## INDEX

AAL-5, 51, 238  
Absorption, optical enabling technologies, 62, 77–78  
Access control protocol, photonic slot routing, 173–175  
Access networks:  
  - challenges for, 191–192  
  - characteristics of, 1–2, 5, 187–188  
ACK bit, 28  
Acknowledge (ACK) message, 262–263, 432  
Acknowledgment number, 27, 30  
Active close, 29  
Adaptive algorithm, 316–317  
Adaptive routing:  
  - algorithms, 359  
  - defined, 366  
Add-drop multiplexers (ADMs):  
  - characteristics of, generally, 2, 5, 425  
  - metropolitan area networks, 188, 192–193, 211  
  - SONET/SDH rings, 210  
  - terabit switching and routing (TSR), 282–283  
Address mapping, 40  
Address resolution protocol (ARP), 40, 213  
Adjacencies, types of, 436–437  
Adjacent waveguides, 75  
Admission control, 305  
ADSL:  
  - modems, 191  
  - services, 217  
Advanced encryption standard (AES) algorithm, 271  
Al-free GaInP/GaInAsP/InGaAs structure, 77  
Algorithms:  
  - capacity-allocation, 175  
  - distance vector, 43–44  
  - link-state, 42–44  
  - slot-assignment, PSR, 173–174  
All-optical networks, 131  
All-optical wavelength conversion, 106  
ALOHA networks, 131, 161  
Amplified spontaneous emission (ASE):  
  - accumulated, 392  
  - EDFA, 80–83  
  - implications of, generally, 319, 519  
  - terabit switching and routing (TSR), 282  
Amplifiers, see specific types of amplifiers  
Analog, generally:  
  - channels, 2  
  - receivers, 160  
  - video broadcast, 231  
Annealing, 312  
Apodization, 73  
A-PON access systems:  
  - characteristics of, 182  
  - MAC protocol, 221–223  
  - physical layer:  
    - distance ranging, 220–221  
    - overview, 219–220  
    - power ranging, 221  
Application-level programming interfaces (APIs), 21  
Arbitrary node aggregation, 388–389  
Arbitration, 291–292  
Architecture, generally:  
  - contention-resolution schemes, 131  
  - differentiated services, 54  
  - future, 4  
  - high costs of, 2  
  - Internet, 2  
  - IntServ, 53  
  - IP switching, 51–52  
  - public network, 186–192  
  - traditional, 3  
  - WPD switches, 109–110  
Arpanet, 362, 369–370, 375–376  
Arrayed waveguide gratings (AWGs), 74  
Assured forwarding (AF), 54, 208, 266  
Assured forwarding (AF-PHB), 200  
Asynchronous deflection networks, 168  
Asynchronous transfer mode (ATM):  
  - adaptation layer 5 (AAL-5), 51, 238  
  - characteristics of, 4, 6–7, 9, 45–47, 184, 293, 511  
  - control architecture, 303  
  - core networks, 181, 190  
  - framing, 346

---

*IP over WDM: Building the Next-Generation Optical Internet*, Edited by Sudhir Dixit.  

535
Asynchronous transfer mode (ATM):
(Continued)
global networks, 184–185
IP over, 7–8, 47–49
IP-over-WDM networks, 344
optical access networks, 219
passive optical networks and, 237–238
PONS, see A-PONS
over SONET/SDH, 8
switching, 10
terabit switching and routing (TSR), 283,
294–295
virtual channel identifiers, 201
Asynchronous transfer mode optical switching
(ATMOS), 164
ATMARP, 48–49
Attributes, defined, 44
Attenuation, 319
Attenuators, optical enabling technologies, 84–85
Audio conferencing, 212
Augmented model, IP-over-WDM networks,
382–383
Automatic protection switching (APS):
characteristics of, 183, 210
optical, 504
Automatic switched optical network (ASON),
189–190, 193, 526–527
Autonomous systems (ASs), 41, 292, 459
Availability, service level agreements (SLAs), 198
Available bit rate (ABR), 46
Average end-to-end delay, 137, 139–140
Average hop distance, 120–121, 137, 139–140
Backbone network, 234, 237
Backbone router, 291
Background noise, EDFA, 78–79
Backup capacity (BC), 496
Backward pumping, EDFA, 82
Bandwidth:
capability, 5
distance multiplier, 1
Ethernet PONs model, 253–256
granularity, 2, 9
network, managed vs. unmanaged, 11–12, 17
SONET/SDH rings, 210–211
utilization, 2
WDM, 83
Bandwidth-on-demand service business model,
513
Banyan fabrics, 289
Baseline, contention-resolution schemes, 133,
137–139
Base offset time, 407, 410
Base stations:
access networks, 192
wireless LAN, 531
Basic band, B-PON access system, 225
Beam splitters, 91
Bell Canada, 218
Bellcore, 182, 262
Bellman-Ford algorithm, 43–44
BellSouth, 192, 217
Benefit analysis:
analytical models:
overview, 114–115
probabilistic model for a class of networks,
119–121
probabilistic model with independent link-
load assumption, 116–117
probabilistic model without independent link
load assumption, 121–122
sparse wavelength conversion, 118–119
gain characterization, 123–124
Best-effort Internet, 5
Best effort service, 467
Bidirectional transmission, 232
Binary modulation techniques, 93
Birefringence, optical enabling technologies, 61
Birth-death process, 120
Bit-error rate (BER):
Ethernet PONs, 249
optical enabling technologies, 89
packet-error rate distinguished from, 171
WDM system development, 91
Bit rate(s):
asynchronous transfer mode (ATM), 46
single-channel, 88
Bit streams, WDM systems, 89, 91
Bit transmission, 20
Blocking probability, 116–117, 119, 121–122,
Border gateway protocol (BGP):
characteristics of, generally, 190, 292, 394
routings, 34, 44, 48–49, 363
Bossy channel restoration, 416–417
B-PON access system:
characteristics of, generally, 223
extended WDM, 224–225
survivability, 223–224
Breakdown per service, 335
Bridge and role approach, 505–506
Bridges, multiprotocol, 33
Brillouin scattering, 65
British Telecom (BT), 217, 526
Broadband access, 5
Broadband access servers (BASs), 184, 186
Broadband intercarrier interface (B-ICI), 47
Broadband PONs (BPONs), 182
Broadcast-and-select architecture, 289–290
Broadcast networks, performance and QoS evaluation:
  MAC protocol, power of, 196–197
  mean access delay, 195
  medium utilization ratio, 194–195
  QoS provisioning, 197–201
Buffering:
  implications of, generally, 17
  multistage, 163
  optical, 131–132, 135, 162–165
  sequential, 130
  single-stage, 163
  terabit switching and routing (TSR):
    implications of, 280
    input, 286–287
    input/output, 287
    output, 285–286
Buffer underrun protection time, 268
Bulk optic demultiplexers, 76
Burst control packet (BCP), 398–402, 411, 416
Burstiness, 332
Burst-mode transceivers, 236–237
Byte-stream service, 23, 27, 31
Cable modem (CM) networks, 229–230, 271
Cable television, 230
Call blocking, 229–230, 271
Capacity:
  fiber, 1
  network, 6–9
  planning, 305
  WAN, 8
Capture effect, 237
Carrier sense multiple access with collision
detection (CSMA/CD), 195, 238–239, 264
Central office (CO), 187, 230–231, 233–234
Centralized algorithms, 359
CFS path computation, 429–430
Channel, generally:
  access, 17
  bit streams, WDM systems, 89
  clear, 102, 186
  spacing, WDM devices, 76, 88, 92
Checksum, 26
Chirping:
  optical enabling technologies, 63, 66–67
  wavelength conversion, 88
Chromatic dispersion, 319
Circuit-oriented phone calls, 183
Circuit provisioning delay, 211
Circuit-switched network, 103
Clark, David, 54
Classful scheme, IP address, 38–39
Classless allocation, IP address, 39
Classless interdomain routing (CIDR), 39
Class of service (CoS), 143
Clear channel, 102, 186
Client(s):
  defined, 28
    optical networks, 342
    -server network architecture, 516–517
    subnetworks, 302–303
  Clock and data recovery, 69
  Clock dispersion, 183
  CMOS technology, 69
  Coaxial cable networks, 230–231
  Code division multiple access (CDMA), 203
  Combiners, defined, 233
  Compensators, polarization-mode dispersion
    (PMD), 92
  Competitive local exchange carriers (CLECs),
    191, 272
  Completeness, 42
  Complexity, signaling protocols, 458
  Conditional free-wavelength distribution, 118
  Conditional probability, in wavelength conversion,
    116–117
Congestion:
  avoidance, service level agreements (SLAs),
    199
  avoidance phase, 32–33
  control, 26, 30–33
  window, 31–32
Connection, TCP:
  establishment, 27–28
  termination, 27–28
Connectionless service, 24
Connectionless transport, 25–26
Connection-level time scale, 305
Connection-oriented service, 23
Connection request message, 463, 468
Connectivity:
  Ethernet PONs, 240
  implications of, generally, 34–36
  Conservation law, 52
  Constant assemble time (CAT), burst assembly,
    406–407
  Constant bit rate (CBR), 46, 223
  Constraint-based LSP (CR-LSP) setup, 446, 448
  Constraint-based routing label distribution
    protocol (CR-LDP):
      characteristics of, 294–295, 323, 344–345, 401,
      425, 481
Constraint-based routing label distribution protocol (CR-LDP): (Continued)
GMPLS extension, 450, 457
optical extension, 449–450
resource reservation protocol:
  overview, 450
  reservation styles, 451
RSVP messages, 451–454
RSVP session, 450–451
routing, 520
RSVP-TE, 454–458
signaling protocol:
  CR-LSP setup through CR-LDP, 448
  comparisons, 457–459
  modification to LDP messages, 447–448
  overview, 438, 445–446
  TLVs, 446–447
Constraint-based shortest-path first (CSPF),
  generally:
    algorithm, 319
    path computation, 429–430
Constraints, in optical networks, 304, 306
Contention probability, 173
Contention-resolution schemes:
  combination schemes:
    characteristics of, 133
    comparison of, 141–142
  hybrid, optical packet switching:
    illustrative results, 151
    node architecture, 149–150, 155
    simulation configuration, 150–151
  optical buffering, 131–132, 135, 162–165
  optical delay line, 130, 151, 173
  overview, 129–130
  performance comparisons, 137–141
  simulation experiments/performance comparisons:
    network topology and configuration, 133–135
    simulation metrics, 137
    traffic generation, 135–137
    space deflection approach, 130, 132–134, 140, 165–168
    wavelength conversion:
      characteristics of, 130, 132, 168–169
      limited, 142–143
Continuous wave (CW), 88, 104, 107
Control channel group (CCG), 401–403
Controlled load, 53
Control packet, 398
Control plane, optical internetworking, 515–516
Control policy, 304
Convergence, overview, 1–4
Converted frequency, 104
Converter bank, 109–110
Core network, 1, 9, 181, 189–190
Cost function:
  link cost, 484
  path cost, 484–485
Cost-optimized networks, 6–7
Cost-performance tradeoff, 22
Count to infinity, 44
CRMA, 197
Crossbar switch, 403
Crossbar switching fabric, 288–289
Cross-connect(s):
  digital system (DCS), 425, 476
  electrical, 189, 209
  fiber-level, 476
  metropolitan networks, 193
  475–477, 491, 495, 499, 501, 506
  wavelength-selective, 476
WDM system:
  characteristics of, 5, 10, 101–102
  wavelength conversion, 108
Cross-gain modulation (XGM):
  network design and, 112
  SOAs, 170
  wavelength conversion, 107, 112
Cross modulation, wavelength conversion, 107–108
Cross-phase modulation (XPM/CPM):
  characteristics of, 65, 67, 93
  nonlinear effects, 392
  semiconductor optical amplifiers (SOAs), 87, 107–108
  wavelength conversion, using SOAs, 107–108
Crosstalk:
  accumulation, 84, 135
  cumulative, multiple channels, 76
  implications of, generally, 319
  isolation, 71, 76
  nonlinear, 68
  optical switching, 84–85
  penalty, 92
  slotted networks, 161
Cumulative acknowledgments, 30
Cutoff condition, optical enabling technologies, 61
Data burst, 405
Data burst channel group (DCG), 401, 403, 411
Data exchange interface (DXI), 47
INDEX 539

Data integrity, 24
Data transfer:
  high-speed, 191
  symmetrical, 203
  WDM networks, 101–102
Dedicated protection, 303, 432, 479, 505
Dedicated protection rings (DPRINGs), 211
Dedicated wavelength-convertible switch, 109
Deexcitation, EDFA, 78
Default, 54
Deflection cost, 167
Deframing, 69
Delayed reservation (DR), 399, 410
Delays, 52. See also specific types of delays
Delta fabrics, 289
Demultiplexing, 24–25, 69
Dense wavelength-division multiplexing (DWDM), 2, 4, 189, 277, 282–283, 293, 346–347, 397, 511
Deserialization, 69
Destination address (DA), 522
Destination port number field, 25
Deterministic routing, 113
Deutsche Telekom, 217
Dial-up modems, 190–191
Diameter, deflection routing, 167, 173
Dielectric films, 71–72
Difference frequency generation (DFG), 107
Differentiated service code point (DSCP), 54
Differentiated services, 52–54
DiffServ, IP, 4–5, 37, 199–200, 359
DiffServ Cloud, 207–208
DiffServ code point (DSCP), 200
Digital cross-connect system (DCS), 425, 476
Digital loop carriers, 1
Digital subscriber line (DSL) technology, 229–231, 271
Digital transparency, 105
Digital video conferencing, 264
Dijkstra algorithm, 43–44, 292, 319, 360, 362, 374
Direct connectivity, 34–36
Direct-detection receivers, 82
Directivity, passive optical networks, 233
Disjoint-link path protection, 491
Disjoint path protection, 431–432
Dispersion:
  chromatic, 62–64, 319
  compensation technologies, 69
  polarization mode (PMD), 319, 392, 519
Dispersion compensation, EDFA, 82
Dispersion-compensating fiber (DCF), 91
Dispersion-shifted single-mode fiber (DSF), 68
Distance vector:
  algorithm, 43–44, 360–361
  protocols, 42
Distinct wavelength constraint, 306
Distributed Bragg reflector (DBR), 108
Distributed feedback (DFB) lasers, 59, 63, 69–70
Distributed routing, 359
Diversity routing constraints, 392–394
DNS, 21
Don’t care nodes, deflection routing, 167
Double-channel spacing, WDM devices, 76
Double-stage EDFA, 89
Downstream transmission, 235, 238–240, 246, 269–270
DQDB, 197
DSL access multiplexer (DSLAM), 230
DSL coverage remote (R-DSLAMs), 230
Dual counterrotating rings, 209–211
Duplicate acknowledgments, 30
DVMRP, 292
Dynamic allocation scheme (DAS), passive optical stars, 203
Dynamic host configuration protocol (DHCP), 39
Dynamic lightpath:
  establishment (DLE), 483
  provisioning and restoration:
    dynamic RWA algorithm performance, 320–321
    route computation, 316–319, 322
    wavelength assignment, 319–320
Dynamic packet transport (DPT):
  implications of, 181, 212
  MAC protocol, 197
  optical metropolitan networks, 212–216
  rings, 210, 213
Dynamic range, attenuation, 84
Dynamic routing algorithms, 113
Dynamic RWA, 309, 316, 320–321
Dynamic synchronization, 161
Dynamic WDM networks, 330
Eavesdropping, 269
Edge routers, 200
Effective ONU load (EOL), 252
Efficient networks, characteristics of, 5, 9
Egress edge router (EER), 400–401
Electrical cross-connects (EXCs), 189, 209
Electrical-to-optical (E/O) conversion, 11, 288
Electroabsorption modulators, 70–71
Electromagnetic interference, 279
Electron-beam evaporation, 72
Electronic control unit, 302
Electronic filtering, 170
Electronic random access memory (ERAM), 507
Electro-optic regenerators, 60
Element management system (EMS), 423
Enabling technologies, WDM systems:
  wavelength-converter design, 104–109
  wavelength-convertible switch design, 109–110
  optical, see Optical enabling technologies,
  WDM systems
Encryption:
  benefits of, generally, 269–270
  methodology, 270–271
End office (EO), 187
End-system discovery, 514
End-to-end delay:
  average, 137, 139–140
  priority-based routing, 145
End-to-end (E2E) principle, 21–23, 33
End-to-end restoration, 482
Enhancement band, B-PON access system, 225
E/O/E conversion, 6
Erbium-doped fiber amplifiers (EDFA):
  characteristics of, 59, 76–83, 88–89
  development of, 202
  noise, 392
terabit switching and routing (TSR), 285
Erlang B loss formula, 474
Erlang’s map, 117
Error handling, signaling, 505
Escalation strategies, survivability, 497–498
Ethernet:
  characteristics of, generally, 47–48, 196, 294, 348
  gigabit, 528–531
  LAN, 262
  PON, see Ethernet PON (EPON)
  standards activity status report:
    IEEE 802, 527–528
    IETF, 523–525
    International Telecommunications Union (ITU-T), 526–527
    Optical Internetworking Forum (OIF), 525–526
    overview, 523, 53
  Ethernet PON (EPON):
    characteristics of, 2, 225, 229
    compliance with 802 architecture:
      combined PtPE and SME mode, 247
      open issues, 247–249
      point-to-point emulation, 245
      shared-medium emulation, 245–246
    COS-aware, 265–268
    defined, 237
    IEEE P80–2.3ah status, 272–273
    IP-based services over:
      circuit emulation, 263–264
      real-time video and voice, 264–268
      slot utilization problem, 261–263
    multipoint control protocol, 241–244
    operation principle, 238–241
    performance:
      bandwidth-allocation schemes, 253–256
      of limited service, 259–261
      model description, 250–253
      overview, 249–250
      simulation results, 256–259
    purpose of, 237–238
    security:
      eavesdropping, 269
      encryption strategies, 269–271
      overview, 268–269
      theft of service, 269
      traffic growth, 229–230
      upgrade scenarios:
        rate, 272
        spatial, 272
        wavelength, 271–272
  Europe, PDH hierarchies, 182
  European ACT KEOPS, 163
  Excited state, EDFA, 80–81
  Expedited forwarding (EF), 54, 208
  Expedited forwarding (EF-PHB), 200
  Explicit routing, 56
  Extended optical line termination (E-OLT), 225
  Extended optical network unit (E-ONU), 225
  Exterior gateway protocol (EGP), 292, 362
  Exterior NNI (E-NNI), 527
  External modulation, 70
  Extinction ratio, 88
  Extra offset time, 408
  Fabry-Perot laser diode, 63
  Failure indication signal (FIS), 469, 504
  Fairness ratio, 123–124, 173, 320–321
  Fast packet switching, 17
  Fast retransmit, 30
  Fate sharing, 22
  Fault detection, 468, 503
  Fault notification, 504
  FDDI-2, 197
  FEC TLV, 440
  Fiber Bragg gratings (FBGs), 73, 84, 217
  Fiber delay lines (FDLs):
    class isolation with, 409–410
class isolation without, 408–409
defined, 403
implications of, 507
Fiber drops, 2
Fiber in the loop (FITL), 192
Fiber-level cross-connects (FXCs), 476
Fiber switching, 426
Fiber to the building (FTTB), 218–219, 231
Fiber to the curb (FTTC), 218–219
Fiber to the home (FITH), 192, 218–219, 233
Files over lightpaths (FOL), 350, 352
File transfer (WWW) service, performance evaluation, 350–352
Filter(s):
optical, 169
optical enabling technologies, 59, 71–76, 88
slotted networks, 160
FILTERSPEC, 453
FIN packet, 29
First fit, 319, 380
First-in/first out (FIFO) queues, 150–152, 291
First mile, defined, 230, 233
First Mile Study Group, 531
First Mile Task Force, 272
Fixed alternate routing, 317, 366
Fixed-bandwidth optical paths, 514
Fixed filter (FF) reservation style, 451
Fixed-length packets, 130, 162–163
Fixed-node aggregation, 388–389
Fixed path routing, 113
Fixed-pipe model, 250
Fixed receiver (FR), 202
Fixed routing:
algorithm, 317, 366
defined, 120
Fixed transmitters (FT), 202
Fixed wavelength conversion, 124, 308
Flag field, 28
Flat-top passbands, 76
Flow classifier, IP switching, 51–52
FLOWSPEC, 453
Forward equivalence class (FEC) assignment, 201, 344, 438–439, 443–445
Forward error-correction algorithms, 69
Forwarding adjacency, 437
Forwarding capability, 34–36
Forwarding equivalent classes (FEC), 55
Four-photon mixing, 106
Four-wave mixing (FWM), 65, 67, 106, 392
Fragmentation/reassembly, 36–38
Frame check sequence (FCS), 213
Frame relay, 9, 54, 184, 294, 476
Frames, defined, 20–21
Framing, IP-over-WDM networks, 69, 346–347
France Telecom, 217
Free capacity (FC), 496
Free-space gratings, 76
Frequency converters, 103
Frequency response, low-pass, 170
Full-duplex MAC, 264
Full-duplex transmission, 220
Full-range converters, 123
Full-service access network (FSAN), 217–219, 223, 237
Full wavelength conversion capability, 307–308
GaAs MESFET technology, 69
G.ASON, 526
GATE message, Ethernet PONs, 241–243
Gated service, Ethernet PONs model, 258
Gate switching, SOA, 85, 163, 165
Generalized label request, 435
Generalized multiprotocol label switching (GMPLS):
adjacencies, 436–437
characteristics of, 10, 293, 295, 300, 322–323, 345–346, 381–382, 404, 520
IP-over-WDM architecture, 477
link management protocol, 437
network control plane, 425
signaling, 435–436, 504–505, 507
General path protection, 491
Generic cell rate algorithm (GCRA), 223
Geometry, waveguide, 74–75
Gigabit Ethernet:
characteristics of, generally, 4, 528
IEEE 802.af Task Force, 530–531
IEEE 802.17, Working Group on Resilient Packet Rings, 521
IEEE 802.3, Ethernet to First Mile Study Group, 531
over copper, 530
Gigabit/terabit switch, 277
Gigabits per second (Gbps), 1
Global resource table (GRT), 466, 468
Granularity:
bandwidth, 2, 9
protection, 493
switching, 5
terabit switching and routing (TSR), 283
traffic, 482
transport network, 6
Greedy insertion, 174
Ground state, EDFA, 80–81
Group communication, SONET/SDH rings, 212
Group velocity dispersion parameter, 62
GTE, 217
Guaranteed forwarding (GF), 266–267
Guaranteed frame rate (GFR), 46
Guaranteed service, 53
Hangman, 197
Header(s):
  length, 28
  optical packet switching, 169–171
  subcarrier multiplexed (SCM), 169–171
  photonic slot routing mesh network, 172–173
Head-of-line (HOL) blocking, 282, 286
Hello messages, 466, 468
Heterogeneity, 33, 36
Hierarchical routing, 361–362, 390–392
High-definition TV (HDTV), 304
High-priority (HP) traffic, 214
High-speed electronics, 69
High-speed transmission, 219–220
High-throughput junction points, 2
Hold-off timers, 497
Homogeneity, 332
Homogeneous broadening, 77
Hop, generally:
  count, 140, 484
  length, significance of, 116–118, 122
  number of, 6
Hop-by-hop routing, 8, 56, 483
Hot-potato routing, 166
HP transit buffer, 215
HTTP, 21
H.323, 21
H.323, 21
Hybrid fiber coax (HFC) networks, 2, 231, 348
Hybrid fiber coaxial (HFC) technologies, 191
Hybrid technologies, 34
iBGP, 48
ICMP, 41, 292
IDC, 277
IEEE:
  MAC address format, 213
  standards, 181, 200, 216, 225, 272, 527–528
  IGMP, 292
In-band signaling channel, 203
Incumbent local exchange carriers (ILECs), 191, 272
Indirect connectivity, 34–37
InGaAsP pump laser diodes, 76
Ingress edge router (IER), 400
Ingress-egress pair, 385
Inhomogeneous broadening, 77
Initial sequence number, 28
Inner ring, dynamic packet transport, 212
InP:
  heterojunction bipolar transistors, 69
  PICs, 94
Input, generally:
  frequency, 104
  port interface (PI), terabit switching and
  routing (TSR):
    characteristics of, 285
    IP-based, 290–291
    signal wavelength, 104–105
Insertion loss:
  accumulated, 135
  passive optical networks, 233
  slotted networks, 161
Integer linear programming (ILP), 483
Integrated routing, 389
Integrated services (IntServ), 53, 199
Integrated services, 52–53
Integrated Services Digital Network (ISDN), 2, 263
Integrated survivability:
  overview, 498–499
  protection schemes:
    characteristics of, 499–500
    dedicated integrated, 502–503
    shared integrated, 501–502
Intelligent optical networks, 512–513
Intelligent protection system (IPS), 362
Intelligent routing, 200
Intensity modulation, WDM transmitters, 70
Interautonomous system (AS) routing, 362
Interdomain routing, 41, 394
Interface speeds, 6–9
Interference:
  EDFA, 83
  electromagnetic, 279
  implications of, 317
  length, 121
Interferometric wavelength converters (IWCs), 108
Interframe gap (IFG), 238
Interior gateway protocols (IGPs), 292, 424, 477
Interior NNI (I-NNI), 527
Inter-LATA communication, 47
Interleaving, WDM devices, 76, 92
Internal routers, 200
International Telecommunications Union (ITU-T):
  functions of, 210, 222–224, 526–527
  grid, 69, 71
  STM-16, 189
Internet Assigned Numbers Authority (IANA), 39

Internet protocol (IP):
- addressing, 37–40
- over ATM, 7–8, 47–49
- characteristics of, 1, 293–294
- connectionless, 9, 50, 147
datagrams, 356
- end-to-end (E2E) principle, 21–23
- integrated dynamic, wavelength routing: implications of, 383
- network model, 383–387
layer, survivability:
- conventional protection, 487–489
- MPLS-based recovery, 489–491
- restoration approaches, 487–489
packet format, 36–37
- routing:
  - characteristics of, 358–359
  - datagram networks, 359–262
  - RWA, layered graph approach, 366–372
  - wavelength networks, 363–366
  - switching, 49–52
- over WDM, 9–10
Internet service provider (ISP), 44, 184, 186, 188, 190–191, 354
Internet telephony, 407
Internet traffic, characteristics of, 135
Interrupted Poisson process (IPP) model, 377
Interswitching system interface (ISSI), 47
Intersymbol interference, 62
Intradomain routing, 41, 44
Intra-LATA communication, 47
IntServ/PRSRP, 359
Ion-beam sputtering, 72
IP/LSR router, 499
IP/MPLS:
- layer, survivability, 499, 502
- networks, 322, 381–387
IP/optical routers, 2
IP telephones, 531
IP-over-WDM architecture, 475–479
IP-over-WDM control:
- optical networks, MPLS/GMPLS control plane:
  - adjacencies, 436–437
  - CSPF path computation, 429–430
  - GMPLS signaling functional requirements, 435–436
- link management protocol, 437
- link-state information dissemination, 428–429
- resource discovery, 428–429
- restoration management, 431–432
- signaling, 432–435
- wavelength assignment, 430–431
- traffic engineering extension, 436
- optical node model, 427
- overview, 422
- sample IP-centric control plan for optical networks:
  - connection module, 463–465
  - main module, 463
  - overview, 461–463
  - protection/restoration module (PRM), 464, 468–469
  - resource management module, 465–468
  - telecommunication NC&M, 422–423
  - traffic engineering control plane, MPLS, 423–427
IP-over-WDM integration:
- implications of, generally, 381–382
- interconnection models, 382–383
IP-over-WDM optical routing, 392–394
IP-over-WDM signaling protocols:
- comparison of, 457–459
- CR-LDP, 445–450
- LDP in MPLS control plane, 438–445
- network boundary, 459–461
- resource reservation protocol, 450–454
- RSVP-TE, 454–457
IP-over-WDM traffic analysis:
- connection-level analysis, 335–338
- demand analysis, 332–334
- end-to-end issues, 347–352
- first-generation WDM networks, 338–340
- framing, 346–347
- second-generation WDM networks, 340–342
- self-similarity, 331–332, 342
- signaling, 342–346
IP-over-WDM waveband routing:
- hierarchical online routing algorithm, 390–392
- hierarchical optical network, 387–388
- waveband models, 388–389
Ipsilon flow management protocol (IFMP), 51
IPv4, 197–198
IPv6, 429
IS-IS, 44, 292, 404, 428
IS-IS-TE, 294
ISO Open Systems Interconnection (ISO/OSI)
- layered model, 20, 44
Jacobson, Van, 54
Japan, access networks, 192
Jitter, 130
Joint path selection (JPS), 487
Just enough time (JET) protocol, 175
Kleinrock, Leonard, 196
KPN, 217

Label distribution protocol (LDP):
characteristics of, 294, 323, 384
signaling protocol, MPLS control plane:
label advertisement mode and LSP control model, 439–440
LSP setup with ordered control and downstream on demand mode, 443–444
LSP setup with other LSP control and advertisement mode combinations, 444–445
messages and processing procedure, 441–443
peer discovery and session establishment, 438–439
TLV encoding, 440–441
Labeling, IP switching, 52
Label set, defined, 435
Label stack, 55
Label-switched paths (LSPs):
control model, 439–440
implications of, 2, 55, 201, 344, 383, 385, 401, 403, 425, 435, 443–445, 495–496, 504
signaling:
RSVP-TE, 456–457
setup, 443–445
Label switching router (LSR):
ID, 429
survivability, 495–496, 501, 504
Label TLV, 441
Lambda switching, 426
LAN emulation (LANE), 48
LAN emulation service (LES), 48
Laser-emitting diodes (LEDs), 235
Last-in-order byte, 30
Latency, 130, 168, 175
Lattices, 65
Layer 2 switching, 425
L-band EDFAs, 88
Least-loaded routing (LLR):
algorithms, 317
implications of, 120–121
Least used method, 319
Length field, 26
Lightpath(s):
blocking probability, 116–117, 119
characteristics of, 6, 102–103, 116
defined, 102, 421
dynamic, 483
load, defined, 124
management, 322
network design and, 113
off-line, 124
optical, metropolitan networks, 193–194
protection, 303, 317–318, 431–432, 495
resource discovery, 322
routing subproblem, 312
semipermanent, 189–190
soft permanent, 190
sparse wavelength conversion, 119
static, 330
switched optical, 190
topology, 322
wavelength conversion, 109
working, 495
Lightpath identifier (lightpath ID), 463
Lightpath table (LT), 463
Limited-range converters, 123
Limited-range wavelength conversion, 112, 123
Limited wavelength conversion, 308
LiNbO3:
development of, 91
external modulators, 70
optical switching, 86
survivability, 508
Line amplifiers:
EDFA, 81–82
two-stage, 91
Linear programming (ILP), 312
Link, generally:
bundling technology, 429
-dependent path protection, 431
-load independence assumption, 121
management protocol (LMP):
adjacency, 437
implications of, 323, 437, 503–504
survivability, 475, 504–505
mileage, 484
protection, 491
restoration, 482
-state, generally:
advertisements (LSAs), 394, 424
approach, 359
information dissemination, 428–429
protocols, 42–45
Load, defined, 317
Local area networks (LANs):
characteristics of, 34, 48–49, 183, 194–197, 528
gateway, 250
high-capacity, 229–230
passive optical networks, 237
SONET/SDH rings, 210
virtual (VLAN), 200, 238, 247
wireless base stations, 531
Local connectivity vector (LCV), 465–467
Local exchange carriers (LECs), 232
Local loop, 230, 232
Local repair, 482
Local span (link):
  protection, 315
  restoration, 318
Logical IP subnets (LISs), 49
Local span (link):
  protection, 315
  restoration, 318
Lower-bound insertion, 174
Low-pass filter, 160
Low-priority (LP):
  relaxation, 313
  traffic, 214–215
  transit buffer, 215–216
Low-throughput junction points, 2
Mach-Zehnder interferometer (MZI):
  cascade, 76
  fiber-optic, 73
  first-stage, 76
  with multiple paths, 74
  optical switching, 85
  tunable, 84
  waveguide, 70
  wavelength conversion, 87, 107–108
Magneto-optic Faraday effect, 73
Main module (MM), sample IP-centric control plane, 462–463
MAN/WAN connection, 530
Manhattan Street Network (MSN), 166–168
Mapping, IP, 40–41
Marking, service level agreements (SLAs), 199
Markov chain, 115, 119
Markov model, 119–120
Maximum-hop-count, 140
Maximum open capacity routing algorithm (MOCA), 386–387
Maximum segment size (MSS), 31–33, 136
Maximum transmission unit (MTU), 40–41, 136, 153
Mean access delay, 195
Mean time to repair (MTTR), 198
Media access control (MAC) protocol:
  A-PON, 221–223
  characteristics of, generally, 5, 21
  Ethernet PON, 238, 241, 245, 248–249
  mean access delay, 195
  medium utilization ratio, 194
  multiple-server approach, 197
  passive optical stars, 203–207
  power of, 196–197
  single-server approach, 197
  10–bit Ethernet, 529
Medium utilization ratio, 194–195
Megabits per second (Mbps), 1
Mega-POPs, 278
Mesh networks:
  characteristics, 2, 6, 378–379, 475–476
  photonic slot routing, 172–173
  survivability, 496
Message-oriented services, 23
Metaring, 197
Metro network, 1, 5, 9
Metropolitan area networks (MANs):
  challenges for, 192–194
  characteristics of, 181, 186, 188–189, 193–194, 197, 199, 209–211
  passive optical networks, 234, 237–238
Michelson interferometer:
  characteristics of, generally, 87
  wavelength conversion, 107–108
Micro-optoelectromechanical systems (MEMS):
  crossbar switch, 403
  optical switching, 85–87, 94
  survivability, 508
Microwave electronics, 169
Minimal wavelength conversion, in WDM rings, 123–124
Mission critical service, 467, 499
Mixed primary-backup grooming policy (MGP), 496
M:N protection, 480
Modulated lasers, 66
MONET, 422
Moore’s law, 1
MP3/S/GMPLS control plane:
  adjacencies, 436–437
  CFS path computation, 429–430
  characteristics of, 426
  GMPLS signaling function requirements, 435–436
MP.S/GMPLS control plane: (Continued)
link management protocol, 437
resource discovery and link-state information dissemination, 428–429
restoration management, 431–432
signaling, 432–435
traffic engineering extension, 436
wavelength assignment, 430–431
MPCP protocol, 242, 253
MPEG-2, 266
MPLS (multiprotocol label switching):
characteristics of, 4–5, 9, 34, 48, 55, 511–512
control plane, 522
DiffServ and, 54
generalized (GMPLS), 10, 293, 295, 302, 322–323, 345–346, 381–382, 404, 520
IP-over-WDM networks, 344, 381, 476–477
labels, 55–56
network control, 424–425
optical code- (OC-), 346
QoS provisions, 199–201
route selection, 56
survivability, 500–501
terabit switching and routing (TRS), 279, 292–295
Multicast routing and wavelength assignment (MC-RWA), 308–309, 314
Multicast-capable OXCs (MC-OXCs), 304, 311, 318
Multichannel WDM multiplexer, 72–73
Multifiber networks, wavelength conversion, 123
Multifiber ring network, 369, 376–377
Multilayer network node, 10–11
Multilayer survivability:
escalation strategies, 497–498
integrated survivability, 498–503
overview, 496–497
Multimedia conferences, 21
Multimedia services, real-time, 5
Multiple access, 192
Multiple ISPs, 23
Multiple-path routing, 130
Multiple protocol interface, terabit switching and routing (TSR), 283
Multiplexing, 24–25, 69
Multiprotocol lambda switching, 381
Multiprotocol over ATM (MPOA), 48–50
Multistage buffering, 163
Multistage interconnection network (MIN), 233, 403
Multistage switching fabric, 289–290
Multitoken rings, 197
Multiwavelength optical buffering, 131
N×N couplers, 232
Narrowband filters, 73
Narrow-linewidth lasers, 66
Near-equivalent service, 54
Near-far problem, 236, 253
Neighbor discovery, 428
Neighbors, defined, 436
Network access servers (NASs), 184, 186
Network address translator (NAT) boxes, 34, 39–40
Network and traffic engineering techniques, 305
Network capacity, service level agreements (SLAs), 199
Network control (NC):
IP-over-WDM control:
implications of, 422
Internet, MPLS traffic engineering control plane, 423–427
telecommunication NC&M, 422–423
MP.S/GMPLS control plane, 426, 428–437
WDM networks, 103, 113–114
Network design, 9, 103, 111–113, 171
Network element system (NES), 423
Network failure detection, 411–412
Network infrastructure, 1
Networking, traditional, 512
Network layer:
implications of, 7, 21
Internet Protocol:
address, 37–40
forwarding paradigm, 34–36
fragmentation and reassembly, 40–41
packet format, 36–37
network service models, 33–34
Network management, networks, 103, 114
Network management system (NMS), 518
Network resources, 300
Network survivability, 17. See also Survivability
Network throughput, 137, 173, 350–351
Network-to-network interface (NNI), 404, 520–521, 526–527
Network-to-node interface (NNI), 47
Network upgrades, 2
Next-generation Internet (NGI), 358
NEXT-HOP, 45
Next-hop label forwarding entry (NHLFE), 56
Next-hop nodes, 130
Next-hop routing protocol (NHRP), 48–49
No-duplicates service, 24
Noise figure, EDFA, 80–82
Noise suppression, 168
Nonblocking switching, 86–87
Nonbroadcast multiple-access (NBMA) subnetworks, 34, 48
Nonlinearity:
imPLICATIONS OF, 319
optICAL enABLING TECHNOLOGIES, 64–65, 89
Nonlinear optical loop mirror (NOLM), 107
Nonzero dispersion fiber, 88–90
Nonzero dispersion single-mode fiber (NZDF), 68, 91
North America, PDH hierarchies, 182
Notification message, 506
NSFNET, 378–380
NTT, 192, 217
Null-MAC, 264
OC-3 (optical channel 3), 188
OC-48, 189
O/E/O:
conversion, 2, 150, 157, 217, 495
routing protocol, 388–389, 392
Offered ONU load (OOL), 252–253, 259–261
Off-line lightpaths, 124
Omega fabrics, 289
One-hop connection, wavelength conversion, 116
1 + 1 architecture, 479–480
1:1 protection, 480
One-way reservation, 398
Online routing algorithm, hierarchical, 390–392
On-off periods, Pareto distribution, 135
On-off-source, IP packets, 135–136
O/O/O, routing protocol, 387, 392
Open shortest path first (OSPF) protocol, 11, 42, 44, 292, 323, 362, 404, 428, 465–466
Operation, administration, and maintenance (OAM), Ethernet, 273
OPML, 412
OPSL, 412, 416
Optical access networks:
A-PON access systems, 219–223
B-PON access system, 223–225
characteristics of, 216–219
Optical add-drop multiplexers (OADM)s, 10, 201, 217, 225, 513
Optical amplification, 168, 217
Optical APS, 504
Optical buffering, 131–132, 135
Optical burst switching (OBS):
architectural aspect of, 399–403
burst assembly, 405–407
characteristics of, 175–176, 330, 340–343
protocol aspect of, 398–399
QoS provisioning:
  class isolation with FDLs, 409–410
class isolation without FDLs, 408–409
overview, 407–408
restoration, 412–416
signaling in optical Internet, 403–405
survivability:
  bossy channel restoration, 416–417
  network failure detection, 411–412
  OBS restoration, 412–416
  unnecessary reservation, 416–417
Optical channel subnetwork connection protection (OCH-SNCP), 492
Optical circuit switching (OCS), 397
Optical circulator, 73
Optical code multiprotocol label switching (OC-MPLS), 346
Optical cross-connects (OXC)s:
  first-generation, 421
  multicast-capable (MC–), 304, 311, 318
  survivability and, 475–477, 491, 495, 499, 501, 506
Optical delay line, 130, 151, 165, 173
Optical Domain Service Interconnection (ODSI), 322, 426
Optical/electrical (O/E) conversion, 69
Optical enabling technologies, WDM systems:
development of, 88–93
overview, 59–60, 93–94
transmission limitations:
  chromatic dispersion, 62–64
  nonlinear optical effects, 64–68
  polarization-mode dispersion (PMD), 64, 71
  single-mode optical fiber, 60–62
WDM components:
  dispersion compensation, 83–84
  erbium-doped fiber amplifiers (EDFA), 59, 76–83, 88–89
  filter components, 59, 71–76
  optical switching devices, 84–87
  transmitters, 69–71
  variable optical attenuators, 84–85
  wavelength converters, 87–88
Optical fiber(s):
  next-generation access network, 231–232
  single-mode, 60–62
Optical filtering, 169
Optical interconnection networks (OINs), 280, 282
Optical Internet:
  end-to-end, 5, 17
  signaling, 403–405
Optical Internetworking Forum (OIF), 322, 324, 342, 426, 499, 525–526
Optical internetworking models:
control plane, 515–516
dedicated protection, 303
end-system discovery, 514
Ethernet standards activity status report:
characteristics of, 523
IEEE 802, 527–528
IETF, 523–525
International Telecommunications Union (ITU-T), 526–527
Optical Internetworking Forum (OIF), 525–526
gigabit Ethernet:
characteristics of, generally, 528
IEEE 802.af Task Force, 530–531
IEEE 802.17, Working Group on Resilient Packet Rings, 521
IEEE 802.3ab, Ethernet to First Mile Study Group, 531
(IEEE 802.3ab), over copper, 530
overlay model:
characteristics of, 516–518
dynamic, 518–521
static, 518
overview, 511–516
peer model, 521–523
rural, 513
service discovery, 514
signaling, 513
Optical isolator, 73
Optical label switching, 171
Optical layer, 10
Optical line termination (OLT):
A-PON access system, 218, 220–223
B-PON access system, 223–224
characteristics of, 234–237
Optical MEMS (micro-optoelectromechanical systems), 85–87, 94
Optical metropolitan networks:
dual counterrotating rings, 209–216
passive optical stars, 201–208
Optical multiplex section protection (OMSP), 492
Optical multiplex-section shared protection ring (OMS-SPR-ing), 493
Optical network:
architecture:
characteristics of, 17, 301–304
dedicated protection, 303
no protection, 303
shared protection, 303
control plane issues, 321–323
design and capacity planning:
importance of, 309
physical topology design, 310–311
survivable optical networks, 314–316
virtual topology design, 311–314
dynamic lightpath provisioning and restoration:
dynamic RWA algorithm performance, 320–321
route computation, 316–319, 322
wavelength assignment, 319–320
engineering, overview, 299–301
standardization, 323–324
traffic:
characteristics of, generally, 304–306
importance of, 304
routing and wavelength assignment, 306–309
Optical networking, historical perspective, 184–186
Optical network-to-network interface (O-NNI), 190
Optical network unit (ONU):
A-PON access system, 218, 220–221
B-PON access system, 223–224
characteristics of, 234–237
Ethernet PONs, 238–248, 250–257, 259–272,
Optical packet switching (OPS):
contention, generally, 129
contention resolution, 162–169
header, 169–170
implications of, generally, 397
optical label switching, 171
orthogonal classification, 130
packet format, 171
slotted networks, 158–161
TCP performance with:
node architecture, 152–153
numerical results, 153–155
simulation configuration, 153–155
unsplotted networks, 131, 161–162
Optical routing:
diversity routing constraints, 392–394
interdomain routing, 394
physical layer constraints, 392
wavelength conversion constraints, 394
Optical single-sideband (OSSB) subcarrier header, 171
Optical SNR, 81, 89, 93, 503
Optical splitters/combiners, 220, 232–234, 239
Optical star networks, passive, 201–208
Optical subwavelength switching, technological advances:
INDEX

Piggybacked acknowledgments, 30
Plain old telephone service (POTS):
    splitters, 217
    traffic, 183–184, 192
Planar lightwave circuit (PLC) technology, 290
Planar waveguide technology, 232
Planck’s constant, 80
Plesiochronism, 182
Plesiochronous digital hierarchy (PDH):
    characteristics of, 182, 186
    defined, 182
    SONET/SDH compared with, 182–183, 211
Point-of-presence (POP), 184
Point-to-multipoint (PtMP) fiber, Ethernet, 273
Point-to-point (PtP), generally:
    fiber, Ethernet, 273
    links, 9, 210
    optical fibers, 186
    topology, 231
Point-to-point emulation (PtPE), 245, 247
Point-to-point protocol (PPP), 9, 346–347
Points of presence (POPs), 278
Poisson distribution, wavelength conversion, 116
Poisson process, 196–197
Polarization:
    beam splitter, 91
    demultiplexing, 91
    input signal, 105
    interleaving, 92
    multiplexing, 93
    optical enabling technologies, WDM systems:
        -mode dispersion (PMD), 64, 71, 319, 392, 519
        single-mode optical fiber, 61
    orthogonal, 91
Polarization mode dispersion (PMD), 319, 392, 519
Policing, service level agreements (SLAs), 199
Port number fields, 25, 36
Power amplifiers, EDFA, 81
Power density:
    amplified spontaneous emission (ASE), EDFA, 81
    optical enabling technologies, 65
Power line communication (PLC), 191
Power range, access networks, 192
Power splitters, 303
Preamplifiers, EDFA, 81–83
Premises access control devices, 531
Primary capacity (PC), 496
Priority-based routing:
    illustrative results, 144–147
    network architecture, 143–144
Private branch exchanges (PBXs), 263
Private networks, 48
Private network-to-node interface (PNNI), 47
Probability density function (pdf), IP packets, 135
Probability distribution function (PDF), IP packets, 135–136
Production networks, 5
Propagation:
    constant, 61
    delays, slotted networks, 159
    single-mode optical fiber, 60–62
Protection:
    IP-over-WDM networks, 479–481
    lightpaths, 495
    sensitive service, 467
    switching, 6, 322
    techniques, 305
Protection/restoration module (PRM), sample
    IP-centric control plane, 464, 468–469
Protocol(s):
    implications of, 6–9
    layering, 19–21
    stacks, 1, 10, 20
Protocol data units (PDUs), 441
 Provisioned bandwidth service business, 512
Public network architecture:
    access networks, 187–188, 191–192
    core networks, 189–190
    ISP networks, 190–191
    metropolitan area networks (MANs), 186, 188–189, 192–194
Public-switched network, 5
Public switched telephone networks (PSTNs), 181–182, 184–185
Pump, generally:
    frequency, 104
    lasers, 76, 89
    propagation, EDFA, 79–80
    wave, 107
    wavelength, 104
Pure-silica core fiber (PSCF), 92
Push-pull electrodes, 70
Quality of service (QoS):
    A-PON access systems, 219
    end-to-end, 189, 198–199, 474
    Ethernet PONs, 238, 240, 264
    implications of, 1–2, 4–5, 7, 17, 22, 49, 52
    IP-over-WDM networks, 341, 476, 501
    optical burst switching:
        class isolation with FDLs, 409–410
        class isolation without FDLs, 408–409
    overview, 407–408
priority-based routing, 143
provisioning:
   DiffServ approach, 199–200
   importance of, 197–198
   MPLS approach, 200–201
parameters in metro and in the access, 198–199
sample IP-centric control plane, 463–464, 467, 469
   signaling protocols, 459
survivability, 501
terabit switching and routing (TSR), 283–284, 292–294
Queuing:
   asynchronous transfer mode (ATM), 45
   contention-resolution schemes, 145, 150–151, 162
   Ethernet PONs model, 258–259
   first in/first out (FIFO), 150–152
   MAC protocol, 194, 196–197
   service level agreements (SLAs), 199
   single-server approach, 194, 196
   theory, conservation law, 52
   virtual output (VOQ), 286–287
Qwest, 218
Radio-frequency signals, WDM transmitters, 70
Raman amplification, 89–92
Raman scattering, 65
Random-access memory (RAM):
   characteristics of, 129–131, 162
   electronic (ERAM), 507
Random early discard (RED) mechanism, 200, 208
Random scheduling algorithm (RSA) protocol, 203–204
Random wavelength assignment, 320
Rayleigh scattering, 62, 89
Reactive traffic engineering, 513
Real-time protocol (RTP), 198
Real-time services, 5
Real-time video, voice-over IP (VoIP) and, 264–268
Receiver(s):
   access networks, 192
   window size, 28
Recirculation fiber loops, 163
Recovery, intelligent optical networks, 513
RedFris, 354
Redundancy, WDM developments, 91
Refractive index:
   narrowband filters and, 73
   nonlinear, 65–67
   single-mode optical fiber, 60
Regenerators:
   characteristics of, 2, 60
   optical 2R, 88
Regional rings, 209
Rekeying, periodic, 271
Relaxing, defined, 44
Reliability:
   cost functions and, 484
   importance of, 2
   service level agreements (SLAs), 198
   signaling protocols, 458–459
TCP, 29–30
Remodulation, 170
REPORT message, Ethernet PONs, 241–243
Rerouting, 6
Research and development for the advanced communications (RACE), 164
Resequencing, 130
Resilient packet ring (RPR), 181, 216
Resource discovery, 428–429
Resource management module, sample IP-centric control plane, 462, 465–468
Resource reservation protocol:
   overview, 53, 200, 295, 384, 450, 491
   reservation styles, 451
   RSVP messages, 451–454
   RSVP session, 450–451
Resource update message, 468
Restoration:
   intelligent optical networks, 513
   IP-over-WDM networks, 482
   management, 431–432
RESV messages, 53, 453
Retransmission, 170
Reverse-dispersion fiber (RDF), 92
Reversion function, signaling, 480, 505–506
RFC 1577, 49
RFC 1953, 51–52
RFC 292
Ring identifier (RI), 212
Ring networks, WDM, 116, 121, 123–124
Round-trip time (RTT):
   A-PON access system, 220
   Ethernet PONs, 241–244
   TCP, 154
Route controller (RC), 291–292
Routers, see specific types of routers
   functions of, generally, 2, 5
   multiprotocol, 33
Routing:
   adjacency, 432
   algorithm, see Routing algorithm
Routing: (Continued)
characteristics of, 17, 41–42
common protocols:
  BGP, 363
  EGP, 362
  OSPF, 362
  RIP, 44, 292, 362
constraints:
  diversity, 392–394
  physical layer, 392
  wavelength conversion, 394
deflection, 130, 165–168, 171, 173, 361
distance vector, 42
hierarchical, 361–362
hot-potato, 166
interdomain, 394
Internet, 41–45
lightpath, 428
link-state algorithms and protocols, 42–45
  multi-path, 130
optical layer intelligence, 513
priority-based, 143–147
store-and-forward, 167
survivable, 485–487
Routing adjacency, 436
Routing algorithms, survivable:
  conventional, 482–483
  joint working and protection routing, 487
  Suurballe’s algorithm, 486
Routing and wavelength assignment (RWA):
  algorithms with/without wavelength converters, 123, 367–369
defined, 113
dynamic routing, 113, 309
layered graph approach:
  dynamic RWA with wavelength conversion, 369
dynamic RWA algorithm without wavelength conversion, 367–369
model, 367
  overview, 366–367
  simulation results, with/without wavelength conversion, 369–372
  multicast (MC-), 308–309, 314
  static routing, 113–114, 124, 309
Routing information protocol (RIP), 44, 292, 362
Rowland circle configuration, 74–75
RPR MAC protocol, 197
RSPEC, 53
RSST bit, 28
RSVP-CR-LDP, 505–506
RSVP-TE:
  GMPLS extension of, 457
  implications of, 323, 344–345, 401, 520
  LSP tunnel setup using, 456–457
  objects, 455–456
  overview, 454–455
  signaling:
    GMPLS extension of, 457
    LSP tunnel setup using, 456–457
    objects, 455–456
    reservation style, 455
Ryan Hankin and Kent (RHK), 277
Satellite networks, 191
S-band amplifiers, 91–92
Scalability:
  implications of, generally, 35–37, 42, 199
  signaling protocols, 458
  terabit switching and routing (TSR), 283, 293
Scale, 33, 35
Scheduling, 17
Secondary path, signaling, 505
Second-order nonlinear interaction, 107
Security sensors, 531
Segment structure:
  TCP, 27–28
  UDP, 26
Segregated primary-backup grooming policy
  (SGP), 496
Select networks, performance and QoS evaluation:
  MAC protocol, power of, 196–197
  mean access delay, 195
  medium utilization ratio, 194–195
  QoS provisioning, 197–201
Self-healing rings, 188
Self-phase modulation (SPM), 65, 67, 88, 392
Semiconductor laser(s):
  diodes, 85
  wavelength conversion, 108
Semiconductor optical amplifiers (SOAs):
  characteristics of, 85, 87–88, 106, 163, 165, 285, 505
  wavelength conversion, 107–108, 112
Semi-lightpath algorithm, 380
Separate routing network, 389
Sequence number, 27–28
Sequential buffering, 130
Serialization, 69
Server(s):
  defined, 29
  network-based, 5
Service discovery, 514
Service interfaces, 20
### Service level agreements (SLAs):
- DiffServ, 199–200
- Ethernet PONs, 249–250
- QoS provisions, 198–199, 474–475
- Setup time, signaling protocols, 458–459
- Shared explicit (SE) reservation style, 451
- Shared-memory optical packet (SMOP) switch, 164
- Shared protection, 303, 318, 480–481
- Shared risk group (SRG), 394
- Shared-medium emulation (SME) sublayer, 245–247
- Share-per-node switch architecture, 109–110
- Share-with-local switch architecture, 110–111
- Shortest-path algorithm for the wavelength graph (SPAWG):
  - algorithm, 374–375
  - implementation, 373–374
  - simulation results, 375–377
- Shortest-path first (SPF) algorithm, 292, 319, 362, 429, 467
- Shot noise, EDFA, 82
- ShuffleNet, 166–168
- SiGe technology, 69
- Signaling:
  - adjacency, 436–437
  - IP-over-WDM networks, 342–346
  - optical Internet, 403–405
  - optical layer intelligence, 513
  - protocol, 5
  - survivability, IP-over-WDM networks, 504–506
- Signal-spontaneous beat noise, 83
- Signal-to-noise ratio (SNR):
  - A-PON access systems, 221
  - degradation, 135
  - EDFA, 80–81
  - optical, 81, 89, 93, 503
- Signal transparency, 6
- Signal wave, 107
- Signtel, 218
- Silica film, 71
- Silica-on-silicon technology, 76, 84–85
- Silicon bipolar technology, 69
- Simplified data link (SDL), 346–347
- Single hop connections, wavelength conversion, 116
- Single-hop lightpaths, 302
- Single-mode fiber, generally:
  - dispersion, 68
  - dispersion-shifted, 68
- IP-over-WDM architecture, 475
- nonzero dispersion, 68, 91
- optical, see Single-mode optical fibers
- standard, 68
- Single-mode optical fibers:
  - dispersion-shifted (DSF), 68
  - nonzero dispersion (NZDF), 68, 91
  - propagation in, 60–62
  - standard (SSMF), 68
  - types of, 68
- Single-mode semiconductor lasers, 108
- Single-stage buffering, 163
- Single-stage switching fabric, 288–289
- Single-wavelength optical buffering, 131
- SIP, 21
- Slot(s):
  - defined, 222
  - utilization, IP-based services, 261–263
- Slotted networks:
  - illustrative results, 148–149
  - implications of, 131
  - network architecture, 147
  - optical packet switching, 158–161
- Slotted rings, 197
- Slow-start phase, 32
- Small and medium enterprises (SMEs), 191, 217
- SMTP, 21
- SNMP, 292
- Soft state, 53
- Source, generally:
  - address (SA), 522
  - -destination pairs, 135, 175
  - port number field, 25
  - station, 102
- Space deflection, 130, 132–134, 140
- Sparse conversion, 308
- Sparse light splitting, 318
- Sparse wavelength conversion, 118–119
- Spatial reuse protocol (SRP), 212–216
- Spectral efficiency, WDM systems, 90–91
- Splitters:
  - functions of, 217
  - passive, 220, 232–234, 239
  - Splitting loss, passive optical networks, 233
  - Split TCP (STCP), 349–350
- Spontaneous emission, EDFA, 78, 80–81
- Square-law process, 83
- Standard single-mode fiber (SSMF), 68
- Stark splitting, 77
- State variables, 27
- Static lightpath:
  - defined, 330
  - establishment (SLE), 483
INDEX

Static routing algorithms, 113–114, 124, 359
Static RWA, 309, 312, 314
Static synchronization, 161
Stimulated Brillouin scattering (SBS), 65–66, 68
Stimulated emission, EDFA, 78
Stimulated Raman scattering (SRS), 65–66, 68, 89–90, 92
Stimulated scattering, 65
STM-4, 212
Stokes wave, 65–66
Store-and-forward routing, 167
Subcarrier multiplexed (SCM) header, 169–171
Subnetwork connection protection rings (SNC-P rings), 211
Subnetworks, wavelength conversion, 114
Subscriber access network, 230, 235, 239
Suggested label, 435
Survivability:
  B-PON access system, 223–224
  IP layer, 487–490
  IP-over-WDM networks:
    fault detection, 503
    fault notification, 504
    future directions for, 506–508
    illustrative example, 493–496
    importance of, 474–475
    layer considerations, 487–503
    overview, 473–474, 508–509
    protection, 479–481
    restoration, 482
    signaling protocol mechanism, 504–506
    survivable routing algorithms, 482–487
    multilayer mechanisms, 496–503
    network, generally, 17
    optical burst switching (OBS), 412–417, 507–508
    optical routing, 392–394
    WDM layer, 491–493
    WDM mesh networks, 496
Survival function, TCP connection, 336–337
Suurballe’s algorithm, 486
Swiss PTT, 217
Switch design, wavelength-convertible, 109–110
Switched virtual circuit (SVC), 518
Switching, generally:
  ATM, 10
  fabric, see Switching fabric
  fast packet, 17
  granularity, 5
  IP, 50–52
  optical, 287
  optical burst (OBS), 175–176
  optical enabling technologies, 84–87
  optical label, 171
  optical packet, see Optical packet switching
  packet, 425
  protection, 6, 322
Switching fabric, terabit switching and routing (TSR):
  multistage, 289–290
  single-stage, 288–289
Switch large optical buffers (SLOBs), 165
SYN bit, 28
SYN segment, 29
Synchronization:
  access networks, 192
  contention-resolution schemes, 147
  slotted networks, 158–161
Synchronous Optical Network (SONET):
  multilayer model, 293
  resource discovery, 428
  restoration management, 431
  signaling, 435
  terabit switching and routing (TSR), 283
Synchronous Optical Network/Synchronous Digital Hierarchy (SONET/SDH) technology:
  access networks, 198
  ATM switching, 10
  characteristics of, generally, 2, 4–7, 182–183, 186, 278, 476, 511, 517
  coexistence with IP traffic, 10
  control architecture, 303
  cross-connect costs, 212
  defined, 182
  digital cross-connect (DCS), 425
  dual counterrotating rings, 209–212
  framing, 346–347
  IEEE standards, 531
  metro, 193, 198
  metropolitan access networks, 210–212
  packet over, 9
  PDH compared with, 182–183
  self-healing rings, 188
  signaling, 342, 345
  survivability, 475, 503
  10–gigabit Ethernet, 530
  terabit switching and routing (TSR), 278, 284
  over WDM, 9
Synchronous Optical Network/WDM, 473
Tagged ONU, 259
Tantalium oxide film, 71
TCP/IP:
  connection, 348
  Ethernet PONs vs., 262–263
stack, 20–21
traffic, 152, 218
TCP Reno, 33
TCP Tahoe, 33
TCP/UDP, 347
Telecordia, 171
Telecom Italia, 217
Telecommunication management network (TMN), 423
Telecommunications, historical perspective, 9
Telefónica, 217
Telephone network, circuit-switched, 101
Telstra, 217
Temperature stabilization, WDM devices, 76
10–bit gigabit, 528–530
Terabit-class routers, 277–278
Terabits per second (Tbps), 1
Terabit switching and routing (TSR):
architectures:
buffering schemes, 285–287
generic, 284–285
port interface, input/output, 285
switching fabric, 287–290
future directions for, 277–278
IP-over-WDM routing, 381
multiprotocol label switching (MPLS):
with, 293–295
without, 292–293
network requirements:
granularity, 283
modular structure, 283
multiple protocol interfaces, 283
quality of service, 283–284
scalability, 283
traffic aggregation, 282–283
opaque, 280–282
optical network nodes, IP implications:
electronic controller, IP-based, 291–292
input port interface (IPI), IP-based, 290–291
output port interface (OPI), 290–291
transparent, 279–280
Terrestrial fiber links, 88–89
Theft of service, 269
Thermal noise, EDFA, 82
Thermo-optic effect, 85
Thin-film filters, 71–72
3G wireless networks, 40
Threshold, 31–32
Thulium-doped fiber amplifiers (TDFA), 92
Time division multiple access (TDMA), 203, 239
Time-division multiplexing (TDM):
characteristics of, generally, 45, 174–175, 182, 209, 211
IP-over-WDM:
arquitectura, 477
routing, 381
network control, 425
terabit switching and routing (TSR), 279
WDM PONs vs., 234–236
Time-to-live (TTL):
errors, 503
implications of, 37, 212–213
mechanisms, 133
TLV (type-length-value) scheme:
characteristics of, generally, 435–436, 440
CR-LDP:
ER-hop TLV, 446–448
explicit route TLV, 447
encoding:
FEC TLV, 440
label TLV, 441
endpoint, 449
ID, 449
parameter, 450
survivability, 495
T1 transmission time, 267–268
Top-down escalation strategy, 498
Topology, generally:
design, 17
update message, 467–468
Topology connectivity matrix (TCM), 465, 467
Torus network, two-dimensional, 116
TOS (type of service), 54, 198–199
Traditional networking, 512
Traffic, generally:
aggregation, 282–283, 479
demand, 304
engineering:
characteristics of, 9, 34, 200, 293–294
extension, 436
reactive, 513
grooming, 476
management goals, 52–53
routing subproblems, 312–313
Traffic stream path (TSP), 496
Transfer/transmission control protocol (TCP), see TCP/IP
characteristics of, 8
derend-end (EE-PPS), 349
high-speed connections, 349–350
split connections, 349–350
QoS parameters, 198
transport layer:
connection-oriented transport, 26–33
Transfer/transmission control protocol (TCP), see TCP/IP (Continued)
generally, 23
photonic slot routing, 174
reliability of, 29–30
Transmission, bidirectional, 232
Transmitters:
access networks, 192
optical enabling technologies, WDM system, 69–71
Transparency, wavelength conversion, 105, 108
Transparent optical, 387
Transparent TSR, 279–280
Transport layer:
characteristics of, 21
service models at, 23–25
TCP and, 23
UDP, 25–26
Transport network granularity, 6
Transport optical networks, global perspective, 182–187
Transport protocol, reliable/unreliable, 24
Transreceivers:
integrated optics bidirectional single-fiber, 94
multiple, 271–272
Troubleshooting, 9
TSpec, 53
Tunable receiver (TR), 202–203
Tunable transmitter (TT), 202
TV:
high-definition, 304
sets, analog, 263
Two-hop connections, wavelength conversion, 117–118
Two-way reservation, 398
Type-of-service (TOS) field, 37
Ultraviolet light, 73
Unfairness factor, 123–124, 321
Unicast communication, 213
UNI/NNI signaling, 405
Uninterruptible power supply (UPS), 531
Uniqueness, IP address, 37
United States, access networks, 192
Unnecessary reservation, 416–417
Unreliable datagram protocol (UDP):
characteristics of, 21, 24–25, 147
connectionless transport, 25–26
segment structure, 26
Unslotted networks:
deflection routing, 168
illustrative results, 148–149
network architecture, 147
optical packet switching, 131, 161–162
Unspecified bit rate (UBR), 46
Up-converted, 107
Upper-bound insertion, 174
Upstream routers, 52
Upstream transmission, 235–236, 238–240, 246, 269–270
URG bit, 28
Urgent pointer, 28
URL, 200
User datagram protocol (UDP), 198
User demand, 309
User-to-network interface (UNI), 47, 303, 322, 342, 382, 404, 426, 477, 516, 519–520, 526
Variable assemble time (VAT), burst assembly, 406
Variable bit rate (VBR):
characteristics of, 46
video, 251
Variable-size packets, 130
VCI/VPI, 280
Velocity dispersion, 392
Verizon, 192, 218
Very high speed digital subscriber line (VDSL) technology, 217, 219–220
Vestigial sideband (VSB) modulation, 90
Video broadcasting, 234
Video conferencing, 212, 264, 407
Video on demand (VoD), 229
Video servers, 190
Video traffic, 263
Virtual channels (VCs), ATM, 47, 49, 51
Virtual circuits, 330
Virtual connection, 186
Virtual containers, 183, 210
Virtual LAN (VLAN), 200, 238, 247
Virtual output queuing (VOQ), 286–287
Virtual paths (VP), ATM, 47
Virtual private networks (VPNs), 54, 193, 210, 293, 315–316
Virtual topology, 309, 311–314, 338
Voice-over IP (VoIP):
defined, 263
real-time video and, 264–268
Voice servers, 190
WAN interface sublayer (WIS), 530
Wavelength assignment:
implications of, 17, 430–431
subproblem, 312
INDEX

Wavelength changers, 103
Wavelength constraint, 102–103
Wavelength continuity, 102
Wavelength continuity constraint, 103, 306–307, 430, 502
Wavelength-continuous networks, 102
Wavelength conversion:
  benefit analysis:
    analysis models, 114–122
    gain characteristics, 123–124
    contention-resolution schemes, 130–132, 168–169
  defined, 103
  fixed, 124
  limited-range, 112, 123
  minimal, 123–124
  multifiber networks, 123
  network control, 113–114
  network design, 111–112
  network management, 114
  overview, 17, 102–104, 124
  routing constraints, 394
  RWA algorithms, 123
  wavelength-converter design, 104–109
  wavelength-convertible switch design, 109–111
Wavelength-convertible networks, 103
Wavelength converters:
  characteristics of, 102–104, 307
  network design, 112
  optical enabling technologies, 87–88
  sharing, 112
Wavelength cut-through, 17
Wavelength-division multiplexing (WDM):
  architecture, 475–479
  characteristics of, 5–6
  defined, 1–2
  design:
    non-Poisson traffic, 377–380
    simulation results, wavelength conversion, 375–377
    SPAWG algorithm, 374–375
    SPAWG implementation, 373–374
    virtual wavelength path (VWP) approach, 372–373, 375–376, 380
  IP over, 9–12, 477
  layer, survivability, 491–493
  metropolitan networks, 193
  optical enabling technologies, 59–94
  routing:
    overview, 363–365
    routing and wavelength assignment (RWA), 365–366
  SONET/SDH over, 9
  TDM PONs vs., 234–236
  technology:
    first-generation, 338–340
    second-generation, 340–342
Wavelength graph (WG):
  shortest-path algorithm (SPAWG), 374–375
  virtual wavelength path algorithm, 373
Wavelength-interchanging cross-connect (WIXC), 107
Wavelength-routed network, characteristics of, 101–103
Wavelength-routed PON (WRPON), 235
Wavelength routing, 101, 301
Wavelength-selective cross-connects (WIXCs), 476
Wavelength shifters, 103
Wavelength translators, 103
Wave mixing, 106
Web, generally:
  cams, 531
  characteristics of, 21, 45
  farms, 5
  servers, 190
Wide area networks (WANs):
  capacity, 8
  characteristics of, 49, 234, 238, 530
  Wildcard filter (WF) reservation style, 451
  Window size, 31–32
Wireless in the loop (WITL), 191–192
Wireless networks, 40
Working group (WG), IntServ, 53
Working lightpaths, 495
WRON, 369, 377
WWW servers, 335–336
xDSL network, 2, 348
X.25, 184
Zero-chirp intensity modulation, 63