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WAVELENGTH DIVISION MUTLIPLEXING (WDM) NETWORKS

FEBRUARY 2000

OFFICE OF THE MANAGER
NATIONAL COMMUNICATIONS SYSTEM
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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:

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Wavelength Division Multiplexing (WDM) Networks

Office of the Manager
National Communications System

February 2000

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1 Introduction

The National Communications System (NCS) is a federation of 23 member organizations across the Federal Government. Its mission is to assist the Executive Office of the President in exercising wartime and non-wartime emergency telecommunications and in coordinating the planning and provisioning of National Security and Emergency Preparedness (NS/EP) communications for the Federal Government under all circumstances, including crisis, emergency, attack, recovery, and reconstitution. To successfully fulfill this mission, The Office of the Manager, National Communications System (OMNCS), and particularly, its Technology and Programs (N2) Division, always seeks to identify new technologies that can enhance NS/EP communications. The N2 Division gains knowledge of such technologies by participating on national and international standards committees.

One such technology identified by the N2 Division is Wavelength Division Multiplexing (WDM). The N2 division is interested in determining the suitability of WDM for supporting various NS/EP requirements. This document examines WDM technology and discusses its suitability to support NS/EP communications.

2 Background

Over the last few years, the demand for high bandwidth has been increasing at an exceptional rate. As a result, the transmission speeds of Time Division Multiplexing (TDM)-based systems have been pushed to their practical limit of 10 Gigabits Per Second (Gb/s). Research has shown that there is a vast amount of bandwidth available in a single optical fiber; approximately 24 Tera Hertz (THz), in the 1.3 μm (1.3×10^{-6}m) and 1.5 μm (1.5×10^{-6}m) low-attenuation bands. As optical fiber becomes the transmission medium of choice for high-speed communication, new techniques that better control the transfer of information at high speeds will be developed.

Recently, there has been a lot of work done in the area of optical network design and the development of techniques that will exploit the potentially unlimited bandwidth of optical fiber cable. One such technique is the Wavelength Division Multiplexing (WDM). WDM allows several optical signals to be simultaneously transmitted in the same direction over a single optical fiber cable. WDM, therefore, will allow more efficient use of the large bandwidth capacity available in optical fiber.

As WDM becomes the technology of choice for high-capacity optical networks, many long distance telecommunications service providers will use it in their response to the increasing demand for network capacity. Telecommunications service providers such as AT&T, Sprint, and MCI Worldcom have already made long-term commitments to use WDM technology as a means to increase their trunk speeds from 2.5 Gb/s to over 40 Gb/s without adding a single optical fiber. Typically, WDM network components are expensive. However, new developments in materials and the WDM technique itself is allowing manufacturers of optical-networking components to reduce costs significantly. As a result, local telecommunications carriers, CATV operators, and supercomputing centers are planning to capitalize on the cost benefits of WDM. Eventually, private network operators, government agencies, and utilities will use WDM-based networks.

WDM represents a major enabling technology for the National Communications System (NCS). The technology will, undoubtedly, make more efficient use of available fiber optic infrastructure during NS/EP conditions. Specific application types that would benefit from the increased speed and bandwidth include, but are not limited to, the following:

- Multimedia Applications (i.e. integration of voice, video and data)
- Telemedicine Applications, and
- Video Conferencing (i.e. full motion video)

The sections that follow present a more detailed discussion on WDM, WDM networks and their applicability in an NS/EP environment.

3 Wavelength Division Multiplexing

Federal Standard 1037C defines WDM as "a technique used in optical fiber communications, by which two or more optical signals having different wavelengths may be combined and simultaneously transmitted in the same direction over one fiber. These signals are then separated, by wavelength, at the distant end." More simplistically, WDM is a technology that leverages optical fiber cable in ways that more than double its available bandwidth. As illustrated in figure 1, optical signals having wavelengths λ_1, λ_2, λ_3, λ_4, and λ_5 are multiplexed and simultaneously transmitted in the same direction over a single optical fiber cable. An analogy to this technique is the Time Division Multiplexing (TDM) technique used in the D-channel of an Integrated Services Digital Network (ISDN) connection. In ISDN, each user's information is assigned a time slot, multiplexed, then transmitted over the cable medium (usually copper).

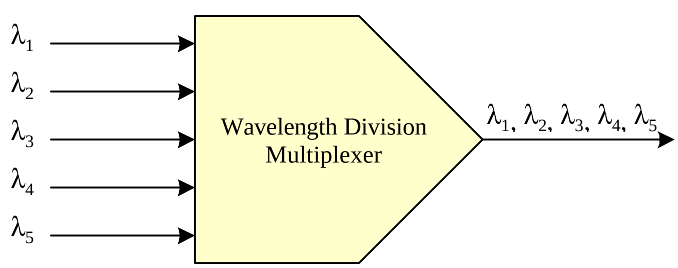

Figure 1: Wavelength Division Multiplexing

On the other hand, WDM technology is photonics based. Photonics provide a method to send bits of information using pulses of light through optical fiber cables. WDM, therefore, uses a technology set that generates many shades of light (also called channels) through a single fiber span, thereby allowing each shade to carry different bits of information. Like TDM, each WDM wavelength represents a different equivalent time slot or, in the case of WDM, a different set of user information. By increasing the number of shades of light over a connection, users are able to achieve higher bandwidths while foregoing the high costs of laying additional optical fiber cable throughout their enterprise.

There are three variations of service levels in WDM. These variations are: (1) Narrowband, (2) Wideband and, (3) Dense; each offering a unique set of bandwidth capabilities.

3.1 Narrowband WDM

Narrowband WDM (NWDM) is a technology that doubles a fiber span's capacity. NWDM implements two wavelengths, typically, 1533 and 1577 nanometers (nm) wavelengths.

3.2 Wideband WDM

Wideband WDM (WWDM) is a technology that also increases a fiber span's capacity by twofold. The difference is that WWDM combines 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.

3.3 Dense WDM

Dense WDM (DWDM) is a technology that can increase a fiber span's capacity by eightfold. DWDM implements 8 wavelengths, which fall into two different bands, a red band and a blue band. Each band is used in opposing directions. The wavelengths for each are as follows:

- Red Band – 1529 nm and 1541 nm wavelengths
- Blue Band – 1549 nm and 1577 nm wavelengths

This separation of paths for "Transmit and Receive" significantly reduces network contention.

4 WDM Networks

Now that a clear understanding of WDM techniques has been established within the industry, the next step is the application of WDM techniques in modern networks. This section focuses on a step-wise process for describing the basic building blocks in WDM networks. Also included in this approach are descriptions of the various network elements (i.e. cable plant, connectors, transmitters, routers, multiplexers and switches) and their overall effect on WDM networks.

4.1 Network Backbone

An essential part of any network is its cable plant or transmission medium. For WDM networks, optical fiber is the medium of choice. Optical fiber is essentially a thin filament of glass that acts as a waveguide and provides enormous bandwidth, low attenuation, low Bit Error Ratio (BER) (less than 10^{-11}), and is immune to electromagnetic interference. Optical fiber is flexible, reliable in corrosive environments, and easily deployable. All these characteristics make optical fiber favorable for emergency communications. There are two types of fibers: multi-mode or single mode. A mode in optical fiber corresponds to one of the many possible paths in which a wave may propagate through the fiber. Depending on the application, a signal can travel in either single mode or multi-mode. Optical fiber also offers some nonlinearities such as Self-Phase Modulation (SPM), Cross-Phase Modulation (XPM), Four-wave mixing (FWM), Stimulated Raman Scattering (SRS), and Stimulated Brillouin Scattering (SBS). These nonlinearities may limit the performance of WDM networks in a similar manner to the affects of capacitance and inductance in coax and copper environments (also see section 8). Notwithstanding, the positive attributes of optical fiber far exceed the negative ones.

4.1.1 Couplers

In general, couplers are devices that combine light into or split light out of a fiber. There are two basic types of couplers: active and passive. An active coupler requires power to function and it has some form of intelligence. A passive coupler simply combines light into or splits light out of a fiber and it does not require power to operate. Couplers are also classified into single mode couplers and multi-mode couplers, thereby corresponding to the two types of optical fiber applications. Single mode couplers are further sub-classified into standard, wavelength flattened, and wavelength independent couplers. Couplers are essential to optical networks, even though they are known to introduce return loss and insertion loss on the signal. If a signal enters the input to a coupler, a small amount of signal power is reflected in the opposite direction and directed back to the input of the coupler. This physical phenomenon is known as a return loss. Insertion loss occurs when the light is directed from a fiber into the coupler. Because of the small dimension of fiber stands, perfect alignment of the fiber core and the coupler input port is very difficult. This imperfection also leads to insertion loss and, although manageable, can affect network performance.

4.1.2 Optical Transmitters

Optical transmitters use Light Amplification by Stimulated Emission of Radiation (LASER). In order to transmit data across an optical fiber, the information is first encoded or modulated onto the laser signal. Both analog modulation techniques (Amplitude Modulation (AM), Frequency Modulation (FM), and Phase Modulation (PM)) and digital modulation techniques (Amplitude-Shift Keying (ASK), Frequency-Shift Keying (FSK), Phase-Shift Keying (PSK)) have been proposed. Of these techniques, ASK is currently the preferred method of modulation because of its simplicity.

Depending on the types of laser (tunable or fixed), optical transmitters can be either tunable or fixed. Tunable lasers can be described using the tuning range, the tuning time, and whether the laser is continuously tunable or discretely tunable. The tuning range is the range of wavelength over which the laser may be operated. The tuning time is the time required for the laser to tune from one wavelength to another.

Some of the most popular tunable lasers are mechanically tuned lasers, acoustooptically and electrooptically tuned lasers, and injection-current-tuned lasers. Mechanically tuned lasers use a Fabry-Perot cavity that is adjacent to the lasing medium to filter out unwanted wavelengths. They can be tuned by physically adjusting the distance between two mirrors on either end of the cavity such that only the desired wavelength interferes with its multiple reflections in the cavity. A major drawback of mechanically tuned lasers is the tuning time. Due the mechanical nature of tuning and the length of the cavity, the tuning time is on the order of milliseconds.

In acoustooptically and electrooptically tuned lasers, the index of refraction in the external cavity is changed by using sound waves and electrical current, respectively. The change in the index of refraction results in the transmission of light at different frequencies. In acoustooptically and electrooptically tuned lasers, the tuning time is limited by the time required for light to build up in the cavity at the new frequency.

Injection-current-tuned lasers allow wavelength selection via diffraction grating. Normally, the grating consists of a wave-guide in which the index of refraction alternates periodically between two values. The wavelengths that match the period and indices of the grating are constructively reinforced and propagate through the wave-guide. All other wavelengths are not propagated through the wave-guide. Depending on the placement of the grating, a laser can be either Distributed Feedback (DFB) or Distributed Bragg Reflector (DBR) laser. In DFB, the grating is placed in the lasing medium. While in DBR, the grating is placed outside of the lasing medium. The tuning time for the DBR laser is less than 10 nanoseconds (ns).

4.1.3 Optical Amplifiers

Typically, an optical signal propagates a long distance before it needs amplification. Both long-haul and local optical networks can benefit from optical amplifiers. The two basic types of optical amplifiers are semiconductor laser amplifiers and optical doped-fiber amplifiers. A semiconductor laser amplifier comprises of a modified semi-conductor laser. It amplifies a weak signal via stimulated emission. The two types of semiconductor laser amplifiers are the Fabry-Perot amplifier and the Traveling-Wave Amplifier (TWA). The main difference between these two amplifiers is the reflectivity of the end mirrors. Fabry-Perot amplifiers have a reflectivity of approximately 30% while TWAs have a reflectivity of approximately 0.01%. The higher reflections in Fabry-Perot amplifiers cause Favry-Perot resonance in the amplifier. This results in narrow passbands of around 5 GHz. This phenomenon is not desirable for WDM systems. Therefore, TWAs are more appropriate then Fabry-Perot amplifiers for WDM networks.

Optical doped-fiber amplifiers are lengths of fiber doped with an element that can amplify light. The most common element is erbium. It provides gain for wavelengths between 1525 nm and 1560 nm. In optical doped amplifiers, a laser is used to pump a strong signal at a lower wavelength, called pump wavelength. This signal excites the doped atoms into a higher energy level. This allows the data signal to stimulate the excited atoms to release photons. Most Erbium-Doped Fiber Amplifiers (EDFAs) are pumped by lasers with a wavelength of either 980 nm or 1480 nm. Typical gain achieved with the EDFAs is around 25 dB. Recently, the Praseodymium-Doped Fluoride Fiber Amplifiers (PDFFAs) have drawn much attention. They provide high gains, around 40 dB, and low crosstalk. PDFAAs are able to operate over a range of around 50 nm in the 1280 to 1330 nm range.

A major limitation of optical amplifiers is the unequal gain spectrum. Optical amplifiers provide gain across a range of wavelengths, but they do not amplify all wavelengths equally. There are a number of proposals to equalize the gain of optical amplifiers.

4.1.4 Optical Receivers

Depending on the filter type (tunable or fixed), an optical receiver can be either tunable or fixed. The most popular tunable filters are Etalon, Acoustooptic, Electrooptic, and Liquid-Crystal (LC) Fabry-Perot. The Etalon comprises of a single cavity formed by two parallel mirrors. Signal from an input fiber enters the cavity and reflects a number of times between the two mirrors. A single wavelength can be chosen for propagation through the cavity by adjusting the distance between the mirrors. The distance between the mirrors can be adjusted mechanically or by changing the index of the material within the cavity. An example of mechanically tuned Etalon is Fabry-Perot Etalon receiver. The Rainbow optical WDM local area network prototype uses Fabry-Perot Etalon receiver.

In Acoustooptic filters, Radio Frequency (RF) waves are passed through a transducer. A transducer is a piezoelectric crystal that converts sound waves to mechanical movement. The sound waves change the crystal's index of refraction and that enables the crystal to act as a grating. By changing the RF waves, a single optical wavelength can be chosen to pass through the material. The tuning range (250 ns) for Acoustooptic receivers covers the 1300 nm to 1560 nm spectrum and allows about 100 channels. The tuning time of the filters is approximately 10 μs.

Electrooptic filters use crystals whose index of refraction can be changed by electrical current. Electrodes resting in the crystal are used to supply current to the crystal. The current changes the crystal's index of refraction, which in turn allows some wavelengths to pass. The tuning time and tuning range of these types of filters are 10 ns and 16 nm, respectively.

In LC Fabry-Perot filters, the cavity consists of a liquid crystal. Electrical current is used to change the refractive index of the liquid crystal. This allows some wavelengths to pass, as in electrooptic filters. The tuning time of LC Fabry-Perot filters is on the order of μs while tuning range is 30 to 40 nm.

Fixed receivers use fixed filters or grating devices to filter out one or more wavelengths from a number of wavelengths from a single fiber. Some of the most popular filters or grating devices are diffraction grating, fiber bragg grating, and thin-film interference filters. The diffraction grating is basically a flat layer of transparent material such as glass or plastic with a row of parallel grooves cut into it. The grating separates light into its component wavelength by reflecting it with the grooves at all angles. At certain angles, only one wavelength adds constructively while all other wavelengths interfere destructively. Thus, a desired wavelength can be selected by tuning the filter to that wavelength at the proper angle.

In fiber bragg grating, a periodically variable index of refraction is directly photo-induced into the core of an optical fiber. The bragg grating reflects a given wavelength of light back to the source and passes the other wavelengths. There are two major drawbacks of this method: (1) inducing a grating directly into the core of a fiber leads to low insertion loss, and (2) the refractive index in the grating varies with the temperature and an increase in temperature reflects longer wavelengths.

Thin-film interference filters are similar to fiber grating devices, but they are fabricated by placing alternate layers of low index and high index materials onto a substrate layer. Major disadvantages of this type of filers are poor thermal stability, high insertion loss, and poor spectral profile.

4.1.5 Passive Routers

Passive routers separately route each of several wavelengths existing on input fiber to the same wavelength on separate output fibers. For example, consider the 2X2 passive router shown in figure 2. As depicted in the figure, wavelengths $\lambda 1$ and $\lambda 2$ existing on input fiber 1 are routed to the same corresponding wavelengths to output fibers 1 and 2, respectively. Similarly, wavelengths $\lambda 1$ and $\lambda 2$ existing on input fiber 2 are routed to the same corresponding wavelengths to output fibers 2 and 1, respectively. Passive routers allow wavelength reuse, i.e., the same wavelength may be spatially reused to carry multiple connections through the router. The wavelength on which an input port gets routed to an output port depends on a routing matrix characterizing the router. This matrix is determined by the internal connections between the multiplexing and demultiplexing stages inside the router. The routing matrix is fixed and cannot be changed. Passive routers are also known as Latin routers, waveguide grating routers (WGRs), wavelength routers (WRs), etc.

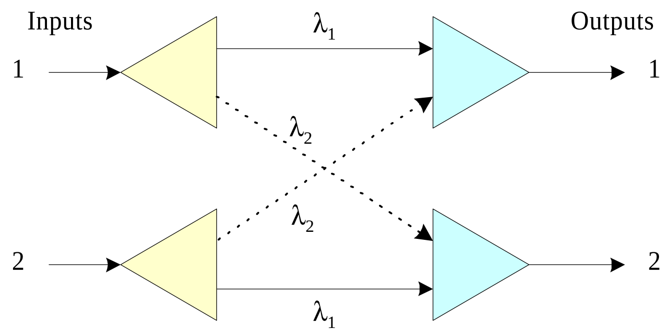

Figure 2: A 2x2 Passive Router

4.1.6 Active Switches

As illustrated in figure 3, active switches use optical switches inside the routing element. On each incoming fiber, there may be N wavelength channels. However, in the figure only two wavelengths are considered. These wavelengths are separated using a grating demultiplexer. The outputs of the demultiplexers are directed to the optical switches. The outputs having the same wavelength are directed to the same switch. Then, they are directed to multiplexers associated with output ports. Finally, the multiplexed output is sent to an output fiber. An active switch is also referred to as a wavelength-routing switch (WRS), wavelength selective cross-connect (WSXC), or cross-connect.

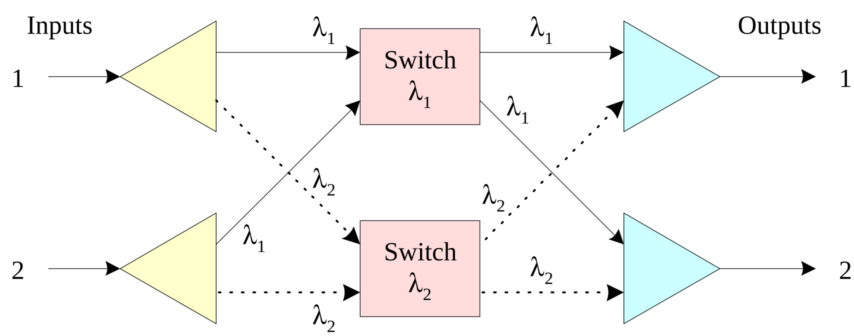

Figure 3: A 2x2 Active Switch

4.1.7 Wavelength Converters

Wavelength converters convert data on an input wavelength onto a different output wavelength. Wavelength converters improve the efficiency in the network by resolving wavelength conflicts in the lightpath. Wavelength converters employ one of the several available techniques for wavelength conversion. These techniques can be broadly classified into two types: opto-electronic wavelength conversion and all-optical wavelength conversion. In opto-electronic wavelength conversion the optical signal is first converted into an electronic signal while in all-optical wavelength conversion the signal remains optical.

4.1.8 Wavelength Add/Drop Multiplexers

Wavelength Add/Drop multiplexers (WADMs) consist of a demultiplexer followed by a set of 2X2 switches followed by a multiplexer. Each wavelength has a corresponding switch. The switch can be in a bar-state or cross-state. In the bar-state, the signal from the upper input port is routed to the upper output port and the signal from the lower input port is routed to the lower output port. In the cross-state, the signal from the upper input port is routed to the lower output port and the signal from the lower input port is routed to the upper output port. If all the switches are in the bar-state, then all of the wavelengths flow through the WADMs undisturbed. However, if any switch is configured into the cross-state via electronic control, then the signal having the corresponding wavelength is dropped locally. A new signal can be added on the same wavelength at the local WADM. Depending on the hardware and processing capability, WADMs can add or drop multiple wavelengths.

4.2 Section Summary

All components described are considered essential to a fully deployed WDM network. With an all-optical network infrastructure in place, users can expect to achieve greater efficiency through the use of WDM technology. Specific user requirements such as faster transmission speeds, greater bandwidth capacity and affordable cost will continue to drive widespread availability.

4.3 WDM LANs

WDM will make full use of available network architecture topologies. For example, the Star, Tree, Bus and Ring network topologies have been proposed for broadcast-and-select WDM network. It is therefore, important that we fully understand the real, or perceived, benefits of the network architecture in a WDM network environment. A brief description of each architecture being examined by the industry follows.

4.3.1 Star Topology

In the star topology, as shown in figure 4, each node is connected to a star coupler via two-way fibers. A node transmits its optical information stream to the star coupler on one available wavelength. However, a collision will occur when two or more nodes simultaneously transmit optical information streams on the same wavelength. The optical information streams from multiple nodes are then combined by the star coupler and the signal power of each stream is equally divided and forwarded to all of the nodes on their RECEIVE fibers. A node's receiver is tuned to only one of the wavelengths using an optical filter so that it can receive the information stream. Also, when a source node transmits on a particular wavelength, for example $\lambda 1$, more than one receiver can be tuned to wavelength $\lambda 1$ and all such receivers can pick up the information stream. This is considered a form of multi-casting service.

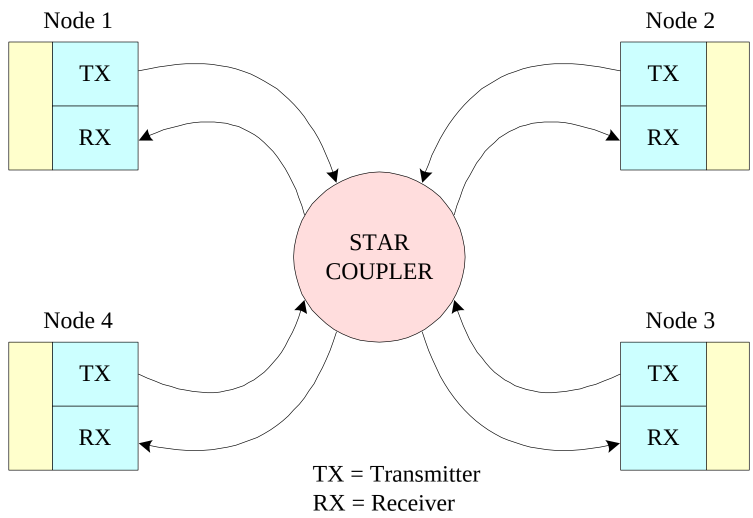

Figure 4: Star Topology

As explained earlier, a coupler can be either active or passive. Accordingly, a star topology can be an active star or a passive star. The passive star topology is generally more attractive because no power is needed to operate the coupler.

Information transfer between source nodes and destination nodes may follow one of two methods: (1) single-hop, or (2) multi-hop. As the name implies, in single-hop method, information is sent directly from the source to the destination. This means a direct point-to-point link needs to be established between each communicating pair of nodes. Accordingly, the source and the destination must operate on the same wavelength for successful information transfer. Additionally, single-hop WDM systems can be further categorized based on whether the nodal transceivers are tunable or not. These categories are: (1) Fixed Transmitter(s) and Fixed Receiver(s) - (FT - FR), (2) Tunable Transmitter(s) and Fixed Receiver(s) - (TT - FR), (3) Fixed Transmitter(s) and Tunable Receiver(s) - (FT - TR), and (4) Tunable Transmitter(s) and Tunable Receiver(s) - (TT - TR).

Multi-hop information passes through intermediate nodes before it reaches its destination. Consequently, connectivity between any arbitrary pair of nodes is achieved by having all nodes in the network also act as intermediate routing nodes. Figure 5 shows an example of a four-node multi-hop network. Node 1 can communicate with node 2 and 3 directly. But, in order to communicate with node 4, information from node 1 must pass either through node 2 or node 3.

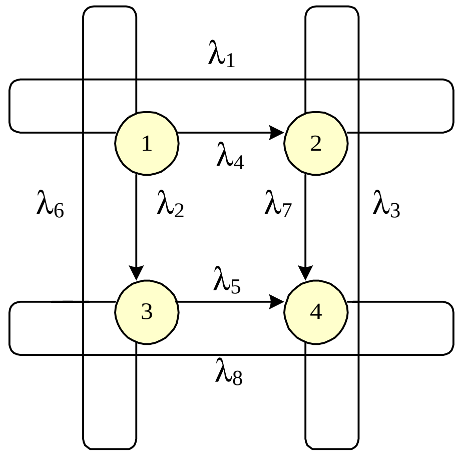

Figure 5: An Example Multi-hop Network

4.3.2 Bus Topology

In the bus topology, all nodes are connected to a single (or folded) bus or two unidirectional buses. Figure 6 illustrates a single or unidirectional folded bus topology. In a dual bus topology, all nodes are connected to two unidirectional buses. Thus, each node on the bus is equipped with a sense tap with which it can access a channel via an attempt-and-defer policy. By tuning the sense tap to a channel, a node can determine whether there is activity on the bus or channel. If there is activity, the node defers transmission to avoid collision. Otherwise, the node transmits until the transmission is complete. The major disadvantages of the bus topology are power loss and tapping loss within the bus. These disadvantages limit the number of nodes that can be attached to the bus without adding optical amplifiers.

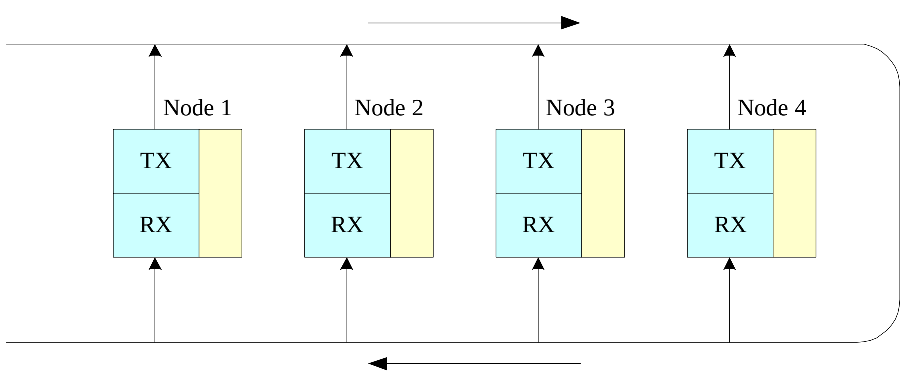

Figure 6: Single Unidirectional Bus

4.3.3 Ring Topology

presentation of a WDM ring topology architecture. Each node on the ring is connected to an Add Drop Multiplexer (ADM). Each ADM can drop a single fixed wavelength, but can add any wavelength or any number of wavelengths simultaneously.

equipped with a tunable transmitter and a fixed receiver. A node can send data to any other node on the ring by transmitting on the wavelength that is dropped

data to the same destination simultaneously. This can be avoided, however, by using

architecture for LANs. Some commercial WDM ring network products have also begun to appear

(MANs) will make full use of the WDM ring architecture.

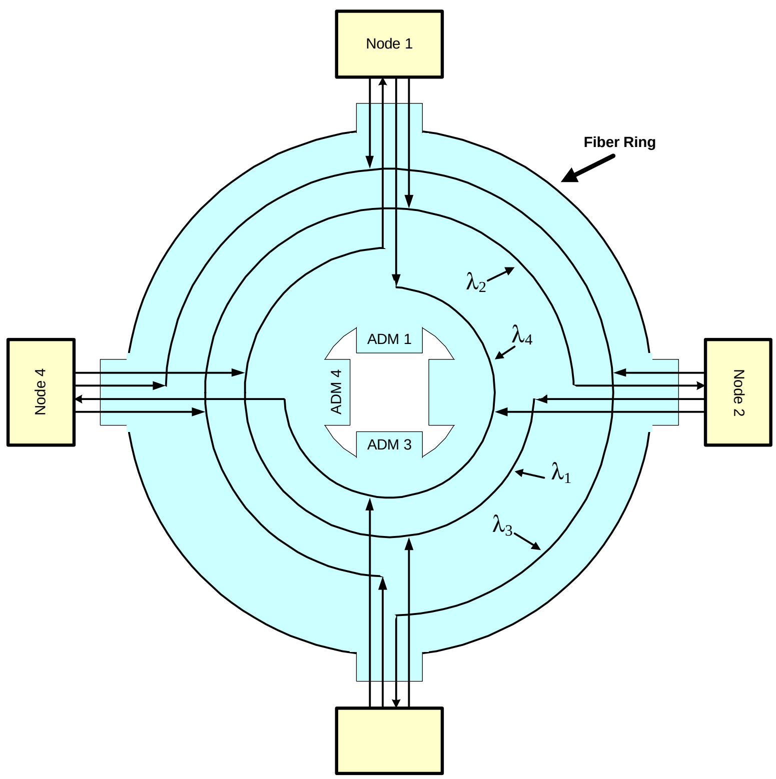

Figure 7: Ring Topology

4.3.4 Tree Topology

A tree topology is illustrated in Figure 8 using six nodes. As the name indicates, nodes and star couplers are connected to form an arbitrary tree topology. Although this topology is not very popular in LANs, it is under consideration for use in MANs.

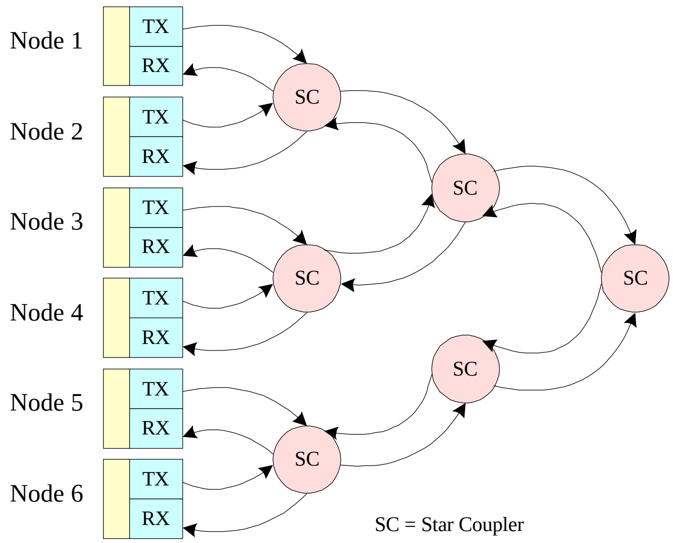

Figure 8: Tree Topology

4.4 Protocols

Several protocols have been proposed for use in WDM networks. Each protocol and its primary attributes are addressed in the sections that follow.

4.4.1 Medium Access Control

Medium Access Control (MAC) protocols have been proposed for use within WDM LANs. The benefit offered by a MAC is that it ensures fair medium access among multiple users. In general, these protocols can be classified as reservation based or pre-allocation based. Reservation based protocols typically use one of the wavelength channels as a control channel. The control channel is used to transmit control information and to reserve access on the data channels. The remaining wavelength channels are used as data channels much in the same way as the D-channel is used in ISDN. Reservation protocols are generally more complex since the information transfer is based on two stages: reservation and transmission. Pre-allocation based protocols pre-assign the channels to nodes, where each node has a home channel that it uses either for data transmission or for data reception. These protocols eliminate the need for a control channel and reduce system complexity. Some of the other MAC protocols proposed are briefly described below.

4.4.1.1 I-SA

The Interleaved Slotted Aloha (I-SA) protocol is simple. I-SA requires one tunable transmitter and one fixed receiver per node before information can be transferred. Each node has a single queue of variable capacity that buffers arriving packets if the transmitter is busy. Each transmission in I-SA consists of two phases: data packet transmission and acknowledgement transmission. During the data packet transmission phase, the transmitter transmits the packet at the head of the queue. If the packet transmission is not successful, the transmitter follows a back-off policy for retransmission.

The acknowledgement phase consists of the destination node protocol processing delay, the transmitter tuning time, and the propagation delay. This phase may be time division multiplexed among the nodes to avoid collisions when the number of nodes is more than the number of channels. An acknowledgement is sent by the destination node immediately after each data packet is received. To ensure proper hand shaking, the source node will hold the channel on which the data packet was transmitted until after the acknowledgment phase is complete. This results in decreased channel utilization, which is considered a major drawback of the protocol. A proposal to use explicit acknowledgement is being considered by the industry.

4.4.1.2 I-SA*

I-SA* is a variation of the I-SA protocol. There are two major improvements in I-SA* over I-SA. First, a node can now have multiple queues. This avoids problems related to querying priority during packet transmit phase. Second, the source node can transmit packets on another channels rather than wait for acknowledgment of previously transmitted packets. These two improvements resulted in an improvement of channel utilization.

4.4.1.3 I-TDMA

Interleaved Time Division Multiple Access (I-TDMA) protocol is a pre-allocation based protocol. It is a multi-channel extension to basic TDMA protocol. In this protocol, time is slotted on each channel where each slot corresponds to a memory-block packet transmission time. All nodes in the system are equipped with a tunable transmitter, a fixed receiver and a single queue of variable capacity. Thus, packets can be buffered if the transmitter is busy. Some drawbacks of I-TDMA are that although it provides very high channel utilization it also offers high latency under light loads due to cycle synchronization. It is also very inefficient in the support of variable sized packets and suffers from the head of the queue problem because of the use of a single queue.

4.4.1.4 I-TDMA*

Interleaved Time Division Multiple Access* (I-TDMA*) protocol has evolved from I-TDMA. It is similar to the I-TDMA protocol, but eliminates the head of the queue problem that significantly impacts the performance of I-TDMA. I-TDMA* employs C transmitter queues at every node, where C is the number of data channels in the network. In I-TDMA*, channels are pre-allocated for packet reception. Each node has one tunable transmitter and one fixed or slow tunable receiver. A source node tunes its transmitter to the home channel of the destination node and transmits according to the access protocol. I-TDMA* avoids collisions by using time division multiplexing to access to the channels. Time is slotted to data packet lengths on each channel. A major advantage of using I-TDMA* is its efficient network utilization.

4.4.1.5 TDMA-C

The TDMA-Collisionless (TDMA-C) protocol uses both the control channel and the data channel to transmit and receive packets. Each mode maintains a status table that records the active status of each channel at the node. Each mode has a tunable transmitter, a fixed receiver and a tunable receiver. Access to the control channel is based on a cyclic slot allocation scheme. The major advantages of the TDMA-C protocol are support of variable sized data packets, no collision on either the control channel or the data channels, simple access arbitration of control channel, and flexibility in using channels since any free channel can be used.

4.4.1.6 High Performance Reservation Protocol with *l* ook ahead

l ook ahead (HiPeR-) is a new protocol for single hop WDM LANs. It is designed to overcome the potential inefficiencies of operating in environments with non negligible processing, tuning, and propagation

-*l*

other nodes about its traffic demands. These control packets are generally transmitted over the same channels used for the transfer of data packets. Each c

reservations for multiple data packets waiting in the queues, thus, reducing network overhead significantly. Upon receipt of a control packet, a node will independently run a

nodes use the same algorithm and input values received in the control packets to ensure that no channel or receiver

HiPeR- protocol also uses agation delay and the processing time. The parameter , also referred to as the "look-

degree of pipelining in the operation of the protocol. To use this pipelining scheme, however, the value of the parameter must be greater than one.

4.4.1.7 -Net/C

D-

Network Topology Section 2). It is a very simple protocol that combines the advantages of both multi channel and train- ator is located at the left end of the bus which launches a locomotive on an outbound bus channel when it senses an -of train (EOT) on the corresponding inbound bus channel. A node waits for the locomotive on the appropriate outbound bus channel and tr

same time, the node senses for upstream transmission. If transmission is detected, the packet being transmitted is aborted. Further, if there is a collision, the node waits for an

channel and re-

4.4.1.8 Fairnet

requires a single tunable transmitter and a fixed-

work properly, the head node in the network generates fixed size data slots on all channels. Each node on the bus will receive a set of transmission probabilities P_{ic}, where $0 \leq i \leq M-1$, $0 \leq c \leq C-1$, M = number of nodes, and C = number of channels. P_{ic} represents the probability that node i transmits on channel c in a given slots. The values of P_{ic} are determined from network traffic distribution and equity constraint. Additional information on Fairnet can be obtained from [11].

4.4.1.9 B-TDMA

B-TDMA is another protocol defined for folded bus network configuration. It is an extension of A Multibus TRAin Communication (AMTRAC) protocol which uses time multiplexed multi-channel access method. In B-TDMA, each node is equipped with a tunable transmitter and a fixed receiver. Like AMTRAC, time is divided into slots of equal length. However, the slot length is equal to the length of a data packet instead of the propagation delay between adjacent nodes.

4.4.1.10 FatMAC

Fat Medium Access Control (FatMAC) is a proposed hybrid protocol. It combines the advantages of pre-allocation and reservation-based medium access control protocols. Transmission in FatMAC is organized into cycles where each cycle consists of a control phase and a data phase. The control phase operates in a broadcast environment. FatMAC reserves access on pre-allocated channels through control packets. The control packets carry control information such as the destination, the data channel, and the packet size (if variable sized packets are supported). They also support broadcast of control information. FatMAC requires a tunable transmitter and a fixed receiver for each node. The major characteristics of this protocol are low implementation complexity, collisionless transmission, low-latency at low loads, stability at high loads, support of varying propagation delays through interleaving cycles, and support of variable packet sizes without segmentation.

4.4.1.11 Request/Allocation Protocol

Request/Allocation Protocol (RAP) is a collision free protocol proposed for WDM ring configuration. In this protocol, time is divided into uniform slots. Each slot is divided into two sections: header and data. The header section contains N mini-slots, where N is the number of nodes in the network. The first mini-slot is used for clock synchronization and the remaining N-1 mini-slots are used to request and allocate bandwidth. The data section is divided into M Data Mini-slots (DMSs). In order to transmit data, a node first requests DMSs and then waits for an allocation. For this reason, the protocol is referred to as the RAP. When a node receives multiple requests for bandwidth, it allocates DMSs in a round robin fashion until all of the requests, or all of the DMSs, are allocated.

4.5 WDM WANs

WDM WANs, a.k.a. wavelength-routed optical networks, typically consist of access nodes and switching nodes connected by fiber links. Access nodes contain tunable transmitters and receivers. Switching nodes contain photonic switches, and perhaps photonic amplifiers and wavelength converters. Figure 9 shows an example a WDM WAN having an arbitrary topology.

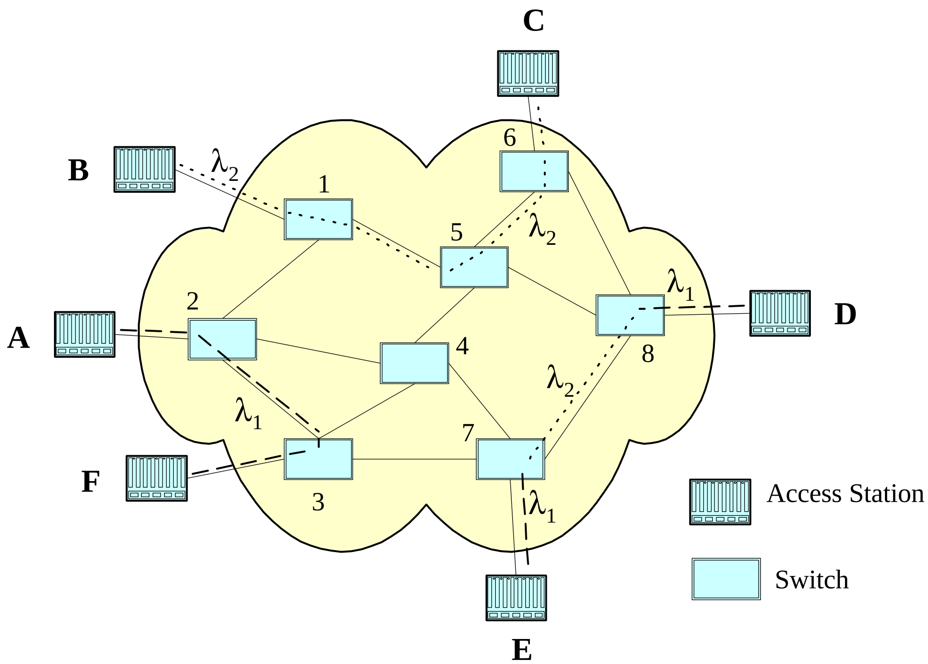

Figure 9: An Example WDM WAN

The basic mechanism of communication in WDM WANs is a lightpath. A lightpath is an all-optical communication channel between two nodes in the network and it may span multiple fiber links. The switching nodes in the fiber path route the lightpath and, if required, wavelength converters convert the wavelength. For example, in figure 9, light paths are established between nodes A and F on wavelength channel λ1 and between nodes B and C on wavelength channel λ2. The lightpath between nodes A and F is routed via switches 2 and 3. The lightpath between nodes B and C is routed via switches 1, 5, and 6. Contrapositively, the light path between nodes D and E is routed from node D to switch 8 on wavelength λ1, converted to wavelength λ2 at switch 8 and then routed to switch 7 on wavelength λ2. Finally, it gets converted back to wavelength λ1 at switch 7 and routed to node E on wavelength λ1. In the absence of any wavelength converters, a lightpath is required to be on the same wavelength channel throughout its path in the network. This requirement is referred to as the wavelength continuity property of the lightpath. Alternatively, two lightpaths that share a common fiber link should not be assigned the same wavelength. 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 WDM WANs.

4.5.1 WDM Routing and Wavelength Assignment

The two basic conveyance mechanisms in WDM networks are routing and wavelength assignment. Both are addressed in the sections that follow.

4.5.1.1 Routing

In WDM networks, a node may have several input and output ports. These ports are connected to either end-nodes, or to other intermediate routing nodes. In routing nodes, each input port may receive signals at different wavelengths. The input port must be able to route these signals to any output port, independent of signals at other wavelengths. This routing may be either static, or dynamic, depending on whether the lightpath requests are known in advance.

4.5.1.1.1 Dynamic Routing

In a Dynamic Routing Environment, lightpath requests may arrive at random between source-destination pairs. This is achieved by dynamically finding and allocating routes between source and destination nodes. Once the routes are determined, the next step is the assignment of wavelengths. As explained earlier (Section 4.5), because of the wavelength-continuity constraint, two lightpaths that have at least a link in common cannot use the same wavelength. If the intermediate nodes do not have the capability to perform wavelength conversion, a lightpath is constrained to operate on the same wavelength through its path. This may reduce the effective utilization of the wavelength in the network because a lightpath may not find the same wavelength in all the physical links it passes through, even if these links may have free wavelengths. Lightpaths that cannot be setup due to this constraint on wavelength are blocked. This is undesirable, particularly, during NS/EP events.

In order to alleviate the blocking probability problem, full wavelength converters can be used in routing nodes. Wavelength converters eliminate the wavelength-continuity constraint and allow better utilization of wavelengths. Nevertheless, there are certain limitations in using wavelength converters. These limitations arise mainly due to the high cost of wavelength converters, sharing of converters, and limited-range wavelength conversion. These limitations are discussed further in Section 8.

Several routing algorithms have been proposed for use in wavelength-convertible networks. For example, one such algorithm has been specified in [3]. It is designed to minimize the long-term lightpath blocking probability. The algorithm uses a centralized dynamic routing scheme in which a central controller is responsible for collecting information from the network and for finding the best routes. The algorithm also involves the use of a graph transformation technique that captures the cost of resources used along the path. It applies the shortest path routing on this transformed graph. (Additional information on this algorithm can be obtained from [3]). Even though there exist many routing algorithms for wavelength convertible networks, the design of efficient routing algorithms that address the above referenced limitations still remains an issue.

4.5.1.1.2 Static Routing

In contrast to the dynamic routing, static routing assumes that all the lightpaths that are to be set up in the network are known initially. Hence, the main objective is to maximize the total number of lightpaths that can be established simultaneously in the network. The Dijkstra algorithm and the Floyd algorithm have been proposed to determine the shortest path between source-destination pairs. Once the lightpaths have been assigned physical routes, the next step is to assign a wavelength to each individual lightpath.

4.5.1.2 Wavelength Assignment

In WDM networks, each wavelength assignment is mapped to a node-coloring scheme. Each node represents one point-to-point connection and each wavelength has a corresponding color. The connections that share a common fiber link are considered neighbors and must be assigned different colors.

A number of algorithms have been proposed to determine the chromatic number of color graphs that can represent WDM networks without wavelength converters. Some of the well-known algorithms are Sequential graph coloring algorithms, Greedy algorithms, Exhausted search, and Tabu-search. Simulated Annealing (SA) and Genetic Algorithms (GA) have also been proposed to solve graph node-coloring problems. A brief description of these algorithms is presented below.

4.5.1.2.1 Sequential Graph Coloring Algorithms

Sequential graph coloring algorithms are very simple when compared to other WDM algorithms. In these algorithms, vertices are sequentially added to the portion of the graph already colored. New colors are determined to include each newly adjoined vertex. At each step, the algorithm tries to minimize the total number of colors required.

4.5.1.2.2 Greedy Algorithms

Greedy algorithms work in phases. In each phase, a decision is made that appears to be good, without regard for future consequences. Typically, the decision is based on some predefined local values such as the node search order number and the number of colors. Based on the decision, the algorithm assigns some free color to each node. The color is assign in such a way that no adjacent nodes have the same color. The order in which nodes are given a color is determined by their degree (i.e. the number of adjacent neighbors). The node with the most neighbors is colored first. When the algorithm terminates, it is assumed that the local optimum is equal to the global optimum. If this is the case, then the algorithm has produced an optimal solution; otherwise, the algorithm has produced a sub-optimal solution. Experimental results show that these algorithms are very fast.

4.5.1.2.3 Exhaustive Search

Exhaustive search algorithm always finds the optimum coloring of a given graph. In each step, the algorithm divides the possible colorings into two different cases until each node is a neighbor of all the other nodes. In each step, it also searches for a pair of nodes that are not neighbors. After the search, these nodes can be colored with the same color or with different colors. If the nodes are given the same color, they are merged into one node each inheriting all the neighbors of the other node. If the nodes are given a different color, an edge is drawn between them. A major disadvantage of this scheme is that the search tree becomes too large to handle as the number of nodes increases.

4.5.1.2.4 Tabu-Search

The Tabu-search has traditionally been used on combinatorial optimization problems. However, it works very well for the graph node-coloring problem. It is basically, a random local search based on a certain predefined value of a cost function. During the search, some movements are forbidden. Hence, movements are called Tabu. Generally, a move leading back to the previous point is classified as a "Tabu-move" for a certain number of rounds. The search ends when the cost function reaches the predefined value or a certain number of rounds elapse. This algorithm differs from other algorithms in that it does not try to find the minimum coloring. Instead, it tries to choose one of the "k" colors for each node in such a way that no neighboring nodes get the same color. Experimental results show that Tabu-search provides the best optimization.

4.5.1.2.5 Simulated Annealing

Simulated annealing is one of the most popular iterative optimization methods. Although this methodology is mainly used in materials science, the basic premise behind the algorithm is useful in WDM networks. The concept borrowed from materials sciences can be described as follows:

> "To produce a solid in a low energy state, such as a perfect crystal, first heat the system to a high temperature, and then slowly cool it. At any given temperature, the probability that a change in the structure with energy change will occur is, min($e^{-\Delta E/kT}$, T), where k is Boltzmann's constant, E is the energy of the system, and T is the temperature of the system in degrees Kelvin. When the temperature is high, the system can change radically and many changes that do not lower the energy level are allowed. As the temperature decreases, fewer and fewer ``bad'' changes are permitted, until finally a fairly optimal state is achieved."

The algorithm is very simple and easy to adapt to different kinds of problems including the graph node-coloring problem. Simply stated, the algorithm assigns each node a unique color. The number of used colors is represented by the parameter E. In each step, the algorithm chooses a random node and a new random color and makes sure that the new color does not lead to an illegal representation. Additional information on this approach can be obtained from [4].

4.5.1.2.6 Genetic Algorithms

Finally, the concept behind genetic analysis can be applied to WDM networks. Genetic algorithms are iterative procedures that consist of a constant-size population of individuals. Each individual is represented by a finite string of symbols, known as the genome. There are many variations of genetic algorithms. The standard genetic algorithm uses either random or heuristically generated population of individuals. At every evolutionary step, known as a generation, the individuals in the current population are decoded and evaluated according to some predefined quality criterion, referred to as the fitness, or fitness function. To form a new population, called the next generation, individuals are selected according to their fitness. In the context of graph node coloring, the algorithm tries to find the best ordering to color the nodes. Additional information on graph node coloring using this algorithm can be obtained from [4].

The above referenced methods of assigning a wavelength to a lightpath is not possible in the dynamic case where lightpaths arrive in a random order. Therefore, under the wavelength continuity constraint, optimal allocation of wavelengths may not be possible in the dynamic case. To alleviate this problem, some researchers are looking into some existing techniques by which it may be possible to reassign existing connections to unused wavelengths and free required wavelengths for new connections. A possible drawback is that this approach may be difficult to implement in multi-hop WDM networks.

5 Connection Control and Management

The primary point of intelligence in a WDM network is the Wavelength Routing Switch (WRS). Figure 10 illustrates a network consisting of four interconnected WRSs. The WRS at each node in the network uses its own controller for setting up, taking down, and maintaining the state of connections. The controllers communicate with each other using a controller communication network that operates either in-band or out-of-band. The controller at each WRS maintains the state of the connections flowing through that WRS in a Connection Switch Table (CST). Each connection is identified by a connection ID that includes a source address, a destination address, and a sequence number. The CST is updated by a connection update procedure. The CST update procedure informs the controllers of the connections passing through the WRS. The controllers periodically or, when the CST is updated, send their neighbors a list of connections that traverse the link shared between them. Additionally, each controller maintains the topology of the network and the availability of wavelengths on each link using a topology database. The topology and wavelength availability information is updated by a topology update protocol. Each controller periodically broadcasts a topology update message to all controllers in the network. The message contains the list of healthy links adjacent to the node and their wavelength usage.

In order to establish a connection, the originator requests all controllers along the route of the connection to reserve the selected wavelength. If the reservation is successful, the connection is setup; otherwise, the reservation is released at all nodes along the route. To release a connection, the originator of the connection sends a release message to each controller along the route. In order to manage link failures, a spanning tree of spare links is maintained at the controllers. Upon a link failure, connections are rerouted using links on the spanning tree. To manage wavelength failure, one wavelength is reserved as a spare on each link of the network. When a controller detects a wavelength failure on a link, it updates its CST, finds a substitute path, and establishes a connection.

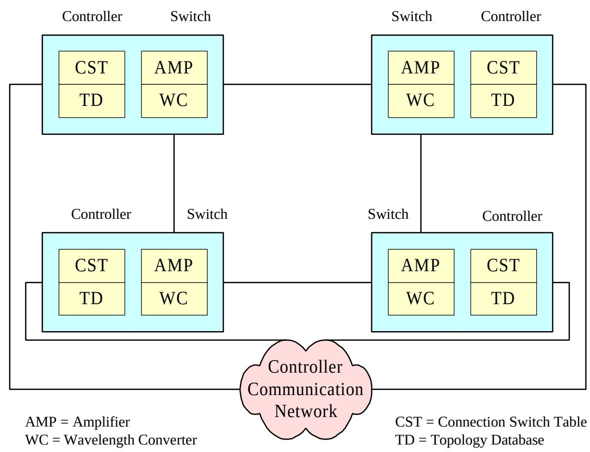

Figure 10: Connection Control and Management

6 Reconfiguration

In an environment where the traffic demands change over time, it is desirable that the network configuration dynamically respond to these demands. WDM networks offer the flexibility of adapting their topology in response to changing traffic patterns. This dynamic reconfiguration function is primarily performed by the WRS. Several proposals for dynamically reconfiguring WDM networks have been presented. However, most of them are only applicable to LANs and MANs through the use of a broadcast medium such as a passive star coupler. There are two reconfiguration techniques suggested for passive star based LANs. The first technique suggests simultaneous re-tuning of all transmitters involved in the logical links that need to be changed. This, however, could lead to substantial network outage and a significant portion of the network may be unavailable during transition. The second technique uses branch-exchange operations that minimize the portion of the network unavailable during the transition. In this technique two channels A and B, for example, interconnecting nodes C-D and E-F, respectively, would be switched to new channels A' and B', interconnecting nodes C-F and D-E, respectively.

For WDM WANs' reconfiguration, circuit rerouting has been proposed. Wavelength retuning or Move-To-Vacant (MTV) techniques can be used for circuit rerouting. Wavelength re-tuning involves re-tuning the wavelength of a circuit while maintaining its path. Its major advantages are improved control and simplified calculation of the optimal rerouting. MTV reroutes a circuit to a vacant route with no other circuits. This technique does not interrupt other circuits during rerouting and preserves information transmission over the old route during the setup of the new route. Thus, it reduces disruptions of the rerouted circuit.

7 WDM Standardization

WDM is an emerging technology and no mature standards are available at this time. However, the International Telecommunications Union – Telecommunications Standardization Sector (ITU-T) and the American National Standards Institute (ANSI) are hard at work to ensure that the minimum interoperability standards are in place for short and long term deployment.

The ITU-T Study Group (SG) 15 is working on several proposed recommendations for optical networking including the use of wavelengths in the 1520-1565nm range. These recommendations will be developed using a phased approach. Phase 1 will emphasize point-to-point WDM line systems, Phase 2 will extend the capabilities of optical add/drop multiplexing and cross-connection, and Phase 3 will include optical layer survivability. Phase 1 was completed in 1998 and the ITU-T is expected to complete Phase 2 and Phase 3 by the year 2000.

In October 1998, the ITU-T approved Recommendation G.692, *Optical Interfaces for Multi-channel Systems with Optical Amplifiers*, which pertains to WDM line systems operating in the 1550 nm window. The recommendation covers, among other areas, point-to-point WDM systems that are optimized for long-haul transport. Additionally, G.692 specifies a frequency grid anchored at 193.1 THz with inter-channel spacing of 100 GHz. Systems that operate within the frequency grid will support up to eight channels operating at speeds of up to 2.5 gigabits per second per channel. The importance of this standard to the NCS is that the NCS would now be able to utilize true gigabit technology to support NS/EP.

8 Limitations and Issues in WDM Networks

Because of their obvious advantages (i.e. speed, bandwidth, etc.), WDM networks are rapidly emerging in long distance carriers, local carriers, and enterprise networks. However, WDM is an emerging technology and there are still a number of issues and limitations to be considered.

8.1 Nonlinearities in Fiber

One limitation to consider is the nonlinearity characteristics of fiber optics. Optical fiber nonlinearities such as SPM, XPM, FWM, SRS, and SBS will have a significant impact on the performance of WDM networks. Unless corrected, these nonlinearities will lead to attenuation, distortion, and cross-channel interference. They also place constraints on the spacing between adjacent wavelength channels, reduce the maximum power of the channel, and limit the maximum bit rate. An explanation of how these nonlinearities affect WDM networks is as follows:

a. SPM is caused by variations in optical signal power. It introduces variations in the phase of signal. In phase shift keying systems, these variations may lead to a degradation of the system performance since the receiver relies on the phase information. Additionally, SPM causes spectral broadening of pulses because the variations in a signal's phase results into instantaneous variations of frequency around the signal's central frequency. This may lead to spreading of pulses, and thereby, affecting the maximum bit rate.

b. XPM is a shift in the phase of a signal. It is caused by a change in the intensity of a signal propagating at different wavelengths. XPM may lead to asymmetric spectral broadening. A combined effect of XPM and SPM may affect pulse shape.

c. FWM occurs when two wavelengths operating at frequencies *f1* and *f2*, respectively, are mixed to produce signals at 2*f1-f2* and 2*f2-f1*. These signals are referred to as sidebands. They can cause interference if they overlap with frequencies used for data transmission. One proposal to reduce the effect of FWM in WDM systems is to use unequally spaced channels.

d. SRS is caused by the interaction of light with molecular vibrations. The scattering results in shifting of a portion of light from the high-frequency part of the spectrum to the low-frequency part. The light generated at the lower frequencies is called the Stokes wave. The range of frequencies occupied by the Stokes wave is determined by the Raman gain spectrum that covers a range of around 40 THz below the frequency of the input signal. In silica fiber, the Stokes wave has a maximum gain at a frequency of around 13.2 THz less than the input signal. As the power of the input signal increases, the fraction of power transferred to the Stokes wave increases rapidly. Under very high input power, SRS transfers almost all of the input signal power to the Stokes wave. SRS effects could be reduced by decreasing the channel spacing and keeping the power on each channel below a certain threshold.

e. SBS is similar to SRS, except that the interaction involves sound waves rather than molecular vibrations. Additionally, the Stokes wave propagates in the opposite direction of the input signal. The intensity of the scattered light is much greater in SBS than in SRS. However, the frequency range of SBS is much lower (on the order of 10 GHz) than that of SRS. To reduce the effects of SBS, the input power should be below a certain threshold. High bit rates, or carrier suppression, can also be used to reduce the effects of SBS.

8.2 Wavelength Conversion

Another limiting factor on WDM networks is the use of wavelength converters. Wavelength conversion has been proposed for use in multi-hop WDM networks as a measure to improve efficiency. However, there are some limitations employing wavelength conversion. These limitations include the following:

a. Wavelength Converters – Wavelength converters are expensive and may not be economically justifiable. Further, the cost of this approach is directly proportional to the number of nodes in the network.

b. Converter Sharing - Several switch architectures have been proposed that allow sharing of converters among the various signals at a switch. However, experiments have shown that the performance of such a network saturates when the number of converters at a switch increases beyond a certain threshold. Furthermore, the problem of quantifying the dependence of the threshold on the network routing algorithm and the desired blocking probability must be dealt with.

c. Semiconductor Optical Amplifiers (SOAs) using Cross-Grain Modulation (XGM) – Converters of the type have been proposed for use in WDM networks. However, this type of converter is known to generate significant signal degradation when the output signal is converted to a higher (up-converted) signal. This could produce a devastating result when a signal of transmitted packet of information passes through cascading (or multiple) converters. However, this converter appears to produce desirable results when the output signal is down converted equal to, or lower than the input signal.

The use of converters that are optimized for WDM networks is essential to the NCS. When signals experience significant degradation as they travel the network, bandwidth contention increases, thus leading to serious network performance limitations. Therefore, the NCS has a vested interest to ensure that optimum converter performance standards are established industry-wide.

8.3 Efficient Dynamic Routing Algorithms

As described in Section 4.5, there are a number of dynamic routing algorithms under consideration for use in WDM networks. However, none of these algorithms allow for the elimination of wavelength converters. As a result, near term WDM technology deployment will produce less than desirable network performance but, at the same time, offer a significant improvement over currently available technologies. The major challenge faced by the NCS in this regard is ensuring that the greatest degree of interoperability is achieved. This accomplishment will ensure that the WDM technology offers the greatest value to NS/EP.

8.4 Quality of Service

Potential applications for WDM networks include ultra high-speed computer interconnects for parallel processing, multimedia applications, distance learning, telemedicine, and digital libraries. Many of these applications demand a guaranteed Quality of Service (QoS) from the network. Although QoS for WDM networks has been recognized, it has not been effectively resolved in the industry. Since this capability will be an important feature in the transmission of NS/EP traffic, any resolution resulting from discussion by the industry will have significance to the NCS.

8.5 Interoperability

The evolution of WDM technology has far outpaced the development of applicable standards. This has created a global concern regarding interoperability. Nonetheless, WDM networks are being implemented throughout the world. Many local and long distance telecommunications carriers have already made long-term commitments to WDM technology since these initial implementations will use vendor-specific products, interoperability is now a global concern.

Recently, the ITU-T has recommended that vendors use wavelengths in the spectrum range of 1520 - 1565 nm, however, such a wide range allows for hundreds of system/product variations. Even when vendors agree to use the same wavelengths, there are still problems switching channels between networks. There are no immediate standards that take into account such factors as fault alarms, or power levels, for WDM networks.

Still, network operators are continuing to implement WDM systems on isolated point-to-point routes, as a relief for fiber exhaust. However, the traffic is kept within their own networks where there is no requirement for interconnecting other networks. While this implementation approach currently represents a potential problem for the NCS, fully connected WDM networks will eventually become standard practice, thus, adding bandwidth relief during NS/EP situations.

9 Conclusions and Recommendations

WDM is an emerging technology that allows multiple optical channels, each operating at up to 2.5Gb/s or even 10Gb/s, to be transmitted over the same optical fiber using different wavelengths. Current WDM systems can carry from 32 to 40 channels. Soon, 96 to 128 channel systems will be available, and systems supporting more than 200 channels have been announced. This represents more than a terabit of information on a single fiber. Since WDM is a protocol-independent technology, it could be used in Ethernet, Fiber Distributed Data Interface (FDDI), Asynchronous Transfer Mode (ATM), and other network architectures.

Because of the high cost, early implementations of WDM systems were limited to long distance telecommunications networks. However, new developments in materials and techniques are allowing manufacturers to significantly reduce the cost of WDM systems. As a result, WDM systems have begun to appear in LANs and MANs.

Since WDM is an evolving technology, it presents many implementation issues and limitations. Some of the issues and limitations arise due to:

- nonlinearities in optical fiber cable,
- use of wavelength converters,
- lack of efficient dynamic routing algorithms,
- QoS support, and;
- Interoperability.

Although effects of these nonlinearities could be reduced by decreasing the channel spacing and keeping the power on each channel below a certain threshold, industry consensus is still needed.

Appendix A: Acronyms

ADM	Add-Drop Multiplexer
AM	Amplitude Modulation
AMP	Amplifier
ANSI	American National Standards Institute
ASK	Amplitude-Shift Keying
ATM	Asynchronous Transfer Mode
BER	Bit Error Ratio
CATV	Community Antenna Television, CAble Television
CST	Connection Switch Table
DBR	Distributed Bragg Reflector
DFB	Distributed Feedback
DMSs	Data Mini-Slots
DWDM	Dense WDM
EDFAs	Erbium-Doped Fiber Amplifiers
EOT	End-Of-Train
FDDI	Fiber Distributed Data Interface
FM	Frequency Modulation
FR	Fixed Receiver
FSK	Frequency-Shift Keying
FT	Fixed Transmitter
FWM	Four-wave mixing
GA	Genetic Algorithms
Gb/s	Gigabits Per Second
GHz	Giga Hertz
HiPeR-ℓ	High Performance Reservation Protocol with ℓook-Ahead
I-SA	Interleaved Slotted Aloha
ISDN	Integrated Services Digital Network
I-TDMA	Interleaved Time Division Multiple Access
ITU-T	International Telecommunication Union – Telecommunication Standardization Sector
LAN	Local Area Network
LASER	Light Amplification by Stimulated Emission of Radiation
LC	Liquid-Crystal

MAC	Medium Access Control
MANs	Metropolitan Area Networks
MTV	Move-To-Vacant
NCS	National Communications System
nm	Nanometer
ns	Nanosecond
NS/EP	National Security and Emergency Preparedness
NWDM	Narrowband Wavelength Division Multiplexing
OMNCS	The Office of the Manager, National Communications System
PDFFAs	Praseodymium-Doped Fluoride Fiber Amplifiers
PM	Phase Modulation
PSK	Phase-Shift Keying
QoS	Quality of Service
RAP	Request/Allocation Protocol
RF	Radio Frequency
RX	Receiver
SA	Simulated Annealing
SBS	Stimulated Brillouin Scattering
SG	Study Group
SOAs	Semiconductor Optical Amplifiers
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
TD	Topology Database
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TDMA-C	TDMA-Collisionless
THz	Tera Hertz
TR	Tunable Receiver
TT	Tunable Transmitter
TWA	Traveling-Wave Amplifier
TX	Transmitter
WADMs	Wavelength Add/Drop Multiplexers
WANs	Wide Area Networks
WC	Wavelength Converter
WDM	Wavelength Division Multiplexing
WGRs	Waveguide Grating Routers

WRs	Wavelength Routers
WRS	Wavelength Routing Switch
WRS	Wavelength-Routing Switch
WSXC	Wavelength Selective Cross-Connect
WWDM	Wideband WDM
XGM	Cross-Gain Modulation
XPM	Cross-Phase Modulation
2X2	Two-by-two

Appendix B: References

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WAVELENGTH DIVISION MULTIPLEXING (WDM) NETWORKS

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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:

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