Optoelectronic technology and optical networking will become the key enablers of the future communications infrastructure through the elimination of the severe restrictions of bandwidth and bit-error rate inherent in traditional electromagnetic signal-based communications. Electromagnetic signals carried over copper (or coaxial) wires suffer attenuation (loss of strength) and are subject to errors due to noise and hence such systems have limited data rates (the upper bound given by Shannon's theorem). When copper or coax is replaced by fiber technology, the achievable bandwidth is in excess of 50T terabps with an almost zero bit-error rate. The full implications of essentially infinite bandwidth and extremely low loss rates are only beginning to be recognized and will radically reshape the computing technologies of the future—including our networks, processors, and applications. While in the past, the communication link was the bottleneck, this link now holds the potential to become the enabler of new modes of computing far beyond those existing today. The goals of this article are threefold:

- To present a general overview of optical networks;
- To discuss how all-optical networks can be integrated into existing and future broadband network architectures; and
- To highlight some of the potential impacts of optical networking on future computing applications.

Drivers for Optical Networks
When a technology class is nascent, it is impossible to predict fully its future impacts and uses. When that technology offers such aggressive improvement in performance parameters as the next-generation lightwave systems, we are on particularly shaky ground. However, optical networks have recently moved from being a research curiosity to becoming a billion-dollar business, as can be seen from several start-ups and commercial activities in North America and elsewhere. Here we briefly review a few important applications that will be enabled by high-speed optical networks.

Internet and Web browsing. Bandwidth requirements for each user of the Web have grown by a factor of eight annually at the same time that large numbers of new users are flocking to the Web. At

C (in bps) = W (in Hertz) * [1 + log2 S/N], where S/N is Signal-to-Noise ratio in db.
the same time most users encounter response times measured in seconds or minutes rather than the milliseconds they want. Applications such as Java-enabled active home pages have introduced the prospect of huge increases in the file sizes downloaded from any server, and technology visionaries have extended these trends to a new paradigm of network computing.

**Graphics and visualization.** The class of graphics and visualization applications is both data- and compute-intensive. At 2,000 x 2,000 12-bit color pixels per frame and 24 frames per second, this adds up to a little over 1Gbps [6]. In order to extend the capabilities of these applications to a distributed mode (for example, 3D terrain visualization using distributed databases, simultaneous viewing of experimental conditions by scientists in multiple locations), both small latency and gigabit rates will be required.

**Medical image access and distribution.** Hospitals are outgrowing storage facilities for film-based images (X-rays, MRIs, etc.) that take up space and are difficult to access quickly in times of need. In a life-threatening emergency, it is common for a surgeon to consult with radiologists and other specialists rapidly to screen a number of 2,000 images for medical consultation to multiple locations, either within a local region or to geographically dispersed locations, will require high-speed networks. This capability is critical in order to realize full telemedicine support, especially to remote rural sites where specialists may not be otherwise available.

**Multimedia conferencing.** The rapid introduction of video conferencing has reduced business costs and travel time by bringing parties together over audio/video channels [4]. However, realization of the full benefits of multimedia conferencing to support distant collaborative meetings depends on the ability of the network to supply the required quality-of-service (QoS). Video typically requires high bandwidth (20–40Mbps for HDTV quality, or 2–6Mbps with MPEG compression), low latency and reasonable loss rates. When the number of such connections is large, the aggregate bandwidth is high and guaranteeing the desired QoS levels for each virtual meeting connection becomes challenging.

**Broadband services to the home.** Telephone companies and cable TV operators are attempting to offer innovative new services to their residential and small business customers. Thus telcos are going after video and Internet services while cable operators are providing data services over cable modems and are also exploring voice connections [2]. The near future promises to deliver exciting applications such as video-on-demand, interactive TV, distance learning, and electronic commerce. To provide such future services, both types of operators are currently upgrading their access infrastructure, often referred to as the “last mile.” Hybrid fiber-coax (HFC), fiber-to-the-curb (FTTC) and fiber-to-the-home (FTTH) are some of the planned access types. Optical networking has been identified as the key technology to bring such broadband services to the home.

Optical networks will change the paradigms possible for tomorrow’s information systems designers by increasing the viability of network-reliant applications. Applications such as those described here are in turn likely to generate innovative new ways of utilizing the gigabit networking capability, perhaps in the same way that email became a dominant application and created a social revolution as well. The ability to deploy distributed data-intensive and compute-intensive applications will make tomorrow’s information systems effectively seamless, and will facilitate the deployment of applications utilizing advanced voice, data, image, and video communications components.

For business organizations, the availability of high-capacity, low-cost networking promises to address today’s business needs as well as effectively eliminate geographic boundaries for the business systems of the future. The increased demand for bandwidth by businesses needing support for digital commerce, remote workers, and client/intranet applications is straining current network capacities and IT budgets. By providing unprecedented low-cost telecommunications capacity, all-optical networks have the potential to address these critical business issues.

**Optical Transmission System Componentry**

The next-generation optical transmission system has three basic elements: the light source, the transmission medium, and the detector. Conventionally, a pulse of light indicates one bit and the absence of light indicates a zero bit. The transmission medium is an ultrathin glass fiber. The detector generates an electrical pulse when light falls on it. Attaching a light source (laser or LED) to one end of optical fiber and a detector to the other creates a unidirectional data transmission system that accepts an electrical signal, converts and transmits it by light pulses, and then reconverts the output to an electrical signal at the receiving end. When the path between the source and the destination remains entirely optical from end to end, such paths are called lightpaths. Each lightpath may be optically amplified or have its wavelength altered along
the way, but it is a purely optical path.

In Figure 1, we consider a simple optical communication system interfaced to regular electronic end systems. The analog signal generated by the telephone is input to the coder that digitizes and encodes it into a 64Kbps binary serial bit stream. This electromagnetic signal is used to modulate the light source, which in turn transmits a series of light pulses into the optical fiber medium. Inside the optical network, the signal may be regenerated by repeaters. At the receiving end, the impulses of light are converted back to an electrical signal by the light detector. The decoder section of the system converts the binary serial bit stream back to the original analog signal that drives a speaker in the phone to create original sound energy. Based on this example, one can easily identify the optical telecommunication system components:

- Light source: infrared light-emitting diodes (LEDs) or injection laser diodes (ILDs)
- Optical fiber: single-mode or multimode fiber
- Amplifiers: electronic repeaters or erbium-doped optical amplifiers
- Light detector: photodiode and phototransistor

The source and end-system devices are typically telephones, computers, video cameras or TVs. The more relevant system components for understanding optical networks are the optical fiber, light sources, detectors, and the amplifier.

**Optical fiber principles.** An optical fiber typically contains a central core, within which the propagating field is to be confined, surrounded by a cladding layer, which is covered by protective jacket. The core and the cladding are made of ultrapure silica or glass, while the jacket and sheaths are made of plastic [7]. A ray of light travels through by reflecting along the interface between the two transparent mediums. Based on the refractive indices, a light ray can be totally confined within the fiber core. The core is manufactured of ultrapure glass while the surrounding cladding is also made of glass, although the index of refraction is typically 1% less than the core. When a ray of light is made to propagate in one direction only along the center axis of the fiber, the fiber is classified as single-mode fiber. If there are a number of paths in which the light ray may travel, the fiber is classified as multimode fiber.

Optical fiber has very high bandwidth (Terabps). Signals do not travel faster in fiber than copper but the density or data capacity of fiber is much greater. Light has higher frequencies and hence shorter wavelengths, so that more “bits” of information can be contained in a length of fiber versus the same length of copper [9]. Fiber has low loss properties and is immune to noise. Two photons can occupy the same space and that is why two flashlight beams, when crossed, simply pass through each other unaffected. Fiber cables are substantially lighter in weight and occupy much less volume than copper cables. Since light does not radiate from a fiber-optic cable, it is nearly impossible to secretly tap into it without detection. Presently, the cost of fiber is comparable to that of copper—approximately $0.20 to $0.50 per yard—and is expected to drop as it becomes more widely used.

Interfacing costs for fiber-optic cable are higher since electronic facilities must be converted to optics and vice versa requiring expensive transmitters, receivers, couplers, and connectors. If the fiber-optic cable breaks, splicing can be a costly and tedious task. Fiber also suffers from dispersion and absorption problems. Dispersion causes pulses of light to spread out as they travel through fiber and interfere with pulses of light ahead and behind. A particular form known as “chromatic” dispersion is caused by the transmitting laser, which is unable to send all the photons at exactly the same wavelength, and different wavelengths travel at different speeds. Solitons, used recently in fiber systems, may provide a solution to the dispersion problem [9]. Solitons are shaped pulses, which counterbalance the effects of dispersion and other physical phenomena.

**Light transmitters and receivers.** A light source must be able to turn on and off several tens of millions and even billions of times per second. It must also be able to emit a wavelength transparent to the fiber. Other properties it should have include efficient coupling of light energy into the fiber, sufficient optical power emitted to transmit through long distances, and relatively low cost. Two commonly used devices that satisfy these requirements are the LED (light-emitting diode) and the ILD (injection laser diode). A photodetector is often used as a receiving device

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3Lasers result in much better performance than LEDs.
that converts light energy into electrical energy. They are made of semiconductor materials and their structure often determines the wavelength that they are sensitive to.

**Optical Networking Technology**

Theoretically fiber has extremely high bandwidth (almost 25THz). However, in the 1980s, only slow speeds of up to 250Mbps were achieved on the point-to-point fiber trunks that were laid underneath the oceans, while 10Gbps speeds were achieved in research labs. These rates were clearly not delivering fiber's theoretical potential. The recent terabit per second breakthroughs are the result of two major developments. One is wavelength-division multiplexing, a method of sending many light beams of different wavelengths simultaneously down the core of an optical fiber. The other is the all-optical amplifier, which restores the signals to their original intensity after they have been attenuated by travel through the fiber. Made of erbium-doped optical fiber, the amplifier brings all the parallel channels back to their original power simultaneously, regardless of their modulation scheme or speed.

**Erbium-doped optical amplifier.** Until the advent of the erbium-doped fiber amplifier, no practical all-optical amplifier existed. Optical signals were instead regenerated electronically to overcome the attenuation inherent in the silica fiber as well as other losses due to optical components along the line. Electronic regenerators have two drawbacks. They are expensive, and they limit a system's performance since each regenerator can operate at only one predetermined incoming bit rate, in one data modulation format, and on one wavelength of a single input channel [12].

The erbium-doped fiber amplifier contains several meters of silica glass fiber that have been doped with ions of erbium, a rare-earth metal. When the erbium ions are excited to a metastable energy state, a population inversion takes place that changes this medium into an active amplifying medium. The amplifier will now accept parallel optical signals at many different wavelengths and amplify them simultaneously, regardless of their individual bit-rates, modulation formats, or power levels.

**Wavelength division multiplexing.** The practicality of wideband optical amplifiers opened the door to multiplexing signals of many wavelengths onto the same optical fiber. This technique, known as wavelength-division multiplexing (WDM) can enhance an optical system's capacity [10]. Since two photons can occupy the same space, many light beams of different wavelengths can travel along a single fiber, carrying many individually modulated data streams. Since frequency and wavelength are inversely related (fλ = c, speed of light), conceptually WDM is similar to frequency division multiplexing or FDM. In the past, we have used FDM to carry many radio channels over the air or several simultaneous TV channels over cable. The carrier wave of each optical WDM channel, however, is a million times higher in frequency (terahertz versus megahertz). A basic WDM arrangement is shown in Figure 2.

To utilize the full potential bandwidth of fiber would require individual optical pulse widths of a few tens of femtoseconds. These are commonly referred to as dense WDM for systems in which the wavelength is on the order of 1 nanometer [1]. In contrast to dense WDM, conventional WDM has been used to upgrade the capacity of installed point-to-point transmission systems, typically by adding two, three or four additional wavelengths usually separated by several tens or even hundreds of nanometers in wavelength. It is important to space channel wavelengths an adequate distance apart. Typical channel spacing range from 0.4nm to 4nm (50GHz to 500GHz).

Traditional time-division multiplexing (TDM) is facing a fundamental problem: In TDM, the bit-rate of the front-end electronics must scale as the product of the number of ports and per port bit rate. As

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This is also called the “electronic bottleneck.”
networks evolve to higher values of this product, it inevitably exceeds that of the fastest available digital technology. However, TDM can complement WDM by interleaving the bits of several lower-speed signals onto a single high-speed optical channel. To mine terahertz bandwidths, both WDM and TDM schemes must be used. Optical time-division multiplexing (OTDM) systems divide the fiber into a smaller number of broader wavebands (possibly only one) and use short pulses to transmit at very high rates (>100 Gbps) per waveband. Although OTDM is far less mature than WDM at this time, it enables very high-speed optical logic which can be used to provide enhanced digital services and functions such as packet routing and error correction.

**All-optical networks.** There are three classes of all-optical networks, based on differences in the topology (see Figure 3). The simplest one, a typical WDM point-to-point link, consists of several wavelength-differentiated distributed feedback (DFB) lasers at the transmitting ends of different wavelength channels and photodetectors at the receiving ends with a passive MUX/DEMUX connecting the two ends of a link. Such WDM links traditionally have been used to boost capacity of installed fibers using both full and half duplex transmission. The pace of improvement for this technology is spectacular: while in 1994 the only commercial product for the telco market multiplexed four OC-48 (2.5Gbps) channels to a distance of 550km, the high-end mux in 1995 has multiplexed 8 such channels; the current record is 16 channels to 600km; and a 32-channel system to 1,200km has been announced.

**Broadcast-and-select networks** are based on a passive star coupler device connected to several stations in a star topology. This device is a piece of glass that splits the signal it receives on any of its ports to all the ports. As a result, it offers an optical equivalent to radio systems: each transmitter broadcasts its signal on a different wavelength, and the receivers can be tuned to receive the desired signal. The main networking challenge in such networks is the coordination of a pair of stations to agree and tune their systems to transmit and receive on the same wavelength. One design issue that must be determined before deciding on such protocols is the tunable part of the system. It is possible to either have the transmitters each fixed on a different wavelength and have tunable receivers, or have fixed receivers and tunable transmitters, or have...
tuning abilities in both components. The advantage of these networks is in their simplicity and natural multicasting capability. However, they have severe limitations since they do not enable reuse of wavelengths and are thus not scalable beyond the number of supported wavelengths. Another drawback is that these systems cannot span long distances since the transmitted energy is split to all the ports. For these reasons, the main application for broadcast and select is high-speed local and metropolitan area networks.

Wavelength routing networks. A scalable optical network can be constructed by taking several WDM links and connecting them with wavelength-selective switching subsystems. The signal’s path through the network is uniquely determined by the wavelength of the signal and the port through which it enters the network. There are actually two types of wavelength switching, one of which dynamically switches signals from one path to another by changing the WDM routing in the network. The other type of wavelength switching is really wavelength conversion, in which the information on a signal is transferred from an optical carrier at one wavelength to another. Such systems may reuse the same wavelength in some other part of the network, as long as both lightpaths do not use it on the same fiber. Since such “spatial reuse” of wavelengths is supported by wavelength routing networks, they are much more scalable than broadcast-and-select networks. Another important characteristic which enables these networks to span long distances is that the energy invested in the lightpath is not split to irrelevant destinations. Given a network, the problem of routing and assigning wavelengths to lightpaths is a complex and important one, and clever algorithms are needed to ensure that this function is performed using a minimum number of wavelengths.

The Latency vs. Bandwidth Issue in Dense WDM Systems

In order to understand both the potential and limitations of all-optical networking, it is important to recognize that gigabit networks have inherent in them a new set of issues that must be addressed by network designers. One major issue that comes to the fore in the gigabit world is the issue of latency vs. bandwidth. Higher bandwidth seems to suggest that we can improve the response time of application messages we transmit into our networks, so that at gigabit speeds and beyond, we should see significant improvement in transmission and response times. However, as described by Kleinrock [8], this is not always the case, as the latency becomes a severe limitation due to the speed of light. In that article, the example of a single transmission link is used to illustrate that the reduction of transmission delay time through additional channel capacity is bounded by propagation delay due to the finite speed of light.

Although WDM provides multiple transmission paths, work by the first author of this article demonstrates that in packet-based WDM systems there also exists a sharp boundary beyond which the system is latency-limited. As in the case of a single transmission path, there is a critical bandwidth level for the channel (Ccrit) beyond which additional channel capacity will not reduce delay time. A major implication for WDM systems is that there is also a critical number of wavelengths (n_crit) beyond which additional wavelengths will not reduce delay. Figure 4 shows Ccrit for an example set of parameters and three WDM configurations. For a full description of this analysis and the calculation of n_crit, the reader is referred to www.cis.gsu.edu/schatter/public_html/CACM/optical.html.

Overall Network Architecture and Optical Services

Our existing networks provide three basic types of transport services: circuits (POTS, T-1, SONET), datagram (IP with its best-effort service) and virtual-circuits (frame-relay and ATM). These are all traditionally electronic domain services. Some or all of such services can now be provided by the optical domain. Figure 5 shows how the optical network (ON) can interface with today’s existing services.
inside an overall broadband network architecture. Network services are provided in the form of layers of various protocols. Several combinations have been used in practice. For example, a user running an application may require packet service (datagram). The message is encoded in an IP datagram which may be delivered directly over ON interface that supports packet service or may be further sent over an ATM layer or ATM-over-SONET layers, among other choices.

There is a clear demarcation between electronic layers and optical services, which is implemented at the User Network Interface (UNI) for the ON. The user above UNI may be an IP router, ATM switches or SONET cross-connects. Each of these avail some kind of optical services offered by the ON. Four categories of optical services can be offered: analog circuits, digital circuits, analog packet/cell, and digital packet/cell.

At this time, an ON uses a single wavelength in a point-to-point fiber link and uses the limited bandwidth to offer optical services. The bandwidth is fast being consumed by network growth. Both WDM and OTDM technologies can potentially boost the bandwidth and actually help mine the terahertz bandwidth of each optical fiber. Optical circuit services are currently mature. To establish an analog circuit between ON adapters, a circuit is assigned a wavelength that is transparently routed through the network [3]. Packet/cell optical services may be beneficial to bursty traffic sources. The adapters could utilize packet/cell optical services to typically carry electronic with limited optical memory, logic, and processing will remain the focus for research in this area.

**WDM Deployment Considerations**

Even though WDM technology has only recently become commercially available, its deployment as a point-to-point transmission technology has been fast-paced. 8- and 16-channel systems are available today, and vendors are currently developing 32- and 40-channel WDM systems. Although transmission capacity on a link can be increased by adding more fibers—space-division multiplexing (SDM) approach—or increasing the transmission bit rate on the fiber—time-division multiplexing (TDM) approach—economic and reliability considerations make the case for WDM particularly compelling in situations where increased capacity is needed over long-distance links or where it may be cost-prohibitive to lay more fiber [10]. These considerations have led major long-distance network providers to employ WDM to upgrade transmission capacity in their backbone networks; WDM has been utilized for undersea networks; and the technology is beginning to emerge in metropolitan wide-area networks.

Because significant challenges need to be overcome before all-optical networking can become a reality, over the next several years network operators will be faced with the need to integrate WDM with other complementary transport technologies into hybrid networks. Advances in optical network management and control capabilities are expected to facilitate the incorporation of both optical transport and optical packet/cell transport traffic. However, they would likely need buffering, synchronization logic and memory.

Current technology severely limits the optical-packet services that can be offered. Memory is extremely difficult to implement optically. Currently, optical memories are based on the concept of injecting light into fiber loops in which the signal theoretically continues to circulate forever [3]. Because of the cyclical nature of the memory, reading of the information is restricted to multiples of the round-trip loop time (packet/cell length). Therefore, truly random access memories do not yet exist. Achieving a better understanding of how and what type of services can be provided...
<table>
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<th>Project &amp; Research Group</th>
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<th>Focus of work and salient characteristics</th>
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<tr>
<td>Columbia University Lightwave Group (<a href="http://www.ctr.columbia.edu/~georgios/lightwave.html">www.ctr.columbia.edu/~georgios/lightwave.html</a>)</td>
<td>Bellcore, AT&amp;T, GTE, Northern Telecom, NEC, Phillips, Southwestern Bell</td>
<td>• Goal is to devise new network architectures using state-of-the-art photonic device technologies that can form the basis for a new optical network infrastructure on a national scale   • Focus more on a systems-level perspective rather than a pure physical-level and device-level approach   • Produce systems-level architecture and new control methodologies appropriate for lightwave networks</td>
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<tr>
<td>IBM Optical Networking Group (<a href="http://www.research.ibm.com/wkm">www.research.ibm.com/wkm</a>)</td>
<td>Work includes collaborative initiatives with Corning and LANL</td>
<td>• Research aims to define the architecture of an optical layer by using multiwavelength WDM technology   • IBM and Corning are investigating scalable architectural issues based on WDM or wavelength routing   • This group has also been developing the Rainbow-II metropolitan area network deployed in an applications testbed at Los Alamos National Laboratory</td>
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<tr>
<td>ACTS (Advanced Communications Technology and Services Programme) Photonics Projects (<a href="http://www.intec.rug.ac.be.horizon/photonic.html">www.intec.rug.ac.be.horizon/photonic.html</a>)</td>
<td>The European Union research programs on photonic technology includes industry, academia, and government partners</td>
<td>• 31 ACTS projects addressing the concepts, design and management of optical networks, customer access networks, multiplexing and transport, sub-system and key component development, and switching and routing   • Major optical networks projects in the Programme include: OPEN, KEOPS, COBNET, METON, PHOTON, MEPHISTO, MOON, PELICAN, DEMON, HORIZON, PLANET, MEPHISTO, and SONATA</td>
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<td>All-Optical Networking Consortium (<a href="http://www.ll.mit.edu/aon/">www.ll.mit.edu/aon/</a>)</td>
<td>AT&amp;T Bell Laboratories, Digital Equipment Corporation, and the Massachusetts Institute of Technology sponsored by DARPA</td>
<td>• Deployment of a static wavelength routing testbed in the Boston metropolitan area to demonstrate feasibility and interaction of architectures, optical technologies and applications</td>
</tr>
<tr>
<td>MONET: Multiwavelength Optical Network (<a href="http://www.bell-labs.com/project/MONET/">www.bell-labs.com/project/MONET/</a>)</td>
<td>Bellcore, Lucent Technologies, AT&amp;T, Bell Atlantic, BellSouth, Pacific Telesis, Southwestern Bell Technologies Resources, Inc. (in cooperation with NSA/NRL; partial support from DARPA)</td>
<td>• Objective is to integrate network architecture, advanced technology, network management, and business drivers to achieve high capacity, high performance, cost-effective, reliable, transparent multiwavelength optical networking   • Develop an understanding of operational issues associated with network deployment</td>
</tr>
<tr>
<td>NTONC: National Transparent Optical Network Consortium (<a href="http://www.ntonc.org/">www.ntonc.org/</a>)</td>
<td>Nortel Networks, GST Telecom, Lawrence Livermore National Laboratory, Sprint Communications Company (DARPA sponsorship)</td>
<td>• Development of an advanced optical networking research testbed running from San Diego to Seattle, with nodes in Los Angeles, San Francisco, and Portland; and an optically switched ring around the San Francisco Bay   • Provide a field test environment for high-bandwidth applications   • Examine &quot;flat network architecture&quot; a meshed network with dynamically adjustable link capacities and nodes that provide data packaging into &quot;containers&quot; for transport</td>
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switching technologies into larger segments of network infrastructures in the future.

Research—The Role of Testbed Initiatives
A critical factor in the research on all-optical networking is the availability of experimental networks, or testbeds. These large-scale initiatives represent major collaborations between academia, industry and government (see Table 1). A wide range of complementary and independent research projects can be incorporated within the scope of a single testbed program; and in some cases previously standalone testbeds are also being linked to provide expanded research environments. Although it is difficult to forecast when the new network paradigm of integrated optics will make the transition from experimental testbed initiatives to full-scale commercial systems, it is expected that 0.1Tbps systems should be on the market within a couple of years and 1.0Tbps systems should be commercially available around 2005 [11].

When the Network Is No Longer the Bottleneck
The vision of an era of ultrahigh-speed networking capability brings with it the opportunity and challenge to create new computing paradigms. Testbed initiatives are already incorporating demonstrations of high-bandwidth applications made possible by the expanded network resources. A fundamental shift will also occur in computer engineering, with the need to create new architectures and software for end hosts as the network bandwidth begins to rival or exceed the bandwidth available inside the computers connected to the network.

Perhaps the major challenge for organizations developing next-generation network infrastructures is to strengthen confidence that the network capacity and economics they will require in the future will be available. As businesses have become increasingly dependent upon intranets and extranets, the ability of networks to continue to meet the exploding demand for bandwidth has become a critical issue. Future information technology strategies such as expansion of business-to-business and customer-to-business electronic commerce, the implementation of transaction processing systems requiring high bandwidth, and deployment of interactive media applications are totally reliant on the ability of networks to deliver the necessary bandwidth. Confidence in the availability of bandwidth will in turn generate innovation in the types of business applications that are developed. One nearer term impact on organizations as a result of the wider deployment of WDM technology may be the ability to 'lease lambdas' from network providers rather than leasing lines.

Conclusion
This article has briefly reviewed the state of the technology and possible future directions for fiber-optic networks. It is clear that significant engineering issues must be addressed and many systems and management problems must be solved before ubiquitous fiber networking is achieved. Cost will not be a trivial issue, but the economics of these optical systems favor them if the bandwidth is in demand. As global infrastructures begin to emerge and a host of broadband services appear and deliver economical service to users at offices and homes, optical networking will become a serious candidate for widespread implementation. While testbed initiatives will continue to be critical in the development of this technology, it is important for the broader set of implementation issues to be actively addressed in order to ensure an all-optical network at a reasonable cost.

References

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