Multiwavelength Optical Networks

Architectures, Design, and Control

Second Edition

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CAMBRIDGE

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Multiwavelength Optical Networks, Second Edition

Updated and expanded, this second edition of the acclaimed *Multiwavelength Optical Networks* provides a detailed description of the structure and operation of modern optical networks. It also sets out the analytical tools for network performance evaluation and optimization for current and next generation networks, as well as the latest advances in enabling technologies.

Backbone optical networks are evolving to mesh topologies utilizing intelligent network elements; a new optical control plane is taking shape based on GMPLS; and significant advances have occurred in Fiber to the Home/Premises (the "last mile"), metropolitan area networks, protection and restoration, and IP over WDM. Each of these is treated in depth, together with new research on all-optical packet-switched networks, which combine the speed of optics with the versatility of packet switching. Also included are current trends and new applications on the commercial scene (wavelengths on demand, virtual private optical networks, and bandwidth trading).

With its unique blend of coverage of modern enabling technologies, network architectures, and analytical tools, the book is an invaluable resource for graduate and senior undergraduate students in electrical engineering, computer science, and applied physics, and for practitioners and researchers in the telecommunications industry.

Thomas E. Stern is Professor Emeritus of Electrical Engineering at Columbia University, New York, and has served as department chair and technical director of Columbia's Center for Telecommunications Research. A Fellow of the IEEE, he holds several patents in networking. He has also been a consultant to a number of companies, including IBM, Lucent, and Telcordia Technologies.

Georgios Ellinas is an Assistant Professor in the Department of Electrical and Computer Engineering at the University of Cyprus, Nicosia. He has held prior positions as an Associate Professor at City College of New York, as a Senior Network Architect at Tellium Inc., and as a Senior Research Scientist at Bell Communications Research. He has authored numerous papers and holds several patents in the field of optical networking.

Krishna Bala is currently the CEO of Xtellus, a company that manufactures fiber optical switches. Krishna was the co-founder and CTO of Tellium (NASDAQ: TELM), a successful optical networking company. Prior to that he was a Senior Research Scientist at Bell Communications Research. He holds a Ph.D. in electrical engineering from Columbia University.

To Monique, who has always been there for me. To our children and our grand-children (T.E.S.)

To my loving mother, Mary, and sister, Dorita, and the memory of my beloved father, Nicos (G.E.)

To my wife, Simrat, and our children, Tegh and Amrita (K.B.)

Preface to the Second Edition

The first edition of this book was published when optical networks were just emerging from the laboratory, mostly in the form of government-sponsored testbeds. Since then there have been fundamental changes in many aspects of optical networking, driven by the move from the laboratory to commercial deployment and by the twists and turns of the world economy. The investment climate in which optical networks have developed has had two major swings as of this writing. During the technology bubble that began at the end of the 20th century, investment in research, product development, and network deployment increased enormously. The activities during this time of euphoria produced advances in the technology base that would not have been possible without the extraordinary momentum of that period. At the same time, commercial network deployment provided a reality check. Some ideas that were pursued in the late 1990s dropped by the wayside because they did not meet the test of commercial viability, and new ones came along to take their place. When the bubble burst after less than a decade of "irrational exuberance," the pendulum swung the other way. Investors and executives who a short time earlier thought the sky was the limit now wondered if demand would ever materialize for all of the fiber capacity in the ground. At this writing a more reasoned approach has taken hold; that seemingly elusive demand has materialized and, hopefully, a more rational and sustainable growth period will ensue.

This is the context for the second edition. It is designed to build on the foundations laid out in the first edition while reflecting the new developments of the past 9 years: a maturing underlying technology, new tools for network control, and a recognition of the latest directions of optical network deployment and research. These new directions include cost-effective metropolitan area network architectures tailored to the strengths of current optical transmission and switching equipment, passive optical networks to bring high-speed access to the end user, hybrid optical/electronic architectures supporting the merging of multiwavelength and Internet technologies, and networks of the future based on all-optical packet switching.

As in the first edition, the emphasis of this book is on concepts and methodologies that will stand the test of time. The first three chapters provide a qualitative foundation for what follows, presenting an overview of optical networking (Chapter 1), the multiwavelength network architecture and its supporting components (Chapter 2), and a high-level view of the different network structures considered throughout the book (Chapter 3). A more detailed picture is provided in the remaining chapters, with a survey of enabling technology (Chapter 4) and in-depth studies of the three basic network structures: static multipoint networks (Chapter 5), wavelength/waveband routed networks (Chapter 6), and optical/electronic (logically routed) networks (Chapter 7). The remaining chapters complete the networking picture: survivability (Chapter 8), network control (Chapter 9), optical packet switching (Chapter 10), and current trends (Chapter 11).

The first three chapters are suitable for the reader who wishes to gain an understanding of multiwavelength networks without delving deeply into the analytical tools for network design and the physical underpinnings of the optical technology. These beginning chapters, together with Chapter 11, would be suitable for a short undergraduate course for electrical engineers and computer science majors.

The first seven chapters provide a largely generic framework for understanding network architectures, performance, and design in an abstract setting. An exception is Chapter 4, which surveys enabling technology from theory to practice, thereby providing the necessary background concerning the physical limitations and possibilities of the network technology. The material through Chapter 7, together with selected material from the remaining chapters (depending on the reader's orientation), can form the basis of a comprehensive graduate course, introducing the student to the latest developments in the field and suggesting a host of different research directions.

The networking developments since the publication of the first edition have served to reorient and expand our treatment in significant ways.

- Recognizing the importance of current activity in the "last mile" (fiber to the home/premises), and in metropolitan area networks, we have added a new section on passive optical networks (PONs) in Chapter 5,[1] and we have included new material in Chapters 4 and 11 to connect our generic networking approach to recent metro network developments.
- Chapter 4 was substantially expanded and updated to provide a glimpse of the impressive new trends in photonic and electro-optic technology. Some of the new and/or expanded topics are photonic crystal fibers, Raman amplification, supercontinuum generation, amplification trends in metro networks, and forward error correction and equalization to improve transmission performance. There are also new and expanded sections on wavelength conversion and signal regeneration with emphasis on all-optical techniques, and a new section on microelectromechanical system (MEMS) devices. The treatment of optical switch architectures has been significantly enlarged with a focus on cost-effective architectures and opacity versus transparency. More emphasis is placed on the effects of signal impairments, including a new section on performance impairments in a network environment. Also, new case studies are included that illustrate methodologies for evaluating the performance of metropolitan area networks.
- Chapter 8, on survivability, protection, and restoration, was extensively updated, consistent with the growing importance of optical layer fault management in current

[1] It is interesting to note that the PON, epitomized by the broadcast star, was the first structure that demonstrated the possibilities of optical networking in the 1980s. However, it was largely ignored for large-scale network deployment until recently, when it has again come into its own as the vehicle of choice for extending optical networks to the end user.

networks. It contains recent work on the subject, including shared line-based protection in mesh networks, path-based protection, ring-based protection, segment protection, the treatment of shared risk groups, and recovery of multicast connections.

- Chapter 9, describing the control plane, was added to present the latest developments in optical network control. It describes the control plane architecture as it has developed through the recent activities of several standards organizations. The chapter offers a detailed discussion of Multiprotocol Label-Switching (MPLS) and Generalized MPLS (GMPLS) as it applies to optical networks.
- Chapter 10, on optical packet-switched networks, was added to provide an introduction to this emergent field.[2] It provides a window on a cutting-edge research area that has the potential to offer the next breakthroughs in optical networking.
- Chapter 11, on current networking trends (replacing the original Chapter 9), is a completely updated description of the current networking environment. This includes a historical perspective describing the pioneering network testbeds, business drivers, and current trends in metro, long-haul, and ultra long-haul netwoks. Included also are some new applications that have emerged on the commercial scene, such as wavelengths on demand, virtual private optical networks, and bandwidth trading.
- This edition places increased emphasis on the practical aspects of hybrid (i.e., electronic/optical and wavelength/waveband) architectures. This includes the importance of grooming, which is required to pack electronically multiplexed channels efficiently into an optical wavelength channel, and to pack wavelength channels into wavebands. Also, the existence of transparent (purely optical) and opaque (electronic/optical) alternatives to network design is stressed throughout. These practical aspects of networking have become important as optical networks have found their place in the real world.

Exercises are provided for most of the chapters, and many of them suggest avenues for future study. The book is meant to offer several different alternatives for study depending on the interest of the reader, be it understanding the current state of the field; acquiring the analytical tools for network performance evaluation, optimization, and design; or performing research on next-generation networks.

[2] Although the idea of using packet switching in optical networks is not new, it has attracted renewed interest as the technology for purely optical packet processing has developed over the past few years, and the advantages of merging Internet and WDM technology have become apparent.

Acknowledgments

The first edition of this book had its origins in 1990, when we organized a small group within the Center for Telecommunications Research (CTR) at Columbia University, to investigate lightwave networks. Among the many colleagues, students, and friends who contributed in various ways to the first edition, there are several who have continued to interact with us in the preparation of the second edition. We specifically express our thanks to Eric Bouillet, Aklilu Hailemariam, Gang Liu, and G.-K. Chang. Special thanks go to Ioannis Roudas for useful discussions and comments. Mischa Schwartz, who was singled out as our guiding spirit in the first edition, is still an indefatigable contributor to communication networking and a continuing inspiration to us.

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