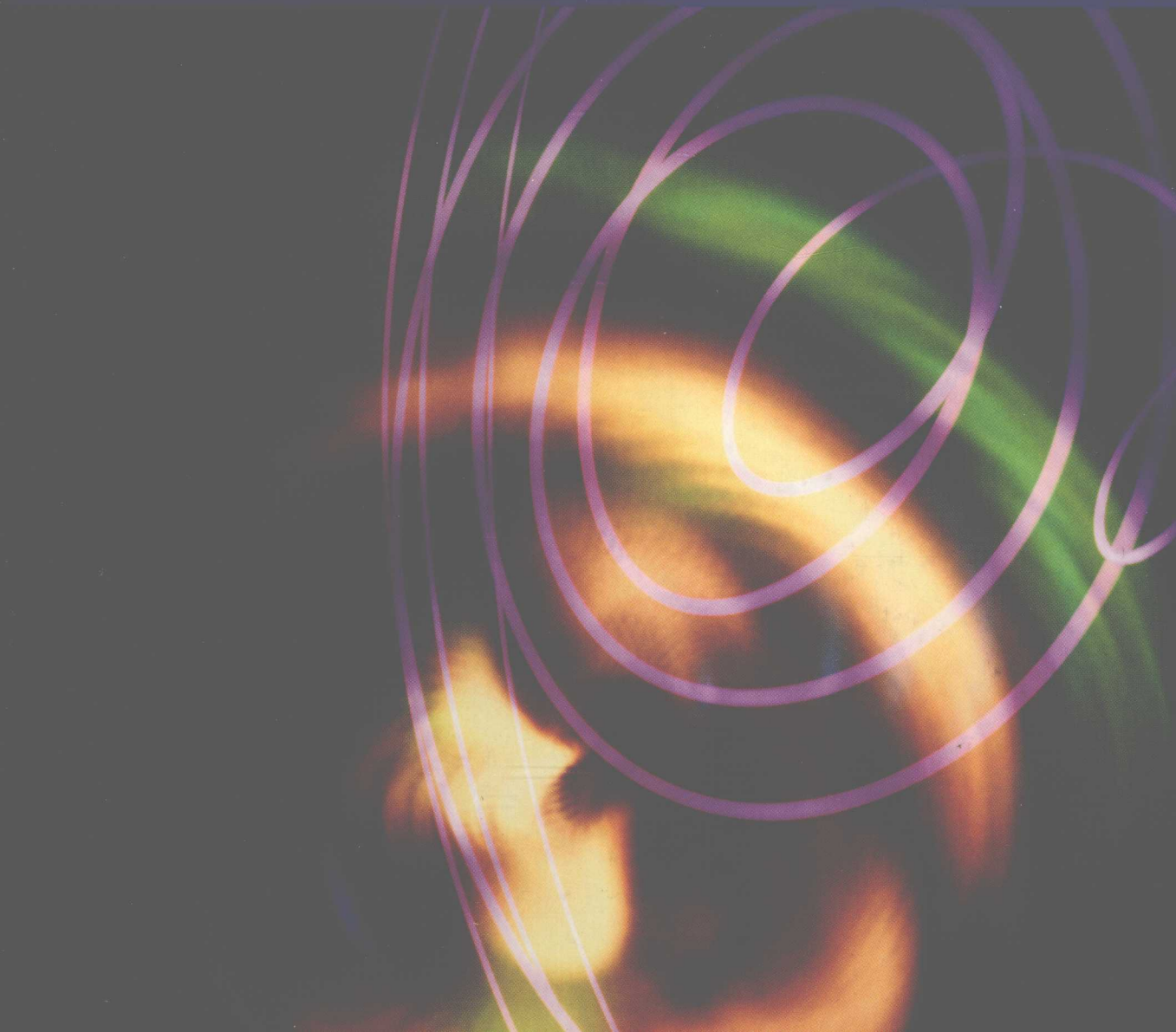
RAJIV RAMASWAMI KUMAR N. SIVARAJAN

OPTICAL NETWORKS

A Practical Perspective



Optical Networks: A Practical Perspective

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To our parents.

Foreword

by Paul E. Green, Jr.
Director, Optical Network Technology
Tellabs, Inc.

Not too many years ago, whenever one wanted to send messages effectively, there were really only two choices—send them by wire or send them by radio. This situation lasted for decades until the mid-1960s, when the fiber optics revolution began, quietly at first, and then with increasing force as people began to appreciate that sending pulses of light through tiny strands of glass wasn't so crazy after all. This revolution is now in full cry, with 4000 strand miles of fiber being installed per day, just in the United States alone. Fiber has been displacing wire in many applications, and gradually it is emerging as one of the two dominant Cinderella transmission technologies of today, wireless being the other. One of these (wireless) goes anywhere but doesn't do much when it gets there, whereas the other (fiber) will never go everywhere but does a great deal indeed wherever it reaches. From the earliest days of fiber communication, people realized that this simple glass medium has incredible amounts of untapped bandwidth capacity waiting to be mined, should the day come when we would actually need it, and should we be able to figure out how to tap it. That day has now come. The demand is here and so are the solutions.

This book describes a revolution within a revolution, the opening up of the capacity of the now-familiar optical fiber to carry more messages, handle a wider variety of transmission types, and provide improved reliabilities and ease of use. In many places where fiber has been installed simply as a better form of copper, even the gigabit capacities that result have not proved adequate to keep up with the demand. The inborn human voracity for more and more bandwidth, plus the growing realization that there are other flexibilities to be had by imaginative use of the fiber, have led people to explore all-optical networks, the subject of this book.

Such networks are those in which either wavelength division or time division is used in new ways to form entire network structures where the messages travel in purely optical form all the way from one user location to another.

When I attempted the same kind of book in 1993, nobody was quite sure whether optical networking would be a roaring success or disappear into the annals of "whatever happened to ..." stories of technology that had once sounded great on paper, but that had somehow never panned out in the real world. My book (*Fiber Optic Networks,* Prentice Hall) spent most of its pages talking about technology building blocks and lamenting their limitations since there was little to say about real networks, the architectural considerations underlying them, and what good they had ever done anybody.

In the last four years, optical networking has indeed really happened, essentially all of it based on wavelength division multiplexing, and with this book Ramaswami and Sivarajan, two of the principal architects of this success, have redressed the insufficiencies of earlier books such as mine. Today, hundreds of millions of dollars of wavelength division networking systems are being sold annually, major new businesses have been created that produce nothing but optical networks, and bandwidth bottlenecks are being relieved and proliferating protocol zoos tamed by this remarkably transparent new way of doing networking; what's more, there is a rich architectural understanding of where to go next. Network experts, fresh from the novelties of such excitements as the Web, now have still another wonderful toy shop to play in. The whole optical networking idea is endlessly fascinating in itself—based on a medium with thousands of gigabits of capacity yet so small as to be almost invisible, transmitters no larger than a grain of salt, amplifiers that amplify vast chunks of bandwidth purely as light, transmission designs that bypass 50 years of hard-won but complex coding, modulation and equalization insights, network architectures that subsume many functions usually done more clumsily in the lower layers of classical layered architectures—these are all fresh and interesting topics that await the reader of this book.

To understand this new networking revolution within a revolution, it is necessary to be led with a sure hand through territory that to many will be unfamiliar. The present authors, with their rare mixture of physics and network architecture expertise, are eminently qualified to serve as guides. After spending some time with this book, you will be more thoroughly conversant with all the important issues that today affect how optical networks are made, what their limitations and potentialities are, and how they fit in with more classical forms of communication networks based on electronic time division. Whether you are a computer network expert wondering how to use fiber to break the bandwidth bottlenecks that are limiting your system capabilities, a planner or implementer trying to future-proof your telephone network,

a teacher planning a truly up-to-date communication engineering curriculum, a student looking for a fun lucrative career, or a midcareer person in need of a retread, this volume will provide the help you need.

The authors have captured what is going on and what is going to be going on in this field in a completely up-to-date treatment unavailable elsewhere. I learned a lot from reading it and expect that you will too.

Preface

Fiber optics has become the core of our telecommunications and data networking infrastructures. Optical fiber is the preferred means of transmission for any data over a few tens of megabits per second and over anything from a kilometer and upwards. The first generation of fiber optic networks used optical fiber predominantly as a replacement for copper cable for transmission at higher bit rates over longer distances. The second generation of fiber optic networks is just emerging. These networks really exploit the capacity of fiber to achieve overall transmission capacities of several tens of gigabits per second to terabits per second. Moreover, they exploit routing and switching of signals in the optical domain. The rapid evolution of technology, coupled with the insatiable demand for bandwidth, is resulting in a rapid transition of these networks from research laboratories into the marketplace.

The fundamentals of optical fiber transmission are covered well in several books. There is, however, a need for a book that covers the transmission aspects of second-generation fiber optic networks, and focuses on the *networking* aspects such as architectures, and control and management issues. Such a book would not be complete without describing the components needed to build these networks, particularly since the network architectures strongly depend on these components, and a person designing optical networks will need to be familiar with their capabilities. Thus this book attempts to cover components, transmission, and networking issues related to second-generation optical networks. It is targeted at professionals who are network planners, designers or operators, graduate students in electrical engineering and computer science, and engineers wanting to learn about optical networks.

Teaching and Learning from This Book

This book can be used as a textbook for graduate courses in electrical engineering or computer science. Much of the material in this book has been covered in courses taught by us. Part I covers components and transmission technology aspects of optical networking, and Part II deals with the networking aspects. To understand the networking issues in Part II, students will require a basic undergraduate-level knowledge of communication networks and probability. We have tried to make the transmission-related chapters in Part I of the book accessible to networking professionals. For example, components are treated first in a simple qualitative manner from the viewpoint of a network designer, but their principle of operation is then explained in detail. Some prior knowledge of electromagnetics will be useful in understanding the detailed quantitative treatment in some of the sections. Advanced sections are marked by an asterisk; these sections can be omitted without loss of continuity.

With this background, the book can be the basis for a graduate course in an electrical engineering curriculum. Alternatively, a graduate course in a computer science department might emphasize network architectures and control and management, by focusing on Part II, and skim over the technology portions of the book in Part I. Likewise, a course on optical transmission in an electrical engineering department might instead focus on Part I and omit the remaining chapters. Each chapter is accompanied by a number of problems, and instructors may obtain a solution manual by contacting the publisher at *orders@mkp.com*.

Second, we have attempted to provide an overview of much recent work in this emerging field, so as to make the book useful to researchers in the field as an up-to-date reference. Each chapter includes an extensive list of references for those who might wish to explore further. The problems include some research topics for further exploration as well. Finally, we hope that the book will also serve as an introduction to people working in other areas who wish to become familiar with fiber optics.

Overview of the Book

Chapter 1 offers an introduction to optical networks. Part I of the book is devoted to the technology underlying optical networks. Chapter 2 describes how light propagates in optical fiber, and deals with the phenomena of loss, dispersion, and fiber nonlinearities, which play a major role in the design of transmission systems. Chapter 3 provides an overview of the different components needed to build a network, such as transmitters, receivers, multiplexers, and switches. Chapter 4 describes how

electrical signals are converted to light signals (the modulation process) at the transmitter and how they are recovered at the receiver (demodulation). Chapter 5 focuses on the physical layer design of the latest generation of transmission systems and networks, and the factors limiting the system performance.

Part II is devoted to a variety of networking aspects of optical networks. Chapter 6 describes the different first-generation optical networks that are deployed widely today. Chapter 7 covers broadcast and select WDM networks that are suitable for LANs and MANs. Different topologies, media-access, and scheduling methods will be described and compared in a uniform framework. Chapter 8 describes networks using wavelength routing. These networks are emerging from the laboratories into commercial deployment. The chapter covers the architectural aspects of these networks and focuses on the key design issues. Chapter 9 describes how to overlay virtual networks, for example, IP or ATM networks over an underlying second-generation optical network. Chapter 10 covers control and management, including connection management, fault management, and safety management. Chapter 11 describes several significant experimental wavelength routing demonstrations, field trials, and prototypes. Chapter 12 describes passive optical network solutions for fiber-to-the-curb and fiber-to-the-home access network applications. Chapter 13 covers the issues associated with deploying the new second-generation technology in different types of telecommunications networks. Chapter 14 covers optical time division multiplexed networks, which are today in the research labs but offer future potential for transmission at very high rates on each WDM channel.

The appendices cover some of the basics of stochastic processes and graph theory for readers as background material for the book. The large number of symbols and parameters used in Part I (Technology) is also summarized in an appendix.

Acknowledgments

First and foremost, we would like to thank Paul Green for introducing us to this field and being our mentor over the years, as well as for writing the foreword to this book. We would like to acknowledge, in particular, Rick Barry, Ori Gerstel, Ashish Vengsarkar, Weyl-Kuo Wang, and Chaoyu Yue for their detailed reviews and discussions of part or all of the material in the book. In addition, we would like to thank Venkat Anatharam, Dan Blumenthal, Kamal Goel, Karen Liu, Roger Merel, Rick Neuner, and Niall Robinson for their comments. We would also like to thank Rajesh M. Krishnaswamy for performing one of the simulations in Section 8.5, A. Selvarajan for answering some of our technology-related questions, and Chandrika Sridhar for helping with the preparation of the solutions manual.

We would also like to thank the folks at Morgan Kaufmann; in particular, our editor, Jennifer Mann, for guiding us through the entire process from start to finish and for her efforts to improve the quality of our book, and our production editor, Cheri Palmer, for orchestrating the production of the book.

Finally, we'd like to acknowledge the invaluable support given to us by our wives, Uma and Vinu, during this endeavor, and to Uma for drawing many of the figures in the book.

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