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A Precompetitive Consortium on Wide-Band All-Optical Networks

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(Invited Paper)

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Abstract—**This paper represents the technical core of a precompetitive consortium formed by AT&T, DEC and MIT to study the technology, architecture and applications of wide-band all-optical networks of local to national (or international) extent. This effort is currently partially sponsored by the Defense Advanced Research Projects Agency (DARPA). Sections I and II of this paper provide a general introduction to all-optical networks and discuss some proposed applications. Sections III, IV and V cover the architecture, technology and test-bed portions of our effort.**

I. INTRODUCTION

THE American Telephone and Telegraph Company (AT&T), Digital Equipment Corporation (DEC), and Massachusetts Institute of Technology (MIT) have formed a precompetitive consortium to address the challenges of utilizing the evolving terahertz bandwidth capability of optical fiber technology to develop a national information infrastructure capable of providing flexible transport, common conventions and common servers.

Our long term goal is to pursue the research and development of the technology, architecture, and applications necessary for the realization of a scalable, universal, wide-band optical network. Our more immediate goal is to determine how these challenges can best be met and to demonstrate that capability in a manner that can be further developed, engineered and produced by the communications and computer industries of the United States. Our vehicle to reach these goals is an extensive test-bed utilizing state-of-the-art components. Research and development on technology, architecture and applications will revolve around this activity.

Our network architecture is all-optical. Optical signals can flow between users across the network without being converted to electronic signals within the network. Thus, the network is unimpeded by optical-to-electronic transformations. This is made possible by the introduction of optical amplifiers and other unique optical components, such as frequency routers and frequency converters. Some of the components are commercially available, but a significant fraction will be unique research devices.

The baseline architecture will potentially allow frequency-division multiplexing to access the 25 THz (200 nm) of fiber bandwidth. The architecture will support three basic services: 1) point-to-point or point-to-multipoint high-speed circuit-switched multi-gigabits-per-second digital or analog sessions, 2) time-division multiplexed (TDM) circuit-switched sessions in the range of a few Mb/s to the full channel rate of multi-gigabits-per-second, and 3) a service used for control, scheduling and network management that can also be used for datagram service. Sevices 1) and 2) have all-optical paths but typically will use electronics for setup and control.

We have in mind the creation of an architecture that is scalable in the dimensions of geographic span, number of users and data rates. Thus, we have developed a hierarchical architecture that includes local area networks (LAN's), metropolitan area networks (MAN's) and wide area networks (WAN's). Since it is designed to scale gracefully to hundreds of thousands of all-optical end-nodes, it provides a framework for a national or global high-speed communication infrastructure. The modular nature of the design allows the incorporation of future technological advances and serves as a guide to such advances. In addition, the flexible high-rate services provided by this architecture will serve as a stimulus to new application areas.

In addition to the more mature technology used in the test-bed, we intend to pursue research in a few technology areas of great potential impact to network architecture and performance, e.g., an all-optical packet switch. These modest research efforts have higher risks, though higher pay-offs, and will not be part of the baseline architecture of the test-bed.

A key theme of our effort is the construction of an extensive test-bed system. It will form a proof-of-concept demonstration

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of a universal, scalable, optical network and will provide a common forum in which the interactions of applications, architectures, and technologies may be investigated. This extensive test-bed will be geographically distributed and will be connected via dark fiber whenever possible.

This unique test-bed will be a tool by which many technical issues in architecture and technology can be clarified and/or resolved experimentally. It provides a near "real-world" environment in which network hardware, terminal equipment, protocols, algorithms, and services can be rapidly developed, tested, and demonstrated. When operational, it will act as a catalyst in the development and demonstration of new network services and applications and also serve as the central point of technology transition within and outside of the consortium.

The potential benefits of accessing the tens of terahertz of bandwidth available in optical fibers are well known. Actually realizing these benefits will require that a network satisfy three fundamental requirements. First, the network must be universal in that it will need to accommodate an enormous diversity of applications, services, interfaces, protocols and signal formats. Second, it must be scalable in terms of the number of users, the data rates supported, and the geographic span of the network. Finally, in order to limit the cost-complexity of network nodes, we feel, to the maximum extent possible, the wide-band optical network must be "transparent" to high-rate users so that the flow of their optical signals within the core of the network is unimpeded by optical-to-electronic transformations, even though that flow may be controlled by electronics. Otherwise, the complexity and associated costs of an all-electronic network node may be unacceptable for very wide-band services. For example, optical-electronic interfaces and electronic switches to support rates of terabits per second per node will be complicated and costly. This cost-complexity issue is often called the "Electronic Bottleneck." For low-rate users and services that require specialized signal processing, we will reserve the possibility of electronic switching and processing within the network.

There are three important aspects of a network—applications, architecture and technology. We will only highlight potential applications since our near-term goal emphasizes architecture, technology, and the test-bed. However, we must understand generic applications well enough to characterize the types of service and performance the network must support.

II. APPLICATIONS

Wide-band networks have commercial scientific, academic and government applications. Over the last few years, long lists of wide-band services have been created. Although market forces and customer preferences will ultimately determine which applications will be accepted, there are already demonstrated needs for:

1. Communications—voice, data, and video
2. Wide-band imagery, sensor data, and scientific data transfer
3. High-performance computing involving connection among supercomputers, high-speed access to databases/libraries and specialized data processing facilities

In order to have some understanding of the applications future network users may desire, we will classify applications into three categories and present some examples from each category. Much work will be required to develop even these few examples and there are undoubtedly many others yet to be created.

The first category contains applications that utilize traditional digital services. The anticipated data rates span the range from kilo to gigabits-per-second so it is useful to subcategorize them by rate into four groups. The first subcategory encompasses applications requiring gigabits-per-second data such as ATM or other fast packet switching, un-compressed HDTV, visualization, simulation, and supercomputer interconnects. The next grouping contains applications in the 100 megabits-per-second class such as LAN (e.g., FDDI) interconnection, compressed HDTV, digitized conventional video, and workstation interconnects. The third grouping consists of 10 Mb/s applications such as multichannel digital audio and Ethernet class computer networks. The last grouping contains those applications requiring 1 Mb/s or less such as conventional telephone service and RS-232 class computer/peripheral interconnects. Traffic from lower-rate applications almost certainly will be aggregated.

The second category contains analog services. This requirement may arise in the distribution of multichannel broadcast television channels where it is advantageous to handle many channels as one unit. The rate at which such a unit should be digitized may be so high that it is simpler and cheaper to keep it in analog form. Our network architecture will not preclude the support of analog services via all-optical transport but we will not work actively on the development of such services.

The third category contains users applications that require an optical interface. This may result from a need for a very high transmission rate, an unanticipated signaling format or a desire to use the unique characteristics of an all-optical network. Future video workstations, massive database servers and multiplexed digital HDTV sources are potential members of this category.

Finally, many future applications will need multi-media and multi-session services. A successful network architecture will need to address these objectives from the beginning.

A. Application Examples

To illustrate the interplay between applications, services, architectures, and technologies we present some examples. They are not intended to be detailed but rather to highlight areas requiring further research.

The first example is a scalable television system that would transmit a video signal from which an image may be created at any resolution, from existing NTSC video, to the very high-definition associated with a wall-size flat panel display. The video information is formatted for a generation of television systems where one is charged for both program content and visual quality. Different users would observe different representations of the information even though they are all receiving the same signal.

A second example is the concept of a network "media bank" as has been proposed by the MIT Media Laboratory.

The media bank is a system-wide resource containing on the order of 10 terabytes of memory that will function as a massive multimedia storage system for images, sounds, and data. For example, a media bank might contain the entire contents of the Library of Congress for access throughout the country. Text information would be accessible not only as ASCII characters but also in ways that preserve the appearance of the printed page. Images, artwork, sound recordings, and drawings would be available. Applications interacting with such a media bank would require the network to resolve issues of access control, multimedia synchronization, multiple user conflicts, and information organization and classification. Ultimately, the social, economic and educational effects of this wide dissemination of information would also need to be addressed.

A third interesting application is medical imaging. In this application, digitized images of various types, such as X-ray, MRI, and CT are stored and transmitted for evaluation by radiologists. Presently, X-ray images are usually stored on film. This has several drawbacks: the film is expensive, such records are easily lost and valuable time is lost physically transferring them from one place to another. These images often represent large quantities of data. For example, a single $2048 * 2048 * 24$ bit image is about 12.5 MB. Because of the nature of the information, there is a reluctance to use compression algorithms. Often, radiologists view several images simultaneously and then rapidly move on to a new set of images. This scenario results in a requirement for bursts of data at very high transmission rates ($\sim$1 Gb/s).

The existence of communication networks capable of handling vast quantities of data is a key to the development of these types of broad-band applications. However, future networks must allow an even wider variety of services to co-exist rather than be tailored to these or any other specific applications. Thus, one must postulate general models for the data these undefined services will present to the network. To that end, data can be classified as bursty traffic, synchronous traffic and analog traffic. Also session topology can be classified as point-to-point, multicast (or broadcast) and conferencing.

Finally, different types of users will require different service grades of "quality of service." In other words, depending on the applications, the performance criteria of the users will be different and the network should be designed to satisfy the various disparate performance requirements.

III. ARCHITECTURE

A. Overview

The low-loss wavelength window of a single-mode optical fiber covers a bandwidth of about 25 THz (200 nm). Our long-term goal is to use this enormous bandwidth efficiently to form the basis of a wide-band information infrastructure. However, the emphasis in our baseline architecture for wide-band all-optical networks is to trade some bandwidth-utilization efficiency for simplicity, flexibility, producibility, and robustness.

Our architecture for all-optical networks (AON's) serves a number of functions. First, it is the architecture to be employed in the test-bed. Second, since the architecture scales gracefully to hundreds of thousands of all-optical end-nodes, it provides the possibility for a national or global all-optical communication infrastructure. Third, the relatively modular nature of the architecture both allows the incorporation of future technology advances and serves as a guide to such advances. Fourth, the flexible high data rate services provided by the network will serve as a stimulus to new application areas. Finally, the existence of such an architecture will encourage focused research on architectural modifications and alternatives. Thus, this architecture provides a framework for our research in technology, applications, and architecture.

Since this architecture is designed as a framework for our research, it differs from commercial architectures in a number of respects. First, we have not yet attempted a precise specification of user interfaces since these interfaces are expected to change with time. Second, we have not yet introduced fault tolerance into the architecture, since this would greatly complicate the structure at this stage and inhibit research in other directions. At the same time, fault tolerance is both an important topic for our research and an issue close to our consciousness. On the other hand, scalability, modularity and flexibility are central to our architecture. Our first priority was to design an architecture that would scale to hundreds of thousands of end-nodes and worldwide extent while at the same time preserving the ability for the network to evolve in time, both in terms of size and technological and architectural improvements. The resulting architecture is based on wavelength[1] division multiplexing (WDM), but provides scalability through frequency reuse over space and the use of novel time-division techniques.

Our architecture employs a three-level hierarchy using WDM as shown in Fig. 1. At the lowest level of the hierarchy are Level-0 AON's which can be viewed as a collection of high-performance local area networks. Each Level-0 network shares wavelengths internally, but there is extensive reuse of wavelengths among different Level-0 networks. The intermediate level, Level-1, can be viewed as a metropolitan area network that connects a set of Level-0 networks and provides frequency reuse through devices such as wavelength routers. The highest level, Level-2, can be viewed as a national or worldwide backbone that connects Level-1 networks using quasi-static wavelength changers and/or switches.

The direct services provided by the network are classified as Type-A, -B and -C services. Roughly speaking, Type-A service provides a dedicated optical-path from point-to-point or point-to-multipoint. This provides for circuit-switched multi-gigabit-per-second digital or perhaps analog sessions with user-determined format. Type-B service uses a TDM structure over an optical-path to provide circuit-switched sessions in the range from a few megabits-per-second to the full channel rate of multi-gigabits-per-second. Type-C service is used internally for control, scheduling and network management and can

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[1] Note: The terms "wavelength" and "frequency" are used interchangeably in this paper.

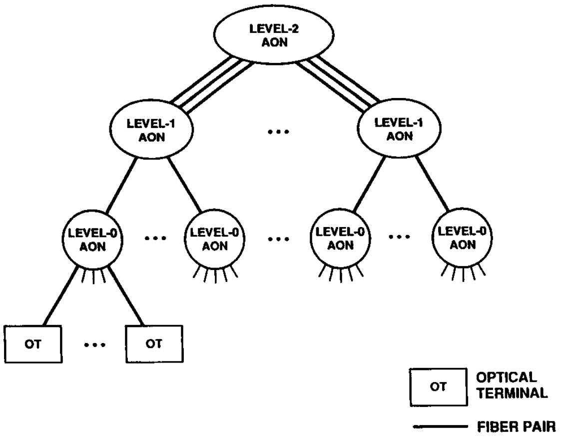


Fig. 1. All-optical network (AON) architecture elements.

also be used for some user datagram service. The A and B services each have all-optical data paths, but typically use some electronics for set up and control. Conventional services such as datagrams, virtual circuits, and ATM can be served by higher layer electronic packet switches that use the A, B, and C services as a physical layer. It is also possible to provide these conventional services directly using all-optical data paths, and this will be an active research area.

Some of the traditional functions required of a complete architecture are: management (control, monitoring, testing, fault isolation), accounting, enforcement of management policies and network protection parameters, fault containment, congestion control, etc. Those functions which are well understood and which scale to higher speeds will not require significant effort, but we will ensure that the architecture permits at least one reasonable mechanism for each.

In subsequent sections, some useful concepts are defined, then the services provided by the AON, its elements, and operation are described.

B. AON Concepts

We define the term "wavelength-path" to denote the internal network path taken by an optical signal traversing all or part of the AON. Any passive or active device which does not either convert the optical signal to electronic form or change its optical frequency is allowed in a wavelength path. Thus, optical amplifiers, filters, and broadcast stars, are allowed, but not frequency changers or electrooptic transducers.

We further define the term "light-path" to be the path an optical signal traverses in the network from a source to a single destination which may include an optical frequency shifter. Therefore a light-path may be a simple wavelength path or may be composed of several wavelength paths interconnected by frequency shifters.

We also define the term "light-tree" to denote a loop-free connected set of branches (i.e., a tree) used to carry an optical signal from a source to multiple destinations. More generally, a light-tree may be used in a multi-access mode to time share optical signals from several sources and to carry the composite signal to multiple destinations. A light-tree may include frequency shifters, so that a light-path can be considered as a special case of a light-tree in which there is a single source and single destination.

C. AON Services

There are three basic types of transmission services to be provided at the user interfaces (Access Points or AP's) of the AON. To avoid confusion over terms, we have found that it is best to define some neutral terms by which we refer to these services. These are:

1) Type-A: Switched—Physical Circuit: This is a "physical circuit-switched" service which uses one or more dedicated light-paths for the duration of the connection to transmit information. Type-A data and modulation format are generally unrestricted although source power levels and bandwidth specifications must not be exceeded at the AP. At connection establishment time, the modulation and data formats are made available to the destination to ensure that it recovers the data properly. The maximum noise added as well as the gain or loss bounds will be specified.

Type-A connections are normally obtained as a result of a request through an AP by the sending node. However, we will allow other mechanisms such as a third-party request and permanent connections specified via network management. Note that there are several subtypes associated with this service. These are:

a) Duplex connection: It is expected that this bi-directional point-to-point connection would be the most commonly requested Type-A service. This type of connection would make use of two dedicated light-paths in the AON. Such a connection would have a number of uses such as a dedicated channel for use by a very-high-speed computer-computer guaranteed-bandwidth channel or by a traditional electronic packet or ATM cell switching system.

b) Multicast connection: With this subtype, the requesting node utilizes a single light-tree to the destination(s) for the purpose of uni-directional transmission. Note that there may be one or more receivers associated with this type of connection which might be used for very-high-speed telemetry or uncompressed HDTV respectively. When this service type is requested, the requester must also specify whether it intends to be a source or destination.

c) Shared connection: With this type of service, each participating node may transmit and receive each transmission on a single dedicated light-tree. Clearly, with this type of service, collisions may occur if an orderly channel access scheme is not used by the participants. However, this architecture does not have to specify how channel contention for this type of service will be resolved. Individual contention algorithms can be agreed upon by the users sharing the connection to suit their applications. Examples of how such a connection might be used are for a shared datagram channel or for an HDTV conference session.

The optoelectronic technologies that enable Type-A service are:

— tunable lasers with wide tuning range, narrow linewidth, and good frequency stability and repeatability

— tunable receivers with wide tuning range, good frequency stability, repeatability, and good sensitivity

— devices which allow frequency re-use, such as: static and dynamic wavelength routers

2) Type-B: Scheduled TDM: This is a "scheduled TDM" service which uses a light-path or light-tree that is time-slotted to transmit information for the duration of a connection. In general, data, and modulation formats within a scheduled time-slot are unrestricted (but specified at connection setup to ensure the receiver properly recovers the signal). With Type-B service, as with Type-A, Duplex, Multicast, and Shared subtypes are available.

Given the desirability for multiple simultaneous network connections at an AP, the architecture should deal with this as well. One possible solution would be for each user to have multiple receivers. This would allow a receiver to be dedicated to a network connection for the period of that connection. However, this approach has several drawbacks. First, it requires more hardware which will add to the cost of connecting to the AON. Second, choosing the number of receivers is problematic—the number of receivers would need to be chosen when the AON interface is designed.

Another important reason for Type-B service is to more efficiently share light-paths. If each Type-B connection requires a dedicated light-path, the AON will quickly run out of this valuable resource.

While it is likely that some users will require multiple receivers (and transmitters) for the aggregate data throughput or the reduced blocking probability they can provide, many users will not need more than one set of optical transceivers (except for an always available control channel). These same users, though, will likely need to have many simultaneous connections. Therefore, some method of sharing is needed. In the architecture described in this paper, we will multiplex each receiver (and transmitter) over time and wavelength according to a schedule that will permit each user to have a number of simultaneous connections while not interfering with other connections to which it is not a party.

The slot duration should be large (of the order of 10 μs) relative to such effects as laser tuning time, AGC stabilization time, clock recovery stabilization, word and frame synchronization, and propagation delay shift. Similarly, the frame delay should be small relative to tolerable end-to-end delay. It appears that on the order of 100 slots per frame is reasonable within these constraints. The above lower limits on slot duration also limit any form of switching within the AON.

For the Type-B service, the issue of call blocking due to the lack of common time slots between the transmitter and the receiver is also being studied. Early results suggest that with a reasonable number of slots per frame ($\sim$100), blocking probabilities should not present too much difficulty until the light-path utilization is relatively high. However, if this is a problem, it is also possible to rearrange time slots to further improve the situation at a cost of added complexity. We are also studying the design and implications of all-optical packet switches.

To enable the AON to offer Type-B service, we will utilize several additional key technologies such as:

—fast tuning lasers and fast tuning receivers

—fast AGC, clock recovery, bit, and word synchronization.

3) Type-C: Unscheduled Datagram This is a service under which users may transmit a "packet of information" in a specific data and modulation format on a "well-known" wavelength. The media-access-control (MAC) protocol will be based on a distributed algorithm such as ALOHA and will NOT require a central resource or central timing since the C-service will be used to auto-configure the network. Network management and control messages also use Type-C service. Datagrams which are for "remote" users may be forwarded by adjunct electronic means.

In addition to the services described above, there are clearly other types of services which may be offered "on top of" the AON. These services are provided by electronic means at a level above the AON. As such, these services simply build upon the AON services described above. An example of such a service might be a high-speed packet switching or ATM cell switching service constructed with electronic nodes using either Type-A or Type-B channels.

D. AON Elements

The various architectural elements of the AON which were illustrated in Fig. 1 are described below.

1) Access Points and Optical Terminals: Optical Terminals (OT's) are user devices that attach to the AON through the Access Point (AP) interface. Optical terminals generally attach to Level-0 AON networks and are the "users" of AON services. OT's are normally the electrooptic devices which source and sink data from the AON. OT's must conform to the protocols specified by the AON architecture when communicating over the AP. Not all OT's support all the transmission service types described above. However, all OT's must support Type-C service for network management and control messages. A specific OT may support Type-A and/or Type-B services in addition.

An AP is essentially an interface to the AON and uses a pair of single-mode fibers—one for input, the other for output. Therefore, the AP is an optical interface. The specifications for this interface will include parameters for wavelength, laser linewidth, chirp, frequency stability, maximum power, maximum bandwidth, dynamic range, and several others.

2) Naming and Addressing: Associated with each OT in the network is one or more names and an associated network layer address (such as an Internet address). The choice of names for each OT is outside the scope of our work, but may be, for example, an Internet domain name. The mapping between this name and address is performed by a mechanism such as the Domain Name Service.

In addition, each OT has one AON address for each AP on that OT. Some OT's may use multiple AP's and will therefore have multiple AON addresses. The AON address associated with each AP is a hierarchical one with parts of the address having topological significance. In addition, one segment of this hierarchical address will be globally unique

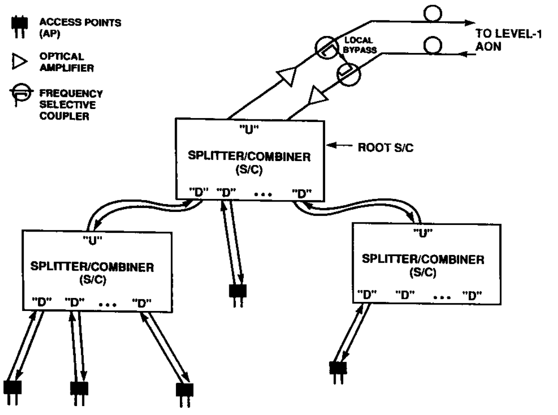


Fig. 2. AON Level-0.

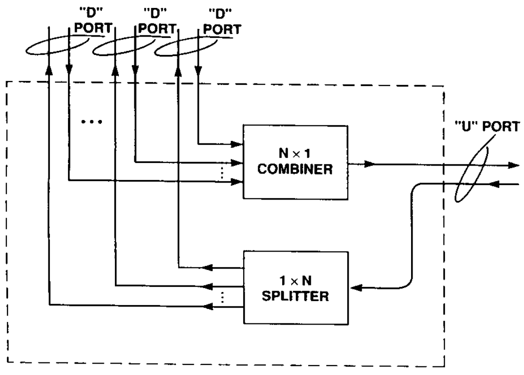


Fig. 3. Splitter-Combiner components.

(such as the IEEE 802 48 bit unique ID) for the purpose of tie-breaking in the distributed election protocols described later in the Network Operations Section.

The mapping between network layer address and AON address is performed by traditional mechanisms similar to the Address Resolution Protocol (ARP) or the OSI ES-IS protocol.

3) AON Level-0: Level-0 is the lowest level network in the AON architecture and is shown in Fig. 2. In general, OT's attach via an AP to the AON through a Level-0 network. It is a "local" broadcast network where each AP can hear everything transmitted by other OT's in the same Level-0 AON on the "L0" wavelength set (to be defined below). A Level-0 AON is itself constructed in a spanning-tree physical topology using building blocks which we call Splitter/Combiners (S/C). This arrangement should allow hundreds of stations in a single Level-0 AON. Also note the frequency-selective local bypass which is used at the "U" port of the root S/C. This device couples the local, or "L0" wavelengths back to the Level-0 AON and also prevents them from entering the Level-1 AON. The "U" port of the root S/C is used to connect to the next higher layer optical network, the Level-1 AON.

Illustrated in Fig. 3, we see an S/C which is built from a $1 \times N$ splitter and an $N \times 1$ combiner. Each S/C has two types of ports—a single "U" (Up) port which is used to connect in the direction of the root of the spanning tree and multiple "D" (Down) ports which provide Access Points for optical terminals (OT's) as well as other S/C devices further from the root. The wavelength-selective local bypass couples virtually all the energy within its band thus eliminating any multipath issues that might arise from loops in the Level-1 AON.

Placing the frequency-selective bypass in this location has three major advantages. First, it limits the physical length (and hence the delay) of the light-path when two OT's in the same Level-0 AON are communicating. Second, it improves the availability of the AON to the OT's because it will allow intra-Level-0 communication even when the Level-0 to Level-1 path has failed. Finally, it allows those frequencies blocked from entering the Level-1 AON to be re-used elsewhere in the network.

We have chosen the tree-of-stars topology due to its operational and installation advantages. However, the Level-0 AON could also be constructed using a bus architecture, which has some natural contention-resolution advantages. The devices used to construct the Level-0 AON will be described further in the Section IV.

At Level-0 the optical wavelengths used to provide the Type-A, B, and C services are divided into two groups:

"L0" Wavelengths—This wavelength set is used for local traffic (within the same Level-0 AON) and is blocked from leaving the local Level-0 network by the frequency-selective local bypass. These wavelengths may be re-used in the Level-2 AON, and in all the other Level-0 AON's. "L1" Wavelengths—This wavelength set is used for communicating among Level-0 AON's connected to the same Level-1 AON. Some of the wavelengths in this set may also be used for inter-Level-1 communication.

Level-0 networks have a "Scheduler Agent" to handle requests for allocating wavelength and time-slot resources among AP's. The Scheduler Agent may be implemented in a dedicated node attached to the Level-0 AON or may be an agent implemented in one of the optical terminals connected to the Level-0 AON.

It is expected that a Level-0 AON would be administered by a single entity such as a corporation or university. As such, some of the privacy difficulties associated with broadcast media are alleviated. Further, the Level-0 Scheduler Agent may be expected to enforce management security policies. However, privacy issues that arise from intra-Level-0 or inter-Level-0 communication are beyond the scope of our current efforts and we would expect that such issues would be resolved by techniques such as encryption performed by the OT's or by the source of the information.

4) AON Level-1: Level-1 networks are first-level wavelength-routing networks that route L1 wavelengths from one Level-0 network to another. Wavelengths may be routed in groups or individually. A Level-1 AON, as shown in Fig. 4, is either a static or dynamic wavelength router coupled with one or more broadcasting stars. Its purpose is to provide a wavelength path or light-tree to one or more directly connected Level-0 AON's or (in conjunction with a Level-2 AON) a light-path or light-tree to one or more Level-0 AON's

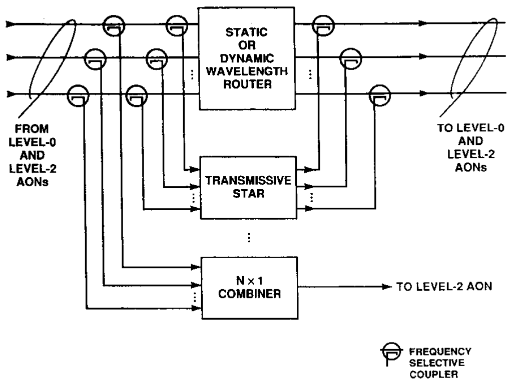


Fig. 4. AON Level-1.

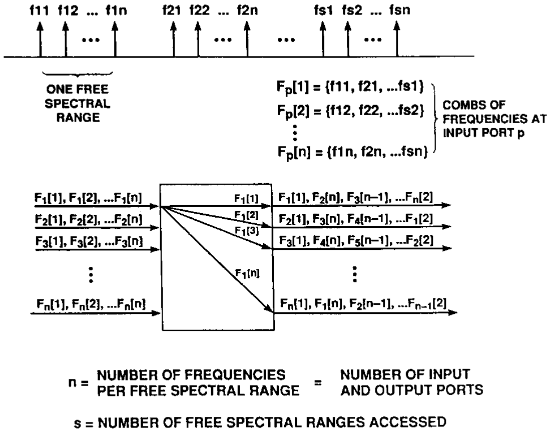


Fig. 5. $N \times N$ static wavelength router.

outside itself. The operation of the static wavelength router has interesting architectural implications that will be summarized here.

Given an $N \times N$ static wavelength router with routing properties as shown in Fig. 5, full connectivity will be provided from each input port to every output port. As viewed from an input port, the selection of an output port is made by the choice of wavelength used. Of course, since multiple wavelengths may be used on each fiber, multiple simultaneous wavelength paths exist from each input fiber. The wavelength routing properties of this device are periodic in two ways. First, the spacing between frequencies for each output selection are equal and second, multiple free spectral ranges exist in the device so that the optical routing property described above also repeats. Furthermore, this is accomplished without power splitting loss as would be encountered in a broadcasting star.

If the router has n input and n output ports, and if the number of available optical frequencies or wavelengths is $r = s \times n$, then use can be made of s free-spectral ranges (each having n frequencies) of the router. Thus, the number of simultaneous wavelength-paths, w, through the router is $w = n \times r = s \times n^2$. In the test-bed, we expect that $n = 8$ and $r = 24$ is realistic yielding $w = 192$. Soon thereafter, $n = 25$ and $r = 100$ should be achievable giving $w = 2500$. It should be possible to construct much more aggressive devices such as $n = 100, r = 500$ yielding $w = 50,000$. Additional details about the operation of this device can be found in Section IV.

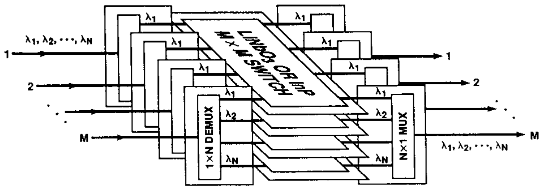


Fig. 6. Dynamic wavelength router.

The static wavelength router is quite simple and elegant and performs best when the traffic matrix is uniform. However, when the traffic matrix is non-uniform, then a dynamically reconfigurable device such as the one shown in Fig. 6 is highly desirable. This device is a generalization of the static wavelength router and allows more than one wavelength from each free spectral range to be routed to the same output through the $N \times N$ spatial switches. As can be seen in the figure, a dynamic wavelength router requires multiple $LiNbO_3$ spatial-switches. As the Scheduling Agents are fully programmable electronic devices, this architecture and the control and scheduling algorithms are capable of dealing with these dynamic devices when they are available. Note that dynamic wavelength routers, such as that shown in Fig. 6, can eliminate the need for optical frequency changers at the interface between Level-1 and Level-2 networks, or within Level-2 network. However, even with such programmable routers, frequency changers would still add considerable flexibility.

Also note the presence of the optical bypass star structures in Fig. 4. These are used for two purposes. First, they allow significant improvement in the utilization of network resources by allowing a single light-tree to be shared for Type-B service by more than one Level-0 AON. Second, they allow multiple light-tree branches at Level-1 for the purpose of providing multicast services.

A Scheduler Agent is also associated with each Level-1 network. Level-1 Agents work with their Level-0 Scheduler Agents to allocate wavelength paths to users who request connections from one Level-0 AON to another on the same Level-1 AON or from a Level-0 AON to the boundary of the Level-2 AON. The Level-1 Agent communicates directly with the Scheduler Agents of attached Level-0 networks (e.g., using Type-C service over the bypass stars of Fig. 4) and with peer Level-1 Agents (over Level-2 AON).

Level-1 networks generally require services from a Level-2 network to transmit information from a locally-attached Level-0 network to a Level-0 network connected to a different Level-1 network.

5) AON Level-2: Fig. 7 illustrates an AON Level-2. Level-2 networks are second-level wavelength-routing networks that provide light-paths (as opposed to wavelength-paths) between Level-1 AON's. Level-2 networks may be as simple as fiber trunks alone or they may employ frequency-changing devices

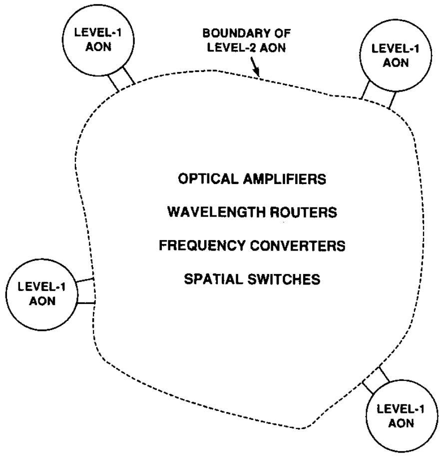


Fig. 7. AON Level-2.

in addition to static or dynamic wavelength routers, that are used to quasi-statically change the routing and resource usage within the Level-2 network.

Although these routing devices will be dynamically controllable devices (that is, the frequency difference from input to output may be changed under electronic control), at present, we envision that the reconfiguration of these devices would be on a timescale very long relative to Type-B service slot time. The reason for this is that although optoelectronic devices can support rapid switching, the computational complexity of doing such a network reconfiguration on a short time scale seems very difficult. However, we have not precluded dynamic reconfiguration of Level-2 in the future if more efficient algorithms and faster processing technology allows it.

The ability to arbitrarily change frequencies at the Level-2 boundary effectively decouples the Level-1 schedulers from the need to have global knowledge of all wavelength assignments when finding a light-path. This will make the scheduling computations easier and will also allow the network better scaling properties.

It is the Level-2 network that contains the long-haul fibers. These are very valuable resources and must be used efficiently for the network to be viable. To do this, there is also a Scheduler Agent associated with a Level-2 network. The Level-2 Agent works with Level-1 and other Level-2 Agents to allocate light-paths from the boundary of one Level-1 AON to the boundary of another. Note that in Fig. 7, there is not full direct connectivity between all Level-1 AON's. It is expected that full logical connectivity would be provided by the establishment of an indirect light-path when necessary by utilizing other Level-2 resources. Also, note that it is the case that some Level-1 AON's are directly connected with fiber/amplifier paths. However, these fiber paths are still managed by the Level-2 Scheduler and are hence viewed as part of the Level-2 AON.

6) Level-0 Scheduling: Within each Level-0 AON, there exists one or more special OT's capable of acting as a Scheduling Agent. If there is more than one OT capable of acting as a scheduler, then they will execute a distributed algorithm to elect one to be the active scheduler. (In the case of a scheduler failure, the distributed election algorithm will be triggered again.)

Once elected, the Scheduling Agent is responsible for a number of primary functions:

— acting as an agent for authenticating, authorizing, and servicing requests for Type-A, -B, and -C connections from AP's in its Level-0 AON,

— distributing and collecting of timing information necessary to establish Type-B connections,

— maintaining an accurate schedule for all the wavelengths for which it is responsible (This includes updating the schedule when connections are made or terminated and recovering resources when an AP fails),

— communicating with its Level-1 scheduler,

— controlling of any tunable wavelength-selective couplers,

— enforcing management policies such as applying authentication and authorization controls to connection requests,

— collecting accounting information,

— performing possible ancillary functions such as a name-to-address mapping service.

A schedule is maintained for each wavelength. The schedule is essentially a data structure used to maintain all the state information required for controlling and allocating that wavelength. The contents of this data structure are dependent on the type of service to which the wavelength is allocated. For example, for a Type-A service, the source and destination addresses, and time allocated, would be maintained. For a wavelength allocated to Type-B service, the schedule is a list of connections on that wavelength together with the source/destination of each, as well as the list of time slots allocated to that connection.

Communication between AP's and their associated Scheduling Agent takes place on a well-known wavelength using a Type-C service and a well-known address for the Scheduling Agent. Upon power up, each AP must register with the Scheduling Agent. This does not require preknowledge of the state of the system and will permit complete, automatic self-configuration.

7) Level-1 Scheduling: The selection and primary responsibilities of a Level-1 Scheduling Agent parallel that of the Level-0 Scheduler. In addition, however, the Level-1 Scheduler must do the following:

— authenticate, authorize and satisfy requests for inter-Level-0 and inter-Level-1 connections—Inter Level-0 requests may be satisfied without resort to the aid of the Level-2 scheduler

— provide a matchmaker function to establish a wavelength-path from one of its constituent Level-0 AON's to another,

— establish multicast connections using the frequency-selective coupler/star

— communicate with its Level-2 scheduler to allocate light-paths as necessary

— provide timing information to its Level-0 AON's for the purpose of arranging Type-B connections.

8) Level-2 Scheduling: Again, the selection and primary responsibilities of this scheduler parallel that of the Level-0 and Level-1 Schedulers. In addition, the Level-2 Scheduler must:

— authenticate, authorize, and satisfy requests for inter Level-1 connections—this is done by finding free wavelength paths (within the Level-2 AON) between the two appropriate Level-1 AON's and then using wavelength changing devices and wavelength routers to provide an end-end light-path over these wavelength-paths.

E. Network Operation

Optical terminals will use a well-known wavelength to communicate connection requests to the Scheduler. Connection requests include the type of requested service, the address of the requested OT, the requested throughput, and priority. Upon receiving a connection request, the Scheduler determines if the destination is also in its Level-0 AON. If so, it determines the availability of the necessary resources (wavelength-path and sufficient common timeslots) and, if adequate resources are available, reliably informs the destinations of the new connection request. If the destination subsequently accepts the connection, then the requesting OT is reliably informed and communication may begin.

However, if the destination is on a different Level-0 AON, but in the same Level-1 AON, then the Level-0 scheduler communicates with its Level-1 scheduler to select a wavelength which provides the wavelength-path between its own Level-0 and the other Level-0. Note that for a Type-B connection request, a light-path might already exist and only the time slot(s) need to be established. If there are insufficient time slots for the required bandwidth, another wavelength-path may be established.

If the destination is not in the same Level-1 AON, then the Level-0 scheduler communicates with its Level-1 scheduler to find a light-path (recall that this may require wavelength changing) using a locally available wavelength. Once a light-path is established, the connection process completes as described above.

For Type-B service requests, in addition to a light-path, available time slots in the source and destination must be identified and allocated. This is an important research issue and work on how to best do this is presently a very active area of our research.

We have identified a promising timing distribution and slot-matching scheme that does not require a universal time source. In this scheme, OT's measure the round-trip time from their AP to their Level-1 AON by transmitting a message on a multicast channel. Then, the Level-1 Scheduler periodically multicasts a timing pulse to each of its Level-0 AON's allowing the OT's to accurately predict when the next timing pulse will arrive at their AP. By subtracting its round-trip delay from the predicted time of the next timing pulse arriving at their AP the OT obtains a local frame-start time reference. The result of this process is that if all OT's in the same Level-1 AON transmit a signal at their local time reference, then all their signals will arrive at the Level-1 simultaneously. Therefore, by adjusting their transmit times relative to their local time reference, the OT's can efficiently share a light-path for Type-B service.

If this alternative proves robust, it is much more desirable than an alternative approach we have identified that uses Global Positioning System (GPS) receivers to provide precise ($\sim$100 ns) time synchronization of each scheduler. Such precise global time synchronization will permit the direct measurement of the propagation delay from any OT to any other at connection setup time. Once known, these propagation delays may be compensated for by adjusting the transmit times appropriately.

F. Architectural Principles

Much additional research is needed to completely specify the AON architecture. However, the architecture has been carried far enough to design the test-bed and the architectural structure is highly scalable. The experience gained from the test-bed, in conjunction with technological advances and continuing architectural research, will be used to guide further architectural research toward a large scale all-optical infrastructure for the future. Our research is guided by the following principles.

1. The architecture developed will be capable of reasonable application over more than one generation of technology. For example, it will anticipate improvements in the tuning range and tuning time of tunable lasers. Further, the eventual availability of fieldable components that currently exist only in the lab will be assumed in some cases. Examples are static or dynamic wavelength routers and dynamic wavelength changers.
2. Notwithstanding point one, the architecture developed will not be critically dependent on individual technology assumptions. For example, if cost-effective wavelength-changing devices appear to be seriously delayed, we will devise alternate architectural components, e.g., based on static multiplexers and dynamic spatial switches (see Fig. 6).
3. End stations using traditional technology must be able to use this network without requiring all new interface hardware and network software. For example, both stations using TCP/IP on today's LAN's and stations using ATM networks will be able to communicate over this network.
4. The network should continue to operate when partitioned. This implies the use of either fully distributed or hierarchically organized control algorithms.
5. Algorithms will be self-stabilizing. That is, given a reasonable frequency of failures, the network will return to stable and correct operation from an arbitrary initial state within a reasonable time.
6. The architecture will permit the network to scale to a level beyond what is reasonable today. The dimensions of scaling will be the number of end-nodes, geographic span and data rate.
7. The architecture will provide mechanisms to limit the scope of network problems caused by faulty or badly behaved end nodes.

IV. TECHNOLOGY

The system architecture discussed in the previous section is based on optical WDM (FDM), star distribution, frequency routing and switching. The components needed to implement our baseline architecture in a test-bed can be grouped into three categories: a) mature technology that is either commercially available or in an advanced stage of development, b) novel research devices that are in an advanced stage of research where feasibility has been demonstrated but device performance and producibility have not been perfected, c) new devices that must be invented to deal with frequency reuse, wide area coverage and contention control. Finally, limitations set by the laws of physics must be explored. These categories of technologies will be described below.

A. Mature Technology

1) Optoelectronics: Complete laser transmitters, APD receiver packages, $LiNbO_3$ external modulators and 16 × 16 spatial switches operating at about 2.5 Gb/s are available as prototypes. Erbium-doped fiber amplifier packages are also commercially available.

2) Gb/s Electronic Components: DEC is developing a chip set for Gb/s optical links that is applicable to the Optical Terminals of the AON. The chips include CMOS encoding/decoding (CODEC) chips and both GaAs and Si chip versions of clock synthesis/recovery modules. The coding chips are based on a DEC-developed code distinguished by providing Forward Error Correction (FEC) [1]. It corrects any single-bit error within a 96-bit coded block. The basic code is a DC-balanced 8b/10b code that allows AC-coupled receivers and has a maximum run length of 4 bits to facilitate clock recovery. On top of this code, additional bits are added for the FEC function. When errors are independent (as expected in fiber-optic links), the FEC coding achieves very low effective error rates. For example, a raw bit-error rate of 10^{-9} results in an effective error rate after FEC of less than 10^{-15}. These very low error rates provide a significant performance advantage, particularly in long-distance, high-speed networks. The CODEC chips have been used in the development of prototype gigabits-per-second links for over a year.

In addition to error-correction, the CODEC chips provide logic and a microprocessor interface that facilitate diagnostics, link initialization, and monitoring of the link performance during operation. Errors are counted by the decoding chip and the bit-error rate can be reported to the microprocessor. The chips have been designed and tested successfully for a data rate of 1.0 Gb/s, which after adding the encoding and FEC overhead, translates into a signaling rate of 1.5 Gb/s.

DEC is cooperating with external vendors to develop clock synthesizer and clock recovery chips for the 1.5 GHz serial channel rate. The transmitter chip synthesizes a 1.5 GHz clock from a 25 MHz reference and muxes the transmitted data into 1.5 GB serial data. The receiver chip recovers the 1.5 GHz clock, retimes the data, and demuxes it for a 16-bit-wide interface to the decoding chip. GaAs versions of these chips have been developed and are being tested and evaluated. Si versions from a second vendor will also be tested and evaluated. The choice between these chips for the test-bed will be based on DEC's testing and evaluation. The clock recovery chips were not designed for fast acquisition times and require about 100 ms to acquire bit synchronization. Once bit-sync is acquired, the decoding chip requires an additional 100 ms (worst-case) to synchronize on the FEC block boundaries. For Type-B and Type-C services, fast-acquisition clock recovery devices and fast synchronizing codes will be developed.

DEC has also designed a 64-bit CRC generator/checker chip for operation at serial data rates up to 1 Gb/s using a DEC-patented CRC polynomial. It detects all single-burst errors up to 64 bits and all double-burst errors up to 24 bits within a data field of up to 64 kbytes. Its data path is 32 bits. The chip is commercially available.

DEC has developed experimental techniques for measuring and evaluating communications links, such as measurement of peak-peak jitter events at 10^{-9} probability that are invisible on oscilloscope eye-pattern measurements. Prototypes have been designed and built that address the practical problems associated with signal integrity of GHz signals on printed circuit boards. An extensive modeling and simulation environment has been developed for the simulation of laser-based communications links, including the clock synthesizer and clock recovery functions [2]. The simulation tools have proved useful in analyzing and understanding the interaction of individual components when functioning as a complete communications link.

3) Electronic Packet Switch: An electronic packet switch can be an OT connected to the AON. These switches perform bridging and routing between the AON and existing network standards such as FDDI and ATM. For example, the DEC GIGAswitch is a switch fabric that connects ANSI-FDDI end-nodes and hence supports a wide variety of end-node types and applications.

The GIGAswitch can be used to concentrate multiple 100 Mb/s streams onto the AON. The switch is modular in that line cards can be added to the switch for additional ports. A special line card, which can handle over 900 Mb/s full-duplex of aggregate traffic, will be designed to interface between the GIGAswitch and the AON. A configuration with an AON connecting multiple GIGAswitches can provide high-speed communication for many hundreds of FDDI users over a wide geographical extent and will allow experimentation with a wide variety of applications developed for FDDI workstations, such as multimedia applications and video conferencing.

B. Novel Research Devices

1) Tunable/Switchable Lasers: Many suppliers have developed single-frequency DFB and DBR lasers that can be selected to provide the required comb of optical carrier frequencies for FDM circuit connections. They have also reported research on multi-electrode DFB and DBR lasers that will allow continuous and/or discrete (mode-hop) tuning of transmitter lasers covering a limited range (~10 nm or ~1 THz). However, the tuning speed has been slow [1 ms] due to thermal and feedback circuit time constants, as illustrated by an experiment to lock a carrier comb to a set of modes of a fiber Fabry-Perot resonator [3].

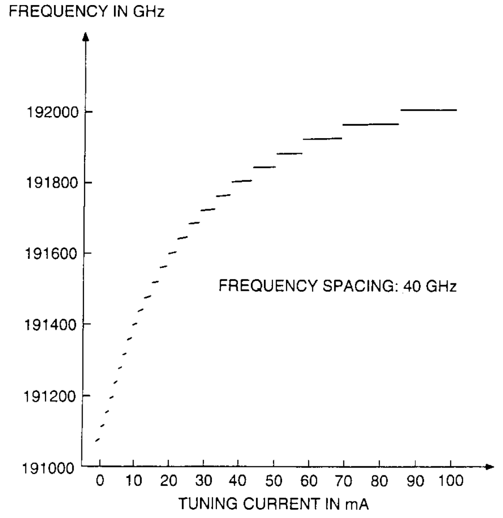


Fig. 8. Optical frequency versus tuning current in DBR section.

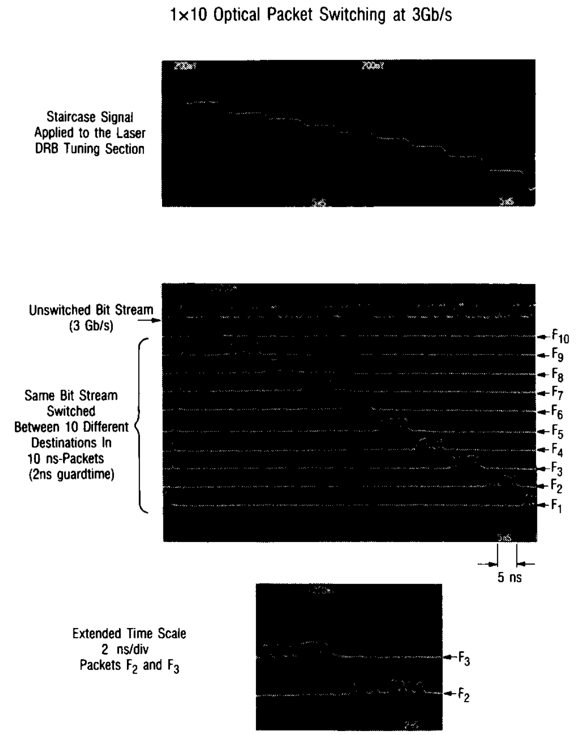


Fig. 9. Frequency switching of packets by DBR laser.

A novel approach to fast frequency switching (< 10 ns) for optical packet distribution that provides access to equi-spaced frequencies reproducible from laser to laser over the full range (960 GHz) of a 2-electrode DBR has been reported by AT&T [4]. The laser consists of a long lasing section acting as a Fabry–Perot (FP) whose longitudinal dimension is selected to provide closely spaced resonances (40 GHz). The lasing section is followed by a distributed-Bragg-reflector (DBR) section acting as frequency-selective mirror for choosing the desired resonance from the FP comb. The DBR reflection bandwidth is designed to select one and only one FP frequency and is tuned by injecting current in the DBR section. As shown in Fig. 8, the laser is tunable by a single variable current to 24 discrete frequencies equally spaced by the free-spectral-range (FSR) of the FP lasing section. All of the frequencies can be accessed by tuning the current through 100 ma. Frequency selection is robust against small relative tuning current variations since the channel spacing Δf (40 GHz) is much larger than the modulation bandwidth (< 5 GHz), and the receiver bandwidth ($\sim\Delta f/2$) is designed to be much greater than the error in a frequency step. Fast switching among the 24 frequencies is realized because locking to the FP resonances is obtained within the laser rather than with an external feedback circuit. The switching time is limited only by the lifetime of the carriers injected into the DBR section, which is a few nanoseconds.

The switching time between two frequencies varies from 2 ns for adjacent frequencies to 8 ns for frequencies separated by 960 GHz. The switching time capability of the laser was also investigated using the 10-staircase waveform switching signal [4] shown in Fig. 9(a). In this case, the output of the laser was ASK modulated at 3 Gb/s by an external optical modulator and switched between 10 different frequencies in 10 ns-packets (including a guard time of 2 ns between packets). In Fig. 9(b), the upper trace displays the continuous 3 Gb/s bit stream, as detected with the laser tuned to one of its frequencies. The other traces show the slicing of the same continuous bit stream into packets detected as the laser is switched to 10 of its frequencies according to the staircase waveform of Fig. 9(a). Fig. 9(c) shows packet switching between two of the destinations on an expanded time scale. The packet lengths were chosen for visualization within the time window of the oscilloscope; similar results are obtained for longer packet durations.

Further research on the switched DBR laser includes reducing Δf (as narrow as 10 GHz), increasing the number of accessible frequencies (as many as 500), and incorporating an absorption modulator and switched branching output in a photonic integrated circuit. Other research approaches to providing wider tuning ranges at AT&T include a *Y*-branch laser and an erbium-doped fiber ring laser.

2) Integrated Star Coupler and Optical Frequency Router: An $N \times N$ star coupler can be fabricated by hand-splicing 3-dB single-mode fiber couplers (2×2 stars). Although the excess loss (the loss in addition to the intrinsic $1/N$ splitting) is small (< 1 or 2 dB), the number of 2×2 couplers required is $C = (N/2)\log_2 N$ which can be very high for large N. Stars with $N = 16$ are commercially available. A star with $N = 128$ has been reported by NTT and fits into a man-high rack.

An integrated 19×19 star with excess loss of ~3 dB has been reported by AT&T [5]. The waveguide technology is denoted "silicon optical bench" and consists of silica waveguides on a silicon substrate. The device consists of an array of phosphorous-doped SiO_2 waveguides on a 1×3 cm

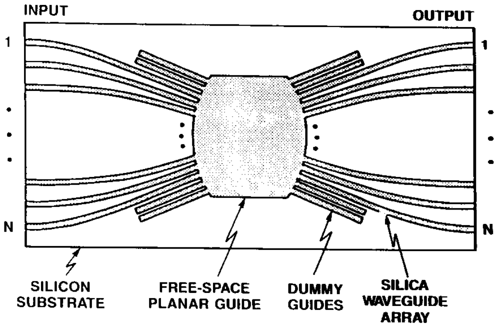


Fig. 10. Integrated star coupler.

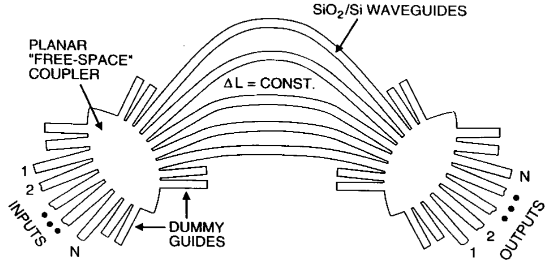


Fig. 11. Integrated frequency router.

substrate. Single-mode fibers are attached to the inputs and outputs for connection to a network. With improved design and processing, it is expected that N can be increased to 50 or 100 and the excess loss reduced significantly. The same technology can be used to construct $1 \times N$ splitters and $N \times 1$ combiners.

The waveguide pattern that realizes the star behavior is illustrated in Fig. 10. The 5-μm waveguides are spaced by 250 μm at the input and output; the gaps between the guides adiabatically approaches zero in the vicinity of the two-dimensional free-space region; additional dummy waveguides are provided in the region where the mutual coupling is strong. It can be shown analytically [6] that in the limit of adiabatic (long) transitions and an infinite periodic array (dummy guides), $1/N$ splitting with negligible excess loss is possible.

An extension of this technology has produced an integrated $N \times N$ mux/demux or frequency router with unique properties [7], [8], that are achievable only with special gratings [9], or with considerably more complex combination of bulk components. The Si optical bench waveguide pattern is shown in Fig. 11. An $N \times N$ star is provided at the input; the N outputs of the star feed a dispersive array of N waveguides whose adjacent path lengths differ by q wavelengths; the array feeds an output $N \times N$ star.

The dispersive array of waveguides rotates the optical phase front incident on the output star as the optical frequency changes, causing light of different frequencies, injected on a given waveguide of the input star, to be separated among the output waveguides of the output star. If f is the optical carrier frequency, the resolution of this demultiplexer is $\Delta f = f/Nq$, the free spectral range (FSR, the frequency increment over which new frequencies periodically "wrap around" to appear at the same output) is FSR = f/q, and the number of resolvable channels is $F = \text{FSR}/\Delta f = N$. If low crosstalk is required, the number of channels will be $< N$. The frequency routing pattern is illustrated in Fig. 12. In effect, it behaves like a column of N diffraction grating demultiplexers followed by a column of N multiplexers.

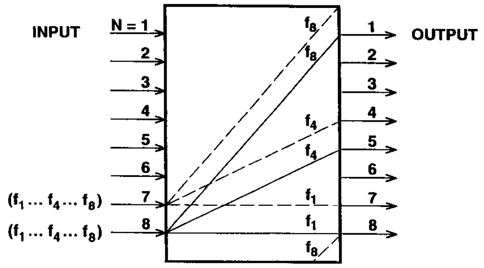


Fig. 12. Routing pattern for an 8×8 router indicating "wrap-around" of f_8 incident on port 7.

Experimental $N \times N$ routers with $N = 7$ and $N = 11$ have been reported [7]. For $N = 7$, the insertion loss is 2.5 dB and crosstalk < -25 dB. At $\lambda = 1.3\mu$m, the FSR = 4100 GHz (23 nm) and $\Delta f = \text{FSR}/N = 585$ GHz (3.3 nm). To achieve this performance the number M of intermediate waveguides was $M = 15 \approx 2$N. It is estimated that resolutions of $\sim$0.1 nm or $\Delta f = 18$ GHz at 1.3 μm and 12.5 GHz at 1.55 μm is feasible. Values of $N = 50$ or 100 may be possible but $N \leq 20$ is comfortable at present.

3) Fiber Fabry-Perot and Fiber-End Filters: Tunable fiber Fabry–Perot filters [10], developed at AT&T, have been made by coating mirrors on the ends of standard single-mode fibers. Various designs allow any free spectral range FSR = $c/2nL$, where $c = 3 \times 10^8$ m/s, $n = 1.5$, and L is the length of the resonator. The typical configuration is shown in Fig. 13. The mirror spacing can be varied through $\lambda/2$ by a piezoelectronic transducer requiring about 10V, thereby tuning the passband through one FSR. The tuning time is $\sim$1 ms, suitable for Type-A circuit switching. The passband width is Δf = FSR/F, where F is the finesse. Research devices have $F = 1000$ with insertion loss $t = 4$ dB and $F = 1900, t = 7$ dB [11]. In practice, the number of channels available with low crosstalk is $< F/6$. Tunable fiber FP's of this design are now commercially available with $F \approx 100$.

Current research at AT&T has also demonstrated fiber-end filters with various bandpass characteristics proposed by multilayer stacks applied directly to the fiber ends [12]. Fiber FP's with fixed length have also been used as optical frequency standards.

C. Development of New Devices

Although our initial test-bed will use existing technology and currently available devices; improvements in the performance of the test-bed will require both improved and new devices. The new devices will provide novel functions,

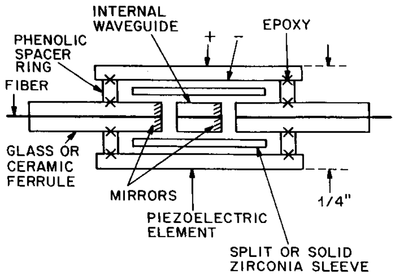


Fig. 13. Tunable fiber Fabry–Perot.

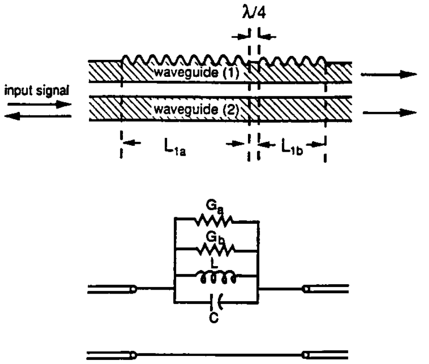


Fig. 14. Schematic and electrical equivalent circuit of side-coupled quarter-wave-shifted DFB resonator.

such as frequency-division switching, as well as improved performance of old functions. Furthermore, analysis and experiment will be required to test the physical realizability of the extreme specifications of FDM bandwidth, transmission distance and pulse width. Fiber nonlinearity and dispersion are prime limiting factors.

1) Improved Channel-Dropping Filters: The initial test-bed will employ existing fiber Fabry–Perot filters. Improved performance can be obtained with an MIT-proposed [13] design of a channel-dropping filter of greater flexibility based on the quarter wave shifted distributed feedback resonant (QWS-DFBR) structure [14]. In its simplest realization, the channel dropping filter is a QWS-DFBR side-coupled to a waveguide (Fig. 14). The total permissible fractional transmission bandwidth Δf/FSR of such side-coupled resonators for a wavelength $\lambda = c/f$ is given by $\Delta f/\mathrm{FSR} = \kappa\lambda/2\pi$ where κ is the DFB coupling coefficient. A value of $\kappa \sim 300\,\mathrm{cm}^{-1}$ has been reported in the literature [15]. This corresponds to a total FSR of 1.5 THz at 1.5 μm. With a channel spacing of 12 GHz corresponding to bit-rates of 2 Gb/s, this permits a total of 125 channels using existing grating technology. The product κL where L is the length of the structure, determines the bandwidth Δf of the individual channel. However, the resulting FSR and Δf are not subject to the same constraints as those of the conventional Fabry–Perot.

The simple structure of Fig. 14 can be refined to achieve several very desirable characteristics:

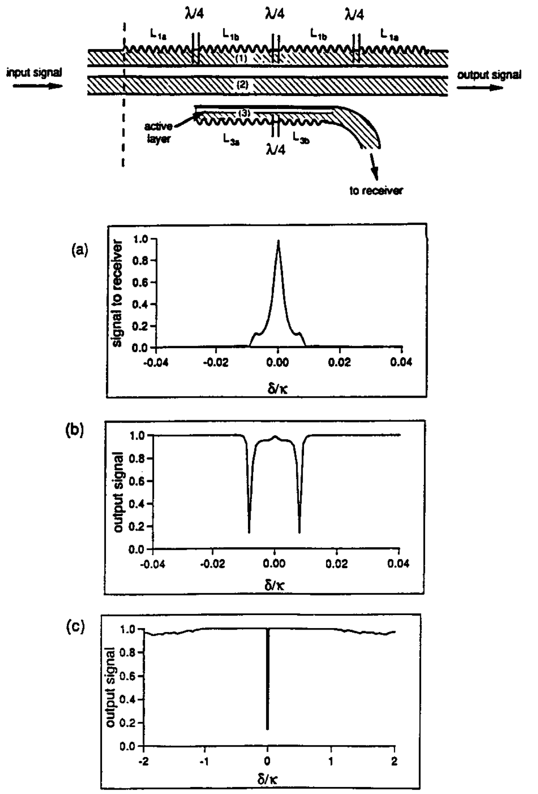


Fig. 15. Schematic of receiver and re-injector with responses.

1. The back-reflected wave in the transmission bus is eliminated within the channel bandwidth by an added QWS-DFBR to realize a lossless channel-dropping bus.
2. By introducing an active layer, signal can be injected along the transmission bus for channel adding in a bus architecture. Fig. 15 shows the schematic of such a structure and the computed transmission and reflection characteristics.

2) Frequency-Division Switch/Translator: A critical component for frequency reuse in the connection from Level-1 to Level-2 converts FDM data bits on N independent channels with carrier frequencies f_K carried on a single input fiber to the same data bits on a permuted set of N carrier frequencies f_L output on a single fiber. It is the frequency domain analog of a space division switch and is denoted here as a frequency-division-switch (FDS).

Optical frequency translators (FT) that convert input bits at f_1 to output bits at f_2 have been proposed and reported in the literature. One method uses 4-wave mixing as noted below. Another uses a multi-contact DFB or DBR laser with an additional unpumped section that prevents laser oscillation. The amplitude-shift-keyed (ASK) bits at f_1 are used to bleach the unpumped section and allow oscillation at f_2 determined by currents in the tuning sections. (A reset current in the gain region may be required to stop oscillations at the end of the bit.)

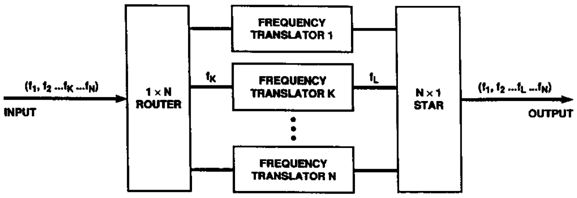
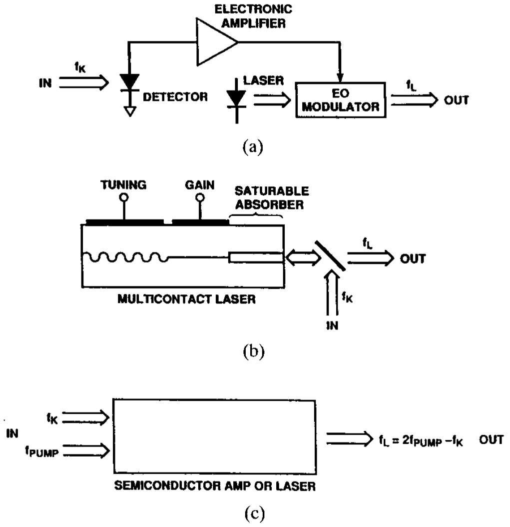


Fig. 16. An optical frequency division switch.



(a)

(b)

(c)

Fig. 17. Optical frequency translator (FT): (a) Straightforward approach. (b) Saturable absorber/multisection laser. (c) Four-wave mixing.

A brute-force approach to the FDS is to employ a $1 \times N$ router to demultiplex the bits at frequencies f_K and send them to N frequency translators, whose output frequencies are set by currents from an electrical control module. The N frequency translator outputs are combined in an $N \times 1$ star coupler to provide the f_K outputs on a single fiber (with $1/N$ combiner loss which may require amplification) as shown in Fig. 16. If necessary, we will attempt to build such an FDS but we will first search for a more elegant solution. Three methods for achieving frequency translation are illustrated in Fig. 17. The first, in Fig. 17(a), can be built with existing parts: a photodiode driving an external light modulator that impresses the input bits on a tunable laser set to f_j. The saturable absorber approach is shown in Fig. 17(b) and the four-wave mixing scheme in Fig. 17(c). The approaches in Fig. 17(a) and (b) work for arbitrary bit-rate ASK (or analog) modulation, while that in Fig. 17(c) preserves ASK, PSK, and FSK modulation.

3) Development of a Multi-THz Bandwidth Frequency Translator: Terahertz frequency shifters that use phase-matched nondegenerate four-wave mixing in semiconductor multiple-quantum-well (MQW) waveguides are uniquely suitable for wide-band optical communication networks. In these structures, the MQW provides the nonlinearity and the waveguide provides optical confinement and a long interaction length. The relevant nonlinear mechanism, one-photon virtual excitonic resonance [16], is ultrafast and broad band and is, therefore, capable of multi-THz frequency shifts, high data rates, and most significantly, arbitrary data formats. Furthermore, optical gain can be introduced for signal amplification, and improved broad-band phase matching can be achieved using multisection structures or two pump wavelengths. A schematic of the device and preliminary results at 0.85 μm are shown in Fig. 18.

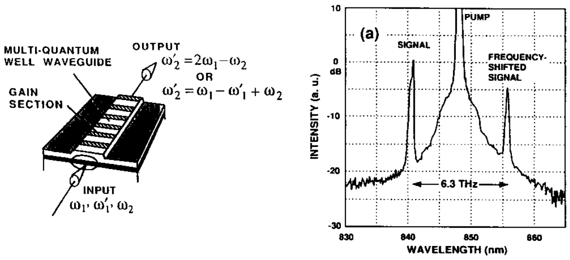


Fig. 18. Third order nonlinear frequency conversion in semiconductor.

4) Self-Routing Optical Packet Switching and Field Coding: The concept of all-optical packet switching is difficult to realize because of the need to read the address header and the necessity of optical storage. An approach investigated at AT&T [17], [18] and elsewhere employs a low bit-rate header which is read on the fly by a photodiode or a contact on a semiconductor amplifier. These electrical bits are fed to a controller that operates an optical switch that sends the unconverted optical data bits, which were delayed in a fiber, along the proper path.

D. Study of Physical Limitations

Because of their small core diameter and long interaction length over long-haul links, low-loss single-mode optical fibers suffer unique nonlinear channel characteristics that limit performance. These nonlinear effects become particularly evident in situations involving many simultaneous wavelengths propagating over long distances, and manifest themselves in a variety of ways including crosstalk, spectral redistribution of power, and effective linewidth broadening. The degree to which they are a problem depends on the power level, number and spacing of channels, data rate, and modulation format. As a result, system engineering of a wide-band optical network employing either FDM or TDM must take into account nonlinear propagation effects in fiber and optical amplifiers. The principal effects are stimulated Brillouin and Raman scattering (SBS and SRS), four-photon mixing (FPM), and carrier-induced phase modulation (CIP).

Our initial efforts focus on developing a unified understanding of how the various nonlinear effects collectively influence the communication channel, and determining the impact of attempts to circumvent or mitigate these effects. As more understanding is gained, experiments will be carried out on the test-bed to verify theoretical predictions and validate models.

V. TEST-BED

A key theme of our effort is the construction of an extensive test-bed system. We intend to make the test-bed the central focus of our research and development program. It will form a proof-of-concept demonstration of a universal, scalable, optical network and will provide a common forum in which the interactions of applications, architectures, and technologies may be investigated. This extensive single test-bed will be geographically distributed and will be connected via dark fiber whenever possible. The DEC site at Littleton, MA. is already connected to a DEC site at Bedford, MA. and will be extended to the nearby Lincoln Laboratory site. AT&T is currently exploring a dark fiber connection (with optical amplifiers) between New Jersey and Massachusetts. This unique test-bed will be a powerful tool by which many technical issues in architecture and technology can be clarified and/or resolved experimentally.

A. Test-Bed Goals

The development of the test-bed system has four primary goals. The first is to provide a near 'real-world' environment in which network hardware, terminal equipment, protocols, and services can be rapidly developed, tested, and demonstrated. This will be accomplished by employing standard data handling and interfacing techniques. Communication channels that are established in the test-bed will be characterized by both conventional error rate, dropped packet counts, and error-free second techniques as well as by demonstrated success in implementing applications and services. Well defined data interface ports supporting HIPPI, FDDI, SONET (and, potentially, ATM), and Ethernet standards will be used to provide most of the lower rate sources and destinations for the data that is to be transported within the test-bed system.

The second goal of the test-bed development is to demonstrate useful services. The test-bed system will initially be a private wide-bandwidth research network providing services to the consortium community on an experimental basis. We will require that the test-bed provide realistic high-speed computer interconnects, text and image file transfers, and video-conferencing capabilities to the consortium. This will fully exercise all of the layers in the test-bed architecture and help uncover and avoid potential technological conflicts.

The test-bed's third goal is to act as a catalyst in the development and demonstration of new network services and applications. The test-bed will permit the many components involved in network architecture to interact in a neutral, non-threatening environment that is largely free from tariff issues, competitive pressures, and regulatory constraints. It will nurture and incubate technologies that may initially be economically unattractive but which may have great leverage in facilitating novel network services and applications.

The fourth goal of the test-bed system is to serve as a central point of technology dissemination. Consortium members will transition test-bed technology into the commercial world through a variety of means including subsequent commercial product development, 'proof-of-concept' demonstrations, open seminars, journal publications and licensing of technologies to interested parties for commercialization.

B. Baseline Test-Bed Architecture

The test-bed will be designed to demonstrate the five characteristics critical to universal, scalable, optical networks. These characteristics, which guided the development of our baseline architecture, are: 1) scalability in the dimensions of number of users, connectivity between users, data rate per user, and geographic span, 2) the feasibility of accessing the majority of the bandwidth available in an optical fiber, 3) all-optical connectivity, switching, and routing over long distances for high-rate users, 4) hierarchical sub-net partitioning to allow frequency re-use, power conservation, and network management, and 5) an inherent ability to support multi-session and multi-media applications.

The baseline test-bed will reflect the architectural principles discussed in Section III. It will utilize tunable semiconductor laser transmitters along with tunable optical receivers to construct a dense FDM system in the 1.5- μm low-loss window that is present in conventional single-mode optical fibers. Additional frequency channels outside of the low-loss window will be utilized in short span systems such as LAN's where long-distance low-loss propagation is not an issue. The low-dispersion window centered at 1.3 μm will also be utilized in some test-bed experiments as control channels for the dense WDM system centered at 1.5 μm.

For test-bed purposes, we will construct a 20-channel FDM system with a nominal channel spacing of 50 GHz. The nominal data rate per FDM channel will be an SONET compatible 1.244 Gb/s but the channel rate can be set anywhere between a minimum of 100 Mb/s and a maximum of 10 Gb/s. Users requiring data rates below 100 Mb/s will be electronically multiplexed before entering the optical core. Users requiring rates of 10 Gb/s or above will be given access to multiple channels and additional guard-band channels to minimize interference.

The test-bed optical network will be partitioned into optical sub-nets as shown in Fig. 19. Sub-net partitioning allows the test-bed to demonstrate scalability in terms of the number of users and geographic extent and will allow frequency reuse. AON Levels-0, 1, and 2 will be incorporated into the test-bed system.

1) Level-0 AON's: There will be six Level-0 AON's included in the lowest layer of the test-bed system. Two Level-0's will be located at AT&T, another at DEC, two at MIT Lincoln Lab and a sixth at MIT Campus. An example of a test-bed Level-0 AON is shown in Fig. 20. Level-0 AON's will be based on simple FDM broadcasting technology. Both single star, separate receive-transmit stars, and optically amplified bus configurations of AON Level-0 will be demonstrated.

The interface between any two AON's may either constrain inter-AON traffic to specific wavelength regions that are common to both networks or it may frequency shift signals passing between networks to the correct channels. Interfaces between Level-0 and Level-1 utilize frequency selective bypasses, which act as simple bandpass and bandblock filters. This limits the FDM channels exiting and entering Level-0 and allows frequency re-use.

2) Level-1 AON's: As shown in Fig. 21, the six Level-0 AON's in the lowest layer of the test-bed will interconnect

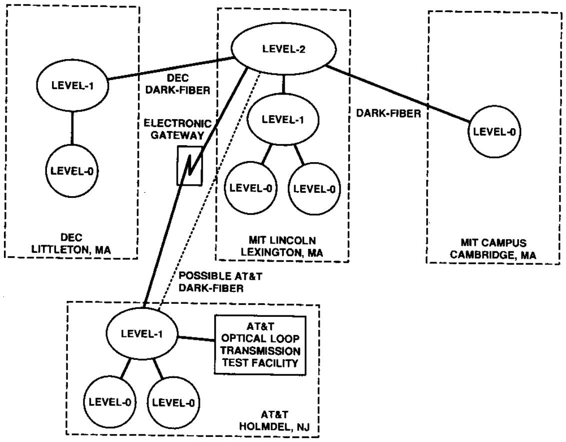


Fig. 19. Test-bed subnet partitions.

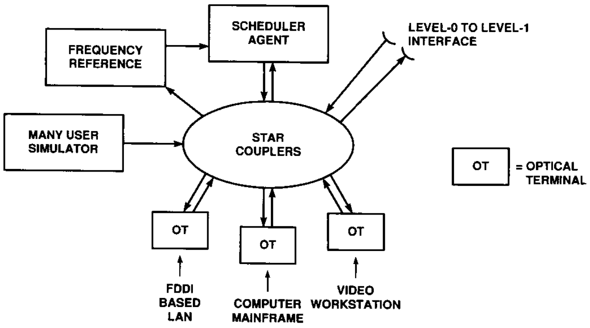


Fig. 20. Example test-bed Level-0 AON.

via three Level-1 AON's that will be located at AT&T, DEC, and MIT. The Level-1's are further interconnected by a Level-2 AON. Within Level-1, carriers are routed according to wavelength region with a region containing several FDM channels. The wavelength or frequency router in Fig. 21, operates by mapping incoming wavelengths onto N possible output routes, which correspond to the wavelength addresses for other AON's. The routers are based on the AT&T wavelength multiplexer/router described in the Section IV. The AT&T router exhibits a periodic frequency response so there are actually several wavelength bands that will correctly address a given output route.

3) Level-2 AON's: Level-2 AON's will utilize combinations of the AT&T wavelength router and optical frequency converters (or frequency-division switches). The latter is used to convert the output carrier frequencies from Level-1 AON's into the correct carrier frequencies for use in other Level-1 AON's. This allows the potential for a large number of Level-1 AON's to interconnect. Simple band-passes and band-blocks will also be used to provide any required non-switched dedicated connections between Level-1 and Level-2 AON's.

The dark fibers described at the beginning of this section are part of the Level-2 network that will connect the Level-1 networks at the various sites. If the New Jersey–Massachusetts fiber is not available in time, that connection will be made electronically, by means of a conventional leased lines.

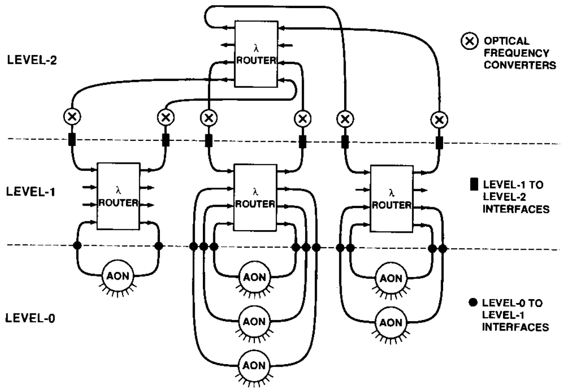


Fig. 21. Test-bed AON interconnections.

C. Test-Bed Technology

1) Laser Sources: There is presently no single tunable semiconductor laser capable of accessing the entire bandwidth available in a fiber. The test-bed will initially simulate the performance of this ultimate device by combining currently available commercial grade lasers with the AT&T research grade devices.

Currently available AT&T research lasers have tuning times in the 2–10 ns range within their wavelength coverage of about 10 nm (1 THz). This is sufficiently fast and broad enough frequency tuning to allow the demonstration of network functions such as data transmission to multiple destinations via rapid frequency switching of a single transmitter laser.

The use of multiple lasers to accommodate extended bandwidth access will not constrain ultimate test-bed performance since each individual test-bed user will still be able to access on the order of 20 FDM channels using a single laser. The test-bed network will also be able to provide additional wavelength conversion functions if needed. Scalability in data rate per user will be accomplished by utilizing multiple FDM channels up to the limitation of an individual laser and then by employing multiple lasers.

2) Frequency Control: Even though limitations in currently available devices prevent us from accessing all potential channels, we will demonstrate the ability to accurately and reliably channelize the available optical bandwidth. FDM channel spacing and absolute frequency accuracy for the initial test-bed will be maintained within each Level-0 AON by a fiber Fabry–Perot that is frequency locked to an atomic absorption line in a gas cell. The use of multiple absorption line standards as well as techniques that allow several AON's to synchronize to a common broadcast frequency references will also be explored.

During network initialization the atomic reference locked Fabry–Perot channel references and the Level-1 AON wavelength routers are frequency aligned by slight adjustments in the wavelength router temperature. The frequency accuracy of

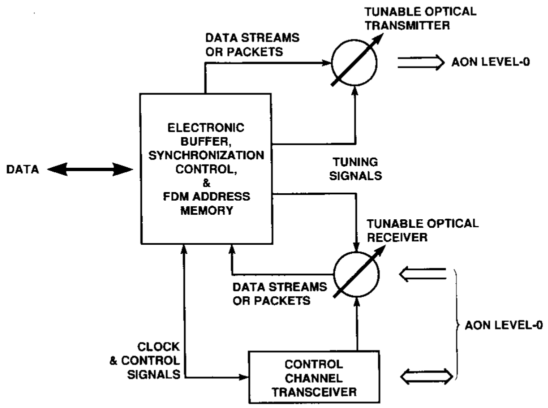


Fig. 22. Optical terminal (OT) components.

an individual user is then determined by the Level-0 Scheduler during the initial session setup. Preliminary measurements indicate that the lasers intended for use in the test-bed are frequency stable over many hours and that once the network frequency standards, wavelength routers, and lasers are temperature aligned, only minor frequency corrections will be needed.

3) Optical Terminals: Users will access the test-bed via an Optical Terminal. An OT is comprised of an electronic interface and the associated optical transmitter and receiver as shown in Fig. 22. The optical transmitter will consist of a semiconductor laser, laser controller, data formatter, and modulator. The receiver consists of either a direct detection receiver employing an optical filter that may be slowly tuned, or a heterodyne receiver that may be rapidly tuned. All laser controllers will employ precision temperature control to maintain frequency stability. The controller for lasers that rapidly switch between FDM channels will also include a high-speed digital-to-analog converter (DAC) to provide switching currents. The DAC is also computer addressable and in conjunction with an auxiliary GaAs switch can change a lasers channel address signal in less than a few nanoseconds. A typical OT will be constructed on one or two circuit cards and will utilize a modified commercial computer bus-card mechanical format for convenience.

Some OT's will provide dedicated connections to high-speed electronic data sources such as HIPPI channels, high-resolution digitized video systems, and direct computer-processor bus connections. Others will provide either bridging or routing between the test-bed and existing computer network standards such as FDDI. The DEC packet switch described in the Section IV will be used to construct FDDI interfaces to the test-bed. This switch will accommodate up to 800 Mb/s of aggregate traffic.

Even though the majority of users will access the test-bed using well defined signaling formats, an important feature of the test-bed will be the ability to support an all-optical interconnection between users. This allows great flexibility with respect to the types of optical carriers, modulation formats, and detection schemes.

Although any optical signals introduced by users directly into the test-bed will eventually have to meet stringent conditioning requirements to guarantee safety, security, and signaling integrity, the initial constraints will be quite loose to facilitate experimentation. Direct optical interconnects will be used to support additional FDM services as well as services utilizing unusual modulation formats such as analog subcarrier modulation, short pulse, and soliton experiments.

4) Simulations of WANS with Large Numbers of Users: By distributing the test-bed over a large geographic extent with a diverse user group we will be able to realistically simulate the unique features of MAN's and WAN's. We will be able to examine and quantify the effects of delays, multi-path effects, frequency reuse techniques, and congestion control algorithms.

In some instances the available resources may prohibit the actual physical implementation of certain network effects. Examples are the propagation delays, fiber and optical amplifier nonlinearities, optical amplifier noise accumulation and bandwidth limitation, and the dispersion that would be encountered in long-haul all-optical communication channels that transit the continent. Effects such as these will be accounted for by combinations of recirculating fiber delay-lines with Erbium amplifiers, electronic simulations, and computer models. The effects of cascades of many optical amplifiers along with channel power imbalances, crosstalk, and fiber nonlinearities will also be accurately accounted for with these techniques.

It is not practical to attempt to connect the test-bed to every possible potential user. Instead we will use a small but meaningful number of real user connections and simulate a large number of additional users. The minimum number of actual active user ports implemented in each Level-0 AON in the test-bed will be three. There will be two users capable of utilizing either Type-A, B, or C services and one user capable of utilizing Type-A services exclusively. As the test-bed evolves and additional electronic and optical access points are constructed, we expect the number of active user ports per Level-0 AON to increase to between five and twenty depending on their physical locations.

Ultimately, the total number of possible simultaneous multi-gigabits-per-second class users in the simple broadcast configurations used in Level-0 AON's is constrained to be between a few hundred and a few thousand by optical power-budget limitations. We will simulate the total load of propagating optical power and the associated channel occupancy due to the presence of this large number of potential users. User simulators will be constructed using the broad-band emissions from super-luminescent diodes that are filtered by Fabry–Perots and then amplified to form extensive combs of occupied frequency slots.

5) Network Control: For initial convenience, the test-bed will first be controlled at the individual sites of the Level-0 AON's located at AT&T, DEC, and MIT. Once the AON sites are interconnected, network control will be coordinated over dedicated FDM channels using distributed algorithms as described in Section III. If any AON's are not able to be optically interconnected an electronic interface will be used.

A simple access control scheme using a 1300-nm broad-band Ethernet system will initially be used in each Level-0

AON to set up the desired sessions. This channel will be used to provide timing signals, control messages, and channel assignments to users. A user will query the local Scheduler Agent for the FDM channel addresses needed during the intended sessions and then provide timing information to the Scheduler Agent regarding the beginning and ending times of the sessions and any corresponding circuit or packet switching information. The Agent will schedule the session according to user and resource availability. The Scheduler Agents will initially be desktop computers. Dedicated custom logic will be utilized later on in the test-bed development if warranted.

D. Services Offered on the Test-Bed

The test-bed will provide realistic network services for both intensive system tests and demonstration purposes. All three types of service will be demonstrated as will multi-cast and multi-session service combinations. Multi-cast will initially be accomplished via explicit prior scheduling and slow-tuning receivers. The network controllers will request that the appropriate receivers tune to the correct channels at the desired time. This will allow the test-bed to support multiple simultaneous multicast trees with each operating on a different FDM channel.

All of the services and applications that are provided by the initial test-bed will utilize terminal equipment that is already in place at consortium member locations. This will minimize the resources expended on conventional terminal equipment and allow us to concentrate on the development of all-optical transport components, advanced interface controllers, and access protocols.

1) Type-A Services: Type-A services do not require a fast-switching laser and consequently they will be offered via commercially available 1.5-μm DFB lasers that are slowly tuned via temperature, requiring tens of seconds to tune to a new channel. This is a scheduled service, where transmitters and receivers are scheduled on a first-come, first-serve basis.

This type of service will be used to create dedicated links carrying continuous traffic between computers, computers and peripherals, and workstations. Type-A service will also be used for video-conferencing, remote broadcast of MIT lectures, and to provide dedicated links between test-bed AON's for switching, routing, and control purposes.

2) Type-B Services: Type-B services require fast-tuning transmitters and tunable receivers. The AT&T laser will be used to provide this type of service since it is capable of switching between FDM channels in less than 10 ns. We will construct both slowly tunable multiple-wavelength direct detection receivers as well as rapidly tunable heterodyne receivers. Utilizing both types of receivers will allow us to accommodate the needs of multi-media, multi-session applications. As described in the Section III, these types of services are also scheduled but on a much faster time scale. The Level-0 test-bed Scheduling Agents will provide a master 1.24416-GHz clock synchronization signal to each user.

3) Type-C Services: Type-C services require fixed tuned transmitters and receivers. The Type-C service for the test-bed will utilize 1300 nm wavelength broad-band Ethernet technology and will use commercial 10BROAD36 modems to interface to the AON. We will interconnect, on an experimental basis, the already existing FDDI- and Ethernet-based LAN's at the various consortium member sites via the test-bed system. We will utilize the DEC fast FDDI packet switch as a server. The LAN interconnection will also introduce many additional users with their corresponding individual application needs and service requirements. By allowing for a large number of potential users, the test-bed network will further facilitate the development and testing of network applications and will allow a more rapid understanding of the interplay between architecture, technology, applications, and services.

4) Advanced Services and New Applications One of our goals for the test-bed effort is to help in the creation of novel all-optical network services and applications. The development of new services and applications is intimately tied to the availability of the supporting terminal equipment. Eventually the available equipment will become an impediment to further progress and the installation of terminal equipment capable of efficiently utilizing the bandwidth and connectivity available in an all-optical network will be required. We hope to make use of the advanced television and imaging work at MIT and the high-speed workstation development efforts underway at DEC to aid the development of novel test-bed

E. Test-Bed Risk Assessment

Implementation of an aggressive test-bed oriented program such as this is not without risk. Optional development paths have been identified should the technologies or architectures we are pursuing prove to be of limited success.

One area of risk lies in the effort to develop an efficient broadband optical frequency converter. This device, if successful would have a marked effect upon all-optical network design. For purposes of the initial test-bed system, frequency converters based on wide-bandwidth photodetectors followed by amplifiers that directly modulate a laser with a faithful reproduction of the incoming waveform and converters based on nondegenerate four-wave mixing as described in the Section IV will be used until the desired devices become available.

Although it is not nearly as attractive a solution, the use of a conventional optical cross-bar switch fabric that incorporates bandpass and bandblock functions could also be used to perform similar switching functions at AON Level-2 at the expense of more restrictive frequency utilization.

A second area of risk concerns the development of tunable lasers capable of 25 THz tuning. Should this effort fail, we still have the option of using multiple lasers to access the entire fiber bandwidth. If multiple lasers are indeed required, we intend to retain the basic device characteristics used in the AT&T fast-switching laser but slightly alter the device doping levels to provide coverage at additional wavelengths. The principle drawbacks to this alternative approach are the development of several versions of the same laser that cannot all access the same frequency slots and the need for additional frequency standards to be included into the network so that channel spacings can be maintained across laser tuning region boundaries.

A third area of risk is the use of dark fiber to interconnect the DEC and MIT portions of the test-bed located in Massachusetts to the AT&T portion of the test-bed located in New Jersey. Although we intend to vigorously pursue the use of dark-fiber for this link, economic and regulatory constraints may conspire to frustrate our best efforts. In the near term, we will connect via electronic means while preparing for a future all-optical interconnect.

VI. CONCLUSION

All-optical communication networks may offer significant advantages in capacity, connectivity, and cost by allowing information to flow unimpeded by optical-to-electronic transformations. Such networks can also be made to scale gracefully in terms of their geographic span, number of users, and data rate per user. The challenge of all-optical networks is to develop techniques to effectively exploit the enormous 25-THz bandwidth potential inherent in single-mode optical fiber. Only recently has optoelectronic technology matured to the point where practical all-optical architectures could be identified, realistic test-beds constructed, and thorough investigations begun. By adopting a consortium structure we have leveraged the strengths of each member and hope to hasten the development, evaluation and deployment of all-optical networks.

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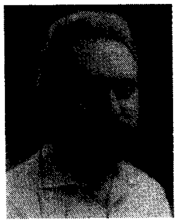

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R. S. Bondurant received the S.B., S.M., and Ph.D. degrees in electrical engineering, all from M.I.T. His graduate studies were on squeezed-state generation and applications. In 1983 he joined the Optical Communication Technology Group at Lincoln where he worked on laser intersatellite communication links. Currently he is Assistant Group Leader of the Optical Technology Group (Group 67). His interests include optical communications, nonlinear and quantum optics, and signal processing.

Donal Byrne (M'89) photograph and biography not available at the time of publication.

Vincent W. S. Chan was born in Hong Kong on November 5, 1948. He received the B.S., M.S., E.E., and Ph.D. degrees in electrical engineering from M.I.T., Cambridge in 1971, 1971, 1972, and 1974, respectively, in the area of communication.

From 1974 to 1977, he was an Assistant Professor with the School of Electrical Engineering at Cornell University, teaching and conducting fundamental research in communication and optics. He joined Lincoln Laboratory, Lexington, MA, in 1977 as a staff member of the Satellite Communication System Engineering Group. In January 1981, he became the Assistant Leader of the Communication Technology Group starting a research and development program on optical space communication based on semiconductor lasers and coherent detection techniques. In July 1983, he formed and became leader of the Optical Communication Technology Group and leader of the LITE Project Office. He is currently the Associate Head of the Communication Division. His research interests are in optical communication, space communication and networks. Of particular interest is the interplay between system and technology, how to create and demonstrate sensible communication systems, and the development of network applications that offers significant improvement on education, industrial productivity and marketability of networks.

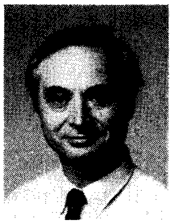
Dr. Chan was the guest editor of a special issue of the Journal of Lightwave Technology and Selected Area in Communications on Coherent Communications. He is currently serving a the Director of the consortium.

Steven G. Finn (M'69) was born in Boston, MA, in 1946. He received the B.S., M.S., and Sc.D. degrees in 1969, 1969, and 1975, respectively, all in electrical engineering from the Massachusetts Institute of Technology.

From 1975 to 1980 he worked for Codex Corporation where he held various positions including Director of Network Processor Research and Development. At Codex he worked on advanced networking products for high-speed data communications networks. Also, while at Codex, he was a member of ANSI and CCITT committees involved in public data networking standards development. In 1980, he founded the Bytex Corporation. He held the position of CEO through 1987 and Chairman until he left Bytex in 1990. In 1990 he returned to M.I.T. as a Vinton Hayes Fellow and Visiting Scientist in the Laboratory for Information and Decision Sciences. Currently, he is a Lecturer in the Electrical Engineering and Computer Science Department at M.I.T. and a Sr. Staff Member at the Lincoln Laboratory. He is also retained as a consultant for Matrix Partners, a venture capital firm. His current research interests are in the areas of optical networks, high-speed data network transport, network architecture, and network management.

Robert Gallager (S'58–M'61–F'68) has been a professor at the Massachusetts Institute of Technology since 1960 and his current title is Fujitsu Professor of Electrical Engineering and Computer Science and Co-Director of the Laboratory for Information and Decision Systems. He is a consultant to Motorola Codex. He is the author of the textbook *Information Theory and Reliable Communication* (New York: Wiley, 1968) and co-author of *Data Networks* (Prentice-Hall, Ed. 2, 1992). His major research interests are data communication networks, information theory, and communication theory

Dr. Gallager received the IEEE Medal of Honor in 1990. He is a member of the U.S. National Academy of Engineering and the U.S. National Academy of Sciences.



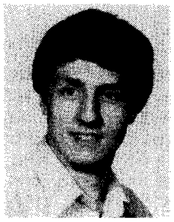
Bernard S. Glance (M'72–SM'85–F'87) received the B.S. degree in electronic engineering, in 1958, from Ecole Speciale de Mechanique et Electricite, Paris, France. He received the M.S. degree in electronic engineering, in 1960, from Ecole Superieure d'Electricite, Paris, France. In 1964 he received the Ph.D. degree from Paris University

From 1958 to 1966 he was with Thompson, CSF, France. During this period he was engaged in research on microwave and millimeter-wave tubes. He worked at Varian Associates from 1966 to 1968 where he worked on microwave tube amplifiers. He has been working at AT&T Bell Laboratories since 1968. His initial field of interest was millimeter-wave integrated circuits and RF sources. He subsequently worked on microwave integrated components for use in communications satellites. He has also been involved in analyses and simulations of digital mobile radio systems and point-to-point digital radio systems. In 1988, he started working on optical coherent communication systems. Presently he is working on optical packet switching based on Wavelength Division Multiplexing.

Hermann A. Haus (S'50–A'55–SM'58–F'62–LF'91) was born in Ljubljana, Slovenia, in 1925. He attended the Technische Hochschule, Graz, and the Technische Hochschule, Vienna, Austria. He received the B.Sc. degree from Union College, Schenectady, NY, in 1949, the M.S. degree from Rensselaer Polytechnic Institute, Troy, NY, in 1951, and the Sc.D. degree from the Massachusetts Institute of Technology, Cambridge, MA, in 1954. He received honorary doctor's degree from Union College and the Technical University of Vienna.

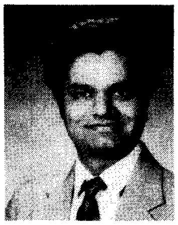
He joined the Faculty of Electrical Engineering at M.I.T. in 1954, where he is an Institute Professor. He is engaged in research in electromagnetic theory and lasers. He is the author or coauthor of five books and over 210 journal articles.

Dr. Haus is a member of the American Physical Society, the National Academy of Engineering, the National Academy of Sciences, and a Fellow of the Optical Society of America and the American Academy of Arts and Sciences.



Pierre Humblet (S'72-M'77-SM'91) received the degrees of electrical engineering from the University of Louvain, Belgium, and the M.S.E.E. and Ph.D. degrees from the Massachusetts Institute of Technology, Cambridge, MA.

After graduating in 1978 he has remained at M.I.T. where he is now a Professor of Electrical Engineering. His teaching and research interests are in the area of communication systems, particularly wide-band optical networks and distributed algorithms. He is a consultant with a number of companies, most recently IBM and Motorola/Codex.



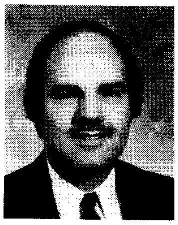
Raj Jain (S'74–M'78–SM'86–F'93) received the Ph.D. degree from Harvard University in 1978. Since then he has been at Digital Equipment Corporation, where he is currently a Senior Consulting Engineer. He serves on the editorial advisory boards of Computer Communications (UK) and the Journal of High Speed Networks. He is the Vice-Chair of ACM Lecturer for 1992.

He received the "Best How-To Book" Computer Press Award for his 1991 book "The Art of Computer Systems Performance Analysis" published by Wiley, NY. His next book entitled "FDDI Handbook: High Speed Networking using Fiber and Other Media" is scheduled to be published this summer by Addison-Wesley, Reading, MA.

Ivan P. Kaminow (A'54–M'59–SM'73–F'74) was born in Union City, NJ, on March 3, 1930. He received the B.S.E.E. degree from Union College, Schenectady, NY, in 1952. He received the M.S.E. degree from the University of California, Los Angeles and the A.M. and Ph.D. degrees in applied physics from Harvard University, Boston, in 1954, 1957, and 1960, respectively. He was a Hughes Fellow at UCLA from 1952 to 1954 and a Bell Laboratories CDTP Fellow at Harvard from 1956 to 1960.

From 1952 to 1954 he worked on microwave antennas at Hughes Aircraft Company, Culver City, CA. Since 1954 he has been at AT&T Bell Laboratories in Whippany and Holmdel, NJ, and has done research on antenna arrays, ferrite devices, electroopic modulators, ferroelectrics, nonlinear optics, Raman scattering, integrated optics, semiconductor lasers, optical fibers, and lightwave networks. He was appointed Head of the Photonic Networks and Components Research Department in 1984. He has been a Visiting Lecturer at Princeton University (1968), at the University of California Berkeley (1977), an Adjunct Professor at Columbia University (1986), and Visiting Professor at Tokyo University (1990–1991). He has published over 200 papers and received 37 patents. He is the author of *An Introduction to Electrooptic Devices* (1974), co-editor (with A. E. Siegman) of the IEEE Press book *Laser Devices and Applications* (1972) and co-editor (with S. E. Miller) of *Optical Fiber Telecommunications II* (1988).

He has been an Associate Editor of the IEEE JOURNAL OF QUAMTUM ELECTRONICS, a member of the Awards Board, and the co-Guest Editor (with D. R. Herriott) of the Joint Issue of the PROCEEDINGS and Applied Optics on Optoelctronics (1966). He was a member of the Administrative Committee of the IEEE Quantum Electronics and Applications Society (1982–1985). He was Chairman of the American Optical Society Richardson Medal Committee. He served on NAS-NRC Evaluation Panels for the National Bureau of Standards in the Optical Physics Division (1972–1975) and the Center for Electronics and Electrical Engineering (1984–1987). He was a consultant member of the DoD Advisory Group on Electron Devices (1982–1984) and an Air Force committee (1984_1985). He was Program Chairman of the IEEE Semiconductor Laser Conference in Kanazawak, Japan (1986) and General Chairman of the IEEE Semiconductor Laser Conference held in Boston (1988). Dr. Kaminow is the American Physical Society and the Optical Society of America. He is a recipient of the Bell Labs. Distinguished Member of Technical Staff Award and the IEEE Quantum Electronics Award. He is a member of the National Academy of Engineering and a Diplomate of the American Board of Laser Surgery.



Mark J. Karol (S'79–M'85–SM'91–F'93) was born in Jersey City, NJ on February 28, 1959. He received the B.S. degree in mathematics and the B.S.E.E. degree in 1981 from Case Western Reserve University, Cleveland, OH, and the M.S.E., M.A., and Ph.D. degrees in electrical engineering from Princeton University, Princeton, NJ, in 1982, 1984, and 1986, respectively. He was a National Science Foundation Fellow and Office of Naval Research Fellow while at Princeton.

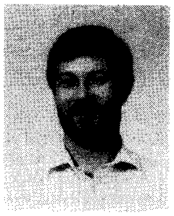
Since 1985 he has been a member of the Network Systems Research Department at AT&T Bell Laboratories, Holmdel, NJ. His current research interests include high-performance packet switching architectures, local and metropolitan area network architectures, and multiuser lightwave communication networks.

Dr. Karol is a member of Eta Kappa Nu and Tau Beta Pi, an associate editor for the JOURNALOF LIGHTWAVE TECHNOLOGY Vice-Chair and General Chair for the IEEE Infocom'93 and Infocom'94 Conferences, respectively, and currently is Vice-Chairman of the Computer Communications Committee of the IEEE Communications Society.

Robert S. Kennedy (S'58–M'63–SM'74–F'75) received the B.S. degree from the University of Kansas in 1955 and the S.M. and Sc.D. degrees in electrical engineering from the Massachusetts Institute of Technology in 1959 and 1963, respectively.

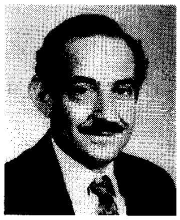
From 1955 to 1957 he served with the Naval Reactors Branch of the U.S. Atomic Energy Commission and from 1963 to 1964, he was a staff member of M.I.T.'s Lincoln Laboratory. Since 1964, he has been at M.I.T. as a faculty member of the Department of Electrical Engineering and Computer Science. He is also a member of the Laboratory for Information and Decision Systems. His early research pertained to communication through random fading dispersive channels such as H.F. radio, microwave tropospheric scatter and orbiting dipole belts. That research culminated in the book *Fading Dispersive Communication Channels*, Wiley & Sons, 1968. Then, through 1980, his professional interests were centered around optics and optical communication, with research emphasis upon communication through scattering channels and quantum channels. His current research is concerned with the principles that should be used to design all-optical communication networks.

Dr. Kennedy is a member of Tau Beta Pi, Sigma Xi, and Eta Kappa Nu. He is a past president of the Information Theory Group of the IEEE, was an organizer of the joint MIT-NASA Williamstown Workshop on Optical Space Communication, Director of MIT's Communications Forum, chairman of the editorial committee for the special IEEE Proceedings issue on Optical Communications, was co-chairman of the Eighth MIT-NSF Grantee-User Meeting on Optical Communication, editor of the special COMTECH Transactions on Fiber Systems and on the editorial board of "Computer Communications." He has served as an advisor and consultant to government and industry. He and his wife were Faculty-in-Residence at M.I.T.'s MacGregor House from 1985 to 1991.



Alan Kirby (M'77) received the B.S. degree in computer science from Worcester Polytechnic Institute and the M.S. degree from the Polytechnic Institute of New York. He is responsible for Advanced Development in the area of computer networking at Digital Equipment Corporation, Littleton, MA. He is also directing Digital's work on the AON. Prior to joining Digital, he was with National CSS, Inc. where he was one of the developers of an early nationwide packet switching network.

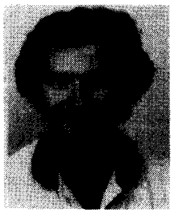
Han Q. Le joined Lincoln Laboratory, Lexington, MA, in 1985 and conducted research on various aspects of III-V semiconductors, including resonant tunneling, ultrafast photoconductive switching, optical nonlinearities, and optically pumped semiconductor lasers.



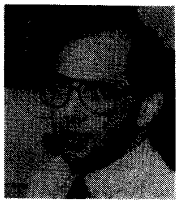
Adel A. M. Saleh (A' 65–M'70–SM'76–F'87) was born in Alexandria, Egypt in July 1942. He received the B.Sc. in electrical engineering from the University of Alexandria in 1963 and the M.S. and Ph.D. in electrical engineering from the Massachusetts Institute of Technology, Cambridge, MA in 1967 and 1970, respectively.

From 1963 to 1965 he was employed as an instructor at the University of Alexandria. In 1970 he joined AT&T Bell Laboratories Crawford Hill Laboratory, Holmdel, NJ, where he was involved in research on microwave and optical components and communications systems. He is currently the Head of the Interconnection Research Department, Murray Hill, NJ where he is leading a research effort on packaging and integration issues for optical and wireless applications.

Dr. Saleh received the AT&T Bell Laboratories Distinguished Technical Staff Award for sustained achievement in 1985. He is a member of Sigma Xi.



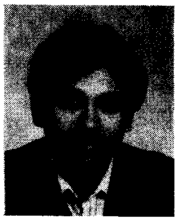
Bruce Allen Schofield was born on May 17, 1952 in Framingham, MA. He received the B.S.E.E. and M.S.E.E. from Northeastern University in 1975 and 1976, respectively. From 1976 to 1978 he was with Harris Corporation in Syoset, NY. In 1978 he joined AIL, Huntington, NY and in 1980 he joined Digital Equipment Corporation, Maynard, MA, where he is currently Principal Hardware Engineer, Network Engineering Advance Development.



Jeffery H. Shapiro (S'67–M'70–SM'84) was born in New York City on December 27, 1946. He received the S.B., S.M., E.E., and Ph.D. degrees in electrical engineering from the Massachusetts Institute of Technology in 1967, 1968, 1969, and 1970, respectively. As a graduate student he was a National Science Foundation Fellow, a Teaching Assistant, and a Fannie and John Hertz Foundation Fellow. His doctoral research was a theoretical study of adaptive techniques for improved optical communication through atmospheric turbulence.

From 1970 to 1973, he was an Assistant Professor of Electrical Sciences and Applied Physics at Case Western Reserve University. From 1973 to 1985, he was an Associate Professor of Electrical Engineering at M.I.T. In 1985, he was promoted to Professor of Electrical Engineering, and in 1989 he became Associate Department Head. His research interests have centered on the application of communication theory to optical systems. He has published extensively in the areas of atmospheric optical propagation and communication, coherent laser radars, and quantum-noise reduction through squeezed state generation.

Dr. Shapiro is a fellow of the Optical Society of America, and a member of the Society of Photo-Optical Instrumentation Engineers. He has been as Associate Editor of the IEEE TRANSACTIONS ON INFORMATION THEORY and the *Journal of the Optical Society of America.*



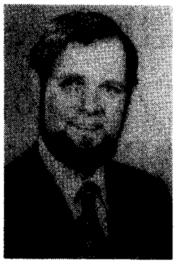
N. K. Shankaranarayanan (S'83–M'92) was born in Erode, India, in 1964. He received the B.Tech. degree from the Indian Institute of Technology, Bombay, India, in 1985, the M.S. degree from Virginia Polytechnic Institute and State University, Blacksburg, VA in 1987, and the Ph.D. degree from Columbia University, NY, NY in 1992, all in electrical engineering. During 1991, he was a visiting researcher at the University of California, Berkeley, CA.

He joined the Photonic Networks and Components Research Department of AT&T Bell Laboratories, Holmdel, NJ in 1992. His research work has included subcarrier frequency-division multiple-access lightwave networks, optical beat interference, and optical fiber sensors, His current research is focussed on FDM lightwave network architecture and technology.

Dr. Shankaranarayanan is a member of OSA.

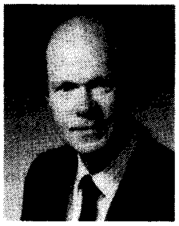
Robert E. Thomas (S'78–M'80) received the Ph.D. degree in computer science from the University of California, Irvine.

He was a Research Associate at the M.I.T. Laboratory for Computer Science for three years while working on fine-grained dataflow architectures. He has been with Digital Equipment Corporation for nine years, as part of Silicon Systems Engineering and then Network Engineering Advanced Development.



Richard C. Williamson (M'72–SM'80–F'82) attended the Massachusetts Institute of Technology and received the B.S. and Ph.D. degrees in physics in 1961 and 1966, respectively.

In 1970, he joined M.I.T. Lincoln Laboratory. Since 1980, he has been the Leader of the Group which carries out research and development on electrooptical devices, including semiconductor lasers, laser arrays, optical communications, integrated optical circuits, and optical-information-processing.



Robert W. Wilson was born in Houston, TX in 1936, where he lived until he attended Caltech. He presently lives in Holmdel, NJ. He received the B.A. degree "with Honors in Physics" from Rice University, in 1957 and the Ph.D. degree from the California Institute of Technology in 1962. After an additional year associated with the Owens Valley Radio Observatory of Caltech as a postdoctoral fellow, he joined AT&T Bell Laboratories in 1963.

He is Head of the Radio Physics Department of the AT&T Bell Laboratories, Holmdel, NJ. The Radio Physics Research Department does research on microwave and millimeter wave semiconductor devices and components and on radio astronomy — a field in which he is an active worker. His early work was in the fields of Galactic radio astronomy and precision measurement of radio source strengths. He is best known for his part in the discovery of the 3 K cosmic black body background radiation, thought to have originated in the early stages of the expansion of the universe (1965). In 1970 he and his co-workers extended radio spectroscopy of the interstellar medium to millimeter wavelengths where many molecules have detectable rotational transitions. This has led to much new information on dense interstellar clouds where star formation is occurring. His recent work has been on structure of nearby molecular clouds. He has also applied astronomical techniques to the measurement of earth-space propagation for satellite communication at centimeter and infrared wavelengths and made infrared propagation measurements along a terrestrial path.

Dr. Wilson is a member of the American Astronomical Society, the American Academy of Arts and Sciences, the International Astronomical Union, the International Union of Radio Science, the American Physical Society, the National Academy of Sciences, 1990 Astronomy and Astrophysics Survey Survey Committee (Babcall Committee), and is an Adjunct Professor at Princeton University, Princeton, NJ. He is co-recipient of the Henry Draper Medal from the U.S. National Academy of Science and the Hershel Medal from the Royal Astronomical Society, London and the 1978 Nobel Prize in Physics.