

Contents

1	Introduction to Optical Networks	1
1.1	Brief Evolution of Optical Networks	1
1.2	Geographic Hierarchy of Optical Networks	3
1.3	Layered Architectural Model	5
1.4	Interfaces to the Optical Layer.....	7
1.5	Optical Control Plane	10
1.6	Terminology	11
1.7	Network Design and Network Planning	15
1.8	Research Trends in Optical Networking	15
1.9	Focus on Practical Optical Networks.....	18
1.10	Reference Networks	19
	References	22
2	Optical Network Elements	25
2.1	Introduction	25
2.2	Basic Optical Components	26
2.3	Optical Terminal.....	27
2.4	Optical-Electrical-Optical (O-E-O) Architecture.....	31
2.5	Optical Bypass	36
2.6	OADMs/ROADMs	38
2.7	Multi-degree ROADM.....	40
2.8	ROADM Architectures.....	44
2.9	ROADM Properties.....	50
2.10	Optical Switch Types	68
2.11	Hierarchical or Multigranular Switches	71
2.12	Optical Reach.....	73
2.13	Integrating WDM Transceivers in the Client Layer.....	75
2.14	Packet-Optical Transport.....	76
2.15	Photonic Integrated Circuits.....	77
2.16	Multi-Fiber-Pair Systems	78
2.17	Exercises	79
	References	84

3 Routing Algorithms.....	89
3.1 Introduction.....	89
3.2 Shortest-Path Algorithms	91
3.3 Routing Metrics.....	93
3.4 Generating a Set of Candidate Paths.....	96
3.5 Routing Strategies	99
3.6 Capturing the Available Equipment in the Network Model.....	105
3.7 Diverse Routing for Protection	108
3.8 Routing Order.....	122
3.9 Flow-Based Routing Techniques	123
3.10 Multicast Routing.....	124
3.11 Multipath Routing	132
3.12 Exercises	137
References.....	143
4 Regeneration.....	147
4.1 Introduction	147
4.2 Factors That Affect Regeneration	148
4.3 Routing with Noise Figure as the Link Metric.....	157
4.4 Impairment-Based Routing Metrics Other Than Noise Figure.....	163
4.5 Link Engineering.....	164
4.6 Regeneration Strategies.....	165
4.7 Regeneration Architectures	172
4.8 Exercises	178
References.....	182
5 Wavelength Assignment.....	187
5.1 Introduction.....	187
5.2 Role of Regeneration in Wavelength Assignment.....	189
5.3 Multistep RWA.....	191
5.4 One-Step RWA	193
5.5 Wavelength Assignment Strategies	200
5.6 Subconnection Ordering.....	205
5.7 Bidirectional Wavelength Assignment	208
5.8 Wavelengths of Different Optical Reach.....	209
5.9 Nonlinear Impairments Due to Adjacent Wavelengths	211
5.10 Alien Wavelengths.....	214
5.11 Wavelength Contention and Network Efficiency	215
5.12 Exercises	221
References.....	226
6 Grooming	229
6.1 Introduction.....	229
6.2 End-to-End Multiplexing	231
6.3 Grooming	234

6.4	Grooming-Node Architecture.....	235
6.5	Selection of Grooming Sites	242
6.6	Backhaul Strategies.....	246
6.7	Grooming Trade-offs.....	248
6.8	Grooming Strategies.....	253
6.9	Grooming Network Study	259
6.10	Evolving Techniques for Addressing Power Consumption in the Grooming Layer.....	263
6.11	Exercises.....	268
	References	272
7	Optical Protection	277
7.1	Introduction.....	277
7.2	Dedicated Versus Shared Protection	279
7.3	Client-Side Versus Network-Side Protection	284
7.4	Ring Protection Versus Mesh Protection.....	288
7.5	Fault-Dependent Versus Fault-Independent Protection.....	292
7.6	Multiple Concurrent Failures	298
7.7	Effect of Optical Amplifier Transients on Protection.....	306
7.8	Shared Protection Based on Pre-deployed Subconnections.....	308
7.9	Shared Protection Based on Pre-Cross-Connected Bandwidth.....	313
7.10	Network Coding	315
7.11	Protection Planning Algorithms	318
7.12	Protection of Subrate Demands.....	325
7.13	Fault Localization and Performance Monitoring	332
7.14	Exercises	336
	References	342
8	Dynamic Optical Networking	349
8.1	Introduction.....	349
8.2	Motivation for Dynamic Optical Networking.....	351
8.3	Centralized Path Computation and Resource Allocation	355
8.4	Distributed Path Computation and Resource Allocation	360
8.5	Combining Centralized and Distributed Path Computation and Resource Allocation	365
8.6	Dynamic Protected Connections	367
8.7	Physical-Layer Impairments and Regeneration in a Dynamic Environment	369
8.8	Multi-Domain Dynamic Networking	374
8.9	Pre-deployment of Equipment	381
8.10	Scheduled or Advance Reservation Traffic	384
8.11	Software-Defined Networking	387
8.12	Exercises	391
	References	395

9 Flexible Optical Networks	401
9.1 Introduction.....	401
9.2 Fiber Capacity Limits.....	403
9.3 Flexible-Grid Architectures.....	409
9.4 Gridless Architectures and Elastic Networks.....	411
9.5 Routing and Spectrum Assignment.....	415
9.6 Spectral Defragmentation.....	421
9.7 Technologies for Flexible-Grid and Gridless Networks	423
9.8 Flexible-Grid Versus Gridless Architectures.....	426
9.9 Programmable (or Adaptable) Transponders	429
9.10 Exercises	432
References	437
10 Economic Studies	441
10.1 Introduction.....	441
10.2 Assumptions	442
10.3 Prove-In Point for Optical-Bypass Technology	445
10.4 Optimal Optical Reach.....	449
10.5 Optimal Topology from a Cost Perspective	455
10.6 Gridless Versus Conventional Architecture.....	459
10.7 Optical Grooming in Edge Networks.....	467
10.8 General Conclusions	470
References	470
11 C-Code for Routing Routines.....	473
11.1 Introduction	473
11.2 Definitions	474
11.3 Breadth-First Search Shortest Paths.....	477
11.4 K -Shortest Paths	479
11.5 N -Shortest Diverse Paths	486
11.6 Minimum Steiner Tree	495
References	503
Appendix.....	505
Index.....	507