

Texts in Theoretical Computer Science

An EATCS Series

Editors: W. Brauer J. Hromkovič G. Rozenberg A. Salomaa

On behalf of the European Association
for Theoretical Computer Science (EATCS)

Advisory Board:

G. Ausiello M. Broy C.S. Calude A. Condon
D. Harel J. Hartmanis T. Henzinger T. Leighton
M. Nivat C. Papadimitriou D. Scott

Subir Bandyopadhyay

Dissemination of Information in Optical Networks

From Technology to Algorithms

In Cooperation with Ralf Klasing

With 95 Figures and 4 Tables



Springer

Author

Subir Bandyopadhyay
School of Computer Science
University of Windsor
401 Sunset Avenue
Windsor
Ontario N9B 3P4, Canada
subir@uwindsor.ca

Series Editors

Prof. Dr. Wilfried Brauer
Institut für Informatik der TUM
Boltzmannstr. 3
85748 Garching, Germany
brauer@informatik.tu-muenchen.de

Prof. Dr. Juraj Hromkovič
ETH Zentrum
Department of Computer Science
Swiss Federal Institute of Technology
8092 Zürich, Switzerland
juraj.hromkovic@inf.ethz.ch

Prof. Dr. Grzegorz Rozenberg
Leiden Institute of Advanced
Computer Science
University of Leiden
Niels Bohrweg 1
2333 CA Leiden, The Netherlands
rozenber@liacs.nl

Prof. Dr. Arto Salomaa
Turku Centre of
Computer Science
Lemminkäisenkatu 14 A
20520 Turku, Finland
asalomaa@utu.fi

ISBN: 978-3-540-72874-0

e-ISBN: 978-3-540-72875-7

Texts in Theoretical Computer Science. An EATCS Series. ISSN 1862-4499

Library of Congress Control Number: 2007937258

ACM Computing Classification (2008): B.4, C.2, F.2, G.2

© 2008 Springer-Verlag Berlin Heidelberg

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable for prosecution under the German Copyright Law.

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Cover Design: KünkelLopka GmbH Heidelberg

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

This book is dedicated to the memory of my parents Sushobhan
and Nandini and my grandparents Krishnadhan, Dhirabati,
Atulyadhan, Nirabati, Sudhansu, and Usha.

Preface

For the last twenty years, communication between computers has been one of the most important and all-pervasive features of the computer revolution. Early computer networks used copper wires as the physical medium for communication. Important limitations of copper as a medium include its relatively high attenuation, susceptibility to malicious attacks, and electromagnetic interference. The tremendous growth of the Internet and the World Wide Web has made high-bandwidth computer communication a crucial and strategic infrastructure. Deregulation of the telephone industry and the dramatic increase of data, as opposed to voice, traffic over communication networks have also spurred the deployment of high-speed networks. The rapid growth of optical networks is primarily due to the inherent high speed and the reliability of optical communication. First-generation optical networks simply replaced copper wires by optical cables, to take advantage of the higher bandwidth of optical communication, with switching and other network operations handled, as before, by electronics. The speed of electronic processing is the bottleneck for such networks. In second-generation optical networks, the routing, switching, and many other network operations are done at the optical level. Second-generation optical networks are being increasingly deployed to meet the ever increasing demand for high speed backbone networks.

This book is the second in a series of books on communication networks. The first book, entitled “Dissemination of Information in Communication Network”, by Juraĳ Hromkoviĉ, Ralf Klasing, Andrzej Pelc, Peter Ruĳiĉka, and Walter Unger, dealt with classical direct communication between connected pairs of nodes of a communication network. This book primarily deals with second-generation optical networks and is intended to be a textbook for graduate students, as well as a monograph, surveying the main areas of research in second-generation optical networks. Every effort has been made to create a self-contained book that stresses the fundamentals, in depth and in detail. In particular, the mathematical programs, often used in optimizing optical networks, have been explained carefully so that the readers can feel confident in developing similar formulations. Interesting problems have been posed as

exercises. Appendices on topics such as linear programming and network flow programming have been included to help readers unfamiliar with these areas. Students will find it convenient to test their understanding of the subject by solving problems given in each chapter. The bibliographic notes section in each chapter gives a comprehensive review of work in the area. Students interested in pursuing further studies in a subtopic should find the bibliographic notes helpful in narrowing down their literature search.

Professor Dr. Juraj Hromkovič, ETH, Zurich, invited me to write this book. I would like to take this opportunity to thank him for his unstinting help and generous advice throughout this period. I also very much enjoyed the warm hospitality I enjoyed during my trips to Zurich. Dr. Ralf Klasing, CNRS, LaBRI, Université Bordeaux, wrote most of Chapter 4. He took enormous pains to proofread the book several times and made many significant improvements to it. I am most grateful to him for his advice, and have learned a lot from his meticulous approach to this project. Drs. Arunita Jaekel and Yash Aneja of the University of Windsor read the book carefully and made numerous useful suggestions for improvements. Dr Jaekel was also very helpful in finalizing the bibliographic notes sections in different chapters. The help I received from my graduate students was very useful. In particular, I would like to mention Ataul Bari, Abul Kalam, Vic Ho, Quazi Rahman, A. K. M. Aktaruzzaman, and Delwar Faruque for their help and suggestions.

This book would not have been possible without the constant support, patience, encouragement and understanding of my family members Bharati, Avik, Anjali, Rupa, Prasenjit, and Nayan.

Windsor, Canada
July 2007

Subir Bandyopadhyay

Contents

1	Introduction to Optical Networks	1
1.1	What Is an Optical Network	1
1.1.1	Important Advantages of WDM Optical Networks	2
1.1.2	Key Terminology in WDM Optical Networks	2
1.1.3	Data Communication in a WDM Optical Network	5
1.2	Categorizations of WDM Networks	7
1.2.1	Broadcasting Networks and Wavelength-Routed Networks	7
1.2.2	Static and Dynamic Lightpath Allocation	8
1.2.3	Single-hop and Multi-hop WDM Networks	9
1.3	Important Problems in WDM Networks and Solution Approaches	9
1.4	A Typical Problem in Multi-hop Wavelength-Routed Network Design	10
1.5	Structure of the Book	13
2	Introduction to Optical Technology	15
2.1	Optical Fiber	15
2.2	Optical Communication Fundamentals	17
2.3	Optical Devices	20
2.3.1	Optical Transmitters, Modulators, and Receivers	20
2.3.2	Optical Couplers	21
2.3.3	Optical Filters and Switches	23
2.3.4	Multiplexers, Demultiplexers, and Cross-connect Switches	24
2.3.5	Add-Drop Multiplexers and Optical Line Terminals	27
2.3.6	Wavelength Converters	29
2.4	Bibliographic Notes	33

3	WDM Network Design	35
3.1	Broadcast-and-Select Networks	35
3.2	Wavelength-Routed Networks	38
3.2.1	Advantages of Second-Generation WDM Networks	42
3.2.2	Single-hop and Multi-hop Networks	45
3.3	Route and Wavelength Assignment Problem in WDM Networks	46
3.3.1	Static and Dynamic Lightpath Allocation	46
3.4	Wavelength-Convertible Networks	48
3.5	Bibliographic Notes	56
3.5.1	Wavelength-Convertible Networks	57
3.5.2	Light-Trail Networks	58
3.5.3	Burst Switching Networks	58
3.5.4	Multicasting Networks	59
4	Route and Wavelength Assignment (RWA) I	63
4.1	RWA as a Graph Coloring Problem	63
4.2	Congestion and Its Relationship to Chromatic Number	67
4.3	Greedy Heuristics for the RWA Problem	68
4.3.1	A Greedy Heuristic for the RWA Problem	68
4.3.2	An Improved Greedy Heuristic for the RWA Problem	70
4.4	Specific Networks	71
4.4.1	The Bidirectional Path	71
4.4.2	The Bidirectional Ring	73
4.4.3	Trees	76
4.5	Specific Instances	78
4.5.1	One-to-All Communication	78
4.5.2	All-to-All Communication	80
4.6	Bibliographic Notes	80
4.6.1	One-to-Many and All-to-All Communication	81
4.6.2	Permutations	82
4.6.3	Miscellaneous	83
5	Route and Wavelength Assignment (RWA) II	87
5.1	Off-line Route and Wavelength Assignment	88
5.1.1	Exact Solution of the RWA Problem in Networks with Full Wavelength Converters	88
5.1.2	Exact Solution of the RWA Problem in Networks Without Wavelength Converters	92
5.2	Route and Wavelength Assignment in a Bidirectional Ring	95
5.3	A Heuristic for Route and Wavelength Assignment	98
5.4	Dynamic Route and Wavelength Assignment	101
5.4.1	Dynamic Routing Using a Central Agent	104
5.4.2	Dynamic Routing Using a Distributed Algorithm	107
5.5	Bibliographic Notes	115
5.5.1	Sparse Wavelength Conversion and RWA	117
5.5.2	Limited Wavelength Conversion and RWA	118

5.5.3	Placement of Wavelength Converters	119
5.5.4	Multi-fiber Networks	120
6	Logical Topology Design I	123
6.1	A Scalable Topology Based on the de Bruijn Graph	125
6.1.1	The Topology of the Network	127
6.2	Addition of an End node to an Existing Network	129
6.3	A Routing Scheme for This Topology	131
6.4	Bibliographic Notes	134
7	Logical Topology Design II	137
7.1	MILP-Based Solution of the Logical Topology Design and the Routing Problem	139
7.2	A Heuristic for Determining the Logical Topology	143
7.3	Routing in Wavelength-Routed Networks Viewed as an MCNF Problem	146
7.4	Routing in Small- and Medium-Sized Networks	147
7.5	Routing in Large Networks	149
7.5.1	The Arc-Chain Representation	150
7.5.2	An LP for the Routing Problem Using the Arc-Chain Representation	151
7.5.3	Solving the LP Specified Using the Arc-Chain Representation	154
7.6	Bibliographic Notes	162
8	Faults in Optical Networks	165
8.1	Categorization of Faults	169
8.2	Important Problems in Protection and Restoration	173
8.3	Schemes for Handling Faults	176
8.3.1	1:1 Path Protection in Wavelength-Convertible Networks Using Static Allocation	177
8.3.2	Dynamic Wavelength Allocation with Wavelength Continuity Constraint	179
8.3.3	Utilizing the Channels Used by Backup Paths When There Is No Fault in the Network	185
8.3.4	1:N Protection Using Static Allocation with Wavelength Continuity Constraint	188
8.3.5	Restoration in Networks That Support Dynamic Lightpath Allocation	199
8.4	Bibliographic Notes	202
8.4.1	Review Papers on Fault	202
8.4.2	Link and Path Protection Schemes	203
8.4.3	Schemes for Restoration	205
8.4.4	Attacks on All-Optical Networks	206
8.4.5	Reducing the Overhead for Fault Tolerance	206

8.4.6	Handling Multiple Faults	208
8.4.7	Survivable Routing	210
8.4.8	Miscellaneous Topics	210
9	Traffic Grooming	213
9.1	Static Traffic Grooming	219
9.1.1	Problem 1	219
9.1.2	Problem 2	223
9.1.3	A Heuristic for Static Traffic Grooming	227
9.2	Dynamic Traffic Grooming	229
9.2.1	A Graph Model for a Network Supporting Dynamic Traffic Grooming	230
9.2.2	Algorithms for Supporting Dynamic Traffic Grooming	235
9.3	Bibliographic Notes	237
9.3.1	Books and Surveys on Traffic Grooming	237
9.3.2	Traffic Grooming on Rings	238
9.3.3	Traffic Grooming Strategies	238
9.3.4	Fault-Tolerant Traffic Grooming	241
Appendix 1: Linear Programming in a Nutshell		245
Appendix 2: The de Bruijn Graph		249
Appendix 3: Network Flow Programming		253
References		261
List of Symbols Used		289
Index		301