), I have typically used the following materials: Chapter 1 (Introduction), Chapter 5 (Access), Chapters 7-9 (RWA and virtual-topology design), Chapter 11 (survivability), Chapters 13-14 (Traffic Grooming), and some aspects of Chapter 16 (Network Control and Management).

Since the major developments in optical communication networks have started to capture the imagination of the computing, telecommunications, and opto-electronic industries, I expect that industry professionals will find this book useful as a well-rounded reference. Through my own industry relationships, I find that there exists a large group of people who are experts in physical-layer optics, and who wish to learn more about network architectures, protocols, and the corresponding engineering problems in order to design new state-of-the-art optical networking products. This group of people is also who I had in mind while developing this book.

Organization Principles and Unique Features

Writing a book on optical networking is not easy since such a book has to cover materials that span several disciplines ranging from physics to electrical engineering to computer science to operations research to telecom business models, and also since the field itself is evolving very rapidly. This has been a very challenging exercise.

This book is *not* intended to cover in any detail the physical-layer aspects of optical communications; readers should consult an appropriate book, e.g., [RaSi01, DuDF02, Agra04], for such material. We summarize these "enabling technologies" in a single chapter (Chapter 2). Our treatment of the material in this chapter should allow us to uncover the unique strengths and limitations of the appropriate technologies, and then determine how the characteristics of the physical devices may be exploited in pragmatic network architectures, while compensating for the device limitations or "mismatches".

An important organizing principle that I have attempted to keep in mind while developing this book is that research, development, and education on optical communication networks should allow tight coupling between network architectures and device capabilities. To date, research on optical network architectures has taught us that, without a sound knowledge of device capabilities and limitations, one can produce architectures which may be unrealizable; similarly, research on new optical devices, conducted without the concept of a useful system, can lead to sophisticated technology with limited or no usefulness.

The book is organized into three parts. Part I introduces WDM and its enabling technologies. Part II is devoted to WDM local, access, and metro optical network architectures. Part III discusses a wide variety of problems in wavelength-routed WDM optical networks for wide-area coverage. The appendices on "where to learn more" and a "Glossary of Important Terms" should also be beneficial to many readers. More details on the book's organization can be found in Section 1.15.

The most unique feature of this book is its timeliness in capturing the state of the art in the fast-moving field of optical WDM networking. Other major salient aspects of the book are its breadth of coverage, depth of analytical treatment, clear identification of recent developments and open problems, an extensive bibliography (535 references), an extensive number of end-of-chapter exercises (a total of 301), an extensive set of illustrations (353 figures, 56 tables), etc.

A solutions manual is currently being developed. Instructors may obtain a copy from the publisher. Please see additional web-based features below.

Web Enhancements

This book is "web-enhanced," i.e., we have (or plan to have) material such as the following available through the web (see author's web address: *http://networks.cs.ucdavis.edu/~mukherje*):

1. table of contents,
2. list of figures,
3. color versions of some figures – some of the figures were drawn originally in color, and the color versions may be more informative than the black-and-white versions appearing in the book,
4. Chapter 1 in its entirety,
5. introductory material for the other chapters,
6. posting of corrections, revisions, updates, etc.,
7. easy mechanism for readers to provide feedback to the author and the publisher, and
8. if and when possible, additional material as deemed useful, e.g., simulations for some single-hop protocols, multicasting, virtual-topology embedding, etc.; allowing animation and remote operation of simulations via parameter selection by the user using Java.

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I welcome email from readers who wish to provide any sort of feedback: errors, comments, criticisms, and suggestions for improvements.

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