

Contents

List of Figures	xiii
List of Tables	xxi
Foreword	xxv
Preface	xxix
1 Optical Networking	1
1.1 Evolution of Optical Network Architectures	1
1.1.1 Transparent Networks	4
1.1.2 Opaque Networks	6
1.1.3 Translucent Networks	11
1.2 Layered Network Architecture	12
1.2.1 Optical Layer	13
1.2.2 Logical Layer	14
1.2.3 Service/Application Layer	14
1.3 Multi-Tier Optical Layer	15
1.3.1 One-Tier Network Architecture	16
1.3.2 Two-Tier Network Architecture	18
1.3.3 Network Scalability	19
1.4 The Current State of Optical Networks	21
1.5 Organization of the Book	22
2 Recovery in Optical Networks	25
2.1 Introduction	25
2.2 Failure Recovery	25
2.3 Fault Recovery Classifications	26
2.4 Protection of Point-to-Point Systems	31
2.4.1 (1 + 1) Protection	31
2.4.2 (1 : 1) Protection	32
2.4.3 (M : N) Protection	32
2.5 Ring-Based Protection	32
2.5.1 Failure Recovery in SONET Networks with Ring Topologies	33
2.5.2 Ring-Based Failure Recovery in Optical Networks with Mesh Topologies	34
2.6 Path-Based Protection	43
2.6.1 Dedicated Backup Path Protection (DBPP) in Mesh Networks	43
2.6.2 Shared Back Path Protection (SBPP) in Mesh Networks	44
2.7 Link/Span-Based Protection	46

2.8	Segment-Based Protection	47
2.9	Island-Based Protection	48
2.10	Mesh Network Restoration	50
2.10.1	Centralized Restoration Techniques	52
2.10.2	Distributed Restoration Techniques	52
2.11	Multi-Layer Recovery	53
2.12	Recovery Triggers and Signaling Mechanisms	56
2.13	Conclusion	58
3	Mesh Routing and Recovery Framework	61
3.1	Introduction	61
3.2	Mesh Protection and Recovery Techniques	62
3.2.1	Link-Based Protection	63
3.2.2	Path-Based Protection	63
3.2.3	Segment-Based Protection	65
3.3	Concept of Shared Risk Groups	67
3.3.1	Shared Link Risk Groups	67
3.3.2	Shared Node Risk Groups	70
3.3.3	Shared Equipment Risk Groups	70
3.4	Centralized vs Distributed Routing	72
3.4.1	Centralized Routing	72
3.4.2	Distributed Routing	74
3.4.3	Centralized vs Distributed Routing Performance Results	76
3.5	Conclusion	80
4	Path Routing and Protection	81
4.1	Introduction	81
4.2	Routing in Path-Protected Mesh Networks	81
4.3	Protection in Path-Protected Mesh Networks	83
4.3.1	Dedicated Backup Path-Protected Lightpaths	84
4.3.2	Shared Backup Path-Protected Lightpaths	86
4.3.3	Preemptible Lightpaths	90
4.3.4	Diverse Unprotected Lightpaths with Dual-Homing	90
4.3.5	Multiple Simultaneous Backup Path-Protected Lightpaths	91
4.3.6	Relaxing the Protection Guarantees	92
4.3.7	Impact of Multi-Port Card Diversity Constraints	94
4.4	Experiments and Capacity Performance Results	96
4.4.1	Performance Results for Path-Based Protection Techniques	96
4.4.2	Experiments with Multi-Port Card Diversity	98
4.5	Recovery Time Analysis	99
4.6	Recovery Time and Capacity Trade-Offs	103
4.7	Conclusion	105
5	Path Routing – Part 1: Complexity	107
5.1	Introduction	107
5.2	Network Topology Abstraction	107
5.2.1	Service Definition	108
5.2.2	Operational Models: Online vs Offline Routing	108

5.3	Shortest-Path Routing	108
5.3.1	Dijkstra's Algorithm	109
5.3.2	Dijkstra's Algorithm Generalization to K -Shortest Paths	110
5.3.3	Shortest-Path Routing with Constraints	111
5.4	Diverse-Path Routing	112
5.4.1	SRG Types	112
5.4.2	Diverse-Path Routing with Default SRGs	112
5.4.3	Diverse-Path Routing with Fork SRGs	114
5.4.4	Diverse-Path Routing with General SRGs	114
5.5	Shared Backup Path Protection Routing	116
5.5.1	Protection Guarantees and Rules of Sharing	117
5.5.2	Complexity of Shared Backup Path Protection Routing	117
5.6	Routing ILP	117
5.6.1	ILP Description	117
5.6.2	Implementation Experience	119
5.7	Conclusion	120
5.8	Appendix	120
5.8.1	Complexity of Diverse-Path Routing with General SRGs	120
5.8.2	Complexity of SBPP Routing	121
6	Path Routing – Part 2: Heuristics	125
6.1	Introduction	125
6.1.1	Operational Models: Centralized vs Distributed Routing	125
6.1.2	Topology Modeling Example	126
6.2	Motivating Problems	126
6.2.1	Heuristic Techniques	128
6.3	K -Shortest Path Routing	128
6.3.1	Yen's K -Shortest Path Algorithm	129
6.3.2	Constrained Shortest-Path Routing	129
6.4	Diverse-Path Routing	131
6.4.1	Best-Effort Path Diversity	132
6.5	Shared Backup Path Protection Routing	133
6.5.1	Sharing-Independent Routing Heuristic	133
6.5.2	Sharing-Dependent Routing Heuristic	133
6.6	Routing Preemptible Services	134
6.7	General Constrained Routing Framework	135
6.7.1	Implementation Experience	136
6.8	Conclusion	137
7	Enhanced Routing Model for SBPP Services	139
7.1	Introduction	139
7.2	Routing Metric	140
7.3	Routing Algorithm	143
7.4	Experiments	144
7.4.1	Effect of ϵ	144
7.4.2	Effect of α	146
7.5	Conclusion	147

8	Controlling Sharing for SBPP Services	149
8.1	Introduction	149
8.2	Express Links	149
8.2.1	Routing with Express Links	150
8.2.2	Analysis and Results	151
8.2.3	Express Links–Conclusion	152
8.3	Limiting Sharing	152
8.3.1	Example	153
8.3.2	Solution Alternatives	153
8.3.3	Analysis of Capping	154
8.3.4	Analysis of Load-Balancing	157
8.3.5	Limiting Sharing–Conclusion	157
8.4	Analysis of Active Reprovisioning	158
8.4.1	Evaluation of Active Reprovisioning	159
8.4.2	Active Reprovisioning–Conclusion	160
8.5	Conclusion	161
9	Path Computation with Partial Information	163
9.1	Introduction	163
9.2	Complexity of the Deterministic Approach	166
9.2.1	Complexity of the Failure Dependent Strategy	166
9.2.2	Complexity of the Failure Independent Strategy	167
9.3	Probabilistic Approach	167
9.3.1	A Problem of Combinations	167
9.3.2	Analogy with SRG Arrangement into a Set of Backup Channels	169
9.4	Probabilistic Routing Algorithm with Partial Information	170
9.5	Locally Optimized Channel Selection	171
9.5.1	Shared Mesh Protection Provisioning Using Vertex Coloring	171
9.5.2	Implementation and Applications	172
9.6	Required Extensions to Routing Protocols	173
9.7	Experiments and Performance Results	175
9.7.1	Accuracy and Distributions of Probability Functions	175
9.7.2	Comparison of Deterministic vs Probabilistic Weight Functions on Real Networks	175
9.7.3	Benefits of Locally Optimized Lightpath Provisioning	178
9.7.4	Summary	179
9.8	Conclusion	179
10	Path Reoptimization	181
10.1	Introduction	181
10.2	Routing Algorithm	182
10.2.1	Cost model	182
10.2.2	Online Routing Algorithm	183
10.3	Reoptimization Algorithm	184
10.4	The Complexity of Reoptimization	185
10.4.1	No Prior Placement of Protection Channels or Primary Paths	186
10.4.2	Prior Placement of Protection Channels or Primary Paths	189
10.5	Experiments	191
10.5.1	Calibration	191
10.5.2	Real Networks	191
10.5.3	Static Network Infrastructure	193
10.5.4	Growing Network Infrastructure	194

10.5.5	Network Dynamics	196
10.6	Conclusion	196
11	Dimensioning of Path-Protected Mesh Networks	199
11.1	Introduction	199
11.2	Network and Traffic Modeling	200
11.3	Mesh Network Characteristics	200
11.3.1	Path Length Analysis	201
11.3.2	Protection-to-Working Capacity Ratio Analysis	204
11.3.3	Sharing Analysis	205
11.4	Asymptotic Behavior of the Protection-to-Working Capacity Ratio	207
11.4.1	Examples	207
11.4.2	General Results	208
11.5	Dimensioning Mesh Optical Networks	211
11.5.1	Node Model and Traffic Conservation Equations	211
11.5.2	Dimensioning Examples and Results	213
11.6	The Network Global Expectation Model	214
11.7	Accuracy of Analytical Estimates	217
11.8	Recovery Time Performance	217
11.9	Conclusion	219
12	Service Availability in Path-Protected Mesh Networks	221
12.1	Introduction	221
12.2	Network Service Availability	221
12.2.1	Motivation	221
12.2.2	Focus on Dual-Failure Scenarios	222
12.2.3	Reliability and Availability	222
12.3	Service Availability in Path-Protected Mesh Networks	225
12.3.1	Dual-Failure Recoverability	225
12.3.2	A Markov Model Approach to Service Availability	225
12.3.3	Modeling Sharing of Backup Channels	227
12.3.4	Impact of Channel Protection	227
12.3.5	Impact of Reprovisioning	228
12.4	Availability in Single and Multiple Domains	228
12.4.1	Network Recovery Architecture—Single Domain	229
12.4.2	Network Recovery Architecture—Multiple Domains	230
12.4.3	Results and Discussion	231
12.4.4	A Simple Model	233
12.5	Availability in Ring and Path-Protected Networks	233
12.5.1	Ring Availability Analysis	234
12.5.2	Results and Discussion	235
12.5.3	The Simple Model Again	236
12.6	Conclusion	237
	Bibliography	239
	Index	261

