

# **Principles of Broadband Switching and Networking**

Tony T. Lee and Soung C. Liew



A JOHN WILEY & SONS, INC., PUBLICATION



# **Principles of Broadband Switching and Networking**

# WILEY SERIES IN TELECOMMUNICATIONS AND SIGNAL PROCESSING

John G. Proakis, Editor  
*Northeastern University*

A complete list of the titles in this series appears at the end of this volume.

# **Principles of Broadband Switching and Networking**

Tony T. Lee and Soung C. Liew



A JOHN WILEY & SONS, INC., PUBLICATION

Copyright © 2010 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey  
Published simultaneously in Canada

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978)-750-4470, or on the web at [www.copyright.com](http://www.copyright.com). Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permissions>.

**Limit of Liability/Disclaimer of Warranty:** While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books. For more information about Wiley products, visit our web site at [www.wiley.com](http://www.wiley.com)

ISBN: 978-0-471-13901-0

***Library of Congress Cataloging-in-Publication Data is available.***

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

*Dedicated to Professor Charles K. Kao for his guidance,  
and to our wives, Alice and So Kuen, for their unwavering support.*



---

# CONTENTS

|                                                              |             |
|--------------------------------------------------------------|-------------|
| <b>Preface</b>                                               | <b>xiii</b> |
| <b>About the Authors</b>                                     | <b>xvii</b> |
| <b>1 Introduction and Overview</b>                           | <b>1</b>    |
| 1.1 Switching and Transmission                               | 2           |
| 1.1.1 Roles of Switching and Transmission                    | 2           |
| 1.1.2 Telephone Network Switching and Transmission Hierarchy | 4           |
| 1.2 Multiplexing and Concentration                           | 5           |
| 1.3 Timescales of Information Transfer                       | 8           |
| 1.3.1 Sessions and Circuits                                  | 9           |
| 1.3.2 Messages                                               | 9           |
| 1.3.3 Packets and Cells                                      | 9           |
| 1.4 Broadband Integrated Services Network                    | 10          |
| Problems                                                     | 12          |
| <b>2 Circuit Switch Design Principles</b>                    | <b>15</b>   |
| 2.1 Space-Domain Circuit Switching                           | 16          |
| 2.1.1 Nonblocking Properties                                 | 16          |
| 2.1.2 Complexity of Nonblocking Switches                     | 18          |
| 2.1.3 Clos Switching Network                                 | 20          |
| 2.1.4 Benes Switching Network                                | 28          |
| 2.1.5 Baseline and Reverse Baseline Networks                 | 31          |
| 2.1.6 Cantor Switching Network                               | 32          |
| 2.2 Time-Domain and Time–Space–Time Circuit Switching        | 35          |
| 2.2.1 Time-Domain Switching                                  | 35          |
| 2.2.2 Time–Space–Time Switching                              | 37          |
| Problems                                                     | 39          |

|          |                                                            |            |
|----------|------------------------------------------------------------|------------|
| <b>3</b> | <b>Fundamental Principles of Packet Switch Design</b>      | <b>43</b>  |
| 3.1      | Packet Contention in Switches                              | 45         |
| 3.2      | Fundamental Properties of Interconnection Networks         | 48         |
| 3.2.1    | Definition of Banyan Networks                              | 49         |
| 3.2.2    | Simple Switches Based on Banyan Networks                   | 51         |
| 3.2.3    | Combinatoric Properties of Banyan Networks                 | 54         |
| 3.2.4    | Nonblocking Conditions for the Banyan Network              | 54         |
| 3.3      | Sorting Networks                                           | 59         |
| 3.3.1    | Basic Concepts of Comparison Networks                      | 61         |
| 3.3.2    | Sorting Networks Based on Bitonic Sort                     | 64         |
| 3.3.3    | The Odd–Even Sorting Network                               | 70         |
| 3.3.4    | Switching and Contention Resolution in Sort-Banyan Network | 71         |
| 3.4      | Nonblocking and Self-Routing Properties of Clos Networks   | 75         |
| 3.4.1    | Nonblocking Route Assignment                               | 76         |
| 3.4.2    | Recursiveness Property                                     | 79         |
| 3.4.3    | Basic Properties of Half-Clos Networks                     | 81         |
| 3.4.4    | Sort-Clos Principle                                        | 89         |
|          | Problems                                                   | 90         |
| <b>4</b> | <b>Switch Performance Analysis and Design Improvements</b> | <b>95</b>  |
| 4.1      | Performance of Simple Switch Designs                       | 95         |
| 4.1.1    | Throughput of an Internally Nonblocking Loss System        | 96         |
| 4.1.2    | Throughput of an Input-Buffered Switch                     | 96         |
| 4.1.3    | Delay of an Input-Buffered Switch                          | 103        |
| 4.1.4    | Delay of an Output-Buffered Switch                         | 112        |
| 4.2      | Design Improvements for Input Queueing Switches            | 113        |
| 4.2.1    | Look-Ahead Contention Resolution                           | 113        |
| 4.2.2    | Parallel Iterative Matching                                | 115        |
| 4.3      | Design Improvements Based on Output Capacity Expansion     | 119        |
| 4.3.1    | Speedup Principle                                          | 119        |
| 4.3.2    | Channel-Grouping Principle                                 | 121        |
| 4.3.3    | Knockout Principle                                         | 131        |
| 4.3.4    | Replication Principle                                      | 137        |
| 4.3.5    | Dilation Principle                                         | 138        |
|          | Problems                                                   | 144        |
| <b>5</b> | <b>Advanced Switch Design Principles</b>                   | <b>151</b> |
| 5.1      | Switch Design Principles Based on Deflection Routing       | 151        |
| 5.1.1    | Tandem-Banyan Network                                      | 151        |
| 5.1.2    | Shuffle-Exchange Network                                   | 154        |

|          |                                                                               |            |
|----------|-------------------------------------------------------------------------------|------------|
| 5.1.3    | Feedback Shuffle-Exchange Network                                             | 158        |
| 5.1.4    | Feedback Bidirectional Shuffle-Exchange Network                               | 166        |
| 5.1.5    | Dual Shuffle-Exchange Network                                                 | 175        |
| 5.2      | Switching by Memory I/O                                                       | 184        |
| 5.3      | Design Principles for Scalable Switches                                       | 187        |
| 5.3.1    | Generalized Knockout Principle                                                | 187        |
| 5.3.2    | Modular Architecture                                                          | 191        |
|          | Problems                                                                      | 198        |
| <b>6</b> | <b>Switching Principles for Multicast, Multirate, and Multimedia Services</b> | <b>205</b> |
| 6.1      | Multicast Switching                                                           | 205        |
| 6.1.1    | Multicasting Based on Nonblocking Copy Networks                               | 208        |
| 6.1.2    | Performance Improvement of Copy Networks                                      | 213        |
| 6.1.3    | Multicasting Algorithm for Arbitrary Network Topologies                       | 220        |
| 6.1.4    | Nonblocking Copy Networks Based on Broadcast Clos Networks                    | 228        |
| 6.2      | Path Switching                                                                | 235        |
| 6.2.1    | Basic Concept of Path Switching                                               | 237        |
| 6.2.2    | Capacity and Route Assignments for Multirate Traffic                          | 242        |
| 6.2.3    | Trade-Off Between Performance and Complexity                                  | 249        |
| 6.2.4    | Multicasting in Path Switching                                                | 254        |
| 6.A      | Appendix                                                                      | 268        |
| 6.A.1    | A Formulation of Effective Bandwidth                                          | 268        |
| 6.A.2    | Approximations of Effective Bandwidth Based on On-Off Source Model            | 269        |
|          | Problems                                                                      | 270        |
| <b>7</b> | <b>Basic Concepts of Broadband Communication Networks</b>                     | <b>275</b> |
| 7.1      | Synchronous Transfer Mode                                                     | 275        |
| 7.2      | Delays in ATM Network                                                         | 280        |
| 7.3      | Cell Size Consideration                                                       | 283        |
| 7.4      | Cell Networking, Virtual Channels, and Virtual Paths                          | 285        |
| 7.4.1    | No Data Link Layer                                                            | 285        |
| 7.4.2    | Cell Sequence Preservation                                                    | 286        |
| 7.4.3    | Virtual-Circuit Hop-by-Hop Routing                                            | 286        |
| 7.4.4    | Virtual Channels and Virtual Paths                                            | 287        |
| 7.4.5    | Routing Using VCI and VPI                                                     | 289        |
| 7.4.6    | Motivations for VP/VC Two-Tier Hierarchy                                      | 293        |

|              |                                                                           |            |
|--------------|---------------------------------------------------------------------------|------------|
| 7.5          | ATM Layer, Adaptation Layer, and Service Class                            | 295        |
| 7.6          | Transmission Interface                                                    | 300        |
| 7.7          | Approaches Toward IP over ATM                                             | 300        |
| 7.7.1        | Classical IP over ATM                                                     | 301        |
| 7.7.2        | Next Hop Resolution Protocol                                              | 302        |
| 7.7.3        | IP Switch and Cell Switch Router                                          | 303        |
| 7.7.4        | ARIS and Tag Switching                                                    | 306        |
| 7.7.5        | Multiprotocol Label Switching                                             | 308        |
| Appendix 7.A | ATM Cell Format                                                           | 311        |
| 7.A.1        | ATM Layer                                                                 | 311        |
| 7.A.2        | Adaptation Layer                                                          | 314        |
|              | Problems                                                                  | 319        |
| <b>8</b>     | <b>Network Traffic Control and Bandwidth Allocation</b>                   | <b>323</b> |
| 8.1          | Fluid-Flow Model: Deterministic Discussion                                | 326        |
| 8.2          | Fluid-Flow On–Off Source Model: Stochastic Treatment                      | 332        |
| 8.3          | Traffic Shaping and Policing                                              | 348        |
| 8.4          | Open-Loop Flow Control and Scheduling                                     | 354        |
| 8.4.1        | First-Come-First-Serve Scheduling                                         | 355        |
| 8.4.2        | Fixed-Capacity Assignment                                                 | 357        |
| 8.4.3        | Round-Robin Scheduling                                                    | 358        |
| 8.4.4        | Weighted Fair Queueing                                                    | 364        |
| 8.4.5        | Delay Bound in Weighted Fair Queueing with Leaky-Bucket<br>Access Control | 373        |
| 8.5          | Closed-Loop Flow Control                                                  | 380        |
|              | Problems                                                                  | 381        |
| <b>9</b>     | <b>Packet Switching and Information Transmission</b>                      | <b>385</b> |
| 9.1          | Duality of Switching and Transmission                                     | 386        |
| 9.2          | Parallel Characteristics of Contention and Noise                          | 390        |
| 9.2.1        | Pseudo Signal-to-Noise Ratio of Packet Switch                             | 390        |
| 9.2.2        | Clos Network with Random Routing as a Noisy Channel                       | 393        |
| 9.3          | Clos Network with Deflection Routing                                      | 396        |
| 9.3.1        | Cascaded Clos Network                                                     | 397        |
| 9.3.2        | Analysis of Deflection Clos Network                                       | 397        |
| 9.4          | Route Assignments and Error-Correcting Codes                              | 402        |
| 9.4.1        | Complete Matching in Bipartite Graphs                                     | 402        |
| 9.4.2        | Graphical Codes                                                           | 405        |
| 9.4.3        | Route Assignments of Benes Network                                        | 407        |

|                     |                                                  |            |
|---------------------|--------------------------------------------------|------------|
| 9.5                 | Clos Network as Noiseless Channel-Path Switching | 410        |
| 9.5.1               | Capacity Allocation                              | 411        |
| 9.5.2               | Capacity Matrix Decomposition                    | 414        |
| 9.6                 | Scheduling and Source Coding                     | 416        |
| 9.6.1               | Smoothness of Scheduling                         | 417        |
| 9.6.2               | Comparison of Scheduling Algorithms              | 420        |
| 9.6.3               | Two-Dimensional Scheduling                       | 424        |
| 9.7                 | Conclusion                                       | 430        |
| <b>Bibliography</b> |                                                  | <b>433</b> |



---

# PREFACE

The past few decades have seen the merging of many computer and communication applications. Enabled by the advancement of optical fiber, wireless communication, and very-large-scale integration (VLSI) technologies, modern telecommunication networks can be regarded as one of the most important inventions of the past century.

Before the emergence of Broadband Integrated Services Digital Network (B-ISDN), several separate communication networks already existed. They include the telephone network for voice communication, the computer network for data communication, and the television network for TV program broadcasting. These networks are designed with a specific application in mind and are typically not well suited for other applications. For example, the conventional telephone network cannot carry high-speed multimedia services, which require diverse quality-of-service (QoS) guarantees to support multirate and multicast connections. In addition, these heterogeneous networks often require expensive gateways equipped with different access interfaces running different protocols.

Meanwhile, the appeal of interactive video communication is on the rise in a society that is increasingly information-oriented. Images and facial expressions are more vivid and informative than text and audio for many types of human interactions. For example, video conferencing has made distant learning, medicine, and surgery possible, while 3D Internet games give rise to real-time interactions between remote players. All these applications are based on high-resolution video with large bandwidth demands. These developments led to the emergence of B-ISDN—the concept of an integrated network to support communication services of all kinds to achieve the most cost-effective sharing of resources was conceived in the late 1980s.

This book focuses on the design and analysis of switch architectures that are suitable for broadband integrated networks. In particular, the emphasis is on packet-switched interconnection networks with distributed routing algorithms. The focus is on the mathematical properties of these networks rather than specific implementation technologies. As such, although the pedagogical explanations in this book are in the context of switches, many of the fundamental principles are relevant to other communication networks with regular topologies. For example, the terminals in a multi-hop ad hoc wireless network could conceivably be interconnected together to form a logical topology that is regular. This could be enabled by the use of directional