

THE COMPETITIVE INTERNET SERVICE PROVIDER

WILEY SERIES IN COMMUNICATIONS NETWORKING & DISTRIBUTED SYSTEMS.

Series Editor: David Hutchison, *Lancaster University*
Series Advisers: Harmen van As, *TU Vienna*
Serge Fdida, *University of Paris*
Joe Sventek, *Agilent Laboratories, Edinburgh*

The 'Wiley Series in Communications Networking & Distributed Systems' is a series of expert-level, technically detailed books covering cutting-edge research and brand new developments in networking, middleware and software technologies for communications and distributed systems. The books will provide timely, accurate and reliable information about the state-of-the-art to researchers and development engineers in the Telecommunications and Computing sectors.

Other titles in the series:

Wright: *Voice over Packet Networks* 0-471-49516-6 (February 2001)
Jepsen: *Java for Telecommunications* 0-471-49826-2 (July 2001)
Sutton: *Secure Communications* 0-471-49904-8 (December 2001)
Stajano: *Security for Ubiquitous Computing* 0-470-84493-0 (February 2002)
Martin-Flatin: *Web-Based Management of IP Networks and Systems*, 0-471-48702-3 (September 2002)
Berman, Fox, Hey: *Grid Computing. Making the Global Infrastructure a Reality*, 0-470-85319-0 (March 2003)
Turner, Magill, Marples: *Service Provision. Technologies for Next Generation Communications* 0-470-85066-3 (April 2004)
Welzl: *Network Congestion Control: Managing Internet Traffic* 0-470-02528-X (July 2005)

THE COMPETITIVE INTERNET SERVICE PROVIDER

NETWORK ARCHITECTURE,
INTERCONNECTION, TRAFFIC
ENGINEERING AND NETWORK
DESIGN

Oliver Heckmann

Technical University Darmstadt, Germany



John Wiley & Sons, Ltd

Copyright © 2006

John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester,
West Sussex PO19 8SQ, England

Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk

Visit our Home Page on www.wiley.com

All Rights Reserved. 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 under the terms of the Copyright, Designs and Patents Act 1988 or under the terms of a licence issued by the Copyright Licensing Agency Ltd, 90 Tottenham Court Road, London W1T 4LP, UK, without the permission in writing of the Publisher. Requests to the Publisher should be addressed to the Permissions Department, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester, West Sussex PO19 8SQ, England, or emailed to permreq@wiley.co.uk, or faxed to (+44) 1243 770620.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered. It is sold on the understanding that the Publisher is not engaged in rendering professional services. If professional advice or other expert assistance is required, the services of a competent professional should be sought.

Other Wiley Editorial Offices

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 42 McDougall Street, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 22 Worcester Road, Etobicoke, Ontario, Canada M9W 1L1

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Library of Congress Cataloging-in-Publication Data

Heckmann, Oliver, 1974-

The competitive Internet service provider : network architecture,
interconnection, traffic engineering, and network design / Oliver Heckmann.

p. cm.—(Wiley series in communications networking & distributed
systems)

Includes bibliographical references and index.

ISBN-13: 978-0-470-01293-2 (cloth : alk. paper)

ISBN-10: 0-470-01293-5 (cloth : alk. paper)

1. Computer networks—Design and construction. 2. Internet. 3. Internet
service providers. I. Title. II. Series.

TK5105.5.H4245 2006

004.67'8—dc22

2006000988

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN-13: 978-0-470-01293-2

ISBN-10: 0-470-01293-5

Typeset in 10/12 Times by Laserwords Private Limited, Chennai, India

Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire

This book is printed on acid-free paper responsibly manufactured from sustainable forestry
in which at least two trees are planted for each one used for paper production.

Acknowledgements

Writing a book is never an easy task and always involves more people than just the author. Therefore, I would like to thank a number of people who helped me in finishing this project.

Most importantly, I would like to thank Bibiana for her invaluable help and patience. I also want to thank Angelika, Klaus, Berit and the rest of my family for their support.

Large parts of this book are based on my PhD thesis at the Technische Universität Darmstadt, Germany. Therefore, special thanks go to Prof. Jens Schmitt, TU Kaiserslautern, from whom I learned so much. I would also like to thank my PhD supervisors Prof. Ralf Steinmetz from TU Darmstadt and Prof. Jon Crowcroft from the University of Cambridge. I also want to acknowledge the help and inspiration of my (ex-)colleagues, especially Nicolas Liebau, Vasilios Darlagiannis, Andreas Mauthe, Martin Karsten, Rainer Berbner, Ivica Rimac, Matthias Hollick, Michael Zink and Utz Roedig. I would like to also thank my students, especially Ian, Martin, Enis, Nikola and Axel.

I am grateful to John Souter, CEO of LINX (London Internet Exchange); Eike Jessen, director of DFN e.V. (German research network); Arnold Nipper, chief technical officer of DE-CIX; Gerhard Hasslinger from T-Systems (Deutsche Telekom); Raza Rizvi, technical manager of the UK ISP REDNET (www.red.net); Frank Kelly, Richard Gibbens, Damon Wischik and Gaurav Raina – all from the Cambridge University – for their valuable input and fruitful discussions.

Last but not the least, I would also like to thank open source software and the open source community.

Contents

Foreword	xiii
List of Figures	xv
List of Tables	xix
List of Abbreviations	xxi
Part I Introduction and Basics	1
1 Introduction	3
1.1 Motivation	3
1.2 Efficiency and Quality of Service	4
1.2.1 Network Efficiency	4
1.2.2 Network Quality of Service	5
1.2.3 Trade-off between Efficiency and Quality of Service	5
1.3 Action Space and Approach	6
1.4 Overview	8
2 Internet Service Providers	11
2.1 A Classification Model for ISPs	13
2.1.1 Definition of Internet Service Providers	13
2.1.2 Internet Service Provider Roles	14
2.1.3 Support Provider Roles	20
2.1.4 End-users	23
2.2 Classification of Selected Providers	23
2.3 Summary and Conclusions	27
3 Performance Analysis Basics	29
3.1 Queuing Theory	29
3.1.1 Introduction	29
3.1.2 Kendall's Notation	30
3.1.3 Little's Law	31
3.1.4 M/M/1 Queueing Systems	32
3.1.5 M/M/1/B Queueing Systems	33
3.1.6 M/G/1 Queueing Systems	34
3.1.7 Other Queueing Systems	35
3.1.8 Queueing Networks	36
3.1.9 Conclusions	36

3.2	Network Calculus	36
	3.2.1 <i>Basics</i>	37
	3.2.2 <i>Example</i>	38
	3.2.3 <i>Conclusions</i>	39
	3.2.4 <i>Outlook</i>	39
3.3	Optimisation Techniques	40
	3.3.1 <i>Introduction</i>	40
	3.3.2 <i>Modelling Optimisation Problems</i>	40
	3.3.3 <i>Solving Optimisation Problems</i>	42
3.4	Summary and Conclusions	45
4	Internet Protocols	47
4.1	The Internet Protocol Stack	47
	4.1.1 <i>IP</i>	48
	4.1.2 <i>UDP</i>	50
	4.1.3 <i>TCP</i>	51
	4.1.4 <i>Lower Layer Protocols</i>	59
4.2	Summary and Conclusions	63
5	Applications	65
5.1	World Wide Web	65
	5.1.1 <i>QoS Requirements</i>	66
	5.1.2 <i>Traffic Model</i>	66
5.2	Peer-to-Peer Applications	69
	5.2.1 <i>QoS Requirements</i>	69
	5.2.2 <i>Traffic Model</i>	69
	5.2.3 <i>The Future of P2P</i>	70
5.3	Online Games	71
	5.3.1 <i>Computer Game Market</i>	71
	5.3.2 <i>Classification of Computer Games</i>	71
	5.3.3 <i>Online Game Architectures</i>	71
	5.3.4 <i>QoS Requirements</i>	73
	5.3.5 <i>Traffic Model</i>	73
5.4	Voice over IP	73
	5.4.1 <i>QoS Requirements</i>	73
	5.4.2 <i>Traffic Model</i>	74
5.5	Traffic Classification	76
	5.5.1 <i>Port-based Traffic Classification</i>	76
	5.5.2 <i>Advanced Mechanisms</i>	76
5.6	Summary and Conclusions	77
Part II	Network Architecture	79
6	Network Architecture Overview	81
6.1	Introduction	81
6.2	Quality of Service Architectures	82
	6.2.1 <i>Components of a Quality of Service System</i>	83
	6.2.2 <i>The Integrated Services Architecture</i>	86
	6.2.3 <i>Stateless Core Architectures</i>	93

6.2.4	<i>The Diffserv Architecture</i>	95
6.2.5	<i>Tuned Best-effort Architectures</i>	103
6.2.6	<i>Other Architectures</i>	109
6.2.7	<i>Classification of Quality of Service Architectures</i>	110
6.3	Data Forwarding Architecture	113
6.3.1	<i>IP Routing</i>	114
6.3.2	<i>Label Switching</i>	116
6.4	Signalling Architecture	118
6.4.1	<i>Routing Protocols</i>	118
6.4.2	<i>Quality of Service Signalling Protocols</i>	119
6.4.3	<i>Label Distribution Protocols</i>	120
6.5	Security Architecture	121
6.6	Admission Control	122
6.6.1	<i>Location</i>	124
6.6.2	<i>Flow and Network Behaviour</i>	127
6.6.3	<i>Guarantees</i>	129
6.6.4	<i>Other Properties</i>	130
6.7	Summary and Conclusions	132
7	Analytical Comparison of Quality of Service Systems	133
7.1	On the Benefit of Admission Control	134
7.1.1	<i>Fixed Load</i>	135
7.1.2	<i>Variable Load</i>	136
7.1.3	<i>Variable Capacity</i>	140
7.1.4	<i>Summary and Conclusions</i>	141
7.2	On the Benefit of Service Differentiation	143
7.2.1	<i>Traffic Types</i>	143
7.2.2	<i>Best-Effort Network Model</i>	144
7.2.3	<i>QoS Network Model</i>	145
7.2.4	<i>Utility Functions</i>	148
7.2.5	<i>Evaluation</i>	150
7.2.6	<i>Summary and Conclusions</i>	156
8	Experimental Comparison of Quality of Service Systems	159
8.1	QoS Systems	162
8.1.1	<i>Intserv/RSVP QoS Systems</i>	162
8.1.2	<i>Standard Diffserv QoS Systems</i>	164
8.1.3	<i>Olympic Diffserv</i>	170
8.1.4	<i>Overprovisioned Best-Effort</i>	170
8.2	Experiment Setup	171
8.2.1	<i>Traffic</i>	171
8.2.2	<i>Topologies</i>	174
8.2.3	<i>Utility</i>	176
8.2.4	<i>Evaluation Metrics</i>	178
8.3	Per-flow versus Per-class Scheduling	179
8.4	Central versus Decentral Admission Control	183
8.5	Direct Comparison	185
8.6	Summary and Conclusions	191

Part III	Interconnections	193
9	Interconnections Overview	195
9.1	A Macroscopic View on Interconnections	196
	9.1.1 <i>Strictly Hierarchical Structure</i>	196
	9.1.2 <i>Fully Meshed Structure</i>	197
	9.1.3 <i>Realistic Structures</i>	198
9.2	A Microscopic View on Interconnections	199
	9.2.1 <i>Taxonomy and Classification of Interconnections</i>	199
	9.2.2 <i>Peering</i>	201
	9.2.3 <i>Transit</i>	202
	9.2.4 <i>Service Level Agreements</i>	202
9.3	Interconnection Method	203
	9.3.1 <i>Internet Exchange Points</i>	203
	9.3.2 <i>Evaluation</i>	204
9.4	Interconnection Mix	205
	9.4.1 <i>Negotiation Process</i>	205
	9.4.2 <i>Determining the Interconnection Mix</i>	206
9.5	Summary and Conclusions	208
10	Optimising the Interconnection Mix	209
10.1	Costs	210
	10.1.1 <i>Description</i>	210
	10.1.2 <i>Evaluation</i>	214
10.2	Reliability	218
	10.2.1 <i>Policies</i>	220
	10.2.2 <i>Evaluation</i>	222
10.3	Quality of Service	224
	10.3.1 <i>Policies</i>	224
	10.3.2 <i>Evaluation</i>	225
10.4	Environment Changes	227
	10.4.1 <i>Adjusting the Basic Models</i>	228
	10.4.2 <i>Evaluation</i>	228
10.5	Summary and Conclusions	233
Part IV	Traffic and Network Engineering	235
11	Traffic and Network Engineering Overview	237
11.1	Network Design and Network Engineering	237
	11.1.1 <i>Network Design</i>	238
	11.1.2 <i>Network Engineering</i>	239
11.2	Traffic Engineering	240
11.3	Traffic Matrix Estimation	243
11.4	Summary and Conclusions	245
12	Evaluation of Traffic Engineering	247
12.1	Traffic Engineering Performance Metrics	248
	12.1.1 <i>Path Length</i>	248
	12.1.2 <i>Maximal Bottleneck Utilisation</i>	249

12.1.3	<i>Average Utilisation</i>	249
12.1.4	<i>Average Load</i>	249
12.1.5	<i>Congestion Costs</i>	250
12.2	Traffic Engineering Strategies	251
12.2.1	<i>Traffic Engineering Objectives</i>	251
12.2.2	<i>Shortest Path Routing</i>	252
12.2.3	<i>Equal Cost Multipath</i>	252
12.2.4	<i>Explicit Routing</i>	252
12.2.5	<i>Path Selection</i>	254
12.3	Experiment Setup	255
12.3.1	<i>Traffic Creation</i>	258
12.3.2	<i>Capacity Assignment</i>	258
12.4	Explicit Routing versus Path Selection	259
12.5	Performance Evaluation	260
12.5.1	<i>Basic Experiment</i>	260
12.5.2	<i>Variation of the Congestion Cost Function</i>	264
12.5.3	<i>Influence of the Topologies</i>	265
12.5.4	<i>Variation of the Traffic Distribution</i>	267
12.5.5	<i>Conclusions</i>	269
12.6	Singlepath versus Multipath	269
12.7	Influence of the Set of Paths	270
12.8	Summary and Conclusions	272
13	Network Engineering	273
13.1	Quality of Service Systems and Network Engineering	273
13.2	Capacity Expansion	276
13.2.1	<i>Capacity Expansion Process</i>	276
13.2.2	<i>Capacity Expansion Strategies</i>	277
13.2.3	<i>Performance Evaluation</i>	283
13.2.4	<i>Recommendations</i>	288
13.3	On the Influence of Elastic Traffic	290
13.3.1	<i>Elasticity of Traffic Matrices</i>	290
13.3.2	<i>Impact on Capacity Expansion</i>	293
13.4	Summary and Conclusions	294
Part V	Appendices	295
A	Topologies Used in the Experiments	297
B	Experimental Comparison of Quality of service Systems	303
C	Analytical Comparison of Interconnection Methods	329
C.1	Internet Exchange Point Cost Models	329
C.1.1	<i>Exchange Router</i>	329
C.1.2	<i>Exchange LAN</i>	330
C.1.3	<i>Exchange MAN</i>	332
C.2	Cost Efficiency of an Internet Exchange Point	332
C.3	LAN versus MAN IXP Structure	336

D	Elasticity of Traffic Matrices – Network Models	339
D.1	Basic Model	339
D.2	Discrete Service Times	341
D.3	Self-similar Traffic	343
D.4	Related Work	343
	Bibliography	345
	Index	365

Foreword

The Internet is a fact of everyday life for vast numbers of people who use it explicitly, or even implicitly, as they go about their business or leisure – doing web searches, downloading files for their next meeting, making Voice-over-IP telephone calls, accessing e-mail, booking holidays, ordering goods, and so on. Users and usage alike are increasing dramatically, all over the globe, and the Internet is firmly established as a critical infrastructure. The user-view of the network comes through the medium of the web browser, and although many factors are jointly responsible for the end-to-end performance experienced by the user, there is no doubt that the Quality of Service (QoS) of the underlying network is one of the most important elements. The role of Internet Service Providers (ISPs), via which most people access the network, is therefore crucial.

In this book, Oliver Heckmann focuses on the world of the ISP and in particular on the efficiency of their network operation and on the QoS that they (aim to) provide. He structures the book into four parts, namely the ISP market, network architecture, interconnection issues, and traffic and network engineering. In that way he situates descriptions of the technology issues and emerging solutions in their proper context. New strategies and insights are presented that can help ISPs realise their QoS targets.

It is an undeniable fact that QoS-engineering has been difficult to ‘sell’ ever since the early work on QoS architectures began to appear in the early to mid 1990s. Partly this was because the proposed solutions seemed too complicated, and partly because it was felt that the Internet could cope without them – especially where over-engineered and where excess bandwidth is available (nearly always the case in the network core). However, perhaps the main reason was the lack of a compelling commercial reason for network operators to deploy QoS solutions. Now, or soon, the time may be right to do so, because of new and increasing competition amongst Internet Service Providers and the commercial pressures that surely dictate the urgent need to assure customers of an excellent level of service at all times.

This book gives a comprehensive coverage of the technical components needed by Internet Service Providers in the world in which they are all competing to succeed. I welcome its addition to the series, and highly recommend it to anyone with an interest in Quality of Service and the efficient operation of networks.

*David Hutchison
Lancaster University
January 2006*

List of Figures

1.1	Trade-off between Network Efficiency and Quality of Service	6
1.2	The Different Parts of this Book	7
2.1	General Role Model	13
2.2	ISP Role Model	14
2.3	INSP Roles	15
2.4	Information Flow from Source to Destination (Example)	16
2.5	Classification of Selected Providers	24
3.1	Queueing Model	30
3.2	Markov Chains	32
3.3	Delay of the M/M/1 Queue as Function of the Utilisation with $1/\mu = 0.1s$	33
3.4	Loss Probability and Queueing Delay of an M/M/1/B Queue with $B = 20$	34
3.5	Expected Queueing Delay of an M/G/1 Queue for Different Coefficients of Variation	35
3.6	Network Calculus Example	37
3.7	Graphical Solution of the Example	43
4.1	Hybrid 5 Layer Reference Model of the Internet	48
4.2	IPv4 Header	49
4.3	IPv6 Header	51
4.4	UDP Header	51
4.5	TCP Header	53
4.6	TCP Example	54
4.7	Square Root TCP Rate Formula	56
5.1	Pareto and Poisson Distributions (Logarithmic Scale)	67
5.2	Self-similarity and Long-range Dependency (from Kramer (2004))	68
5.3	Classification of Computer Games	72
5.4	Computer Game Architectures	72
6.1	Network Architecture	82
6.2	QoS System, Based on Schmitt (2001)	83
6.3	Intserv Control Path	87
6.4	Intserv Routers	89
6.5	Guaranteed Service (Arrival and Service Curve)	90
6.6	Diffserv Edge and Core Routers	96
6.7	Charny Bound	99
6.8	Diffserv Service Level Agreements	102

6.9	Trie Structure	115
6.10	Admission Control Systems	123
7.1	Utility Functions for $\tilde{b} = 1, \kappa = 0.62086$	136
7.2	Load Distribution Functions (Continuous)	137
7.3	Results of the Variable Load Model	139
7.4	Equalising Price Factors	142
7.5	Overprovisioning Factors for the Configuration of Table 7.1	152
7.6	Overprovisioning Factors for Different Utility Parameters	153
7.7	Overprovisioning Factors for Different Buffer Spaces	154
7.8	Overprovisioning Factors for an Increase in Bandwidth and Buffer Space	155
7.9	Overprovisioning Factors for Different Packet Sizes	155
7.10	Isolation of the Service Rate Effect	156
8.1	Utility Functions	176
9.1	Macroscopic and Microscopic View on Interconnections	196
9.2	Archetypical Structures	197
9.3	Network Edges and Interconnection Types	200
9.4	IXP Network Structure	204
10.1	Cost Functions	211
10.2	Performance Evaluation	217
10.3	Performance Evaluation	219
10.4	Evaluation of the Computational Complexity, Time to Solve for OPT	220
10.5	Evaluation of the Reliability Policies	223
10.6	Evaluation of the QoS Strategies	227
10.7	Evaluation of the Dynamic Strategies, Dependency on the Policy Parameters	231
10.8	Evaluation of the Dynamic Strategies, Dependency on the Scenario	232
11.1	Network Design	238
11.2	Network Engineering	240
12.1	Congestion Functions	250
12.2	Basic Results	262
12.3	Influence of n on the Performance	271
12.4	Influence of Δl on the Performance	271
13.1	Utility of the TCP Flows for Different QoS Systems as a Function of the Capacity	274
13.2	Utility of the Accepted Inelastic Flows for Different QoS Systems as a Function of the Capacity	275
13.3	Capacity Expansion Process	277
13.4	Costs of the Different Capacity Expansion Strategies for $c = 1, \Delta e = 3, \Delta p = 3$	285
13.5	Costs of the Different Capacity Expansion Strategies for Different Cost Ratios c ; $\Delta e = 3, \Delta p = 3$	287
13.6	Total Costs for Variation of the Parameters Δe and Δp of the Capacity Expansion Process; $c = 1$	289
13.7	Single Link Experiment Results	291
13.8	Rate Increase for Different Topologies	292
A.1	Topologies (1)	298
A.2	Topologies (2)	299

A.3	Topologies (3)	300
B.1	Per-flow versus Per-class Scheduling, DFN Topology, Utility of the Accepted Flows	304
B.2	Per-flow versus Per-class Scheduling, DFN Topology, Acceptance Rate	305
B.3	Per-flow versus Per-class Scheduling, DFN Topology, Dropping and Delay Bound Violation Probability	306
B.4	Per-flow versus Per-class Scheduling, DFN Topology, Change of the Acceptance Rate when Decreasing the Delay Bound to 10 ms/hop	307
B.5	Per-flow versus Per-class Scheduling, DFN Topology, Change of the Acceptance Rate when Increasing the Delay Bound to 40 ms/hop	308
B.6	Central versus Decentral Admission Control, DFN Topology, Acceptance Rate in Situation A (Contingents Match Flow Distribution)	309
B.7	Central versus Decentral Admission Control, DFN Topology, Acceptance Rate in Situation B (Contingents do not Match Flow Distribution)	310
B.8	Central versus Decentral Admission Control, DFN Topology, Utility of the Accepted Flows in Situation A (Contingents Match Flow Distribution)	311
B.9	Central versus Decentral Admission Control, DFN Topology, Utility of the Accepted Flows in Situation B (Contingents do not Match Flow Distribution)	312
B.10	Central versus Decentral Admission Control, DFN Topology, Dropping and Delay Bound Violation Probability in Situation A (Contingents Match Flow Distribution)	313
B.11	Central versus Decentral Admission Control, DFN Topology, Dropping and Delay Bound Violation Probability in Situation B (Contingents do not Match Flow Distribution)	314
B.12	Direct Comparison, DFN Topology, Traffic Mix A, Utility of the Accepted Flows	315
B.13	Direct Comparison, DFN Topology, Traffic Mix A, Overall Utility	316
B.14	Direct Comparison, DFN Topology, Traffic Mix A, Acceptance Rate	317
B.15	Direct Comparison, DFN Topology, Traffic Mix A, Dropped Packets	318
B.16	Direct Comparison, DFN Topology, Traffic Mix A, Delayed Packets	319
B.17	Direct Comparison, DFN Topology, Traffic Mix A, Throughput	320
B.18	Direct Comparison, DFN Topology, Traffic Mix A, Share of Traffic Volume	321
B.19	Direct Comparison, Artificial-3 Topology, Traffic Mix A, Utility of the Accepted Flows	324
B.20	Direct Comparison, Artificial-3 Topology, Traffic Mix A, Acceptance Rate	325
B.21	Direct Comparison, Artificial-3 Topology, Traffic Mix A, Dropped Packets	326
B.22	Direct Comparison, Artificial-3 Topology, Traffic Mix A, Delayed Packets	327
C.1	Internet Exchange Point Costs Models	330
C.2	Exchange Router Structure	331
C.3	The Exchange LAN Structure	331
C.4	The Exchange MAN Structure	332
C.5	Quadratic and Circular Distribution	333

List of Tables

2.1	ISP Services as in Greenstein (1999)	12
2.2	Service Provider as in Sun Microsystems (2000)	12
2.3	Service Providers as in Lakelin <i>et al.</i> (1999)	12
2.4	Classification of Internet Markets	19
3.1	Production Time per Batch	41
4.1	Selected RFCs Related to TCP	52
4.2	SONET/SDH Data Rates	60
4.3	Comparison of SONET and Long-distance Ethernet	62
5.1	Composition of Traffic by Application Type from Azzouna and Guillemin (2003)	66
5.2	QoS Requirements of Real-time Network Games	74
5.3	Traffic Models of Real-time Network Games	75
5.4	Standard Ports of Some Applications	76
6.1	Duplicate Scheduling with Deadlines Events	108
6.2	Classification of QoS Architectures Part 1	111
6.3	Classification of QoS Architectures Part 2	112
6.4	Section of a Routing Table (Example)	114
7.1	Default Parameter Values for the Evaluation	150
8.1	Default Scheduling and Configuration	169
8.2	Trace File Parameters	172
8.3	Session and Flow Parameters	173
8.4	Traffic Mix–Number of Started Flows in a Time Window of One Minute	174
8.5	Traffic Mix–Percentage of Transfer Volume	174
8.6	Bandwidth Settings and Average Path Length	175
8.7	Traffic Weight Distribution	176
8.8	Abbreviations for the Different Quality of Service Systems	179
8.9	Per-flow vs. Per-class Scheduling, Cross and Star Topology, Dropped or Delayed Packets [%], Summary	181
10.1	Constant Parameter Intervals	215
10.2	Scenario-dependent Parameter Intervals	215
10.3	Constant Parameters	230
10.4	Scenario-dependent Parameters	230
12.1	Explicit Routing versus Path Selection, Multipath	259
12.2	Explicit Routing versus Path Selection, Singlepath	259

12.3	Abbreviations of the Traffic Engineering Strategies	260
12.4	Results of the Basic Experiment	261
12.5	Congestion Cost Metric for Different Strategies and Congestion Cost Functions	265
12.6	Normalised Congestion Costs for Different Topologies	266
12.7	Maximum Utilisation for Different Topologies	267
12.8	Variation of the Traffic Distribution	268
12.9	Relative Difference in <i>Congestion Costs</i> and <i>Maximum Utilisation</i> of the Singlepath Strategy Compared to the Multipath Strategies for Different Topologies	270
A.1	Properties of the Topology Graphs	301
A.2	Tiers Parameters Used for the Generation of the Artificial Topologies	301
B.1	Abbreviations for the Different Quality of service Systems	303
B.2	Direct Comparison, DFN Topology, Traffic Mix B and C Utility of the Accepted Flows and Overall Utility	322
B.3	Direct Comparison, DFN Topology, Traffic Mix B and C Acceptance Rate and Dropping respectively Delay Bound Violation Probability	323
C.1	Variables and Parameters of the Cost Models	330
D.1	Assessment of the Approximations	341

List of Abbreviations

General Abbreviations

1GE	1-Gigabit Ethernet
10GE	10-Gigabit Ethernet
ABE	Alternative Best-effort
AC	Admission Control
ACK	Acknowledgement (Packet)
ADSL	Asymmetric Digital Subscriber Lines
AdSpec	Advertisement Specification
AF	Assured Forwarding
AH	Authentication Header
AIMD	Additive Increase - Multiplicative Decrease
AISP	Access Internet Service Provider
ANSI	American National Standards Institute
AOL	America Online
API	Application Programming Interface
APS	Automatic Protection Switching
AQM	Active Queue Management
AS	Autonomous System
ASP	Application Service Provider
ATM	Asynchronous Transfer Mode
B&B	Branch & Bound
B2B	Business to Business
B2C	Business to Consumer
BA	Behaviour Aggregate
BB	Bandwidth Broker
BE	Best-effort
BGP	Border Gateway Protocol
BRITE	Boston University Representative Internet Topology Generator
BSD	Berkeley Software Distribution
BSP	Backbone Service Provider
CAIDA	Cooperative Association for Internet Data Analysis
CBQ	Class Based Queueing
CBR	Constant Bit-rate

CD	Compact Disc
CDN	Content Delivery Network
CIDR	Classless Inter-domain Routing
CL	Controlled Load Service
COPS	Common Open Policy Service
CoS	Class of Service
CP	Content Provider
CPU	Central Processing Unit
CR-LDP	Constraint-based Routing Support for LDP
CSFQ	Core-stateless Fair Queueing
CSMA/CD	Carrier Sense Multiple Access with Collision Detection
CS	Class Selector
DCCP	Datagram Congestion Control Protocol
DE-CIX	Deutscher (German) Commercial Internet Exchange
DFN	Deutsches Forschungsnetz (German Research Network)
Diffserv	Differentiated Services
DNS	Domain Name System
DP	Dynamic Programming
DPS	Dynamic Packet State
DPT	Dynamic Packet Transport
DRR	Deficit Round Robin
DS	Diffserv, Differentiated Services
DSCP	Differentiated Services Codepoint
DSD	Duplicate Scheduling with Deadlines
DSL	Digital Subscriber Lines
DVD	Digital Versatile Disc
ECN	Explicit Congestion Notification
EDF	Earliest-deadline-first
EF	Expedited Forwarding
EIGRP	Enhanced Interior Gateway Routing Protocol
ENO	End-user Network Operator
ESP	Encapsulating Security Payload
FCFS	First Come First Serve
FEC	Forwarding Equivalence Class
FF	Fixed Filter
FFQ	Frame-based Fair Queueing
FIFO	First In First Out
FilterSpec	Filter Specification
FlowSpec	Flow Specification
FPS	First Person Shooter
FTP	File Transfer Protocol
GCRA	Generic Cell Rate Algorithm
GE	Gigabit Ethernet
GMPLS	Generalised MPLS
GS	Guaranteed Service
GT-ITM	Georgia Tech Internetwork Topology Models

HDLC	High-level Data Link Control
HFSC	Hierarchical Fair Service Curve
HPFQ	Hierarchical Packet Fair Queueing
HTML	Hypertext Markup Language
HTTP	Hypertext Transfer Protocol
ICMP	Internet Control Message Protocol
IEEE	Institute of Electrical and Electronics Engineers, Inc.
IETF	Internet Engineering Task Force
IGMP	Internet Group Management Protocol
IGRP	Interior Gateway Routing Protocol
IKE	Internet Key Exchange Protocol
ILEC	Incumbent Local Exchange Carrier
IMAP	Internet Message Access Protocol
InfoSP	Information Service Provider
INSP	Internet Network Service Provider
Intserv	Integrated Services
IOS	(Cisco) Internet Operating System
IOTP	Internet Open Trading Protocol
IP	Internet Protocol
IPng	Internet Protocol, Next Generation (=IPv6)
IPsec	IP Security Protocol
IPv4	Internet Protocol Version 4
IPv6	Internet Protocol Version 6
IS	Intserv, Integrated Services
ISDN	Integrated Services Digital Network
IS-IS	Intermediate System to Intermediate System Routing Protocol
ISP	Internet Service Provider
IT	Information Technology
ITU-T	International Telecommunications Union – Telecommunications Standardization Sector
IXP	Internet Exchange Point
JUNOS	Juniper Network Operating System
LAN	Local Area Network
LDP	Label Distribution Protocol
LFVC	Leap Forward Virtual Clock
LINX	London Internet Exchange
LP	Linear Programming
LSP	Label Switched Path
LSR	Label Switching Router
MAC	Media Access Control
MAN	Metropolitan Area Network
MBone	Multicast Backbone
MIP	Mixed Integer Programming
MLD	Multicast Listener Discovery
MMORPG	Massive Multiplayer Online Roleplaying Game
MPEG	Motion Pictures Experts Group

MPLS	Multi-protocol Label Switching
MPλS	Multi-protocol Lambda Switching
MPRASE	Multi-period Resource Allocation at System Edges
MSS	Maximum Segment Size
MTU	Maximum Transmission Unit
NAP	Network Access Point
NAT	Network Address Translation
NNTP	Network News Transfer Protocol
NS2	Network Simulator 2
NSF	National Science Foundation
NSFNet	National Science Foundation Network
OC	Optical Carrier
OLO	Other Local Operator
OSI	Open Systems Interconnection
OSPF	Open Shortest Path First
OXC	Optical Cross-connect
P2P	Peer-to-peer
PCBE	Price-controlled Best-effort
PDB	Per Domain Behaviour
PDH	Plesiochronous Digital Hierarchy
PDU	Protocol Data Unit
PGPS	Packetised General Processor Sharing
PPP	Point-to-point Protocol
PHB	Per Hop Behaviour
PI	Proportional Integrator
PLC	Packet Loss Concealment
PLR	Packet Loss Recovery
PMP	Paris Metro Pricing
POP	Point of Presence
POTS	Plain Old Telephone Service
PPP	Point to Point Protocol
QBSS	QBone Scavenger Service
QoS	Quality of Service
RAM	Random Access Memory
RED	Random Early Detection
REM	Random Exponential Marking
RFC	Request for Comments
RIP	Routing Information Protocol
RP	Retail Provider
RSpec	Reservation Specification
RSVP	Resource Reservation Protocol
RSVP-TE	RSVP Traffic Engineering Extensions
RTP	Real-time Transport Protocol
RTS	Real-time Strategy (Game)
RTT	Round-trip Time
SACK	Selective Acknowledgement

SCFQ	Self-clocked Fair Queuing
SCORE	Stateless Core
SCP	Strategic Consultant Provider
SDH	Synchronous Digital Hierarchy
SDL	Simplified Data Link
SFQ	Start Time Fair Queueing
SIP	Session Initiation Protocol
SLA	Service Level Agreement
SLO	Service Level Objective
SLS	Service Level Specification
SMS	Short Message Service
SMTP	Simple Mail Transfer Protocol
SNMP	Simple Network Management Protocol
SONET	Synchronous Optical Networking
SP	Service Provider
SSH	Secure Shell
SSP	Storage Service Provider
STM	Synchronous Transfer Mode
TCAM	Ternary Content Addressable Memories
TCP	Transmission Control Protocol
TCS	Traffic Conditioning Specification
ToS	Type of Service
TSpec	Traffic Specification
TTL	Time to Live
UDP	User Datagram Protocol
UMS	Unified Messaging Service
URL	Uniform Resource Locator
US	United States
VBR	Variable Bit-rate
VC	Virtual Clock
VoIP	Voice over IP
VPN	Virtual Private Network
VPOP	Virtual POP (Point Of Presence)
VQ	Virtual Queue
WAN	Wide Area Network
WDM	Wavelength-division Multiplexing
WFQ	Weighted Fair Queueing
WF2Q	Worst-case Fair Weighted Fair Queueing
WRR	Weighted Round Robin
WWW	World Wide Web
YESSIR	Yet another Sender Session Internet Reservations

Abbreviations of Models and Algorithms

Chapter 8	see also Table 8.8
IS-α_{GS}	Intserv QoS System with parameter α_{GS}
sDS-c-p	Standard Diffserv with Central Bandwidth Broker and Parameter p
sDS-d-p	Standard Diffserv with Decentral Bandwidth Broker and Parameter p
sDS-n	Standard Diffserv without Bandwidth Broker
oDS-c-p	Olympic Diffserv with Central Bandwidth Broker and Parameter p
oDS-d-p	Olympic Diffserv with Decentral Bandwidth Broker and Parameter p
oDS-n	Olympic Diffserv without Bandwidth Broker
BE-OF	Best-effort System with Overprovisioning Factor OF
Chapter 10	
OPT	Minimal Cost Interconnection Model (Model 10.1)
HTR	Transit Heuristics
HPA	Peer-with-all Heuristics
HPS	Peer-at-selected-IXPs Heuristics
HEV	Evolution Heuristics
MT	Minimum Number of Transit Providers Policy (Model 10.2)
MC	Minimum Free Capacity Policy (Model 10.3)
AF	Anticipating Failure Policy (Model 10.4)
MCAF	Combined MC and AF Policy
PB	Peering Bonus (Model 10.5)
HC	Hop Constraint (Model 10.6)
HP	Hop Count Penalty Costs Policy (Model 10.7)
PC	Penalty Costs Policy (Model 10.8)
LC	Limiting Change Policy (Model 10.9)
Chapter 12	see also Table 12.3
SP	Shortest Path Routing
CC	Path Selection Strategy Minimising (Weighted) Congestion Costs
CC_{uw}	Path Selection Strategy Minimising Unweighted Congestion Costs
U_{max}	Path Selection Strategy Minimising Max. Utilisation
U_{max}L_{av}	Path Selection Strategy Minimising Max. Utilisation and Av. Load
U_{max}P_{av}	Path Selection Strategy Minimising Max. Util. and Av. Path Length
U_{max}U_{av}	Path Selection Strategy Minimising Max. Utilisation and Av. Utilisation

U_{av}	Path Selection Strategy Minimising Av. Utilisation
U_{av}P_{av}	Path Selection Strategy Minimising Av. Util. and Av. Path Length
p_{av}L_{av}	Path Selection Strategy Minimising Av. Path Length and Av. Load
L_{av}	Path Selection Strategy Minimising Av. Load
Chapter 13	
CE	Capacity Expansion
TMCE	Combined Traffic Engineering and Capacity Expansion
T	Threshold-based Capacity Expansion Strategy