M. Jonsson, "High-performance fiber-optic communication networks for distributed computing systems," Research report CCA-9709, Centre for Computer Systems Architecture (CCA), Halmstad University, Sweden, Apr. 1997.

High-Performance Fiber-Optic Communication Networks for Distributed Computing Systems

Magnus Jonsson

Halmstad University, Halmstad, Sweden
email: magnus.jonsson@cca.hh.se

Abstract

Interconnection networks have a key role in distributed processing systems of today but to follow the evolution in processing power, new technologies are needed. Multiple-channel fiber-optic communication can solve the emerging demand of bandwidth. New protocols must, however, be used to coordinate the use of multiple high-speed channels. This paper describes protocols and fiber-optic network architectures that are considered to be useful as flexible interconnection networks in future parallel and distributed computing systems. Also, a short overview of system components and system technologies is presented.

Contents

1. Introduction

Optical fibers for communication systems offer a bandwidth of more than 30 THz [Brackett 1990]. This makes fiber-optics very potential for future computer communication networks for data intensive applications. In this survey, representative examples of high-performance fiber-optic networks and MAC (Medium Access Control) protocols [Rom and Sidi 1990] for those networks are described. WDMA (Wavelength Division Multiple Access, described below) networks, and passive optical networks (PONs) are given special attention. The focus is on optical LANs [Kazovsky et al. 1994] and similar networks that can be used for flexible communication in parallel and distributed computing systems. Many proposed fiber-optic networks, although developed with a specific application in mind, can be used in a wide range of applications and we are therefore not necessarily sorting those networks out. Nevertheless, e.g., pure telecommunication networks are not treated here. Previous overviews covering high-capacity fiber-optic networks for computer communication are found in [Acampora and Karol 1989] [Green 1991] [Ramaswami 1993].

An overview of fiber-optic network technologies, components, and classifications is presented in Sections 2 through 5. Examples of WDMA networks [Mestdagh 1995] are described in Section 6. Section 7 is a conclusion and summary.

2. Multiple Access Methods

To access and share the huge amount of optical bandwidth among the multiple nodes in a fiber-optic network is a challenging problem. Four multiple access methods are described below: WDMA, TDMA (Time Division Multiple Access), SCMA (SubCarrier Division Multiple Access), and CDMA (Code Division Multiple Access). The most popular one to achieve high aggregated bandwidth seems to be WDMA, especially in end-user systems because of simple transceiver designs. Additional information on multiple-access methods are found in [Gagliardi and Karp 1995].

2.1 Wavelength Division Multiple Access

When using WDMA, multiplexing is done in the spectral domain of the light [Hill 1989] [Kaminow 1989] [Green and Ramaswami 1990]. In this way, several optical carriers, or channels, are implemented in the network. For systems with denser wavelength-spacing than 1 nm the WDMA technique is also referred to as optical FDM (Frequency Division Multiplexing) [Agrawal

1992]. One way to use the wavelength channels is to have several nodes transmitting simultaneously on different channels. Data is then sent bit-serially between nodes tuned to the same channel. Which channel each transmitter and receiver are tuned to for the moment is controlled by the MAC (Medium Access Control) protocol. Another way is to synchronously transmit on several channels in parallel, i.e., bit-parallel byte-serial transmission [Loeb and Stilwell 1988] [Loeb and Stilwell 1990]. Compensation for bit-skew due to group-delay dispersion (different wavelength channels travel with different speeds in the fiber) may, however, be needed in these systems [Jeong and Goodman 1996].

The practical limit (e.g., because “the impracticality of administering a network with a very large number of differing lasers”) in number of wavelengths in LAN networks and similar networks is expected to be somewhere between 16 and 32 [Brackett 1996]. However, a WDM (Wavelength Division Multiplexing) system with 100 channels has already been demonstrated [Toba et al. 1990], and systems with thousand 1 Gb/s channels is likely in the near future [Wailes and Meyer 1991]. Experimental WDM demonstrations include:

- Experiments with 16 channels at 2 Gb/s [Lin et al. 1988]. Tunable Fabry-Perot filters (see Section 3.1) were used for channel selection.

- A WDM experiment with 16 channels, each at 622 Mb/s [Toba et al. 1989]. One of the channels were selected by a tunable filter consisting of Mach-Zehnder interferometers (see Section 3.1).

- A system with 100 channels, each carrying data at a bit-rate of 622 Mb/s [Toba et al. 1990].

- A commercially available WDM link called MuxMaster [Janniello et al. 1995]. A MuxMaster link has 20 wavelengths on a single fiber which implement 10 full-duplex protocol-independent connections. Experiments with a bit-rate of 200 Mb/s on each wavelength were reported but bit-rates in the order of Gb/s are possible. Maximum distance is 50 km.

- A 160 Gb/s system with 8×20 Gb/s channels and a channel spacing of 4 nm [Sorel et al. 1996].

- 1 Tb/s aggregated capacity with 50 channels each modulated at a rate of 20 Gb/s [Chraplyvy et al. 1996].

2.2 Time Division Multiple Access

TDMA networks can be divided into two groups, those using *packet-interleaving* and those using *bit-interleaving*. Networks using packet-interleaving, for example, [Barry et al. 1996], divide the access to the medium into time slots. The length of each slot normally equals the transmission duration of a packet. Simple MAC protocols can be used but each node has to work at the speed of the aggregated bit-rate in the network.

When using bit-interleaving each node only sends one bit at a time at regular intervals. If N nodes transmit simultaneously, the bit stream from one node will have a bit-to-bit interval of N bit-slots. The width of the optical pulse is, however, normally several times shorter than the duration of a bit-slot. Bit-synchronization must be maintained in a bit-interleaved TDMA network which is very difficult when a bit-rate of multiple Gb/s is used. Experiments with a 250 Gb/s network were reported in [Prucnal et al. 1994]. The optical pulse width was 1 ps, the bit-slot was 4 ps, and the bit-to-bit interval from one node was 10 ns. This resulted in the capacity of supporting a 100 Mb/s bit-stream to each of 2 500 nodes. Bit-interleaved TDMA networks and technologies to implement such networks are reviewed in [Spirit et al. 1994] [Seo et al. 1996].

2.3 Subcarrier Division Multiple Access

The data from each node in a SCMA network is used to modulate node-specific microwave subcarriers, i.e, multiplexing is done in the microwave frequency domain [Darcie 1987]. The subcarrier then modulates an optical carrier. All subcarriers are detected at the receiver photo-diode but only the desired one is demodulated using conventional microwave techniques. SCMA can be contrasted to WDMA where multiplexing also is done in the spectral domain but on the lightwave carrier, about 10^{14} Hz, while the subcarrier microwave frequency is at 10^8 to 10^{10} Hz [Mestdagh 1995].

A typical application that SCMA is suited for is distribution of analog video channels [Chang et al. 1995]. The video channels can then remain analog through the whole network and similar FM-techniques as used today can be employed. However, SCMA has also been proposed for use in data communication networks [Darcie 1987].

In [Georges and Lau 1993], an SCMA network experiment using self-pulsating CD laser-diodes was reported. By changing the pulse frequency (2 to 4 GHz) a node can tune to another subcarrier channel. A bit-rate of 150 Mb/s was used in the experiment.

2.4 Code Division Multiple Access

Several CDMA methods for fiber-optic communication have been proposed. Most work is done on the method to have a set of orthogonal code sequences of *chips*, where each chip either has value “1” or value “0” [Salehi 1989] [Salehi and Brackett 1989] [Marhic 1993]. Each code sequence then corresponds to the destination address of a specific node. When transmitting, each “1” bit is encoded with the destination node’s code sequence of chips while a “0” bit is encoded with a sequence of only “0” chips. The drawback of this scheme is that each transceiver must work with a speed N times higher than the bit rate, where N is the length of the code, i.e., the number of chips. In wireless communication systems this method is referred to as Direct Sequence Spread Spectrum (DS-SS) [Bantz and Bauchot 1994].

Decoders to be used in the receivers can be implemented optically [Prucnal et al. 1986]. CDMA experiments using an optical decoder were reported in [Prucnal et al. 1986B]. The optical decoder consisted of P delay lines where P is the number of chips that are set to one in the receiving node’s code sequence. By matching the delay lines to the corresponding positions of the “1” chips in the code sequence, an autocorrelation function sensitive to the code sequence is obtained. A similar method was proposed to be used in the transmitter. A bit-rate of 3.125 Mb/s was achieved on a 100 Mbaud fiber-optic link, using 32 chips per bit.

Instead of having the code sequence spread in time, spectral encoding can be used. In [Zaccarin and Kavehrad 1993], the light from a LED (Light Emitting Diode) is spatially split into a discrete number of spectral components by a diffraction grating. The light is then passed through a spatial amplitude mask with the code sequence and then combined into the fiber. In this way, each of the spectral components is encoded with one of the chips and the LED only need to be modulated with the bit-rate. A similar technique is used in the receiver. In [Weiner et al. 1988], the code sequence is also applied in the spectral domain but with a phase mask instead of an amplitude mask.

Another CDMA method called PFDM (Pulse Frequency Division Multiplexing) is described in [Frenkel 1992]. Short laser pulses with a node specific repetition rate is used to encode the data. The received signal can be decoded with optical delay-lines, having delays proportional to the pulse frequency, and optical AND gates.

2.5 Discussion

The different properties of the multiple-access methods make them suitable for different applications/systems. In the kind of systems focused on in this report, a limited number of users share the network cost (opposite to telecommunication backbone networks). CDMA and bit-interleaved TDMA are therefore considered too complex. When a bit-rate of several Gb/s is needed from each node in the network simultaneously, packet-interleaved TDMA will also be too complex because every node has to work at the aggregated bit-rate of the network. SCMA is also sorted out because the limited network capacity [Mestdagh 1995]. What is left is WDMA that gives easy access to the channels when tunable components reach reasonable costs, and where each node only has to work at the speed of its own bit-rate.

Several proposed network architectures use WDMA in combination with one of the other multiple access methods, for example, TDMA [Jonsson et al. 1995], and SCMA [Shankaranarayanan et al. 1991]. As an example, data packets can be carried on wavelength channels while network control information is carried on subcarrier channels [Chiang et al. 1996]. This kind of hybrids can give new valuable properties to the networks, for example, flexible real-time properties when combining TDMA and WDMA [Jonsson et al. 1996].

3. Components for WDMA Networks

A fiber-optic communication system typically consists of a transmitter, a receiver, and some form of transmission medium based on optical fibers. Common optoelectronic components used in the transmitter are LEDs and laser diodes where laser diodes can be divided into multimode and single-mode laser diodes. Single-mode laser diodes have narrower spectral widths than multimode laser diodes by incorporating a grating filter inside or outside the cavity. The conventional multimode laser diode is called Fabry-Perot laser while two common single-mode laser diodes are the DBR (Distributed Bragg Region) and the DFB (Distributed FeedBack) laser diodes [Carroll et al. 1993]. In the receiver the commonly used components are PIN (P-insulator-N) diodes and APDs (Avalanche Photo Diode). The three classic types of optical fibers are multimode step-index fiber, multimode graded-index fiber, and single-mode step-index fiber, each with its own core/cladding design and dispersion characteristics. Further readings on fiber-optic communication systems and their components are found in [Keiser 1991], while an overview of components specially needed in WDMA networks is presented here.

Components for WDMA networks is a big research field and examples of proposed components is given below. The component descriptions are given from a systems view, explaining what system function they are to perform and to what degree the performance can be expected. The aim is to give necessary knowledge before going over to the presentation of architectures and protocols, while leaving implementation details. In most parallel and distributed computing systems, the longest possible distance between two end-nodes is rather short. Topics related to long distance communication are therefore not described here, e.g.:

optical amplifiers: may be needed when the optical signal is splitted to many nodes but are otherwise used when the signal is passed and attenuated through long distances of fiber

coherent detection: although it offers narrow channel spacing it is too complicated for end-user systems

different kinds of fibers: performance trimming of fibers (lower attenuation and dispersion) is important for telecommunication but less relevant for short-distance communication

More information on WDMA components are found in [Brackett 1990] [Green 1993].

3.1 Tunable Receivers

A receiver in a WDMA network must tune in one of all the wavelengths from the incoming fiber. Since a photo-diode itself detects a broad band of wavelengths a wavelength filter must be used. Tunable optical filters include interferometer filters, filters based on mode coupling, filters based on resonant amplification, and grating based filters. Fast tuning and a broad tuning range is desired while the pass-bandwidth should be adapted to the incoming channels, i.e., it should pass the whole energy of one channel while preventing energy from other channels to be detected.

The Mach-Zehnder interferometer filter splits the incoming light into two beams, delay one of the beams slightly more than the other, and then lets the two beams interact with each other [Hecht 1987]. Tuning is obtained when the delay is changed. By cascading several Mach-Zehnder interferometer filters, a greater wavelength selectivity is achieved. In [Wooten et al. 1996], a tree-stage electro-optically tunable Mach-Zehnder interferometer with 50 ns tuning latency over a tuning range of eight channels is demonstrated. Experiments with a 16-channel (four stages) interferometer was reported in [Oda et al. 1989], while a 128-channel (seven stages) interferometer was used in the 100-channel transmission experiment reported in [Toba et al. 1990].

The Fabry-Perot filter is another interferometer, where two mirrors form a resonant cavity [Hecht 1987]. With a mirror reflectivity of less than 100 percent, some of the resonated light will came out. The Fabry-Perot filter is tuned by changing the distance between the mirrors, i.e., moving one of the mirrors. The distance must be short to limit the number of resonating wavelengths to one in the working range of the communication system. Because the need of mechanically moving one of the lenses, the tuning latency is large. Piezoelectric-transducers are commonly used to change the distance [Miller and Janniello 1990], while another method is to rotate (relative to the incoming and outgoing beams) a Fabry-Perot filter with a fixed distance [Frenkel and Lin 1988]. Experiments with cascaded Fabry-Perot filters to enhance performance have also been reported [Kaminow et al. 1989]. The two-stage filter described in [Miller and Miller 1992], supports 1000 channels in a 40 nm range. A tunable Fabry-Perot filter without moving parts is described in [Patel et al. 1990]. The cavity was filled with liquid crystals and wavelength tuning was obtained by applying an electric field to change the refractive index of the liquid crystals.

Tunable filters based on mode coupling refers to filters with wavelength dependent coupling between optical fields (modes) where either acousto-optic, electro-optic, or magneto-optic effects are used [Kobrinski and Cheung 1989]. The optical signal is first split into two orthogonal polarization states and then passed through a resonant structure [Green 1993]. For a wavelength corresponding to the resonant frequency, the polarization state will be changed 90 degree. A second polarization splitter at the output will filter this wavelength out from the rest of the wavelength channels. The different kinds of mode coupling filters generates the resonant structure in different ways. Electro-optic filters has low tuning latencies while acousto-optic filters has a broad tuning range and supports multiwavelength filtering by applying multiple acoustic frequencies. Acousto-optic filters are reviewed in [Cheung 1990].

If a single-mode laser diode is biased below threshold it will start emitting when incoming light, at the wavelength selected by the grating in the laser, is present. If a tunable single-mode laser (see below) is used, a wavelength tunable filter with amplification is achieved. A tuning latency as low as 1 ns has been demonstrated [Kobrinski et al. 1988], but the tuning range is very limited. As an example, the tuning range demonstrated in [Numai et al. 1989] was 0.95 nm. Although, an 18-channel wavelength selection was expected with the filter.

In a grating based filter the incoming light is spatially split into its wavelength components. If a photo diode array is used to detect all of the wavelength components (one wavelength per photo diode) like proposed in [Kirkby 1990], a multichannel receiver is achieved where the electronic switching time sets the tuning latency, i.e., very fast. A grating integrated monolithically with a photo diode array detecting 42 wavelength channels spaced by 4 nm was reported in [Cremer et al. 1992]. In [Parker and Mears 1996], one digitally tunable wavelength is steered to the output fiber by using a SLM (Spatial Light Modulator) together with a fixed grating. Tuning to discrete wavelengths spaced by 1.3 nm over a tuning range of 38.5 nm was demonstrated.

3.2 Tunable Transmitters

With wavelength-tunable transmitters a certain wavelength can be chosen to transmit on, either from a continuous range or from a discrete number of wavelengths. From system engineers point of view, an ideal tunable laser diode has a tuning range of about 100 nm and a tuning latency in the order of nanoseconds [Mestdagh 1995]. Many components with the aim to meet one of the two requirements have been proposed, while some components meet both rather well. The linewidth (spectral width; normally measured as the FWHM, Full Width Half Maximum) of the emitted light gives a hint of the possible number of channels but other parameters such as receiver selectivity must be considered when designing a WDM communication system. Wavelength-tunable laser diodes are reviewed in [Lee and Zah 1989].

The simplest way to achieve a tunable transmitter is temperature tuning. The fact that the refractive index of the active layer is temperature dependent is used. Although a tuning range of 10.8 nm has been demonstrated [Kameda et al. 1993], only limited tuning range and long tuning latency are achieved with this method.

In [Kobrinski et al. 1990], a demonstration of a tuning latency of less than 15 ns over a tuning range of 2.2 nm and experiments with 16 wavelength channels are reported. A three-section DBR laser was used where two of the sections was used for wavelength tuning by changing the values of the injected currents and hence the index of refraction. As a consequence of changing the index of refraction of the grating in a DBR, the lasing wavelength (optical frequency) is changed. In [Goodman et al. 1988], eight-channels was achieved from a double-section DFB with a tuning speed less than 5 ns. A four-wavelength DBR laser array is reported in [Delorme et al. 1996]. Each laser is a three-section DBR tunable over a range of 12 nm. The total tuning range of the component is 28 nm.

By activating one laser in an array of laser diodes emitting at different wavelengths a discretely tunable laser is achieved. A 7×11 [Chang-Hasnain et al. 1991B] and a 7×20 [Chang-Hasnain et al. 1991] VCSEL (Vertical Cavity Surface Emitting Laser) array with each laser emitting a unique, nonredundant wavelength has been reported. The latter array had a wavelength span of 43 nm and WDM experiments were made where four of the lasers each was coupled to a fiber. The fibers were combined by a star coupler and each laser was simultaneously modulated at 155 Mb/s. A 2 × 8 VCSEL array with a small overlap in wavelength range between the two rows but with each laser capable of 5 Gb/s operation was reported in [Maeda et al. 1991]. Other WDM VCSEL arrays include a 2 × 2 densely-packed array [Huffaker and Deppe 1996], and other WDM array components include a DFB laser array with 20 lasers emitting at ten 2 nm spaced wavelengths (two diodes per wavelength) [Lee et al. 1996].

One of the disadvantage with array components is the difficulty to couple the light from all laser diodes into one fiber. However, integration of a 21-wavelength DFB laser array, a star coupler, and two optical amplifiers on one chip was reported in [Zah et al. 1988].

Another way to get multiple parallel wavelength channels is by spectral slicing of the output light from a number of broad-spectrum LEDs [Zirngibl et al. 1996]. By filtering out a different wavelength from each diode, a wavelength tunable transmitter is obtained when selecting one of the diodes for modulation. In [Chapuran 1991], experiments with a 16-channel 150 Mb/s system employing spectral slicing was reported.

Several external-cavity laser diodes with external filters for wavelength tuning have been reported. By antireflection-coating one of the output facets on a laser diode and having an external mirror, the cavity length is extended. If a diffraction grating is used as the external mirror, tuning is obtained by moving the grating (fine-tuning by changing the cavity length) or rotating the grating (a different longitudinal mode is selected from the grating) [Mellis et al. 1988]. Tuning ranges exceeding 240 nm have been demonstrated with external-cavity grating-based laser diodes [Bagley et al. 1990] [Tabuchi and Ishikawa 1990]. The drawback of these grating-based lasers is the large tuning-latency caused by the mechanical movement of the grating. However, devices with shorter tuning latencies have been demonstrated. One way of avoiding the mechanical moving mechanism is to exchange the diffraction grating with a acousto-optic filter that selects the lasing wavelength, and allows for tuning latencies in the range of microseconds [Coquin and Cheung 1988]. Another fully electronically tunable laser diode is the MAGIC (Multistripe Array Grating Integrated Cavity) laser diode [Soole et al. 1992]. The MAGIC laser chooses one wavelength for lasing by activating one of several waveguide stripes. A fixed diffraction grating couples a specific wavelength into each stripe.

In [Larson and Harris 1996], a 15 nm tuning range and a 0.14 nm linewidth are demonstrated for a single VCSEL laser. A movable mirror was placed on top of the laser with a air gap in between. By moving the mirror the cavity length and hence the wavelength of the emitted light are changed. A LED with the same tuning mechanism, a tuning range of 39 nm, and a linewidth of 1.9 nm is presented in [Larson and Harris 1995].

A diode-laser pumped tunable fiber laser is reported in [Chieng and Minasian 1994]. Light in the 1550 nm range goes through an Erbium-doped fiber ring where it is amplified. A tunable Mach-Zehnder interferometer selects one wavelength which is re-amplified. A tuning range of 39 nm is achieved. In [Chollet et al. 1996], a fiber laser with an electro-optic filter is reported. The laser supports 50 wavelength channels over a spectral range of 10 nm with 50 ns tuning latency.

3.3 Other WDM Components

Essential system components when building fiber-optic networks like those described in the next section includes splitters, combiners, stars, WDM demultiplexers, and WDM multiplexers. Several of the mentioned components are commercially available with limited features, e.g., a small number of input/output ports.

An $1 \times N$ fiber-optic splitter splits the light from one input fiber to N output fibers. Both symmetric and asymmetric splitters are available where an asymmetric splitter split an unequal amount of light to the different output ports. A combiner works in the opposite way combining input signals from several fibers to one output fiber. An $N \times N$ fiber-optic star (often refereed to as a passive optical star) can be viewed as an $N \times 1$ combiner followed by an $1 \times N$ split. The conventional way to build a star is to use a number of 2×1 combiners and 1×2 splitters. However, it is difficult to build large stars using this technique and other techniques have been proposed to overcome the problem [Okamoto et al. 1992] [Yun and Kavehrad 1992]. A 144×144 passive optical star is described in [Okamoto et al. 1992B] and [Kato et al. 1993].

A WDM demultiplexer is a splitter that splits the incoming signal on one fiber to several output fibers, each with a different spectral component of the input signal. The demultiplexer either splits the input signal into groups of wavelength channels or into one separate wavelength channel per output fiber. The most common methods to demultiplex the input signal are to use an interference filter or a diffraction grating [Straus and Kawasaki 1987]. A WDM multiplexer couples together different wavelengths on different fibers into one outgoing fiber. Although there exist WDM multiplexers with wavelength selective inputs, the simplest way to get a WDM multiplexer is to use an ordinary $N \times 1$ combiner.

The add/drop filter is another component, where one or several wavelengths may be added/dropped to/from a bypassing fiber. The component can be used in, e.g., WDM ring networks (described in next section). An add/drop filter based on two fixed wavelength multilayer Fabry-Perot filters is described in [Hamel et al. 1995]. A components where the wavelength to be added/dropped can be tuned over a discrete number of wavelengths is described in [Glance 1996].

4. Interconnection Architectures

The simplest fiber-optic transmission system is to have a point-to-point link between two nodes. By using several point-to-point links, a network can be built. These so-called point-to-point linked networks have been commercially available for a while and are described in Section 4.1. However, all-optical multiaccess networks are spawn to be popular in the future (described in Section 4.2).

4.1 Point-to-Point Linked Networks

In a fiber-optic point-to-point linked network a number of optically-isolated links connects the nodes in the network. If, for example, wavelength division multiplexing should be used to increase the bandwidth, the technology must therefore be implemented separately in each point-to-point link. The main types of point-to-point linked networks that falls under the scope of this report are ring networks [Davies and Ghani 1983] and switched networks.

In the Fibre Distributed Data Interface (FDDI) network [Ross 1989] [Jain 1993] the nodes are connected in a unidirectional primary ring where each node receive from one link and transmit on another. A node acts like a repeater for all incoming messages accept for those which are addressed to the node and for those which are sent by the node and should be removed from the ring after one round. In addition to the primary ring, some, or all, nodes are connected to a secondary ring which, for example, can be used as a backup ring. A transmission rate of 125 Mbaud is used which gives a data rate of 100 Mb/s because of the employed 4b/5b encoding. A token protocol is used for medium access control. Guarantees can be given for both latency and bandwidth in the FDDI network and in it’s successor, FDDI-II [Ross 1989] [Jain 1993].

In the Wavelength Distributed Data Interface (WDDI) network described in [Ramamurthy et al. 1995], multiple FDDI networks are obtained on logical rings in a WDM ring network. Only a subset of the total number of nodes in the network is connected to each logical ring. Some of the nodes act as bridges to interconnect two or more logical rings.

In switched networks one or several switches connects the nodes together. All traffic in the network passes one switch at least. One well known switched network is ATM (Asynchronous Transfer Mode). ATM is developed to carry a wide range of traffic like video, voice, and data, both at the local and the global level. To ease the transition from current LAN technologies, ATM LAN emulation has been developed to support emulation of a broadcast media [Truong et al. 1995] [Finn and Mason 1996].

The ATM Adaptation Layer (AAL) provides four classes of services to support different requirements of applications. The four classes are [Reilly 1994] [Suzuki 1994]:

- *Class A* Constant Bit Rate (CBR). Connection-oriented with minimal and constant delay between the end-nodes. Can be used for, e.g., voice over ISDN.
- *Class B* Variable Bit Rate (VBR). Connection-oriented with minimal and constant delay between the end-nodes. Designed to handle video and audio where, e.g., the compression ratio can vary.
- *Class C* Connection-oriented data transmission.
- *Class D* Connection-less data transmission.

Real-time service is supported by Class A and Class B, but the cells (data units in ATM each consisting of 48 byte data and a 5 byte address) can still be thrown away if congestion occurs in a switch. It can therefore be argued that ATM is not suitable for hard real-time systems.

Electronic ATM-switches and integrated switching circuits are commercially available [Goldberg 1994] while optically switches are proposed [Nishio et al. 1993] [Jajszczyk and Mouftah 1993] [Blumenthal et al. 1994]. How to use ATM networks in parallel and distributed computing systems is discussed in [Hariri and Lu 1996]. Another network for parallel processing systems, using fiber-optic point-to-point interconnections, is Nectar where one or several electronic crossbars switch the traffic [Arnould et al. 1989].

A multi-stage switching system with WDMA interconnections between the stages and wavelength conversion inside the switching stages was reported in [Fujiwara et al. 1988]. Wavelength conversion was obtained by converting the optical signal into electronic form and then back to optical again, but at another wavelength.

A system component that has reached the market recently is the fiber ribbon link [Bursky 1994B]. Several links can be used to build high-bandwidth point-to-point linked networks [Hahn et al. 1995]. With ten parallel fibers each carrying data at a bit rate of 400 Mb/s an aggregated bandwidth of 4 Gb/s is achieved [Schwartz et al. 1996].

4.2 All-Optical Multiaccess Networks

In an all-optical network, the data stream remains in the optical form all the way from the transmitter to the receiver. Three basic architectures for all-optical multiaccess networks are the ring, the bus, and the star. These network architectures will be discussed below.

An all-optical multiaccess ring network differs from a traditional ring network in the sense that all other nodes can be reached in a single hop without any intermediate optoelectronic conversion. In contrast to the repeating function of a node in, for example, a FDDI network, messages just pass a node through passive optics in an all-optical multiaccess ring network. This is true for all messages except for own messages that should be removed from the ring after one round. Just a fraction of the optical power contained in the bypassing fiber is tapped to the receiver, which gives all nodes the opportunity to read the message, i.e., a multicast (one to many) or a broadcast (one to all). Outgoing messages are inserted into the ring and, in a multi-channel system, mixed together with bypassing messages on other channels.

In the WDMA ring network described in [Irshid and Kavehrad 1992], each node is assigned a node-unique wavelength to transmit on. Transmitted messages are then accessed by tunable receivers. Experiments with a WDMA unidirectional ring network is reported in [Chawki et al. 1995], while a WDMA bi-directional ring network is described in [Elrefaie 1993]. WDMA ring networks with central electronic switching are described in [Wagner and Chapuran 1992].

A hierarchical ring network is described in [Louri and Gupta 1996] [Louri and Gupta 1997]. One ring is dedicated to each cluster for intra-cluster communication, while a hierarchical all-optical (no optical-to-electrical conversion, or vice versa, in the gateway nodes) ring network is used for inter-cluster communication. A TDMA protocol is investigated for use in the network.

In an optical bus the light is only traveling in one direction. This makes it necessary to have two buses (upper and lower), one for each direction (higher or lower node index of destination nodes). This kind of bus architecture is called *dual bus*. The disadvantage with the dual bus is that two transceivers are needed in each node. This is avoided in *folded bus*, where the two buses are connected together with a wrap-around connection at one end of the buses [Tseng and Chen 1982]. In the folded bus, transmitters are connected to the upper bus while receivers are connected to the lower bus.

Several bus architectures and hybrids where the bus is part of the architectures, are discussed in [Nassehi et al. 1985]. A WDMA dual bus network is described in [Cheung 1992] while a WDMA folded bus network is described in [Chlamtac and Ganz 1988]. WDMA dual bus networks where messages not always remains unchanged until the end of the bus, but where the protocols support several transmissions on the same wavelength channel simultaneously (wavelength reuse) are presented in [Huang and Sheu 1996] [Huang and Sheu 1997].

In a star network, the incoming lightwaves from all nodes are combined and uniformly distributed back to the nodes. In other words, the optical power contained in the middle of the star is equally divided between all nodes. WDMA star networks are described in numerous papers and are specially treated in Section 6. In addition to LANs and similar networks, WDMA star networks have also been proposed for use internally in packet switches [Eng 1988] [Brackett 1991].

Hierarchical WDM star networks include the wavelength-flat (all nodes share the same wavelength space) tree-of-stars network [Dowd et al. 1993], the tree-of-stars network (called LIGHTNING) that has wavelength routing elements between each level [Dowd et al. 1996], the star-of-stars network that has an electronic gateway node between each cluster and the backbone star [Jonsson and Svensson 1997], and the multiple star network where each node is directly connected to both a local star and a remote star [Ganz and Gao 1992B].

All of the three basic network architectures have different advantages. The ring has the least amount of fibers, a bus network's medium access protocol can utilize the linear ordering of the nodes [Nassehi et al. 1985], and the attenuation for an (ideally) star only grows logarithmically with the number of nodes. However, star networks are the most popular ones, accounting the number of published papers.

5. Classifications of WDMA Networks

The classifications below give the terminology and the background knowledge assumed in the overview of proposed networks and protocols (medium access control protocols) in the next chapter. If not otherwise is mentioned, multiaccess single-hop broadcast-and-select networks (explained below) are assumed in the following chapters. More information on WDMA networks is found in [Brackett 1990] [Green 1993] [Mestdagh 1995]. Predictions of future directions in WDMA networking are found in [Brackett 1996] [Green 1996].

5.1 Broadcast-and-Select and Wavelength Routing

The difference between broadcast-and-select networks and wavelength routing networks is whether there exist any wavelength dependent routing in the network or not [Gerstel 1996]. The path taken from a transmitter to a receiver in a wavelength routing network is determined by the selected wavelength. As long as two paths does not have any common fiber links they can use the same wavelength simultaneously (wavelength reuse). This is not possible in a broadcast-and-select network where all receivers always have all transmitted channels available on the incoming fiber. However, a broadcast-and-select network does not need any wavelength selective devices out in the network. Instead, the receivers decide (based on the used protocol) when to receive and/or which channel to tune in.

Several wavelength routing networks have been proposed, for example, the three-level hierarchical network described in [Alexander et al. 1993]. Another hierarchical wavelength routing network is LIGHTNING [Dowd et al. 1995] [Dowd et al. 1996]. The topology in LIGHTNING is a tree-structure of passive optical stars where each level is separated by a *lambda partitioner*. The lambda partitioner selects which wavelengths that are to stay in the levels beneath the partitioner and which to pass to the levels above. In this way, the number of wavelengths in each fiber has its minimum at the top level (only top level wavelengths exist) and maximum at the bottom level (wavelengths for all levels exist). All wavelengths that are not passed to a certain level can be reused in each cluster on the level below.

The focus in this report is on broadcast-and-select networks and examples of such networks are found in Section 6.

5.2 Single-Hop and Multihop Networks

In a single-hop network, all nodes can reach any other node in a single hop. This means that the transmitted data is not passed through any intermediate routing stages and remains in optical form all the way from the source node to the destination node. A disadvantage with single-hop networks is that each transmitter and/or receiver must be equipped with tunable components. Advantages are flexibility and the absence of extra latency at intermediate nodes.

In a multihop network, fixed-wavelength (or slowly tunable) transmitters and receivers are configured to shape a virtual topology. As an example, a node might be able to transmit on λ_1 , λ_2, and λ_3 in a broadcast-and-select network, where the three neighbors in a virtual binary 3-dimensional cube have receivers tuned to λ_1 , λ_2, and λ_3 respectively. A number of virtual topologies have been investigated, e.g., perfect shuffle in Shufflenet [Acampora and Karol 1989]. An experimental multihop network was reported in [Gidron 1992]. An advantage with multihop networks is that no components with low tuning-latency are needed. By having slowly tunable components, the virtual topology can be reconfigured when the overall traffic demands in the network are changed.

Although multihop networks can be reconfigurable, single-hop networks are more flexible. This paper is focused on single-hop networks. Single-hop networks are reviewed in [Mukherjee 1992], while multihop networks are reviewed in [Mukherjee 1992B].

5.3 Networks with and without Control Channel

A number of protocols for WDMA networks assume a separate control channel. This control channel is normally used to reserve access on the data channels. Hence, these protocols are sometimes called *reservation* protocols. Protocols for networks with more than one control channel have also been proposed, for example, N-DT-WDMA [Humblet et al. 1992] [Humblet et al. 1993]. Non-control channel based networks often assign a fixed home channel to each node, either on the transmitter side or on the receiver side. Protocols for these networks are then called *pre-allocation* protocols. Protocols for networks without control channel but where the access to the data channels is divided into a control-phase and a data-phase are found in [Sivalingam and Dowd 1995] [Jonsson et al. 1996]. These protocols are called *hybrid* protocols.

Instead of having an additional wavelength channel for the control channel, SCMA can be used to achieve a number of control channels [Su and Olshansky 1993]. In the proposed network, the subcarrier carrying a node's control data is modulating the same laser diode as the data is transmitted on. Two photo-diodes is used in the receiver, one with a filter that filters out the wavelength with the data and one without filter to receive all subcarriers in the network. One of the subcarriers is then selected using microwave techniques.

5.4 Receiver and Transmitter Tunability

The most flexible networks are those with both tunable transmitters and tunable receivers. However, protocol complexity and node cost decrease when fixed-wavelength units are used in either the transmitter or the receiver. Using the classification scheme given in [Mukherjee 1992] WDM networks can be divided into:

- FT-FR (Fixed Transmitters and Fixed Receivers)

- TT-FR (Tunable Transmitters and Fixed Receivers)
- FT-TR (Fixed Transmitters and Tunable Receivers)
- TT-TR (Tunable Transmitters and Tunable Receivers)

Some networks have more than one transmitter and/or receiver in each node. A network with i fixed transmitters, j tunable transmitters, m fixed receivers, and n tunable receivers can be described as:

$FT^{i}TT^{j}\text{-}FR^{m}TR^{n}$

if no control-channel is used, or as:

$CC\text{-}FT^{i}TT^{j}\text{-}FR^{m}TR^{n}$

if the network is control channel based. The number of nodes in a network is denoted as M. As an example, an TT-FR^{M} network has one tunable transmitter and M fixed receivers in each node.

In a packet switched network the tuning latency is critical for the network performance. This issue was addressed in the discussion on tunable components in Section 3. Also, fast locking clock-recovery circuits must be used instead of the PLL-based circuits used in point-to-point links. Several methods to recover the clock signal on one or a few bits have been proposed [Banu and Dunlop 1992] [Jonsson and Moen 1994] [Cerisola et al. 1995].

5.5 Random-Access Protocols

In a network using a random-access protocol, all nodes compete for a transmission channel in a random (uncontrolled) way [Halsall 1992]. Random-access protocols can be contrasted to protocols with dynamic or static pre-assigned transmission patterns. The original single-channel random-access protocol is the Aloha protocol where transmission is done with no regard to other nodes. If two messages from different nodes overlaps in time, both are corrupted. Several protocols are more or less pure improvements of the Aloha protocol, e.g., Slotted Aloha, CSMA (Carrier-Sense Multiple-Access), and CSMA/CD (CSMA with Collision Detection). In slotted Aloha, all nodes are synchronized and transmissions are only allowed to be started at the beginning of a time slot. In this way, the probability of collision is decreased. In CSMA, the transmission medium is sensed before transmission starts. If a carrier was sensed, the transmission is postponed until the current message has reached its end. If two nodes sense the medium at the same time and find it free, they both begin to send and a collision will appear. In this case, the medium is busy for the whole duration of the corrupted transmissions. This is avoided in the CSMA/CD protocol where a collision can be detected during transmission. If a collision is detected by two nodes, both nodes stop and wait for a random time before trying again beginning with the carrier-sense mechanism. Common to the random-access protocols is that they do not perform well at high traffic-loads due to increased probability of collision, but experience low latency at light loads.

In multiple-channel networks, a random-access protocol can be used both on the data channels and on the control channel if present. Random access protocols for control channel based networks are known as X/Y protocols where X denotes the protocol used on the control channel while Y denotes the protocol on the data channels. An example of an X/Y protocol is the Slotted Aloha/Aloha protocol described in [Habbab et al. 1987].

5.6 Time-Wavelength Assignment Schemes

Several algorithms have been proposed to solve different kinds of time-wavelength assignment problems [Rouskas and Ammar 1995]. One specific problem is to schedule a traffic matrix (containing the communication demands between every possible pair of nodes) on a limited number of wavelength channels minimizing the number of time-slots needed [Pieris and Sasaki 1994]. Other aspects may also be considered, for example, minimizing the number of tuning periods, that is, period where the tuning of the transmitters and the receivers are not changed [Ganz and Gao 1992] [Ganz and Gao 1992B].

6. Single-hop WDMA Star Networks and Protocols

A number of single-hop broadcast-and-select WDMA star networks and protocols for this kind of networks have been proposed. They are suggested for a wide range of applications but in general they can all be used in LANs and distributed computing systems. Several of these networks are summarized in Table 1, Table 2, Table 3, and Table 4. Table 1 lists network experiments, while Table 2 and Table 3 lists MAC protocols for non-control channel based and control channel based networks respectively. Although the listed protocols is for packet-switched traffic, protocols for circuit-switched traffic have been proposed [Dono et al. 1990]. Some papers describing single-hop WDM star networks, that do not fit into the scope of any of Table 1, Table 2, or Table 3, are listed in Table 4. Several of these papers are application suggestions and early contributions of conceptual thoughts.

Name/ Reference	Tunability classification	Number of wavelengths	Channel bandwidth	Organization/other info.
FOX [Arthurs et al. 1988]	TT-FR	2	1 Gb/s	Bellcore; two stars, one for each direction
HYPASS [Kobrinski et al. 1988B]	TT-FR & FT-TR	8	1.2 Gb/s	Bellcore; two stars, one for each direction
[Kaminow et al. 1988]	FT-TR	2	45 Mb/s	AT&T Bell Lab.
Lambdanet [Kobrinski et al. 1987]	FT-FR^M	18	1.5 Gb/s	Bellcore
Rainbow-I [Janniello et al. 1992]	FT-TR	6	300 Mb/s	IBM T. J. Watson; circuit switched traffic

Table 1: Experimental single-hop WDMA star networks. M is the number of nodes and N is a positive integer greater than zero.

Name/ Reference	Tunability classification	Number of channels	Protocol type	Packet length
Slotted Aloha [Dowd 1991]	TT-FR	N	Slotted Aloha with ACK-control slots	Fixed
I-TDMA [Sivalingam et al. 1992]	TT-FR	N	Static TDMA	Fixed
I-TDMA* [Bogineni et al. 1993]	TT-FR	N	Static TDMA	Fixed
FatMAC [Sivalingam and Dowd 1995]	TT-FR	N	TDMA with control phase for reserving	Variable (fixed units)
TD-TWDMA [Jonsson et al. 1996]	FT-TR	M	TDMA with control phase for reserving	Fixed

Table 2: Non-control channel based protocols for single-hop broadcast-and-select WDMA networks. M is the number of nodes and N is a positive integer greater than zero.

Of the network experiments in Table 1, Lambdanet [Kobrinski et al. 1987] [Goodman et al. 1990] was the first to reach “industrial strength” [Green 1996]. Other remarkable experimental demonstrations include the two-star FOX network for shared memory multiprocessors [Arthurs et al. 1988], and the circuit switched Rainbow network [Dono et al. 1990]. The experimental demonstrations of Rainbow-I was reported in [Janniello et al. 1992].

Of the protocols for non-control channel based networks (Table 2), several are TDMA variants. For example, I-TDMA [Sivalingam et al. 1992] and I-TDMA* [Bogineni et al. 1993] are multiple-channel variants of the traditional static TDMA. Random access protocols have also been proposed for non-control channel based networks. One example described in [Dowd 1991], is a variant of the Slotted Aloha protocol.

Name/ Reference	Tunability classification	Num. of chan.	Control ch. protocol	Data ch. protocol	Packet length
Aloha/Aloha [Habbab et al. 1987]	CC-TT-TR	$N + 1$	Aloha	Aloha	Fixed
Slotted Aloha/Aloha [Habbab et al. 1987]	CC-TT-TR	$N + 1$	Slotted Aloha	Aloha	Fixed
Aloha/CSMA [Habbab et al. 1987]	CC-TT-TR	$N + 1$	Aloha	CSMA	Fixed
CSMA/Aloha [Habbab et al. 1987]	CC-TT-TR	$N + 1$	CSMA	Aloha	Fixed
CSMA/N-Server Switch [Habbab et al. 1987]	CC-TT-TR	$N + 1$	CSMA	N-Server Switch	Fixed
DT-WDMA [Chen et al. 1990]	CC-FT^2-FRTR	$M + 1$	Uniform static TDMA	Distributed algorithm	Fixed
Improved Slotted Aloha/ Aloha [Mehravari 1991]	CC-TT-TR	$N + 1$	Slotted Aloha	Aloha	Fixed
Slotted Aloha/N-Server Switch [Mehravari 1991]	CC-TT-TR	$N + 1$	Slotted Aloha	N-Server Switch	Fixed
Slotted Aloha [Sudhakar et al. 1991]	CC-TT-TR	$N + 1$	Slotted Aloha	Aloha	Fixed
Reservation Aloha [Sudhakar et al. 1991]	CC-TT-TR	$N + 1$	Slotted Aloha	Aloha	Fixed
DAS [Chipalkatti et al. 1992]	CC-FT^2-FRTR	$M + 1$	Uniform static TDMA	Distributed algorithm	Fixed
Hybrid TDM [Chipalkatti et al. 1992]	CC-FTTT^N-FR^{N+1}	$M + 1$	Uniform static TDMA	Two different protocols	Fixed
TDMA-C [Bogineni and Dowd 1992]	CC-TT-FRTR	$M + 1$	Uniform static TDMA	Distributed algorithm	Var.
N-DT-WDMA [Humblet et al. 1993]	CC-FTTT-FRTR	$2M$	slotted	slotted	Fixed
[Yan et al. 1996]	CC-FTTT^N-FR^{N+1}	$M + 1$	Token	Distr. alg.	Var.
MultiS-Net [Jia and Mukherjee 1996]	CC-TT-TR	$N + 1$	Slotted random access	Distributed algorithm	Fixed

Table 3: Control channel based protocols for single-hop broadcast-and-select WDMA networks. M is the number of nodes and N is a positive integer greater than zero.

Numerous protocols for control channel based networks have been proposed (Table 3). One of the first papers, [Habbab et al. 1987], describing protocols for WDMA networks presents five random access protocols utilizing a control channel. Several variants and improvements of these protocols have been proposed later, for example, those described in [Mehravari 1991]. Several of the protocols for control channel based networks use uniform static TDMA on the control channel and some form of distributed algorithm to schedule access to the data channels. Some of the protocols support variable sized packets, for example, the TDMA-C protocol [Bogineni and Dowd 1992]. Protocols with other remarkable features include: protocols utilizing multiple control channels, for example, N-DT-WDMA [Humblet et

Name/ Reference	Tunability classification	Other features
Photonic knockout switch [Eng 1988]	$FT\text{-}FR^N$	*Application*: centralized packet-switches. A separate electrical control network is used.
Broadcast SYMFONET [Westmore 1991]	$FT\text{-}FR^M$	*Application*: shared memory multiprocessors. Synchronization issues and timing are discussed.
MCA [Wailes and Meyer 1991]	$TT^N\text{-}TR^N$	*Application*: massively parallel computers.
[Brackett 1991]	FT-TR	*Application:* centralized packet-switches.

Table 4: Other proposed single-hop WDM star networks. M is the number of nodes and N is a positive integer greater than zero.

al. 1993], where N is the number of nodes and control-channels; tell-and-go protocols (data is sent immediately after the control information, without waiting for the control information from the own and/or other nodes to return), for example, the Aloha/Aloha protocol [Habbab et al. 1987]; protocols not requiring dedicated hardware for the control channel, for example, MultiS-Net [Jia and Mukherjee 1996]. Protocols for single-hop networks are reviewed in [Mukherjee 1992].

Some of the networks and protocols listed in Table 1 to Table 4 are described in the sub-sections below for example purposes. Section 6.1 - 6.2 are network oriented while Section 6.3 - 6.6 are protocol oriented. The protocol descriptions are given at a level trying to explain the basic function and important features. If nothing else is mentioned, a passive optical star is assumed as the physical topology when describing the protocols. However, the passive optical star can often be exchanged with another multiaccess network, without any big modifications of the protocol. The focus on single-hop broadcast-and-select networks is motivated by the simple architecture needed to support flexible traffic between end-nodes.

6.1 FOX

The FOX network reported in [Arthurs et al. 1988] is an interconnection architecture for parallel computers with shared memory. Two stars are used, one for communication from the processing elements and to the memory modules, and one for the opposite direction. Both the star networks are TT-FR networks with a unique wavelength for each receiver. If two processing elements transmits to the same memory module at the same time, collision will occur. With the motivation of a low cache miss-rate, collision detection and retransmission is proposed to be a feasible solution to this problem. Experiments with two wavelengths and less than 20 ns tuning latency where reported.

A related network is the HYPASS switching system [Kobrinski et al. 1988B] [Goodman et al. 1988]. HYPASS also employs one star for each direction, but internally in a switch. One star is used for the data transport while the other passes back control information from the output stages.

6.2 Lambdanet

The Lambdanet WDMA star network presented in [Kobrinski et al. 1987] is classified as FT-FR^{M}, where M is the number of nodes. Although Lambdanet was designed to have one specific wavelength per node as a transmitter home channel, two extra wavelengths was used in the 16 node experiment, i.e., a total number of 18 wavelengths. Commercial DFB laser diodes was selected to obtain a channel spacing of 2 nm, while a grating wavelength demultiplexer was used in the receiver to select one of the incoming wavelengths. Further experiments was reported in [Goodman et al. 1990], where the channel bit-rate was increased from 1.5 Gb/s to 2 Gb/s.

6.3 DT-WDMA

The DT-WDMA (Dynamic Time-Wavelength Division MultiAccess) protocol for CC-FT^{2}-FRTR networks, described in [Chen et al. 1990], divides the access to both control channel and data channels into equal sized slots. Slots on the control channel are, however, further divided into mini-slots, one to each transmitter. When node i wants to transmit to node j, it waits for its next mini-slot on the control channel. An address field in the control packet is set with the address of node j. Another field is set with a delay value related to the generation time of the message. The data message is then sent in the data slot succeeding the control slot. After each slot when all mini-slots are received, a deterministic distributed algorithm (separately computed in each node with the same outcome) is run in each node. Based on the distributed algorithm, node j will choose to tune in the node with the largest delay value of all the nodes that have had set the address of node j in the address field. All other messages destined to node j will get lost. In a pipeline fashion, several messages can be sent before success or not of the first message is known.

The DT-WDMA protocol tries to minimize the maximum packet-delay. It also tries to cope with large propagation delays by using the pipeline mechanism. In addition to packet-switched traffic, circuit-switched traffic is also supported by DT-WDMA.

6.4 A Distributed Adaptive Protocol

In [Yan et al. 1996] and [Yan et al. 1996B], a protocol, not named in the papers, supporting soft-real-time traffic is described. The QOS (quality of service) associated with a real-time packet in the network is the probability of missing the deadline. The distributed algorithm used, tries to globally minimize the number of packets not managing the QOS by adaptively changing the priority of the queued packets. The network architecture is CC-FTTT^{N}-FR^{N+1} where the fixed transmitter and one of the fixed receivers are dedicated to the control channel. The N tunable transmitters and N of the fixed receivers are dedicated to the N data-channels.

The access to the control channel is based on a circulating token. The token is always broadcasted to every other node so they can take part of the status information, about the sending node, contained in the token. In each node, the latest version of this information, from every other node, is stored in a table. In this way, the current system state is known by all nodes and an identical copy of the distributed algorithm can be run on each node. When a node has the token it determines which data channels to acquire or release, in a way trying to globally meet the QOS demands. The determination is based on the current system state and on information about the own queued messages, e.g., deadline and acceptable deadline missing fraction. The node which the token is passed to is also determined according to the QOS demands of all messages in the network.

Even if the protocol has sophisticated methods for real-time messages, it is only targeted for soft-real-time traffic. Guarantees can not be given that a message will meet its deadline.

6.5 Interleaved TDMA

The I-TDMA (Interleaved TDMA) protocol described in [Sivalingam et al. 1992] is an extension of the traditional static uniformly TDMA protocol. The protocol assumes a non-control channel based network with tunable transmitters and fixed receivers. The access to each channel is divided into M slots, where M is the number of nodes. The assignement is fully static and gives each node one slot per cycle and channel to transmit in. Each node has access to one channel at the time at the most. If there are M channels in the network, each node always has access to exactly one channel. An extension to I-TDMA, called I-TDMA*, is described in [Bogineni et al. 1993]. The only difference is that I-TDMA* has C queues, where C is the number of channels, for outgoing messages in each node instead of one queue. Head-of-line problems are hence avoided. The head-of-line problem means that a node has a packet to send but can not reach it in the queue because there are other packets (with a destination not possible to transmit to for the moment) in front of it. As with traditional TDMA, these protocols reach high bandwidth utilization but have large tuning latencies at low traffic intensities.

6.6 FatMAC

The FatMAC protocol is proposed to be used in distributed shared memory multiprocessors [Sivalingam 1994] [Sivalingam and Dowd 1995]. No control channel is used and the network is classified as TT-FT. By choosing a laser diode array as the tunable transmitter, broadcast is made possible through simultaneous activation of all laser diodes in the array. The access to the channels is divided into cycles of variable length. The cycles have two parts, a control phase followed by a data phase. Each node has a slot with broadcast capability in the control phase, where it transmits its transmission demands for the cycle. The packet is scheduled in the data phase among other demanded transmissions, following the same order as the control slots. The length of the data phase depends on the number of demanded transmissions. Positive features of the network include: support for variable length packets, no control channel needed, and collisionless transmission.

A related protocol is TD-TWDMA that also have a control phase and a data phase instead of a separate control channel [Jonsson et al. 1996] [Jonsson et al. 1997]. The TD-TWDMA protocol is, however, developed for distributed real-time systems and has features for those systems.

7. Conclusions

In this paper, an introduction to high-performance fiber-optic networks has been presented. The emphasis has been on multiple-channel passive optical networks, especially WDMA networks, because these networks have the highest potential to meet future bandwidth demands at reasonable cost. Numerous applications have been proposed in the literature but most of the networks and protocols referred to in this paper can be used in distributed computing systems. WDMA star networks are foreseen to have a key role in future high-performance computer communication networks, and examples of such networks and protocols for them have been described. Many of the demonstrated components for WDMA networks, as reviewed in this paper, further indicates that high-performance WDMA networks for end-user systems will be available in the near future.

8. References

[Acampora and Karol 1989] A. S. Acampora and M. J. Karol, "An overview of lightwave packet networks," *IEEE Network*, pp. 29-41, Jan. 1989.

[Agrawal 1992] G. P. Agrawal, *Fiber-Optic Communication Systems*. John Wiley & Sons, Inc., 1992, ISBN 0-471-54286-5.

[Alexander et al. 1993] S. B. Alexander et al., “A precompetitive consortium on wide-band all-optical networks,” *Journal of Lightwave Technology*, vol. 11, no. 5/6, pp. 714-732, May/June 1993.

[Arnould et al. 1989] E. A. Arnould, F. J. Bitz, E. C. Cooper, H. T. Kung, R. D. Sansom, and P. A. Steenkiste, "The design of Nectar: a network backplane for heterogeneous multicomputers," *Proc. ASPLOS-III*, pp. 205-216, 1989.

[Arthurs et al. 1988] E. Arthurs, J. M. Cooper, M. S. Goodman, H. Kobrinski, M. Tur, M. P. Vecchi, "Multiwavelength optical crossconnect for parallel-processing computers," *Electronics Letters*, vol. 24, no. 2, pp. 119-120, Jan. 21, 1988.

[Bagley et al. 1990] M. Bagley, R. Wyatt, D. J. Elton, H. J. Wickes, P. C. Spurdens, C. P. Seltzer, D. M. Cooper, and W. J. Devlin, "242 nm continuous tuning from a GRIN-SC-MQW-BH InGaAsP laser in an extended cavity," *Electronics Letters*, vol. 26, no. 4, pp. 267-269, Feb. 15, 1990.

[Bantz and Bauchot 1994] D. F. Bantz and F. J. Bauchot, "Wireless LAN design alternatives," *IEEE Network*, pp. 43-53, Mar./Apr. 1994.

[Banu and Dunlop 1992] M. Banu and A. E. Dunlop, "Clock Recovery Cuircuits with Instantaneus Locking," *Electronics Letters*, vol. 28, no. 23, pp. 2127-2130, 5 Nov., 1992.

[Barry et al. 1996] Barry et al., "All-optical network consortium - ultrafast TDM networks," *IEEE Journal on Selected Areas in Communications*, vol. 14, no. 5, pp. 999-1013, June 1996.

[Blumenthal et al. 1994] D. J. Blumenthal, P. R. Prucnal, and J. R. Sauer, ”Photonic packet switches: architectures and experimental implementations,” *Proceedings of the IEEE*, vol. 82, no. 11, Nov. 1994.

[Bogineni and Dowd 1992] K. Bogineni and P.W. Dowd, "A Collisionless Multiple Access Protocol for a Wavelength Division Multiplexed Star-Coupled Configuration: Architecture and Performance Analysis," *Journal of Lightwave Technology*, vol. 10, no. 11, pp. 1688-1699, Nov. 1992.

[Bogineni et al. 1993] K. Bogineni, K. M. Sivalingam, and P. W. Dowd, "Low-complexity multiple access protocols for wavelength-division multiplexed photonic networks," *IEEE Journal on Selected Areas in Communications*, vol. 11, no. 4, pp. 590-604, May 1993.

[Brackett 1990] C. A. Brackett, "Dense wavelength division multiplexing networks: principles and applications," *IEEE Journal on Selected Areas in Communications*, vol. 8, no. 6, pp. 948-964, Aug. 1990.

[Brackett 1991] C. A. Brackett, “On the capacity of multiwavelength optical-star packet switches,” *IEEE LTS*, pp. 33-37, May 1991.

[Brackett 1996] C. A. Brackett, “Foreword: Is there an emerging consensus on WDM networking?,” *Journal of Lightwave Technology*, vol. 14, no. 6, pp. 936-941, June 1996.

[Bursky 1994B] D. Bursky, "Parallel optical links move data at 3 Gbits/s," *Electronic Design*, vol. 42, no. 24, pp. 79-82, Nov. 21, 1994.

[Carroll et al. 1993] J. E. Carroll, L. M. Zhang, and M. E. Bray, "A Bragg about lasers," *Electronics & Communication Engineering Journal*, pp. 325-337, 1993.

[Cerisola et al. 1995] M. Cerisola, T. K. Fong, R. T. Hofmeister, L. G. Kazovsky, C. L. Lu, P. Poggiolini, and D. J. M. Sabido IX, "Subcarrier multiplexing of packet headers in a WDM optical network and a novel ultrafast header clock-recovery technique," *Conference on Optical Fiber Communication, OFC’95 Technical Digest*, pp. 273-274, 1995.

[Chang et al. 1995] Chang et al., "Subcarrier multiplexing and ATM/SONET clear-channel transmission in a reconfigurable multiwavelength all-optical network test bed," *Conference on Optical Fiber Communication, OFC’95 Technical Digest*, pp. 269-270, 1995.

[Chang-Hasnain et al. 1991] C. J. Chang-Hasnain, M. W. Maeda, J. P. Harbison, L. T. Florez, and C. Lin, “Monolithic multiple wavelength surface emitting laser arrays,” *Journal of Lightwave Technology*, vol. 9, no. 12, Dec. 1991.

[Chang-Hasnain et al. 1991B] C. J. Chang-Hasnain, J. R. Wullert, J. P. Harbison, L. T. Florez, N. G. Stoffel, and M. W. Maeda, “Rastered, uniformly separated wavelengths emitted from a two-dimensional vertical-cavity surface-emitting laser arrays," *Applied Physics Letters*, vol. 58, no. 1, pp. 31-33, Jan. 7, 1991.

[Chapuran 1991] T. E. Chapuran, S. S. Wagner, R. C. Menendez, H. E. Tohme, and L. A. Wang, "Broadband multichannel WDM transmission with superluminescent diodes and LEDS," *Proc. IEEE Global Telecommunications Conference (GLOBECOM'91)*, pp. 612-618, 1991.

[Chawki et al. 1995] M. J. Chawki, V. Tholey, E. Delevaque, S. Boj, and E. Gay, "Wavelength reuse in a WDM unidirectional ring network by using a fiber-grating add/drop multiplexer," *Conference on Optical Fiber Communication, OFC'95 Technical Digest*, pp. 272-273, 1995.

[Chen et al. 1990] M. Chen, N. R. Dono, and R. Ramaswami, "A media-access protocol for packet-switched wavelength division multiaccess metropolitan area networks," *IEEE Journal on Selected Areas in Communications*, vol. 8, no. 6, pp. 1048-1057, Aug. 1990.

[Cheung 1990] K.-W. Cheung, "Acoustooptic tunable filters in narrowband WDM networks: system issues and network applications," *IEEE Journal on Selected Areas in Communications*, vol. 8, no. 6, pp. 1015-1025, Aug. 1990.

[Cheung 1992] K.-W. Cheung, "Design and implementation considerations for wavelength-division multiplexed (WDM) photonic dual bus," *Proc. IEEE International Conference on Communications (ICC'92)*, Chicago, IL, USA, June 1992, pp. 848-854.

[Chieng and Minasian 1994] Y. T. Chieng and R. A. Minasian, "Tunable erbium-doped fiber laser with a reflection Mach-Zehnder interferometer," *IEEE Photonics Technology Letters*," vol. 6, no. 2, pp. 153-156, Feb. 1994.

[Chiang et al. 1996] T.-K. Chiang, S. K. Agrawal, D. T. Mayweather, D. Sadot, C. F. Barry, M. Hickey, and L. G. Kazovsky, "Implementation of STARNET: a WDM computer communication network," *IEEE Journal on Selected Areas in Communications*, vol. 14, no. 5, pp. 824-839, June 1996.

[Chipalkatti et al. 1992] R. Chipalkatti, Z. Zhang and A. S. Acampora, "High speed communication protocols for optical star coupler using WDM," *Proc. INFOCOM'92*, Florence, Italy, May 1992, pp. 2124-2133.

[Chlamtac and Ganz 1988] I. Chlamtac and A. Ganz, "A multibus train communication (AMTRAC) architecture for high-speed fiber optic networks," *IEEE Journal on Selected Areas in Communications*, vol. 6, no. 6, pp. 903-912, July 1988.

[Chollet et al. 1996] F. Chollet, J.-P. Goedgebuer, H. Porte, and A. Hamel, "Electrooptic narrow linewidth wavelength tuning and intensity modulation of an erbium fiber ring laser," *IEEE Photonics Technology Letters*," vol. 8, no. 8, pp. 1009-1011, Aug. 1996.

[Chraplyvy et al. 1996] Chraplyvy et al., “1-Tb/s transmission experiment,” *IEEE Photonics Technology Letters*," vol. 8, no. 9, pp. 1264-1266, Sept. 1996.

[Coquin and Cheung 1988] G. A. Coquin and K. W. Cheung, "Electronically tunable external-cavity semiconductor laser," *Electronics Letters*, vol. 24, no. 10, pp. 599-600, May 12, 1988.

[Cremer et al. 1992] C. Cremer, N. Emeis, M. Schier, G. Heise, G. Ebbinghaus, and L. Stoll, “Grating spectrograph integrated with photo diode array in InGaAsP/InGaAs/InP,” *IEEE Photonics Technology Letters*," vol. 4, no. 1, pp. 108-110, Jan. 1992.

[Darcie 1987] T. E. Darcie, “Subcarrier multiplexing for multiple-access lightwave networks,” *Journal of Lightwave Technology*, vol. 5, no. 8, pp. 1103-1110, Aug. 1987.

[Davies and Ghani 1983] P. Davies and F. A. Ghani, “Access protocols for an optical-fibre ring network,” *Computer Communications*, vol. 6, no. 4, pp. 185-191, Aug. 1983.

[Delorme et al. 1996] F. Delorme, S. Grosmaire, G. Alibert, S. Slempkes, and A. Ougazzaden, “Simple multiwavelength device fabrication technique using a simple-grating holographic exposure,” *IEEE Photonics Technology Letters*," vol. 8, no. 7, pp. 867-869, July 1996.

[Dono et al. 1990] N. R. Dono, P. E. Green, K. Liu, R. Ramaswami, and F. F. Tong, "A wavelength division multiple access network for computer communication," *IEEE Journal on Selected Areas in Communications*, vol. 8, no. 6, pp. 983-994, Aug. 1990.

[Dowd 1991] P. W. Dowd, "Random access protocols for high-speed interprocessor communication based on an optical passive star topology," *Journal of Lightwave Technology*, vol. 9, no. 6, pp. 799-808, June 1991.

[Dowd et al. 1993] P. W. Dowd, K. K. Bogineni, A. Aly, and J. A. Perreault, “Hierarchical scalable photonic architectures for high-performance processor interconnection,” *IEEE Transactions on Computers*, vol. 42, no. 9, pp. 1105-1120, Sept. 1993.

[Dowd et al. 1995] P. W. Dowd, J. A. Perreault, J. C. Chu, D. C. Hoffmeister, and D. Crouse, "LIGHTNING: A scalable dynamically reconfigurable hierarchical WDM network for high-performance clustering," *Proc. of the fourth IEEE International Symposium on High Performance Distributed Computing (HPDC-4)*, Pentagon City, Virginia, Aug. 1995.

[Dowd et al. 1996] P. Dowd et al., “LIGHTNING network and systems architecture,” *Journal of Lightwave Technology*, vol. 14, no. 6, pp. 1371-1387, June 1996.

[Elrefaie 1993] A. F. Elrefaie, "Multiwavelength survivable ring network architectures," *Proc. IEEE International Conference on Communications (ICC’92),* Geneva, Switzerland, May 1993, pp. 1245-1251.

[Eng 1988] K. Y. Eng, "A photonic knockout switch for high-speed packet networks," *IEEE Journal on Selected Areas in Communications,* vol. 6, no. 7, pp. 1107-1116, Aug. 1988.

[Finn and Mason 1996] N. Finn and T. Mason, “ATM LAN emulation,” *IEEE Communications Magazine,* no. 6, pp. 96-100, June 1996.

[Frenkel 1992] A. Frenkel, “Pulse frequency division multiplexing is a new way to increase the capacity of a local fiber-optic communications network,” *Journal of Lightwave Technology,* vol. 10, no. 11, Nov. 1992.

[Frenkel and Lin 1988] A. Frenkel and C. Lin, "Inline tunable etalon filter for optical channel selection in high density wavelength division multiplexed fibre systems," *Electronics Letters,* vol. 24, no. 3, pp. 159-161, Feb. 4, 1988.

[Fujiwara et al. 1988] M. Fujiwara, N. Shimosaka, M. Nishio, S. Suzuki, S. Yamazaki, S. Murata, and K. Kaede, "A coherent photonic wavelength-division switching system for broadband networks," *Proc. of the 14th European Conference on Optical Communication (ECOC’88),* pp. 139-142, 1988.

[Gagliardi and Karp 1995] R. M. Gagliardi and S. Karp, *Optical Communications.* John Wiley & Sons, Inc., 1995, ISBN 0-471-54287-3.

[Ganz and Gao 1992] A. Ganz and Y. Gao, “A time-wavelength assignment algorithm for a WDM star network,” *Proc. INFOCOM’92,* Florence, Italy, May 1992, pp. 2144-2150.

[Ganz and Gao 1992B] A. Ganz and Y. Gao, "Traffic scheduling in multiple WDM star systems," *Proc. IEEE International Conference on Communications (ICC’92),* Chicago, IL, USA, June 1992, pp. 1468-1472.

[Georges and Lau 1993] J. B. Georges and K. Y. Lau, ”Self-pulsating laser diodes as fast--tunable transmitters in subcarrier multiple-access networks,” *IEEE Photonics Technology Letters,*" vol. 5, no. 2, pp. 242-245, Feb. 1993.

[Gerstel 1996] O. Gerstel, "On the future of wavelength routing networks," *IEEE Network*, pp. 14-20, Nov./Dec. 1996.

[Gidron 1992] R. Gidron, “Teranet: a multi-gigabits per second ATM network,” *Computer Communications*, vol. 15, no. 3, pp. 143-152, Apr. 1992.

[Glance 1996] B. Glance, ”Wavelength-tunable add/drop optical filter,” *IEEE Photonics Technology Letters*," vol. 8, no. 2, pp. 245-247, Feb. 1996.

[Goldberg 1994] L. Goldberg, "ATM switching: a brief introduction," *Electronic Design*, pp. 87-103, Dec. 16, 1994.

[Goodman et al. 1988] M. S. Goodman, E. Arthurs, J. M. Cooper, H. Kobrinski, and M. P. Vecchi, "Demonstration of fast wavelength tuning for a high performance packet switch," *Proc. of the 14th European Conference on Optical Communication (ECOC’88)*, pp. 255-258, 1988.

[Goodman et al. 1990] M. S. Goodman, H. Kobrinski, M. P. Vecchi, R. M. Bulley, and J. L. Gimlett, "The LAMBDANET Multiwavelength Network: Architecture, Applications, and Demonstrations," *IEEE Journal on Selected Areas in Communications*, vol. 8, no. 6, Aug. 1990.

[Green 1991] P. E. Green, Jr., “The future of fiber-optic computer networks,” *Computer*, pp. 78-87, Sept. 1991.

[Green 1993] P. E. Green, *Fiber Optic Networks*. Prentice-Hall, Inc., 1993, ISBN 0-13-319492-2.

[Green 1996] P. E. Green, Jr., "Optical networking update," *IEEE Journal on Selected Areas in Communications*, vol. 14, no. 5, pp. 764-779, June 1996.

[Green and Ramaswami 1990] P. E. Green and R. Ramaswami, “Direct detection lightwave systems: why pay more?,” *IEEE LCS*, pp. 36-49, Nov. 1990.

[Habbab et al. 1987] I. M. I. Habbab, M. Kavehrad, and C. W. Sundberg, "Protocols for very high-speed optical fiber local area networks using a passive star topology," *Journal of Lightwave Technology*, vol. 5, no. 12, pp. 1782-1794, Dec. 1987.

[Hahn et al. 1995] K. H. Hahn et al., "POLO: parallel optical links for workstation clusters and switching systems," *Conference on Optical Fiber Communication, OFC’95 Technical Digest*, pp. 112-112, 1995.

[Halsall 1992] F. Halsall, *Data communications, computer networks and open systems*. Addison-Wesley, 1992.

[Hamel et al. 1995] A. Hamel, D. Laville, A. Tromeur, P. Mouazan, T. Ben Meriem, R Richier, E. Pelletier, E. Tanguy, and S. Menard, "Multilayer add-drop multiplexers in a self-healing WDM ring network," *Conference on Optical Fiber Communication, OFC'95 Technical Digest*, pp. 84-85, 1995.

[Hariri and Lu 1996] S. Hariri and B. Lu, "ATM-based parallel and distributed computing," in *Parallel and distributed computing handbook*. A. Y. Zomaya Ed., McGraw-Hill, Inc., pp. 811-838, 1993.

[Hecht 1987] E. Hecht; with contributions by A. Zajac, *Optics*. Addison-Wesley, Inc., 1987, ISBN 0-201-11611-1.

[Hill 1989] G. R. Hill, "Wavelength domain optical network techniques," *Proceedings of the IEEE*, vol. 77, no. 1, pp. 121-132, Jan. 1989.

[Huang and Sheu 1996] N.-F. Huang and S.-T. Sheu, "A wavelength reusing/sharing access protocol for multichannel photonic dual bus networks," *Journal of Lightwave Technology*, vol. 14, no. 5, pp. 678-692, May 1996.

[Huang and Sheu 1997] N.-F. Huang and S.-T. Sheu, "An efficient wavelength reusing/migrating/sharing protocol for dual bus lightwave networks," *Journal of Lightwave Technology*, vol. 15, no. 1, pp. 62-75, Jan. 1997.

[Huffaker and Deppe 1996] D. L. Huffaker and D. G. Deppe, "Multiwavelength, densely-packed 2 × 2 vertical-cavity surface-emitting laser array fabricated using selective oxidation," *IEEE Photonics Technology Letters*," vol. 8, no. 7, pp. 858-860, July 1996.

[Humblet et al. 1992] P. A. Humblet, R. Ramaswami, and K. N. Sivarajan, "An efficient communication protocol for high-speed packet-switched multichannel networks," *Proc. SIGCOMM'92*, Baltimore, MD, USA, Aug. 17-20, 1992, pp. 2-13.

[Humblet et al. 1993] P. A. Humblet, R. Ramaswami, and K. N. Sivarajan, "An efficient communication protocol for high-speed packet-switched multichannel networks," *IEEE Journal on Selected Areas in Communications*, vol. 11, no. 4, pp. 568-578, May 1993.

[Irshid and Kavehrad 1992] M. I. Irshid and M. Kavehrad, "A fully transparent fiber-optic ring architecture for WDM networks," *Journal of Lightwave Technology*, vol. 10, no. 1, Jan. 1992.

[Jain 1993] R. Jain, "FDDI: current issues and future plans," *IEEE Communications Magazine*, no. 9, pp. 98-105, Sept. 1993.

[Jajszczyk and Mouftah 1993] A. Jajszczyk and H. T. Mouftah, “Photonic fast packet switching,” *IEEE Communications Magazine*, vol. 31, no. 2, pp. 58-65, Feb. 1993.

[Janniello et al. 1992] F. J. Janiello, R. Ramaswami, and D. G. Steinberg, "A prototype circuit-switched multi-wavelength optical metropolitan-area network," *Proc. IEEE International Conference on Communications (ICC’92)*, Geneva, Switzerland, May 1993, pp. 818-823.

[Janniello et al. 1995] F. J. Janniello, R. A. Neuner, R. Ramaswami, and P. E. Green, Jr., "Multiplex-protocol optical-fiber multiplexer for remote computer interconnection," *Conference on Optical Fiber Communication, OFC’95 Technical Digest*, pp. 163-164, 1995.

[Jeong and Goodman 1996] G. Jeong and J. W. Goodman, “Long-distance parallel data link using WDM transmission with bit-skew compensation,” *Journal of Lightwave Technology*, vol. 14, no. 5, pp. 655-660, May 1996.

[Jia and Mukherjee 1996] F. Jia and B. Mukherjee, “MultiS-Net: a high-capacity, packet-switched, multichannel, single-hop architecture and protocol for a local lightwave network,” *Journal of High Speed Networks*, vol. 5, no. 3, pp. 221-241, 1996.

[Jonsson and Moen 1994] M. Jonsson, U. Moen, “A high performance fiber-optic time-deterministic communication network,” *Master thesis, Centre for Computer Systems Architecture (CCA), Halmstad University, Sweden*, 1994.

[Jonsson and Svensson 1997] M. Jonsson and B. Svensson, “On inter-cluster communication in a time-deterministic WDM star network,” *to appear in Proc. 2nd Workshop on Optics and Computer Science (WOCS)*, Geneva, Switzerland, Apr. 1, 1997.

[Jonsson et al. 1995] M. Jonsson, K. Nilsson, and B. Svensson, “A fiber-optic interconnection concept for scaleable massively parallel computing,” *Proc. Massively Parallel Processing using Optical Interconnections (MPPOI’95)*, San Antonio, TX, USA, Oct. 23-24, 1995, pp. 313-320.

[Jonsson et al. 1996] M. Jonsson, A. Åhlander, M. Taveniku, and B. Svensson, “Time-deterministic WDM star network for massively parallel computing in radar systems,” *Proc. Massively Parallel Processing using Optical Interconnections (MPPOI’96)*, Maui, HI, USA, Oct. 27-29, 1996, pp. 85-93.

[Jonsson et al. 1997] M. Jonsson, K. Börjesson, and M. Legardt, “Dynamic time-deterministic traffic in a fiber-optic WDM star network,” *to appear in Proc. 9th Euromicro Workshop on Real Time Systems*, Toledo, Spain, June 11-13, 1997.

[Kameda et al. 1993] T. Kameda, H. Mori, S. Onuki, T. Kikugawa, Y. Takahashi, F. Tsuchiya, and H. Nagai, “A DBR laser employing passive-section heaters, with 10.8 nm tuning range and 1.6 MHz linewidth,” *IEEE Photonics Technology Letters,*" vol. 5, no. 6, pp. 608-610, June 1993.

[Kaminow 1989] I. P. Kaminow, "Non-coherent photonic frequency-multiplexed access networks," *IEEE Network*, pp. 4-12, Mar. 1989.

[Kaminow et al. 1988] I. P. Kaminow, P. P. Iannone, J. Stone, and L. W. Stulz, “FDMA-FSK star network with a tunable optical filter demultiplexer,” *Journal of Lightwave Technology*, vol. 6, no. 9, pp. 1406-1414, Sept. 1988.

[Kaminow et al. 1989] I. P. Kaminow, P. P. Iannone, J. Stone, and L. W. Stulz, "A tunable vernier fiber Fabry-Perot filter for FDM demultiplexing and detection,” *IEEE Photonics Technology Letters,*" vol. 1, no. 1, pp. 24-26, Jan. 1989.

[Kato et al. 1993] K. Kato, K. Okamoto, H. Okazaki, Y. Ohmori, and I. Nishi, ”Packaging of large-scale integrated-optic NxN star couplers,” *IEEE Photonics Technology Letters*, vol. 4, no. 3, pp. 348-351, Mar. 1993.

[Kazovsky et al. 1994] L. G. Kazovsky, T. Fong, and T. Hofmeister, “Optical local area network technologies,” *IEEE Communications Magazine*, vol. 32, no. 12, pp. 50-54, Dec. 1993.

[Keiser 1991] G. Keiser, *Optical Fiber Communications*. McGraw-Hill, Inc., 1991, ISBN 0-07-100785-7.

[Kirkby 1990] P. A. Kirkby, "Multichannel wavelength-switched transmitters and recievers-new component concept for broad-band networks and distributed switching systems," *Journal of Lightwave Technology*, vol. 8, no. 2, Feb. 1990.

[Kobrinski and Cheung 1989] H. Kobrinski and K.-W. Cheung, “Wavelength-tunable optical filters: applications and technologies,” *IEEE Communications Magazine*, no. 10, pp. 53-63, Oct. 1989.

[Kobrinski et al. 1987] H. Kobrinski, R. M. Bulley, M. S. Goodman, M. P. Vecchi, C. A. Bracket, L. Curtis, and J. L. Gimlett, "Demonstration of high capacity in the Lambdanet architecture: a multiwavelength optical network," *Electronics Letters*, vol. 23, no. 16, pp. 824-826, July 30, 1987.

[Kobrinski et al. 1988] H. Kobrinski, M. P. Vecchi, E. L. Goldstein, and R. M. Bulley, "Wavelength selection with nanosecond switching times using distributed-feedback laser amplifiers," *Electronics Letters,* vol. 24, no. 15, pp. 969-971, July 21, 1988.

[Kobrinski et al. 1988B] H. Kobrinski, E. Arthurs, R. M. Bulley, J. M. Cooper, E. L. Goldstein, M. S. Goodman, and M. P. Vecchi, "An optoelectronic packet switch utilizing fast wavelength tuning," *Proc. IEEE Global Telecommunications Conference (GLOBECOM'88),* pp. 948-953, 1988.

[Kobrinski et al. 1990] H. Kobrinski, M. P. Vecchi, M. S. Goodman, E. L. Goodman, E. L. Goldstein, T. E. Chapuran, J. M. Cooper, M. Tur, C. E. Zah, and S. G. Menocal, Jr., "Fast wavelength-switching of laser transmitters and amplifiers," *IEEE Journal on Selected Areas in Communications,* vol. 8, no. 6, pp. 1190-1202, Aug. 1990.

[Larson and Harris 1995] M. C. Larson and J. S. Harris, Jr., "Broadly-tunable resonant-cavity light-emitting diode," *IEEE Photonics Technology Letters,*" vol. 7, no. 11, pp. 1267-1269, Nov. 1995.

[Larson and Harris 1996] M. C. Larson and J. S. Harris, Jr., "Wide and continuous wavelength tuning in a vertical-cavity surface-emitting laser using a micromachined deformable-membrane mirror," *Applied Physics Letters,* vol. 68, no. 7, pp. 891-893, Feb. 12, 1996.

[Lee and Zah 1989] T. P. Lee and C. E. Zah, "Wavelength-tunable and single-frequency semiconductor lasers for photonic communications networks," *IEEE Communications Magazine,* no. 10, pp. 42-52, Oct. 1989.

[Lee et al. 1996] T. P. Lee et al., "Multiwavelength DFB laser array transmitter for ONTC reconfigurable optical network testbed," *Journal of Lightwave Technology,* vol. 14, no. 6, pp. 967-976, June 1996.

[Lin et al. 1988] C. Lin, H. Kobrinski, A. Frenkel, C. A. Brackett, "Wavelength-tunable 16 optical channel transmission experiment at 2 Gbit/s and 600 Mbit/s for broadband subscriber distribution," *Electronics Letters,* vol. 24, no. 19, pp. 1215-1217, Sept. 15, 1988.

[Loeb and Stilwell 1988] M. L. Loeb and G. R. Stilwell, "High-speed data transmission on an optical fiber using a byte-wide WDM system," *Journal of Lightwave Technology,* vol. 6, no. 8, pp. 1306-1311, Aug. 1988.

[Loeb and Stilwell 1990] M. L. Loeb and G. R. Stilwell, "An algorithm for bit-skew correction in byte-wide WDM optical fiber systems," *Journal of Lightwave Technology,* vol. 8, no. 2, pp. 239-242, Aug. 1988.

[Louri and Gupta 1996] A. Louri and R. Gupta, ”Hierarchical optical ring interconnection (HORN): a scalable interconnection-network for multiprocessors and massively parallel systems,” *Proc. Massively Parallel Processing using Optical Interconnections (MPPOI'94),* Maui, HI, USA, Oct. 27-29, 1996, pp. 247-254.

[Louri and Gupta 1997] A. Louri and R. Gupta, ”Hierarchical optical ring interconnection (HORN): scalable interconnection network for multiprocessors and multicomputers," *Applied Optics,* vol. 36, no. 2, pp. 430-442, Jan. 10, 1997.

[Maeda et al. 1991] M. W. Maeda, C. Chang-Hasnain, A. Von Lehmen, H. Izadpanah, C. Lin, M. Z. Iqbal, L. Florez, and J. Harbison, “Multigigabit/s operation of 16-wavelength vertical-cavity surface-emitting laser array,” *IEEE Photonics Technology Letters,*" vol. 3, no. 10, pp. 863-865, Oct. 1991.

[Marhic 1993] M. E. Marhic, “Coherent optical CDMA networks,” *Journal of Lightwave Technology,* vol. 11, no. 5/6, pp. 854-863, May/June 1993.

[Mehravari 1991] N. Mehravari, "Performance and protocol improvements for very high speed optical fiber local area networks using a passive star topology," *Journal of Lightwave Technology,* vol. 8, no. 4, pp. 520-530, Apr. 1990.

[Mellis et al. 1988] J. Mellis, S. A. Al-Chalabi, K. H. Cameron, R. Wyatt, J. C. Regnault, W. J. Devlin, M. C. Brain, "Miniature packaged external-cavity semiconductor laser with 50 GHz continuous electrical tuning range," *Electronics Letters,* vol. 24, no. 16, pp. 988-989, Aug. 4, 1988.

[Mestdagh 1995] D. J. G. Mestdagh, *Fundamentals of Multiaccess Optical Fiber Networks.* Artech House, Inc., 1995, ISBN 0-89006-666-3.

[Miller and Janniello 1990] C. M. Miller and F. J. Janniello, " Passively temperature-compensated fibre Fabry-Perot filter and its application in wavelength division multiple access computer network," *Electronics Letters,* vol. 26, no. 25, pp. 2122-2123, Dec. 6, 1990.

[Miller and Miller 1992] C. M. Miller and J. W. Miller, " Wavelength-locked, two-stage fibre Fabry-Perot filter for dense wavelength division multiplexing in erbium-doped fibre amplifier spectrum," *Electronics Letters,* vol. 28, no. 3, pp. 216-217, Jan. 30, 1992.

[Mukherjee 1992] B. Mukherjee, "WDM-based local lightwave networks part I: single-hop systems," *IEEE Network,* pp. 12-27, May 1992.

[Mukherjee 1992B] B. Mukherjee, "WDM-based local lightwave networks part II: multihop systems," *IEEE Network,* pp. 20-32, July 1992.

[Nassehi et al. 1985] M. M. Nassehi, F. A. Tobagi, and M. E. Marhic, "Fiber optic configurations for local area networks," *IEEE Journal on Selected Areas in Communications*, vol. 3, no. 6, pp. 941-949, Nov. 1985.

[Nishio et al. 1993] M. Nishio, S. Suzuki, K. Takagi, Ichiro Oguro, T. Numai, K. Kasahari, and K. Kaede, “A new architecture of photonic ATM switches,” *IEEE Communications Magazine*, vol. 31, no.4, Apr. 1993.

[Numai et al. 1989] T. Numai, S. Murata, and I. Mito, “1.5 µm tunable wavelength filter using a phase-shift-controlled distributed feedback laser diode with a wide tuning range and a high constant gain," *Applied Physics Letters*, vol. 54, no. 19, pp. 1859-1860, May 8, 1989.

[Oda et al. 1989] Channel selection and stabilization technique for a waveguide-type 16-channel frequency selection switch for optical FDM distribution systems,” *IEEE Photonics Technology Letters*," vol. 1, no. 6, pp. 137-139, June 1989.

[Ohshima et al. 1985] S. Ohshima, T. Ito, K.-I. Donuma, H. Sugiyama, and Y. Fujii, “Small loss-deviation tapered fiber star coupler for LAN,” *Journal of Lightwave Technology*, vol. 3, no. 3, pp. 556-560, June 1985.

[Okamoto et al. 1992] K. Okamoto, H. Takahashi, M. Yasu, and Y. Hibino, ”Fabrication of wavelength-insensitive 8x8 star coupler,” *IEEE Photonics Technology Letters*, vol. 4, no. 1, pp. 61-63, Jan. 1992.

[Okamoto et al. 1992B] K. Okamoto, H. Okazaki, Y. Ohmori, and K. Kato, ”Fabrication of large scale integrated-optic NxN star couplers,” *IEEE Photonics Technology Letters*, vol. 4, no. 9, pp. 1032-1035, Sep. 1992.

[Parker and Mears 1996] M. C. Parker and R. J. Mears, “Digitally tunable wavelength filter and laser,” *IEEE Photonics Technology Letters*," vol. 8, no. 8, pp. 1007-1008, Aug. 1996.

[Patel et al. 1990] J. S. Patel, M. A. Saifi, D. W. Berreman, C. Lin, N. Andreadakis, and S. D. Lee, “Electrically tunable optical filter for infrared wavelength using liquid crystals in a Fabry-Perot etalon," *Applied Physics Letters*, vol. 57, no. 17, pp. 1718-1720, Oct. 22, 1990.

[Pieris and Sasaki 1994] G. R. Pieris and G. H. Sasaki, "Scheduling transmissions in WDM broadcast-and-select networks," *IEEE/ACM Transactions on Networking*, vol. 2, no. 2, Apr. 1994.

[Prucnal et al. 1986] P. R. Prucnal, M. A. Santoro, and S. K. Sehgal, "Ultrafast all-optical synchronous multiple access fiber networks," *IEEE Journal on Selected Areas in Communications*, vol. 4, no. 9, pp. 1484-1493, Dec. 1996.

[Prucnal et al. 1986B] P. R. Prucnal, M. A. Santoro, T. R. Fan, “Spread spectrum fiber-optic local area network using optical processing,” *Journal of Lightwave Technology*, vol. 4, no. 5, pp. 547-554, May 1986.

[Prucnal et al. 1994] P. R. Prucnal, I. Glesk, and J. P. Sokoloff, ”Demonstration of all-optical self-clocked demultiplexing of TDM data at 250 Gb/s,” *Proc. Massively Parallel Processing using Optical Interconnections (MPPOI’94)*, Cancun, Mexico, Apr. 26-27, 1994, pp. 106-117.

[Ramamurthy et al. 1995] S. Ramamurthy, B. Mukherjee, and B. Moslehi, “Optimized partitioning of a wavelength distributed data interface ring network,” *Journal of Lightwave Technology*, vol. 13, no. 10, pp. 1971-1984, Oct. 1995.

[Ramaswami 1993] R. Ramaswami, “Multiwavelength lightwave networks for computer communication,” *IEEE Communications Magazine*, vol. 31, no. 2, pp. 78-88, Feb. 1993.

[Reilly 1994] P. Reilly, “PDH, broadband ISDN, ATM, and all that: a guide to modern WAN networking, and how it evolved,” *Silicon Graphics, Inc.*, 1994.

[Rom and Sidi 1990] R. Rom and M. Sidi, *Multiple access protocols : performance and analysis*. Springer-Verlag, Inc., 1990, ISBN 0-387-97253-6.

[Ross 1989] F. E. Ross, "An overview of FDDI: the fiber distributed data interface," *IEEE Journal on Selected Areas in Communications*, vol. 7, no. 7, pp. 1043-1051, Sept. 1989.

[Rouskas and Ammar 1995] G. N. Rouskas and M. H. Ammar, "Analysis and optimization of transmission schedules for single-hop WDM networks," *IEEE/ACM Transactions on Networking*, vol. 3, no. 2, Apr. 1995.

[Salehi 1989] J. A. Salehi, "Code division multiple-access techniques in optical fiber networks - Part I: fundamental principles," *IEEE Transactions on Communications*, vol 37, no. 8, pp. 824-833, Aug. 1989.

[Salehi and Brackett 1989] J. A. Salehi and C. A. Brackett, "Code division multiple-access techniques in optical fiber networks - Part II: Systems performance analysis," *IEEE Transactions on communications*, vol 37, no. 8, pp. 834-842, Aug. 1989.

[Schwartz et al. 1996] D. B. Schwartz, K. Y. Chun, N. Choi, D. Diaz, S. Planer, G. Raskin, and S. G. Shook, "OPTOBUS™ I: performance of a 4 Gb/s optical interconnect," *Proc. Massively Parallel Processing using Optical Interconnections (MPPOI'96),* Maui, HI, USA, Oct. 27-29, 1996, pp. 256-263.

[Seo et al. 1996] S.-W. Seo, K. Bergman, and P. R. Prucnal, "Transparent optical networks with time-division multiplexing," *IEEE Journal on Selected Areas in Communications*, vol. 14, no. 5, pp. 1039-1051, June 1996.

[Shankaranarayanan et al. 1991] N. K. Shankaranarayanan, Stuart D. Elby, and Kam Y. Lau, "WDMA/subcarrier-FDMA lightwave networks: limitations due to optical beat interference," *Journal of Lightwave Technology*, vol. 9, no. 7, Jul. 1991.

[Sivalingam 1994] K. M. Sivalingam, "High-speed communication protocols for all-optical wavelength division multiplexed computer networks," *Doctoral thesis, Department of Computer Science, State University of New York at Buffalo, Buffalo, NY, USA*, June 1994.

[Sivalingam and Dowd 1995] K. M. Sivalingam and P. W. Dowd, "A multilevel WDM access protocol for an optically interconnected multiprocessor system," *Journal of Lightwave Technology*, vol. 13, no. 11, pp. 2152-2167, Nov. 1995.

[Sivalingam et al. 1992] K. M. Sivalingam, K. Bogineni, and P. W. Dowd, "Pre-allocation media access control protocols for multiple access WDM photonic networks," *Proc. ACM SIGCOMM'92*, Baltimore, MD, USA, Aug. 17-20, 1992, pp. 14-26.

[Soole et al. 1992] J. B. D. Soole, K. Poguntke, A. Scherer, H. P. LeBlanc, C. Chang-Hasnain, J. R. Hayes, C. Caneau, R. Bhat, and M. A. Koza, " Multistripe array grating integrated cavity (MAGIC) laser: a new semiconductor laser for WDM applications," *Electronics Letters*, vol. 28, no. 19, pp. 1805-1807, Sept. 10, 1992.

[Sorel et al. 1996] Y. Sorel, A. O'Hare, J.-F. Kerdiles, and P.-L. François, "160 Gb/s in 28-nm WDM transmission over 238 km of DSF with standard fiber compensation," *IEEE Photonics Technology Letters*," vol. 8, no. 5, pp. 727-729, May 1996.

[Spirit et al. 1994] D. M. Spirit, A. D. Ellis, and P. E. Barnsley, "Optical time division multiplexing: systems and networks," *IEEE Communications Magazine*, no. 12, pp. 56-62, Dec. 1994.

[Straus and Kawasaki 1987] J. Straus and B. Kawasaki, "Passive optical components," in *Optical-Fiber Transmission*. E. E. Basch Ed., SAMS, pp. 241-264, 1987.

[Su and Olshansky 1993] S. F. Su and R. Olshansky, “Performance of WDMA networks with baseband data packets and subcarrier multiplexed control channels,” *IEEE Photonics Technology Letters*, vol. 5, no. 2, Feb. 1993.

[Sudhakar et al. 1991] G. N. M. Sudhakar, N. D. Georganas, and M. Kavehrad, "Slotted aloha and reservation aloha protocols for very high-speed optical fiber local area networks using passive star topology," *Journal of Lightwave Technology*, vol. 9, no. 10, pp. 1411-1422, Oct. 1991.

[Suzuki 1994] T. Suzuki, “ATM adaptation layer protocol,” *IEEE Communications Magazine*, no. 4, pp. 80-83, Apr. 1994.

[Tabuchi and Ishikawa 1990] H. Tabuchi and H. Ishikawa, "External grating tunable MQW laser with wide tuning range of 240 nm," *Electronics Letters*, vol. 26, no. 11, pp. 742-743, May 24, 1990.

[Toba et al. 1989] H. Toba, K. Oda, K. Nosu, and N. Takato, "16-channel optical FDM distribution/transmission experiment utilising multichannel frequency stabiliser and waveguide frequency selection switch," *Electronics Letters*, vol. 25, no. 9, pp. 574-576, Apr. 27, 1989.

[Toba et al. 1990] H. Toba, K. Oda, K. Nakanishi, N. Shibata, K. Nosu, N. Takato, and K. Sato, "100-channel optical FDM transmission /distribution at 622 Mbit/s over 50 km utilising a waveguide frequency selection switch," *Electronics Letters*, vol. 26, no. 6, pp. 376-377, Mar. 15, 1990.

[Truong et al. 1995] H. L. Truong, W. W. Ellington Jr., J. L. Boudec, A. X. Meier, and J. W. Pace, “LAN emulation on an ATM network,” *IEEE Communications Magazine*, no. 5, pp. 70-85, May 1995.

[Tseng and Chen 1982] C.-W. Tseng and B.-U. Chen, "D-Net. A new scheme for high data rate optical local area networks," *Proc. IEEE Global Telecommunications Conference (GLOBECOM’91)*, pp. 949-955, 1982.

[Wagner and Chapuran 1992] S. S. Wagner and T. E. Chapuran, "Multiwavelength ring networks for switch consolidation and interconnection," *Proc. IEEE International Conference on Communications (ICC’92)*, Chicago, IL, USA, June 1992, pp. 1173-1179.

[Wailes and Meyer 1991] T. S. Wailes and D. G. Meyer, “Multiple channel architecture: a new optical interconnection strategy for massively parallel computers,” *Journal of Lightwave Technology*, vol. 9, no. 12, pp. 1702-1716, Dec. 1991.

[Weiner et al. 1988] A. M. Weiner, J. P. Heritage, and J. A. Salehi, “Encoding and decoding of femtosecond pulses,” *Optics Letters*, vol. 13, no. 4, pp. 300-302, Apr. 1988.

[Westmore 1991] R. J. Westmore, "SYMFONET: interconnect technology for multinode computing," *Electronics Letters*, vol. 27, no. 9, pp. 697-698, Apr. 25, 1991.

[Wooten et al. 1996] E. L. Wooten, R. L. Stone, E. W. Miles, and E. M. Bradley, “Rapidly tunable narrowband wavelength filter using LiNbO3 unbalanced Mach-Zehnder interferometers,” *Journal of Lightwave Technology*, vol. 14, no. 11, pp. 2530-2536, Nov. 1996.

[Yan et al. 1996] A. Yan, A. Ganz, and C. M. Krishna, “A distributed adaptive protocol providing real-time services on WDM-based LANs,” *Proc. INFOCOM’96*, 1996, San Francisco, CA, USA, Mar. 24-28, 1996, pp. 962-969.

[Yan et al. 1996B] A. Yan, A. Ganz, and C. M. Krishna, “A distributed adaptive protocol providing real-time services on WDM-based LAN’s,” *Journal of Lightwave Technology*, vol. 14, no. 6, pp. 1245-1254, June 1996.

[Yun and Kavehrad 1992] G. Yun and M. Kavehrad, ”$N \times N$ passive fiber star coupler using grating degeneration and sandwich structures,” *IEEE Photonics Technology Letters*, vol. 4, no. 9, pp. 1035-1037, Sep. 1992.

[Zaccarin and Kavehrad 1993] D. Zaccarin and M. Kavehrad, ”An optical CDMA system based on spectral encoding of LED,” *IEEE Photonics Technology Letters*," vol. 4, no. 4, pp. 479-482, Apr. 1993.

[Zah et al. 1988] C. E. Zah et al., "Monolithic integration of multiwavelength compressive-strained multiquantum-well distributed-feedback laser array with star coupler and optical amplifiers," *Electronics Letters*, vol. 28, no. 25, pp. 2361-2362, 3 Dec., 1992.

[Zirngibl et al. 1996] M. Zirngibl, C. R. Doerr, and L. W. Stulz, “Study of spectral slicing for local access applications,” *IEEE Photonics Technology Letters*," vol. 8, no. 5, pp. 721-723, May 1996.

Index