

Optical Networks: Backbones for Universal Connectivity

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Communications traffic in the world's fiber-optic backbone network is growing more than 10% per year and the growth rate is accelerating. The ever-increasing bandwidth demands are being met by an array of technological innovations including higher time-division multiplex (TDM) transmission rates combined with wavelength-division multiplex (WDM) overlays.

We are living in a revolutionary age. Communications traffic is growing explosively. In this article we attempt to characterize and quantify this growth, and then comment on technologies to upgrade the usable bandwidth of the fiber-optic backbones of the world's communication networks.

Voice, data, fax, video—these are the forms of electronic communication that are growing at unprecedented rates. A large and increasing proportion of the messages are digital. This is because digital signals can be made practically error-free, and the computers that process them are cheap and getting cheaper and more powerful.

How can we quantify all this? Since all these signals are digital, the universal measure is the bit rate: how many bits per second leave the signal source.

The aggregate bit rate of all the sources is the total communications traffic.



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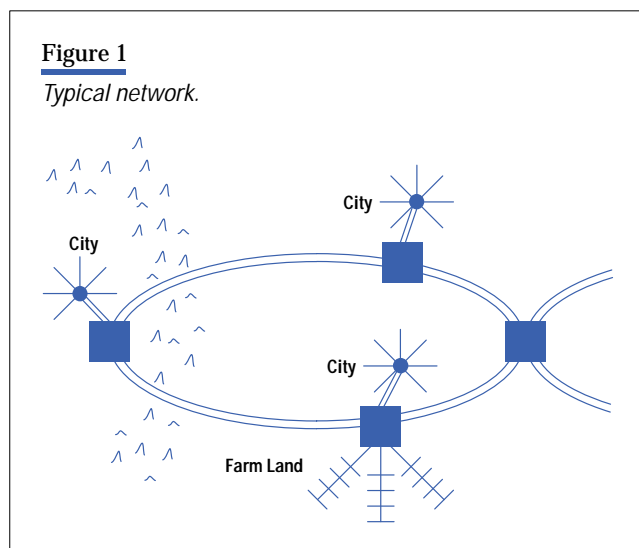
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A single telephone call is sampled at 8 kbits/s with 8-bit resolution in each direction. The two-way conversation thus represents traffic of 128 kbits/s. One million conversations thus represent traffic of 128 Gbits/s. In one month's time this traffic will have delivered a payload of $(30 \text{ days}) \times (86,400 \text{ s/day}) \times (128 \text{ Gbits/s}) = 331,776,000 \text{ Gbits} = 331.776 \text{ Pbits}$. Typical voice telephone calls last five minutes. Average traffic is less than the daily peak traffic by a factor we will assume to be three.

Twisted pairs, coaxial cables, optical fibers, radio-frequency and microwave wireless, satellites, infrared—these are the media that carry the messages. The special role of single-mode optical fiber is as the high-capacity backbone of global connectivity. No other medium comes close to being able to fill this role.

Network Overview

Taking a look at a hypothetical network, we might see various network shapes such as rings linking various sites, as shown in **Figure 1**. Star and tree structures may branch from the network depending on the locality, which could be dense metropolitan, suburban, or rural. Geographic features also influence the local network topology.



The *core network* consists of all trunk lines between major central offices in the larger cities, including transoceanic submarine links, festoon links, and long-haul terrestrial links.

Metropolitan networks consist of rings connecting major customers—that is, business locations—in the regions near large cities. An advantage of the ring architecture is that data can be sent in the opposite direction around the link should a break in the fiber cable occur. Both the core network and the metropolitan networks consist of single-mode optical fiber.

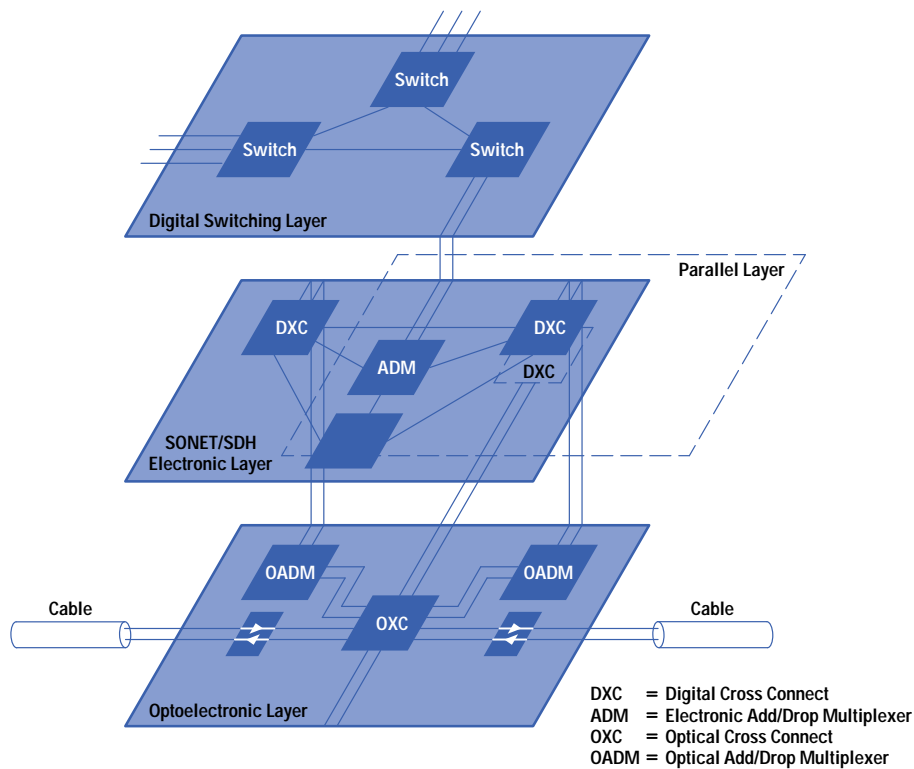
The *local access network* consists of the distribution network from a telephone company central office switch to and from customers. These networks are typically a star configuration of twisted-pair lines. The signals are analog until they undergo analog-to-digital conversion, either at the central office or at a remote station in the local loop. At that point multiple calls are multiplexed to a higher bit rate. This description applies to traditional wireline communications, which is supplemented by newer wireless networks. Cellular telephone systems are wireless networks that offer local access to mobile customers. At present many local access networks contain optical fiber lines carrying multiplexed traffic from central offices to local substations, where a local star network of twisted-pair lines branches out to individual customers.

Fiber to the home (FTTH) and fiber to the curb (FTTC) networks have had numerous trials but no large-scale deployments. This may change in the near future as one alternative to enable broadband services such as high-speed Internet access to homes.¹

At the network nodes, a number of operations are performed to provide for information routing and multiplexing. A layered model for a network node is shown in **Figure 2**. It provides a useful way of understanding the roles of the various network elements. In the optical layer, incoming signals in the form of modulated light are redirected to other optical network paths or converted to electrical signals and sent to an electronic layer. In the SONET/SDH layer, digital switches and electronic add/drop multiplexers route and partition the data streams. These data streams are sent to the electronic switching layer where a finer level of partitioning occurs such as ATM (Asynchronous Transfer Mode) switching. Alternatively, the SONET/SDH layer can send data directly back to the optical layer after performing switching at a coarse level. The activities described above are performed on a large scale in the central office and at a smaller level at remote nodes.

Figure 2

Layered model of a network node.



Traffic on the Core Network

Core network telecommunications traffic within the U.S.A. has been estimated to be in the range of 200 to 400 Gbits/s, or the equivalent of 1.5 to 3 million telephone conversations.² This estimate includes the combined voice, data, fax, and video traffic on all U.S. long-distance carriers during midday daily peak traffic. The average annual growth rate of this traffic in 1995 was 10%.

Core telecommunications network traffic outside the U.S.A. has been estimated to be comparable to the U.S. traffic. This is intracountry traffic, which does not cross international boundaries. The exact growth rate is not known, but we believe it to be less than the U.S. growth rate at the present time because of higher rate structures and less developed services outside the U.S.

International telecommunications traffic is well-documented by the International Telecommunication Union (ITU), with a three-year delay.³ As shown in **Table I**, calculations from ITU records estimate that U.S. outgoing international traffic in 1993 was 2.8 Gbits/s on average, or a bit more than one OC-48 link. Total worldwide international traffic was 11.9 Gbits/s on average, or more than one OC-192 link. These figures include, but are not limited to, the undersea cable traffic.

Origin	1993 Calls/Day (millions)	1993 Average Traffic (Gbits/s)	1992 to 1993 Growth
U.S.A.	5.3	2.8	11%
Asia	4.6	2.2	21%
Europe	10.5	5.5	12%
World	21.7	11.9	18%

Market Drivers

The worldwide demand for communications drives the need for increased network capacity. Four factors in this capacity growth are:

- Upgrades of existing networks
- Increased global teleconnectivity
- Worldwide deregulation of the telecommunications industry
- Introduction of new broadband services.

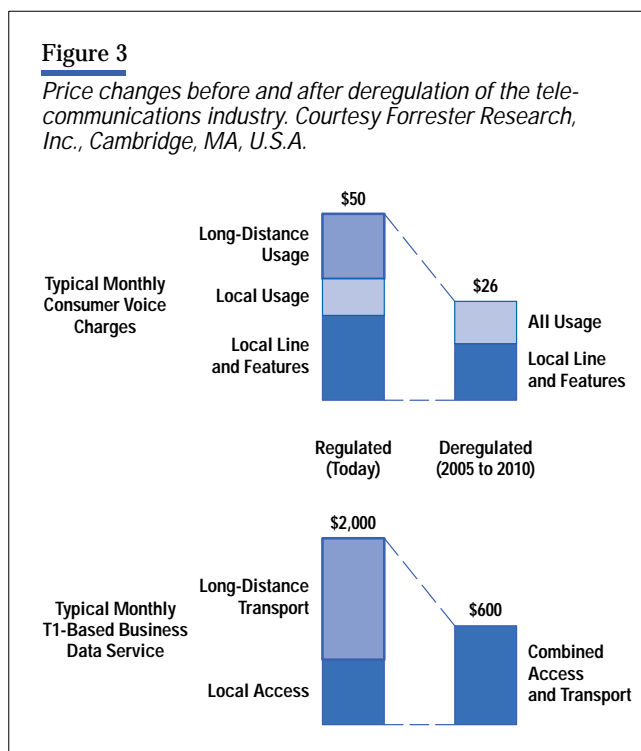
Upgrades of Existing Networks. In the U.S.A., all carriers are presently upgrading their terrestrial networks, replacing repeater huts with optical amplifiers.⁴⁻⁷ This provides them with a significant cost savings, as well as a network that is much less data rate dependent. Increased reliability is achieved by configuring the network in a redundant, self-healing ring architecture. In this system, two redundant paths that are physically separated are provided between any two access points. If a fault occurs on one path, for example if an errant backhoe cuts a buried cable, network supervisory software automatically redirects traffic along the alternate path after the fault is detected.

Increased Global Teleconnectivity. Around the world, backbone networks of optical fiber continue to be installed at a remarkable rate. 30-count single-mode optical fiber cable is installed at an average rate of 80 km/hr, around the clock, all year long.⁸ A reported 1.06 million fiber-km were installed in China alone in 1994. China plans to add between 75 million and 100 million new lines to homes and businesses by the year 2000.

So far, U.S.\$11.6 billion has been invested in undersea systems that connect 70 countries, with 17 more countries connected in 1996. In the next three years, it is expected that U.S.\$13.9 billion will be invested in new undersea systems, with less than 10 percent of the cable going into the Atlantic. With completion of the TAT-12/13 and TPC-5 cable systems, the transatlantic and transpacific routes each have installed redundant, self-healing capacity of 10 Gbits/s.^{9,10} This capacity

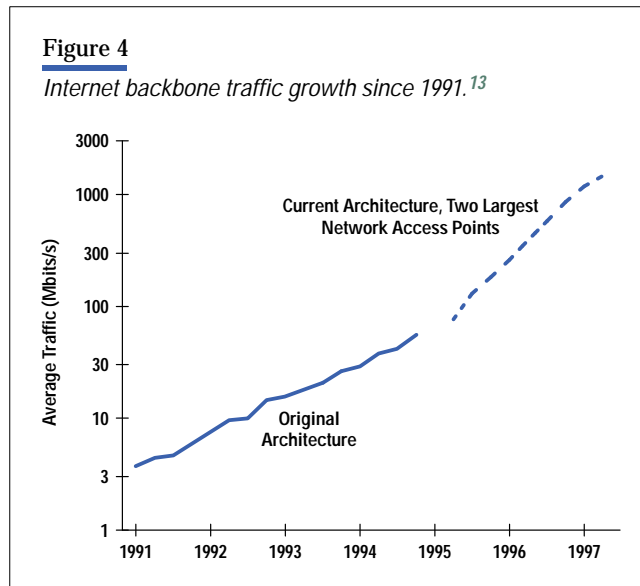
was originally forecast to exceed the demand until 2006. However, by early 1997 the capacity on these cables was completely subscribed. New cables with capacity of 100 Gbits/s are planned.^{11,12}

Deregulation. Deregulation in the telecommunications industry will break down the present barriers to competition in all sectors of the market. Throughout the world, government owned or controlled telecommunications monopolies are undergoing deregulation. The U.S.A. is further along than most countries. The current grouping of service providers in the U.S.A.—regional Bell operating companies (RBOCs), interexchange carriers, and CATV providers—is quickly blurring through mergers, acquisitions, and collaborations between segments. The competitive nature of this market opening will likely stimulate installation of redundant capacity in different providers' networks. This should lead to lower prices (**Figure 3**) and an increased growth rate for telecommunications traffic. The consulting firm Forrester Research predicts a growth of 250% in traffic by the year 2005.



New Broadband Services. While telecommunications traffic growth rates of 10 to 17 percent are impressive, these growth rates are low compared to those for existing and new data services. The Internet has grown exponentially for at least seven years, as shown in **Figure 4**. Backbone traffic on the U.S. National Science Foundation's NSFNET exceeded 50 Mbits/s on average in late 1994, having doubled yearly for several years until then. The architecture changed in 1995 to the present network access point structure with multiple backbone services. Traffic is exchanged between services at network access points, the largest of which—MAE-East (Washington, D.C.) and MAE-West (San Jose, California)—have combined traffic that has more than quadrupled in each of the two years since 1995—truly astounding growth! This combined traffic has reached about 1.5 Gbits/s on average in mid-1997, a number that still seems small, that is, the equivalent of about 12,000 telephone calls. The seemingly small traffic volume reflects the fact that the Internet is connectionless. It also reflects the fact that the Internet is insufferably slow! The connectionless nature of the Internet means that packets of data move from source to destination through a network of routers without a circuit being reserved as it would be for telephone service.¹⁴ This is true for an Internet exchange as it traverses the core telecommunications network. However,

if that exchange originates in a local access network, a local call to the Internet service provider (ISP) does tie up a circuit through the telephone company's central office switch for the duration of the connection. Local telephone companies have based their service on an economic model that assumes that telephone calls last five minutes on average, and have not yet absorbed all of the calls to Internet service providers that last an hour or more.¹⁵



To predict Internet traffic growth to the year 2000 and beyond, we must recognize the following Internet traffic growth drivers:

- Connections worldwide double yearly.
- PCs will continue to proliferate.
- Faster PCs and LANs (1-GHz and 1-Gbit/s) will be widespread by 2000.
- Demand for faster access (ISDN lines, 50-Mbit/s cable modems) is rising.
- Demand for bandwidth-hungry services (3D graphics, video clips) will grow.
- Network software (Java) will increase network average bit rates.
- Lower telecommunications rates will unleash demand.
- Corporate intranets linking sites of the same firm, enabling efficiencies and savings, will proliferate.

Figure 5 shows the predictions of a model that accounts for the yearly doubling of Internet connections and the further, compounded explosive growth in Internet traffic that is likely to occur as the result of the factors listed above. In this model, the peak daily worldwide core network Internet traffic rises from 360 Mbits/s in 1996 to 110 Gbits/s in 2000.

To see the effect of the Internet traffic, we plotted the projected U.S. telecommunications peak long-haul traffic with and without Internet use in **Figure 6**. The lower curve shows the projected U.S. daily peak core telecommunications traffic through the year 2000 using a 10% growth rate. The upper curve adds the estimated Internet traffic. The model predicts that the Internet accounts for 10 to 20 percent of the total core telecommunications network traffic by 2000.

Figure 5

Internet traffic growth.

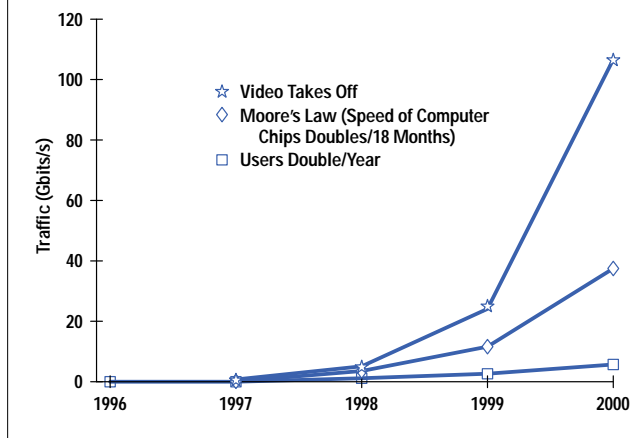
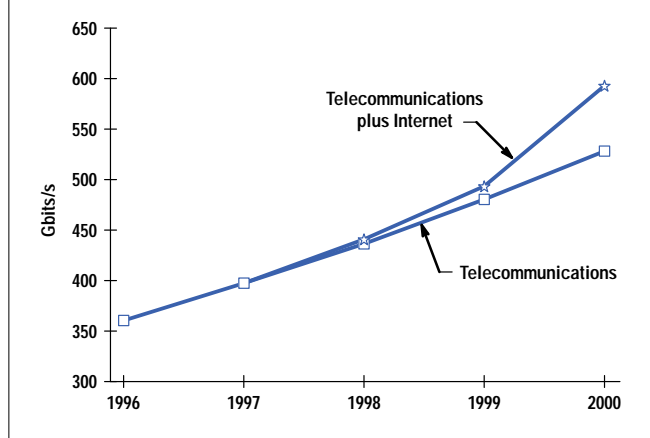


Figure 6

Telecommunications traffic increase from Internet activity.



Technologies to Increase Bandwidth

Single-mode optical fiber has enormous untapped bandwidth. Each nanometer of the spectrum near 1550 nm, where loss is at a minimum, represents 125 GHz of bandwidth.

Worldwide demand for increased network capacity has pushed core network service providers to find the best alternative to increase bandwidth beyond the 2.5-Gbit/s rate on a single optical fiber. The increased demand for bandwidth has forced a reevaluation of network designs and the development of network topologies based on wavelength-division multiplexing (WDM). The challenge for today's network designer is to exploit more of the bandwidth of the fiber.

The way information is physically encoded onto the transport layer involves a number of trade-offs between utilization of existing infrastructures, investment in new technologies, and scalability of the network. Traditionally, a single optical carrier per fiber has been used in fiber-optic networks. Originally, optical networks were based on direct detection receivers and regeneration at periodic intervals along the core. Later research pointed towards the use of coherent receivers to increase the distances between regenerators.¹⁶ This was quickly put on the back burner with the emergence of the erbium-doped fiber amplifier (EDFA).⁴⁻⁷ The EDFA provides low-noise, polarization independent optical gain to overcome propagation losses in the fiber (~ 0.3 dB/km). Initial systems employed purely single-carrier information transport based on time-division multiplexing (TDM) until it became apparent that increased capacity could be economically implemented with a WDM overlay on the existing TDM network structure.

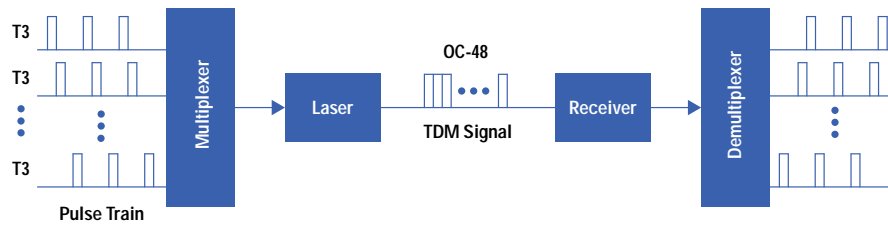
The goal of network designers is to use the right combinations of optical carriers and data rates to maximize the network performance in terms of reliability, cost, and future growth. In the next sections, we will discuss TDM and WDM techniques used to obtain higher data throughput and issues associated with deployment of these techniques.

Time-Division Multiplexing

TDM has been the traditional method for combining information channels. This approach is illustrated in **Figure 7**. Increased data rates are made possible by interleaving more and more pulses while shrinking the pulse width at the same time. This is similar to packing more cars on a single-lane highway with a fixed speed limit. At a certain point we must shrink the size of the car. Similarly, as the pulse packing increases, the electronics must operate at higher and higher frequencies to accommodate the shorter pulse widths.

Figure 7

Time-division multiplexing (TDM).



Starting from the most fundamental data rate, the voice call, the TDM system combines other calls through interleaving or multiplexing. The 64-kbit/s call, referred to as a DS0, is multiplexed with 23 other calls for a total of 1.544 Mbits/s, which is designated as a T1 (**Figure 8**). The next level up is the T3, which represents a data rate of 43.008 Mbits/s. Add about 7 Mbits/s for overhead and we have the first optical carrier (OC) designation, OC-1.

With the evolution of standards in various parts of the world, different nomenclatures and rates have been designated. At higher data rates, these standards have merged into the SONET/SDH designations. A comparison of the most common SONET hierarchies is shown in **Table II**.

Table II
SONET Signal Rates

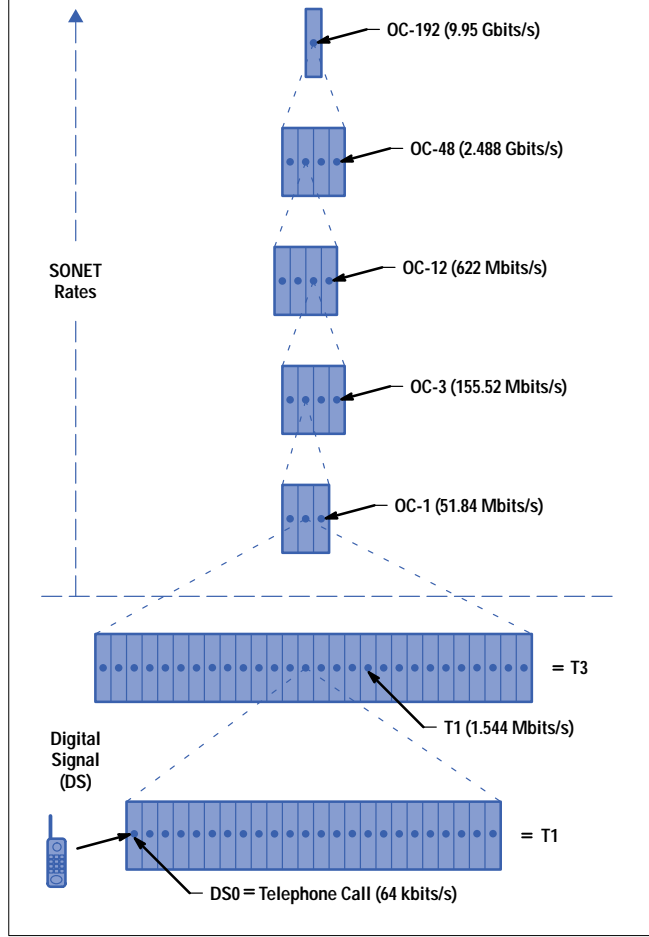
Electrical Signal	Optical Signal	Data Rate (Mbits/s)
STS-1	OC-1	51.84
STS-3	OC-3	155.52
STS-12	OC-12	622.08
STS-48	OC-48	2488
STS-192	OC-192	9953

The lower-rate OCs are multiplexed together to form the OC-48 transmission at a rate of 2.488 Gbits/s. OC-48 rates are practical with today's technologies and OC-192 is in early deployment. Obviously, a great deal of multiplexing is required to achieve these data rates. As the data rate increases, so does the cost of the electronic terminal equipment that converts the optical signals to electrical signals and demultiplexes the data to lower rates for electronic switching and routing. Other challenges also present themselves at high data rates, particularly the dispersion in the optical fiber. Fiber dispersion places limits on the permissible channel bandwidth to keep pulse distortion to an acceptable level.

Fiber Dispersion. The problem of dispersion is tied to the bandwidth that the signal occupies. Chromatic dispersion refers to the frequency dependence of the velocity of light in the optical fiber. The signal bandwidth scales inversely with twice the pulse width for NRZ (nonreturn-to-zero) transmission. The frequency chirp of a directly modulated laser significantly increases the bandwidth occupied by the signal. Chirping refers to the unwanted optical carrier frequency excursions created during intensity modulation.^{17,18} The magnitude of the chirp increases with the pulse rate. The chirped optical pulses propagating along the fiber are spread out by the combined effects of linear and nonlinear dispersion in the single-mode optical fiber. Eventually, it becomes difficult to distinguish between a logical 1 and a logical 0 as the dispersion causes the pulses to overlap in time.

Figure 8

Hierarchy of time-division multiplexed (TDM) signals.

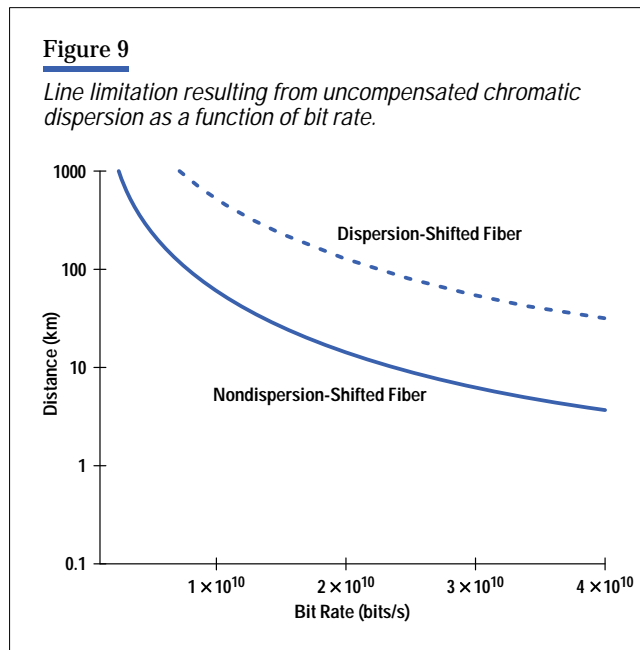


Given that the dispersion of the installed fiber is fixed, we must apply dispersion compensation or reduce the bandwidth occupied by the channel. The bandwidth is reduced by minimizing transmitter chirp and employing different encoding techniques. Low-chirp electroabsorption and Mach-Zehnder modulators have been developed. Electroabsorption modulators are integrated with DFB (distributed feedback) lasers to eliminate the extra fiber coupling required with external modulators. These devices provide low negative chirp to help compensate for pulse spreading caused by the Kerr effect.¹⁹

Approximately 95% of the world's installed fiber base has its dispersion zero near 1310 nm.⁸ At the low-loss wavelength of 1550 nm, this fiber has a dispersion of approximately 17 ps/nm · km. A simple relationship estimates the maximum span length allowed by linear chromatic dispersion spreading effects on the transmitted signal:

$$L_{\max} = \frac{0.8c}{DB^2\lambda^2}$$

where $c = 2.997925 \times 10^8$ m/s is the velocity of light, D is the dispersion parameter, B is the bandwidth, and λ is the wavelength of the light. This relationship is plotted in **Figure 9** for a wavelength of 1550 nm for standard nondispersion-shifted fiber as well as for dispersion-shifted fiber with dispersion of ~ 2 ps/nm · km.



Obviously the use of zero-dispersion fiber would increase the maximum TDM rate. However, there are two compelling reasons not to use it. One is that installing new fiber under the ground is quite expensive, and the other is that zero-dispersion fiber is incompatible with present WDM technology because of four-wave mixing effects.²⁰ An alternative and promising method is to compensate for the fiber dispersion.

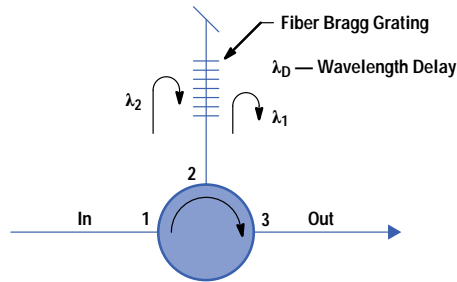
Dispersion Compensation. A number of technologies are being investigated to reduce the pulse spreading in TDM links. Dispersion compensating fibers with special core designs are fabricated to yield the required wavelength dependent time delay to compensate for standard telecommunications fiber.²¹ Dispersion compensating fiber lengths on the order of 10 km are required to compensate for the installed-fiber dispersion characteristic for typical spans. Some issues encountered with the dispersion compensating fiber technique include insertion loss, polarization-mode dispersion, and Kerr-effect nonlinearity. Dispersion compensating fibers are often characterized by a figure of merit that describes the ratio of the dispersion to the loss. The loss of the dispersion compensating fiber is approximately 0.1 dB per compensated-span kilometer. Research is being directed towards improving the dispersion compensating fiber performance through careful fiber waveguide design.

Another approach uses the fiber Bragg grating. The phase response versus frequency for the fiber Bragg grating can compensate for fiber dispersion. Both reflection-type and long-period transmission gratings are under consideration. As an example, in **Figure 10** a fiber Bragg grating is used in conjunction with an optical circulator to compensate for fiber dispersion. Its operation is as follows. The circulator passes light in the direction of the arrow from port 1 to port 2. The fiber Bragg grating is a reflective type with a wavelength delay that compensates for the wavelength dependent delay of the fiber span. The compensated light then goes to the output, port 3. In this way, dispersion compensation is achieved with as little as 2 dB of optical path loss. Research is ongoing to extend the bandwidth over which the dispersion compensation can be employed. Multiple wavelengths can be independently compensated with separate fiber Bragg gratings. In a recent experiment, 6000 ps/nm, or equivalently, compensation for 5000 km of nondispersion-shifted fiber, was demonstrated by a group at the University of Southampton.²²

Dispersion compensation has allowed a significant increase in TDM rates using installed fiber. However, the cost of the terminal equipment including transmitters and receivers increases significantly at the higher bit rates. A way to achieve the increased aggregate bit rate using lower-bandwidth optoelectronics is to add a WDM overlay.

Figure 10

Circulator-based dispersion compensator.



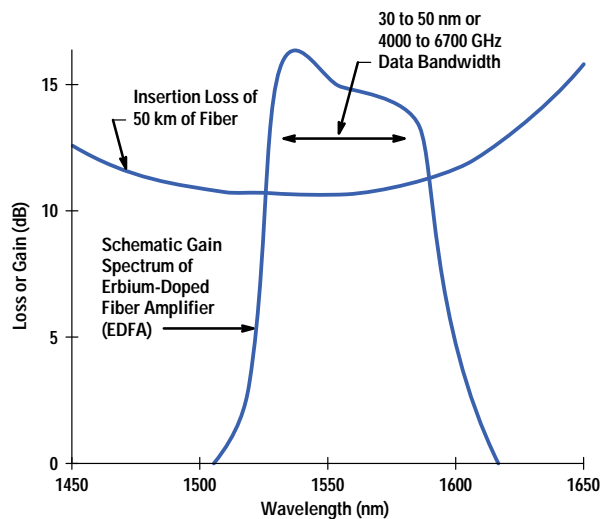
Wavelength-Division Multiplexing

The push towards WDM is being driven by cost considerations. The ability to compensate for chromatic dispersion combined with the expense of high-speed receivers makes WDM an appealing candidate for realizing the required aggregate data rates. While TDM is analogous to packing more cars on a single-lane highway, WDM adds more lanes to the highway.

Wavelength-division multiplexing permits true access to the tremendous bandwidth available from single-mode optical fiber. The available bandwidth is illustrated in **Figure 11**. The fiber itself supports approximately 25,000 GHz of bandwidth. This bandwidth is typically broken up into two bands, centered at 1300 nm and 1550 nm. The 1550-nm band overlaps fortuitously with the gain spectrum of the erbium-doped fiber amplifier (EDFA) as shown in **Figure 11**. In the region around 1550 nm, approximately 5000 GHz of gain bandwidth is available from the erbium-doped fiber amplifier (EDFA). The EDFA is simply a length of optical fiber whose center is doped with erbium ions. Pumping the fiber with a

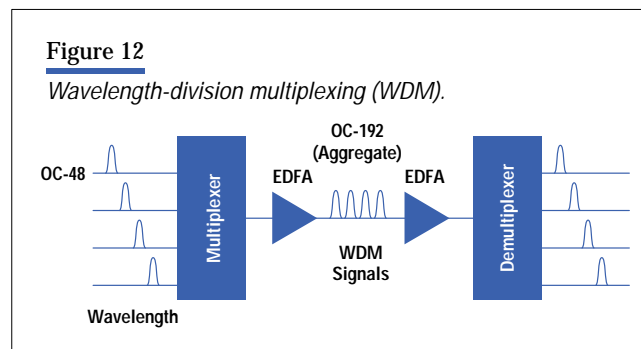
Figure 11

Bandwidth availability of installed single-mode optical fiber. The fiber itself supports approximately 25,000 GHz of bandwidth. In the region around 1550 nm, approximately 5000 GHz of gain bandwidth is available from the erbium-doped fiber amplifier (EDFA).



laser operating at 980 nm or 1480 nm causes the ions to absorb the pump energy. Later, the ions give up the energy to the incoming 1550-nm wavelength signal, resulting in amplification. Optical gains of 30 dB and noise figures of ~5 dB are routinely achieved from EDFAs, making them nearly ideal devices for overcoming the propagation loss in optical fibers. For WDM applications, the broad gain bandwidth of the EDFA makes it capable of simultaneous amplification of many wavelength channels. This is a cost-effective use of the EDFA.

WDM terminals consist of multiple, independent TDM transmitters at different wavelengths in the 1550-nm band and an equal number of independent TDM receivers, as shown in **Figure 12**. The outputs of the transmitters are optically multiplexed together onto a common output interface to the optical transmission network. The optical input to the WDM terminal is optically demultiplexed and the separated signals are fed to TDM receivers.



WDM can be considered as a way of summing together many TDM channels on a single fiber. The alternative solution would be to lay more fiber, which is costly. Increasing the aggregate transmission rate using WDM is technically viable and cost-competitive. Increasing TDM rates from say, 10 Gbits/s to 40 Gbits/s is very challenging by today's technical standards. On the other hand, using four WDM channels at 10 Gbits/s to achieve an aggregate rate of 40 Gbits/s is feasible.

WDM is making the "tera era" a reality. Laboratories have already demonstrated transmission capacity beyond 1 Tbits/s on a single fiber.^{23,24} In a recent laboratory experiment, 132 lasers were combined onto a single fiber to transmit information at a 2.6-terabit-per-second rate.²⁵ The tremendous progress in transmission capacity of a single fiber is shown in **Figure 13**, which shows laboratory WDM achievements over the last couple of years. Going beyond 6 Tbits/s on a single fiber will probably require adding another wavelength band such as 1300 nm, or a significant widening of the 1550-nm band.

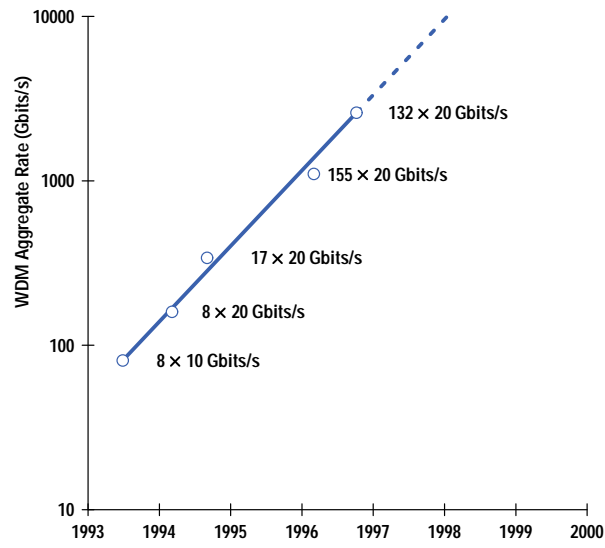
WDM Network Elements. To make WDM systems possible, a number of new components are required to perform optical amplification, wavelength multiplexing, and routing. For example, wavelengths can be separated from the data stream using optical add/drop multiplexers (OADMs). OADMs and optical crossconnect switches are also envisioned for future wavelength-routed networks.

A key element in WDM networks is the EDFA, which provides nearly wavelength-transparent optical gain.⁴⁻⁷ As a result, the EDFA gain spectrum has determined the wavelength band of WDM systems. The EDFAs are placed along the links at varying intervals depending on the data rates, system quality, and other factors. A separation of 80 km is very reasonable. It is important that the EDFA gain response be fairly constant across the wavelength span of interest. If it is not, channel-by-channel power compensation is required in long-haul networks.

The 1300-nm telecommunications window is also available, since the fiber loss is still quite acceptable there. At this wavelength, however, optical amplifiers have not been able to achieve the spectacular results obtained by EDFAs at 1550 nm. Some candidates include gain-clamped polarization independent semiconductor amplifiers, praseodymium or neodymium fiber amplifiers, or Raman-effect fiber amplifiers.²⁶

Figure 13

Year-to-year demonstrated WDM transmission rates.



While it is beyond the scope of this paper to discuss each element of the WDM network in detail, the summary in **Table III** provides a partial list of the network elements available to system designers and the technologies involved.^{27,28}

Table III

WDM Network Elements

Device	Abbreviation	Function	Technologies
Erbium-doped fiber amplifier	EDFA	Provides flat gain spectrum to WDM channels	Silica-based or fluoride-based fibers, laser pumps
Multiplexer/demultiplexer	MUX/DMUX	Combines/separates multiple wavelength channels onto/from a single fiber	Waveguide arrays, zig-zag filters, interference filters, diffraction gratings, fiber gratings, fuse couplers
Wavelength add/drop multiplexer	WADM	Adds or drops one or more wavelength channels without terminating the entire layer	Fused couplers, interference filters, circulators and fiber Bragg gratings, Mach-Zehnder interferometers
Wavelength interchange crossconnect	WIXC	Crossconnects signals with allowance for wavelength interchange	Optoelectronic regeneration, cross-gain modulation, optical nonlinearity, mechanical
Wavelength-selective crossconnect	WSXC	Crossconnects individual wavelengths without wavelength interchange	Fused couplers, interference filters, circulators and fiber Bragg gratings, Mach-Zehnder interferometers
Optical crossconnect	OXC	Optical signal switching	Electromechanical, electrooptic

The use of specific technologies in realizing certain network elements depends on the requirements for network transparency. Ideally, an all-optical network could provide data-rate-transparent operation, allowing easy upgrade to higher data rates. In such a network, wavelength conversion would have to be performed with all-optical methods. Optoelectronic regeneration has limits on bandwidth set by the detection and regeneration circuitry and would not be strictly transparent. Discussion continues on the need for transparency in view of the difficulties of coherent cross talk and vendor interoperability associated with transparent network designs.

WDM Challenges. Other challenges facing WDM networks relate to optical frequency standards and network architectures. Setting wavelength and frequency standards is challenging in a competitive environment. The stability requirement on laser center wavelengths is stringent with narrow channel separations. It is further complicated by physical phenomena such as four-wave mixing, which discourages the use of uniformly spaced channel frequencies. Currently, the ITU-T (International Telecommunications Union, under United Nations charter) has allocated wavelength channels on a frequency grid with 100-GHz spacings referenced to 193.1 THz. This is helpful, but noting the approximately 5000 GHz of available bandwidth, the possibilities are still limited that vendors will choose the same points on the grid for their 16-channel systems. The ITU-T optical frequencies and their respective wavelengths from 1530 nm to 1560 nm are shown **Table IV**.

Four-wave mixing, in which the nonlinear behavior of the optical fiber causes different channels to mix, causes problems by scattering signal power to other wavelengths.²⁰ Low-dispersion fiber, while helpful for TDM, increases the efficiency of the undesirable four-wave mixing. Therefore, WDM links must be designed to have local dispersion to reduce four-wave mixing but achieve low global dispersion. Dispersion maps showing the dispersion with distance along the link are commonly used as part of the link design.²⁹

The complexity of network management for WDM systems can vary tremendously depending on the architecture. For point-to-point WDM systems, the management is not unlike a network that simply added more fibers along a span instead of using WDM. In transparent networks, on the other hand, signals pass without bandwidth limitations, which implies no optoelectronic regeneration. Thus, transparent networks require wavelength interchange and switching capability allowing wavelength reuse. The management of transparent networks is considerably more complex and is still in active investigation.

Conclusion

Communications traffic in the world's fiber-optic backbone network is growing more than 10% per year. The growth rate shows promise of accelerating further. Ever-increasing communications bandwidth demands prompted by voice, fax, video, and Internet activity are being met by an array of technological innovations. Higher TDM transmission rates combined with WDM overlays have provided an economical alternative to putting more fiber in the ground. Development of standards for WDM networks will allow the possibility of interoperability between equipment from different manufacturers.

Acknowledgments

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Table IV**ITU-T Standard Optical Frequencies**

Frequency (THz)	Wavelength (nm)	Frequency (THz)	Wavelength (nm)
192.1	1560.61	194.1	1544.53
192.2	1559.79	194.2	1543.73
192.3	1558.98	194.3	1542.94
192.4	1558.17	194.4	1542.14
192.5	1557.36	194.5	1541.35
192.6	1556.55	194.6	1540.56
192.7	1555.75	194.7	1539.77
192.8	1554.94	194.8	1538.98
192.9	1554.13	194.9	1538.19
193.0	1553.33	195.0	1537.40
193.1	1552.52	195.1	1536.61
193.2	1551.72	195.2	1535.82
193.3	1550.92	195.3	1535.04
193.4	1550.12	195.4	1534.25
193.5	1549.32	195.5	1533.47
193.6	1548.51	195.6	1532.68
193.7	1547.72	195.7	1531.90
193.8	1546.92	195.8	1531.12
193.9	1546.12	195.9	1530.33
194.0	1545.32	196.0	1529.55

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