Introduction to Optical Transmission in a Communications Network

Definition

In a telecommunications network, one begins at the terminal site at the customer premises; the access part of the process is the first mile. In essence, it is the part that connects the end user to the first piece of equipment in the network. Next comes the equipment that performs the connection of data or voice from one side to another, and then, finally, transmission may occur. Transmission is really the part of the process people take for granted when they casually draw a line to connect all of the pieces of equipment in the network.

Overview

This tutorial introduces key topics and new terminology with regard to transmission, focusing on the basic concepts necessary to study synchronous and optical transmission further. It will provide a more complete view of a telecommunications network, illustrating the access, switching, packet multiservice, synchronous digital hierarchy (SDH)/synchronous optical network (SONET), and optical layers. It will clarify the function performed by the SDH/SONET layer and what happens further down in the optical layer.

Topics

1. History of Transmission
2. Why Optical Transmission?
3. Transmission Signal Parameters
4. Types of Transmission Networks
5. Overview of Multiplexing
6. WDM and TDM
7. Types of Network Elements

Self-Test
Correct Answers
Glossary

1. History of Transmission

Transmission is about communication, and people have communicated for a long time. For example, smoke signals or the presence or absence of fire communicated information in millennia past. Information was also transmitted in antiquity via light-emitting devices. In both of these examples, however, communication depended on the ability of the parties involved to see each other; a cloud in the way would impede effective transmission.

Thus, people had to free themselves from this line-of-sight constraint, and sending a signal over a wire offered a solution. What was sent was no longer a visible signal, but rather voltage on a wire. Wire enabled the signal to travel vast distances without losing strength. How does a message originate and terminate such a line? The telephone provided a convenient user interface to the network.

2. Why Optical Transmission?

To understand why the world has shifted to optical transmission requires an explanation of the shift from metal to glass. First of all, light traveling in a glass fiber is immune to electrical interference. Plus, it does not radiate anything because the entire signal remains contained in the cable. Also, fiber is less bulky than other cables, and the signal travels longer distances.

With advances in technology, the cost has become very low, and a huge amount of information can be transmitted on a single fiber strand. Sending more information on metal wire means sending it a shorter distance. Fiber, however, seems to have infinite capacity.

The technology was first explored in 1966; indeed, the pioneers of the optical network discovered its possibilities more than 30 years ago. It was necessary to turn a signal into '1s' and '0s', prove the propagation along the fiber, and, of course, design the fiber itself.

A fiber is a tube of glass, as thin as a hair (see *Figure 1*). It is made of two types of glass: the inner tube is very small and maintains the flow of the light, and the outside cladding prevents the light from escaping. At present, we have many variants of optical fiber optimized for different rates of transmission and distances.

Figure 1. Fiber Strand: Very Thin Core and Large Cladding to Keep the Light Inside

3. Transmission Signal Parameters

A transmission signal has two components. The first is the information to be sent, which is represented by '1s' and '0s'. The second is the optical signal that travels on the fiber. It is worth making the distinction here that all of the network elements' functions covered here exist in the synchronous as well as the optical layer.

The principles are the same; i.e., the elements in each layer just process different things. For example, the synchronous layer handles the '1s' and '0s' (the signal transmitted optically between the points is translated back to electrical for processing in the node), whereas the optical layer juggles light signals only and is all about prisms and mirrors.

How do light and '1s' and '0s' relate? The data to be sent is in the form of an electrical signal or a series of electrical voltages represented by '1s' and '0s'. The '1s' and '0s' are translated into pulses of light by a laser. As an appropriate analogy, imagine that you are in the dark with a torch, and your means of communication is to switch your torch on and off. After a code is established, communication may occur. The other end of the link needs someone with a good eye to detect the light pulses, and this is the equivalent of what the photo diode does to reconstitute the electrical signal from the pulses of light received.

The transmission path is like a road; it is capable of going in two directions. Most telecommunications circuits are bidirectional, meaning that they can transmit and receive—except, perhaps, when dealing with broadcasting or video distribution applications.

If each data switch, telephone exchange, or radio terminal is called a point, then a transport network is something that enables these points to be connected. The transport network provides the ability to carry traffic between the points. Transmission is like plumbing in that each pipe is set up according to a certain size, and it remains the same whether data flows through it or not. Other technologies such as asynchronous transfer mode (ATM) have some virtual circuits (VCs) that do not take bandwidth if no data flows. This does not occur in the transmission network; resources are allocated and reserved, and no facilities are overbooked.

Also, congestion does not take place in transmission networks. If two signals enter an element, the signal going out is designed to be big enough to accommodate the two coming in.

4. Types of Transmission Networks

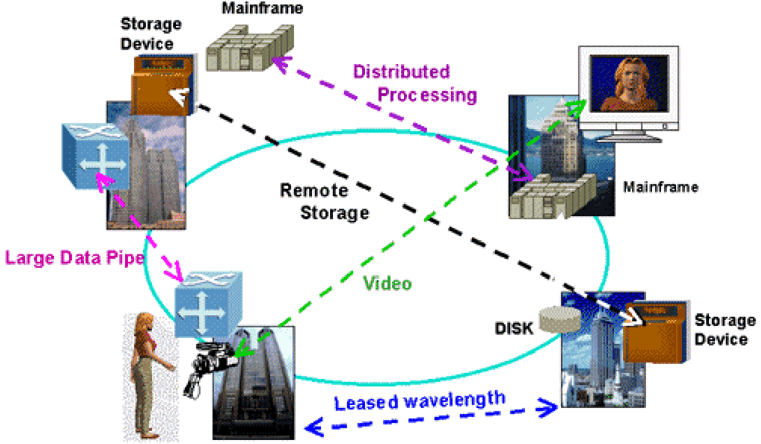
Metro versus Long-Haul

Two different transmission scenarios—one for the metro environment and one for the long-haul environment—are significant. Broadly speaking, the long haul is about creating big pipes. The types of services there are not numerous. The network shape is relatively stable; however, as traffic grows dramatically, the size of the pipes must be able to grow easily, too. On the metro side, many different services of different sizes are observable, and the shape of the network is changing rapidly as new, big customers come on board. Metro means short distances between nodes, and this is important when it comes to optical solutions (optical signals going shorter distances are cheaper than the ones going longer distances).

Apart from the traditional voice and leased-line services not represented here, new services appearing in the metro environment include the following:

- **data storage**—This service connects disc with storage medium.
- **distributed application**—This is made up of functions residing in separate geographical locations, cooperating together.
- **video link**—This is a large data pipe to carry computer traffic or a large pipe that can carry anything (leased wavelength).

Figure 2. New Metro Services



The backbone network is the traditional long-haul network that has been around for many years. Typical backbone networks have the following characteristics:

- There are an extensive number of points where traffic is going onto or leaving the network.
- Distances of a circuit (a service) transported on this network are less than 600 km.
- A new type of network is appearing: the express or super-express network, largely driven by Internet protocol (IP) traffic.
- The networks tend to be characterized by nodes that pick up a huge amount of traffic (much more than in the backbone).
- Mostly end-to-end traffic is involved, with less add/drop.
- Distances of a circuit (a service) transported on this network are greater than 1000 km.

Network Requirements

To build an economical network, the following elements are required:

- **flexibility**—This involves significant interchanges to offload traffic in various ways and is present in both metro and long-haul scenarios.
- **optics adapted to the distances**—This means going to two extremes. In the long-haul express, systems must allow the optical signal to go several thousand kilometers without requiring regeneration. In the metro, however, cheap optics for the shorter distances are preferred. Also, to save cost, each road where the traffic is

heavy must be able to carry maximum traffic, which leads to the final requirement.

- **option for a number of signals to share the same optical fiber**—This may enable the best use of the fiber, if this is important. Installing cable is expensive, especially on long distances. Getting the right of way and digging takes time and money, and this is not an attractive proposition for a telecom carrier that hopes to get its network running and producing revenues.

5. Overview of Multiplexing

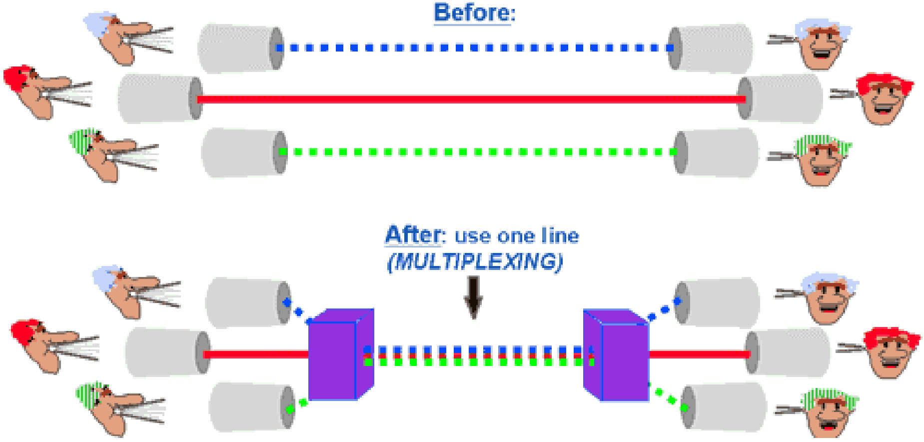
Suppose a company with a link between two cities wished to maximize the traffic between them. First, the data (or "cars") must be sent faster. Then, more lanes must be acquired. This is the basis of time division multiplexing (TDM) and wavelength division multiplexing (WDM). The capacity of this link is the sum of the speed of each of the lanes. Transmission technology deals with the concept of multiplexing, clarifying TDM and WDM.

The transport network has been defined as a set of links between telecommunication sites. Before multiplexing was discovered, each telephone call needed its own link to be transmitted. Many telephone calls needed many links, which was expensive.

A way to put more than one telephone call on each link must be found to save money. The best way to put more than one telephone call on each link is to multiplex the calls. This makes best use of the links.

The easiest way to understand multiplexing is to remember the transmission game one played as a child: two tin cans connected by a piece of string (see *Figure 3*). In essence, that was a private link. Multiplexing, however, enables several telephone calls to be sent on the same line. The end users have the illusion of being on their own private link. In effect, multiplexing creates a virtual telephone link for all of the users, which is an early telephone version of virtual reality. Synchronous multiplexing is TDM. Optical transmission uses a different type of multiplexing, WDM, which will be clarified later in the tutorial.

Figure 3. Multiplexing

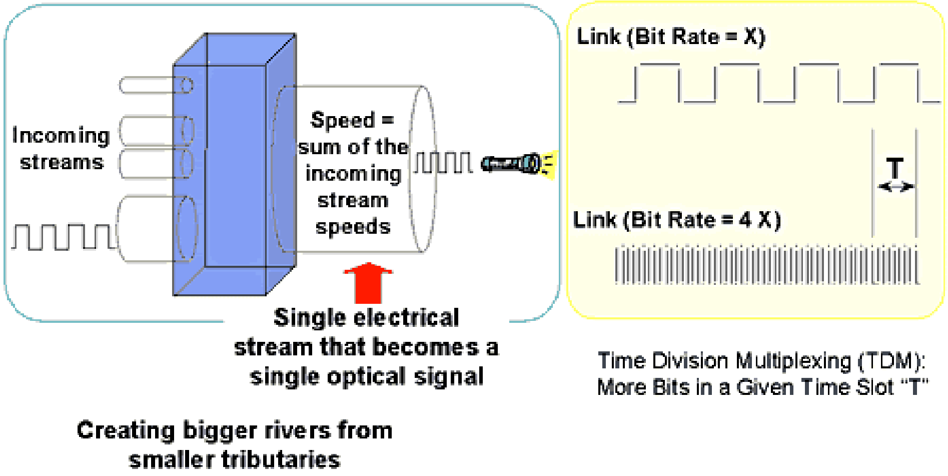


As seen earlier, a way to put more than one call or streams of '1s' and '0s' on a line is to combine them together. Imagine a conveyer belt between two places getting fed by four other conveyer belts. If each of the feeding belts are dropping a widget to be transported every four seconds, then how fast does the middle one need to work to serve the four other belts? If it goes at the same speed, would it work?

The answer is yes, for if the system is to function effectively, the belts should be synchronized, and each widget should be sent one after the other. This means that the middle conveyor belt could carry four times more widgets than any of the other four feeding conveyor belts by placing the widgets closer together.

In TDM, all of the speeds add up, and, hence, neither SDH nor SONET have any concept of congestion or priority (see *Figure 4*). The size of the pipes going in a node equals the size of the traffic pipe out of a node. If the incoming traffic arrives from four places at 2.5 Gbps, the outgoing pipe will be 4 Gbps by 2.5 Gbps, which is 10 Gbps.

Figure 4. TDM Multiplexing



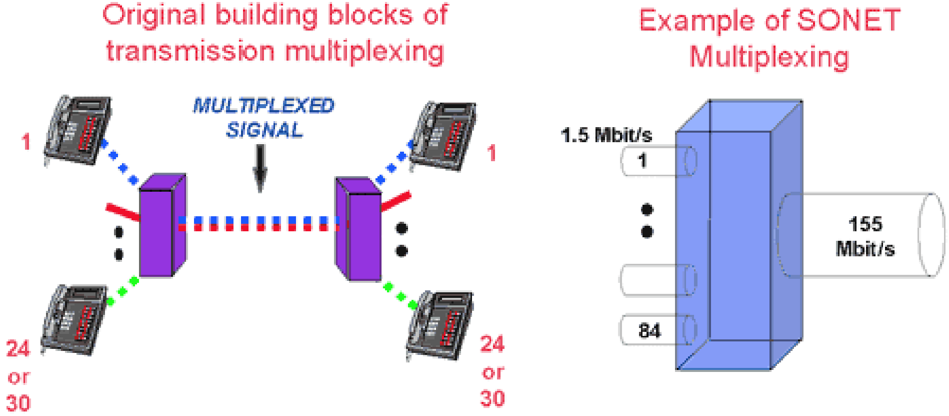
The resulting bit stream is converted into light using a laser and then becomes one of the input light streams of an optical multiplexer, if WDM is in the network.

In the first stage of multiplexing phone calls, the resulting bit rate is 1.5 Mbps and called T1/DS1 in North America, or it is 2 Mbps and called E1 outside of North America. It deals with the smallest stream handled by a transmission network.

Transmission systems that are designed according to European rules work with groups of 30 telephone calls. A group of 30 telephone calls is multiplexed into a 2–Mbps digital signal, and throughout most transmission documents and presentations, constant references to 2–Mbps channels may be found. These 2–Mbps streams are the basic building blocks for multiplexing.

Transmission systems that are designed according to North American rules work with groups of 24 telephone calls (see *Figure 5*). A group of 24 telephone calls is multiplexed into a 1.5–Mbps digital signal. These 1.5–Mbps channels are the basic building blocks for multiplexing in North America. A SONET multiplexing example shows how 84 T1 or DS1 combine into a 155–Mbps stream. An SDH picture would show how 63 E1 combine into a 155 Mbps stream.

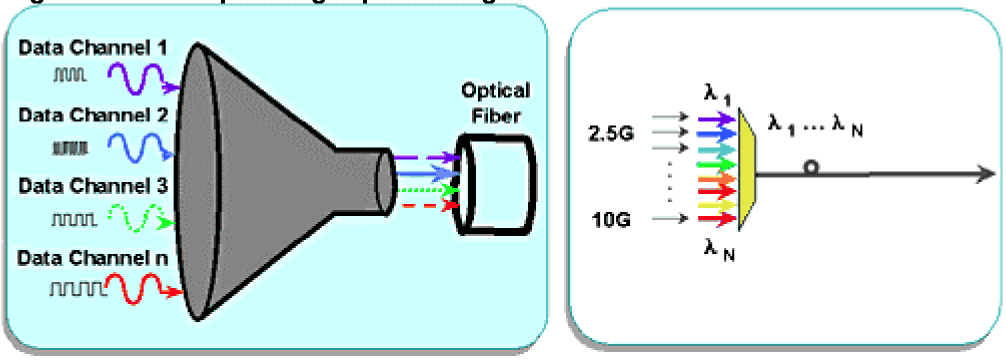
Figure 5. Multiplexing Examples



6. WDM and TDM

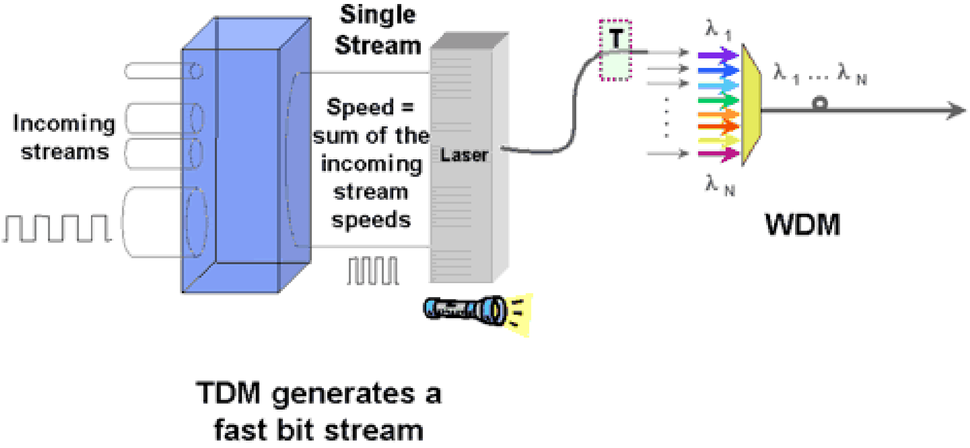
WDM takes optical signals (each carrying information at a certain bit rate), gives them a color (a wavelength or specific frequency), and then sends them down the same fiber (see *Figure 6*). Each piece of equipment sending an optical signal has the illusion of having its own fiber. WDM gets more cars to travel, not by increasing their speed but by getting them to travel in parallel in their own dedicated lanes. Traffic in each lane can travel at different speeds, as each lane is independent. The wavelengths used for WDM are chosen in a certain range of frequencies (around 1550 nm), also called a window.

Figure 6. Multiplexing Optical Signals



TDM is there to generate the fastest bit stream possible or economical in a part of the network (see *Figure 7*). The fastest stream deployed now is 10 Gbps. This stream can then be fed into a WDM system, creating the greatest capacity on a fiber—which is now 160 wavelengths at 10 Gbps or 1.6–Tbps capacity on a single fiber.

Figure 7. Relation between TDM and WDM



The development of the next TDM transmission speed (40 Tbps) is now underway. Trials of WDM at this speed have already been completed. If the TDM (synchronous) multiplexer cannot generate the proper color needed for the WDM system, an adaptor (called a wavelength converter) can be used.

The synchronous multiplexers generate the correct colors for the WDM system, saving this extra piece of equipment. However, this wavelength converter is still useful to pick up traffic from other sources.

Similar functions in the TDM and WDM environment may be identified. In fact, TDM simply manipulates bit streams, while WDM manipulates wavelengths (or streams of light).

7. Types of Network Elements

Fixed versus Flexible

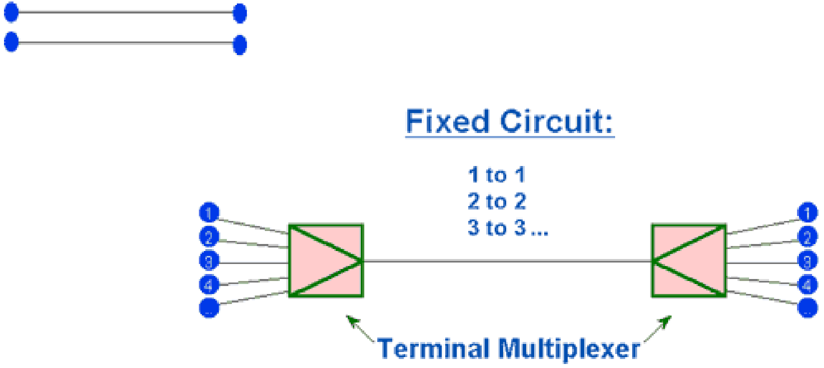
The objective of a transmission network is to connect points, and two approaches are possible:

- a fixed, point-to-point link
- a road with crossroads and junctions

A simple, fixed, point-to-point network does not allow changes to the way the traffic is delivered between the points; it is very inflexible. A flexible network allows changes to the way the points are connected and can respond to new connection requests faster than a fixed network.

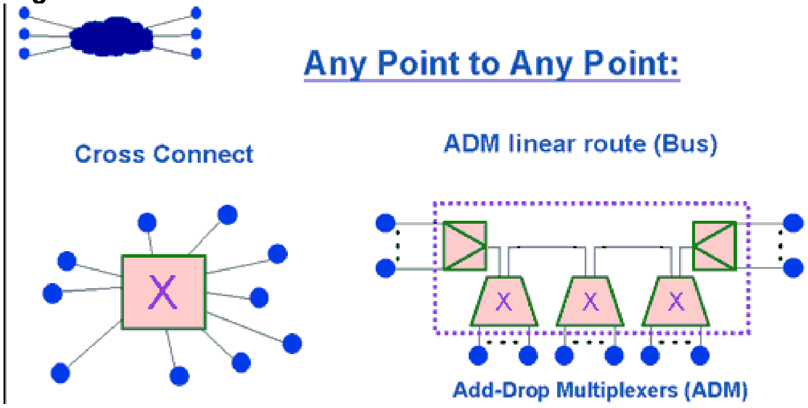
A fixed, point-to-point network is used when the end-user connections are not expected to change—hence, no flexibility is required (see *Figure 8*). The equipment used to implement a point-to-point connection is called in TDM a terminal multiplexer (mux) or line system. In WDM, it is called an optical mux/demux. A mux offers fixed connections between end-user termination points.

Figure 8. Fixed Point to Point



The other type of connection is through a flexible network (see *Figure 9*). This can be implemented using cross-connects or bus structures. A cross-connect is a piece of equipment that provides flexible connections between its termination points. A bus structure allows, in the same way, flexible connections between the termination points of the elements making up the network. The bus route has some bus stops, and the flexibility of going from one point to any other point comes from being able to jump on, jump off, or stay on at any bus stop by means of the add/drop multiplexer (ADM).

Figure 9. Flexible Network



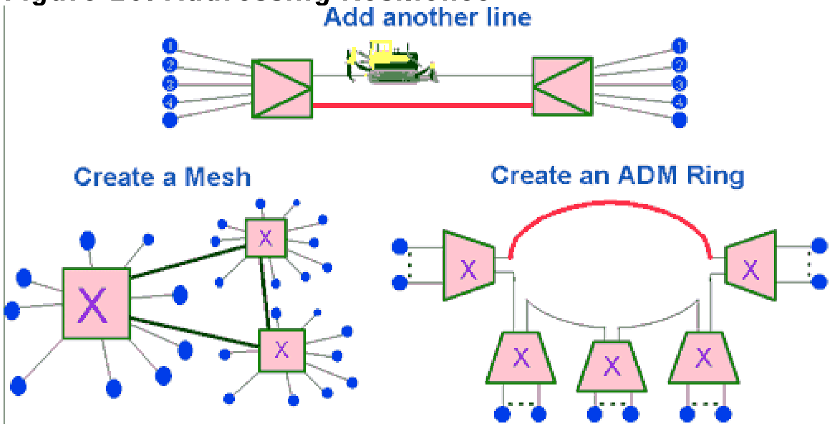
The dotted line around the bus structure in the *Figure 9* shows that the bus can be considered a cross-connect to some extent. In TDM (handling bit streams), the cross-connect is called digital cross-connect system (DCS). In WDM, it is called the photonic cross-connect (PXC). In TDM, the synchronous mux is just an ADM. In WDM, it is an optical add/drop multiplexer (OADM), which handles wavelengths.

Network Survivability

Network survivability is a key issue because it reduces operating costs (the carrier need not send a team out in the middle of the night) and provides the carrier with an opportunity for increased revenue (as a result of offering better quality of service [QoS]).

How can a connection remain up if a node fails or if a link breaks? First, a simple circuit setup must be made more resilient. In a point-to-point scenario, link resilience can be introduced by duplicating the link (see *Figure 10*). Maximum protection is achieved if these two links are routed separately. In the case of a flexible network implemented with a cross-connect, a mesh with its multiple routes offers survivability options. In a bus structure, resilience is achieved by adding an extra link to the network to make a ring, offering simple alternative routes for the connections should they be needed.

Figure 10. Addressing Resilience

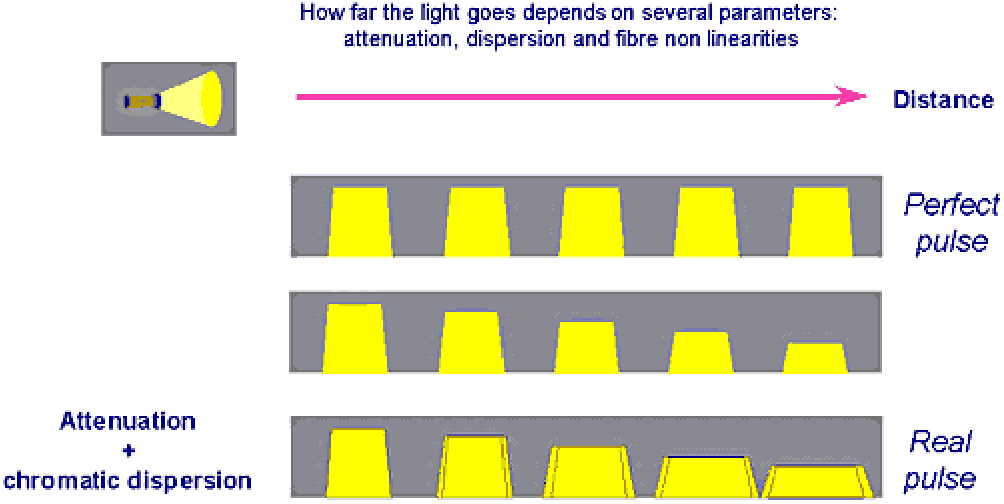


Another network element not yet mentioned is the regenerator. It does not add functionality in terms of traffic handling but is present for transmission purposes.

Attenuation and Dispersion

Two main effects will be discussed here: attenuation and chromatic dispersion (see *Figure 11*). With distance, pulses get smaller, as a result of attenuation. Pulses also get fatter or more spread out, as a result of chromatic dispersion. The game is to keep the pulses tall and thin so that the receiver at the end can recognize and separate them. Small and fat pulses would indeed blur together after some distance, making the receiver unable to recognize the original signal.

Figure 11. Attenuation and Dispersion



Pulses of light must go as far as possible along a fiber to minimize the cost of the link. Light can typically travel 40 or 80 km before it gets too attenuated or dispersed. The farther it can travel without needing a site with equipment to boost the signal, the cheaper the resulting network will be.

The typical way to get light to go farther has been to terminate the link (i.e., go back to electrical signal) and start again. This process is simple, neat, and unfortunately, expensive at high data rates as a result of the cost of the opto-electronics to receive the optical signal, generate the electrical signal from it, and regenerate an optical signal.

In a network, it means that after a given distance (depending on the source, receiver, and type of fiber—perhaps 40 to 60 miles), a site is needed to house a regenerator. Other less expensive options revolve around the optical layer and the amplifier.

The alternative to regeneration is to simply give more energy to the light signal without terminating it. If one imagines a relay race, regenerating is getting a new runner to run part of a span (passing the relay), whereas amplification is keeping the same runner for the whole race but feeding her at strategic places to keep her going. Regeneration is expensive because it must be done per wavelength, whereas amplification technology is attractive because it boosts the entire optical signal in one try—hence, the numerous wavelengths. The cost is in this way shared between the various channels.

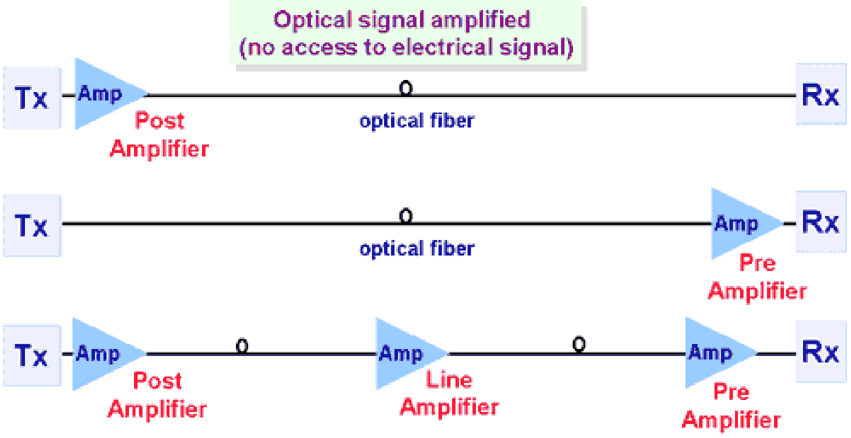
Figure 12 shows types of amplifiers.

- **post-amplifier**—This comes just after the transmitter. A post amp may just give the reach needed to get to the other end without the necessity of an intermediate site.

- **pre-amplifier**—This may be added just before the receiver if a post-amplifier is not enough.

- **line amplifiers**—One or more of these are added in the middle of the span. A combination of post-, pre-, and line amplifiers gives a reach of several hundred kilometers. A number of amplifiers can be cascaded (used one after the other), but there is a limit after which regeneration is needed.

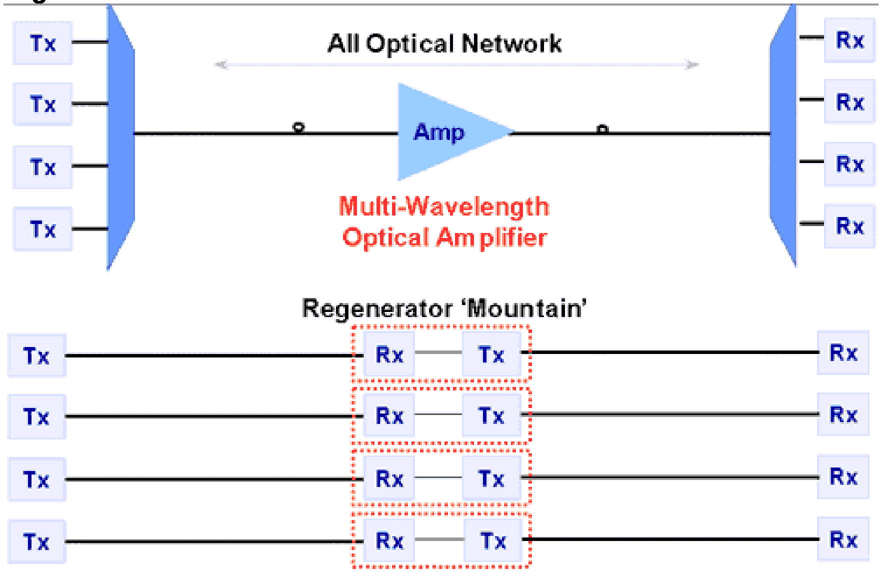
Figure 12. Amplifiers/Repeaters



Economics

Figure 13 shows one of the business cases for WDM. The WDM signal made up of several wavelengths is given extra energy by an optical amplifier. The most common of these are erbium-doped fiber amplifiers (EDFA). The alternative before amplifiers was to use regenerators, and in the case of WDM, this meant that a regenerator was needed for each of the optical signals or colors.

Figure 13. WDM Network Economies

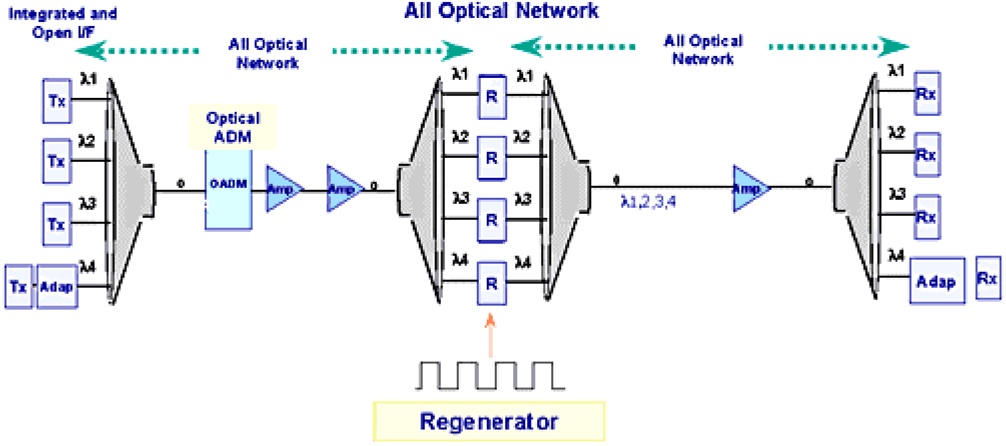


Thus, using amplifiers on a WDM system becomes very economical in comparison to the stack of regenerators that would be needed otherwise. The expense of fiber and equipment needed on the line are eliminated. However, the advent of amplifiers does not mean the end of regenerators in a WDM system.

When a span is so long that the maximum number of amplifiers cascaded is reached, then regenerators must be used.

Figure 14 is an example of a link with two spans, each with amplifiers. The maximum number is reached, although not all are represented here. Regenerators work on individual wavelengths and therefore all individual wavelengths of the optical signal must be muxed/demuxed at the regenerator point.

Figure 14. Complete Point-to-Point Optical Link



Overview

The following is an overview of the main elements of a point-to-point WDM system:

The optical transmitter of the transmission equipment sends the correct wavelength; if the equipment does not have a transmitter generating the precise color required by the WDM system, then a wavelength translator can be used to terminate the optical signal and generate the WDM wavelength. A wavelength translator allows any optical traffic to be supported by the WDM system. However, synchronous equipment suppliers supporting the complete transmission portfolio (SONET/SDH–based multiservice platforms and the optical portfolio) can choose to have their transmitter generate the correct wavelength directly and thus eliminate an extra component and create more reliable and economical systems.

What gets in the way of light transmission is attenuation and dispersion. Here is a quick overview of the solutions to address the chromatic dispersion issue:

- **fibers**—These are designed to minimize dispersion. However, special fiber means extra cost.

- **dispersion compensation module (DCM)**—The fiber type in a network determines the amount of dispersion to which the optical signal will be submitted. This can be remedied by the use of DCM. A DCM is a length of fiber that distorts the light pulses in a manner that creates a better pulse shape at the other end of the link.

- **transmitters**—Another way to address dispersion is to design the light source to generate a cleaner pulse.

Lasers can be modulated in two ways: direct modulation or external modulation. Direct modulation means that the laser is switched on and off. The technology to do this is cheap but would not be effective for long distances. External modulation consists of leaving the laser on and masking the signal; this is more advanced and more expensive technology. However, long distances can be achieved with this.

Self-Test

1. ______________ prevents light from escaping in a fiber.

   a. inner tube

   b. cladding

2. A transmission signal has ____________ components.

   a. one

   b. two

   c. three

   d. four

3. Metro means ______________ distances between nodes.

   a. short

   b. long

4. The best way to put more than one telephone call on each link is to multiplex the calls.

   a. true

   b. false

5. Transmission systems that are designed according to North American rules work with groups of __________________ calls.

    a. 24

    b. 26

    c. 30

    d. 32

6. With WDM, traffic in each lane must travel at the same speed.

    a. true

    b. false

7. ________________ is there to generate the fastest bit stream possible or economical in a part of the network.

    a. TDM

    b. WDM

8. ________________ manipulates bit streams while ________________ manipulates wavelengths.

    a. WDM; TDM

    b. TDM; WDM

9. With distance, pulses get smaller, as a result of _______________.

    a. dispersion

    b. attenuation

10. Longer distances can be achieved with _______________ than with _________________.

    a. direct modulation; external modulation

    b. external modulation; direct modulation

Correct Answers

1. ______________ prevents light from escaping in a fiber.

    a. inner tube

    b. cladding

    See Topic 2.

2. A transmission signal has ____________ components.

    a. one

    b. two

    c. three

    d. four

    See Topic 3.

3. Metro means ______________ distances between nodes.

    a. short

    b. long

    See Topic 4.

4. The best way to put more than one telephone call on each link is to multiplex the calls.

    a. true

    b. false

    See Topic 5.

5. Transmission systems that are designed according to North American rules work with groups of __________________ calls.

    a. 24

    b. 26

    c. 30

   d. 32

   See Topic 5.

6. With WDM, traffic in each lane must travel at the same speed.

   a. true

   b. false

   See Topic 6.

7. ________________ is there to generate the fastest bit stream possible or economical in a part of the network.

   a. TDM

   b. WDM

   See Topic 6.

8. ________________ manipulates bit streams while ________________ manipulates wavelengths.

   a. WDM; TDM

   b. TDM; WDM

   See Topic 6.

9. With distance, pulses get smaller, as a result of _______________.

   a. dispersion

   b. attenuation

   See Topic 7.

10. Longer distances can be achieved with _______________ than with ________________.

    a. direct modulation; external modulation

    b. external modulation; direct modulation

    See Topic 7.

Glossary

ATM
asynchronous transfer mode

ADM
add/drop multiplexer

DCM
dispersion compensation model

DCS
digital cross-connect system

EDFA
erbium-doped fiber amplifier

IP
Internet protocol

OADM
optical add/drop multiplexer

PXC
photonic cross-connect

QoS
quality of service

SDH
synchronous digital hierarchy

SONET
synchronous optical network

TDM
time division multiplexing

VC
virtual circuit

WDM
wavelength division multiplexing