NCS TIB 00-7

NATIONAL COMMUNICATIONS SYSTEM

TECHNICAL INFORMATION BULLETIN 00-7

ALL-OPTICAL NETWORKS (AON)

AUGUST 2000

OFFICE OF THE MANAGER
NATIONAL COMMUNICATIONS SYSTEM
701 SOUTH COURTHOUSE ROAD
ARLINGTON, VIRGINIA 22204-2198

NCS TECHNICAL INFORMATION BULLETIN 00-7

ALL-OPTICAL NETWORKS (AON)

AUGUST 2000

PROJECT OFFICER

Dale D. Barr, Jr.
DALE BARR, JR.
Sr. Electronic Engineer
Technology and Programs Division

APPROVED FOR PUBLICATION:

Peter M. Fonash
PETER M. FONASH
Chief, Technology
and Programs Division

FOREWORD

Among the responsibilities assigned to the Office of the Manager, National Communications System, is the management of the Federal Telecommunications Standards Program. Under this program, the NCS, with the assistance of the Federal Telecommunications Standards Committee identifies, develops, and coordinates proposed Federal Standards which either contribute to the interoperability of functionally similar Federal telecommunications systems or to the achievement of a compatible and efficient interface between computer and telecommunications systems. In developing and coordinating these standards, a considerable amount of effort is expended in initiating and pursuing joint standards development efforts with appropriate technical committees of the International Organization for Standardization, the International Telecommunication Union-Telecommunications Standardization Sector, and the American National Standards Institute. This Technical Information Bulletin presents an overview of an effort which is contributing to the development of compatible Federal and national standards in the area of high speed telecommunications. It has been prepared to inform interested Federal and industry activities. Any comments, inputs or statements of requirements which could assist in the advancement of this work are welcome and should be addressed to:

Office of the Manager
National Communications System
Attn: N2
701 S. Court House Road
Arlington, VA 22204-2198

This document was prepared under contract to the

Office of the Manager
National Communications System

Contract # DCA100-96-C-0038

by

Communication Technologies, Inc.
503 Carlisle Drive, Suite 200
Herndon, Virginia 20170

703-318-7212 (Voice)
703-318-7214 (Fax)
www.comtechnologies.com

ALL-OPTICAL NETWORKS (AONs)

Abstract

All-Optical Networks (AONs) are expected to come out of the laboratory and grow rapidly in popularity over the next several years due to their high speed and ability to overcome the “electronic bottleneck” offered by today’s electronic or electro-optic networks. It is anticipated that communications infrastructures will evolve to support gigabit and terabit speeds, and new applications such as desktop videoconferencing, distance learning, telemedicine, and video-on-demand will evolve to become important commonplace capabilities. These and many other bandwidth-intensive applications have great potential to improve National Security and Emergency Preparedness (NS/EP) communications. This report examines AONs, addresses issues associated with their applications, and discusses their applicability into NS/EP environments.

Table of Contents

Figures

Tables

1. Introduction

The National Communications System (NCS) is a federation of 23 member organizations across the Federal Government. It was established through a Presidential Memorandum signed by President Kennedy on August 21, 1963. The memorandum assigned NCS the responsibility of providing necessary communications for the Federal Government under national emergency conditions by linking together, improving, and expanding the communication capabilities of the various Federal Government agencies. In April 1984, President Ronald Reagan signed Executive Order (E.O.) 12472, *Assignment of National Security and Emergency Preparedness (NS/EP) Telecommunications Functions*, to broaden the NCS responsibility. The E.O 12472 established the mission of the NCS to assist the President, the National Security Council, the Director of the Office Science and Technology Policy and the Director of the Office of Management and Budget in (1) the exercise of the telecommunications functions and responsibilities, and (2) the coordination of the planning for and provisioning of NS/EP communications for the Federal Government under all circumstances, including crisis or emergency, attack, recovery, and reconstitution.

To fulfill this responsibility, the Office of the Manager, National Communications System (OMNCS), and in particular its Technology and Programs Division (N2), pursues new technologies to enhance NS/EP communications. Upon identification of such technologies, the N2 division evaluates them for their applicability into NS/EP environments.

All-Optical Networking (AON) is one of the new technologies identified by the N2 division for enhancing NS/EP communications. This report covers the basic concepts of AON, different types of AONs, applications of AONs, and issues associated with the use or applications of AONs.

2. Background

Over the last few years, optical fiber has become the transmission medium of choice because it provides large bandwidth {approximately 24 TeraHertz (THz)}, low attenuation, and low Bit Error Rate (BER) (less than 10^{-11}). In today's networks, electronic devices such as switches and routers are interconnected by optical fiber links. A major limitation of these types of networks, often referred to as electro-optic networks, is “electronic bottleneck”. This electronic bottleneck is caused by the fact that information transfer involves time-consuming processes of optical-to-electronic conversion, electrical signal processing, and electronic-to-optical conversion of data signals at intermediate network nodes. Additionally, all of the information carried on optical fibers must be processed at electronic data rates that are compatible with electronic circuitry (in the order of few Gigabits Per Second (Gb/s)), thereby limiting network throughput.

Over the last decade, processors and other related peripherals have advanced in speed by two orders of magnitude, however electronic interconnecting devices such as switches and routers by only one order of magnitude. Therefore, the amount of information that can be carried over an optical fiber link is limited by the information processing speed of the interconnecting electronic devices used at each end of the link and not by the fiber itself.

Recently, a new concept, called all-optical networking, has been developed to overcome these effects. Using this concept, information can be transmitted using optical signals and without optical-to-electronic conversion and vice versa. Networks constructed using this concept are called AONs.

3. All-Optical Networks

In AONs, as the name indicates, information is transmitted entirely in optical form. There are no optical/electronic conversions within the network. One major advantage of AONs with respect to their electro-optic counterparts is their much higher bandwidth. Elimination of electronic/optical conversion reduces delays, increases capacity, and improves flexibility of networks. In this regard, AONs are a natural solution to the ever-increasing demand for higher speeds and larger capacities. At present, optical transmission links supporting 30 to 40 Gb/s are commercially available and 100 Gb/s products have been announced. Additionally, various AON test-beds and laboratory experiments have achieved an aggregate network throughput of over 1 Terabits per Second (Tb/s) and higher throughputs are expected in the near future.

3.1 Multiplexing Techniques

Optical fiber can provide a large bandwidth, approximately 24 THz. To share this bandwidth, various multiplexing techniques have been proposed for AONs. These techniques include Wavelength Division Multiplexing (WDM), Optical Time Division Multiplexing (OTDM), and Optical Code Division Multiplexing (OCDM). Recently, hybrid-multiplexing techniques such as WDM/OTDM and WDM/OCDM have also been proposed for all-optical networks. These techniques are briefly described below.

3.1.1 Wavelength Division Multiplexing WDM

In WDM, two or more optical signals having different wavelengths are combined and simultaneously transmitted in the same direction over an optical fiber. WDM is a rate and format independent technology, and it can support any combination of interface rates including synchronous or asynchronous Optical Channel (OC) OC–3, OC–12, OC–48, or OC–192 on the same fiber at the same time. It is already at an advanced stage of development and WDM networks can be deployed using commercially available components and systems.

There are three variations of WDM: Narrowband WDM (NWDM), Wideband WDM (WWDM) and Dense WDM (DWDM). Typically, NWDM is implemented by using two wavelengths: 1533 and 1577 nanometers (nm). WWDM, on the other hand, is implemented by combining a 1310 nm wavelength with another wavelength into the low-loss window of an optical fiber cable between 1528 nm and 1560 nm in wavelength.

Technically, WDM and DWDM are similar, however, as the name implies, DWDM supports many more wavelengths. The number of wavelengths that a DWDM system can support depends on the ability of the system to accurately filter and separate them. Initial implementations of DWDM systems support either 8 or 16 wavelengths. However, current DWDM systems are capable of supporting 32 or 40 wavelengths. Recently, DWDM systems capable of supporting as many as 80 and 128 wavelengths have been announced.

3.1.2 Optical Time Division Multiplexing OTDM

Time-Division Multiplexing (TDM) is a scheme that combines numerous signals for transmission on a single communications line or channel. Each communications line or channel is divided into many time segments, each having very short duration. A multiplexer at the source end of a communications link accepts the input from each individual end user, divides each signal into segments, and assigns the segments to time slots in a rotating sequence. The flexibility TDM offers is mostly in the variation of the number of signals being sent along the line.

In OTDM, many lower-speed data channels, each transmitted in the form of ultra-short-duration [10^{-12} seconds (or pico-second (ps)) or 10^{-15} seconds (or femto-second (fs)) duration] optical pulses, are time-interleaved to form a single high-speed (100 Gb/s and higher) data stream. This high-speed data stream is then transmitted over an optical fiber. Note, however, that OTDM is an emerging technology and is less mature when compared to its WDM counterpart.

Special considerations are required to generate ultra-short duration optical pulses. In particular, since the pulse repetition rate should be in the Gigahertz (GHz) range, gain-switched semiconductor lasers and mode-locked lasers are currently used to generate such optical pulses. However, gain-switched semiconductor laser has limitations such as spectral spread due to high chirp rates and non-negligible levels of timing jitter. These limitations can be overcome by using optical fibers with appropriate dispersion compensation, optical filtering, and pulse compression.

3.1.3 Optical Code Division Multiplexing OCDM

Over the past few years, Code Division Multiplexing (CDM) has been studied in the context of wireless microwave communications. In CDM, data signals are digitized and encoded, and then spread out over the entire available bandwidth. Multiple signals are overlaid on a channel with each signal having a unique sequence code. An OCDM has been developed for use in optical networks. In OCDM, an optical source is connected to a number of transmitters. Each transmitter codes and modulates an optical signal, and this coded and modulated signal is broadcast over the network. In order to distinguish individual transmission, each user is assigned a unique code. A receiver that is adjusted to the correct code is able to selectively receive the desired transmission.

OCDM is a protocol independent technology with the capability of transporting any digital signal. OCDM is used only in a broadcast environment while WDM is used both in a broadcast and a switched environment. However, OCDM offers several advantages over other multiplexing technologies such as WDM and OTDM. The major advantages are:

- OCDM systems are more effective in the sense of spectral efficiency since the data are recognized by codes instead of by wavelengths. In WDM systems, large guard bands around each wavelength channel are used to prevent interference resulting from frequency drift. The use of large guard bands drastically reduces the spectral efficiency and degrades network's possible performance.

- OCDM systems are inherently asynchronous. OTDM systems require a high level of synchronization between the transmitter and the receiver. A small delay can lead to interference between the bits in adjacent slots of an OTDM frame and thus a loss of data.

OCDM can be implemented using either coherent or non-coherent detection techniques. In coherent detection, a receiver looks at both the amplitude and phase of the signal, whereas in non-coherent detection looks only at the amplitude and not at a signal's phase. Generally, coherent detection systems have better performance but are more difficult to implement. Therefore, OCDM systems today use non-coherent techniques such as time spreading, frequency hopping, and hybrid wavelength/time spreading.

3.1.4 Hybrid Multiplexing Techniques

WDM techniques can be combined with other multiplexing techniques such as OTDM and OCDM. Through the combinations of multiplexing techniques, the number of users that can be accommodated on a single communications line or channel is dramatically increased. WDM with OTDM and WDM with OCDM are examples of hybrid multiplexing techniques. Note that these combinations will find great applicability in NS/EP situations where communications resources may be limited yet the demand for bandwidth remains high. Using a scheme that involves hybrid Multiplexing is a way to allow more users on a network to communicate simultaneously

3.2 Types of AONs

AONs can be classified as Passive Optical Networks (PONs), Transparent Optical Networks (TONs), and Ultra-high-speed Optical Networks (UONs). These networks are discussed in the following sections.

3.2.1 Passive Optical Networks (PONs)

PONs use passive optical components such as optical fibers, directional couplers, star couplers, splitters, passive routers, and filters. In general, PONs are designed for communications over short distances, usually less than 30 miles. For such short distances, optical signals do not require signal amplification. They eliminate the use of all active components that require electrical power to operate. PONs also offers low cost, high reliability, and high bandwidth. As a result, they are considered as the preferred solution for Local Area Networks (LANs) and Metropolitan Area Networks (MANs). Passive all-optical LANs and MANs can be configured using star, tree, bus, and ring topologies. They can also be used in the following applications:

a) Fiber-To-The-Curb (FTTC)
b) Fiber-To-The-Building (FTTB)
c) Fiber-To-The-Home (FTTH)

Additionally, PONs can be used with other networks to feed optical signals in point-to-multi-point communication. These networks includes Digital Loop Carrier (DLC) Integrated Access, Wireless Local Multi-point Distribution System (LMDS), Wireless Multi-channel Multi-point Distribution System (MMDS), High Data-rate Digital Subscriber Line (HDSL) and Very High Data-rate Digital Subscriber Line (VDSL).

Using a PON can lower the cost of DLC by providing a multi-point optical fiber feeder solution. A PON system can be used between the Central Office and the DLC remote terminal, thus, providing a low cost broadband local loop solution.

Broadband wireless networks require a high-bandwidth feeder network from the Central Office to multiple base stations. The multiple base stations can be connected and the traffic back to the Central Office can be aggregated using PON. PON will offer a lower cost, higher bandwidth, and multi-point alternative compared to a microwave network.

Traditionally, analog coaxial bus architecture has been primarily used in CATV (cable television) networks. Coaxial networks requiring costly coaxial amplifiers are expensive to maintain, and currently are designed for unidirectional services. Hybrid Fiber Coax (HFC) architecture allows CATV networks to provide bi-directional services. Typically, an HFC network can provide 30 to 40 Mb/s of downstream capacity using a single 6 Mega Hertz (MHz) analog channel spectrum shared by approximately 100 to 250 homes. However, HFC has upstream capacity problem, which could be overcome by deploying PON between the cable head-end station and fiber nodes. A PON over current HFC technologies provides a fault tolerant, symmetric, and bi-directional service that is needed for truly interactive broadband applications.

PONs can employ WDM, Sub-Carrier Multiplexing (SCM), OTDM or any combination of these to carry any mix of video, voice, and data services, including Plain Old Telephone Service (POTS), Integrated Services Digital Network (ISDN), T1/E1, T3/E3, OC-3, OC-12, OC-48, and Analog and Digital Television.

3.2.2 Transparent Optical Networks (TONs)

TONs allow signals to traverse network nodes independent of signal modulation, data rate, and other particular characteristics. PONs can be assembled in many ways. However, flexibility, high performance, and local to global coverage are among the primary objectives for using PONs. While most optical components can be designed to be signal type independent, transmission limitations exist due to different end-to-end performance requirements for signal formats and data rates. Different signal types have different sensitivities to cumulative degradation from sources such as chromatic and polarization dispersion, amplified spontaneous noise, cross-talk noise, and optical nonlinearities. Further, it is very difficult to support transmission of analog signals because of their sensitivity to optical reflections and stringent linearity requirements for the lasers used in wavelength converters. Thus, transparent AONs may not offer transparency in its purest form. To alleviate this problem, there are some recent proposals that define the levels of transparency in transparent AONs. These levels are as follows:

a) **4T-transparent--**Transparent regarding modulation format, line code, clock frequency, and transmission format
b) **3T-transparent--**Transparent regarding line code, clock recovery, and transmission format
c) **2T-transparent--**Transparent regarding clock frequency and transmission format
d) **1T-transparent--**Transparent regarding transmission format

3.2.3 Ultra-High Speed Optical Networks

Ultra-high-speed AONs use the tremendous speed characteristics of various optical phenomena to transmit ultra-short optical pulses (or solitons), at 100 Gb/s or more over very long distances. Some of the key technologies required for the construction of ultra-high speed AONs include generation of ultra-short optical pulses, multiplexing, ultra-fast transmission of solitons, clock recovery, and optical buffers. Ultra-short optical pulses can be generated using gain-switched semiconductor lasers and Mode-Locked Lasers (MLLs). Typically, Ultra-high-speed AONs use OTDM (this was also addressed in Section 3.1.2 of this document).

There are two physical characteristics of optical fiber that drive the design of an optical network. The first is chromatic dispersion. This is a linear property of all optical fiber that causes light of different frequencies to travel at different speeds. If left alone, pulses of light will tend to lengthen and eventually grow together making it impossible to recover the bit stream. The second property is when light travels in fiber; it causes tiny changes in the refractive index of the fiber that effectively compresses the pulse. These changes are defined by the power and shape of the pulse, which is called the Kerr effect. Solitons are specially formatted pulses (in both power and shape) that take advantage of both characteristics. This results in a balanced dispersion and compression effect that cancel each other. Unfortunately pulses lose power due to loss of light in the fiber.

When the power drops, the non-linear compression stops, and the pulse begins to spread. This requires that dispersion-compensating fibers (DCF) be used in the network to recompress the pulse.

In OTDM, clock recovery is essential to accurately estimate the timing information in the incoming signal at the receiving end. It enables the receiver to synchronize with the incoming information stream. Two clock recovery techniques have been proposed for ultra-high speed AONs employing OTDM. In the first technique, a local optical clock whose repetition rate is controlled by a RF drive source is locked to the incoming OTDM pulse stream. In the second technique, a Nonlinear Optical Loop Mirror (NOLM) is used as an optical bit phase sensor. The NOLM consists of a 3-db fiber coupler with two of the ports joined through a length of optical fiber. Optical clock pulses are split at the coupler into two counter-propagating pulses that acquire identical pulse shifts as they traverse the loop. To shift the phase of one of the pulses, a high-power data pulse is introduced into the loop. As a result, the two clock pulses are no longer in phase when they arrive back at the coupler and some fraction of the input signal is transmitted through the output port. The NOLM output power is then used as an error-correcting signal to synchronize the local clock with the incoming optical signal.

Having recovered the optical clock, the demultiplexer needs to buffer the desired slot or header of the incoming optical signal using an optical storage device. Further, it needs to slow down the data rate in order to interface the desired signal with the receiver for subsequent data processing. However, no general-purpose random-access optical memory exists, instead, the use of optical delay lines or loops as optical buffers has been proposed.

Ultra-high speed AONs offer many performance advantages, however many of the key technologies needed to support various functions in ultra-high-speed AONs are not mature at this time. Thus, ultra-high-speed AONs are viewed as a longer-term solution for NS/EP purposes.

3.3 AON Architectures

As a result of various research and development efforts, several AON architectures have been developed. These architectures can be classified into functional architecture and network architectures. This section discusses some of these architectures.

3.3.1 Functional Architecture

The International Telecommunication Union – Telecommunication Standardization Sector (ITU-T) has developed functional transport architecture for optical transport networks. This functional transport architecture is specified in the ITU-T Recommendation G.872.

The transport architecture describes the AON functionalities from a network level viewpoint. It takes into account an optical network layered structure, client characteristic information, client/server layer associations, networking topology, and layer network functionality. The layer network functionality covers optical signal transmission, multiplexing, routing, supervision, performance assessment, and network survivability. The present scope of the architecture is limited to digital signals only. Further, the architecture only addresses WDM. Other optical multiplexing techniques such as OTDM and OCDM require further study.

The functional transport architecture uses the modeling methodology described in ITU-T Recommendation G.805, *Generic functional architecture of transport network*. According to this methodology, the optical transport network is decomposed into independent transport layer networks. Each layer network can be separately partitioned in a way that reflects the internal structure of that layer network. Figure 1 depicts the layered structure of optical transport network. They consist of an optical channel layer network, an optical multiplex section layer network, and an optical transmission section layer network.

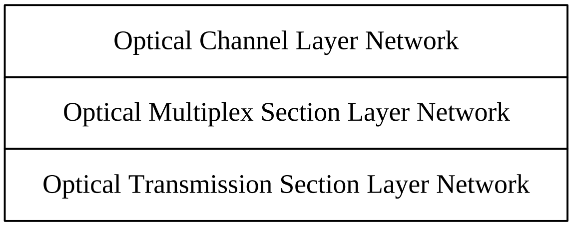

Figure 1: Layered Structure of Optical Transport Network

3.3.1.1 Optical Channel Layer Network

The Optical Channel Layer Network provides end-to-end networking of optical channels for transparently conveying client information of varying formats, such as Synchronous Digital Hierarchy (SDH), Plesiochronous Digital Hierarchy (PDH) and Asynchronous Transfer Mode (ATM). To provide end-to-end networking, the following capabilities are included in the optical channel layer network:

- Optical channel connection rearrangement for flexible network routing;

- Optical channel overhead processes to ensure integrity of the optical channel adapted information; and

- Optical channel supervisory functions to enable network level operations and management functions such as connection provisioning, Quality of Service (QoS) parameter exchange, and network survivability.

3.3.1.2 Optical Multiplex Section Layer Network

Optical Multiplex Section Layer Network provides functionality for networking of a multi-wavelength optical signal. The following networking capabilities are included in an optical multiplex section layer network:

- Optical multiplex section connection rearrangement for flexible multi-wavelength network routing;

- Optical multiplex section overhead processes to ensure integrity of the multi-wavelength optical multiplex section adapted information; and

- Optical multiplex section supervisory functions to enable section level operations and management functions such as multiplex section connection provisioning and network survivability.

3.3.1.3 Optical Transmission Section Layer Network

The Optical Transmission Section Layer Network provides functionality for transmission of optical signals on optical media of various types such as single-mode optical fiber and multi-mode optical fiber. This functionality also includes capabilities for supervision of optical amplifiers or repeaters when present in the optical transmission section layer network.

3.3.2 Network Architectures

There are a number of all-optical network architectures currently under development. Each must be examined from an NS/EP perspective to ensure that special interests do not restrict NS/EP capabilities. Several of these architectures are presented below.

3.3.2.1 AT&T/MIT-LL/DEC AON Architectures

A consortium made up of the American Telephone and Telegraph company (AT&T), Digital Equipment Corporation (DEC), and Massachusetts Institute of Technology Lincoln Laboratory (MIT-LL) have developed two network architectures based on WDM and OTDM. These architectures were examined for applicability with NS/EP.

3.3.2.1.1 WDM-based Architecture

This architecture provides scalability through wavelength reuse and Time Division Multiplexing (TDM). As illustrated in Figure 2, the architecture specifies a three-level {i.e., Level-0 (L-0), Level –1 (L-1), and Level-2 (L-2)} hierarchy of sub-networks. Each sub-network is an AON capable of autonomous operation.

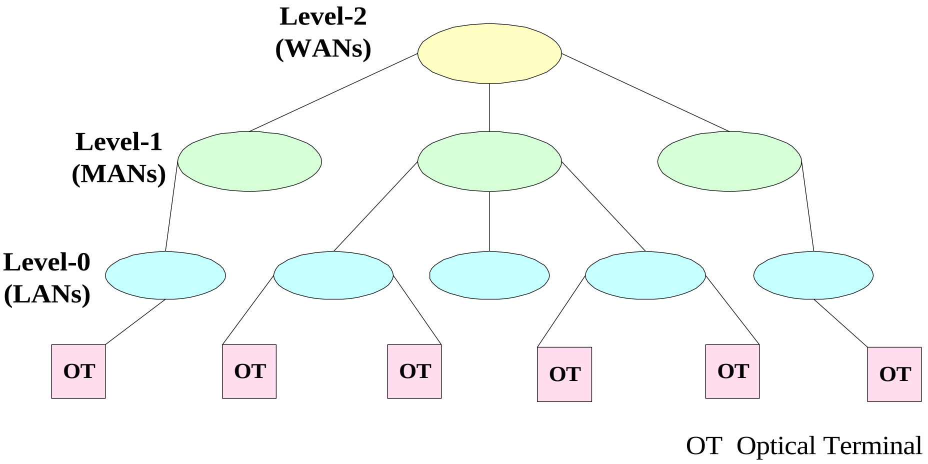

Figure 2: WDM-based Network Architecture

At the lowest level of hierarchy are L-0 sub-networks, each consisting of a collection of high performance Local Area Networks (LANs). Users access L-0 sub-networks through Optical Terminals (OTs). Each OT is connected to an L-0 sub-network using a pair of optical fiber cables. Each L-0 sub-network shares wavelengths internally with an extensive reuse of wavelengths among different L-0 sub-networks. At the middle level of hierarchy are L-1 sub-networks or Metropolitan Area Networks (MANs). Each MAN interconnects a set of L-0 sub-networks and provides wavelength reuse among different L-0 sub-networks via passive wavelength routing. At the highest level of hierarchy is L-2 sub-network. This sub-network is a Wide Area Network (WAN) that consists of many nodes connected in a mesh topology. It interconnects Level-1 sub-networks using wavelength routers and wavelength converters.

Each sub-network provides three types of services to the sub-networks or OTs below it. These services are classified as Type-A, Type-B, and Type-C service and perform the following functions:

- **Type-A service:** This service provides a dedicated optical path for point-to-point, point-to-multi-point, and multi-point-to-multi-point communications. For instance, the optical terminals through Type-A service might provide point-to-point OC-192 and point-to-multi-point video multicast. A "virtual" shared media LAN, a.k.a. V-LAN, can be configured through a multi-point-to-multi-point A-channel. Optical terminals on the V-LAN communicate via the multiple access protocol such as slotted ALOHA. ALOHA is a multiple channel access method, developed by the University of Hawaii.

- **Type-B service:** This is a scheduled TDM service that is transparent within its time slots and it is useful for lower bandwidth applications. A user can transmit data in any modulation rate and format within a slot or a group of slots, however they should be specified at connection setup to ensure the proper recovery of signal at the receiver. The Type-B service, like Type-A service, supports point-to-point, point-to-multi-point, multi-point-to-multi-point, duplex, and simplex connections. The services that optical terminals provide through B-channels include OC-3 connections and Ethernet or Fiber Distributed Data Interface (FDDI) virtual networks.

- **Type-C service:** This is an unscheduled datagram service. In this service, a packet of information may be transmitted in a specific data and modulation format on a specific wavelength. This service is not transparent since it must serve as a common communication link between all users of the AON. It can be used for auto-configuration of the network, network management and control, signaling network that is primarily used for resource scheduling, network operation, administration, and maintenance.

Each sub-network has a “scheduler agent” to handle various functions including wavelength and time-slot allocation among the various Access Points (APs). These APs are optical interfaces between OTs and the AON. The scheduler agent may be implemented in one or more OTs or in a dedicated node attached to each level sub-network. A distributed algorithm is used to elect one OT as an active scheduler agent between the OTs. If there is a scheduler agent failure, the distributed algorithm is triggered again. Based on the sub-network levels, the scheduling is classified into three levels; Level-0 (L-0), Level-1 (L-1), and Level-2 (L-2) scheduling and the following functions are performed at the respective level:

- **Level-0 Scheduling:** The L–0 scheduler agent is responsible for the following functions.

  - ✓ Authenticate, authorize, and service requests for Type-A, Type-B, and Type-C connections from AP’s in its L-0 AON;
  - ✓ Distribute and collect timing information necessary for the establishment of Type-B connections;
  - ✓ Maintain an accurate schedule for all the wavelengths and update the schedule when connections are setup or terminated;
  - ✓ Collect accounting information; and
  - ✓ Communicate with its L-1 scheduler, enforce control and management policies, and perform a number of ancillary functions including name-to-address mapping.

- **Level-1 Scheduling:** In addition to L-0 scheduler agent’s functions, a L-1 scheduler agent must perform the following:

  - ✓ Authenticate, authorize, and satisfy requests for inter L-0 and inter L-1 connections;
  - ✓ Provide a matchmaker function to establish a wavelength path from one of its constituent L-0 AONs to another;
  - ✓ Establish multicast connections using the frequency selective coupler or star;

- ✓ Communicate with its L-2 scheduler agent to allocate light paths as necessary; and
- ✓ Provide timing information to its L-0 AONs to establish Type-B connections.

- **Level-2 Scheduling:** In addition to the L-0 and L-1 scheduler agents' responsibilities, the L-2 scheduler agent must authenticate, authorize, and satisfy requests for inter L-1 connections.

In this hierarchical architecture, when an OT needs to establish a connection, it sends a connection request to the L-0 scheduler agent. The connection request includes various criteria such as the type of requested service, the address of the requested OT, the desired throughput, and priority. Upon receiving a connection request, the scheduler agent determines whether the destination is also in its L-0 AON or not. If the destination is on its L-0 AON, then it determines the availability of the necessary resources. If the resources are available, then it establishes the connection.

If the destination is on a different L-0 AON, but in the same L-1 AON, then the L-0 scheduler agent requests its L-1 scheduler to select a wavelength to provide a light path between its own L-0 and the other L-0. If the destination is not in the same L-1 AON, then the L-0 scheduler requests its L-1 scheduler agent to find a light path using a locally available wavelength. Once a light path is established, the connection establishment process is completed as described above.

We have has examined the use of the priority function at the OT level. While the "priority" simply refers to the allocation of logical and physical resources, it is envisioned that a means to link this capability to NS/EP could be of value to the NCS.

3.3.2.1.2 OTDM-based Architecture

The OTDM-based architecture was developed to handle ultra high-speed communications. However, there are several design concerns to consider:

1) The need for an architecture that will provide both guaranteed bandwidth (GBW) and random access bandwidth on demand (BOD) services at the same time;

2) The need for a policy that will govern the sharing of bandwidth efficiently and fairly among BOD users under any network traffic conditions;

3) The need for algorithms simple enough to execute at the rates required by optical networks.

Based on these concerns, the Helical LAN (HLAN) was proposed. The HLAN is a frame-based slotted architecture and appears to simultaneously satisfy all the above criteria. It uses a helical unidirectional bus and can also be implemented in a linear structure, which may be more appropriate for MAN.

The HLAN architecture is designed to operate at 100 Gb/s, and it is scalable to faster rates. In this architecture, as shown in Figure 3, an optical fiber is divided into three non-overlapping segments; Transmitter (GBW and BOD), and Receiver (RCV). The GBW segment is used to transmit traffic requiring guaranteed bandwidth. The BOD segment is used to transmit traffic that requires BOD and the RCV segment is used to receive the traffic transmitted on the bus.

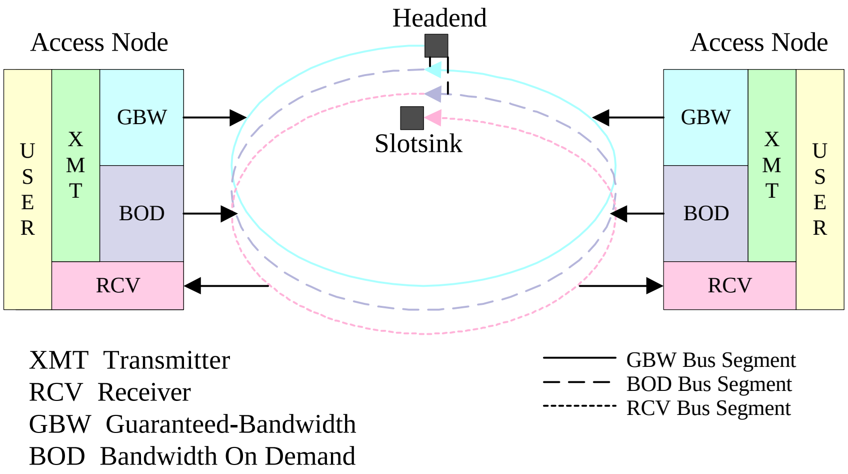

Figure 3: The HLAN Architecture

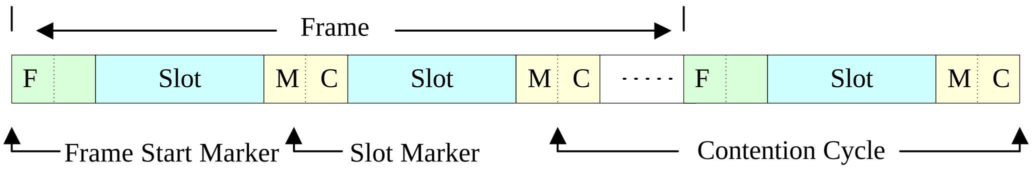

Figure 4: HLAN Frame Structure

Each node on the bus is equipped with a headend/slot processor, protocol logic unit, clock recovery mechanism, and buffers. A headend generates frames of empty slots and puts them on the bus. The HLAN architecture can support slot rates of 10^7 to 10^8 slots per second. The frame structure is illustrated in Figure 4. Each node obtains services by requesting them from the headend over the BOD service or any of the other facility. For GBW service requests, the headend allocates reserved slots, if available, to the requesting node on the GBW segment. Any unused GBW slots are used for BOD service. For BOD service requests, the headend creates credit allocations using slot markers. Allocating a certain number of credits for each slot marker received does this. Additionally, credits are reduced each time a slot is used. When there is no data to send, a node's credit count is reset back to the original number of credits.

In order to prevent lockouts from high traffic nodes, the headend monitors free slots at the end of the bus. If no free slots are observed for a specified period of time, the length of the credit allocation interval is increased. This results in a decrease in the bandwidth available to individual nodes. If the headend observes multiple slots at the end of the bus, it reduces the length of the credit allocation interval. This provides more bandwidth to individual users.

3.3.2.2 Bellcore's AON Architecture

Bellcore, Columbia University and several other research laboratories jointly developed another architecture. This high capacity WAN architecture is based on DWDM and wavelength routing, and is scalable and modular in terms of the number of networked users, the number of nodes, the geographical range of coverage and the aggregate network capacity.

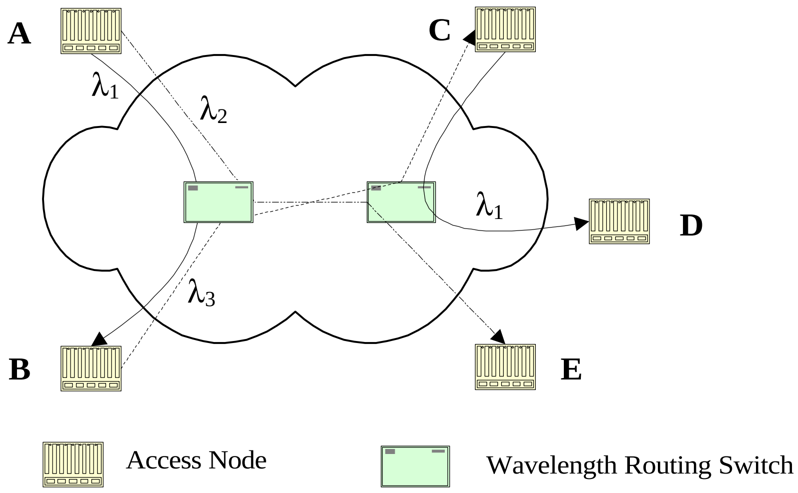

Figure 5: Bellcore's Multi-wavelength All-Optical Network Architecture

As shown in Figure 5, the network architecture consists of an all-optical inner portion that contains wavelength-routing switches. According to the wavelength-continuity constraint for wavelength-routed networks, two lightpaths (a.k.a. optical communication channels) that share a common fiber link should not be assigned the same wavelength. In the Figure, λ_1, λ_2, and λ_3 are available wavelengths of the network. Wavelength λ_1 is being used in two lightpaths for A-B and C-D connections since the two paths use different wavelength-routing switches. λ_2, and λ_3 can occupy the path between wavelength-routing switches because they are different frequencies. However, if a switching or routing node is also equipped with a wavelength converter, then the wavelength-continuity constraint disappears, and a lightpath can be switched between different wavelengths on its route from its source to its destination. For this reason, routing and wavelength assignment is a major challenge in wavelength-routed networks without wavelength converters. Further, the lack of wavelength conversion increases the probability of connection blocking because the same wavelength may not be available at all nodes for a particular lightpath on its route from its source to its destination. Wavelength converters are very expensive and are not used at all nodes in the network. Bellcore's architecture uses wavelength converters only at selected nodes in its network.

3.3.2.3 OCDM-based Architecture

A typical OCDM based architecture is shown in Figure 6. In this architecture, nodes are connected to a passive NxN star coupler. The OCDM encoder of each transmitting node represents a "1" bit by a series of ultra-fast optical pulses called the address code or the signature sequence. The "0" bit is not encoded and is represented by an all zero sequence. Each node's separately encoded signal is sent to the N×N star coupler and broadcast to all nodes.

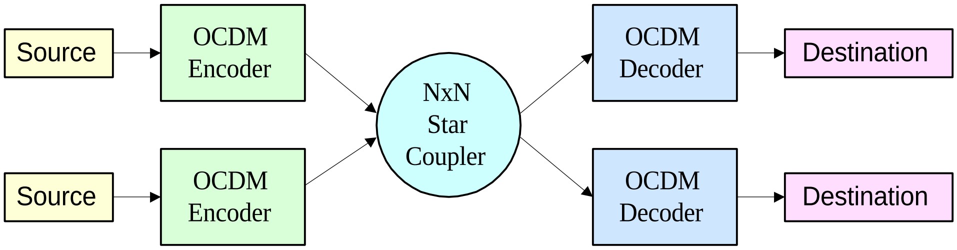

Figure 6: OCDM-based Network Architecture

The primary goal of an OCDM system is for each node to extract data with its address code in the presence of all other users' optical pulse sequences. Hence, an OCDM system is designed with the following three conditions in mind:

- The auto-correlation for an OCDM code should be as large as possible to ensure that the received signal is much larger than the background noise in the system.

- The cross-correlation between two different codes should be as small as possible to ensure each code can be easily distinguished from every other OCDM code.

- The shifted auto-correlation for a given OCDM code should be minimized to allow OCDM to operate without the need for synchronization.

3.4 CONTROL AND MANAGEMENT OF AON

Control and management of AON is essential for efficient and continuous operation of various network resources. This is achieved by using efficient network management and network survivability techniques. Network management is "the execution of the set of functions required for controlling, planning, allocating, deploying, coordinating, and monitoring the resources of a telecommunications network, including performing functions such as initial network planning, frequency allocation, predetermined traffic routing to support load balancing, cryptographic key distribution authorization, configuration management, fault management, security management, performance management, and accounting management" (Federal Standard 1037C, *Telecommunications: Glossary of Telecommunication Terms*, August 1996).

Accordingly, network management in AONs is responsible for monitoring the operating conditions of each component, detecting the conditions of continuity, connectivity and quality of optical fiber links, and responding to faulty and degraded performance conditions. This is achieved by exchanging control and management information between the management console and network resources, also called Network Entities (NEs). In AONs, a separate channel, called Optical Supervisory Channel (OSC), is used to exchange the control and management information. Presently, most of the work in AON management addresses configuration, fault, and performance management, and is mainly geared towards WDM systems. The following sections discuss configuration management, performance management, fault management, and network survivability.

3.4.1 Configuration Management

Once the equipment and fibers are in place, software functions are invoked to configure the network. A Network Management System (NMS) constructs a view of the network by:

a) Issuing queries to the NEs;
b) Monitoring notifications triggered by NE configuration updates;
c) Issuing requests to change the nodal configuration; and
d) Issuing requests to set up end-to-end optical paths.

Thus, configuration management-related functions such as automatic topology discovery and end-to-end connection establishment play important roles in configuration management.

3.4.1.1 Automatic Topology Discovery

Automatic topology discovery enables the NMS to discover and verify link connectivity between adjacent NEs. For AONs, link connectivity discovery allows the management system to build a network fiber map, often referred to as physical medium map. This map is essential for subsequent optical path setup and fault isolation. The three methods that can be used for automatic topology discovery in optical networks are:

a) OSC-Assisted Adjacency Table Update;
b) OSC-Assisted Adjacency Table Update for Non-OSC Supporting Links; and
c) Management System Coordinated Topology Discovery.

3.4.1.1.1 OSC-Assisted Adjacency Table Update

In this method, an OSC is used to determine the adjacency of two NEs connected by the same optical fiber supporting the OSC. Upon determination of connectivity to the adjacent nodes, NEs update their adjacency tables. Unique names or identifiers are used for the NEs and the ports so that adjacency information can be exchanged and used to form an entry into the adjacency tables. An entry for the adjacency tables includes port name, adjacent NE name, and adjacent NE port name. The management system queries adjacency tables for all NEs to construct a network fiber map.

3.4.1.1.2 OSC-Assisted Adjacency Table Update for Non-OSC Supporting Links

Because of cost constraint, every WDM link between the same pair of NEs may not support an OSC channel. However, the adjacency information table can be updated over all the fibers if at least one pair of fiber to an adjacent node supports an OSC. This method requires all ports to have optical sources, optical sinks, and modulation detection capabilities. The method is invoked during the pre-provisioning phase for the links under consideration. A major limitation of this method is that it can be invoked only during the pre-provisioning stage, and cannot be used once the service-bearing wavelengths are introduced.

3.4.1.1.3 Management System Coordinated Topology Discovery

In this method, the presence of OSC is not necessary and the NEs do not have to update adjacency tables. However, an NE must be able to respond to a request from the management system to modulate the signal on any specified output port with a fixed bit pattern, and then detect and report the presence of such modulation on any input port. The management system determines the fiber links between NE ports by issuing such a request on successive NE-ports and monitoring for appropriate notifications.

3.4.1.2 End-to-End Connection Establishment

There are two methods for making an end-to-end optical connection: provisioning system based and control, or signaling, based. In the provisioning system-based method, the management system coordinates route selection and cross-connect activation at NEs along the path. In contrast, a control or signaling based method relies on peer-to-peer signaling between the control software loaded into NE’s. This method does not require management system intervention. The signaling could take place over an overlay network (similar to public switched network used today) or over OSC. However, this method requires standardization of the signaling protocol to ensure interoperability among different systems that coexist within the network.

3.4.1.2.1 Connection Provisioning

During connection provisioning, the selection of an optical path may be accomplished using one of the following approaches:

a) The operator may hand-select the exact path for the connection;

b) The operator may be partially assisted by identifying one or a few tandem points in the path; or

c) The path selection may be completely automated.

In the last case, a route is assigned by a path provisioning system based upon input request parameters such as the identity of source and end points, source wavelength, and level of QoS required.

There are a number of constraints that must be enforced for optical path setup. Some of these constraints are as follows:

- Path provisioning must not impact existing services. An introduction or removal of a signal at any wavelength should not impact the signals on other wavelengths.

- An optical loop must not be created since it can result in immediately bringing down all the services in the path of the loop.

- Maximum value of hop count must not exceed a maximum value over any given span. Because the signals of different rates and formats have different end-to-end performance requirements, a connection manager must be able to determine the maximum hop count and choose a route that meets the requirements. This constraint must be satisfied even when the protection switching is activated.

- Existence or absence of a wavelength due to provisioning or fault must be clearly noticeable.

3.4.1.2.1.1 Optical Path Provisioning Sequence

In high-speed optical transmission networks, the light over a particular link stays present and constant regardless of the path provisioning process and the unexpected disappearance of light is an indication of failure. Hence, the specification of the signal propagation sequence during the path provisioning process is important to clearly isolate fault conditions.

There are two procedures that specify the signal propagation sequence during optical path provisioning. They are sequenced-verified connection setup procedure and concurrent commit procedure.

- In sequenced-verified connection setup procedure, the management system issues connection requests sequentially from upstream to downstream NEs. An NE activates a cut-through only if the provisioning request signal on a particular wavelength and port is observed. The NE sends a confirmation message to the management system on verifying the proper signal at the output port. The management system then issues the next connection request to the following NE. This sequenced-verified connection setup procedure allows the management system to track the propagation of a new signal and to promptly and properly identify failures.

- In concurrent commit procedure, the management system issues simultaneous requests to all the NEs without waiting for cut-through verification from each node. An NE returns success connection request confirmation after cut-through activation without signal verification. With this procedure, the management system relies on separate event notifications from the NEs indicating appropriate signals were detected in order to verify successful end-to-end connection.

3.4.1.2.1.2 Multi-domain Path Setup and Switched Circuit Setup

To establish an end-to-end connection through multiple networks or administrative domains requires sequencing of light propagation and messaging. These can be achieved by exchanging messages between management systems. Typical messages involve Connection Setup Request (CSR), Connection Setup Confirmation (CSC), Connection Complete Confirmation (CCC), Release Request (RR), and Release Request Confirmation (RRC). For example, consider a scenario involving three networks. The first network with an end-user receives a connection request and forwards the CSR message to next network, and so on until the CSR is delivered to the end-network. The CSR message may contain the address of the end-users, the identification of the ports at the network boundary, and, possibly, the incoming wavelength. After the destination is verified and the end user accepts the connection request, the end-network activates a bi-directional connection so that the optical signal from the destination point is propagated in the backward direction with a CSC message. Finally, when all the connections have been activated in all the intermediate networks including the networks with two end-users, the optical signal in the forward direction is transmitted, and the CCC messages are issued so that the two end-users can start communicating with each other.

3.4.1.2.1.3 Switched Connection Setup

In Switched Connection Setup, end-users directly control the network resources to set up end-to-end connections. The network relies on NE control software and signaling instead of a management system to set up end-to-end connections. This is so because the connections can be held during an arbitrary length of time and a management system cannot be expected to track the creation and release of connections in real time. This fact introduces a new challenge to performing fault diagnostics and releasing faulty circuits. Similarly, new management challenges may be introduced when the ability to carry switched circuits is combined with the ability to carry different signal types.

3.4.2 Performance Management

All-optical networks should be able to detect performance degradations in order to avoid failures and maintain end-to-end QoS within and between administrative domains. To accomplish this objective, a set of performance metrics is required. Presently, The American National Standards (ANS) Committee T1X1.5 is working on the development of such a set for each layer of the functional architecture of AON. As explained in section 3.3.1, the functional architecture specifies Optical Channel Layer Network, Optical Multiplex Section Layer Network, and Optical Transmission Section Layer Network. Table 1 shows proposed performance metrics addressing the application of various performance-related attributes to these layers. Currently, the metrics include performance-related attributes such as loss of continuity, connectivity supervision, signal quality supervision, maintenance indication, equipment failures, and non-intrusive payload monitoring. The metrics may be refined as the work progresses.

No.	**Fault Condition**	**OCL Layer**		**OMS Layer**		**OTS Layer**	
		Client Channel	**Supervisory Channel**	**Client Channel**	**Supervisory Channel**	**Client Channel**	**Supervisory Channel**
1	Loss of Continuity	R	R	R	R	R	R
1.1	Loss of signal	R	R	R	R	R	R
1.2	Laser bias current	A	A	A	A	A	A
1.3	Optical power Transmitted	R	R	R	R	R	R
1.4	Optical power Received	R	R	R	R	R	R
2	Connectivity Supervision	R	R	R	R	R	R
2.1	Trail Trace Identification		R		R		R
3	Signal Quality Supervision	R		R		R	
3.1	Spectral filtering / Spectral mask	R		R		O	
3.1	Cross-talk	R	R	R	R	O	O
3.3	Quality factor	R	R	R	R	O	O
4	Maintenance Indication	R	R	R	R	R	R
4.1	Forward defect indication	R	R	R	R	R	R
4.2	Backward defect indication	R	R	R	R	R	R
5	Equipment Failures	R	R	R	R	R	R
6	Non-intrusive Payload Monitoring	A		A		A	

R: Required; A: Application Specific; O: Optional, and Blank: Not applicable.

Table 1: Performance Metrics

3.4.3 Fault Management

Fault management is a set of functions that (a) detect, isolate, and correct malfunctions in a telecommunications network, (b) compensate for environmental changes, and (c) maintain and examine error logs. Fault management includes; accepting and acting on error detection notifications, tracing and identifying faults, carrying out sequences of diagnostics tests, correcting faults, reporting error conditions, and localizing and tracing faults by examining and manipulating database information.

Generally, network level faults are discovered through alarm surveillance, detection of secondary symptoms such as performance degradation, or through customer call-in. Alarm surveillance generates alarm notifications indicating presence of fault conditions. Typical alarms include hardware failure alarms, software failure alarms, communications alarm, and environmental alarms. The communications alarms are of particular importance to optical networking because they indicate signal loss or degradation. They rely on the signal monitoring points that are located within a network element. Typical parameters that may be monitored using communications alarms include optical signal power, optical Signal to Noise Ratio (SNR), and wavelength registration.

For efficient fault management, alarm thresholds for most parameters should be standardized. Further, since network can simultaneously carry signals at different rates, per-channel thresholds such as SNR limits may be configured on a per-connection basis. For example, the SNR requirement is much more stringent for a wavelength carrying 10 Gb/s signal compared to a channel carrying 600 Mb/s.

An alternative is to use common threshold value for all channels and to select this threshold to meet the most stringent signal requirement. A major drawback of the common threshold approach is that an alarm may be generated even when the optical signal degradation does not impact the requested service. To overcome this problem, another scheme has been developed where the alarm surveillance between the optical layer and digital layer are coupled via optical supervisory channel communications. Thresholds are set for the optical signals, but the actual alarms are generated only if optical signal degradation is accompanied by digital signal failure. Use of this scheme requires interoperable signaling between optical NE’s and client digital NE’s. Additionally, transparent optical network does not monitor digital signals. Due to this fact, some failure modes are too difficult to isolate by means of optical monitoring alone. These modes include optical cross-connect failure and a failure in electronics of the wavelength-interchanging module.

3.4.4 Optical Network Survivability

Optical network survivability techniques enhance the survivability of AONs from link and node impairments. These techniques encompass both protection and network restoration capabilities. A protection mechanism or backup capacity makes use of pre-assigned capacity between nodes. The simplest architecture is a one-to-one relationship between the working path and the backup path, while the most complex architecture is a many-to-many relationship. ITU-T Recommendation G.872 considers two types of protection mechanisms: trail protection and sub-network connection protection.

Trail protection is a dedicated protection mechanism that can operate in a unidirectional or a bi-directional manner. It can be used for any topologies including mesh, ring, or mixed. Further, it can be applied in both the Optical Channel Layer and Optical Multiplex Section Layer of the optical transport functional architecture. A protection trail replaces a working trail in case of working trail failure or performance degradation below the required level. Like trail protection, sub-network connection protection can be used for any physical topologies. Additionally, it can be used to protect part or all of a network connection. In general, network restoration capabilities involve rerouting. These capabilities are under further study.

3.5 AON Security

A major concern of the National Communications System is Network Integrity, particularly during NS/EP conditions. As new technologies are introduced security will become increasingly important in the effort to reduce network vulnerability.

It is clear that AONs are emerging as a viable technology for future telecommunications networks. However, security differences with respect to existing electronic and electro-optic networks have drawn considerable attention. Some of the features and vulnerabilities are as follows:

- Because of the very high data rates (on the order of Tb/s) in AONs, large amount of data (i.e. number of "bits in flight") may be corrupted or damaged, even in the cases of short or infrequent attacks.

- End users may continue to use protocols such as TCP/IP that are designed for slower electronic networks. Use of such protocols at very high bit rates over large distances can allow service denial attacks using sporadic or relatively low power methods. Such attacks are very difficult to detect.

- Transparent AONs allow routing and switching of optical signals within the network without regeneration. This transparency raises many security vulnerabilities that do not exist in electro-optic or electronic networks involving signal regeneration. For example, attackers may transmit malicious signals that can pass through transparent components and disable portions of a network. Such situations do not exist in the networks involving signal regeneration because a regenerating node does not propagate an anomalous signal.

To provide secure and reliable AONs, various security issues should be considered including physical security and information security. Physical security prevents unauthorized access to network resources. Information security, on the other hand, prevents unauthorized access to information, and assures confidentiality and integrity of the information. Currently, most of the research efforts on AONs security are geared towards the physical security, and a little work has been done on the information security, in particular, the cryptographic needs of AONs. Accordingly, the following sections focus on the physical security of AONs.

3.5.1 Physical Security

Service disruption and tapping are the two most common threats to the physical security of AONs. The most commonly used AON components including optical fiber cables, combiners, splitters, multiplexers, demultiplexers, optical amplifiers, optical transmitters (or lasers), and optical receivers are susceptible to service disruption and tapping attacks.

3.5.1.1 Service Disruption Attacks

Service disruption attacks can cause data delay, service denial, QoS degradation, and spoofing. These attacks are discussed in the context of optical fibers, amplifiers, and Wavelength Selective Switches (WSSs) since these devices are the fundamental building blocks of AONs. Under normal operating conditions, optical fibers radiate a negligible amount of power from the fiber compared to other wave-guide media such as coaxial cable. However, like coaxial cable, service can be easily disrupted by cutting or in some way disrupting the optical fiber. A less disruptive attack is to slightly bend the optical fiber so that light may be radiated into or out of the fiber.

Two other most widely used methods of service disruption attacks are in-band jamming and out-of-band jamming. In in-band jamming, an attacker injects a signal designed to reduce the ability of the receiver to interpret the transmitted data correctly. The attack can degrade a signal on that link, and affects other links attached to the node at which the attack signal reaches first. This is primarily due to transparency feature of AONs that lets signals flow through nodes without regenerating them.

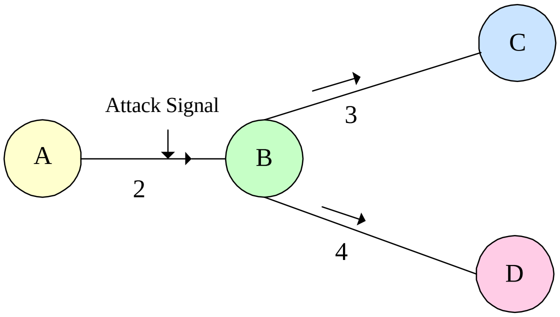

Figure 7: In-band Jamming Attack

In-band jamming also can be used to attack WSSs (Figure 7). WSSs in AONs are used to route signals of different wavelengths to different outputs. These WSSs can have cross-talk levels of –20 dB to –30 dB depending on their building blocks such as multiplexers and demultiplexers. Although these cross-talk levels are adequate for most communication purposes, an attacker can use them to disrupt or deny service. For example, for service denial attack, the attacker injects a very strong signal (in-band jamming) into the device.

In out-of-band jamming, an attacker reduces communication signal component by exploiting leaky components or cross-modulation effects. An out-of-band jamming attack can be used to exploit crosstalk in various components. In this type of attack, an attacker injects a signal at a different wavelength from the communication bands, but within the amplifier passband. The amplifier provides gain to attack signals and legitimate network communication signals indiscriminately from a finite supply of gain because it cannot distinguish between those signals. The gain intended for communication signal is robbed by the attack signal and the power of the attack signal is increased large enough to propagate through transparent nodes. The level of damage due to this attack is dependent on the distance between the amplifier and the attacking location, specifications of amplifier, and the network architecture.

It is believed that directed Electromagnetic Pulses (EMP) could cause both in-band and out-of-band jamming. Therefore, this should be a subject for further study by the NCS.

3.5.1.2 Tapping Attacks

Tapping can be used to gain unauthorized access to information that may be used for eavesdropping or traffic analysis. Tapping attacks are possible at several points within the network due to component crosstalk. For example, contemporary demultiplexers within network nodes separate each individual signal (or wavelength) received from a single fiber on to separate physical paths. These demultiplexers may exhibit cross-talk levels between 0.03% and 1.0%. These cross-talk levels allow a little of each signal to leak onto the wrong path. Yet these signals may have enough fidelity to permit an attacker to detect their presence and recover a portion of data.

At high signal levels, such as at the output of an optical amplifier, fibers exhibit some cross-talk that may be used for tapping by co-propagating a signal on the fiber. In some optical amplifiers, the gain competition among signals occurs at the modulation rate. In such cases, tapping can be achieved by observing cross-modulation effects.

Tapping can also be combined with jamming for very powerful service disruption attack. Since delays vary extremely slowly with respect to data rates, an attacker can tap a signal and then inject a signal downstream of the tapping point. This type of attack is called a correlated jamming attack. This attack is very harmful to users with very low Signal to Noise Ratio (SNR).

3.5.1.3 Attack Prevention

For secure and reliable communications, attack prevention measures must be taken. These measures can be classified into three categories: techniques that reduce the vulnerabilities which are intrinsic to the hardware, transmission techniques that are effective against certain attacks, and protocols and architecture designs adapted to AONs.

Some hardware measures can be employed to alleviate service disruption attacks. For example, using Optical Limiting Amplifier (OLA) limits the output power to a specified maximum. Setting limits on light power also limits crosstalk and, therefore, crosstalk detection. Band-limiting filters may be used to discard signals outside a certain bandwidth. This can prevent gain competition attacks in optical amplifiers. A physical tap into the fiber can be prevented using physical strengthening, alarming the cladding, or attempting to detect small losses of power due to tapping. However, physical strengthening and alarming the cladding need tremendous changes in the existing infrastructure, and that entail significant expense. Additionally, physically securing optical fiber against physical tapping does not provide protection against tapping via crosstalk. As an alternative, devices with lower crosstalk may mitigate both service disruptions and tapping attacks.

Transmission schemes may play an important role in preventing service disruption and tapping attacks. The transmission schemes cover many techniques including acclimated modulations that are inured against certain attacks, coding to protect against jamming attacks, intelligent limiting of signals to certain bandwidth and power constraints, and diversity mechanisms that make attacks more difficult.

In protocols and architecture designs, there may be some issues such as avoidance of easily compromised links for sensitive communications, and judicious wavelength and path assignments that seek to separate trusted users from not-trusted users.

3.5.1.4 Attack Detection

Various existing supervisory techniques and automatic diagnostics can be applied to detect attacks upon AONs. Supervisory techniques are classified into two categories; methods that perform statistical analysis of data, (Power detection and Optical Spectrum Analysis (OSA) methods fall into this category.), and methods that measure a signal devoted to diagnostic purposes (Pilot tones and Optical Time Domain Reflectometry (OTDR) methods fall into this category.).

- **Power detection methods:** These methods are based on the comparison of received optical signal power to the expected value of optical signal power. Any change in the received optical signal power with respect to the expected signal power could be used to determine security attacks. There are two major drawbacks of these methods. Firstly, a slight decrease in optical signal power is difficult to detect. Secondly, small but detectable changes in optical signal power resulting from component aging and fiber repairs may not be attributable to attacks, and may not adversely affect optical signals. Power detection techniques, with the selected thresholds matched to the level at which communication services will be degraded, are used.

- **Optical spectrum analysis methods:** These methods measure the spectrum of an optical signal. They are able to detect a change in spectrum shape, even if that change in shape does not involve a change in power over the whole channel. For example, two optical signals can have the same total power, but they can have a different spectrum. Optical spectrum analysis methods provide more information than power detection methods. However, they rely on statistical comparisons between sample averages and statistical averages that require additional processing time that makes them slower than some other attack detection methods.

- **Pilot tone methods:** These methods use highly defined and unique signals, called Pilot tones, which travel along the same links and nodes as the communications data. They are used to detect transmission disruptions.

- **Optical time domain reflectometry methods:** Optical time domain reflectometry methods are a special application of pilot tones. They analyze the pilot tone's echo. These methods are typically used to detect attacks that involve fiber tampering.

These attack detection methods can be used to detect service disruptions and tapping attacks. This is explained in the following sections.

3.5.1.4.1 Detection of Service Disruptions Attacks

3.5.1.4.1.1 Power Detection Methods

In an in-band jamming attack, the signal power at the receiver increases. The increase in the signal power can be detected by power detection methods. However, sporadic jamming attacks may degrade the BER to unacceptable levels without causing a strong enough rise in signal power to generate an alarm, particularly, if the statistics of the received signal are not well specified.

3.5.1.4.1.2 Optical Spectral Analysis (OSA) Methods

OSA methods usually provide more information than power detection methods except for jamming through crosstalk. Therefore, they may be more appropriate to detect changes in spectrum shape even when there are not sporadic or pulsed attacks.

The source of a gain competition attack may be determined by the use of OSA methods as long as the analyzed band is sufficiently large to encompass the carrier frequency of an out-of-band attack. For example, an attacker can introduce a signal in the most peaked area of the gain spectrum and an OSA may be able to show the presence of such an attacker even though power detection on the individual channels will not.

3.5.1.4.1.3 Pilot Tone Methods

These methods use highly defined and unique signals, called Pilot tones, which travel along the same links and nodes as the communications data. They are used to detect transmission disruptions. Pilot tones are unique and distinguishable from the communications data. They are often transmitted at different carrier frequencies than the transmitted signal, but they can be distinguished from the communications data by certain time slots (in TDM systems) or certain codes (in CDM systems). The pilot tones are usually referred to as Sub-Carrier Multiplexed signals if they are present, in frequency, in the close vicinity of the communications transmissions. The Sub-Carrier Multiplexed signals allow the transmission of network signaling or of a pilot tone at the same carrier wavelength as the payload signal. The tone may be dynamically tunable to transmit network control information.

Pilot tone methods can be used to detect jamming attacks. But, if the carrier wavelengths of pilot tones are not attacked, this method is not effective in detecting jamming attacks. The ability to detect an attack depends upon the modulation and the SNR of the pilot tone. Gain competition affects all wavelengths through an amplifier, although not all wavelengths are equally affected. If the pilot tones traverse the same amplifiers as the communication signals, then the pilot tones are affected by gain competition when communication signals are. If the pilot tones are amplified separately, they cannot detect a gain competition attack.

Pilot tone methods detect tapping attacks by determining whether the pilot tones on the tapped channel are affected or not. The pilot tones are affected if the tapping attack causes significant degradation of the signal.

3.5.1.4.1.4 Optical time domain reflectometry methods

Optical time domain reflectometry methods are a special application of pilot tones. They analyze the pilot tone's echo rather than analyze pilot tone. These methods are typically used to detect attacks that involve fiber tampering.

For an in-band jamming attack, some of the jamming signal is returned in the reflections. This jamming signal is observable. If there is some modulation on the OTDR probe signal, then detection of a jamming signal superimposed on the OTDR probe signal may be fairly sensitive. In branched networks where wavelengths are demultiplexed onto different fibers, different branches could be probed with different wavelength probe signals. Therefore, jamming may be detected over different branches and its spreading through a branched network could be traced.

The probing of Erbium-Doped Fiber Amplifiers (EDFAs) by OTDRs is different from the probing of fiber lines by OTDRs. If EDFAs are unidirectional, then they are not useful for amplifying reflected signals and a bi-directional amplifier is required. Thus, OTDRs are not generally useful in determining gain competition among signals over a cascade of EDFAs. However, if EDFA is used as a preamplifier for the OTDR as well as a power amplifier for the communication system, then gain competition at an EDFA is detectable over the reflected OTDR.

Optical time domain reflectometry methods may be used to detect in-line eavesdropping. These methods detect discontinuities or losses in the fiber due to the extraction of a portion of the signal for eavesdropping. On the other hand, optical time domain reflectometry methods cannot reliably detect tapping occurring through crosstalk that is legitimately present in the network. This can be overcome by searching for traces of optical time domain reflectometry probe signals that may be carrying communications tapped from other fibers.

3.5.1.5 Security and Architectural Concerns

As described earlier in this document, different AON architectures can have different topologies, each with unique security properties. For example, in WDM ring topologies, attacks can be relatively easily localized because of the structured interconnectivity of nodes. Additionally, WDM ring topologies allow easy rerouting because there is only one logical link upon which traffic can be rerouted when an attack is detected. However, service restorations on ring networks can generally require more work because all of the traffic on each ring is co-routed. In mesh topologies, on the other hand, the richer node interconnectivity generally guarantees easier service restoration. In star topologies, attacks are commonly received at many stations. This may make attack detection easier than other topologies. However, compromise of the hub disrupts all network services.

Each topology provides its own intrinsic security advantages and no topology ensures the absolute best network security. Most detection methods can support any topology, but with different level of effectiveness.

3.6 AON Applications

There is a wide range of potential AONs applications (Figure 8) in commercial, government, scientific, and academic arenas. In the near-term, most of these applications can be individually supported by electronic or electro-optic networks. However, the aggregation of many services and the cost, flexibility, and transparency supported by AONs may prove superior to electronic or electro-optic networks.

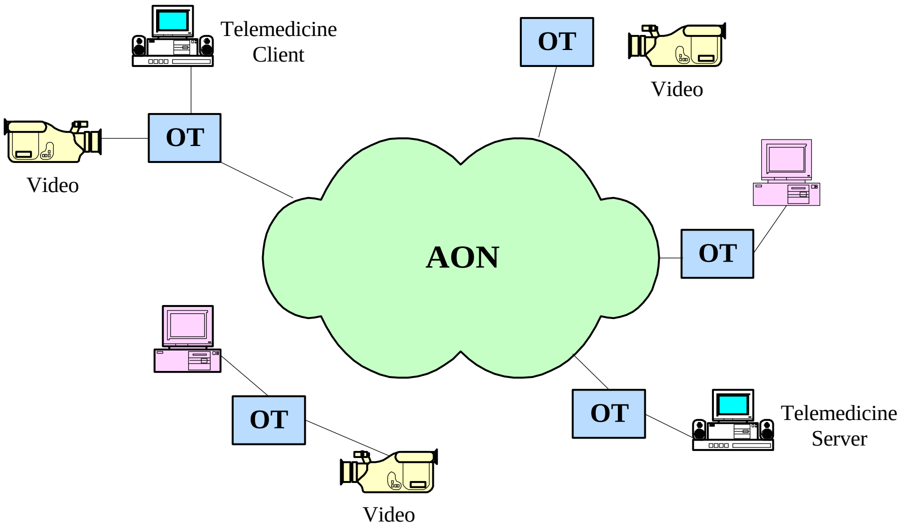

Figure 8: AON Applications

The range of applications can be classified into three categories. The first category contains applications utilizing traditional digital services. The data rates of these applications range from Kb/s to Gb/s. They can be further classified into four subcategories that include applications requiring Gb/s, fast-packet switching such as ATM, visualization, simulation, and supercomputer interconnects. The second covers applications requiring 100 Mb/s data such as LAN interconnections, compressed High Definition Television (HDTV), digitized conventional video, and workstation interconnects. The third consists of 10 Mb/s applications such as multi-channel digital audio and Ethernet class computer networks, and the fourth subcategory covers applications requiring 1 Mb/s or less such as telephone services and RS-232 class.

The second category includes analog services. For example, in the distribution of multi-channel broadcast television channels, many channels are handled as one unit. Since the rate at which such a unit should be digitized may be high, it is cheaper and simpler to keep it in an analog form.

The third category contains user applications that require an optical interface. These applications 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. Potential applications in this category include future video workstations, massive database servers, and multiplexed digital HDTV sources.

Various AON test-beds have demonstrated a number of applications from the above categories. For example, the Advanced Research Project Agency (ARPA) sponsored AON consortium, made up of the AT&T, DEC, and MIT-LL, tested videoconferencing, telemedicine, supercomputer interconnects, remote classroom learning and other applications.

3.7 Standardization

In addition to the ANS T1X1.5 efforts to develop the United States standard for All Optical Networks, the ITU-T is actively working on the development of global optical network standards. The ITU-T has developed a number of recommendations including G.692, G.872, and G.982.

ITU-T Recommendation G.692, *Optical interfaces for multi-channel systems with optical amplifiers* specifies multi-channel, optical line system interfaces for the purpose of providing future transverse compatibility among such systems. It defines interface parameters for systems of 4, 8 and 16 channels operating at bit rates of up to STM-16 on optical fibers, as described in Recommendations G.652, G.653 and G.655 with nominal span lengths of 80 km, 120 km and 160 km, and target distances between regenerators of up to 640 km. Further, it specifies a frequency grid anchored at 193.1 THz with inter-channel spacing at integer multiples of 50 GHz and 100 GHz as the basis for selecting channel central frequencies.

As mentioned earlier in this report, ITU-T Recommendation G.872 specifies functional architecture of optical transport networks. ITU-T Recommendation G.982, *Optical access networks to support services up to the ISDN primary rate or equivalent bit rates,* deals with the characteristics of an Optical Access Network (OAN) with the capability of transporting interactive services over the Optical Distribution Network (ODN) based on point-to-multipoint configuration using passive optical branching components. It considers an OAN for both business and residential customer service requirements based on 64 Kb/s bearer capabilities up to and including ISDN primary rate services.

Although much progress has been made on various aspects of optical networks, enhancements of the existing Recommendations or the development of new Recommendations is required. Some of the important topics under study in the current ITU-T study period include configuration management, fault management, performance management, protection switching management, selectively suppressing or utilizing optical nonlinearities, soliton transmission, and optical time-division multiplexing.

3.8 Issues and Limitations

AONs offer significant advantages in capacity, connectivity, and cost by allowing information to flow without optical-to-electronic conversions and vice versa. However, the concept of all-optical networking is relatively new and presents a number of new challenges and issues. Some of the issues and limitations of AONs are discussed below.

Various multiplexing techniques such WDM and OTDM have been proposed to share large bandwidth of optical fiber. The OTDM technique can be used to build very high capacity AONs. Then again, compared to WDM-based AONs, OTDM-based networks are in their infancy because many of the essential devices are very expensive and they are still confined to research laboratories. Therefore, near term feasibility seems to lie more with WDM-based networks than with OTDM-based networks.

Transparency has become one of the major attributes in AONs. However, there are varying forms of transparency, and not all networks offer transparency in its purest form; that is, not all groups of optical signals may be transmitted regardless of linearity requirements and modulation format. This is mainly due to the effects of cross-talk propagation, amplification, wavelength selective elements, and SNR limitations.

The concept of layered transport functional architecture offers many advantages, including the possibility of each layer to evolve independently of the other layers. Still, care must be taken to ensure interoperability of the various layers, especially in their management and control functions. The challenge is two fold: First, NE-to-NE interoperability features for both hardware and software should be identified. Second, an NMS needs to be designed and developed to integrate layer-specific and vendor-specific element management systems. There are some activities in the ANS T1X1.5 in this direction.

Control and network management in AONs also presents new challenges. These include such network management functions as fault management, performance management, and configuration management. Standardization of network management functions is essential to achieve interoperability across multiple supplier systems and multiple administrative domains. Presently, the ITU-T and the ANS T1X1.5 are working on the standardization of these functions.

Security is an important aspect of AONs and requires special considerations since a large amount of data may be corrupted or damaged even in cases of short or infrequent attacks. This aspect is not fully addressed yet. More advanced means to detect possible attacks including sporadic jamming, multipoint attacks, and control system and protocol attacks are necessary.

3.9 Conclusions and Recommendations

Today's traditional networks consist of, for the most part, a collection of electronic switches interconnected by point-to-point optical fiber links that span local, metropolitan, and national distances. Over the last few years, a significant demand has been placed on the networks to provide higher bandwidth, higher speed, and greater flexibility. In order to meet these increasing demands, existing networks are being enhanced either by adding more fibers and switches or upgrading switches. A major limitation of these networks is the "electronic bottleneck" consisting of two factors. First, all of the information carried on optical fibers must be processed at electronic data rates that are compatible with the electronic switching equipment in the order of few Gb/s, and second, the information transfer involves time-consuming process of optical-to-electronic conversion, electrical signal processing, and electronic-to-optical conversion of data signals at all intermediate network nodes.

AONs can transmit information at very high speeds and without optical-to electronic conversion and vice versa. Further, AONs tap into the vast bandwidth capacity of optical fiber and effectively utilize it to meet the ever-increasing demand for high bandwidth. Typically, WDM, OTDM, or OCDM are used to effectively utilize optical fiber bandwidth. OTDM and OCDM are less matured compared to WDM and their applications are still limited to various test-beds.

Depending on their functional characteristics, there are three general types of AONs: passive, transparent, and ultra-fast. Passive and transparent AONs can employ WDM or OTDM, but ultra-fast AONs only employ OTDM. These AONs can be used in business, commercial, medical, government, and educational arenas to support a wide range of applications. Potential applications include ultra-high speed computer interconnects, access to vast electronic libraries, telemedicine, video conferencing, video on demand, distance learning, and other multimedia communications. Many of these applications can be used to enhance NS/EP communications during emergency situations. Thus, AONs can be viewed as potential alternatives to electronic or opto-electronic networks during emergency situations.

Since all-optical networking is an emerging concept, further work is needed in security, interoperability, and control and management of AONs. Various standards bodies such as ITU-T and ANSI and other research efforts are addressing these issues. When the technology and standards matures, AONs may prove a viable means to support NS/EP communications during emergency situations.

Appendices

Appendix A: Acronyms

AON	All-Optical Network
AP	Access Point
ARPA	Advanced Research Project Agency
AT&T	American Telephone and Telegraph Company
ATM	Asynchronous Transfer Mode
BER	Bit Error Ratio
BOD	Bandwidth on Demand
CATV	Cable Television
CCC	Connection Complete Confirmation
CSC	Connection Setup Confirmation
CSR	Connection Setup Request
DEC	Digital Equipment Corporation
DFB	Distributed Feed-Back
DLC	Digital Loop Carrier
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-Doped Fiber Amplifier
EO	Executive Order
EOP	Executive Office of the President
EQC	Extended Quadratic Congruence
FDDI	Fiber Distributed Data Interface
fs	femto-second
FTTB	Fiber-To-The-Building
FTTC	Fiber-To-The-Curb
FTTH	Fiber-To-The-Home
Gb/s	Gigabits Per Second
GBW	Guaranteed Bandwidth
GHz	Gigahertz
HDSL	High Data-rate Digital Subscriber Line
HDTV	High Definition Television
HFC	Hybrid Fiber Coax
HLAN	Helical Local Area Network
ISDN	Integrated Services Digital Network

ITU-T	The International Telecommunications Union – Telecommunication Standardization Sector
L-0	Level-0
L-1	Level –1
L-2	Level-2
LAN	Local Area Network
LMDS	Local Multi-point Distribution System
MAN	Metropolitan Area Network
MHz	Megahertz
MIT-LL	Massachusetts Institute of Technology Lincoln Laboratory
MLL	Mode-Locked Laser
MMDS	Multi-channel Multi-point Distribution System
N2	Technology and Programs Division
NCS	National Communications System
NE	Network Entity
NMS	Network Management System
NOLM	Nonlinear Optical Loop Mirror
NS/EP	National Security and Emergency Preparedness
NWDM	Narrowband Wavelength Division Multiplexing
OAN	Optical Access Network
OCDM	Optical Code Division Multiplexing
ODN	Optical Distribution Network
OLA	Optical Limiting Amplifier
OMNCS	the Office of the Manager, National Communications System
OSA	Optical Spectrum Analysis
OSC	Optical Supervisory Channel
OT	Optical Terminal
OTDM	Optical Time Division Multiplexing
OTDR	Optical Time Domain Reflectometry
PDH	Plesiochronous Digital Hierarchy
PON	Passive Optical Network
POTS	Plain Old Telephone Service
ps	pico-second
QoS	Quality of Service
RDI	Remote Defect Indication
RF	Radio Frequency
RR	Release Request
RRC	Release Request Confirmation

SCM	Sub-Carrier Multiplexing
SDH	Synchronous Digital Hierarchy
SDM	Space Division Multiplexing
SNR	Signal to Noise Ratio
SONET	Synchronous Optical Network
TDM	Time Division Multiplexing
THz	Terahertz
TON	Transparent Optical Networks
VDSL	Very High Data-rate Digital Subscriber Line
V-LAN	Virtual Local Area Network
WAN	Wide Area Network
WDM	Wavelength Division Multiplexing
WIXC	Wavelength Interchanging Cross-Connect
WSS	Wavelength Selective Switch
WSXC	Wavelength Selective Cross-Connect
WWDM	Wideband Wavelength Division Multiplexing

Appendix B: Bibliography

1. Mari W. Maeda, “Management and Control of Transparent Optical Networks,” *IEEE Journal of Selected Areas in Communications*, Vol. 16, No. 7, Sep. 1998

2. ANSI T1X1.5/99-033, “Optical Network Performance Management Requirements Network Provider View,” Jan. 1999

3. ANSI T1X1.5/99-074, “Optical Network Performance Management Requirements Network Provider View Revised,” Apr. 1999

4. ANSI T1X1.5/98-034, “Draft ITU-T Recommendation G.otn v3.0,) Feb. 1998

5. Mathias Bischoff, Manfred N. Huber, Oliver Jahreis, Siemens AG, Frown Derr, and Fachhochschule Ulm, “Operation and Maintenance for an All-Optical Transport Network,” *IEEE Communications Magazine*, Nov. 1996

6. Hiroshi Yoshimura, Ken-ichi Sato, and Noboru Takachio, “Future Photonic Transport Networks Based on WDM Technologies,” *IEEE Communications Magazine*, Feb. 1999

7. Marco Ajmone Marsan, Andrea Bianco, Emilio Leonardi, Alessandro Morabito, and Fabio Neri, “All-Optical WDM Multi-Rings with Differentiated QoS,” *IEEE Communications Magazine*, Feb. 1999

8. All-Optical Networks, http://cello.asc.cise-nsf.gov/ncri/giga/allopticalnets.paper.txt

9. Chun-Kit Chan, Lian-Kuan Chen, and Kwok-Wai Cheung, “A Fast channel-Tunable Optical Transmitter for Ultrahigh-Speed All-Optical Time-Division Multiaccess Networks,” *IEEE Journal on Selected Areas in Communications*, Vol. 14, No. 5, Jun. 1996

10. “Hitachi Announces Product Strategy for Ultra-High-Speed Optical Networking,” http://www.hitel.com/news_release_vision.htm

11. “Passive Optical Networks,” http://www.alloptic.com/FAQ_body.htm

12. ANSI T1X1.5/99-071, “Optical Network Indicators – Network Provider View,” Apr. 1999

13. Richard Barry, Vincent Chan, and et al., “All-Optical Network Consortium – Ultrafast TDM Networks,” *IEEE Journal on Selected Areas in Communications*, Vol. 14, No. 5, Jun. 1996

14. Muriel Medard, Douglas Marquis, Richard Barry, and Steven Finn, “Security Issues in All-Optical Networks,” *IEEE Network*, May/June 1997

15. Muriel Medard, Douglas Marquis, and Stephen Chinn, “Attack Detection Methods for All-Optical Networks,” *the Internet Society’s Symposium on Network and Distributed System Security*, 1998

16. Jay Yoo, and Subrata Banerjee, “Design, Analysis, and Implementation of Wavelength-Routed All-Optical Networks: Routing and Wavelength Assignment Approach,” http://www.comsoc.org/pubs/surveys/Yoo/yoo.html, May 1997

17. ANSI T1X1.5/99-148R2, “Optical Network Management Requirements Network Provider View,” May 1999

18. Chung-Sheng Li, and Rajiv Ramaswami, “Automatic Fault Detection, Isolation, and Recovery in Transparent All-Optical Networks,” *Journal of Lightwave Technology*, Vol. 15, No. 10, Oct. 1998

19. “Secure All-Optical Networking,” http://www.ll.mit.edu/aon/secureaon.html

20. Paul E. Green, Jr., “Optical Networkin *IEEE Journal on Selected Areas in Communications*, Vol. 14, No. 5, Jun. 1996

21. Stephen Alexander, R. Bondurant, and et al. “A Precompetitive Consortium on Wide-Band All-Optical Networks,” *Journal of Lightwave Technology*, Vol. 11, No. 5/6, May/June 1993

22. I.Kaminow, C. Doerr, and et al. “A Wideband All-Optical WDM Network,” *IEEE Journal on Selected Areas in Communications*, Vol. 14, No. 5, Jun. 1996