

Optical Networks

A Practical Perspective

Third Edition

Rajiv Ramaswami
Kumar N. Sivarajan
Galen H. Sasaki



AMSTERDAM • BOSTON • HEIDELBERG • LONDON
NEW YORK • OXFORD • PARIS • SAN DIEGO
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Morgan Kaufmann Publishers is an imprint of Elsevier



Contents

- Foreword xxi

- Preface to the First Edition xxv

- Preface to the Second Edition xxix

- Preface to the Current Edition xxxiii

- 1 Introduction to Optical Networks 1**
 - 1.1 Telecommunications Network Architecture 2
 - 1.2 Services, Circuit Switching, and Packet Switching 5
 - 1.2.1 The Changing Services Landscape 8
 - 1.3 Optical Networks 10
 - 1.3.1 Multiplexing Techniques 11
 - 1.3.2 Second-Generation Optical Networks 13
 - 1.4 The Optical Layer 15
 - 1.5 Transparency and All-Optical Networks 22
 - 1.6 Optical Packet Switching 24
 - 1.7 Transmission Basics 26
 - 1.7.1 Wavelengths, Frequencies, and Channel Spacing 26
 - 1.7.2 Wavelength Standards 28
 - 1.7.3 Optical Power and Loss 29
 - 1.8 Network Evolution 30

| | | |
|-------|---|----|
| 1.8.1 | Early Days—Multimode Fiber | 30 |
| 1.8.2 | Single-Mode Fiber | 33 |
| 1.8.3 | Optical Amplifiers and WDM | 34 |
| 1.8.4 | Beyond Transmission Links to Networks | 37 |
| | Summary | 38 |
| | Further Reading | 39 |
| | References | 40 |

I Technology 45

| | | |
|-------|---|-----|
| 2 | Propagation of Signals in Optical Fiber | 47 |
| 2.1 | Loss and Bandwidth Windows | 48 |
| 2.1.1 | Bending Loss | 51 |
| 2.2 | Intermodal Dispersion | 51 |
| 2.2.1 | Geometrical Optics Approach | 52 |
| 2.2.2 | Bit Rate–Distance Limitation | 54 |
| 2.2.3 | Controlling Intermodal Dispersion: Graded-Index Multimode Fiber | 55 |
| 2.2.4 | Multimode Fiber in Practice | 57 |
| 2.3 | Optical Fiber as a Waveguide | 58 |
| 2.3.1 | Wave Theory Approach | 59 |
| 2.3.2 | Fiber Modes | 63 |
| 2.3.3 | Polarization Modes and Polarization-Mode Dispersion | 65 |
| 2.3.4 | Other Waveguides | 68 |
| 2.4 | Chromatic Dispersion | 70 |
| 2.4.1 | Chirped Gaussian Pulses | 71 |
| 2.4.2 | Controlling the Dispersion: Dispersion-Shifted Fibers | 75 |
| 2.5 | Nonlinear Effects | 78 |
| 2.5.1 | Effective Length and Area | 79 |
| 2.5.2 | Stimulated Brillouin Scattering | 81 |
| 2.5.3 | Stimulated Raman Scattering | 82 |
| 2.5.4 | Propagation in a Nonlinear Medium | 83 |
| 2.5.5 | Self-Phase Modulation | 85 |
| 2.5.6 | SPM-Induced Chirp for Gaussian Pulses | 88 |
| 2.5.7 | Cross-Phase Modulation | 90 |
| 2.5.8 | Four-Wave Mixing | 92 |
| 2.5.9 | Fiber Types to Mitigate Nonlinear Effects | 95 |
| 2.6 | Solitons | 99 |
| 2.6.1 | Dispersion-Managed Solitons | 102 |
| 2.7 | Other Fiber Technologies | 103 |

| | | |
|-----------------|--|------------|
| 2.7.1 | Photonic Crystal Fiber | 103 |
| 2.7.2 | Plastic Optical Fiber | 105 |
| Summary | | 106 |
| Further Reading | | 107 |
| Problems | | 108 |
| References | | 110 |
| 3 | Components | 113 |
| 3.1 | Couplers | 114 |
| 3.1.1 | Principle of Operation | 116 |
| 3.1.2 | Conservation of Energy | 117 |
| 3.2 | Isolators and Circulators | 118 |
| 3.2.1 | Principle of Operation | 119 |
| 3.3 | Multiplexers and Filters | 121 |
| 3.3.1 | Gratings | 124 |
| 3.3.2 | Diffraction Pattern | 128 |
| 3.3.3 | Bragg Gratings | 129 |
| 3.3.4 | Fiber Gratings | 132 |
| 3.3.5 | Fabry-Perot Filters | 136 |
| 3.3.6 | Multilayer Dielectric Thin-Film Filters | 139 |
| 3.3.7 | Mach-Zehnder Interferometers | 141 |
| 3.3.8 | Arrayed Waveguide Grating | 145 |
| 3.3.9 | Acousto-Optic Tunable Filter | 149 |
| 3.3.10 | High Channel Count Multiplexer Architectures | 154 |
| 3.4 | Optical Amplifiers | 157 |
| 3.4.1 | Stimulated Emission | 158 |
| 3.4.2 | Spontaneous Emission | 159 |
| 3.4.3 | Erbium-Doped Fiber Amplifiers | 160 |
| 3.4.4 | Raman Amplifiers | 165 |
| 3.4.5 | Semiconductor Optical Amplifiers | 167 |
| 3.4.6 | Crosstalk in SOAs | 171 |
| 3.5 | Transmitters | 172 |
| 3.5.1 | Lasers | 172 |
| 3.5.2 | Light-Emitting Diodes | 182 |
| 3.5.3 | Tunable Lasers | 184 |
| 3.5.4 | Direct and External Modulation | 192 |
| 3.5.5 | Pump Sources for Raman Amplifiers | 196 |
| 3.6 | Detectors | 198 |
| 3.6.1 | Photodetectors | 198 |
| 3.6.2 | Front-End Amplifiers | 203 |

| | | |
|----------|--|------------|
| 3.7 | Switches | 205 |
| 3.7.1 | Large Optical Switches | 207 |
| 3.7.2 | Optical Switch Technologies | 213 |
| 3.7.3 | Large Electronic Switches | 220 |
| 3.8 | Wavelength Converters | 221 |
| 3.8.1 | Optoelectronic Approach | 222 |
| 3.8.2 | Optical Gating | 224 |
| 3.8.3 | Interferometric Techniques | 225 |
| 3.8.4 | Wave Mixing | 228 |
| | Summary | 229 |
| | Further Reading | 230 |
| | Problems | 231 |
| | References | 237 |
| 4 | Modulation and Demodulation | 245 |
| 4.1 | Modulation | 245 |
| 4.1.1 | Signal Formats | 246 |
| 4.2 | Subcarrier Modulation and Multiplexing | 248 |
| 4.2.1 | Clipping and Intermodulation Products | 249 |
| 4.2.2 | Applications of SCM | 251 |
| 4.3 | Spectral Efficiency | 251 |
| 4.3.1 | Optical Duobinary Modulation | 252 |
| 4.3.2 | Optical Single Sideband Modulation | 254 |
| 4.3.3 | Multilevel Modulation | 255 |
| 4.3.4 | Capacity Limits of Optical Fiber | 255 |
| 4.4 | Demodulation | 256 |
| 4.4.1 | An Ideal Receiver | 258 |
| 4.4.2 | A Practical Direct Detection Receiver | 259 |
| 4.4.3 | Front-End Amplifier Noise | 260 |
| 4.4.4 | APD Noise | 261 |
| 4.4.5 | Optical Preamplifiers | 261 |
| 4.4.6 | Bit Error Rates | 264 |
| 4.4.7 | Coherent Detection | 269 |
| 4.4.8 | Timing Recovery | 271 |
| 4.4.9 | Equalization | 272 |
| 4.5 | Error Detection and Correction | 273 |
| 4.5.1 | Reed-Solomon Codes | 276 |
| 4.5.2 | Interleaving | 278 |
| | Summary | 278 |
| | Further Reading | 279 |

| | |
|---|------------|
| Problems | 280 |
| References | 285 |
| 5 Transmission System Engineering | 289 |
| 5.1 System Model | 289 |
| 5.2 Power Penalty | 290 |
| 5.3 Transmitter | 292 |
| 5.4 Receiver | 294 |
| 5.5 Optical Amplifiers | 295 |
| 5.5.1 Gain Saturation in EDFAs | 296 |
| 5.5.2 Gain Equalization in EDFAs | 297 |
| 5.5.3 Amplifier Cascades | 299 |
| 5.5.4 Amplifier Spacing Penalty | 300 |
| 5.5.5 Power Transients and Automatic Gain Control | 302 |
| 5.5.6 Lasing Loops | 303 |
| 5.6 Crosstalk | 304 |
| 5.6.1 Intrachannel Crosstalk | 305 |
| 5.6.2 Interchannel Crosstalk | 307 |
| 5.6.3 Crosstalk in Networks | 309 |
| 5.6.4 Bidirectional Systems | 309 |
| 5.6.5 Crosstalk Reduction | 311 |
| 5.6.6 Cascaded Filters | 313 |
| 5.7 Dispersion | 314 |
| 5.7.1 Chromatic Dispersion Limits: NRZ Modulation | 315 |
| 5.7.2 Chromatic Dispersion Limits: RZ Modulation | 317 |
| 5.7.3 Dispersion Compensation | 320 |
| 5.7.4 Polarization-Mode Dispersion (PMD) | 325 |
| 5.8 Fiber Nonlinearities | 328 |
| 5.8.1 Effective Length in Amplified Systems | 329 |
| 5.8.2 Stimulated Brillouin Scattering | 331 |
| 5.8.3 Stimulated Raman Scattering | 332 |
| 5.8.4 Four-Wave Mixing | 334 |
| 5.8.5 Self-/Cross-Phase Modulation | 338 |
| 5.8.6 Role of Chromatic Dispersion Management | 340 |
| 5.9 Wavelength Stabilization | 341 |
| 5.10 Design of Soliton Systems | 342 |
| 5.11 Design of Dispersion-Managed Soliton Systems | 343 |
| 5.12 Overall Design Considerations | 347 |
| 5.12.1 Fiber Type | 347 |
| 5.12.2 Transmit Power and Amplifier Spacing | 348 |

| | | |
|--------|--|-----|
| 5.12.3 | Chromatic Dispersion Compensation | 348 |
| 5.12.4 | Modulation | 349 |
| 5.12.5 | Nonlinearities | 349 |
| 5.12.6 | Interchannel Spacing and Number of Wavelengths | 349 |
| 5.12.7 | All-Optical Networks | 350 |
| 5.12.8 | Wavelength Planning | 351 |
| 5.12.9 | Transparency | 353 |
| | Summary | 353 |
| | Further Reading | 354 |
| | Problems | 355 |
| | References | 362 |

II Networks

367

| | | |
|----------|--|------------|
| 6 | Client Layers of the Optical Layer | 369 |
| 6.1 | SONET/SDH | 371 |
| 6.1.1 | Multiplexing | 373 |
| 6.1.2 | VCAT and LCAS | 377 |
| 6.1.3 | SONET/SDH Layers | 378 |
| 6.1.4 | SONET Frame Structure | 379 |
| 6.1.5 | SONET/SDH Physical Layer | 384 |
| 6.1.6 | Elements of a SONET/SDH Infrastructure | 386 |
| 6.2 | Optical Transport Network | 389 |
| 6.2.1 | Hierarchy | 391 |
| 6.2.2 | Frame Structure | 392 |
| 6.2.3 | Multiplexing | 395 |
| 6.3 | Generic Framing Procedure | 396 |
| 6.4 | Ethernet | 399 |
| 6.4.1 | Frame Structure | 402 |
| 6.4.2 | Switches | 403 |
| 6.4.3 | Ethernet Physical Layer | 406 |
| 6.4.4 | Carrier Transport | 407 |
| 6.5 | IP | 411 |
| 6.5.1 | Routing and Forwarding | 413 |
| 6.5.2 | Quality of Service | 414 |
| 6.6 | Multiprotocol Label Switching | 415 |
| 6.6.1 | Labels and Forwarding | 417 |
| 6.6.2 | Quality of Service | 419 |
| 6.6.3 | Signaling and Routing | 420 |

| | | |
|----------|--|------------|
| 6.6.4 | Carrier Transport | 420 |
| 6.7 | Resilient Packet Ring | 421 |
| 6.7.1 | Quality of Service | 422 |
| 6.7.2 | Node Structure | 423 |
| 6.7.3 | Fairness | 424 |
| 6.8 | Storage-Area Networks | 425 |
| 6.8.1 | Fibre Channel | 426 |
| | Summary | 427 |
| | Further Reading | 428 |
| | Problems | 429 |
| | References | 430 |
| 7 | WDM Network Elements | 433 |
| 7.1 | Optical Line Terminals | 436 |
| 7.2 | Optical Line Amplifiers | 438 |
| 7.3 | Optical Add/Drop Multiplexers | 438 |
| 7.3.1 | OADM Architectures | 441 |
| 7.3.2 | Reconfigurable OADMs | 447 |
| 7.4 | Optical Crossconnects | 452 |
| 7.4.1 | All-Optical OXC Configurations | 458 |
| | Summary | 461 |
| | Further Reading | 463 |
| | Problems | 464 |
| | References | 466 |
| 8 | Control and Management | 469 |
| 8.1 | Network Management Functions | 469 |
| 8.1.1 | Management Framework | 471 |
| 8.1.2 | Information Model | 473 |
| 8.1.3 | Management Protocols | 474 |
| 8.2 | Optical Layer Services and Interfacing | 476 |
| 8.3 | Layers within the Optical Layer | 478 |
| 8.4 | Multivendor Interoperability | 479 |
| 8.5 | Performance and Fault Management | 481 |
| 8.5.1 | The Impact of Transparency | 481 |
| 8.5.2 | BER Measurement | 482 |
| 8.5.3 | Optical Trace | 483 |
| 8.5.4 | Alarm Management | 483 |
| 8.5.5 | Data Communication Network (DCN) and Signaling | 485 |
| 8.5.6 | Policing | 487 |

| | | |
|----------|--|------------|
| 8.5.7 | Optical Layer Overhead | 487 |
| 8.5.8 | Client Layers | 492 |
| 8.6 | Configuration Management | 493 |
| 8.6.1 | Equipment Management | 493 |
| 8.6.2 | Connection Management | 494 |
| 8.6.3 | Adaptation Management | 499 |
| 8.7 | Optical Safety | 501 |
| 8.7.1 | Open Fiber Control Protocol | 503 |
| | Summary | 505 |
| | Further Reading | 506 |
| | Problems | 507 |
| | References | 508 |
| 9 | Network Survivability | 511 |
| 9.1 | Basic Concepts | 513 |
| 9.2 | Protection in SONET/SDH | 518 |
| 9.2.1 | Point-to-Point Links | 518 |
| 9.2.2 | Self-Healing Rings | 521 |
| 9.2.3 | Unidirectional Path-Switched Rings | 523 |
| 9.2.4 | Bidirectional Line-Switched Rings | 525 |
| 9.2.5 | Ring Interconnection and Dual Homing | 530 |
| 9.3 | Protection in the Client Layer | 532 |
| 9.3.1 | Protection in Resilient Packet Rings | 533 |
| 9.3.2 | Protection in Ethernet | 534 |
| 9.3.3 | Protection in IP | 536 |
| 9.3.4 | Protection in MPLS | 538 |
| 9.4 | Why Optical Layer Protection | 541 |
| 9.4.1 | Service Classes Based on Protection | 548 |
| 9.5 | Optical Layer Protection Schemes | 549 |
| 9.5.1 | 1 + 1 OMS Protection | 552 |
| 9.5.2 | 1:1 OMS Protection | 552 |
| 9.5.3 | OMS-DPRing | 552 |
| 9.5.4 | OMS-SPRing | 553 |
| 9.5.5 | 1:N Transponder Protection | 553 |
| 9.5.6 | 1 + 1 OCh Dedicated Protection | 553 |
| 9.5.7 | OCh-SPRing | 557 |
| 9.5.8 | OCh-Mesh Protection | 557 |
| 9.5.9 | GMPLS Protection | 563 |
| 9.6 | Interworking between Layers | 564 |
| | Summary | 565 |

| | |
|---|------------|
| Further Reading | 566 |
| Problems | 567 |
| References | 569 |
| 10 WDM Network Design | 573 |
| 10.1 Cost Trade-Offs: A Detailed Ring Network Example | 577 |
| 10.2 LTD and RWA Problems | 584 |
| 10.2.1 Lightpath Topology Design | 585 |
| 10.2.2 Routing and Wavelength Assignment | 590 |
| 10.2.3 Wavelength Conversion | 593 |
| 10.3 Dimensioning Wavelength-Routing Networks | 596 |
| 10.4 Statistical Dimensioning Models | 599 |
| 10.4.1 First-Passage Model | 600 |
| 10.4.2 Blocking Model | 601 |
| 10.5 Maximum Load Dimensioning Models | 609 |
| 10.5.1 Offline Lightpath Requests | 610 |
| 10.5.2 Online RWA in Rings | 615 |
| Summary | 618 |
| Further Reading | 618 |
| Problems | 619 |
| References | 623 |
| 11 Access Networks | 629 |
| 11.1 Network Architecture Overview | 631 |
| 11.2 Enhanced HFC | 636 |
| 11.3 Fiber to the Curb (FTTC) | 638 |
| 11.3.1 PON Evolution | 648 |
| Summary | 649 |
| Further Reading | 650 |
| Problems | 650 |
| References | 651 |
| 12 Photonic Packet Switching | 653 |
| 12.1 Optical Time Division Multiplexing | 658 |
| 12.1.1 Bit Interleaving | 660 |
| 12.1.2 Packet Interleaving | 661 |
| 12.1.3 Optical AND Gates | 665 |
| 12.2 Synchronization | 668 |
| 12.2.1 Tunable Delays | 670 |
| 12.2.2 Optical Phase Lock Loop | 671 |

| | |
|---|------------|
| 12.3 Header Processing | 673 |
| 12.4 Buffering | 674 |
| 12.4.1 Output Buffering | 676 |
| 12.4.2 Input Buffering | 677 |
| 12.4.3 Recirculation Buffering | 678 |
| 12.4.4 Using Wavelengths for Contention Resolution | 680 |
| 12.4.5 Deflection Routing | 683 |
| 12.5 Burst Switching | 688 |
| 12.6 Testbeds | 689 |
| 12.6.1 KEOPS | 690 |
| 12.6.2 NTT's Optical Packet Switches | 691 |
| 12.6.3 BT Labs Testbeds | 693 |
| 12.6.4 Princeton University Testbed | 693 |
| 12.6.5 AON | 694 |
| 12.6.6 CORD | 694 |
| Summary | 696 |
| Further Reading | 696 |
| Problems | 698 |
| References | 699 |
| 13 Deployment Considerations | 707 |
| 13.1 The Evolving Telecommunications Network | 707 |
| 13.1.1 The SONET/SDH Core Network | 709 |
| 13.1.2 Architectural Choices for Next-Generation Transport Networks | 712 |
| 13.2 Designing the Transmission Layer | 718 |
| 13.2.1 Using SDM | 719 |
| 13.2.2 Using TDM | 720 |
| 13.2.3 Using WDM | 721 |
| 13.2.4 Unidirectional versus Bidirectional WDM Systems | 722 |
| 13.2.5 Long-Haul Networks | 724 |
| 13.2.6 Long-Haul Network Case Study | 725 |
| 13.2.7 Long-Haul Undersea Networks | 732 |
| 13.2.8 Metro Networks | 734 |
| 13.2.9 Metro Ring Case Study | 736 |
| 13.2.10 From Opaque Links to Agile All-Optical Networks | 738 |
| Summary | 739 |
| Further Reading | 740 |
| Problems | 741 |
| References | 744 |

| | | |
|----------|--|------------|
| A | Acronyms | 747 |
| B | Symbols and Parameters | 757 |
| C | Standards | 761 |
| C.1 | International Telecommunications Union (ITU-T) | 761 |
| C.1.1 | Fiber | 761 |
| C.1.2 | SDH (Synchronous Digital Hierarchy) | 761 |
| C.1.3 | Optical Networking | 762 |
| C.1.4 | Management | 762 |
| C.2 | Telcordia | 763 |
| C.2.1 | Physical and Environmental | 763 |
| C.2.2 | SONET | 763 |
| C.2.3 | Optical Networking | 764 |
| C.3 | American National Standards Institute (ANSI) | 764 |
| C.3.1 | SONET | 764 |
| C.3.2 | Fibre Channel | 764 |
| D | Wave Equations | 765 |
| E | Pulse Propagation in Optical Fiber | 769 |
| E.1 | Propagation of Chirped Gaussian Pulses | 772 |
| E.2 | Nonlinear Effects on Pulse Propagation | 773 |
| E.3 | Soliton Pulse Propagation | 776 |
| | Further Reading | 777 |
| | References | 777 |
| F | Nonlinear Polarization | 779 |
| G | Multilayer Thin-Film Filters | 781 |
| G.1 | Wave Propagation at Dielectric Interfaces | 781 |
| G.2 | Filter Design | 785 |
| | References | 788 |
| H | Random Variables and Processes | 789 |
| H.1 | Random Variables | 789 |
| H.1.1 | Gaussian Distribution | 790 |
| H.1.2 | Maxwell Distribution | 791 |
| H.1.3 | Poisson Distribution | 791 |
| H.2 | Random Processes | 792 |
| H.2.1 | Poisson Random Process | 793 |

| | | |
|----------|---|------------|
| H.2.2 | Gaussian Random Process | 794 |
| | Further Reading | 794 |
| | References | 794 |
| I | Receiver Noise Statistics | 795 |
| I.1 | Shot Noise | 797 |
| I.2 | Amplifier Noise | 798 |
| | References | 800 |
| J | Asynchronous Transfer Mode | 801 |
| J.1 | Functions of ATM | 802 |
| J.1.1 | Connections and Cell Forwarding | 803 |
| J.1.2 | Virtual Paths | 804 |
| J.2 | Adaptation Layers | 805 |
| J.2.1 | AAL-1 | 805 |
| J.2.2 | AAL-5 | 806 |
| J.3 | Quality of Service | 806 |
| J.4 | Flow Control | 807 |
| J.5 | Signaling and Routing | 807 |
| | Bibliography | 809 |
| | Index | 845 |