Module 11 - Fiber Optic Networks and the Internet

Dr. Alan Kost

Associate Research Professor Of Optical Sciences, University Of Arizona

Dr. Alan Kost is an Associate Research Professor of Optical Sciences in the University of Arizona. His areas of research include optical data storage, optical communications, integrated optics, nano-optics.

Email: akost@arizona.edu

Introduction

A fiber optic network is a collection of electronic and optical nodes separated by optical links. Optical networks fall into multiple categories. Opaque optical networks contain electronic nodes where optical signals are converted into the electrical domain and then back into the optical domain, a process called OEO conversion. A network with OEO conversion is called *opaque* because an optical signal cannot pass freely through the OEO. Optical networks that contain no OEO conversion are called *transparent networks* or *all-optical networks.* All-optical networks contain optical nodes that are used to route, restore, or convert the frequency of light signals without the use of electronics. In general, "node" refers to a point within a network that is connected by more than two links and where electrical, optical, or electro-optical switching and routing takes place.

A passive optical network (PON, pronounced "pawn") is a special case of an all optical network in which the optical nodes consists of passive optical components (i.e. components that do not need power sources to operate) such as optical splitters, optical couplers, and wavelength routers. Passive optical networks are employed for distributing optical signals to private residences, an application called *fiber-to-the-home* (FTTH).

There are two approaches that are used to combine data streams on an optical fiber so as to take advantage of the very large bandwidth - *time division multiplexing* (TDM) and *wavelength*

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division multiplexing (WDM). TDM has been a mainstay of opaque optical networks for many years. The full potential of WDM is realized with all-optical networks.

Data networks have developed a complex layered structure that is currently undergoing an evolution to a simpler form. Consider the way in which, until recently, Internet communications have been transmitted, as illustrated in **Figure 11.1**. E-mail messages such as “Hi, where’s Jeff?” are encoded into data packets using Internet protocol (IP). Next the IP packets are encoded using ATM protocol. ATM is also a packet-based communication protocol that can be used to encode multiple forms of data, including IP data. The ATM packets are prepared for transmission over the optical network using the Synchronous Optical Network (SONET) protocol. Finally the optical layer, which contains the physical fiber optic connections, transmits the message to a remote site where it is decoded up the layer stack.

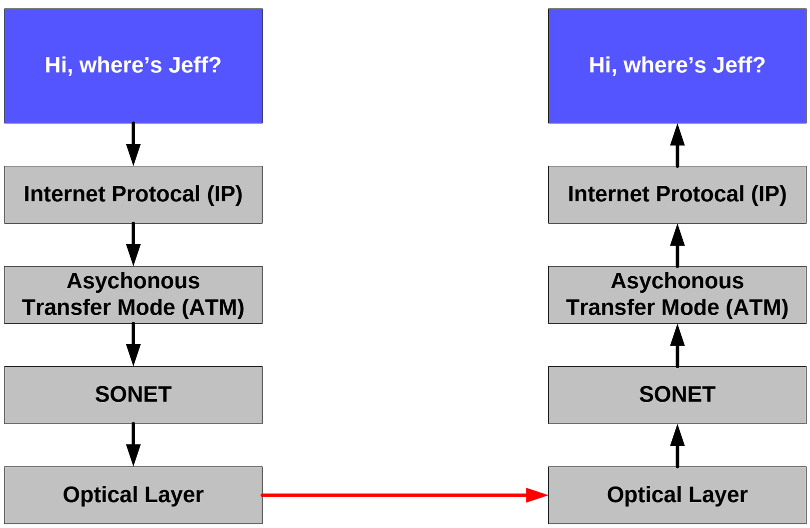

Figure 11.1: *The transmission of the e-mail message “Hi, where’s Jeff?” over the Internet.*

The current trend is to merge the ATM layer into the IP layer, and the SONET layer into the optical layer to produce a simplified *IP over Optical* layer structure shown in **Figure 11.2**. The advantages of the “simplified” (or “collapsed”) structure with the merged protocol layers are manifold: They lie in less complex systems (reducing capital as well as operational expenditures), in a potentially higher throughput, and in the unified platform they will provide for diverse services.

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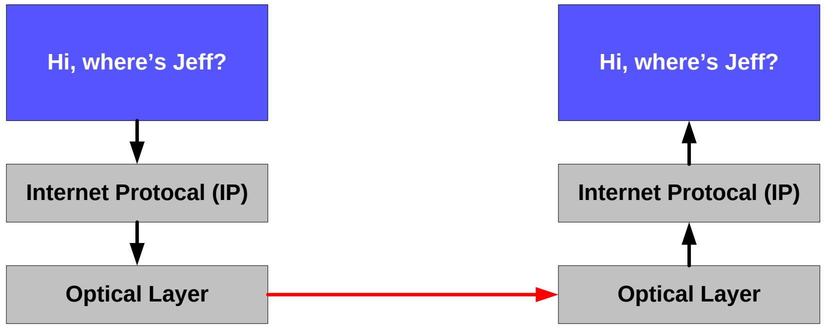

Figure 11.2: *An e-mail message sent with IP over Optical layers.*

11.1 Network Topology

Optical networks come in various *topologies* each of which may be particularly suited for particularly situations. The decision about the actual topology to be chosen and implemented – made by the network operator – includes complex considerations regarding the area to be covered by the network (ranging from in-house to national backbones); the number, location and proximity of subscribers; security, availability, and resilience to be provided; and many more. The network topologies and the way in which they are interconnected, called the *network hierarchy*, are discussed in subsequent sections.

The simplest network, the *point to point* type shown in **Figure 11.3**, consists of two electronic nodes separated by an optical link.

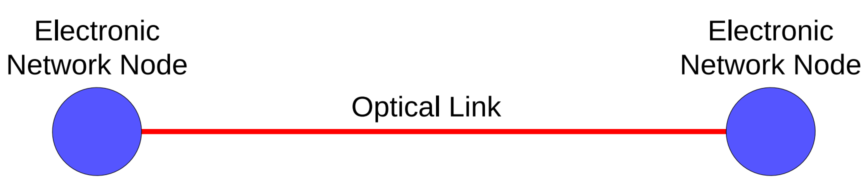

Figure 11.3: *A simple, point to point optical network.*

Each electronic node contains at least one (Figure 11.4) or more (Figure 11.5) optical transceivers. **Figure 11.4** depicts a transceiver with a directly modulated light emitting diode or laser. For higher data rates it is common to use a laser with a continuous output and an external optical modulator.

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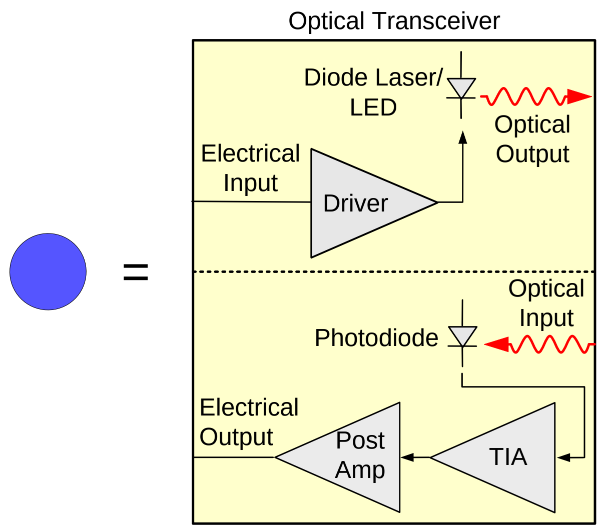

Figure 11.4: *An electronic network node that contains an optical transceiver.*

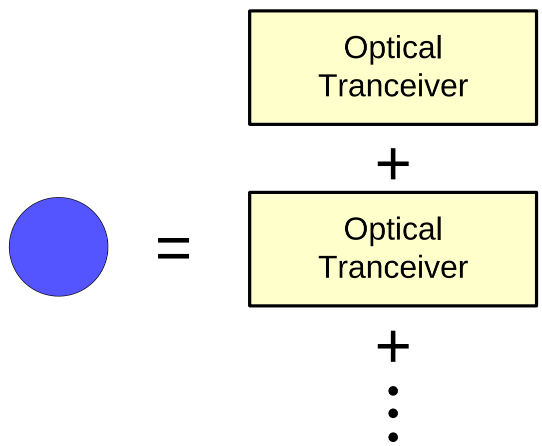

Figure 11.5: *An electronic network node that contains multiple optical transceivers.*

An optical link consists of optical fiber, to carry optical signals, as pictured in **Figure 11.6**. Optical signals most often carry digital information represented by variations in the amplitude or phase of one or more guided light waves. Optical amplifiers are frequently used to boost the optical output from a transceiver and to compensate for optical attenuation as an optical signal traverses the optical fiber. An optical amplifier may also be used to boost the optical signal just before it reaches the receiver, increasing the signal-to-noise ratio at the receiver and reducing transmission error. Dispersion compensation modules are included in links in order to mitigate the detrimental effects of optical pulse spreading. The length of uninterrupted fiber between elements such as optical amplifiers or dispersion compensation modules is sometimes referred to

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as a span. In current terrestrial networks the length of a span is approximately 80 km (60…100 km); for "single-hop" (one-span) connections it can be significantly longer (200 km); for submarine systems it is usually shorter (50 km).

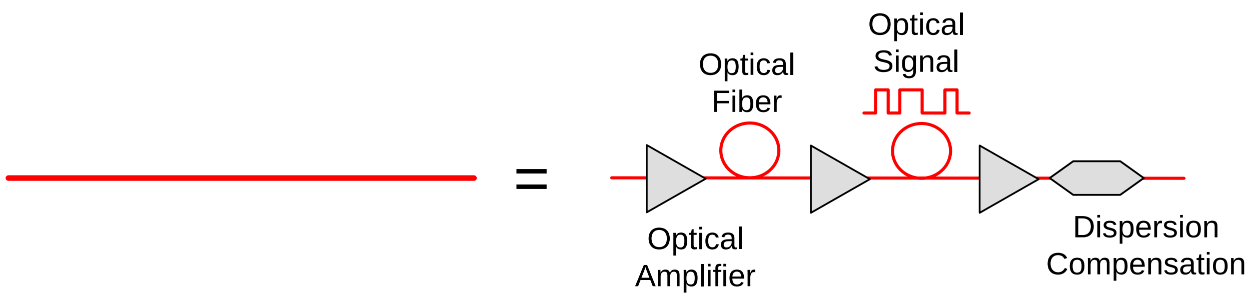

***Figure 11.6**: An optical link in a fiber optic network.*

Note that the inclusion of an optical amplifier in the link produces an asymmetry with respect to direction of transmission because of optical isolators that are included as part of the optical amplifiers. The asymmetry means that optical signals can only be transmitted in one direction. Bi-directional connections between optical nodes requires at least two optical fibers if the links contain optical amplifiers. On the other hand, optical amplification is generally not necessary if an optical link is no longer than few tens of kilometers. In this case bi-directional transmission can be implemented with a single optical fiber.

Mesh Networks

A fiber optic mesh network is pictured in **Figure 11.7**. Black arrows indicate a connection between two electronic nodes. Note that as data traverses an electronic node, an incoming optical signal is converted to an electronic signal and then back to an optical signal using transceivers. This is called "OEO" conversion, and a network that uses OEO conversion is called a "multi-hop" network.

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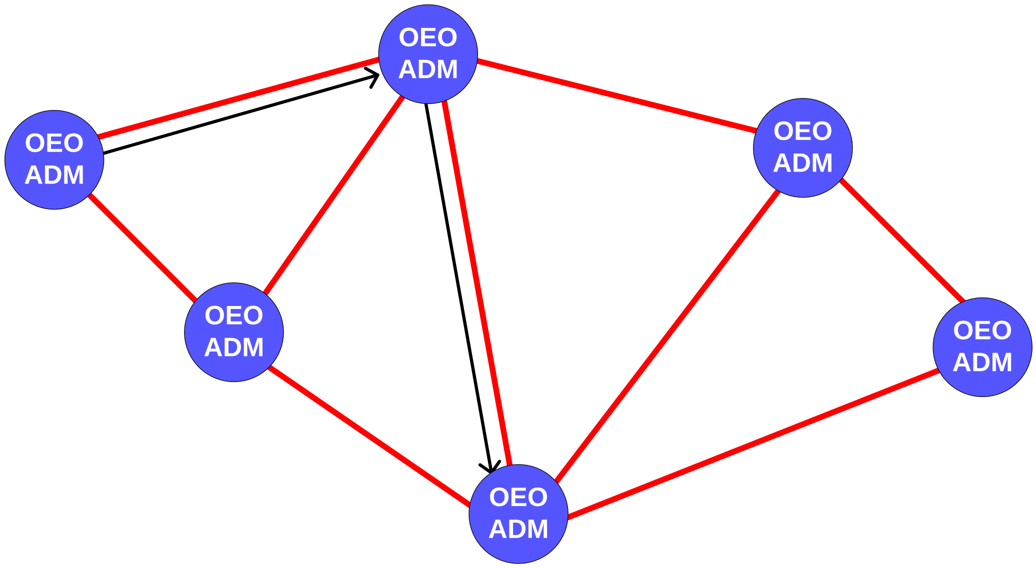

***Figure 11.7**: A fiber optic mesh network. The black arrows indicate a connection between two electronic nodes.*

Each electronic OEO node contains at least one pair of optical transceivers and often also contains an add-drop multiplexer that is used to terminate ("drop") a portion of the signal (or, better, one channel out of many) locally or to "add" a locally generated channel form/to the traffic stream passing by (**Figure 11.8**).

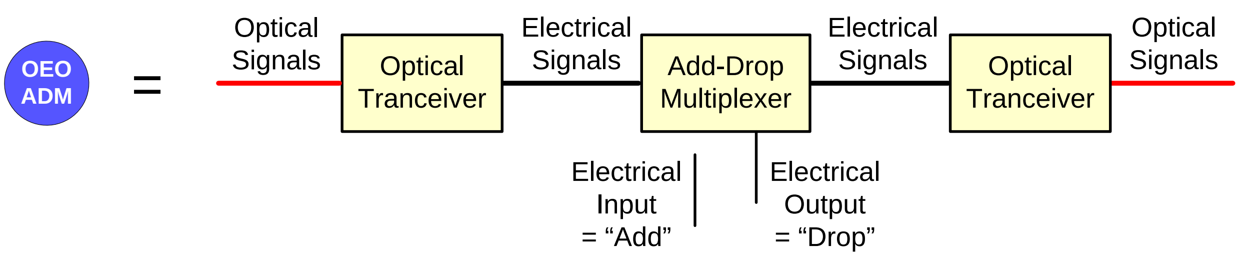

***Figure 11.8:** An electronic node with optical-to-electrical-to-optical conversion and an add-drop multiplexer.*

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A mesh network has a property that makes it more than just a simple collection of point to point networks – it is *reconfigurable*. Suppose that a link in the network becomes overused or damaged, as indicated by the "x" in **Figure 11.9**.

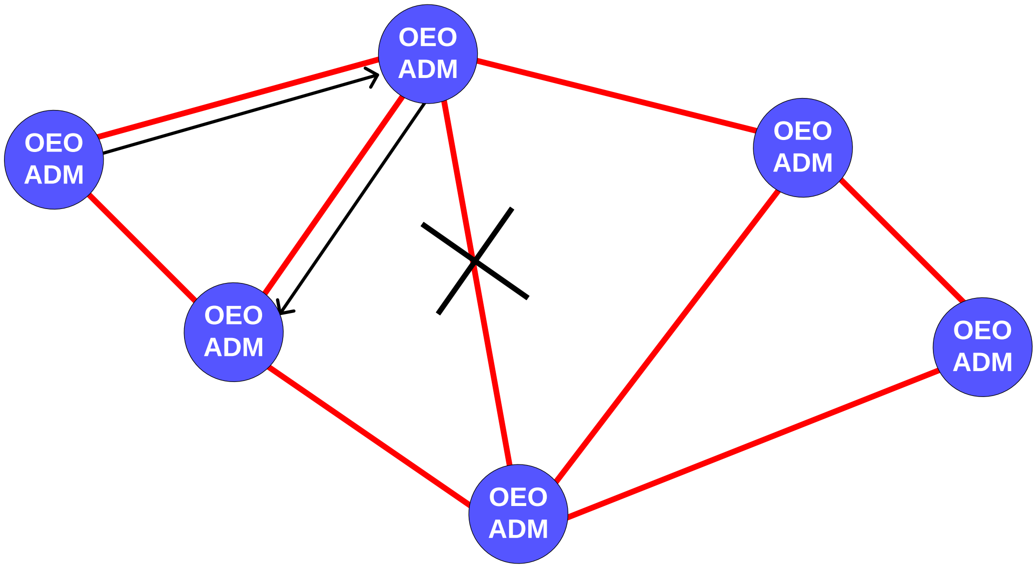

Figure 11.9: ***A mesh network reconfigured to compensate for an overused or damage optical link.***

The mesh topology allows rerouting of a connection, as indicated by the black arrows in **Figure 11.9.** When reconfiguring has been carried out because of a damaged link, we say that the network has been *healed*. Mesh networks are most often used as national backbone networks.

Fiber Optic Ring

An example of an optical network with a ring topology is shown in **Figure 11.10**. A signal circulates counterclockwise in the working fiber optic path labeled "W". The path labeled "P" is a protection path that is unused in normal operation, but vital for operation of a damaged ring. Data is added to or removed from the signal add-drop multiplexers at each electronic node.

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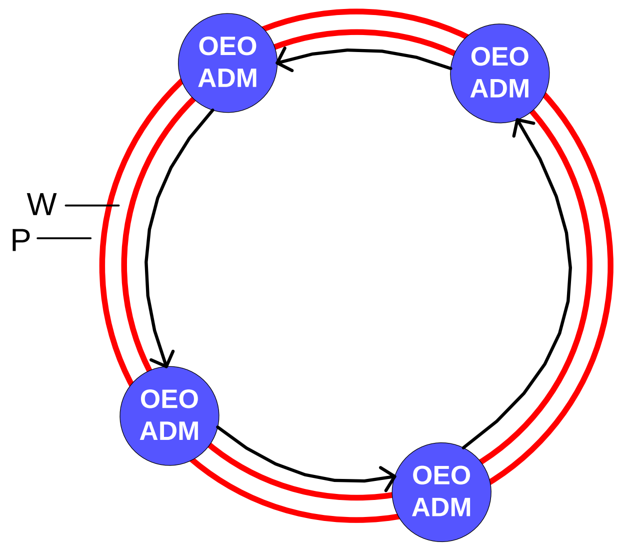

Figure 11.10: ***A fiber optic ring network.***

Fiber optic rings are particularly robust and self-heal in the case of damage to the ring. There are several configurations used to promote healing of fiber optic rings. In order to see how the ring of **Figure 11.10** *self-heals*, consider **Figure 11.11**, where an x indicates a cut that prevents data from

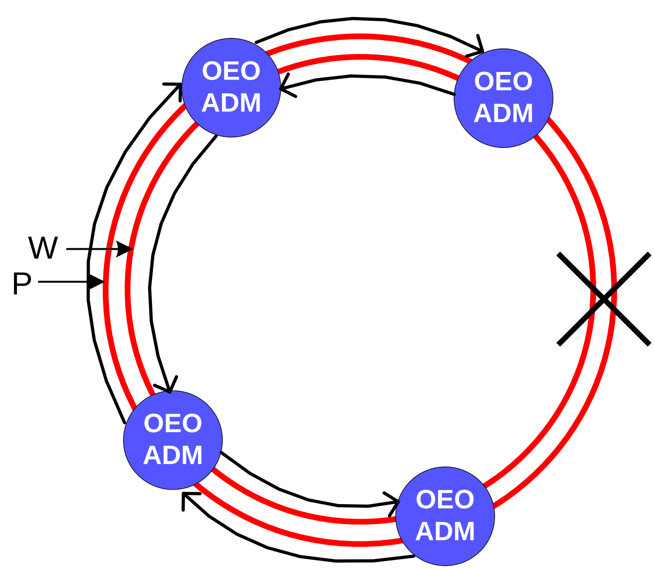

Figure 11.11*:* ***A "healed" fiber optic ring with a signal rerouted to avoid a cut.***

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traversing a portion of the ring. Sensing the cut, the ring reroutes the signal through the protection path as shown. Ring architectures are most often used for metropolitan area networks (MAN).

Star Network

For a fiber optic network with a star topology, as shown in **Figure 11.12**, several electronic nodes are connected through a central hub. The star topology is particularly suited for broadcasting a signal from one node to all the other nodes in the network, by way of the hub.

It is not necessary that the hub in a star network be an electronic node. A fiber optic power splitter, for example, can readily distribute an optical input among several optical outputs without OEO conversion. **Figure 11.13** illustrates a star network with an optical node - a fiber optic splitter – for the network hub. We use the label OO for the optical node to indicate that the node, in a general sense, is an optical to optical converter. An OO hub is simpler, more reliable, and less expensive than an OEO hub.

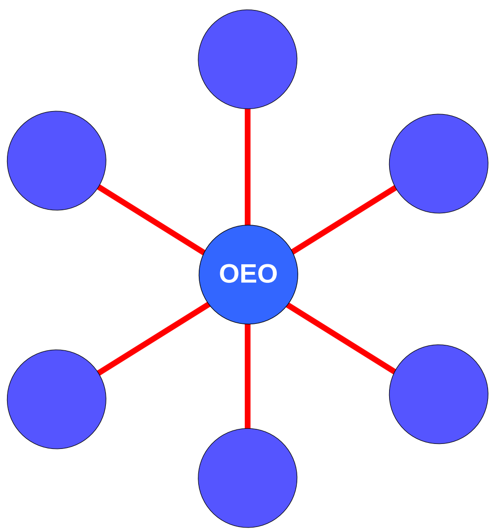

Figure 11.12: ***A signal is broadcast to multiple nodes through a hub in an optical star network.***

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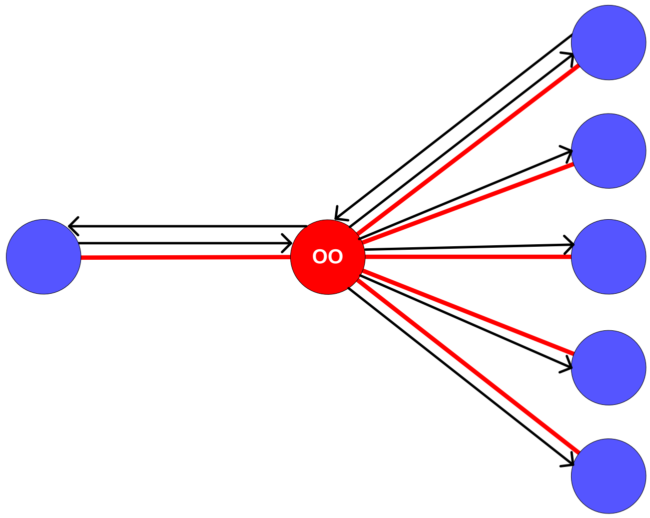

***Figure 11.13**: A star network with an optical node broadcasting a signal from one to many electronic nodes and receiving from one of the nodes.*

Optical Bus

Optical signals can also be distributed among many electronic nodes by means of the bus topology pictured in **Figure 11.14**. An advantage of the bus is that additional optical-electronic node pairs can easily be added to the end of the bus. The passive optical nodes can be implemented with four point optical couplers as described in the paper by Karmacharya and Irvine-Halliday [1]. Note that bus topology of **Figure 11.14** and the star topology of **Figure 11.13** are both examples of passive optical networks.

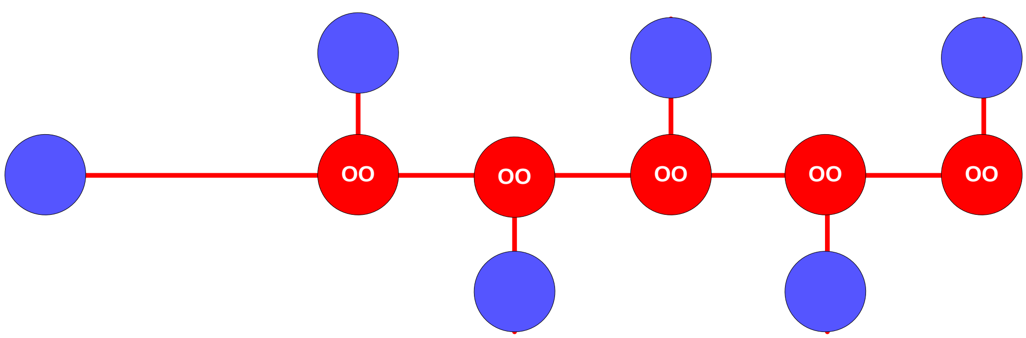

***Figure 11.14**: An optical bus topology*

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11.2 Time Division Multiplexing and SONET

The very large bandwidth of optical fibers means that many electrical signals can be combined to be transmitted over a single optical fiber. One way to combine signals is to assign bits in slower (i.e. low data rate) signals to slots in faster signals. This process, illustrated in **Figure 11.15**, is known as time division multiplexing or TDM. A total of twenty-four 64 kbit/sec data streams, each carrying one voice grade channel, can be multiplexed onto a D1 digital signal that is carried on a T1 line.

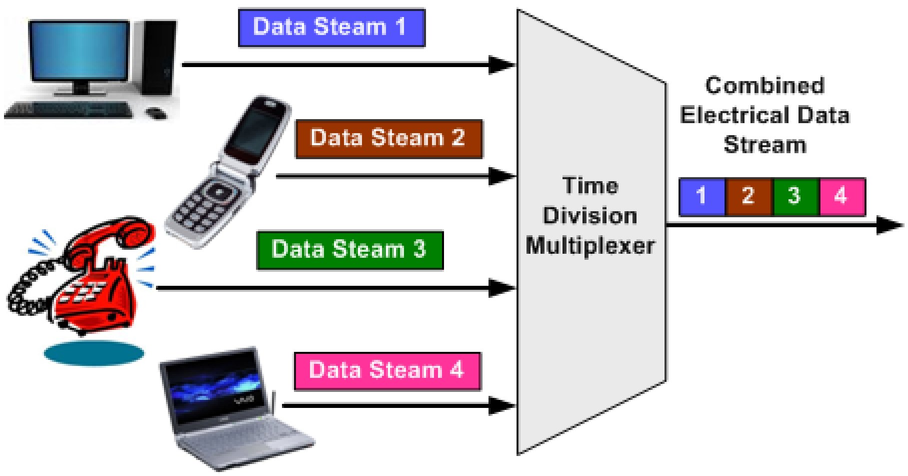

***Figure 11.15**: Time division multiplexing.*

D1 signals can be further multiplexed for fiber optic transmission. In the mid 1980's a Synchronous Optical Network (SONET) standard was adopted which provides uniform rules for multiplexing signals to be transmitted on an optical fiber; this standard is still in use today. SONET allows twenty-eight D1 signals to be multiplexed to form an STS-1 electrical signal (**Figure 11.16**). The STS-1 electrical signal can be used as input to an optical transmitter to produce an OC-1 optical signal.

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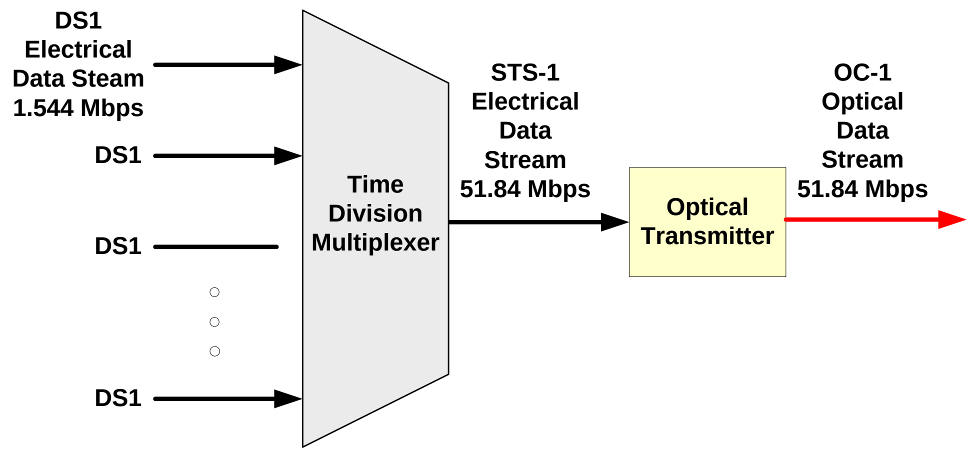

Figure 11.16: *Multiplexing of twenty-eight DS1 signals to produce an OC-1 SONET signal.*

The basic unit of a SONET signal is referred to as a frame. Each frame is 125 microseconds in length. An OC-1 frame (**Figure 11.17**) consists of 9 data packets called rows. Each row has 90 data bytes, with the first three bytes dedicated to transmission management. The 87 byte payload also contains a management byte. The *line rate* for an OC-1 signal is

$$\left(9 \text{ rows} \times 90 \frac{\text{bytes}}{\text{row}} \times 8 \frac{\text{bits}}{\text{byte}}\right) \Big/ 125 \text{ microseconds} = 51.84 \text{ Mbits/sec}.$$

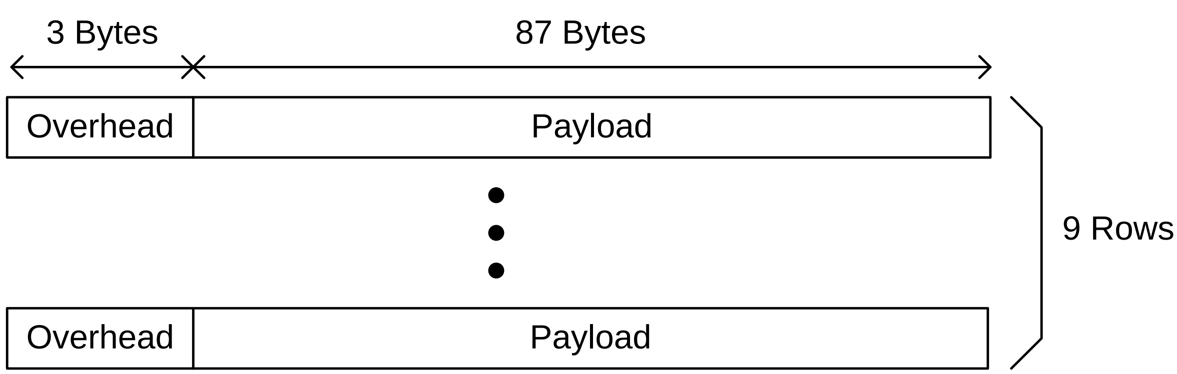

Figure 11.17: *An OC-1 SONET frame.*

The SONET standard also provides for higher line rates and the multiplexing of more data streams on an optical signal. An OC-N electrical signal is formed by interleaving the bytes of N

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OC-1 SONET frames to produce an OC-N frame that is similar to that pictured in **Figure 11.17** but with 90 x N bytes per row. Note that with minor modifications the ANSI SONET standard, developed in the United States, was adopted by the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) and renamed the Synchronous Digital Hierarchy. The most commonly used SONET/SDH levels and corresponding line rates are listed in **Table 1**. The numbers of 64 kbit/sec voice/data lines that can be multiplexed on the levels are also shown for comparison.

Table 1. SONET and Synchronous Digital Hierarchy Levels

SONET Level	SDH Level	Line Rate (Mbits/sec)	Equivalent number of 64 kbit/sec voice/data signals
OC-3	STM-1	155.52	2,016
OC-12	STM-4	622.08	8,064
OC-48	STM-16	2,488.32	32,256
OC-196	STM-64	9,953.28	129,024
OC-768	STM-256	39,813.12	516,096

The SONET standard also specifies two network topologies - the point to point linear topology and the ring topology, both described above.

11.3 Wavelength Division Multiplexing

Wavelength division multiplexing (WDM) is a way to dramatically increase the carrying capacity of optical fibers without the need to increase line rates. The very fastest electronic circuits currently available are required to operate a SONET OC-768 signal at approximately 40 Gbits/sec (corresponding to a bandwidth of approx. 40 GHz).On the other hand, this represents only a small fraction of the bandwidth of an optical fiber. To see just how small the fraction is, consider the low-optical-loss window in silica optical fiber that extends from approximately

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1460 nm to 1625 nm. This wavelength span corresponds to a frequency bandwidth of 20,860 GHz. WDM allows us to utilize a greater portion of this bandwidth by encoding independent signals at different wavelengths.

Dense Wavelength Division Multiplexing

WDM is illustrated in **Figure 11.18**. Multiple optical transmitters produce optical signals – each signal at a different optical wavelength. A wavelength division multiplexer is used to combine the optical signals. The combined signals are transmitted by an optical fiber line, which may contain additional optical amplifiers and dispersion compensation elements. A wavelength de-multiplexer is used at the receiving end of the fiber line to separate the combined optical signal into its wavelength components. The de-multiplexed signals are converted to electrical signals with optical receivers.

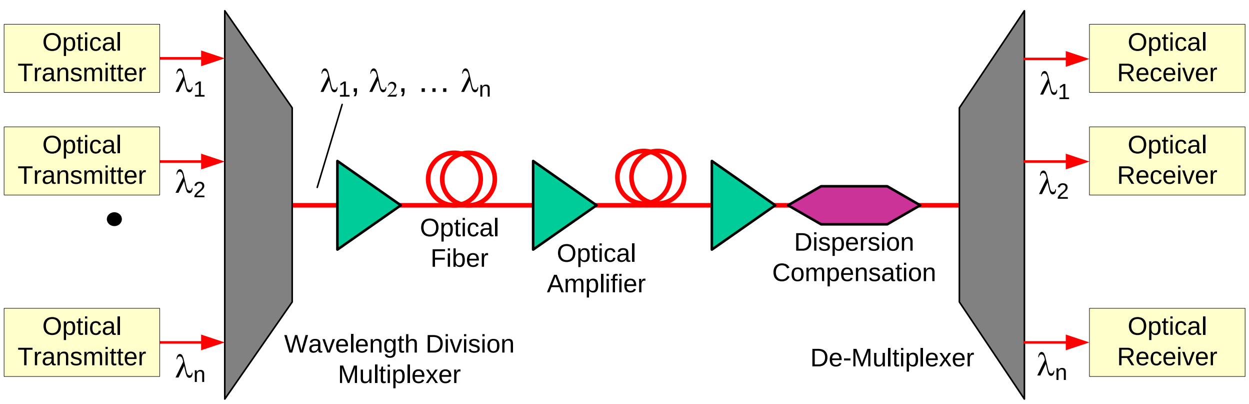

***Figure 11.18**: A point-to-point data link that uses wavelength division multiplexing (WDM).*

The ITU-T specifies wavelengths to be used for wavelength division multiplexing. The International Telecommunication Union ("ITU"), the eldest organization in the UN family still in existence, section Standardization ("T"). **Figure 11.19** shows a portion of the *ITU grid* that spans wavelengths of 1530 to 1565 nm, a range referred to in optical communications as the *C band* (conventional band). The center frequency of the grid is 193.1 THz and grid frequencies are separated by 100 GHz. WDM that uses the ITU grid wavelengths is called *Dense WDM* or *DWDM*.

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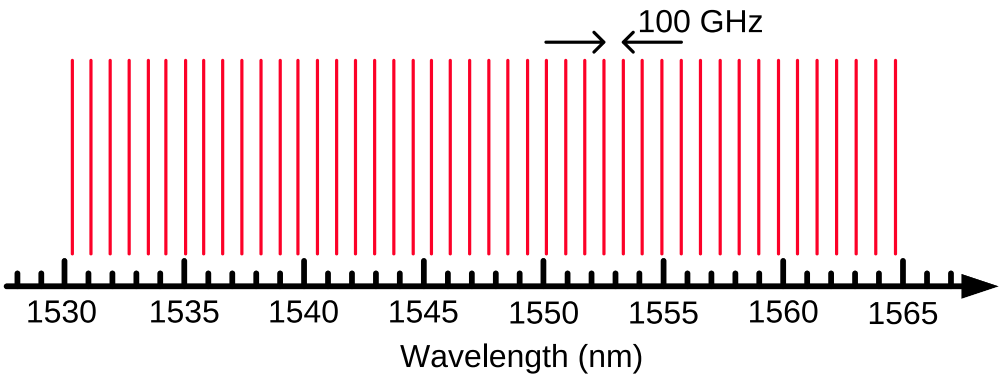

Figure 11.19: ***The ITU-T DWDM grid.***

Coarse Wavelength Division Multiplexing

The ITU-T also specifies wavelengths to be used for coarse wavelength division multiplexing or CWDM. Eighteen wavelengths between 1270 and 1610 nm, separated by 20 nm are used for CWDM (**Figure 11.20**). CWDM does not offer the data capacity of DWDM because of the smaller number of available wavelength channels. On the other hand, the wide channel spacing for CWDM means it is compatible with less expensive WDM components such as unstabilized lasers (i.e. sources whose frequency/wavelength fluctuates) and broadband optical filters. CWDM is most suitable for use in medium and short haul applications because most of the CWDM wavelengths are outside of the low-loss window for optical fiber. Where no optical amplification is needed – CWDM channel allocation reaches far beyond the amplification wavelength range of the EDFA.

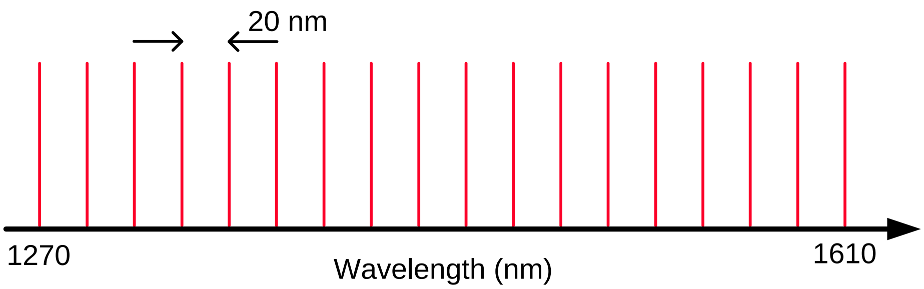

Figure 11.20*:* *Wavelengths allocated for coarse wavelength division multiplexing.*

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Optical Network Nodes for WDM

Wavelength division multiplexing offers more than just increased data carrying capacity. WDM also enables new ways to both statically and dynamically route and allocate optical signals and bandwidth. This section introduces WDM components that serve as optical network nodes. These components form the basis for current and future all-optical networks.

Figure 11.21 illustrates the operation of an optical add-drop multiplexer or OADM, which is used to add or drop (i.e. remove) a signal of a particular wavelength to or from a collection of wavelength multiplexed signals. As compared to an electronic add-drop multiplexer, an OADM functions with out OEO conversion. These days most OADMs are reconfigurable, meaning it is possible to change the wavelength to be added or dropped. A reconfigurable OAD is called an ROADM.

Figure 11.22 illustrates the function of a WDM optical cross-connect. The purpose of this component is to route one or more wavelengths between optical fibers. **Figure 11.22** shows the interchange of two wavelength signals between two fibers. A fully functional optical cross-connect can exchange any number of signals between fibers and can be reconfigured to accommodate changing demands for information bandwidth.

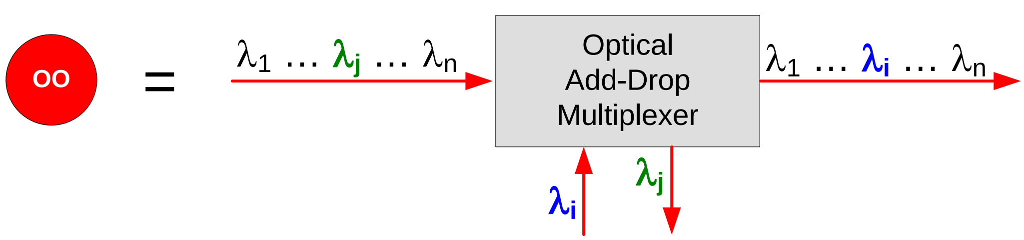

Figure 11.21: ***An optical node element known as an optical add-drop multiplexer (OAD).***

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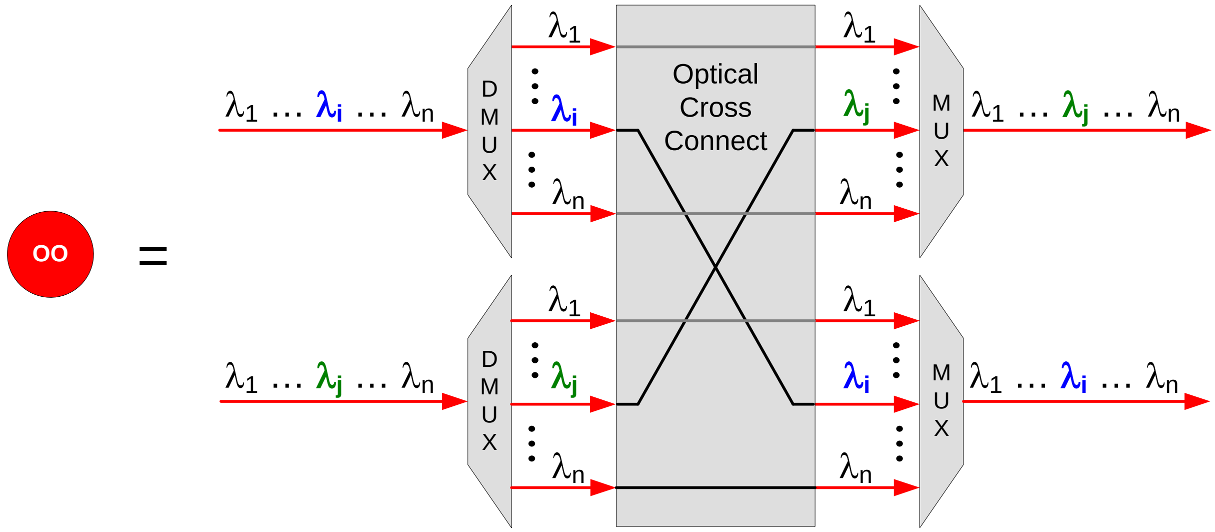

***Figure 11.22:** A WDM optical cross-connect.*

Figure 11.23 illustrates the function of a WDM wavelength converter, which finds use in larger optical networks where the same wavelength may be used for separate data signals in different portions of the network. If a signal with wavelength λi enters a portion of a network where the wavelength is already in use, a wavelength converter can be used to change the wavelength to an available value, say λj.

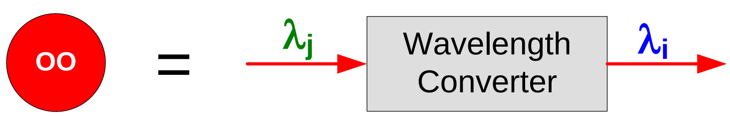

***Figure 11.23**: An optical wavelength converter.*

The WDM components of **Figures 11.21, 11.22, and 11.23** can be combined to produce optical network nodes with greater functionality and flexibility.

11.4 The Optical Network Hierarchy

The optical network currently in place can be described with a hierarchy of sub-networks as illustrated in **Figure 11.24**. Large geographic regions with dimensions of 100's or 1000's of kilometers, such as countries and continents, are spanned by long-haul networks also called core networks. A core network has a mesh topology and optical links generally have very large data

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carrying capacity – often employing tens of WDM wavelengths, each an OC-196 signal operating at 10 Gbits/sec.

The core connects metropolitan networks that span cities. Metropolitan networks are generally a collection of interconnected SONET rings. As a general rule, the metropolitan networks employ fewer WDM wavelengths and operate at slower data rates than the core.

Metropolitan networks are connected to access networks that supply data to the end users. At the present time, access networks are a combination of opaque and passive optical networks (PONs). A PON employs only two widely spaced WDM wavelengths, 1.5 µm and 1.3 µm for transmission to and from the end user respectively, and operates at modest data rates of 55 Mbits/sec to 1.25 Gbits/sec depending on the local infrastructure of the network, on what services local providers offer based on this installed infrastructure, and on what the subscriber is willing to pay. Most end users are still connected to the access network with an electrical wire or cable. The trends for optical access networks include replacement of opaque geometries with PONs and the use fiber to transmit data almost all the way to the end user.

Note that the mesh networks that span continents are connected by point-to-point data links that are implemented with undersea fiber optic cables.

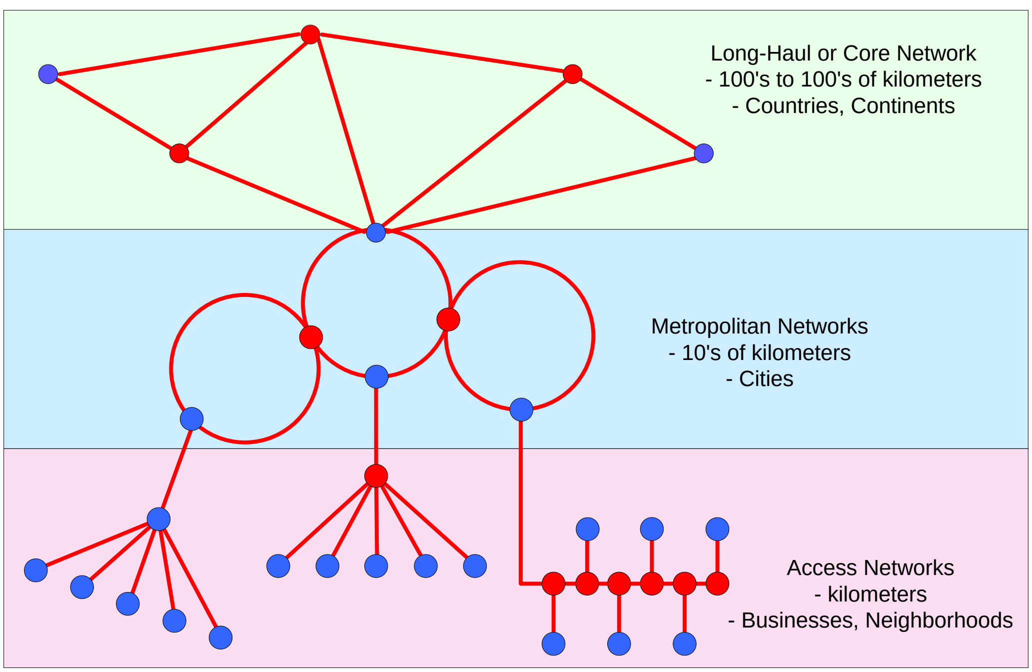

***Figure 11.24**: The optical network hierarchy*

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