CHAPTER 17

STATE OF THE ART

17.1 INTRODUCTION

Dense wavelength division multiplexing (DWDM) is a technology that depends heavily on optical components, many of which are state of the art, produced in low volumes, and thus costly. Consequently, research continues to develop new and better performing optical components as well as integrated optical compact components at low cost. Amplifiers, multiplexers, filters, signal conditioners, transmitter arrays, and receiver arrays are among the items in development. These components should perform such that center frequencies and power level are compatible, conforming to standard physical interfaces. In addition, standard transport protocols and network management standards are necessary for interoperability and uniform quality of service. This chapter addresses some areas in which intense research is being conducted. Areas not included are not less important; we simply cannot mention them all.

17.2 CURRENT ISSUES

17.2.1 Optical Materials

Artificial new solid-state optical materials with unusual characteristics are in the experimental stage. Such characteristics are based on extremely high values of index of refraction, polarization, and switching properties when a varying field is applied. Other properties are based on optical energy absorption and coherent photoluminescence in a wide spectrum range that covers the C- and L-bands, or beyond.

Experimental materials in addition to solid-state materials include organic compounds that can absorb one wavelength and emit another (wavelength conversion, memory) or can absorb a wavelength and emit it when stimulated (memory).

17.2.2 Integration

Optical integration will also be the "next step" in the evolution of optical devices. Integration, combined with sophisticated packaging, will yield devices with complex functionality that could perform optical signal processing with no need to convert the optical signal to electrical. Soon optical devices will follow an evolutionary path similar to those of the transistor and the intergrated devices. A few years ago it was a dream to approach a million transistors in a chip. Today, this dream is past tense and unimpressive.

17.2.3 Lasers and Receivers

Low-cost lasers are important in many applications. Some researchers are even experimenting with organic compounds to create inexpensive high-density plastic lasers and other components. Development of high-power tunable lasers that are inexpensive and laser arrays with narrow line width and sufficient optical power for DWDM applications is another activity. Tunable receivers and receiver arrays at low cost are in development. In the same venue, some techniques generate hundreds of wavelength channels with a single laser.

A similar activity is to produce tunable receivers and receiver arrays at low cost. In this venue, some have succeeded to generate hundreds of wavelength channels with a single laser.

17.2.4 Line Coding Techniques

As the number of wavelengths per fiber increases (approaching 1000), and as the number of bits per second increase (currently 40 Gb/s), the optical signal becomes more vulnurable to errors due to dispersion and other linear and nonlinear phenomena. This vulnurability increase, however, should not compromise in any way the qualityof the signal; the signal must be maintained at acceptable and expected levels despite the aggregate bandwidth benefit. This means that signal error countermeasures must be developed to compensate for and correct induced errors on the signal.

Such countermeasures may be based on the new intersymbol interference (ISI) resistant coding techniques, or they may be based on error detection/correction mechanisms that are able to locate and correct errors, or a combination of both line coding and error correction. A metric of good line coders (for 10 Gb/s) is to produce an acceptable eye diagram at the receiver such that the uncertainty of the state (1 or 0) of the received bits is less than 1 bit per second per hertz (< 1 b/s/Hz). Error rates (as specified in ITU-T standards) may be les than 10^{-12} BER.

17.2.5 Optical Cross-Connect

As the number of wavelengths increases beyond 200 and approaching 1000, 1000 × 1000 low-loss, nonblocking, and fast-switching optical cross-connect devices are a challenge. Although there have been interesting proposals to produce such devices, it remains to be seen which become commercial products.

In addition, there is research under way to develop ultrafast switching devices based on glasses that contain chalcogenides. Chalcogenide glasses (Ge-Se-Te) have an index of refraction 1000 times higher than SiO2 glass, an ultrafast response time (they can switch from high nonlinear absorption to low) in less than 1 ps, a low linear loss a low nonlinear loss and a high figure of merit (FOM), in the order of 20.

17.2.6 Optical Add–Drop Multiplexers

Low-cost optical add–drop multiplexers (OADMs) are key components in optical networks. OADM devices allow the dropping off and addition of wavelengths selectively, and their passage through all other wavelengths. Low-loss and low-cost OADM devices that add or drop groups of wavelengths on a selective basis are another challenge.

Fibers will soon be connected to the desktop computer and multimedia devices. The 1960s bit rate to the home of 64 Kb/s will be higher than 1.5 to 2 Mb/s in the 2000s (in some cases it may be up to 50 Mb/s). These applications will demand extremely low-cost and reliable optical devices (transmitters, receivers, and filters).

17.2.7 Optical Memories and Variable Delay Lines

Optical delay lines consist of fiber cut at lengths that, based on travel time of light in the fiber medium, can delay light by a fixed amount of time. This principle is already used in monolithic interferometers. However, compact optical devices that can store a light pulse of the necessary length would allow construction of a true optical memory and a variable delay. Such devices could be used to treat light pulses like electronic pulses and to construct optical integrated subsystems with time division concepts as well as computational properties.

17.2.8 Nonintrusive Optical Monitoring

Nonintrusive optical signal monitoring is difficult to perform but important. The optical signal needs to be monitored for power, noise, "eye" closure (enough power to be detected by the receiver), wavelength accuracy, and line width. In addition, if a wavelength channel carries supervisory information, including telemetry, some information needs to be terminated, whereas some other needs to be passed transparently. In general, nonintrusive optical monitoring reduces the amount of optoelectronics, reduces latency, and increases reliability.

17.2.9 DWDM System Dynamic Reconfigurability

System dynamic reconfigurability implies dynamic wavelength and bandwidth management and thus, fast tunable optical devices (lasers, receivers, and filters), as well as fast and intelligent protocols.

17.2.10 Optical Backplanes

The incoming optical signal at a port will be monitored and the optical signal will be directly coupled to an optical backplane that routes the signals to another unit of the system (e.g., an optical cross-connect fabric). Optical backplanes provide a cost-effective and compact solution to an all-optical system.

17.2.11 Standards

Currently, standards have been issued (see end-of-chapter listing), others are being drafted, and others are in the proposal phase. As DWDM evolves, more proposals are expected to be submitted to address emerging issues on all aspects of DWDM systems and networking. The standards bodies are evaluating the proposed standards.

17.2.12 Network Issues

DWDM in optical networks is new territory and thus many new issues emerge. These issues boil down to performance, efficiency, flexibility, reliability, scalability, and cost. Since a vast amount of work is in progress to resolve these issues, we should identify some of them.

- Are all nodes in the DWDM network optically transparent, or are they opaque?
- If they are transparent, how do we establish end-to-end (from optical source to destination) wavelength connectivity?
- How do we determine the optimum number of optical components on the end-to-end optical connection (the number of optical components may not be the same from one end to the other) throughout the network?
- How do we execute performance monitoring in the optical regime?
- What are the rules and mechanisms for fault detection, fault avoidance, and fault restoration on the optical node, optical network, level, and wavelength levels?
- What are the rules and the mechanisms for DWDM network survivability?
- How do we assure service reliability, service integrity, and quality of service in DWDM?
- What are the mechanisms for optical network management?
- How do we transport over the same DWDM network a variety of services IP, SONET/SDH, ATM, Ethernet-type, and others)?
- How do we assign or reassign wavelengths across a DWDM optical network?
- How do we assure security of network and of data?
- As DWDM systems are further deployed and evolve, how do we cope with new emerging issues?

17.2.13 Ultrahigh Speeds at Longer Spans

DWDM systems enable a tremendous bandwidth per fiber. However, competition and pressures for service at lower cost fuel research and thinking. Once a speed has been achieved, a higher speed is contemplated. Once transmission over a longer fiber span without amplification has been achieved, a longer span yet is planned for. Currently, 40 Gb/s at 8×80 km^2 spans (with amplification) is reality. If signal integrity, device noise, and loss figures improve, then optical signal loss, signal noise, and bit error rate will be reduced, allowing longer yet fiber spans (for the same receiver sensitivity as before). In addition, improvements in forward error correction techniques (e.g., digital wrapper) further reduce BER and further extend the fiber span.

17.2.14 Opaque Systems

DWDM technology increases the aggregate bandwidth in a fiber, and large systems terminate many fibers. Thus, the aggregate system bandwidth is the sum of aggregate bandwidth of each fiber. For example, a system with 10 fibers, 40 wavelengths per fiber, and 2.5 Gb/s per wavelength has an aggregate bandwidth of 1 Tb/s. Presently, an all-optical switching system with a capacity of terabits per second is not economical. System cost is dominated by optical device cost and by ultrafast electronic devices for clock recovery, signal equalization, framing, synchronization, and switching. Thus, systems at these capacity levels are by and large electro-optical (opaque) systems; that is, the system itself is electronic and the interfaces and transmission medium are optical. A possible opaque system in the terabits-per-second range is shown in Figure 17.1.

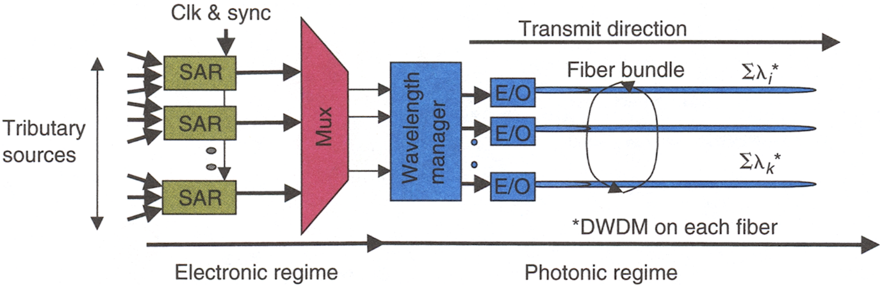


Figure 17.1 Possible DWDM system for operation in the terabits-per-second range.

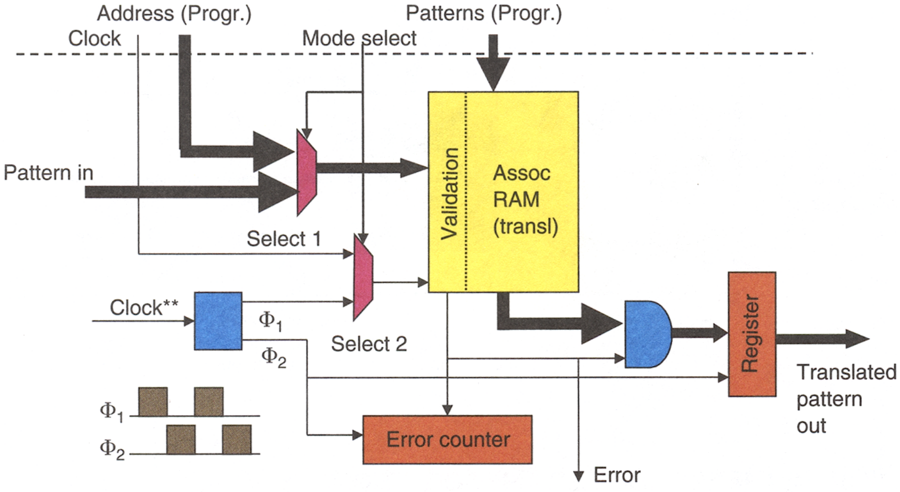
17.3 ULTRAFAST PATTERN RECOGNITION

One of the key functions in ultrafast, ultrahigh-bandwidth systems is real-time pattern recognition, that is, framing decoding, IP/ATM header field decoding, error code decoding, address (source/destination) decoding, and so on. At bit rates of 10 Gb/s (or 40 Gb/s), ultrafast digital electronic circuitry with picosecond switching capability is required at the high-speed physical layer. (Pattern recognition in the optical regime—all photonic and without electronics—has not been cost-effectively implemented yet.) Thus, depending on data traffic type, millions of patterns per second may need to be recognized, and perhaps each one will have to be translated to another pattern.

This ultrafast electronic "recognizer" circuitry should not be complex; it may be limited to clock circuitry and a simple shift register to capture a byte or a word in real time. Reading bytes or words reduces the recognition speed by 8 or 16 times the bit rate. Thus, the "recognizer" can operate a little more slowly—in the nanosecond range, not the picosecond.

Devices that can perform fast pattern recognition and translation are known. Content-addressable memories (CAM) are one example. When a pattern is applied at the parallel data input of the CAM, the device recognizes it and translates it to another pattern, if needed. The complete operation takes place in one clock cycle. However, commercially available CAMs operate in the order of 100 ns, the pattern set is limited, and the power consumption is relatively high, increasing complexity and thus cost of the system.

A different approach, which uses fast random access memory (RAM) devices with an access cycle of less than 4 ns, is capable of recognizing and translating millions of patterns. This simple approach, known as *associative RAM-based CAM* (AR-CAM), cost-effectively accomplishes pattern recognition and translation at giga patterns per second (Figure 17.2).



**Clock is derived from the line rate

Figure 17.2 Implementation of an associative RAM-based CAM (AR-CAM).

17.3.1 Example: SONET/SDH

SONET and SDH systems are based on synchronous frame communication principles. Each frame is repeated every 125 μs. The first bytes of a frame (2 bytes in an

OC-3, 8 bytes in an OC-12) contain a fixed pattern that is used for synchronization purposes. Other bytes are used for error control, pointers in the payload area, protection switching, and so on. See Table 14.2 for SONET and SDH rates.

A signal at ~10 Gb/s that consists of 196 OC-3 multiplexed signals presents a challenge in recognizing synchronization patterns and other patterns in the overhead section of OC-3 frames. AR-CAMs with an address bus 8 bits wide can cope comfortably with such high pattern recognition rates.

17.3.2 Example: ATM

ATM consists of 53-byte frames that do not all arrive synchronously. However, ATM cells may have been mapped onto the STM payload. ATM cells consist of a 5-byte header and a 48-byte payload. The 5 bytes of the ATM cell header are partitioned (in the case of network-to-network interface or NNI) as follows:

- Virtual path identifier: 12 bits
- Virtual channel identifier: 16 bits
- Payload type identifier and cell loss priority: 4 bits
- Head error control: 8 bits

In a high cell-rate STM case, there may be 350,000 ATM cells per second. That is, pattern recognition in 1.4 μs is required. However, assuming that there are 16 incoming sources, each with 350,000 cells/s, then recognition time is 8.5 ns. A single AR-CAM could accomplish this task very comfortably, whereas a CAM could not. Thus, ATM cells may be quickly recognized and rerouted with the minimum amount of latency.

17.3.3 Example: Internet Protocol

IP packets based on Internet Protocol version 4 (IPv4) consist of an IP header (6 × 32 bits) and a datagram (up to 65,535 octets); future IP versions such as IPv6 will be similarly constituted. A router fragments the datagram and attaches to each one an IP packet header. Fragments may not be of equal length. Based on the network used (SONET/ATM/other) to transport IP packets, the packet may be further segmented by the segmentation and reassembly (SAR) function. The receiving terminal reassembles all fragments, based on flags and offset (flags and offset are contained in the IP header). The IP header contains information such as the following:

- Version field (IP format, version of protocol): 4 bits
- Internet header length (measured in 32-bit words): 4 bits
- Type of service (QoS): 8 bits
- Total length (of datagram, up to 65,535 octets): 16 bits

- ID (unique for each datagram used to reassemble): 16 bits
- Flags (O, DF, DM): 3 bits
- Fragment offset (up to 8192 fragments): 12 bits
- Time to live (time to remain on Internet): 8 bits
- Protocol (upper layer protocol): 8 bits
- Header checksum: 16 bits
- Source address.: 32 bits (IPv4), 128 bits in *colon hexadecimal* (IPv6)
- Destination address.: 32 bits (IPv4), 128 bits in *colon hexadecimal* (IPv6)
- Options and padding: 32 bits

Thus, AR-CAMs may be used to recognize multiple IP packets fast (within a clock cycle), with negligible latency, thus addressing one of the optical networks issue, namely, fast routability (via fast recognition).

17.4 CURRENT RESEARCH: WAVELENGTH BUS

Current DWDM systems have a number of wavelengths (channels) in a fiber but each wavelength is allocated for one channel. Therefore, the total bandwidth capacity of the DWDM fiber is the sum of bandwidth of each channel. To maximize the efficiency of the bandwidth per fiber, wavelengths may be organized in parallel buses (e.g., five buses each consisting of 8 wavelengths), or fewer buses and individual wavelengths to meet different requirements and provide compatibility with existing systems.

Now, consider a multiplicity of data tributaries. In addition, consider that bytes from each tributary are in parallel (not serial) and the tributaries are byte-multiplexed, forming a multiplexed 8-wavelength bus. The parallel multiplexed data is now transmitted over 8 wavelengths of an 8-wavelength bus.

All wavelengths of a bus carry modulated information at the same bit rate (e.g., 10 Gb/s). In this case, the total bandwidth of the bus is $8 \times 10 = 80$ Gb/s. Because tributaries are multiplexed, many tributaries, each at a different rate, may be multiplexed, up to a total aggregate of 80 Gb/s. This method establishes flexibility, scalability, and efficient bandwidth utilization that typically cannot be readily achieved with traditional DWDM systems where, for example, each of 8 wavelength channels would carry data at a different rate. In addition, an 8-wavelength bus allows for more than eight users to share the total aggregate bandwidth, as opposed to traditional DWDM, which allows for as many users as the number of wavelengths in the fiber.

Figure 17.3 illustrates a multiplicity of tributaries that are terminated at a physical interface (PHY). If serial data are converted into parallel (SP), D_i, all parallel data are multiplexed by the multiplexer unit to form a high-speed, high-aggregate-bandwidth parallel bus (b_0-b_7), each rail of which modulates a laser transmitter to form a parallel wavelength bus ($\lambda_1-\lambda_8$), with each rail transmitting at the same rate.

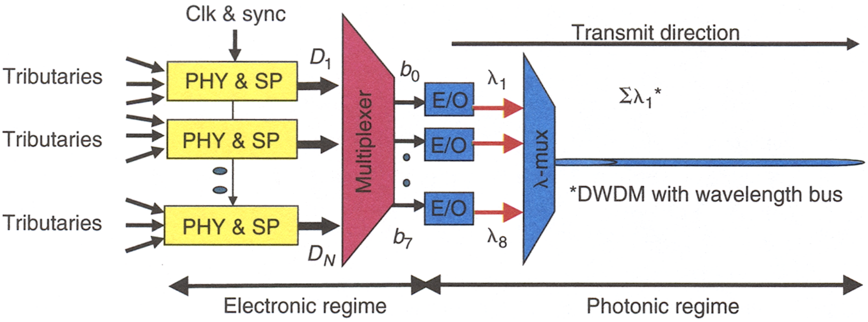


Figure 17.3 Parallel data buses (D_1–D_N) are multiplexed to form a high-speed, high-aggregate-bandwidth parallel bus (b_0–b_7), each rail of which is launched into the fiber to construct a parallel wavelength bus (λ_1–λ_8).

In the receive direction (Figure 17.4), the reverse takes place. A parallel wavelength bus ($\lambda_1 - \lambda_8$) is received and converted to an electrical parallel bus ($b_0 - b_7$), and since each rail is at the same rate, only one clock circuit is necessary. The parallel bus feeds a fast recognizer (AR-CAM) that recognizes the target destination of each multiplexed channel (packet, cell or timeslot), and in conjunction with a demultiplexer, each payload is delivered to its target destination.

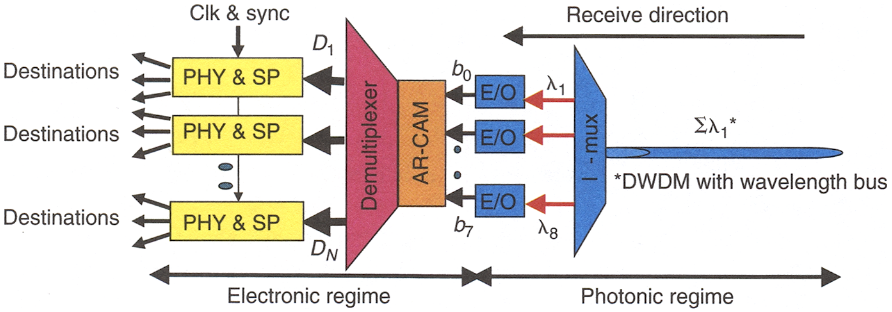


Figure 17.4 Received parallel multiplexed data (b_0–b_7) from the wavelength bus (λ_1–λ_8) are demultiplexed to form lower speed parallel buses (D_1–D_N), each with different destination. AR-CAM circuitry performs rapid address recognition of each multiplexed traffic.

REFERENCES

[1] S.V. Kartalopoulos, *Understanding SONET/SDH and ATM: Communications Networks for the next millennium*, IEEE Press, Piscataway, NJ, 1999.

[2] R. Ramaswami and K.N. Sivarajan, *Optical Networks*, Morgan Kaufmann, San Francisco, 1998.

[3] B. Mukherjee, *Optical Communication Networks*, McGraw-Hill, New York, 1997.

[4] I.P. Kaminow, ed., and T.L. Koch, ed., *Optical Fiber Communications IIIA* and *Optical Fiber Communications IIIB*, Academic Press, San Diego, CA, 1997.

[5] E. Traupman, P. O'Connell, G. Minnis, M. Jadoul, and H. Mario, "The Evolution of the Existing Infrastructure," *IEEE Communications Magazine,* vol. 37, no. 6, 1999, pp. 134–139.

[6] A.G. Malis, "Reconstructing Transmision Networks Using ATM and DWDM," *IEEE Communications Magazine,* vol. 37, no. 6, 1999, pp. 140–145.

[7] T.-H. Wu, *Fiber Network Service Survivability.* Artec House, Boston, 1992.

[8] L. Boivin, M.C. Nuss, W.H. Knox, and J.B. Stark, "206-Channel Chirped-Pulse Wavelength-Division Multiplexed Transmitter," *Electronics Letters,* vol. 33, no. 10, pp. 827–828, 1997.

[9] J.M. Simmons et al., "Optical Crossconnects of Reduced Complexity for WDM Networks with Bidirectional Symmetry," *IEEE Photonics Technology Letters,* vol. 10, no. 6, June 1998, pp. 819–821.

[10] E.A. De Souza et al., "Wavelength-Division Multiplexing with Femtosecond Pulses," *Optics Letters,* vol. 20, no. 10, 1995, pp. 1166–1168.

[11] S.V. Kartalopoulos, "An Associative RAM-Based CAM and Its Application to Broad-Band Communications Systems," *IEEE Transactions in Neural Networks,* vol. 9, no. 5, 1998, pp. 1036–1041.

[12] S.V. Kartalopoulos, "Ultrafast Pattern Recognition in Broadband Communications Systems," *ISPACS'98 Conference Proceedings,* Melbourne, Australia, November 1998.

[13] A. Asthana et al., "Towards a Gigabit IP Router," *Journal of High-Speed Networks,* vol. 1, no. 4, 1992.

[14] S.V. Kartalopoulos, "The λ-Bus in Ultra-fast DWDM Systems."

[15] S.V. Kartalopoulos, "Synchronization Techniques Ultra-fast DWDM Systems: The λ-Bus."

[16] S.V. Kartalopoulos, "Add-Drop with Ultra-fast DWDM/λ-Bus."

[17] S.V. Kartalopoulos, "Increasing Bandwidth Capacity in DWDM/λ-Bus Systems."

[18] S.V. Kartalopoulos, "Cryptographic Techniques with Ultra-fast DWDM/λ-Bus Systems."

[19] C.A. Brackett, "Dense Wavelength Division Multiplexing Networks: Principles and Applications," *IEEE Journal on Selected Areas in Communications,* vol. 8, no. 6, August 1990.

[20] Internet study group: http://www.internet2.edu.

[21] H. Yoshimura, K-I. Sato, and N. Takachio, "Future Photonic Transport Networks Based on WDM Technologies," *IEEE Communications Magazine,* vol. 37, no. 2, February 1999, pp. 74–81.

[22] L.H. Sahasrabuddhe and B. Mukherjee, "Light-Trees: Optical Multicasting for Improved Performance in Wavelength-Routed Networks," *IEEE Communications Magazine,* vol. 37, no. 2, February 1999, pp. 67–73.

[23] M.A. Marsan, A. Bianco, E. Leonardi, A. Morabito, and F. Neri, "All-Optical WDM Multi-Rings with Differentiated QoS," *IEEE Communications Magazine,* vol. 37, no. 2, February 1999, pp. 58–66.

[24] Y. Pan, C. Qiao, and Y. Yang, "Optical Multistage Interconnection Networks: New Challenges and Approaches," *IEEE Communications Magazine,* vol. 37, no. 2, February 1999, pp. 50–56.

[25] K. Sato, *Advances in Transport Network Technologies—Photonic Networks, ATM and SDH,* House, Boston, 1996.

[26] N. Takachio and S. Ohteru, "Scale of WDM Transport Network Using Different Types of Fibers," *IEEE Journal on Selected Areas in Communications,* vol. 16, no. 7, 1998, pp. 1320–1326.

[27] B. Mukhergie, *Optical Communications Networks,* McGraw-Hill, New York, 1997.

[28] P.E. Green Jr., *Fiber Optic Networks,* Prentice Hall, Englewood Cliffs, NJ, 1993.

[29] M. A. Marsan et al., "Daisy: A Scalable All-Optical Packet Network with Multi-Fiber Ring Topology," *Computer Networks and ISDN Systems,* vol. 30, 1998, pp. 1065–1082.

[30] I. Gidon and Y. Ofek, "MetaRing—A Full-Duplex Ring with Fairness and Spatial Reuse," *IEEE Transactions on Communications,* vol. 41, no. 1, January 1993, pp. 110–120.

[31] S. Ohteru and K. Inoue, "Optical Time Division Multiplexer Utilizing Modulation Signal Supplied to Optical Modulation as a Reference," *IEEE Photon,* vol. 8, no. 9, 1996, pp. 1181–1183.

[32] J.R. Freer, *Computer Communications and Networks,* IEEE Press, Piscataway, NJ, 1996.

[33] R. Handel and M.N. Huber, *Integrated Broadband Network,* Addison Wesley, Reading, MA, 1991.

[34] R.D. Gitlin, J.F. Hayes, and S.B. Weinstein, *Data Communications Principles,* Plenum, New York, 1992.

[35] S.V. Kartalopoulos, "A Manhattan Fiber Distributed Data Interface Architecture," *Globecom'90,* San Diego, CA, December 2–5, 1990.

[36] S.V. Kartalopoulos, "Disaster Avoidance in the Manhattan Fiber Distributed Data Interface Network," *Globecom'93,* Houston, TX, December 2, 1993.

[37] S.V. Kartalopoulos, "A Plateau of Performance?" *IEEE Communications Magazine,* September 1992, pp. 13–14.

[38] A.E. Willner, "Mining the Optical Bandwidth for a Terabit per Second," *IEEE Spectrum,* April 1997, pp. 32–41.

[39] S.V. Kartalopoulos, *Understanding Neural Networks and Fuzzy Logic,* IEEE Press, Piscataway, NJ, 1995.

[40] Members of the Technical Staff, *Transmission Systems for Communications,* Bell Telephone Laboratories, Murray Hill, NJ, 1982.

[41] J. Nellist, *Understanding Telecommunications and Lightwave Systems,* IEEE Press, Piscataway, NJ, 1996.

[42] W.Y. Zhou and Y. Wu, "COFDM: An Overview," *IEEE Transactions on Broadcasting,* vol. 41, no. 1, March 1995, pp. 1–843.

[43] K.-I. Kitayama, "Code Division Multiplexing Lightwave Networks Based upon Optical Code Conversion," *IEEE Journal on Selected Areas in Communications,* vol. 16, no. 7, September 1998, pp. 1309–1310.

[44] T. Shiragaki et al., "Optical Cross-Connect System Incorporated with Newly Developed Operation and Management System," *IEEE Journal on Selected Areas in Communications,* vol. 16, no. 7, September 1998, pp. 1179–1189.

[45] S. Johansson et al., "A Cost-Effective Approach to Introduce an Optical WDM Network in the Metropolitan Environment," *IEEE Journal on Selected Areas in Communications,* vol. 16, no. 7, September 1998, pp. 1109–1122.

[46] Y. Miyao and H. Saito, "Optimal Design and Evaluation of Survivable WDM Transport Networks," *IEEE Journal on Selected Areas in Communications,* vol. 16, no. 7, September 1998, pp. 1190–1198.

[47] B. Van Caenegem, W. Van Parys, and P.M. Demeester, "Dimensioning of Survivable WDM Networks," *IEEE Journal on Selected Areas in Communications,* vol. 16, no. 7, September 1998, pp. 1146–1157.

[48] O. Crochat and J-Y. Le Boudec, "Design Protection for WDM Optical Networks," *IEEE Journal on Selected Areas in Communications,* vol. 16, no. 7, September 1998, pp. 1158–1165.

[49] M.W. Maeda, "Management and Control of Transparent Optical Networks," *IEEE Journal on Selected Areas in Communications,* vol. 16, no. 7, September 1998, pp. 1008–1023.

[50] E. Karasan and E. Ayanoglu, "Performance of WDM Transport Networks," *IEEE Journal on Selected Areas in Communications,* vol. 16, no. 7, September 1998, pp. 1081–1096.

STANDARDS

[1] ANSI T1X1.5/99-002, "A Proposal for Providing Channel-Associated Optical Channel Overhead in the OTN," George Newsome and Paul Bonenfant, Lucent, January 1999.

[2] ANSI T1X1.5/99-003, "A Proposed Implementation for a Digital 'Wrapper' for OCh Overhead," James Ballintine, Lucent, January 1999.

[3] ANSI T1X1.5/99-004, "Optical Channel Overhead Carried on the Optical Supervisory Channel," George Newsome and Paul Bonenfant, Lucent, January 1999.

[4] ANSI T1X1.5/99-146, "Proposed OCh—OH Assignments for the OCh Frame," James Ballintine, Lucent, May 1999.