

PHOTONIC MULTIPLE-ACCESS NETWORKS: ROUTING AND MULTIPLEXING

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Lightwave technology is well-established for long-haul and point-to-point applications, but current research is looking at ways to extend it to multiple-access computer networks and the distribution plant. How do we interconnect more than 100 users at data rates above 1Gb/s? What novel optoelectronic components are needed to realize the photonic networks of the future? We answer these questions here and in another paper in this issue. The companion paper discusses the constraints that photonic components impose on topologies for multiple-access networks.¹ Here, we examine how the unique properties of photonic components can be exploited to realize novel routing and multiplexing functions. We show that specific applications and types of traffic carried will determine the configurations of future photonic networks. We conclude that ambitious photonic solutions will compete strongly with electronic approaches.

Introduction

Passive branched topologies—such as the *star* or *tree*—are the simplest photonic networks to implement for reasons noted in the companion paper.¹ The most-common modulation schemes to permit multiplexing of many users are optical time-division multiplexing (TDM), and frequency-division multiplexing (FDM)—or, equivalently, wavelength-division multiplexing (WDM). (Panel 1 defines acronyms and some terms used in this paper.) For FDM or WDM networks, demultiplexing and detection may use coherent (heterodyne or homodyne) or noncoherent (tunable filter) receivers.

Microwave subcarrier frequency-division modulation (SFDM) is an attractive low-cost format for analog or digital signals.

Space-division multiplexing (SDM), which is topologically an active star, may be based on an electronic $N \times N$ switch with optical-to-electronic (O/E) and electronic-to-optical (E/O) converters, or on a

Panel 1. Acronyms and Terms			
ASK	amplitude-shift keying	Λ	bandwidth of wavelength-division-multiplexed network
B	modulation bit rate	λ	wavelength
c	velocity of light in a vacuum	L	length of fiber
c/n	propagation velocity in fiber	l	length of fiber ($= cT/2n$) for mode-locked laser
DBR	distributed Bragg reflector	LAN	local-area network
DFB	distributed feedback (laser)	N	number of stations (entry and exit points) in the network
E/O	electronic-to-optical	n	effective refractive index
F	finesse; the ratio of free spectral range (or tuning range) to passband width	NRZ	nonreturn to zero
F	FDM bandwidth	O/E	optical-to-electronic
f	frequency (c/λ)	p	number of frequency segments or time slots
f_c	optical channel spacing	RC	resistance-capacitance product
f_d	optical frequency deviation	SDM	space-division multiplexing
FDM	frequency-division multiplexing	SFDM	subcarrier frequency-division multiplexing
FFP	fiber Fabry-Perot	T	duration of a frame
f_{FP}	Fabry-Perot passband width	T/p	duration of a time slot
f_H	heterodyne intermediate frequency	τ	duration of an optical pulse
f_{LO}	local-oscillator frequency	TDM	time-division multiplexing
FM	frequency modulation	Ti:LiNbO ₃	titanium-diffused lithium niobate
f_s	optical-signal frequency	TV	television
FSK	frequency-shift keying	WDM	wavelength-division multiplexing
FSR	free spectral range		
GaAs	gallium arsenide		
IC	integrated circuits		

photonic $N \times N$ switch that avoids the optoelectronic conversions. (N is the number of stations—entry and exit points—in the network.) Any $N \times N$ multiple-access network is topologically and functionally equivalent to an $N \times N$ circuit switch, although the switch's terminals are in a smaller box. Hence, photonic switch and network technology are similar.

This paper reviews recent research efforts on photonic distribution methods.

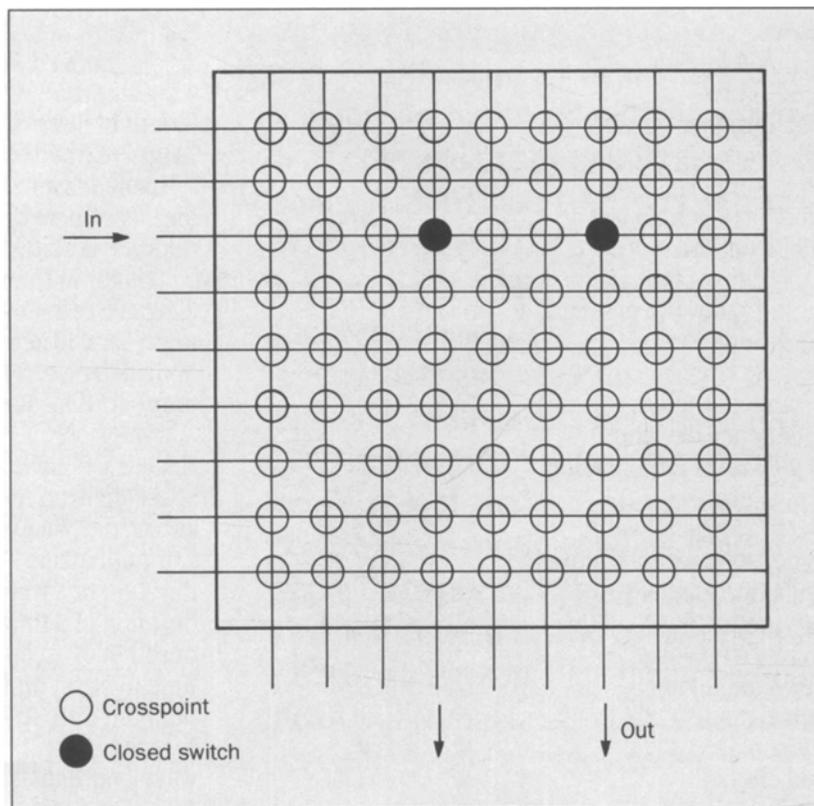
Space Division

The crossbar switch (Figure 1) is the simplest means for connecting any set of N inputs to any set of N outputs. In addition, any subset of interconnections can

be rearranged without disconnecting other connections; i.e., the configuration is strictly "nonblocking." Furthermore, the same message can be broadcast or narrowcast from one input to all or several outputs. But to realize this flexibility, we need N^2 crosspoint switches.

Several other configurations that require fewer switches are possible, but at the expense of more complexity and less flexibility.² For example, a 2×2 switch that has two states (bar and cross), as indicated in Figure 2a, can serve as a crosspoint in various switch matrices, including the crossbar. Only $N(N-1)/2$ 2×2 switches are required to produce a "rearrangeably nonblocking," $N \times N$ switch.³ Thus, adding a new interconnection may require that we change some paths through the switch

Figure 1. Crossbar matrix switch. In this example, the solid circles represent closed switches.



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for existing connections, temporarily interrupting service. However, this switch cannot support broadcasting.

Figure 2b illustrates a 4×4 example of an $N \times N$ switch that satisfies the special constraint that connections between 2×2 elements do not cross. Thus, it is suitable for use in planar integrated-optics applications. If crossovers are allowed, the number of elements required can be reduced to about $N \log_2 N$. An electro-optically controlled directional coupler, for which the coupling ratio switches between "1" (cross) and "0" (bar), can serve as the 2×2 switch element in an $N \times N$ photonic switch.⁴

Various $N \times N$ switches have been realized

electronically, using silicon integrated circuits (ICs), and optically, using directional coupler switches constructed of titanium-diffused lithium niobate (Ti:LiNbO_3) waveguides.^{5,6} For both these matrix switches, we must define two speeds:

- The rate at which the network can be rearranged
- The bit rate of signals that can be transported through the network without distortion, i.e., the throughput rate.

In optical switches, the throughput rate is practically unlimited because the refractive-index dispersion for path lengths shorter than about 10 cm (centimeters) is negligible even at 10 GHz (gigahertz). For ICs, on the other

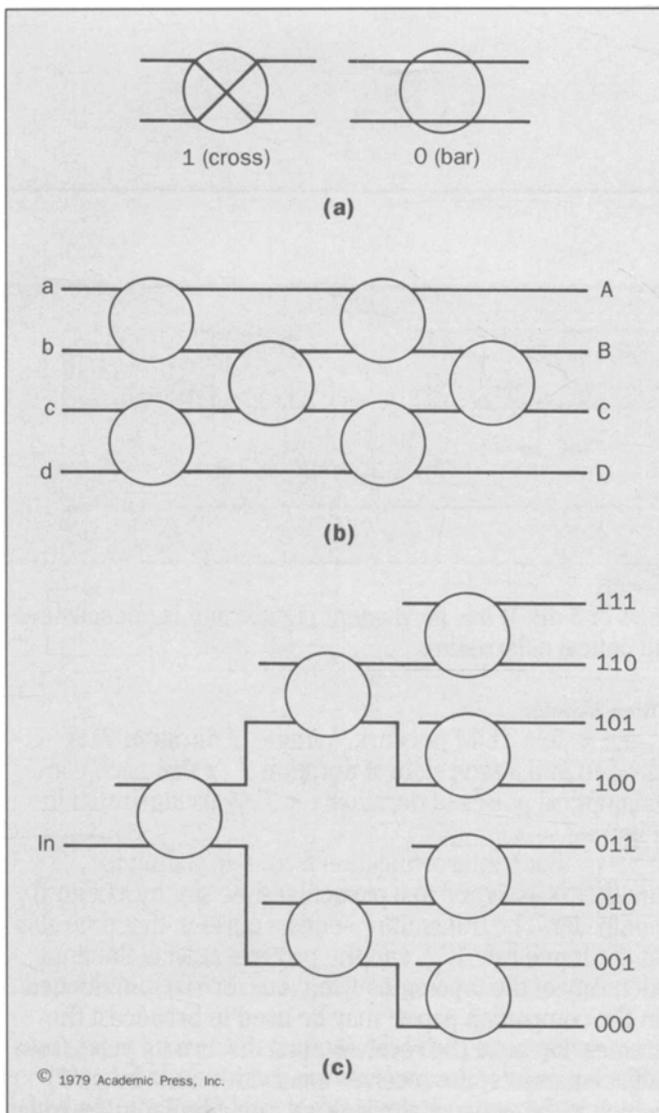


Figure 2. Configurations that require fewer switches: (a) a two-state 2×2 directional-coupler; (b) a 4×4 rearrangeably nonblocking switch; and (c) a 1×8 branching switch. Output addresses (at the right in c) correspond to states of 2×2 switches in each rank (after Kaminow and Li⁴).

hand, the capacitive loading introduced by the metallic paths between switches produces significant dispersion. The rearranging rate in both types of device is limited by transit times in the leads and the resistance \times capacitance (RC) time constants in the switch elements themselves. Individual Ti:LiNbO₃ switches have operated at rates of

about 10 GHz. Individual silicon transistors can operate at about 1 GHz, while discrete gallium arsenide (GaAs) transistors can operate at about 10 GHz.⁷

The IC arrays have a fabrication advantage for large N because large-scale IC technology is well established and each transistor occupies a small chip area [about 10 μm (micrometers) by 10 μm]. Because electrical pulses can be reformed and retimed on the IC chip, large $N \times N$ arrays can be built up from smaller subarrays. Pulse regeneration may occur at each crosspoint or, for simple gates, at the edge of the subarray. But for large N , an important limitation is the cost and complexity of O/E and E/O converters to get on and off the chip.

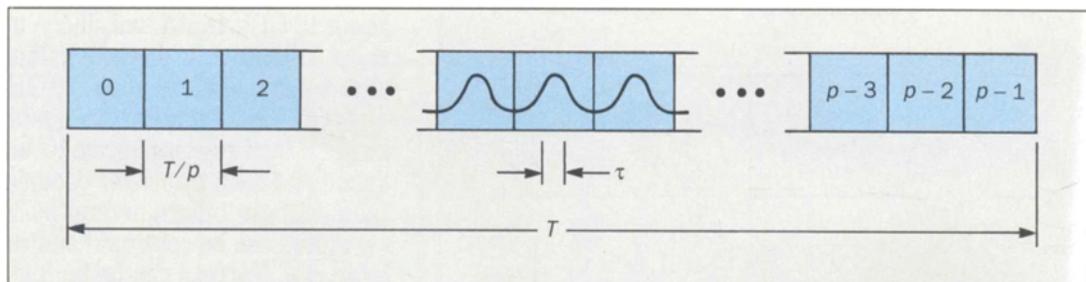
On the other hand, each optical directional-coupler switch requires a large, elongated area [about 20 μm by 1 cm (centimeter)]. But available substrates are of limited extent, so large arrays are difficult to realize. Also, the required large substrate extent contributes to control circuit capacitance and optical loss. Finally, optical pulse reforming is not possible.

Thus, with current technology, the applications of electronic and optical switches are complementary. For small N (less than about 16) and high throughput rate [above 1 Gb/s (gigabits per second)], optical switches may have the advantage. For large N at low throughput rates, electronic switches may be preferable.

A 4×4 GaAs matrix has switched a 2-Gb/s signal with a 1-ns (nanosecond) rearrangement time.⁸ This matrix was incorporated in a three-chip optoelectronic circuit with four input and four output optical fibers that switched 560-Mb/s (megabits per second) data with low crosstalk.⁹ The four-channel GaAs laser transmitter array could operate at 1.5 Gb/s.¹⁰

Recently, IBM Corporation reported¹¹ a 16×16 GaAs crosspoint switch chip that operates at 1.7 Gb/s and uses 10,000 FETs (field-effect transistors). Transmitter and receiver chips also provided four optical-fiber-coupled outputs and inputs at 1 Gb/s. The complexity of these experiments highlights the difficulty of bringing many fibers onto and off an optoelectronic IC chip.

Figure 3. TDMA frame with p slots and frame rate $1/T$. τ is the duration of an optical pulse.



Several state-of-the-art Ti:LiNbO₃ photonic-switch matrices have been reported.¹²⁻¹⁴ The emphasis has been on dimensionality, crosstalk, optical loss, and switching voltage, but not rearrangement speed. We may assume that large throughput rates (more than 10 Gb/s) will not be a problem. But because each crosspoint switch may contain two or three electrodes, the ultimate rearrangement rate (which is limited by the crosspoint itself due to circuit parasitics) may prove difficult to realize.

Ericsson reported¹² an 8 × 8 nonblocking crossbar matrix that contains 64 directional coupler switches and operates at about 1300 nm (nanometers) with a voltage of 26V (volts) and end-to-end throughput loss of 7 dB. The crosstalk, which is the fraction of power at a given input port that appears at any output port that is not meant to be connected to the input port, is about -20 dB. The substrate area is about 0.6 cm by 6 cm for this switch.

A fully packaged and pig-tailed Ti:LiNbO₃ 8 × 8 matrix switch that operates stably at 1300 nm was reported recently by AT&T.¹³ It is based on a novel rearrangeably nonblocking architecture that incorporates 48 simplified directional coupler switches, each requiring the same voltage of 9V. The throughput loss is 14 dB and the crosstalk about -20 dB. The technology demonstrated in this matrix switch offers the prospect of optically coupling a number of substrates to form a much larger switch array.

A 1 × 16 branching-switch array,¹⁴ similar to the 1 × 8 array illustrated in Figure 2c, has also been fabricated with 15 Ti:LiNbO₃ switches and has a throughput

loss of 3 dB. It has permanent pigtails and is not sensitive to optical polarization.

Time Division

In a TDM network, a frame of duration T is divided into p time slots of duration T/p that each contain optical pulses of duration $\tau < T/p$, as illustrated in Figure 3.

Each interconnection from one station to another is assigned to a particular time slot by a central controller. The transmitter sends a pulse in that time slot at the frame rate $1/T$, and the receiver selects the time slot. Any of the topologies (ring, bus, or star) mentioned in the companion paper¹ may be used to broadcast the frames. Because the receiver must discern its pulse from adjacent pulses, the receiver bandwidth must be p/T , which is the network throughput rate. Similarly, the transmitter must be able to generate pulses that have this large bandwidth. Hence, a network that has 100 stations ($p = 100$), each operating simultaneously at $1/T = 100$ Mb/s, would require terminals with a speed of 10 Gb/s, which is difficult to realize inexpensively using electronic means. The challenge is to do the multiplexing and demultiplexing optically.

Synchronization of the receiver with its assigned time slot is also a challenge when T/p is much less than 1 ns. Both the clock frequency and clock phase must be precisely synchronized between transmitter and receiver for synchronous detection of long data streams. For short packets, the clocks need not be precisely synchro-

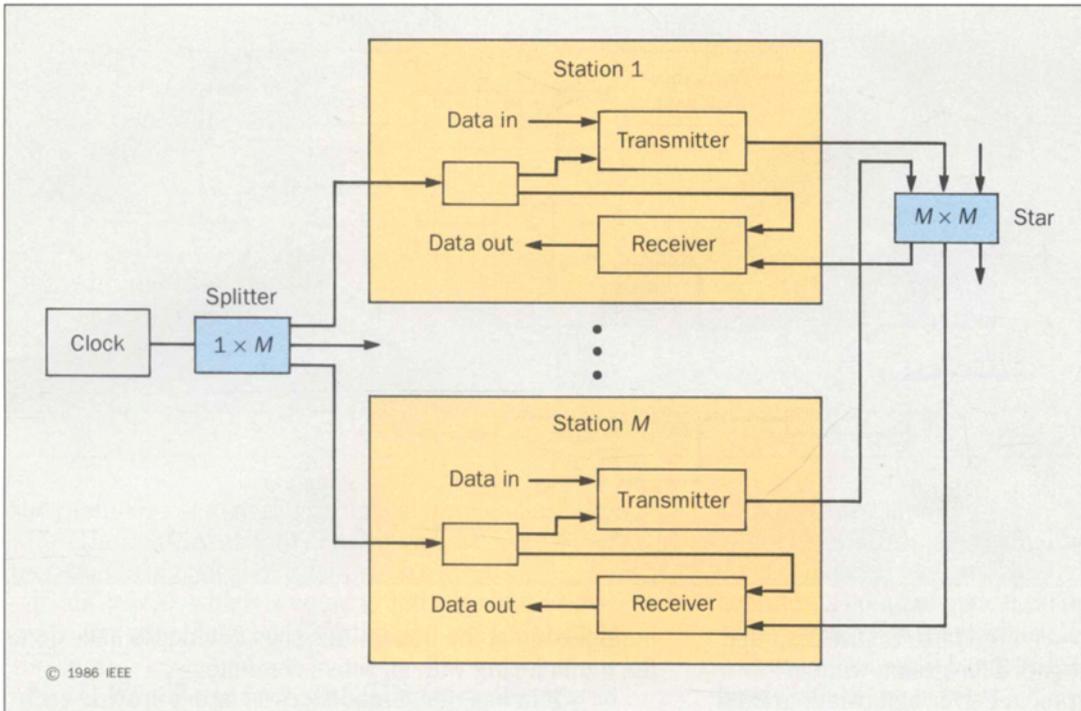


Figure 4. An optical TDMA network based on a central clock and passive star.¹⁶

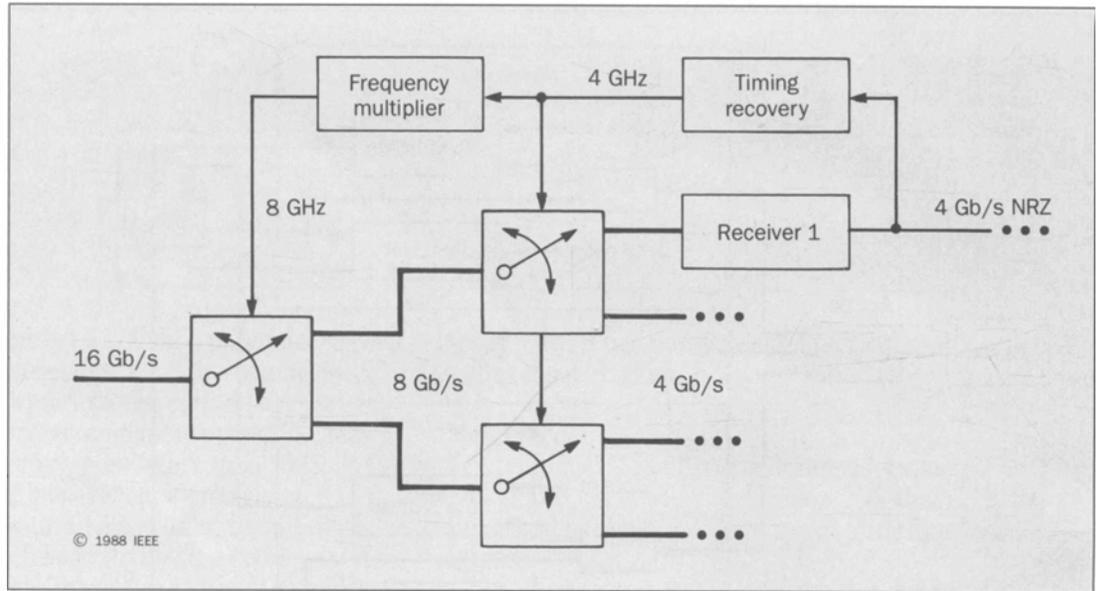
nous (asynchronous detection), and the phase may be recovered at the receiver during the packet header. Established methods used in electronic data networks for timing recovery between remote stations can be adapted to the higher speeds of photonic networks.¹⁵

Alternatively, optical clock pulses can be transmitted from a central node to the communicating stations, as demonstrated in an optical TDM experiment.¹⁶⁻¹⁸ As Figure 4 shows, the centralized clock is the focus of the network. The optical clock pulses can be provided by a pulsed laser or by a mode-locked semiconductor laser¹⁹ that consists of a semiconductor laser gain element, a length of fiber ($l = cT/2n$) that determines the repetition rate $1/T$, and a sinusoidal current drive at frequency $1/T$ to excite and synchronize the pulses. (In the expression for fiber length, c is the velocity of light in a vacuum, and

n is the effective refractive index.) The wide bandwidth of the laser gain medium automatically generates mode-locked optical pulses as narrow as 10 ps (picoseconds) at rates of about 10 GHz. A $1 \times M$ passive splitter sends the clock pulse to each station where it is divided between the transmitter and receiver. The transmitter is a Ti:LiNbO₃ electro-optic gate that passes the coded optical bits to a passive $M \times M$ star, where the bit stream is distributed to all the receivers.

To provide suitable optical delays for multiplexing, fiber lengths must be precisely tailored, so that each of the M stations produces a bit in the proper time slot at the $M \times M$ star. A suitable optical delay must also be provided in the receiver so that the clock and time slot of the assigned channel coincide at the receiver. An optical coincidence gate—or, equivalently, a logical AND operation

Figure 5. Block schematic of demultiplexer and associated electronics for a four-channel system.¹⁵



between signal and clock—can then extract the assigned channel from the multichannel data stream without resorting to an optoelectronic receiver bandwidth greater than the channel rate $1/T$. Although not demonstrated in the network experiment, it was shown separately that a pair of photoconductive switches in series can serve as the optical AND gate.²⁰

In another approach, Tucker et al.¹⁵ used a Ti:LiNbO₃ electro-optic TDM demultiplexer, based on the waveguide tree structure in Figure 2c. Figure 5 shows the receiver terminal for their long-haul TDM experiment. A four-channel 16-Gb/s data stream on a single fiber is demultiplexed by a sinusoidally driven, 16-GHz, 1×2 switch and two sinusoidally driven, 4-GHz switches. This active demultiplexer does not introduce splitting loss and requires only narrowband (sinusoidal) electronic and electro-optic devices. In the experiment, they provided timing recovery at the receiver. Although they used a passive combiner, with 6-dB combiner loss for

multiplexing at the transmitter, they could also have done the multiplexing with an active combiner.

If independent mode-locked lasers provide each transmitted channel, then extreme care is required to assure identical repetition rates and wavelengths for each transmitter to avoid channel overlap caused by asynchronism and delay dispersion along the paths to the receiver. To eliminate asynchronism and dispersion effects, one can derive each channel from a common optical clock at the transmitter.

Frequency and Wavelength Division

In a WDM network, the available wavelength bandwidth Λ is divided into p segments. An optical carrier at wavelength λ is located at the center of each segment, and adjacent carriers are separated by Λ/p . Traditionally, optical sources have been described in terms of wavelength, so it is customary to speak of WDM. But from the engineering standpoint, it is simpler

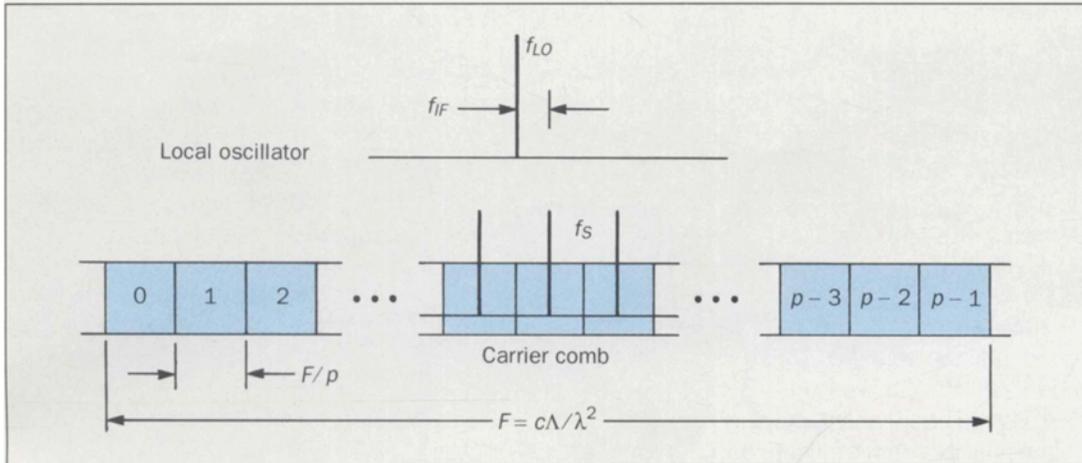


Figure 6. FDM band with p optical carriers. For heterodyne detection, the carrier of the signal f_s is separated from the local oscillator f_{LO} by the intermediate frequency f_{IF} .

and more logical to deal with optical frequencies. Thus, with c the velocity of light in a vacuum, we have $f = c/\lambda$. Increments in optical frequency f are given by $-df/d\lambda = c/\lambda^2$, which is equal to 180 GHz/nm (gigahertz per nanometer) at 1300 nm and 125 GHz/nm at 1550 nm.

We will use the term WDM for widely spaced carriers (say, greater than 1 nm) and reserve FDM for minimally spaced carriers (say, within a few times the modulation bit rate B). For network applications, we will be concerned mainly with the FDM domain in order to make efficient use of the available spectrum.

Optical fibers have losses that are low enough [less than about 0.5 dB/km (decibels per kilometer)] for local communications over enormous bandwidths near 1300 and 1550 nm. Each of the two bands is wider than 20 THz [terahertz, 1 THz = 10^{12} Hz (hertz)]. However, the terminal components will limit the network bandwidth. A particularly critical component is an electronically tunable, single-frequency laser. Tunable, three-electrode, distributed Bragg reflector (DBR) lasers²¹⁻²³ and two-electrode, distributed feedback (DFB) lasers^{24,25} that have tuning ranges of about 250 GHz have been reported at

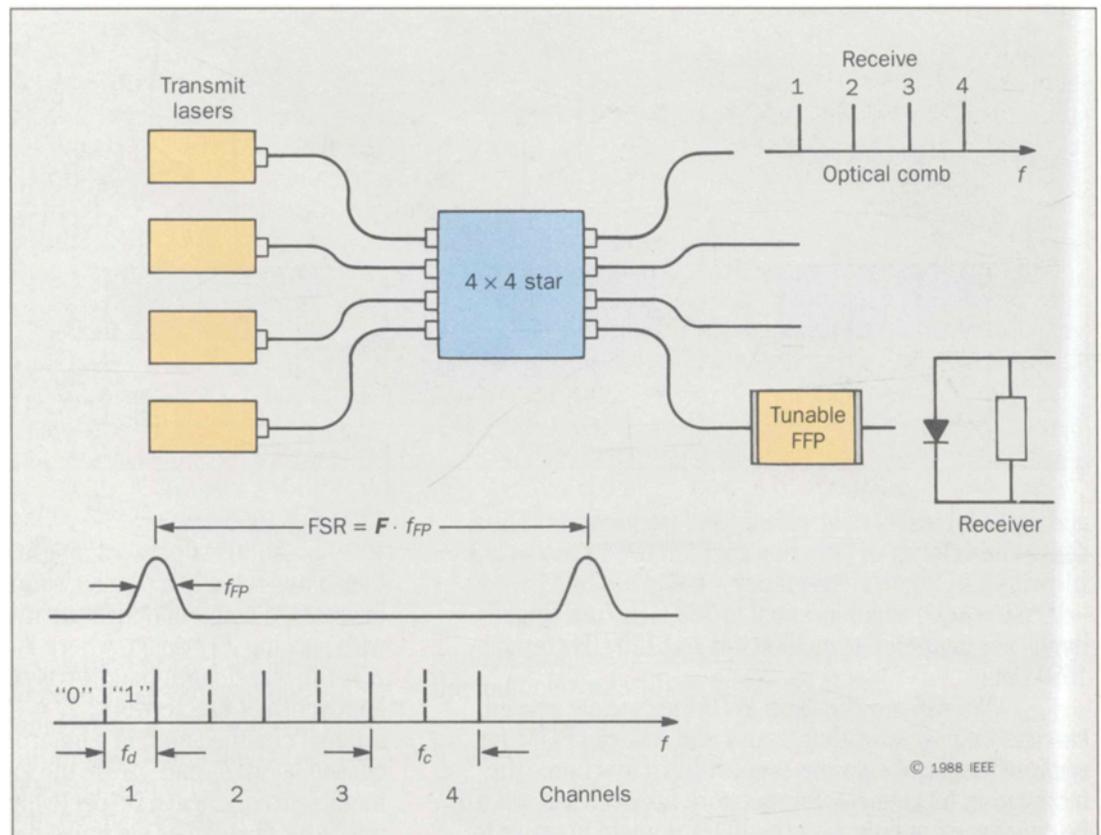
1300 and 1550 nm.

An FDM network might consist of several stations connected to a passive star or bus. As Figure 6 illustrates, a comb of optical carriers must be stabilized with spacing F/p apart, where $F = c\Lambda/\lambda^2$. (In the figure, Λ is the wavelength band; F is the optical-frequency bandwidth of the network; f_s is the carrier frequency at a signal channel; and, in a heterodyne system to be discussed later, f_{LO} and f_{IF} are the local oscillator and intermediate frequencies, respectively.) The spacing F/p might be as small as six times the terminal bit rate B .²⁶⁻²⁸ With $F = 600$ GHz, one could support as many as one hundred 1-Gb/s channels.

A central controller would assign a frequency channel to interconnect a transmitter with a receiver. The receiver could be a tunable filter that has a passband width of about F/p and a tuning range F , followed by a direct detector.²⁹ At present, piezoelectrically tunable fiber Fabry-Perot (FFP) filters with a finesse F of 200 have been demonstrated.³⁰ *Finesse* is defined as the ratio of free-spectral-range (or tuning range) to passband width.

The FFP is ideally suited to a fiber network and

Figure 7. FDM-FSK network with tunable filter demultiplexing and detection. An FSK channel is selected and converted to ASK by tuning the fiber Fabry-Perot (FFP) filter to the desired channel's "1" frequency.²⁶ Then, "1" bits will pass to the direct-detection receiver, and the "0" bits will be rejected. The FFP has a finesse F , free spectral range (FSR), and passband (f_{FP}); the FSK has a deviation frequency f_d , and the channels are spaced by $f_c = 2f_d$.



is built with standard single-mode fiber, inexpensive precision parts from commercial connectors, and multi-layer dielectric mirrors. Higher sensitivity, at the expense of greater complexity, can be realized using optical heterodyne or homodyne detection methods, which require a more elaborate receiver with a tunable local oscillator laser and polarization control for efficient mixing of signal and local oscillator. For either a filter or a heterodyne receiver, one of the most difficult challenges for an FDM network is to maintain a stable, equally spaced comb of carriers produced by many independent transmitter lasers that, in general, will not be co-located.

We now describe a few representative heterodyne and filter network experiments.

A long-haul WDM experiment used ten free-running DFB, single-frequency, laser carriers; each was intensity modulated at 2 Gb/s.³¹ The closest channel spacing was 1.35 nm or 180 GHz at 1500 nm. A simple diffraction grating filter afforded enough resolution to demultiplex the channels.

In the LAMBDANET[®] experiment,³² 18 intensity-modulated DFB lasers that operated near 1500 nm and were separated by 2 nm were modulated at 1.5 or 2 Gb/s, and the channels were demultiplexed with a diffraction

grating or with angle-tuned bulk Fabry-Perot filters.³³ (LAMBANET is a registered trademark of Bell Communications Research.) Because of the wide carrier separations, no elaborate carrier-comb stabilization was used.

A two-channel FDM demonstration³⁴ used 1500-nm DFB lasers that were separated by 11 GHz and intensity modulated at 450 Mb/s by an external electro-optic intensity modulator. The lasers were independently stabilized to Fabry-Perot resonators and temperature controlled to $\pm 0.01^\circ\text{C}$. A tunable Mach-Zehnder waveguide interferometer array was used as a demultiplexer.³⁵

These three experiments used amplitude-shift-keying (ASK) modulation.

A tunable fiber Fabry-Perot filter, with a star coupler, lends itself nicely to a simple and potentially inexpensive FDM network,²⁶ as Figure 7 illustrates for four terminals connected through a star coupler. Frequency-shift keying (FSK), which was used in this experiment, takes advantage of intrinsic semiconductor behavior. A small current deviation from the direct-current-drive level causes an optical frequency deviation f_d that represents shifts between the 0 and 1 bits of the data. The tunable FFP both demultiplexes and detects the desired channel by passing only the 1 spectrum of the desired channel, thereby converting FSK to ASK, as illustrated schematically in Figure 7.

An analysis predicts and an experiment (with $B = 45\text{-Mb/s}$ channels) confirms, a minimum channel spacing of $f_c = 2f_d = B/6$. This channel spacing is similar to what can be realized for heterodyne systems.^{27,28} The maximum number of channels is:

$$N = F/6 \quad (4)$$

and is independent of B . We expect that the finesse F of FFPs can be improved beyond the current 200 to approach 1000.

Ideally, this FDMA-FSK-star-filter network could then support up to 150 multigigabit channels. In such a network, the channel density is comparable to that of a

heterodyne network but without need for a local oscillator or polarization control. With the higher finesse available in commercial, bulk Fabry-Perot filters, the number of channels can be well over 1000, as Chraplyvy et al. simulated in a recent network experiment.³⁶ Research in noncoherent FDM networks with ASK or FSK modulation is reviewed in more detail elsewhere.³⁷

Figure 8 shows Linke and Gnauck's optical heterodyne star network.³⁸ To demultiplex the channels, they mix the signal with a tunable optical local oscillator. The potential receiver sensitivity is much greater (about 10 dB) than for the tunable filter with direct detection and, therefore, permits greater system margin, without optical amplification. To realize the ideal performance, one must provide a strong, widely tunable local oscillator laser and optical polarization control for efficient mixing. The channel density is comparable to that of the filter network, but the tuning range of the local oscillator laser determines the number of channels. Thus, with today's continuous tuning range of about 1000 GHz, channel spacing of $f_c \approx 6B$, and $B = 1\text{ Gb/s}$, the network could support more than 150 channels.

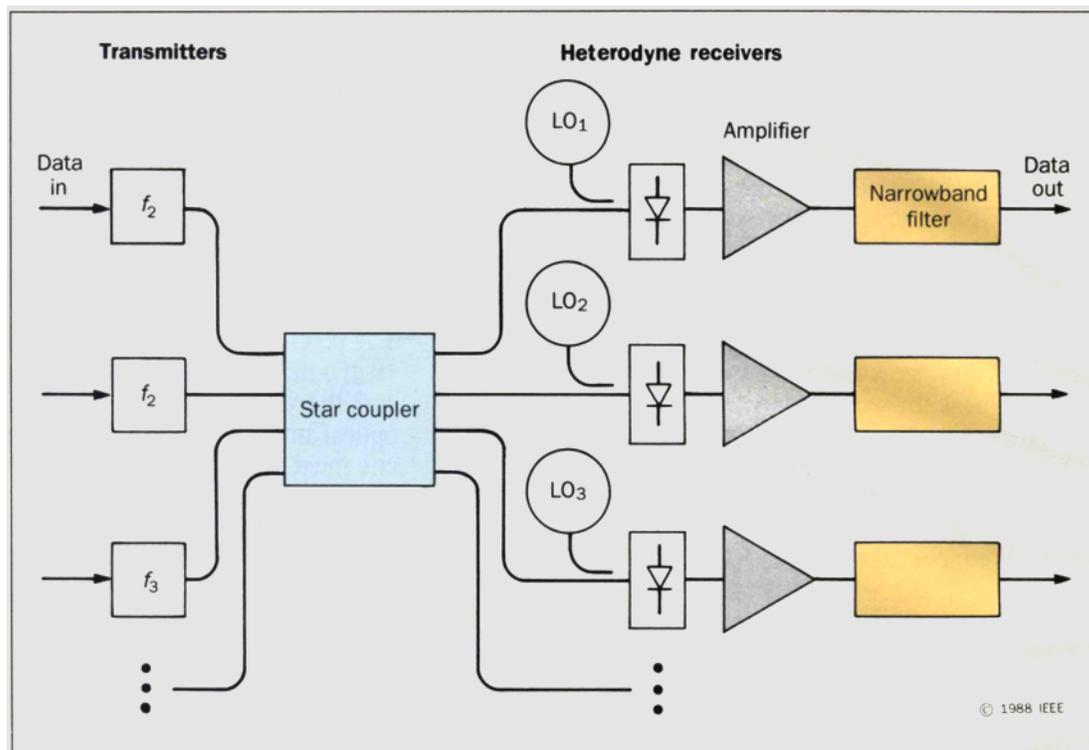
An experimental FDM-FSK heterodyne star network³⁹ showed high sensitivity (-61 dBm) with 45-Mb/s channels separated by 300 MHz. In the same experiment, schemes for stabilizing the comb of optical carriers on the resonances of a fixed fiber Fabry-Perot filter were demonstrated. This method, combined with an atomic reference,⁴⁰ provides an absolutely stabilized carrier comb. Coherent networks are reviewed in more detail elsewhere.⁴¹

Subcarrier Frequency Division

A proposed subcarrier frequency-division multiplexed (SFDM) network⁴² avoids the need for high-speed receivers that is inherent in TDM and the need for inter-carrier stabilization and optical filtering or optical heterodyning that is inherent in FDM. The price is a lower network margin and restricted bandwidth, which might be tolerable in some local applications.

In operation, digital or analog information from

Figure 8. FDM coherent-star network configuration.³⁸ Optical-carrier frequencies are f_1 , f_2 , and f_3 for the transmitters; LO_1 , LO_2 , and LO_3 are the local oscillators for the receivers.



individual channels is modulated onto separate microwave sinusoidal subcarriers, which are added in a standard microwave combiner. The sum of these subcarriers modulates the current in a single semiconductor laser. Alternatively, each subcarrier can be modulated onto a separate laser, whose wavelength need not be controlled, and these channels can be combined optically. In either case, after distribution on a fiber bus or star, the multiplexed optical signals are photodetected and the channels are demultiplexed at radio frequencies by standard, inexpensive microwave filters or microwave heterodyne methods. For a given channel, the receiver electronics need only have a bandwidth (centered at the subcarrier frequency) that corresponds to the channel width and not the network bandwidth, as in TDM.

Laser linearity is an important constraint, especially where we use analog modulation of the subcarrier. In certain applications, we must limit the subcarrier band to an octave to avoid second harmonic distortion; in broadcast networks, we must limit the subcarrier optical modulation depth to avoid intermodulation distortion.

In a network experiment⁴³ at 1300 nm, two lasers that were modulated in the 3.5-to-4.0 GHz band were coupled to a bus, as shown in Figure 9. One laser supports two 44-Mb/s channels and the other one 44-Mb/s channel. The two subcarriers on a single laser were spaced by 150 MHz. Darcie et al. also demonstrated⁴⁴ a bidirectional loop-distribution network that connects a head end to eight nodes fed by a passive splitter. Data for each node (at 180 Mb/s) and return data (at 45 Mb/s)

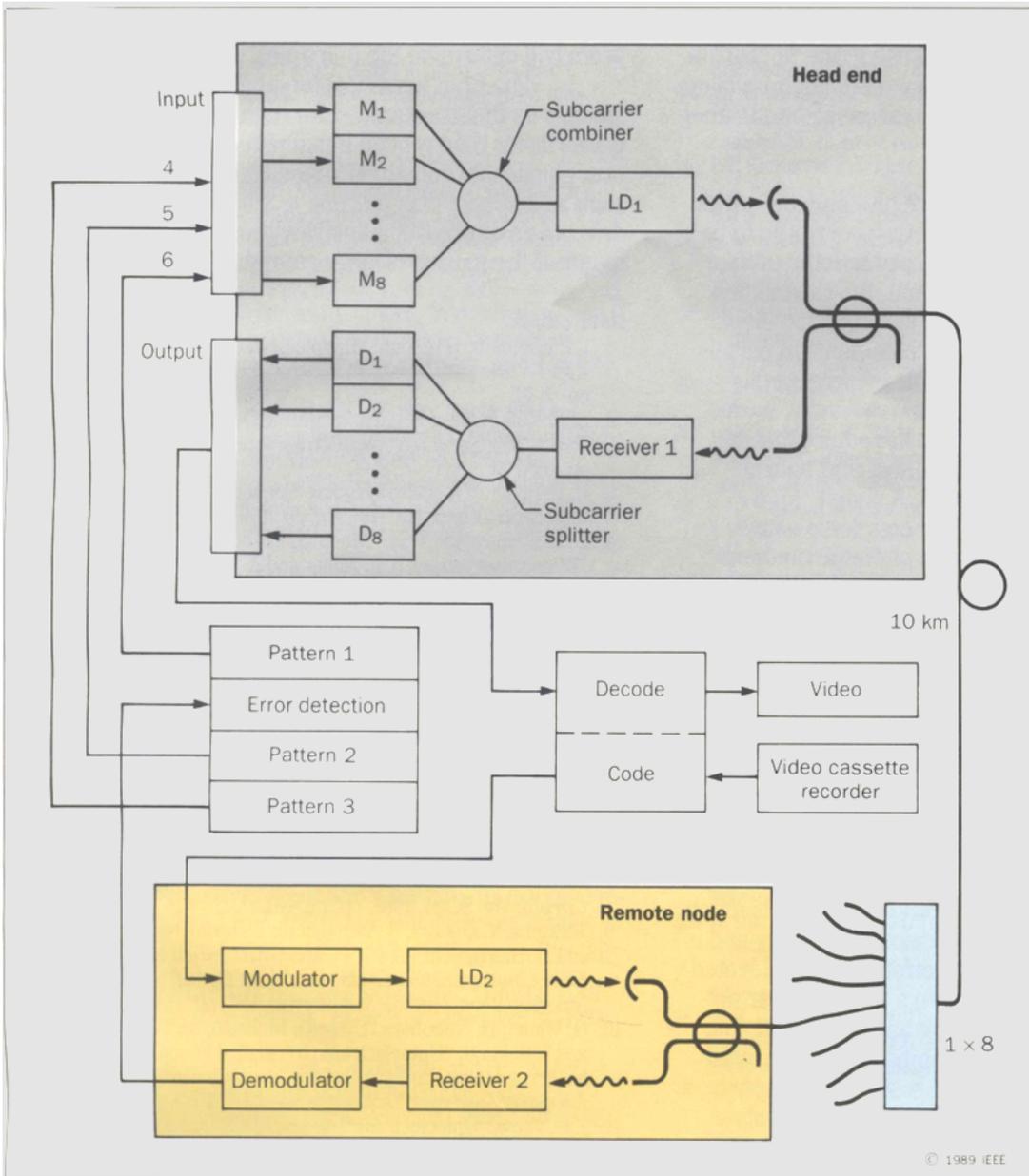


Figure 9. SFDM loop-distribution demonstration experiment. One remote node is connected to the head end through a 10-km single-mode fiber and a 1×8 passive splitter. The out-bound channels are modulated at 180 Mb/s and the return channel at 45 Mb/s. Voltage-controlled oscillators are used for FSK subcarrier modulation (Darcie et al.⁴¹). M_x is a subcarrier modulator, D_x is a subcarrier demodulator, and LD_x is a laser diode.

are transmitted as FSK subcarriers, between 2.5 and 5 GHz. Olshansky and Lanzisera also used⁴⁵ the SFDM approach to transmit 60 FM (frequency modulation) analog TV (television) channels over 18 km of single-mode fiber.

Conclusion

The configurations of future photonic networks will depend on the applications and types of traffic to be distributed. The applications will depend on the unique capabilities of photonic networks. And, the capabilities will depend on novel optical, electronic, and optoelectronic components that permit enhancements in performance and cost beyond that available by present-day methods.

Passive distribution networks require that we develop higher power laser transmitters and optical amplifiers to support more stations. A simple, high-performance, integrated-optics star coupler is a key component. The implementation of photonic random-access and packet-switched networks requires high-speed and high-capacity buffer memories. FDM networks require stabilization techniques and precisely tunable lasers with good FM response. TDM networks require fast, sensitive optical coincidence gates to demultiplex signals cheaply. Because terminal costs cannot be shared, we must substantially reduce the cost of terminal components—such as single-mode connectors and optoelectronic interfaces—through clever design, integration of optical and electronic circuits, and large-scale production.

Electronic integrated-circuit technology is much further advanced than photonic device technology and is advancing faster because greater effort is being devoted to ICs. Thus, electronic solutions to a switched-star network or to high-speed multiplexing and demultiplexing will compete strongly with the ambitious photonic solutions proposed here. The ultimate result may simply be a high-speed electronic node and electronic terminals joined by single-mode fiber-optic data links. Advances in

photonic and electronic circuits during the next few years will determine the outcome.

The brief history of long-haul lightwave systems teaches us that the demand for high-bit-rate services grows faster than we can imagine today. And, the history of sophisticated consumer optoelectronic appliances, such as compact disk players, teaches us that we can drive costs down dramatically without sacrificing performance if the market is large enough.

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